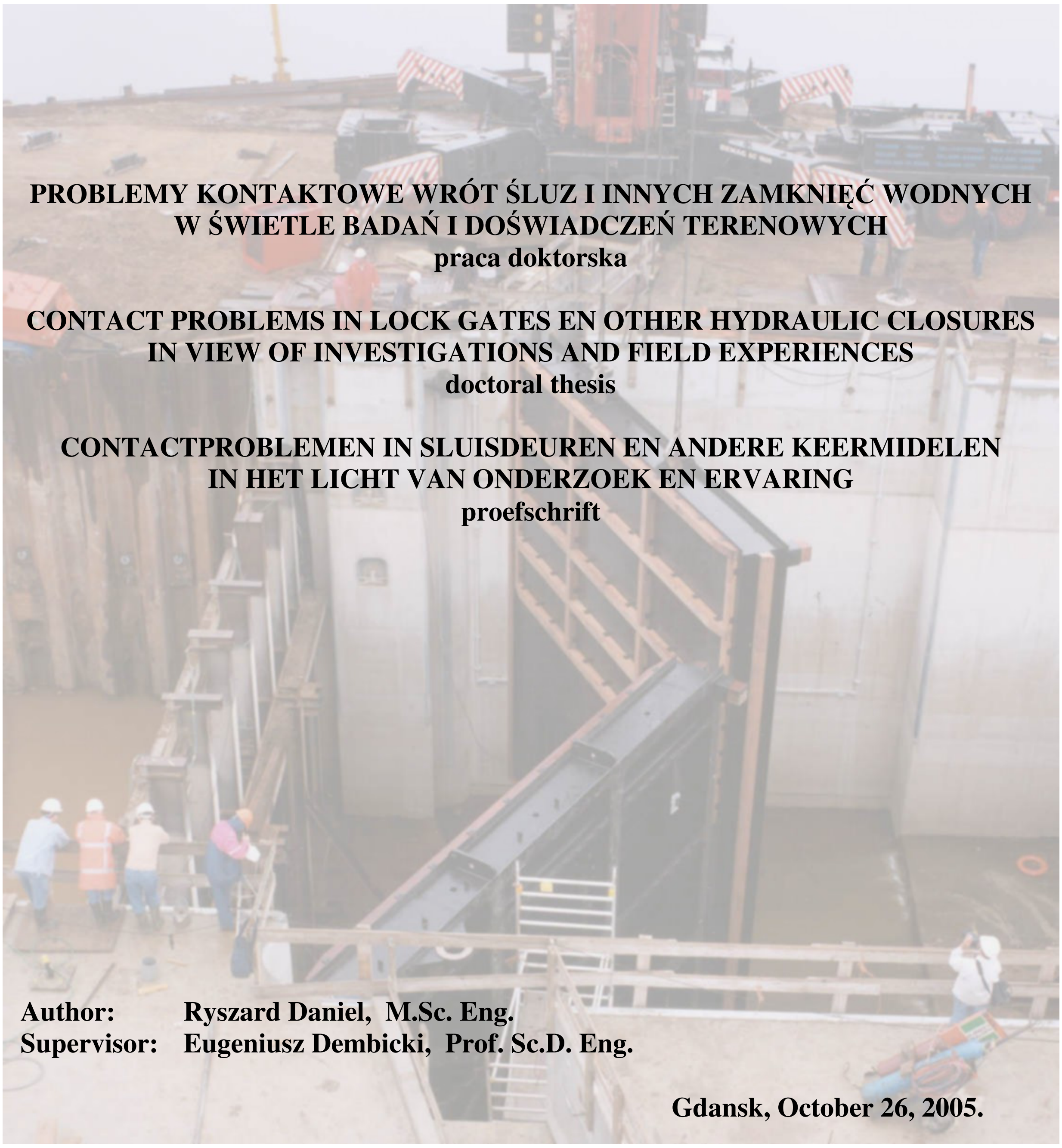
Gdansk University of Technology
Civil and Environmental Engineering Faculty



PROBLEMY KONTAKTOWE WRÓT ŚLUZ I INNYCH ZAMKNIĘĆ WODNYCH W ŚWIETLE BADAŃ I DOŚWIADCZEŃ TERENOWYCH
praca doktorska

CONTACT PROBLEMS IN LOCK GATES EN OTHER HYDRAULIC CLOSURES IN VIEW OF INVESTIGATIONS AND FIELD EXPERIENCES
doctoral thesis

CONTACTPROBLEMEN IN SLUISDEUREN EN ANDERE KEERMIDELEN IN HET LICHT VAN ONDERZOEK EN ERVARING
proefschrift

Author: Ryszard Daniel, M.Sc. Eng.
Supervisor: Eugeniusz Dembicki, Prof. Sc.D. Eng.

Gdansk, October 26, 2005.

This page is deliberately left blank.

Gdansk University of Technology
Civil and Environmental Engineering Faculty

PROBLEMY KONTAKTOWE WRÓT ŚLUZ I INNYCH ZAMKNIĘĆ WODNYCH
W ŚWIETLE BADAŃ I DOŚWIADCZEŃ TERENOWYCH
praca doktorska

CONTACT PROBLEMS IN LOCK GATES AND OTHER HYDRAULIC CLOSURES IN VIEW OF INVESTIGATIONS AND FIELD EXPERIENCES

doctoral thesis

CONTACTPROBLEMEN IN SLUISDEUREN EN ANDERE KEERMIDDELEN
IN HET LICHT VAN ONDERZOEK EN ERVARING
proefschrift

Author:	Ryszard Daniel, M.Sc. Eng.
Address:	Ministry of Transport, Public Works and Water management of the Netherlands, Civil Engineering Division, P.O. Box 59, 2700AB Zoetermeer, The Netherlands
Supervisor:	Eugeniusz Dembicki, Prof. D.Sc. Eng. Politechnika Gdańska, Wydział Inżynierii Lądowej i Środowiska, ul. G. Narutowicza 11/12, 80-952 Gdansk, Poland

Place, date: Gdansk, October 26, 2005.

This doctoral thesis has been completed at the Gdansk University of Technology, Faculty of Civil and Environmental Engineering, on the authority of:

- Janusz Rachoń, Prof. PhD. Eng., rector of the Gdansk University of Technology;
- Krzysztof Wilde, Prof. PhD. Eng., dean of the Civil and Environmental Engineering Faculty.

The thesis was publically defended by the author on October 26, 2005 in the auditorium of the Civil and Environmental Engineering Faculty of the Gdansk University of Technology, Narutowicza 11/12, 80-952 Gdansk, Poland. The defence covered a number of propositions which can be summarized by the following statement:

"In the design and execution of hydraulic structures, contact issues ought to be:

- dealt with starting from the very early stage of the project;
- considered broadly, in an interdisciplinary manner."

The statutory opposition to this thesis was delivered by:

- Władysław Buchholz, Prof. PhD. Eng., of the Szczecin (Stettin) University of Technology;
- Bolesław Mazurkiewicz, Prof. PhD. Eng., of the Gdansk (Danzig) University of Technology;

and answered by the author along with the questions that were forwarded by the audience.

CONTENTS

ACKNOWLEDGEMENTS

The author would like to thank all individuals who raised the idea of this thesis, managed to incite his enthusiasm for it and helped to realize this idea by supervising, commenting and setting up propitious conditions for this work. This includes in particular Prof. E. Dembicki, the supervisor of this thesis, and Dr. K.Wilde, the dean of the Civil and Environmental Engineering Faculty of the Gdańsk University of Technology, Prof. Bolesław Mazurkiewicz of the Gdańsk University of Technology and Prof. Władysław Buchholz of the Szczecin University of Technology, the opponents, Prof. J. Głomb of the Polish Academy of Sciences, Prof. H. Huis in ‘t Veld of the TNO Institute in Eindhoven and Dr. S. Rienstra of the Eindhoven University of Technology.

Although the work on this thesis did not make part of any subsidized project, nor was it financially supported in another way, the majority of the used material was collected from the author’s research, design and other activities in the Civil Engineering Department of the Dutch Ministry of Transport, Public Works and Water Management. The employment in this department gave the author a unique opportunity to participate in a number of fascinating hydraulic projects. The thanks for that opportunity are extended to Mr. W. Seinen, Mr. H. van der Weijde and Mr. J.C.F. Hendriks – as well as to all colleagues of the Civil Engineering Department (Bouwdienst Rijkswaterstaat).

Special thanks are addressed to Mrs. J.N. Stelling, the author’s wife, who took diverse family tasks over, tolerating her husband’s long evenings behind the PC during the work on this thesis. This thesis would not be possible without her encouraging support.

STRESZCZENIE

Niniejsza praca doktorska jest próbą zebrania doświadczeń i rezultatów badań autora w problematyce podparć i innych elementów kontaktowych zamknięć hydraulicznych, takich jak wrota śluz, jazów i ruchomych zapór. Ujęcie tematu ma charakter interdyscyplinarny. Praca zawiera zarówno przegląd obciążeń, zjawisk trybologicznych i innych istotnych do projektowania i utrzymania elementów kontaktowych, jak i przedstawienie wpływu szeroko pojętego zachowania się tych elementów na proces wyboru i projektowania całych ustrojów zamknięć hydraulicznych.

Zebrany materiał oraz przedstawione rozwiązania pochodzą głównie z 20-letniej praktyki autora w zakresie projektowania, badań, i organizacji budów obiektów hydrotechnicznych – przede wszystkim zamknięć wodnych. Przeważającą część tej praktyki autor zdobył pracując jako inżynier prowadzący projekty infrastrukturalne w Wydziale Inżynierii (Bouwdienst Rijkswaterstaat) holenderskiego Ministerstwa Transportu, Gospodarki Wodnej i Robót Publicznych. Obok opracowań i rozwiązań własnych w pracy wykorzystano także szereg doświadczeń kolegów autora, dostępną literaturę oraz wiedzę uzyskaną drogą kontaktów międzynarodowych, w tym poprzez Stałe Międzynarodowe Stowarzyszenie Kongresów Żeglugi (PIANC), którego autor jest czynnym współpracownikiem.

W niniejszej pracy autor stara się uwypuklić rangę problematyki kontaktowej w projektowaniu wrót śluz, jazów i zapór. Przedstawiona i udowodniona zostaje teza, że problematyce tej należy poświęcać uwagę we wszystkich fazach projektu – od określenia oczekiwanego rezultatu do jego użytkowania włącznie. Jest to teza o tyle nowa, iż w praktyce inżynierskiej problemy kontaktowe najczęściej traktuje się jako rzecz do rozwiązania na etapie dopracowywania szczegółów. Tymczasem podjęcie ich na etapie np. doboru ustroju nośnego pozwoliłoby uniknąć szeregu późniejszych kłopotów.

Tezę pracy bliżej przedstawiono w **rozdziale 1**. Zgodnie z przyjętą metodologią podziału projektu na fazy **rozdział 2** poświęcony jest wymaganiom, jakie należy sformułować pod adresem przyszłego zamknięcia wodnego, a szczególnie jego podpór i innych elementów kontaktowych, przed przystąpieniem do projektowania. Temat ten przedstawiono w systematyce, jaką zaleca się stosować w holenderskiej praktyce inżynierskiej. Ze względu na różnorodność spotykanych zamknięć skoncentrowano się na wrotach śluz i (w mniejszym stopniu) ruchomych zapór jako zamknięciach, w których element ruchu współdecyduje o rozwiązaniu obszarów kontaktowych. W przykładach ograniczono się do trzech najczęiej w Holandii stosowanych rodzajów, tzn. wrót wspornych, pionowych i przesuwnych.

W **rozdziale 3** omówiono kwestię wyboru ustroju statycznego zamknięć wodnych z uwzględnieniem problematyki kontaktowej. Przedstawiono różnice wpływu różnych rodzajów podpór – oraz parametrów podpór tego samego rodzaju – na zachowanie się całych ustrojów. Szczególne nmiejsce zajmują w tej dziedzinie problemy wrót śluz przenoszących obciążenia hydrauliczne ze zmiennych kierunków. Przedstawiony został również krótko wpływ takich czynnników jak czas i temperatura.

Tematem **rozdziału 4** jest systematyka doboru obciążeń projektowych w obszarach kontaktowych na podstawie podprzypadków obciążeń wrót jako całości. Okazuje się, że prawidłowe rozwiązanie projektowe stref kontaktowych (obszarów łożysk, podpór, zawiesi, zderzaków, uszczelnień itp.) wymaga często rozpatrzenia większej liczby przypadków obciążeń niż wymiarowanie samych wrót. Wynika to m.in. z jednostronnego charakteru podparć, stosowania nieizotropowych materiałów itp. Nieuwzględnienie tej okoliczności może prowadzić do zakłóceń w pracy oraz awarii wrót.

W **rozdziale 5** przedstawiono analizę wybranych problemów kontaktowych zamknięć hydraulicznych. Po krótkim wprowadzeniu teoretycznym przedstawiono – na przykładach zrealizowanych obiektów – opracowania szeregu typowych dla zamknięć hydraulicznych problemów kontaktowych. Szczególną uwagę poświęcono wybranym zjawiskom nieliniowym, jak ekspansja (w niektórych przypadkach również zawężanie się) stref kontaktowych pod wpływem obciążeń. Większość przytoczonych

przykładów pochodzi z praktyki inżynierskiej autora; inne z projektów prowadzonych przez jego kolegów z Wydziału Inżynierii holenderskiego „Rijkswaterstaat'u".

Ważne miejsce w projektowaniu elementów kontaktowych zajmuje dobór materiałów. W **rozdziale 6** przedstawiono program i wyniki przeprowadzonych pod kierownictwem autora badań laboratoryjnych w tym zakresie. Badania te odbyły się w kilku seriach w Laboratorium Mechanicznym „Schielab" w Bredzie i objęły szereg kombinacji materiałów kontaktowych łożysk śluz – zarówno stosowanych jak i nowych. Badano właściwości mechaniczne tych materiałów, takie jak odporność na lokalne naciski powierzchniowe w warunkach stacjonarnych i przy poślizgu, tarcie, ścieralność, generowanie ciepła i jego wpływ na zachowanie się materiału, zmiany w jego mikrostrukturze. Parametry badań były tak dobrane aby odpowiadały one rzeczywistym warunkom pracy łożysk wrót śluz. Rezultaty tych badań umożliwiły autorowi i jego kolegom zastosowanie nowych, lepszych rozwiązań materiałowych i konstrukcyjnych w łożyskach zamknięć wodnych.

W **rozdziale 7** przedstawiono koncepcję nowego, jeszcze nie zrealizowanego, systemu podparcia wrót wspornych i jednoskrzydłowych – tzw. „wrota wiszące". Koncepcja ta ma szereg zalet wynikających przede wszystkim z faktu, że przejęcie pionowej reakcji wrót (głównie od ciężaru własnego) odbywa się poza ich łożyskami. Zebrane przez autora doświadczenia terenowe wykazały, iż to właśnie kombinacja obciążenia pionowego (osiowego) i poziomego (radialnego) w jednym bloku łożyskowym prowadzi do nadmiernej ścieralności i zakłóceń w pracy wrót. Koncepcja wrót wiszących eliminuje strukturalnie źródło tych zakłóceń.

W podsumowaniu pracy w **rozdziale 8** powtórzono najważniejsze wnioski i zalecenia w zakresie tak samego podejścia do problematyki kontaktowej zamknięć wodnych jak i konkretnych rozwiązań technicznych w ramach tej problematyki. Jednocześnie zasygnalizowano obszary i kierunki zalecanych dalszych badań w tym zakresie.

Załącznikiem do niniejszej pracy jest program komputerowy autora, DISCO, umożliwiający analizę dwu- i trójwymiarowych układów prętowych o nieciągłych (discontinuous) warunkach podparcia. Program oparty jest na oryginalnym algorytmie iteracyjnym sprawiającym, że komputer sam znajduje aktywne, przy danym układzie obciążeń, strefy podparć i generuje odpowiadające temu kompletne rozwiązanie problemu. Aczkolwiek DISCO oferuje jedynie analizę układów prętowych, to za pomocą tego programu można jednak symulować całą gamę problemów kontaktowych – zarówno w budownictwie wodnym jak i w innych dziedzinach techniki.

SUMMARY

This doctoral thesis contains a collection of the author's research results and practical experiences in the field of supports and other contact components in hydraulic closures, such as lock gates, gates of weirs and movable storm surge barriers. The subject has been approached in an interdisciplinary manner. Presented are an overview of design loads, tribological and other phenomena significant for the design and maintenance of contact components, and the impact of those components behavior on the type selection and design process of the entire hydraulic gate systems.

The reference material and presented solutions are mainly collected from the author's 20 years' experience in engineering, research and construction management of water related projects, particularly hydraulic gates. Predominate part of this experience is related to his function of lead design engineer for infrastructural projects by the Civil Engineering Department (Bouwdienst Rijkswaterstaat) of the Dutch Ministry of Transport, Public Works and Water Management. In addition to his own solutions, several works of the author's colleagues' have been consulted, as well as the available literature and international contacts – among others within the Permanent International Association of Navigation Congresses (PIANC), to whose works the author actively contributes.

In this study, an attempt is taken to emphasize the role of contact related issues in the design of lock, weir and barrier gates. The presented and proved thesis argues that these issues ought to be considered at all project stages, beginning with the definition of the project result and ending at its satisfactory operation. This thesis is new insofar that in engineering practice the contact problems are usually seen as an issue to be dealt with at the stage of detailed engineering. The fact is that an attention to those problems e.g. at the stage of structural system selection would help avoiding many troubles.

The thesis mentioned above has closer been presented in **chapter 1**. In line with the assumed project organization in phases, **chapter 2** deals with the requirements which must be specified for an intended hydraulic closure, in particular for its supports and other contact zones, prior to entering the design phase. This subject has been presented in a structured way, which is also the way it is advised to be approached in the Dutch engineering practice. Due to the large variety of closures, the attention has been focused on lock gates and (to less extend) movable barriers, as the closures in which the motion aspect weights the heaviest in the solutions of contact areas. As examples, three in the Netherlands most frequently used gate types are discussed: mitre gates, vertical lift gates and rolling gates.

In **chapter 3**, the selection of hydraulic gate structural system has been discussed with particular consideration to the contact issues. Presented are different impacts of various support types (and various support parameters within the same type) on the behavior of entire systems. A special problem in this matter is the tendency to let lock gates operate under alternating hydraulic loads. Also, the significance of time and heat generation aspects is discussed.

The subject of **chapter 4** is methodical selection and determination of design loads in contact areas, in relation to the loading cases for entire gates. It turns out that the correct design solutions of contact areas (such as bearing zones, supports, suspensions, buffers, seals etc.) often require considering larger numbers of loading cases than the dimensioning of entire gate structures. The main reasons for that are single-sided support character, applications of anisotropic materials etc. Ignoring this peculiarity may result in serious gate malfunctions or a failure.

In **chapter 5**, analyses of some selected contact problems of hydraulic gates have been presented, preceded by a brief theoretical introduction. The discussed problems, their backgrounds and solutions can be considered typical for hydraulic closures. In this view, special attention has been paid to selected non-linear phenomena, such as expansion (in some cases also narrowing) of contact zones under load. Presented examples are all realized works – large part of them from the author's engineering practice; the rest from the projects lead by his colleagues in the Civil Engineering Department.

An important issue in design of contact components is the material selection. **Chapter 6** presents the program and the results of laboratory investigations in this matter, which have been conducted by the author. The investigations took place in few series at the “Schielab” Mechanical Laboratory in Breda, and covered a number of material combinations for hydraulic gate hinges – from the known to entirely new applications. The investigated material properties were: local compression bearing capacity in stationary conditions and in motion, friction, wear, heat generation and its impact on material behavior, distortions of microstructure. The test parameters were chosen in a way narrowly reflecting the operation conditions of gate hinges. The investigation results enabled the author and his colleagues to introduce new, better materials and detailing solutions in hydraulic gate contacts.

In **chapter 7**, a new, not yet realized supporting system idea for mitre gates and single-leaf gates has been presented – the so-called “suspension gate”. This idea has several advantages, caused mainly by the fact that the reception of the gate vertical reaction (primarily from own weight) takes place outside the hinges. The field experiences collected by the author prove that it is the combination of the vertical (axial) and horizontal (radial) load in one bearing that causes excessive wear and other gate operation malfunctions. The idea of suspension gate removes the structural source of those malfunctions.

The recapitulation of this study in **chapter 8** presents its main conclusions and recommendations concerning both the approach to contact problems in hydraulic closures and the actual technical solutions to those problems. Additionally, the prosperous fields and the directions of further investigations in this area have been suggested.

As an **enclosure** to this thesis, the author’s computer program DISCO has been attached, which can be used to analyze 2- and 3-dimensional skeletal systems with discontinuous (single-sided) supporting conditions. The essential task in this program is carried by an original iterative algorithm which allows the computer find the active support zones by itself, for any given load combination. Subsequently, a complete appropriate problem solution is generated. Despite that only linear elements (members) can be input, the program makes it possible to simulate a wide range of contact problems – in hydraulic as well as in any other types of structures.

SAMENVATTING

Dit proefschrift bevat een verzameling van de onderzoeksresultaten en praktijkervaringen van de auteur op het gebied van ondersteuningen en andere contactonderdelen van waterkerende constructies, zoals sluisdeuren, keermiddelen van stuwen en stormvloedkeringen. Het onderwerp is interdisciplinair aangepakt. Gepresenteerd zijn: het overzicht van de ontwerpbelastingen, tribologische en andere voor het ontwerp of onderhoud relevante fenomenen, en de invloed van het gedrag van de contactonderdelen op de keuze en het ontwerpproces van de hele kerende constructie.

Het verzamelde materiaal en de gepresenteerde oplossingen zijn voornamelijk afkomstig van de 20-jarige ervaring van de auteur in ontwerp, onderzoek en projectbegeleiding van waterbouwkundige constructies, in het bijzonder stalen keermiddelen. Deze ervaring heeft de auteur vooral opgedaan in zijn functie van projectleider ontwerp bij infrastructurele projecten van de Bouwdienst Rijkswaterstaat – een dienst binnen het Nederlandse Ministerie van Verkeer en Waterstaat. Naast de eigen werken heeft hij ook materiaal gebruikt dat afkomstig was van de projecten die onder leiding van de collega's stonden, of verkregen waren via zijn internationale contacten – onder andere binnen de Permanente Internationale Associatie voor Navigatiecongressen (PIANC), waarvan hij actief lid is.

Het voorliggende werk vormt een poging om de contactproblematiek meer betekenis toe te kennen in het ontwerp van de deuren van sluizen, stuwen en keringen. De in dit proefschrift gepresenteerde en bewezen stelling is dat men aan deze problematiek de aandacht dient te schenken in alle projectfasen, van de definitiefase tot en met nazorg tijdens bedrijf. Dit is nieuw in zover dat de contactvraagstukken nog steeds als een kwestie van detaillering worden gezien. De praktijk leert dat wanneer men de aandacht hieraan bijv. al bij de keuze van het lastdragende systeem van de deur schenkt, veel problemen kunnen worden voorkomen.

De bovengenoemde stelling is nader beschreven in **hoofdstuk 1**. In lijn met de aangenomen fasering van projecten zijn in **hoofdstuk 2** de eisen besproken welke gesteld dienen te worden aan de beoogde waterkerende deur, en in het bijzonder aan zijn steunpunten en andere contactelementen. De presentatie van dit onderwerp vindt plaats binnen de systematiek die in de Nederlandse ontwerppraktijk wordt aanbevolen. Gezien de grote verscheidenheid aan deurtypen, wordt in deze context op de deuren gefocust waarin de beweging een grote rol speelt – te weten sluisdeuren en (in mindere mate) deuren van beweegbare waterkeringen. Als voorbeeld zijn in details de contactaspecten van de drie meest in Nederland voorkomende deurtypen behandeld: puntdeuren, hefdeuren en roldeuren.
In **hoofdstuk 3** is de relatie tussen de keuze van het lastdragende systeem en de contactvraagstukken gepresenteerd. Toegelicht zijn o.a. de invloeden van verschillende typen steunpunten (en verschillende parameters van dezelfde typen steunpunten) op het gedrag van hele systemen. Een bijzonder probleem in deze context is de tendens om de sluisdeuren als dubbelzijdig kerend uit te voeren. Toegelicht is ook de bijzondere betekenis van tijds- en warmteaspecten.

Hoofdstuk 4 is gewijd aan systematische bepaling van de ontwerpbelastingen in contactgebieden, met als uitgangspunt de belastingsgevallen van de deuren als geheel. Het blijkt dat een goede ontwerpoplossing van contactgebieden (omgeving van lagers, steunpunten, ophangingen, aanslagen, afdichtingen enz.) vaak om beschouwing van meer belastingsgevallen vraagt dan een sterkteberekening van de deur als geheel. De redenen hiervoor zijn onder andere het enkelzijdige karakter van de steunpunten en het gebruik van anisotropische contactmaterialen. Het negeren van deze bijzonderheden kan leiden tot ernstige storingen of een uitval van het hele keermiddel.

Analysen van enkele contactproblemen van waterkerende sluitingen zijn gegeven in **hoofdstuk 5**. Na een korte theoretische inleiding zijn – met de voorbeelden uit de praktijk – de uitwerkingen van enkele karakteristieke contactproblemen van keermiddelen gepresenteerd. Hierbij is een bijzondere aandacht besteed aan enkele niet-lineaire verschijnselen, zoals expansie (in sommige gevallen ook vernauwing) van de contactgebieden onder belasting. De meeste voorbeelden komen uit de ingenieurspraktijk van

de auteur; sommige andere van de projecten die door zijn collega's binnen de Bouwdienst Rijkswaterstaat werden begeleid.

Een belangrijke plaats in het ontwerp van contactonderdelen neemt de materiaalkeuze. In **hoofdstuk 6** zijn het programma en de resultaten van een laboratoriumonderzoek in deze materie gepresenteerd. Dit onderzoek, begeleid door de auteur, werd gehouden in enkele series in het Mechanisch Laboratorium "Schielab" in Breda. Onderzocht werd een aantal materiaalcombinaties voor de lagers van sluisdeuren – zowel al eerder toegepaste als innovatieve. De beproevingen waren gefocust op de eigenschappen zoals toelaatbare locale vlaktedrukken in stationaire toestand en tijdens beweging, wrijving, slijtage, verstoring van materiaalstructuur, warmteontwikkeling en de invloed ervan op materiaalgedrag. De parameters van de proeven waren zo gekozen dat de bedrijfscondities van sluisdeuren konden worden nagebotst. De resultaten van dit onderzoek maakten het voor de auteur en zijn collega's mogelijk om diverse nieuwe oplossingen van sluisdeurlagers te ontwerpen en toe te passen.

In **hoofdstuk 7** is een nieuw, nog niet gerealiseerd idee van een steunsysteem voor puntdeuren en draaideuren voorgesteld – een zgn. "hangdeur". Dit idee heeft diverse voordelen die vooral te wijten zijn aan het feit dat de opname van de verticale reactie (in hoofdzaak uit eigen gewicht) buiten de deurlagers geschiedt. De praktijkervaringen, verzameld door de auteur, laten zien dat juist de combinatie van de verticale (axiale) en de horizontale (radiale) belasting in één lagerblok tot overmatige slijtage leidt en ernstige storingen veroorzaakt tijdens bedrijf. Het voorgestelde concept van de hangdeur biedt een structurele oplossing voor dit probleem.

Bij de recapitulatie van dit proefschrift in **hoofdstuk 8** zijn de belangrijkste conclusies en aanbevelingen met betrekking tot zowel de aanpak van de contactproblematiek als de concrete technische oplossingen ervan op een rij gezet. In aanvulling hierop zijn ook de gebieden en richtingen gesuggereerd voor toekomstig verder onderzoek aan dit onderwerp.

Als **bijlage** is aan dit proefschrift het door de auteur ontwikkelde computerprogramma DISCO toegevoegd. Dit programma biedt de mogelijkheid om 2- en 3-dimensionale staafwerksystemen met discontinue oplegcondities te analyseren. De rekenmethode is een iteratieproces, gebaseerd op een origineel algoritme waarin het probleem zodanig convergeert dat er voor elke belastingscombinatie de juiste, actieve steungebieden worden gevonden. Vervolgens wordt een complete oplossing van het probleem gegenereerd. Ondanks de inputbeperking tot staafwerksystemen, is het mogelijk om een brede groep contactproblemen hiermee te simuleren – in waterbouw en op andere technische gebieden.

This page is deliberately left blank.

1. SUBJECT, SCOPE AND THESIS OF THIS WORK

1.1. Contact areas in lock gates and other hydraulic closures

Hydraulic closures, such as lock gates, movable weirs, flood and storm surge barriers, are structures which adopt a number of positions during operation. Therefore, the support conditions of these structures are usually complex. This applies to “outer” supports, i.e. to the surrounding civil works, as well as to “inner” supports, hinges etc., like contact elements between gate leaves, joints between sections or other subassemblies. The complexity of support conditions is in fact an important property which distinguishes hydraulic closures from other location-tied, heavily loaded structures, like bridges, large industrial or utility buildings etc.

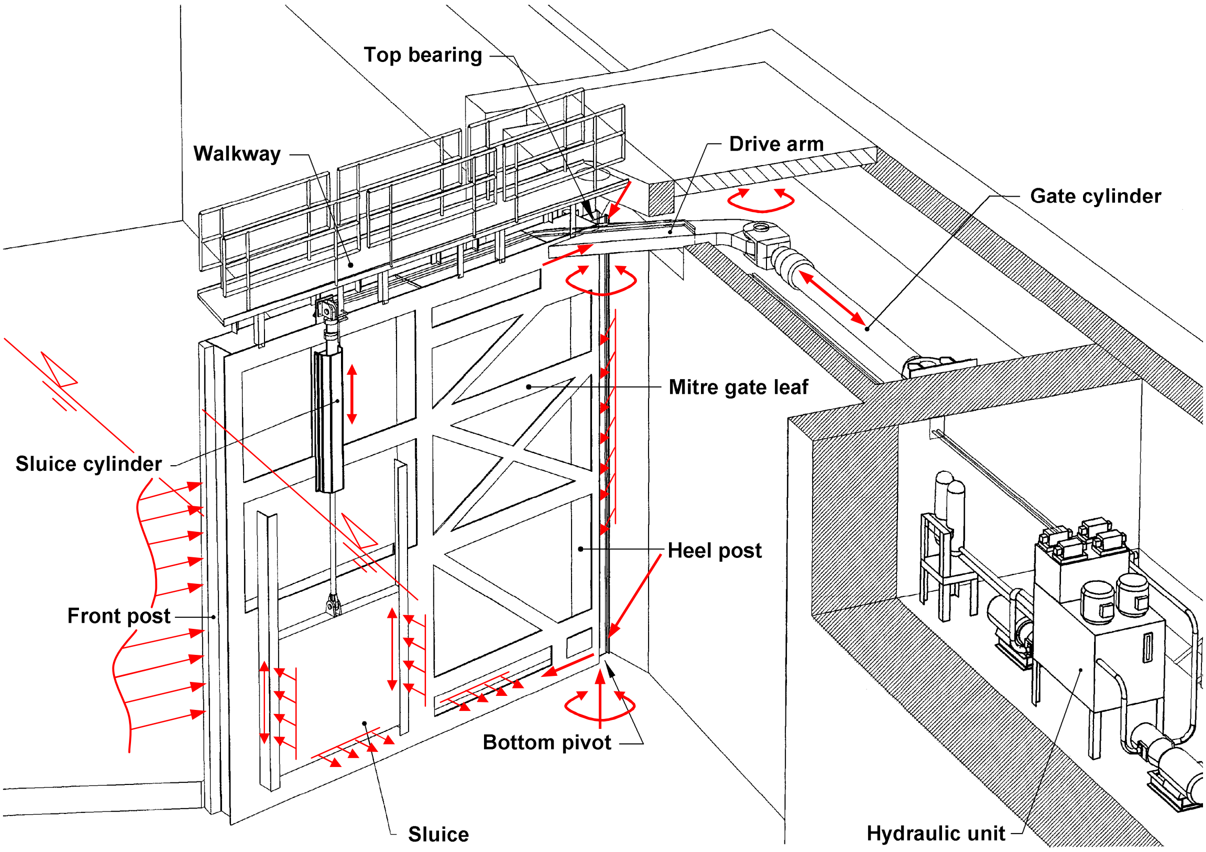


Fig. 1. Principal support areas and loads on a mitre gate leaf

As example, principal support areas and loads on a mitre gate are schematically shown in Fig. 1. For clarity reasons, only one of the two gate leaves has been sketched. The gate support system represents in this case the principle of so-called “fixed” rotation points [1], [2], in which all hydraulic loads are passed to the gate hinges; and the heel posts bear only small pressure from sealing elements. Yet, one can observe that the support system is complex. There is a large variety in the character of support loads. These loads can be classified in a number of ways. We shall refrain from load distinction with respect to the time factor (duration, frequencies, amplitudes, inertial effects etc.) at this moment; and try to set up a simple classification focused on the contact character. For the purpose of this study, distinction will be made between contact loads as shown in Table 1. The time factor, if significant, will be considered in other sections of this thesis.

Table 1. Contact loads and characters on a mitre gate leaf from Fig. 1

Load character		Contact character		
Geometrical	**Mechanical**	**Stationary**	**Rolling**	**Sliding**
Point wise	**Forces**	• Top and bottom hinge horizontal reaction to hydraulic load. • Bottom hinge vertical reaction to gravity and buoyancy loads. • Sluice cylinder loads.	• Top and bottom hinge horizontal loads from gate weight in motion (e.g. roller bearings). • Radial load on a fixed side of hinge bushing during gate motion.	• Top and bottom hinge horizontal loads from gate weight in motion (shaft/ring bearings). • Radial load on a slide side of hinge bushing during gate motion.
	Moments	• Static friction moment on gate hinges. • Static friction moment on cylinder hinges.	• Small friction moment on gate hinges in case of roller bearings. • Friction moment on a fixed side of (e.g. ball) hinge slide bushing.	• Friction moment on gate hinges from own weight in motion. • Friction moment from drive load on hydraulic jack hinges.
Linear or surface	**Equally distributed**	• Pressure on heel post seal in closed gate. • Pressure on bottom beam seal in closed gate.	• Pressure in (if present) roller guides during sluice motion. • Further not in Fig. 1. Present in other types of gates, e.g. in strap hinges of flap gates.	• Incidental contact of open gate with passing vessels. • Pressure on sluice slide guides during sluice motion.
	Unequally distributed	• Contact compression on front posts lining under hydraulic load. • Contact load on other linings – if not sealed. • Radial load on hinge elements in stationary gate position – when zoomed in.	• Radial load on a fixed side of hinge bushing during gate motion – when zoomed in. • More examples in gates of other types.	• Compression on gate lining from hydraulic load build-up (due to strain, clearances etc.) if no elastic seals are applied. • Radial load on a slide side of hinge bushing during gate motion – when zoomed in.

Obviously, this distinction is relative and it depends on the size of the considered detail and the accuracy of the analysis. In fact, point wise and linear loads do not exist. Loads always occupy a surface – as there are no absolutely rigid contact materials – and they are always unequally distributed. There exist also contacts of other characters than mentioned in Table 1, e.g. some extreme forms of wear like galling [3] or ploughing [4]. At this moment, however, it is important to observe that there are numerous contact areas and loads – both of diverse characters – in hydraulic gates. Considering Fig. 1 and Table 1, an engineer should be convinced that a correct recognition of these contact areas and loads is essential for a number of issues in gate design, e.g.:

- gate mechanical stability and invariability of shape;
- definition of gate structural system, in particular support conditions;
- dimensional stability and strength of surrounding civil works;
- manufacturing accuracy of the gate structure;
- hinge types, materials, gate detailing in hinge vicinities;
- sill edge, front and heel post (or other in other gate types) structural detailing;
- permissible leakage, wear, choice of post lining, sealing etc.;
- requirements in regard to gate (and sluice, if present) drive loads.

1.2 Recommended significance and place of contact analysis

The issues mentioned above are important (some even crucial) in hydraulic gate design. Despite this, the contact related problems do not, in general, receive appropriate attention in gate design yet. Gate modeling focuses usually on the input of structure geometry, internal rigidity relations and hydraulic loads. Less effort is made to model contact areas and loads in a way, which would simulate the actual contact mechanisms. This situation does not reflect the needs of waterway management authorities. According to the author's survey, a significant part of maintenance problems and costs is caused by contact malfunctions and insufficient consideration to contact mechanisms during design and execution of hydraulic gate projects.

In this thesis, more weight and a more thorough consideration to contact issues are pleaded. In support of this plea, a broad, systematic approach to such issues is introduced. Detailed discussion is provided on the impact of contact related problems on a number of crucial steps in hydraulic projects. This discussion also covers some selected theoretical and experimental background. Generally, the proposed position of contact related activities in hydraulic gate projects is presented in Fig. 2.

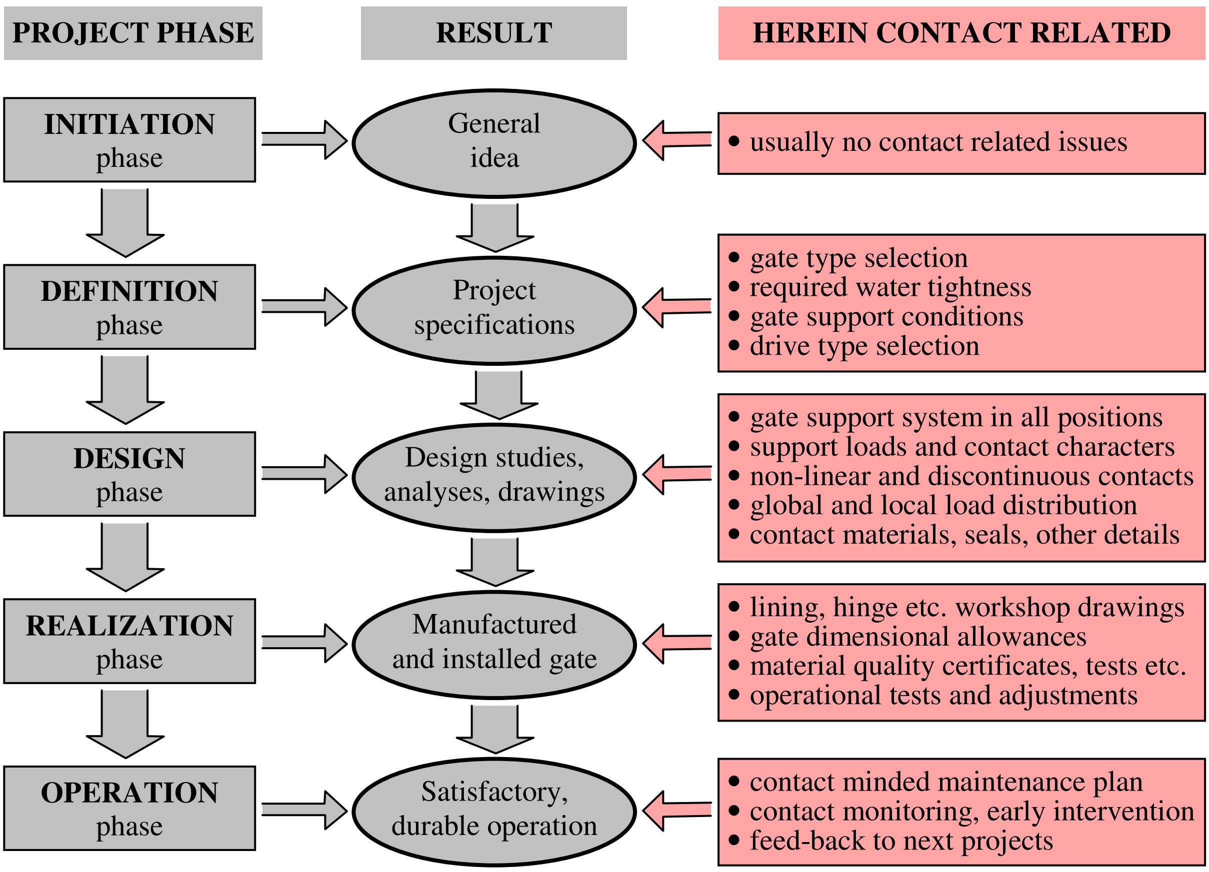


Fig. 2. Proposed position of contact related activities in hydraulic gate projects

Observe that the contact related activities are already significant in the definition phase of a project, although not everybody realizes that the issues like gate type selection or gate support conditions are – to a large extent – contact issues. This flow-chart has an indicative character. Additional or different contact issues will have to be considered as result of local conditions, specific design choices etc. At this moment it should primarily be noted, that contact related issues are significant throughout the entire project cycle. The meaning (still popular between the engineers) that these issues are a matter of so-called "final touch", "fine-tuning" etc., is incorrect.

1.3 Practical use and target group of this study

The intention of this study is, globally, to give a deeper insight into:
- the mechanisms of diverse contact phenomena in hydraulic gate structures,
- the impact of those phenomena on the functioning of structures in a global and local sense,
- the approach methods and the solutions to some frequently forthcoming contact problems.

The investigation method used to realize this intention is a combination of theoretical and experimental analysis, supported by the author's and his colleagues' practical experience with several hydraulic gate projects. A number of cases from those projects are discussed in this study. The investigation results cover useful numerical values as well as a large number of design, engineering and construction recommendations. In addition, the computer program named DISCO is included, enabling an engineer to analyze structures with complex, discontinuous support conditions. The program is based on the author's original algorithm, which has not been published earlier.

The study aims at two goals simultaneously:
- to satisfy the requirements of the Gdańsk University of Technology for a doctoral thesis;
- to provide the readers with a tool helping them to recognize and solve diverse contact problems in hydraulic closures.

Regarding the second goal, the target group of this study comprises engineers, students and other professionals active in the field of civil (primarily hydraulic) engineering. As this doctoral thesis has been promoted and guided from Poland but is mainly related to the author's engineering practice in the Netherlands, the readers from these two countries constitute the primary target group. However in a broader sense, the study is addressed to professionals and students anywhere the world, with no distinction of national or other borders.

2. CONTACT REQUIREMENTS IN DESIGN OF HYDRAULIC GATES

2.1. General classification of requirements

Hydraulic gate constructions are projects of considerable economical, environmental and other impact to large areas. Such projects affect usually many people in many ways, varying from the safety of their homes to the nature of their means of income. The processes which generate those effects are often complex, and can be short-term (e.g. immediate solution to a flooding problem) as well as long-term (e.g. economical growth attracted by navigation possibilities). As shown in Fig. 2, the contact related issues should globally be considered already in the definition phase, at the stage of gate type selection. This selection is not only a matter of engineering, economy, politics or other privileged discipline and its people. It is, in fact, a matter of the entire community living or having other interests in the areas in question. This implies that the project specifications with respect to the gate contact areas should directly originate from the primary, multi-criteria requirements for the entire hydraulic project.

As every individual gate project is usually different, it is probably not advisable to standardize those multi-criteria requirements, nor to establish strict procedures to be followed in this matter. Having said that, we shall outline a simple set of criteria, which can – with possible adjustments – be used as an example in some gate projects. The number of criteria is deliberately kept small in this set. In general, this number should not be higher than 6 ÷ 8, otherwise it is usually difficult to produce well balanced choices [5]. If more criteria are brought under attention, one should consider clustering them.

Table 2. Gate selection criteria and requirements with respect to the contact issues

Criterion	Weight factor	Possible requirements
1. Total costs	0.30	**General:** Moderate or low construction costs; low operation and maintenance costs; no of low financial disadvantage to third parties (e.g. navigation, agriculture etc.). **Contact related:** Low-cost contact maintenance; no financial claims due to leakage, excessive navigation hold-ups for maintenance etc.
2. Operation	0.25	**General:** Easy operation; high reliability; low (human) intervention requirements; no operational malfunctions. **Contact related:** Robust, highly reliable contact areas; no contact malfunctions due to wear or deformations; no contact sensitivity to weather, filth, corrosion etc.; long material service life.
3. Navigation	0.15	**General:** Easy, safe ship passage; short locking time; no uncontrolled flows, waves etc. in lock chamber; gates not easily hurt by a ship. **Contact related:** Contact areas not sensitive to ship collision; quiet, smooth gate motion; little leakage or other navigation obstruction; navigation friendly inspection and maintenance in contact areas.
4. Maintenance	0.15	**General:** Few (preferably none) maintenance requirements, inspection and maintenance activities easy, healthy and safe. **Contact related:** No intensive maintenance on hinges, linings, seals etc.; maintenance dependent contacts easily accessible and preferably removable for maintenance outside the lock chamber.
5. Environment	0.10	**General:** Environmentally friendly (preferably sustainable) structure materials, maintenance procedures etc.; fish passage; barrier to water pollution in emergency cases; no erosion due to excessive flows. **Contact related:** No toxic contact materials; little or no lubrication, sealing against pollution; environmentally friendly maintenance.
6. Aesthetics	0.05	**General:** Form, color etc. in harmony with gate function, load distribution and the surrounding; perceptional experiments welcome when well thought out and not contrary to engineering logics. **Contact related:** Legible support and other contact areas, no filth collection, lubricant leaks etc. in those areas.

2.2. From performance requirements to gate type selection

Weight factors in Table 2 represent the significance of all individual criteria in relation to the complete set of criteria. The most convenient way is to assign the weight factors of the range 0.00 ÷ 1.00 to all criteria, in such a way that the sum of these factors amounts 1.00. Nevertheless, other numerical scales (e.g. in percents) can be used as well. There is no way to assign such factors in an entirely objective, undisputable manner. Alike the criteria themselves, their weight factors are chosen arbitrary, sometimes in hot discussions or even arguments within the project team. It is a good habit to let the project owner have a decisive voice in these discussions. The values in Table 2 are only an example.

Once the weight factors issue is settled, we can take some basic choices concerning the project. Gate type selection is probably the most important of them in regard of this study. The gate types to be considered are usually brought upon by the project team in a brain storm session. There are various ways to do that, depending on the size and the expertise of the team, the project complexity, the involved sensitivities etc. One of these ways is to do it in two stages:

- Generate and collect ideas under the motto "every idea is good".
- Make a pre-selection by mutual comparisons, global feasibility assessments etc.

This should produce no more than, again, some 6 ÷ 8 gate types, which can be considered interesting for the project. The following step is to fill a selection matrix in which these gate types are evaluated with respect to the agreed criteria. In order to estimate the significance of contact issues in this stage, we shall consider two practical cases of gate type selection. The first case is a flood barrier on the Meuse-Waal Canal in Heumen, the Netherlands. Any of the two rivers could flood in this project, but the Meuse presented a higher danger. The second case is a navigation lock on the Meuse in Lith, the Netherlands. In both projects, four gate types were pronounced suitable in a pre-selection (Fig. 3).

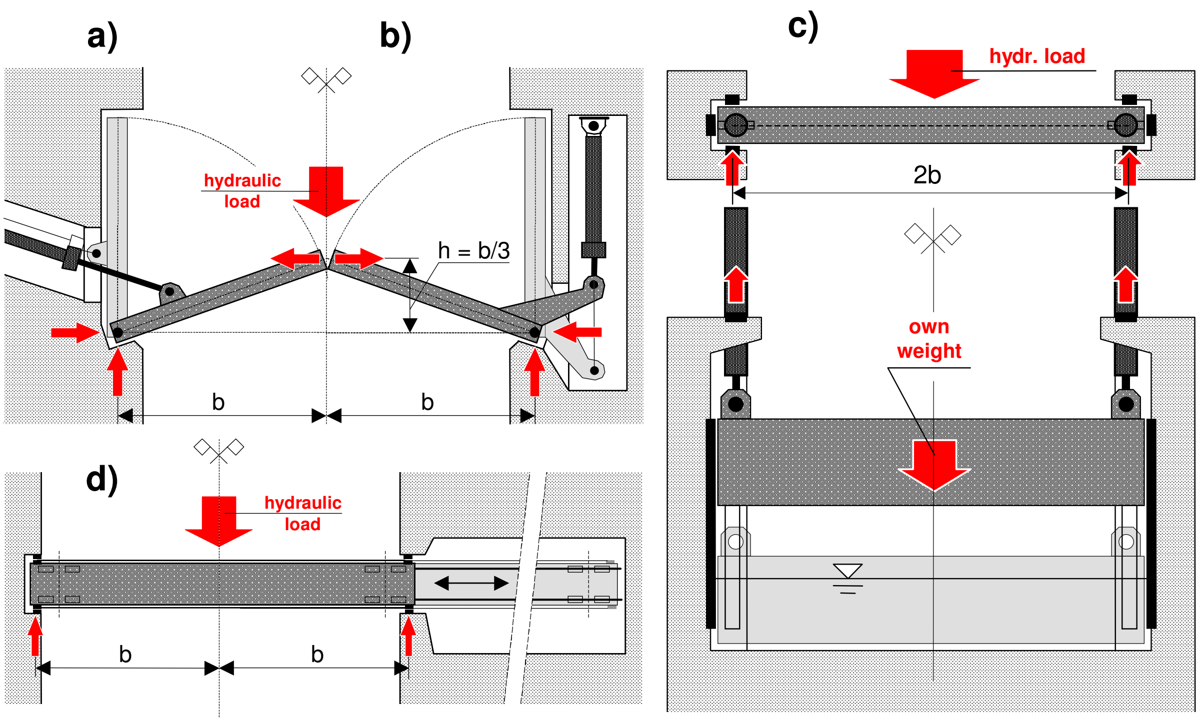


Fig. 3. Gate types for a barrier on the Meuse-Waal Canal; and for a navigation lock on the Meuse:
a) Mitre gate conventionally driven
b) Mitre gate with rotation arm
c) Vertical lift gate
d) Rolling (or sliding) gate

The selection matrices for both projects are presented in Tables 3 and 4[1)]. In these matrices, a ranking range from 0 to 10 was used to express gate performances in all the criteria. The ranking was done by project teams comprising specialists of engaged disciplines – usually by consensus, in some cases by taking a mean value. The total scores were obtained by multiplying the rankings by the criteria weight factors; and taking the totals of the products[2)].

Table 3. Gate type selection matrix for a flood barrier on the Meuse-Waal Canal in Heumen

		Gate type			
Criterion	Weight factor	Mitre gate type (a)	Mitre gate type (b)	Vertical lift gate (c)	Rolling gate (d)
1. Total costs	0,30	8,0	7,5	9,0	5,0
2. Operation	0,25	7,0	7,0	8,5	8,0
3. Navigation	0,15	8,0	8,0	6,0	9,0
4. Maintenance	0,15	7,0	7,5	9,0	7,0
5. Environment	0,10	7,0	8,0	7,0	6,5
6. Aesthetics	0,05	8,5	8,0	5,5	7,0
Total score	1,00	7,53	7,53	8,05	6,90

Table 4. Gate type selection matrix for a new navigation lock on the Meuse in Lith

		Gate type			
Criterion	Weight factor	Mitre gate type (a)	Mitre gate type (b)	Vertical lift gate (c)	Rolling gate (d)
1. Total costs	0,30	8,5	7,5	8,0	5,0
2. Operation	0,25	8,0	8,0	6,5	7,0
3. Navigation	0,15	8,5	9,0	5,0	8,5
4. Maintenance	0,15	7,5	8,0	8,5	7,0
5. Environment	0,10	7,0	7,5	7,0	6,5
6. Aesthetics	0,05	8,5	8,0	5,0	7,0
Total score	1,00	8,08	7,95	7,00	6,58

It can be observed that the assessment results are significantly different. While a vertical lift gate was the best choice for the barrier project in Heumen, mitre gates were favored for the navigation lock in Lith. The reason can partly be found in contact related issues. Here are some of them:

- A barrier gate closes once or twice a year (including tests), while a lock gate closes 20÷30 times a day. By high closing frequencies, the wear of contact zones becomes important; and that wear can in general be better controlled on a mitre gate.
- In incidental operation (barrier), vertical lift gates require less costs and effort for contact area maintenance. This advantage decreases in intensive operation (lock).

A barrier gate does not need to be water tight; a lock gate does. Gate leakage, excessive as it can be, presents no problem of land inundation but it can slower the locking of vessels. Mitre gates carry higher contact compression and give potentially less leakage than vertical lift gates.

[1] Some differences in the assessment approach between both projects (e.g. slightly different weight factors) have been interpolated for the purpose of this discussion.
[2] In the digital version of this thesis, both tables are MS Excel files, which helps tracing the formulas.

2.3. Choice of gate support system

2.3.1. Support systems of mitre gates

Having chosen a gate type, an engineer is faced with a number of options concerning its structural system – in particular the support system. In case of a mitre gate, the first decision to be made is where to pass the gate reactions from hydraulic load. There are, globally, three possibilities in this matter:

a) to gate hinges;
b) to gate heel post lining;
c) to gate heel post saddles.

Another question is where to take over the vertical load (from own weight, buoyancy, walkways etc.). The conventional way is to do it on the bottom hinge, but there are other possibilities as well. Here are the three ways worth considering:

d) on gate bottom hinges;
e) on gate top hinges;
f) on gate suspension (not realized yet).

The support systems resulting from these six possibilities are shown schematically in Fig. 4.

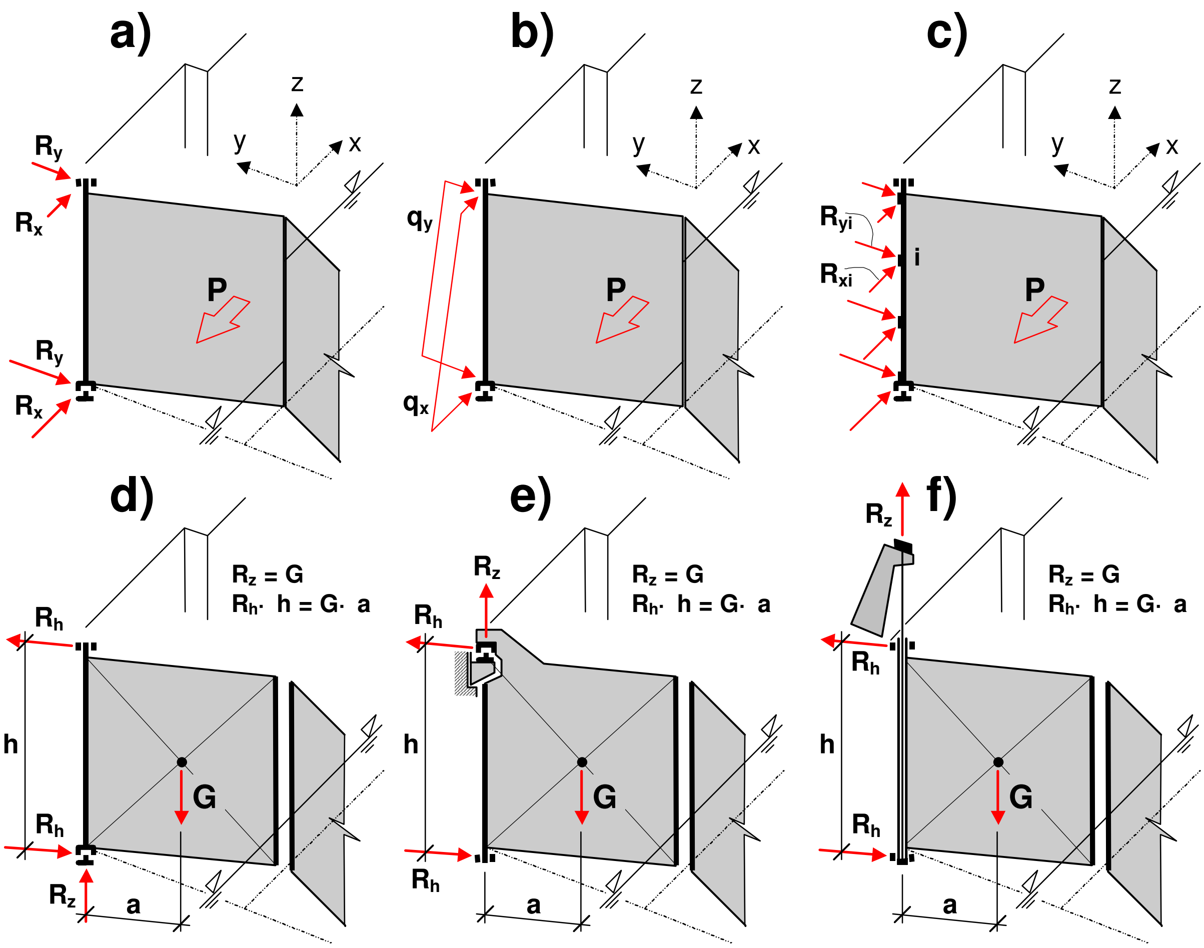


Fig. 4. Gate support systems in regard of hydraulic load (above) and own weight (below)

Other systems – e.g. combined (hybrid) response to hydraulic load, full buoyancy response to vertical loads etc. – can not be excluded, but they have not been successfully applied yet. The selection of gate support system is very sensitive to local geometry, load conditions and other requirements. With this reservation, some global advantages and disadvantages of each of the six systems are discussed.

a) Hydraulic load to gate hinges

Advantages:

- Clear system with always the same, well localized and defined supports;
- Gate motion in one plane, no lift-up by closing. All contact surfaces easy to construct;
- Gate positions and motion well controllable, more precision possible;
- No or little clearances in hinges required, wear better controllable;
- Better suited for complex materials and technologies due to system controllability;
- Little leakage under reverse, so-called 'negative' hydraulic load;
- Thanks to elastic seals, no fitting corrections in situ (e.g. to linings) required;

Disadvantages:

- Hydraulic load does not contribute to gate tightness, seals required;
- Heavily loaded hinges and their anchors, highly concentrated loads on concrete;
- Loads in gate not economically spread, high concentration around the hinges;
- System not robust, specialized service required to restore potential malfunctions;
- Risk of ice-bound seals or other damage by freezing, precautions required;
- In general, more vulnerability to ship collision, obstacles on the bottom etc.
- Installation not easy due to narrow clearances and vulnerable components;

b) Hydraulic load to heel post lining

Advantages:

- Well-thought out system, hydraulic load contributes to gate tightness;
- Remarkably stable and infallible thanks to the optimal use of natural loads;
- Loads well spread in the plane of the gate, optimal use of material strength;
- Under unidirectional loads (no reverse head), usually no additional seals required;
- Easy to manufacture and install using simple materials and technologies;
- Hinges bear only gate own weight and (small) drive loads, no hydraulic loads;
- Thanks to robust construction, little risk (and easy repair) of local damages.

Disadvantages:

- Load passage to heel posts (during lift-up by closing) somewhat "rough";
- Wear and other erosion difficult to control due to large gaps and clearances;
- Heel and front post lining must usually be fitted (e.g. planed) in situ;
- In general, not suited for reverse loads, due to large leakages through gaps and clearances;
- Little precision in the system, limited use of modern materials and technologies;
- Precautions needed in gate drive hinges for the lift-up during closing (e.g. ball hinges);
- Hardly suitable for gates with drive arms (difficult heel post detachment by opening).

c) Hydraulic load to heel post saddles

Advantages:

- Suitable for very high loads if e.g. cast-steel or composite saddles are applied;
- Hydraulic load contributes to gate tightness but to less extend than in case (b);
- Little wear on saddles and no global geometry distortions during service life;
- Under unidirectional loads (no reverse head), usually no additional seals required;
- Well spread loads in the plane of the gate and to lock chamber walls;
- Hinges bear only gate own weight and (small) drive loads, no hydraulic loads;

Disadvantages:

- High dimensional accuracy required, complex saddle positioning and stabilizing in situ;
- Due to stiff saddles, additional seals usually required to seal the post gaps;
- Stiff gate, sensitive to foundation distortions, thermal expansion etc., no "self-fitting";
- Water tightness under reverse hydraulic load as bad as in case (b);
- Little precision in the system, limited use of modern materials and technologies;
- Precautions needed in gate drive hinges for the lift-up during closing (e.g. ball hinges);

d) Vertical load to gate bottom hinge

Advantages:

- Until shortly, the "standard" system, therefore much expertise collected;
- Top hinge, basically, only horizontally loaded, no or little moments in anchoring;
- Light top hinge anchors, well suited for limited space – e.g. in machine room ceilings;
- Simple heel post shape, no shape precautions for gate installation required;
- Gate installation easy and quick thanks to neck collar construction of the top hinge ring;
- Applicable to all the three systems (a, b and c) of hydraulic load passage from Fig. 4.

Disadvantages:

- The most loaded (pivot) hinge comes under water – not an optimal solution;
- Difficult access, therefore little inspection and maintenance on the bottom hinge;
- Quick and complex wear (so-called "thread" forming) on bottom hinge shaft;
- Lubrication required but difficult to apply and control under water – environmental pollution;
- Very limited repair possibilities in case of foundation sagging or other distortions;
- Difficult and expensive reinforcements etc. in case of renovations.

e) Vertical load to gate top hinge

Advantages:

- The most critical hinge comes above water – a logical solution for maintenance;
- Condition of the most critical hinge easy to inspect, large maintenance possibilities;
- Modern materials and less robust solutions applicable to the most critical hinge;
- Light bottom hinge anchoring, no foundation for vertical reaction in the chamber bottom;
- Better wear and lubrication control, less pollution risk for the environment;
- Good option in renovations of old locks where bottom condition is questionable
- Better repair possibilities in case of foundation sagging or other geometry distortions.

Disadvantages:

- So far, not often applied yet – less expertise available than in case (d);
- Top hinge anchoring requires more solid concrete → space problems in machine rooms;
- Heel post construction quite complex and less favorable in structural sense;
- Gate installation not easy, more precision required than in case (d);
- Construction and installation costs somewhat higher than in case (d);
- More vulnerable to ship collisions etc. which usually appear in high gate areas;
- Well proven only in combination with system (a), with (b) and (c) questionable;

f) Vertical load to gate suspension

Advantages:

- No vertical reaction on hinges, wear problems ("thread" forming) solved to large extend;
- Light hinges and anchors due to no moments – applicable in e.g. machine room ceilings;
- Favorable, stable vertical reaction (discussed in 7.2), prefarable e.g. for post lining;
- Undisturbed and structurally logic heel post shape, load well spread over gate surface;
- Maintenance costs and environmental pollution probably the lowest of all the three systems;
- Applicable in combination with any (a, b or c) system of hydraulic load passage;
- Possible aesthetical values: highly expressive effect of towers, accentuated gate location.

Disadvantages:

- Long suspension (cable, chain etc.) – hollow heel posts and/or suspension towers required;
- Difficult (but hardly required) inspection and maintenance of suspension cable;
- If towers used, walkway adjustments required to avoid collision with suspension cables;
- Gate installation not easy, more precision required than in case (d);
- Construction and installation costs somewhat higher than in case (d);
- System not proven yet (components proven), some "beginners toll" not excluded;
- Towers can form obstacles, e.g. to radar communication, some unusual vessels etc.

This idea has so-far only been studied [6]; it has not been brought into practice yet. The remarks in this section are, therefore, anticipated. Detailed discussion on this idea is presented in chapter 7.

2.3.2. Support systems of vertical lift gates

As shown in section 2.3.1, there are a number of support systems possible for a particular gate type. This applies not only to mitre gates but, in fact, to all types of hydraulic closures. A discussion on all possible support systems by all known gate types goes beyond the scope of this thesis. Therefore, only some global remarks and selected cases are presented in the next two sections. The discussion focuses on two gate types – vertical lift gates and rolling gates – which (along with mitre gates) are most frequently used on navigable waterways. Weir gates are skipped for the size reasons of this study.

Alike the mitre gates, the support systems of vertical lift gates can be distinguished from each other in respect of hydraulic loads and vertical loads. Known support systems are as follows:

Hydraulic loads:

a) to fixed guide wheels;
b) to free (e.g. Stoney) roller trains;
c) to guide pads, locally;
d) to guide strips, continuously.

Vertical loads:

e) to gate sill, continuously;
f) to end post saddles, locally;
g) to locking devices in towers;
h) to gate suspension.

Analogously, the advantages and disadvantages of each of these systems can be specified. However, we should not full ourselves by assuming that everything in engineering is rational. The actual choice of gate support system depends sometimes also on engineer's personal view, national (or other local) preferences, tradition etc. An interesting example of this is the comparison of vertical support systems in two large vertical lift gate projects[1)]: the Hartel Canal Barrier in the Netherlands (spans 98.0 m and 49.3 m) [8] and the Ems Barrier in Germany (spans 63.5 and 50.0 m)[2)] [9], see Fig. 5. Both projects are quite recent (construction years respectively 1996 and 2002) and they represent storm surge barriers designed to protect large land areas against the intrusion of sea waters during heavy storms.

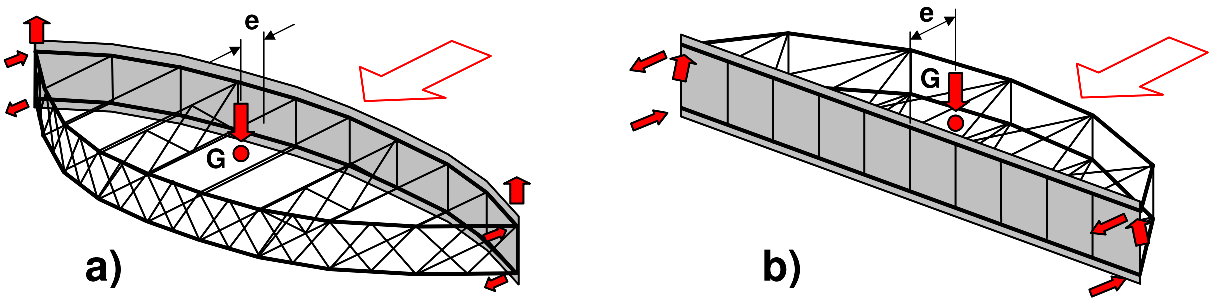


Fig. 5. Gate support systems in regard of vertical loads of the:
a) gate L = 98.0 m of the Hartel Canal Barrier near Rotterdam (NL)
b) gate L = 63.5 m of the Ems Barrier near Emden (D)
Note: the blank arrows show the direction of hydraulic loads from storm surges.

Apart from a number of other differences, the vertical lift gates in both projects represent significantly different views on the most essential issue: reliability of closing. The gates of the Hartel Canal Barrier are hooked to hydraulic lift jacks; their own weight resting in fact permanently on the oil columns in the jacks. The gates of the Ems Barrier are also hooked to hydraulic jacks, but they are locked in the

[1] Principal technical data of the vertical lift gates in these projects have also been presented in [7].
[2] This barrier contains also gates of other types than vertical lift gates,

stand-by position by hydraulically driven locking devices. The details of both solutions are shown on the photographs in Fig. 6.

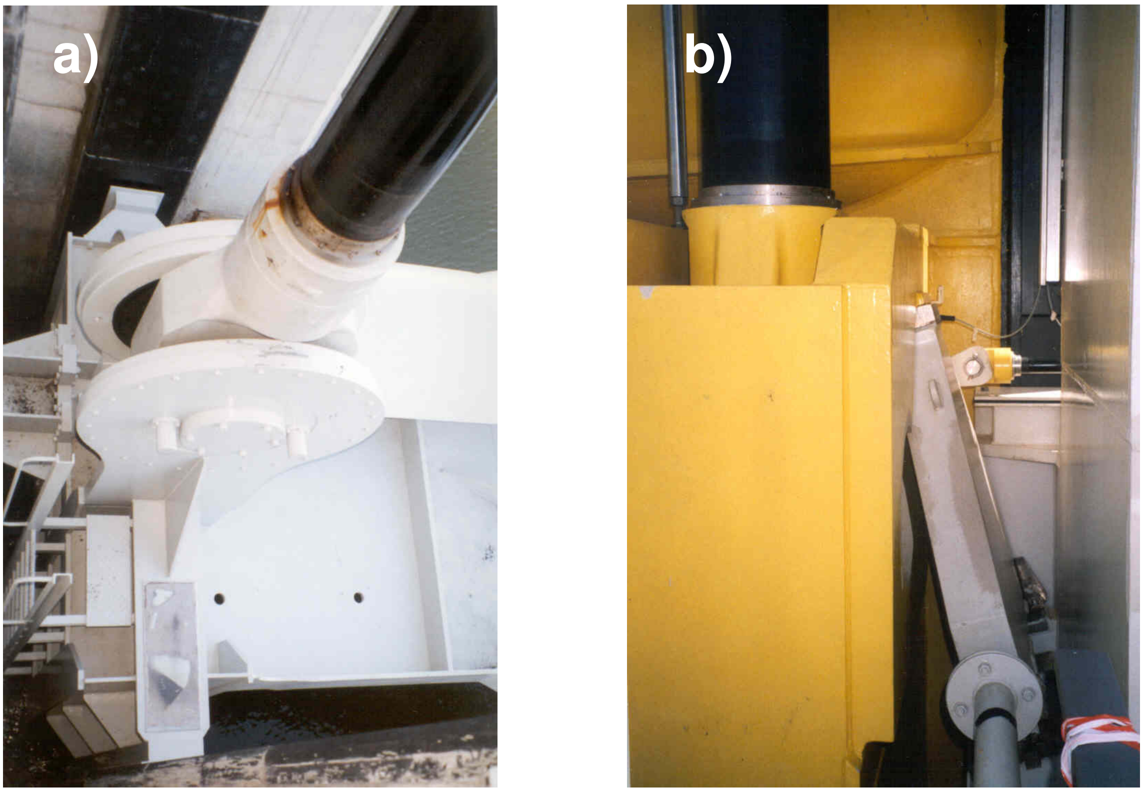


Fig. 6. Own weight support of the vertical lift gates:
a) of the Hartel Canal Barrier – on a hydraulic lift jack
b) of the Ems Barrier – on a locking device

The idea to lock a gate instead of letting it permanently hang on hydraulic jacks, is understandable to every engineer. Yet, it is not a good idea in respect of the reliability of closing – and therefore also the reliability of land protection against the sea[1)] which is the primary function of those gates. A locking device, solid as it can be, is just another component with a probability of failure at the moment when the gate is supposed to close. Since both – the gates and the locking devices – are driven by hydraulic jacks, this probability is of the same order as the failure chance of the gate drive. Roughly estimating, a gate of the Ems Barrier will fail to close twice as often as a gate of the Hartel Canal Barrier.

This is yet another example in support of the thesis (see section 1.2) that the gate contact issues should be considered throughout the entire project cycle, to begin with the definition phase.

Another difference, interesting in respect of contact issues, concerns the overturning moment from the gate own weights in lifted position. The own weight of both gates is about equal – some 6500 kN. As shown in Fig. 5, the Hartel Canal gate has an arch-traced retaining wall. This makes the manufacturing more complex, but it enables placing the gravity center of the gate not far from the plane of suspension. The Ems Barrier gate has a simpler, flat retaining wall, which does not offer such a possibility. The eccentricity of its gravity center (thus the overturning moment) is, therefore, much larger. Both gates have, in fact, very similar slide guides. The German engineers had, therefore, to deal with more severe wear and other problems resulting from the contact pressure, than the Dutch engineers. While

[1] German engineers will possibly disagree with this opinion. Also other readers are encouraged to take an independent view. Author was lead engineer of the Hartel Canal gates; and is aware that his opinion is not impartial.

the previous difference concerned the project definition phase (see Fig. 2 in section 1.2), this one is an example of the significance of contact related issues in the design phase of a project.

2.3.3. Support systems of rolling and sliding gates

We shall consider rolling and sliding gates as belonging to the same type, as the difference between roll and slide supports alone is of a secondary nature. The support systems of these gates can also be distinguished from each other in respect of hydraulic loads and vertical loads:

Hydraulic loads:	Vertical loads:
during motion:	e) to vertical wheel or slide units underneath
a) to vertical wheel or slide units;	f) to vertical wheel or slide units diagonal
b) to horizontal wheel or slide units;	g) to hydrostatic bearings;
in closed position:	h) to bottom support devices in recess;
c) to side posts and sill linings;	i) to top support devices in recess;
d) as (c) and wheel or slide units;	j) to separate cat-way above the gate

Rolling gate support systems are perhaps the most complex of the three gate types under consideration. The major problem is that the gate needs a clearance of a few centimeters during motion, but it must stick tight to its casing in closed position. This requires a lateral movement across the direction of rolling, which is a quite difficult engineering task. There exist various solutions to this problem, e.g. transverse rollers in lateral cradle supports to wheel units [10], rubber supporting blocks atop the wheel units etc. – all with or without transverse positioning devices (e.g. jacks) operating under water. Important as it is, this problem will not be discussed here. We shall focus on the three most frequently used support systems for vertical loads (e), (f) and (g), as shown in Fig. 7. Systems (h) and (i) are mainly used for maintenance reasons; while (j) is an obsolete system, to see only in small, old gates nowadays. We shall also ignore the efforts, usually unsuccessful, to let a gate be entirely carried by buoyancy. Obviously, a partial own weight balancing by buoyancy is widely practiced in rolling gates.

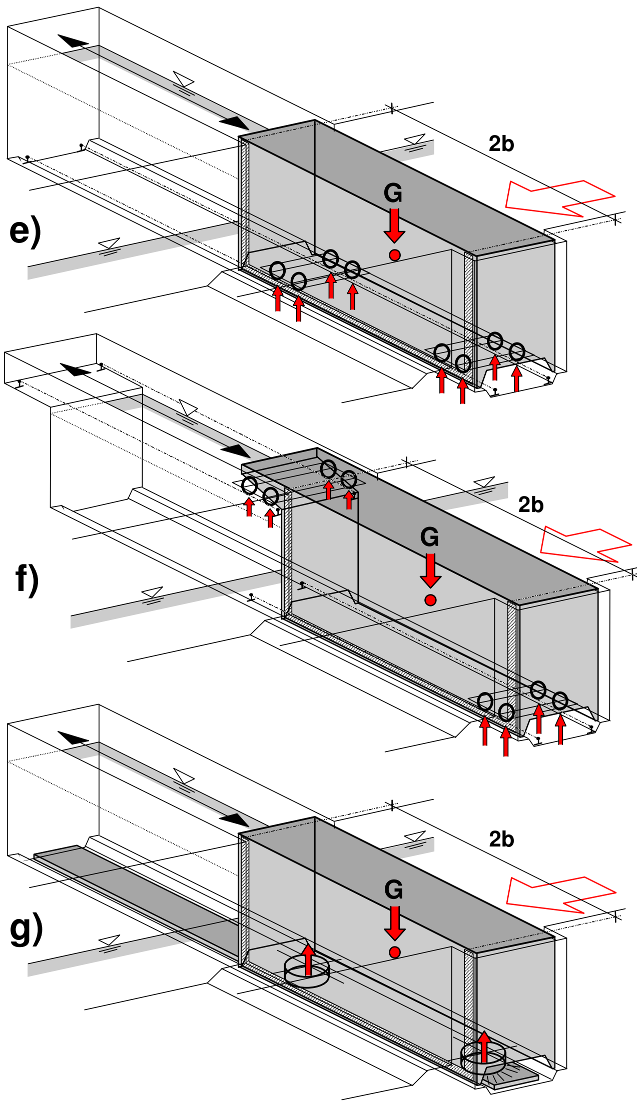


Fig. 7. Three rolling gate support systems in regard to vertical loads:
e) to wheel units underneath;
f) to wheel units diagonal – so-called "barrow" system;
g) to hydrostatic bearings.

e) Vertical load to wheel units underneath

This is the "classical" support system of a rolling gate. The wheel units contain 4 or (in larger gates) 8 wheels each, wheel pressures carefully equalized by a system of balance beams. Some best known examples of this support system are the gates of:

- Northern Lock in IJmuiden (NL) [10], [11], width 50 m;
- new Holtenau and Brunsbüttel Locks in the Kiel Canal (D) [12], width 45 m;
- Middle Lock in Terneuzen (NL) [13], width 40 m.

The main advantages in relation to the other two systems are: relatively simple, compact system with repeatable components, the lowest construction costs (although rolling gates as such are usually an expensive solution) and much existing expertise. Disadvantages are: unfavorable stability conditions during closing and opening (residual fall, waves); and many machine components under water. Needless to say, choosing this solution gives a quite symmetrical structural system of the entire gate, which is not the case in solution (f). It is, therefore, yet another argument in support of early consideration to the contact issues in hydraulic gate design.

f) Vertical load to wheel units diagonal

This so-called "barrow" system combines some advantages of low wheel units with those of system (j), in which the gate is hooked to a cat-way structure above it. The disadvantages of both are, however, avoided. In particular, there is no obstacle to navigation in the form of a cat-way. It is a system favored by Belgian engineers, which is – to some extend – another example of national traditions in engineering. The world largest rolling gates of the "barrow" system are in:

- 4th Harbor Lock in Wilhelmshafen (D) [14], width 57 m;
- Zandvliet Lock between the Scheldt and Canal Dock (B) [15], width 57 m;
- François I Sea Lock in Le Havre (F) [16], width 67 m
- Berendrecht Lock, parallel to the Zandvliet Lock (B) [15], [17], width 68 m;
- New Van Damme Lock in Zeebrugge (B) [15], width 57 m;

An unquestionable advantage of this system is a better gate stability during closing and opening. We see that, the gate gravity center (also after taking buoyancy into account) and the resultant of the residual hydraulic load (including waves), are both not far from the diagonal plane through the wheel units. This improves the stability conditions, which is particularly desirable in large maritime locks. Not accidentally, the Belgian and the French "barrow" gates are the largest rolling gates in the world. In this case, the intelligent choice of gate supporting system allows for extension of feasible dimensions. The price of that is, however, significant. The gate recess is larger and more complex; the wheel loads and mountings are not uniform; there is no symmetry advantage in the gate structural system.

g) Vertical load to hydrostatic bearings

Wheels and other submerged mechanical parts are a weak point of rolling gates, as they require much maintenance but are barely accessible. An idea to replace wheels by slide pads has, therefore, always attracted engineers. Josephus Jita, lead engineer of the Northern Lock in IJmuiden, designed that lock originally for slide gates, changing wooden slide lining at the last moment for wheels due to stability problems as result of high buoyancy requirements. That buoyancy was needed to limit the wear. In the last years of his life Mr. Josephus Jita still lobbied for sliding gates [18]. Yet, the wear problem he faced was long time unsolvable. Large sliding gates were only thinkable as barrier gates, operating a few times a year at most.

This changed when an idea was born to pump water into slide pads, in such a way that a gate would move on a thin water layer rather than in direct contact between the slide pads and the track. The known gates with such an idea are the following:

- caissons of Mersey Locks in the Liverpool Docks (GB) [19], width 40 m;
- gates of New Orange Lock in Amsterdam (NL) [20], width 24 m;
- gates of Venice Barrier Lock (I) [21], width 52 m, under construction.

The thickness of the water film under the pads is only about 0.1 mm. Nevertheless, the tests performed for the New Orange Locks in Amsterdam proved that the wear and the coefficient of friction are about 100 times lower than without that film [22]. This is the great advantage of such supports, as it results in tremendous reduction of maintenance costs and a much easier lateral positioning.

More details and discussion on the idea of hydrostatic bearings are presented in section 5.5 of this thesis, under the headline “Hydrostatic feet of a sliding gate (case New Orange Lock)”.

2.4. Sample case: Contact requirements for mitre gates

2.4.1. Functional reliability and dimensional requirements

Mitre gates are the most frequently used lock gates on navigable waterways in Europe. Navigation locks in the Netherlands – usually their upper heads – often make part of dykes protecting land against inundation. Functional reliability requirements of gate contact elements (mainly hinges, front and heal posts) originate, therefore, from the two main tasks: secure navigation and reliable land protection. In general, such reliability requirements can be expressed in a stochastic way – as probabilities of failure to fulfill each of these two tasks. These probabilities can be obtained in a so-called risk analysis, e.g. by a fault-tree method. Atop the tree, there is a failure criterion of the main function, to be taken from design codes, other official regulations, or to be negotiated with the customer. In Fig. 8, an example of this technique is given with regard to the two tasks mentioned above.

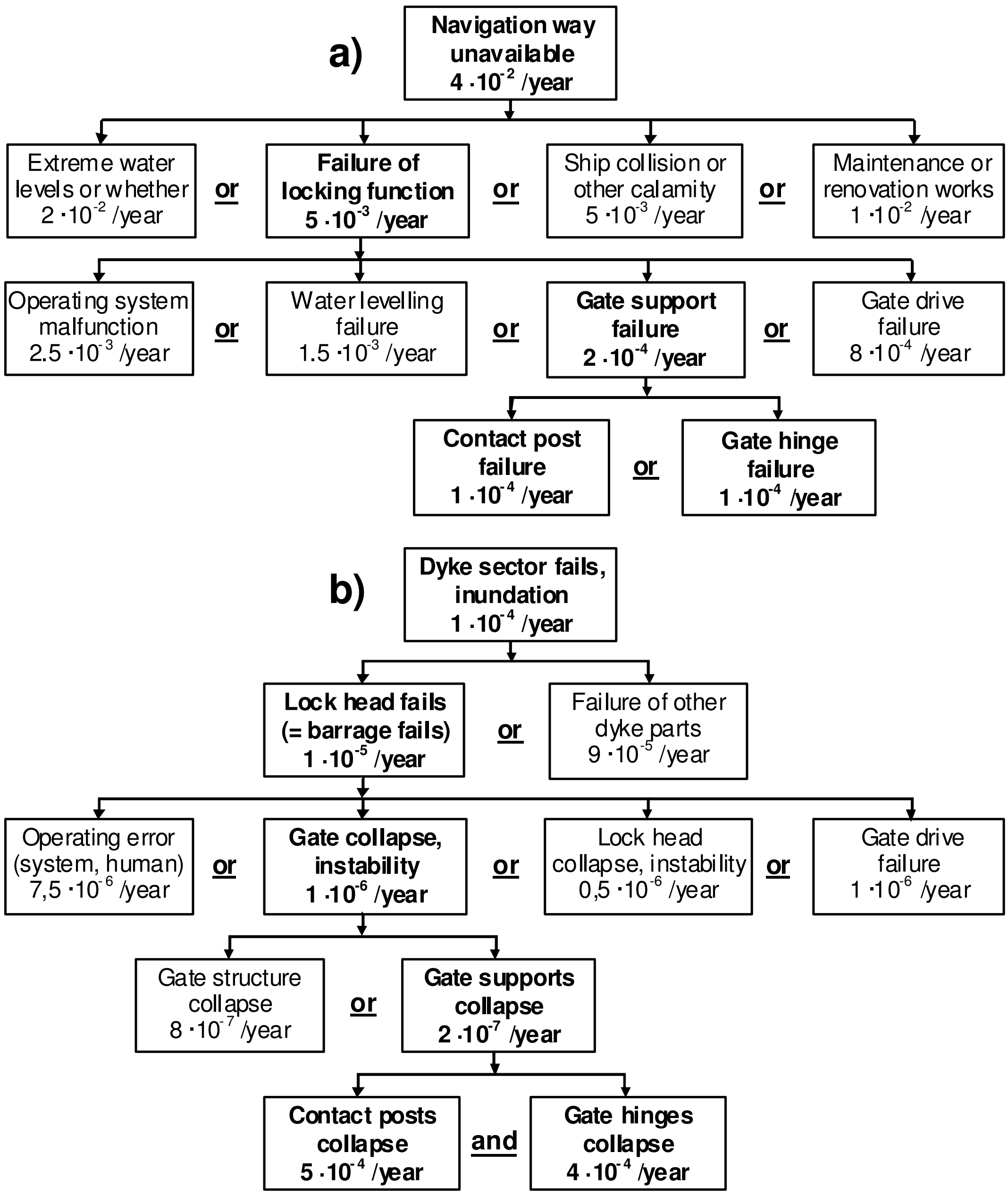


Fig. 8. Fault trees for the navigation (a) and land protection (b) tasks - example

The example in Fig. 8 concerns a lock mitre gate of type (b) from Fig. 4, which combines both tasks. The probability figures are hypothetical, but they reflect the engineering practice in the Netherlands in this field. An interesting phenomenon is that although the land protection task has a much “sharper” (here 400 times) failure criterion, the navigation task ends up with not less “sharp” requirements concerning the gate contact components – end posts and hinges[1)]. We see that the risk analysis of an entire project may have direct impact on the design criteria for gate contact components.

2.4.2. Mechanical requirements

The next question is how to convert the functional reliability requirements, expressed in probabilities of failure, into directly applicable design values of loads and material mechanical properties. The approach methods in this matter depend on project complexity and scale; and vary from so-called semi-probabilistic to entirely probabilistic methods [23], [24]. A discussion on this subject goes beyond the scope of this thesis. Moreover, an engineer will usually not be faced with this subject, as a big part of work has already been done in national design codes or other official regulations. E.g. in the Netherlands, a country of great dependence on water, special regulations for hydraulically loaded structures [25] exist in addition to the official design codes. In most cases, these regulations are sufficient to collect design specifications in terms of loads and material properties. Full probabilistic analyses are usually practiced for large and complex individual projects, e.g. [26].

In the most general terms – i.e. without consideration to individual project specifications, support system, materials etc. – the mechanical requirements concerning mitre gate contact (and contact related) components can be described as follows:

- None of the loads[2)] and load combinations under consideration may result in a rupture or stability loss of gate contact components. This concerns all combinations of the ultimate limit states as well as the serviceability limit states – in the sense of proper design codes, e.g. [27].
- None of the loads and load combinations under consideration may result in excessive deformations of gate contact components, such that no satisfactory operation of the gate is possible. This concerns all combinations of the serviceability limit states.
- In the two requirements above, the terms “rupture”, “stability loss” and “deformations” apply to static overload cases, as well as dynamic, fatigue, impact, thermal and/or other excessive loads.
- Plastic (residual) deformations are, in general, not acceptable under the loads of serviceability limit states. This applies not only to the areas of direct contacts (hinges, contact posts) but also to their vicinities – in actual gate structures as well as in lock chambers.
- In case of overloading in closed position (e.g. due to ship collision or other calamity), the failure mechanism must be such that the resulting damage is minimized. Possible damage to other objects, like vessels in lock chambers, must also be minimized. It is good, e.g., to take care that the gate remains in its hinges after such a damage.
- In gate hinges with single-sided contact lining (types (b) and (c) from Fig. 4), special attention must be paid to load cases caused by obstacles during gate motion. The resultant hinge reaction

[1)] This conclusion is disputable because there exists some correlation between the probability of end posts and hinges collapse under extreme loads: When the first fall, the other become loaded. It is, therefore, premature to consider support collapse in the fault tree (b) as a product of both figures. It is done here to explain the method.
[2)] Eurocode 3 [27] refers in this context not to loads but to “actions”. In this thesis the term “loads” is assumed to represent the same, i.e. also temperature effects, foundation settlements etc.

may possibly fall outside the contact lining in such cases, which can damage the hinge.

- The wear of hinge bushings, post linings etc. must be so small that it has no significance for gate operation within the assumed maintenance cycle. In particular, this wear may not result in any disturbance of the gate support system.

- Friction in hinges must be kept as small as possible. This friction may not result in considerable increase of the required gate drive capacity. It should also not cause any perceptible noise, stick-slip, shock or other unfavorable effects.

- Heat generation inside gate hinges should be so small that it has no considerable effect on the mechanical properties of hinge components, particularly the bushings. This applies particularly to the materials like plastics, composites etc. which are sensitive to heat generation.

- Friction in hinges generates also (tensile or compressive) normal loads along the gate rotation axis, see global discussion further in this study. These loads must be considered in hinge (anchorage) design. A well proven engineering practice for the top hinge (in case of no detailed investigation) is to consider a vertical load which amounts 30% of the hinge operating horizontal reaction.

2.4.3. Dimensional precision requirements

Functional reliability of gate contact components is very sensitive to dimensional precision. Therefore, it is advised to specify dimensional precision requirements in a lock construction contract. The most essential requirements are those for the contact components to be fixed in lock chambers. Obviously, the contact details of the gate itself should have the same or still higher precision, but that is easier to obtain because the gate is manufactured in a construction shop, not in field. Moreover, civil contractors who usually position the contact components in concrete forms, are not accustomed to millimeter accuracies. Fig. 9 gives an example of some most essential dimensional accuracy requirements (tolerances) for a mitre gate location in an about 12 ÷ 16 m wide chamber.

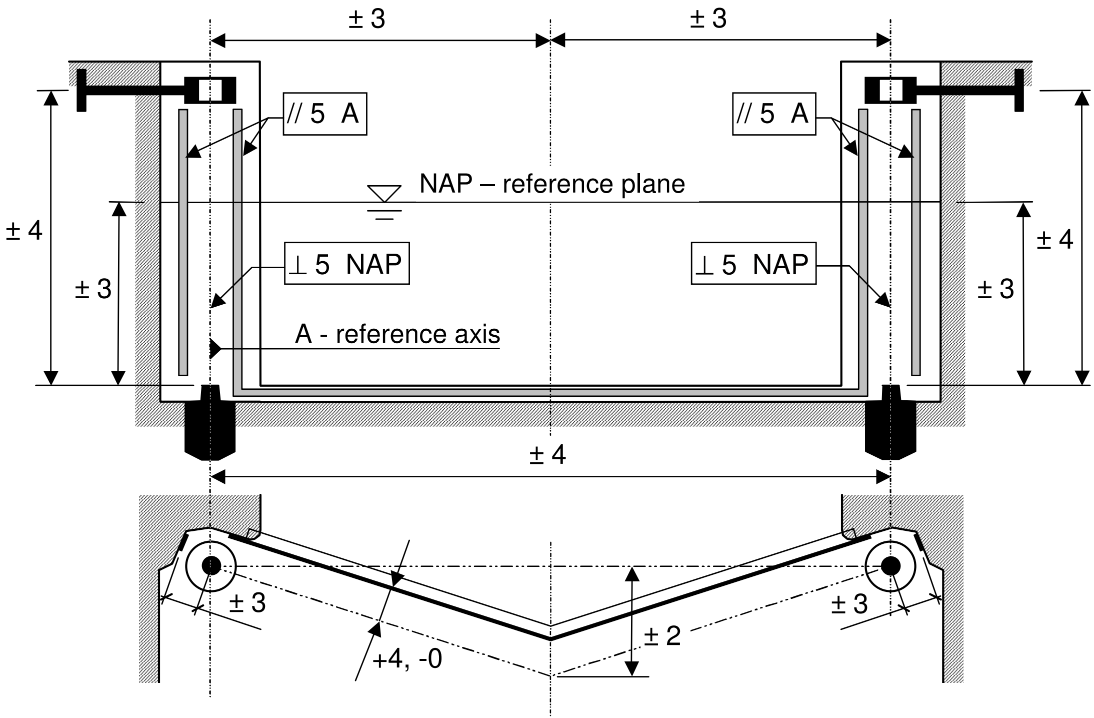


Fig. 9. Dimensional tolerances for a mitre gate contact items in a chamber – example

The dimensional precision requirements of the range as in Fig. 9 reflect the Dutch engineering practice for the mitre gates with small hinge clearances (e.g. type (a) from Fig. 4). Using large clearances (e.g. type (b) from Fig. 4), elastic contact materials, special seals etc. allows for somewhat larger dimensional tolerances. Nonetheless, is should be noted that those tolerances are narrow when compared to most other civil construction projects. Moreover, although they become verified on project delivery, no significant excesses of these tolerances should occur during the entire service life of the gate.

There are various ways to comply with the accuracy requirements. Most of them employ special (often adjustable) auxiliary structures for positioning contact items in concrete forms and holding them there during concreting. It is advisable to do it in temporary niches after the main chamber structure has been concreted. The prior concern is the position of gate rotation axes. Fig. 10 presents an example of an auxiliary structure used to fix the top and the bottom (submerged) hinge items during the reconstruction of the Orange Locks in Amsterdam in 1996 [28]. The new gates of these locks (see Fig. 11) pass their hydraulic loads to the hinges, and the vertical loads to the top hinges (respectively type (a) and (e) from Fig. 4). Such an arrangement requires high dimensional precision.

Fig. 10. Auxiliary structure for positioning and grouting gate hinge supports

2.4.4. Assembly and maintenance requirements

As hinges and other contact items determine gate location and fixity in the chamber, they obviously play crucial role in gate installations and disassemblies. The engineer should keep in mind that these handlings take place several times during the service life of the gate. Their frequency depends on the maintenance requirements, the risk of ship collision etc. and varies roughly from once in the 6 till 20 years. This gives some 4 to 12 gate assemblies and disassemblies in the service life of about 60 ÷ 80 years. Removing a gate – e.g. for maintenance purposes – usually shuts the waterway down for navigation, which brings economic losses to many parties. These and other arguments give ground to the assembly and maintenance requirements which should be specified in a construction contract. In the most general terms, these requirements can be specified as follows:

- The gate hinges, edge posts etc. must be detailed in such a way that an installation or removal of the gate leaves is possible at any time and in any angular position. In particular, the vertical clearance in the gate shaft-ring hinges must be sufficient to settle/lift the gate leaves in vertical position on/from their pivot bearings.

- In case the gate assembly or disassembly requires special devices (templates, pilot cones, guides, locking devices, replaceable parts etc.), such devices should be in possession of the waterway authority. In new construction projects, the customer shall usually wish that these devices – used by the contractor during assembly – make part of the delivery.

- All components subject to impact loads during gate assembly must have sufficient strength and stability to sustain these loads. Own weight and other relevant loads should be taken into account with proper impact factors in the design of impact exposed components.

- The construction contractor should be provided with proper information in cases when shape, materials etc. of gate contact components generate special assembly requirements or limitations. E.g., gate leaves with little clearance in hinges must usually be installed in exactly vertical position, i.e. without canting. Incidental assembly loads should especially be avoided for items of brittle or anisotropic materials, some plastics, composites etc.

- From the assembly point of view, large clearances should be provided between the contact items. These clearances are, however, not in favor of the correct load input, water tightness etc. The engineer should, therefore, seek a compromise between these two criteria. If load is passed to heel posts (types (b) and (c) in Fig. 4), the hinge release mechanism may determine the size of the clearance.
- Gate installation can be carried out in several ways, e.g. using a floating crane (Fig. 11), a mobile crane (Fig. 12), buoyancy tanks, under "dry" or "wet" conditions etc. Appropriate transport and assembly precautions should be taken to guarantee the safety of contact components.

Fig. 11. Gate installation in a "wet" chamber by a floating crane, Amsterdam Orange Locks

Fig. 12. Gate installation in a "dry" chamber by a mobile crane, the Meuse Lock in Lith

2.4.5. Aesthetical and environmental requirements

The significance of aesthetical and environmental requirements in mitre gate contact design is largely indirect. Contact components as such are usually not the eye-catchers of the structure. The environmental impact of their material selection, mechanical behavior etc. is also limited. Nonetheless, contact issues determine to large extend the gate shaping, the choice of gate materials and diverse ecological performances of the gate. In this sense, the aesthetical and environmental requirements often apply to gate contact areas. The design considerations in this matter are, e.g., as follows:

- The classical esthetical rules give much value the structure legibility. A crucial issue in this matter is the legibility of the support system. The engineer should, therefore, clearly define (possibly even accentuate) all gate supports and other contact areas. A small number of gate supports (e.g. type (a) in Fig. 4) is better legible than a large number (e.g. type (c) in Fig. 4).

- Not only the shaping but also the condition of gate contact areas contributes to the aesthetical value of the structure. Any difficult to maintain contact details (e.g. Fig. 13), places of dirt collection, water leakages under front and heel posts etc. should be avoided.

Fig. 13. Aesthetically well shaped but difficult to maintain top hinge of the Orange Locks gates in Amsterdam

- Smooth and reliable gate operation contributes to safe, orderly and convenient navigation passage, which in turn has far reaching environmental consequences. Gate hinges and other contact components play a crucial role in gate operation. In this sense, the performances of those components can affect the environmental condition of large areas.

- In several cases (e.g. by division between salt and sweet water, risk of water pollution) gate water tightness presents an issue of environmental significance. This generates additional requirements to gate edge post linings and other contact areas. Such requirements can be formulated in functional terms (permissible leakage), or in technical precautions (special seals, contact precision etc.).

- The gate operation requires energy input. Low energy consumption is always preferable in the environmental sense. This speaks for low friction hinges and other precautions concerning contact components. Also, when hydraulic loads are unstable or change their direction (not unusual in the Netherlands), additional energy is required to hold the gate in closed position. This energy depends – to some extend – on the solution of contact issues.

- The conventional solution to the reversible hydraulic load problem is a double (in a mirror image) mitre gate in a lock head. This solution has two environmental disadvantages: It requires twice as much material and it occupies twice as much space. Its environmental advantage is that no devices, energy etc. are required to hold the load bearing gate in position – the nature itself (hydraulic load) does this job. The engineer should consider this while choosing the gate system.

- The gate (i.e. also contact components) material selection is of environmental significance as well. E.g. in a wooden gate contact posts, sustainable forest management should be a precondition, even when it results in new, innovative timber applications [29]. Ecological material selection is not yet systematically practiced in hydraulic gate projects, but its importance grows steadily. The methods of analysis can be borrowed from other related disciplines, e.g. bridge construction [30], [31].

- In ecological material selection for gate contact components, the entire life cycle should be taken into account. This covers the winning of raw materials, their processing, product manufacturing and installation, maintenance and utilization after the service life. An requirement in regard of maintenance is, e.g., low (preferably none) lubrication of hinges.

2.5. Some other contact requirements and requirements for other gates

The specification of contact requirements as presented for mitre gates in section 2.4 can also be drawn up for other types of gates. The division as well as several specific requirements will then be the same. A number of other requirements will, obviously, be different. There are also requirements which refer to some general principles of contact engineering rather than to a specific type of gate. This section gives a brief discussion – sometimes only a notice – on such requirements.

2.5.1. General notes on slide and roller contacts

There is a tendency to step down from roller supports to slide supports in hydraulic gate engineering. This tendency can be observed through all types of gates in the recent decennia, but it is most visible in vertical lift gates and in rolling gates. In general, three reasons for this tendency can be named:

- Slide supports offer better possibilities to combine the mechanical functions (load bearing, motion) with the requirement of water tightness. This is a valuable advantage in terms of integrated design approach, as it significantly reduces the number of gate components.

- Roller supports require much maintenance. This applies in particular to submerged components. Nowadays, the prevailing view in the Netherlands and many other countries is that any submerged axial rotation item is a potential maintenance problem and should, if possible, be avoided.

- The steadily developing material technology produces new, wear resistant materials and material combinations. In the recent decennia, slide supports became feasible in many heavily loaded applications where rolling supports had been used before.

Naturally, the technology of roller supports is still important in hydraulic engineering – if only for the sake of maintenance of numerous existing gates. However, the future belongs to slide supports. The collected experience allows giving a number of general design principles regarding the applications of slide supports in hydraulic gates. Below are some of them:

- Using identical material in both items of direct slide contact should, in general, be avoided. Such arrangements proved to cause tribological problems, like high friction coefficients, premature wear, so-called galling etc. An example is the so-called *thread forming* in hard (e.g. manganese) steel contact items of the mitre gate bottom pivots, Fig. 14.

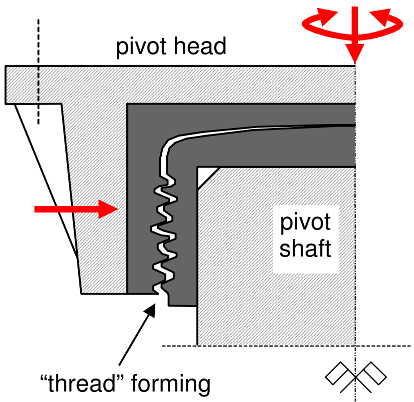


Fig. 14. "Thread" forming in a mitre gate bottom pivot (magnified)

- While using two different contact materials, the one that shows more abrasive wear should, in general, be used on the gate side – not on the chamber side. This applies particularly to submerged hinges, saddles etc. The reason is the ease of replacement during the gate maintenance services in construction shop. Obviously, there are no objections to fix such materials on the chamber (also recess, lift tower etc.) side when such an arrangement enables easy replacement.

- Due to slow motion, irregular operation, long interruptions, weathering, pollution, etc., there is an increased risk of a so-called stick-slip behavior in slide supports. The engineer should take proper measures to eliminate that risk or to limit the consequences of such a behavior in case it appears.

- A result of stepping down from roller to slide supports is, in general, a higher friction. Friction is always an important design consideration, even if it does not determine the required drive capacity. One of the problems to consider is the warmth generated by friction. The mechanical properties of many modern slide materials are very sensitive to temperature.

2.5.2. Some requirements concerning calamity engineering

Needless to say, calamity prevention is better than its engineering. Nevertheless, it is worthwhile to review and – wherever possible – to direct the hypothetically possible damage mechanisms. The general principle of gate calamity engineering has already been mentioned in section 2.4.2:

- In case of overloading in closed position (e.g. due to ship collision or other calamity), the failure mechanism must be such that the resulting damage is minimized. Possible damage to other objects, like vessels in the lock chamber, must also be minimized. E.g., it is good to take care that the gate remains in its hinges after such a damage.

In the recent years, the engineer's attention has painfully been drawn to another possible calamity source: the terrorism. A full discussion on this subject goes beyond the scope of this thesis; and will probably still take place in a wide technological context. However, this should not withhold engineers from submitting the requirements which in their view decrease both, the vulnerability to terrorist acts and the damage caused by such acts. In this sense, the following comments and requirements can be considered regarding the gate contact areas, e.g.[1)]:

- In general, the following categories of terrorist attacks can be considered relevant in the design of hydraulic gate supports and other contact components:
  a) Direct attack on a lock, weir or barrier gate, with the purpose to (threaten to) inundate the area causing casualties, chaos and fear;
  b) Attack on a lock, with the purpose to destroy a vessel or to capture it, get it out of the lock and use in bargaining for another objectives;
  c) Getting control of a vessel nearby a lock, weir or barrier; then letting it run into the loaded gate causing inundation of the area ("wet version" of 9/11);
  d) False information about intended attack, with the purpose to mislead public institutions, cause chaos etc. (Let us also call it a terrorist attack in this study).
  e) Electronic (e.g. hacker) attack on a hydraulic gate operating system through internet, radio waves etc., with the purpose as in the above mentioned categories.

- From the terrorist point of view, the known (possibly prestigious) gates located in urban areas and bearing large hydraulic loads will be the most attractive targets. As the protective measures cost money, it seems advisable to estimate in which degree this description applies to a particular gate, before selecting the protective measures.

- Hydraulic gate supports should easily be accessible for maintenance crews – but difficult for unauthorized persons. The contradiction of this requirement can partly be solved by e.g. camera surveillance, good visibility of gate supports to the public etc. If there is little confidence in social control, the opposite strategy can be assumed – e.g. fencing the area (despite aesthetical and other disadvantages), restricting the access, covering or camouflaging the sight of supports.

- There exist some simple constructive measures which increase the security of gate supports. E.g., the top hinges of a mitre gate can be lowered to discourage unauthorized access. In the same case, placing the gate retaining plate on the downstream side will remove (or significantly obstruct) the

[1)] As the subject of structure vulnerability to terrorist attacks is rather new, the comments in this section are not yet supported by scientific research. Their purpose is to awake the discussion rather than to produce definite answers. Nonetheless, these comments reflect the concern based on the existing field practices.

possibility of climbing down the gate girders or stiffeners to access those hinges. For maintenance reasons, removable local platforms, ladders etc. can be supplied in such cases.

- In order to let the gate deform, open or get torn rather than fall out of its supports, all load bearing details in the support areas should be over-dimensioned. Attention should be paid to fact that, e.g., a ship collision may result in loads in different directions than other load cases to be considered in gate design. Also an impact load model should be applied where appropriate.

- Holding a gate in its supports in case of explosion, fire, ship collision etc. is particularly important when the walkway atop the gate makes part of the lock or weir evacuation route – or when it offers the only access for a rescue operation. Such arrangements are not advisable but, wherever they are made, special measures should be taken to secure the gate position after damage.

- In order to minimize the damage, the use of easily inflammable materials in gate supports can be prohibited or limited to submerged items. Many modern bearing materials, contact linings etc. are, in fact, inflammable. The non-inflammability requirement can, therefore, become an obstacle to modern technology. Nevertheless, it can be justified under some circumstances.

- A very frequent and disturbing hostile act is a bomb hoax. As bomb alerts should usually be taken serious, it is important that a proper service team can have a quick visual inspection of all gates. In this context, it is advisable to shape the areas of gate supports in such a way that no hidden places for explosives are provided. The gate clearance for operation will then be given sooner.

3. SELECTION OF STRUCTURAL SYSTEMS AND FIXITIES

3.1. Variable systems and fixities

A great majority of structures in civil engineering have more or less determined, constant structural systems which do not depend on the position or the loadings of the structure. Exceptions are some (not all) types of movable bridges, cranes etc. Most civil engineering structures are not supposed to change their positions anyway, and if they do – like e.g. overhead cranes – it does not affect their structural systems. Also the supports (fixities) are more or less determined, making organic parts of the systems. All this is usually not the case in hydraulic gates. Below, the changes of gate structural system and its supporting conditions have schematically been shown for two gate types: a mitre gate (Fig. 15) and a rolling gate (Fig. 16). Only the passage from open to loaded position is discussed; all other cases, like assembly and maintenance positions, supporting conditions as result of obstacles etc., are ignored.

- **Mitre gate:**

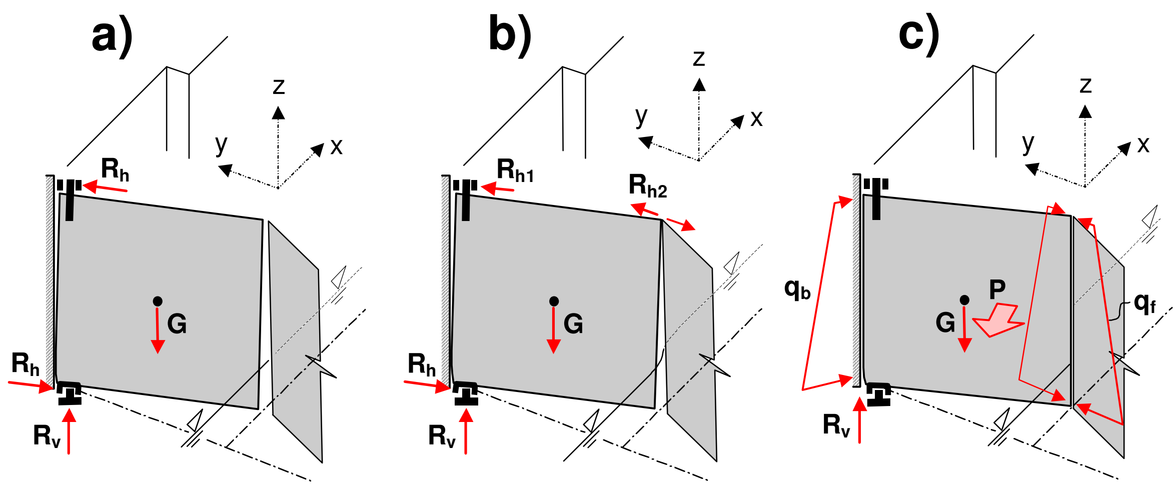


Fig. 15. Systems and supporting conditions of a mitre gate during closing

Let us consider the mitre gate of type (b) from Fig. 4 as an example. In the open position and (ignoring some drive and inertial forces) during motion, the gate leaves are basically loaded in their planes by own weight and buoyancy loads. Due to the hinge clearances, the leaves are slightly sagged in their planes (Fig. 15 a) until the moment when they meet. The reactions lay then also in the leaf planes and are carried by the hinges: the top hinge carrying here the horizontal reaction and the bottom hinge carrying the horizontal and the vertical reaction. When the gate leaves meet, the first contact appears atop the front posts (Fig. 15 b). This is also the moment when the first out of plane loads appear, as the contact plane is not perpendicular to the leaf planes. While the post contact force R_{h2} grows, the top hinge horizontal reaction R_{h1} decreases, until the hinge shaft falls entirely within the ring clearance and there is no contact there any more. Then the water head builds up. The moment of the R_h reaction in plane pushes the front post up and makes the leaf sag disappear. At the same time the bottom hinge horizontal contact becomes released and the entire hydraulic pressure goes as line load to the heel post. Obviously, the front post carries then about the same load figure (Fig. 15 c). The gate is now heavily loaded in the leaf planes as well as out of these planes. Note that also the vertical reaction R_v changes (at least for a big part) its location at this stage. It moves from the bottom hinge to the heel post contact plane. This phenomenon will be discussed later on.

- **Rolling gate:**

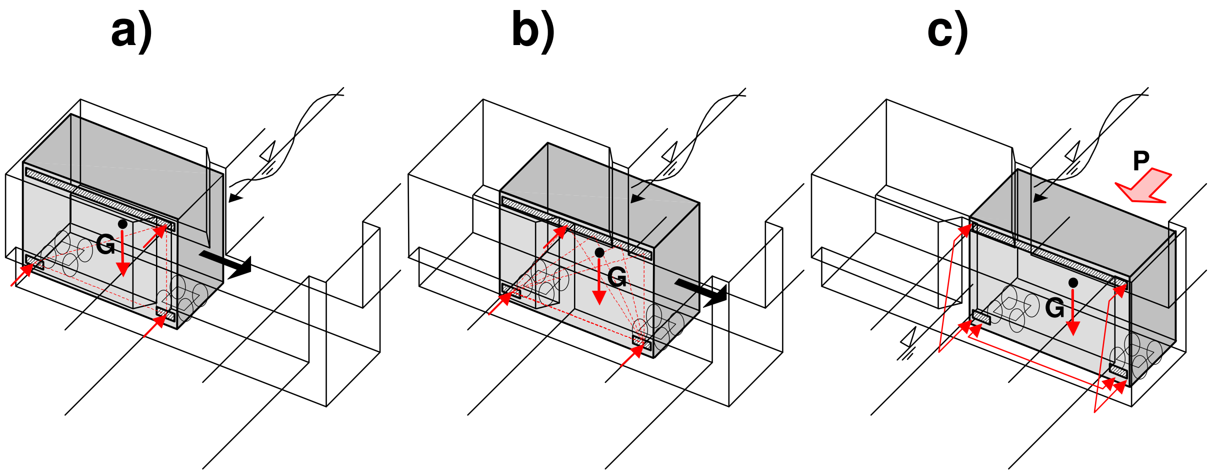


Fig. 16. Systems and supporting conditions of a rolling gate during closing

As an example, we shall consider the rolling gate of type (e) from Fig. 7, but this discussion applies to a great degree also to other types of rolling gates. The water level in gate recess follows basically the movements of the water level outside. Therefore, when the gate is open or when it moves, it still bears oscillating hydraulic loads from waves, current etc. As modern gates are elastically mounted to their wagons, these loads only slightly affect the wheel reactions. They must be balanced in another way. This normally takes place in a triangle of contact forces on each side on the gate[1)]. Expansion devices are the best known measure for this task. They usually consist of horizontal wheels or slide supports, springy supported to the sill curbs (on the gate below) and to the gate guide beams (in the recess entry above), see Fig 16 a. When the gate moves, the top corner remains in the recess (Fig. 16 b) and the triangle changes gradually into its horizontal mirror image. At that moment the gate is closed, but it is not ready to bear large hydraulic loads yet. At first, the expansion devices become released. The growing water pressure moves then the gate towards the downstream recess walls which respond in trapezoidal load figures (Fig. 16 c). Simultaneously, the lowest vertical plate strake – so-called "elastic skirting" – bends under water pressure towards the sill curb and seals the gate horizontally. We see that the more or less concentrated reaction forces during gate motion made place for linearly distributed support reactions in the closed, loaded position. Also the location of support reactions, the load bearing devices etc. are now quite different.

- **Concluding remarks:**

As shown, a number of structural systems and supporting conditions become activated in succession during the procedure of gate closing. The designer must be aware of that and should take care that the selected gate system is able to follow these changes with equal reliability. When choosing the gate structural system, it is not sufficient to focus e.g. on the gate position under extreme hydraulic loads. In fact, such approach has often been the source of errors in gate engineering. All possible support conditions must be taken into consideration at the stage of gate system selection. The engineer should allow for system modifications – if necessary even entire change – with respect to those conditions. Moreover, it is not enough to consider those conditions in terms of static structural analysis. If relevant, other analyses should be performed at that stage (e.g. dynamic analysis, analysis of time related phenomena like fatigue, strain relaxation, wear etc.), at least in the scope of feasibility studies. Only such approach results in a successful, well balanced choice of a hydraulic gate structural system.

[1] In Fig. 16, the contact forces are shown on one (front) side only for clarity reasons.

3.2. Contact levels, selection of pointed, linear or surface supports

Having globally determined the gate structural system, the engineer knows in which areas the supports should be located. At that point he usually still has a choice how large and how shaped the actual supporting areas should be. This choice is important for prosperous gate performances, therefore it may even – if required – result in an adjustment of the gate structural system. Indulging in a generalization, one may say that there are two schools in shaping gate supports:

a) "Purists", i.e. engineers shaping the structures in the way which gives maximum conformity with analytical models (systems). This group will prefer sharply located, pointed supports.
b) "Naturalists", i.e. engineers following the material and loading properties rather than analytical models, even at the cost of accuracy. This group will prefer line or surface supports.

In case of, e.g., a mitre gate response to hydraulic load (see section 2.3.1), a "purist" will choose the system (a) and "naturalist" the system (b) from Fig. 4.

This subjectivity does not mean that there are no objective criteria to follow when designing support areas. Such criteria exist but they are hardly comparable to each other and, therefore, difficult to assess using uniform measures. Applying the multi-criteria assessment method – as discussed for the entire gate selection in sections 2.1 and 2.2 – seems too laborious. Therefore, we shall confine to specifying the main design considerations in this matter. Prior to that, a working definition of pointed, linear and surface contact shall be given.

We shall refer to **pointed contacts** as contacts which areas are in all directions a magnitude smaller than the dimensions of the contacting bodies. In this section, we consider the gate as a whole and its entire contact frame in lock crown as contacting bodies. When focusing e.g. on the gate bearings and shafts as contacting bodies (to be discussed later in this study), the pointed contacts from this section may likely become linear or surface contacts. Similarly: **linear contacts** are contacts which sizes in one direction are comparable with the appropriate dimensions of contacting bodies; **surface contacts** are contacts which areas cover significant parts of proper projections of the contacting bodies.

This definition is relative. The contact type depends in it on a level in which the "contacting bodies" are defined. For the purpose of this study, four levels shall be distinguished, as drawn below using a mitre gate top hinge as a contact example (Fig. 17):

a) system level;
b) component level;
c) segment level;
d) asperity level.

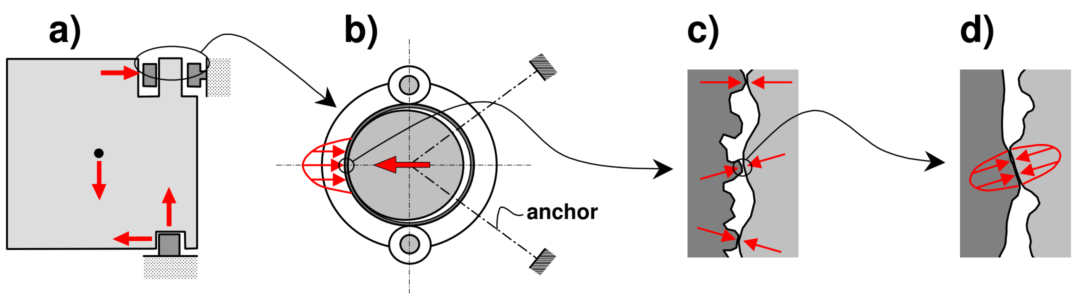


Fig. 17. Levels of contact: **a)** system, **b)** component, **c)** segment, **d)** asperity

In tribological literature, levels (b) and (c) are also referred to as , respectively, "macroscopic" and "microscopic" contacts [33], [34]. In this thesis, however, contact issues are seen wider than only in tribological sense. The attention is focused on the impact of contact parameters on the performances of entire gate systems. Therefore, the contact levels are referred to in an object-orientated (rather than view-orientated) way, as presented above.

When focusing on contacting items (component level) rather than entire gates (system level), a great majority of pointed and linear contacts in hydraulic gate engineering comply with the assumptions of the Hertzian theory [35]. Such a conclusion can not be drawn in regard to the system level or segment level. In regard to the asperity level, however, some resemblances to the Hertzian model can again be recognized, see Fig. 17.

The main design considerations involved in the selection of pointed, linear or surface supports for hydraulic gates (on the system level, if not mentioned otherwise) are as follows:

- Pointed supports go, in general, well along with skeletal systems like trusses, grids and frames. Linear and surface supports suit better to superficial (plate, membrane, shell) and massive (solid or flexible body) systems. Although hydraulic gates often combine the elements of both groups, this general rule can still be followed – in particular in support areas.

- Due to the better conformity with analytical models, pointed supports allow, in general, for better control of load distribution within the entire structure. This advantage becomes less visible when powerful FEM-software is employed that allows simulating large contact areas. Yet, the sharper support location, the smaller risk of unforeseen load distribution in the structure.

- Choosing linear or surface rather than pointed supports can be a manner to avoid stress peaks in support areas. However, this measure can also have an opposite effect if not used properly: A linear or surface reaction distribution causes usually bending in support components, which can easier be eliminated in pointed supports.

- Pointed supports result, obviously, in higher contact stress than linear or surface supports. High contact stress can be seen as an energetically instable condition which does not often appear in nature. Surface supports are in this (“naturalistic”) view energetically more stable; and therefore in better harmony with the nature and less vulnerable to collapse.

- High contact stress in pointed supports limits the choice of contact materials to hard metals, some natural stones, special hard composites etc. There is usually more material choice in supports which distribute the contact stress over a certain distance or surface. Selecting a system with pointed supports bears, in this sense, more risk for detailed design.

- High contact stresses are particularly unfavorable in sliding contacts. The main reasons are wear and warmth generation which can decrease the material contact performances. The ways to avoid it at the stage of gate system definition are: choosing large contact distances or areas, or e.g. roller instead of slide supports.

- The choice between pointed and linear supports affects (sometimes determines) the gate sealing system. When a closed gate responds pointed to hydraulic load, separate edge seals are usually required. When the gate response is linear, a logical choice is to integrate the response and the sealing function in gate support linings.

- Gate supports and other contact components are items which usually require more inspection and maintenance than the components which do not receive contact loads. In this sense, it can be advisable to choose pointed supports e.g. when such arrangement brings the maintenance sensitive items above water (compare mitre gate types d, e and f from Fig. 4 in section 2.3).

- Gate edge seals and the unsealed contact linings have often impact on the gate vibration stability. Flows through narrow gaps are known to cause vibration problems. Seals and linings can cure these problems, but they can also increase them. Good examples are the solutions to vibration problems on the Haringvliet Barrier (Fig. 18 a/b) [36] and on the Hagestein Weir (Fig. 18 c/d) [37]. In the first case, changing the bottom edge seal from **a** to **b** was proposed (not realized yet) to cure vibrations due to the seal suction (or so-called “hydraulic downpull force” [41]). In the second case, changing the bottom edge seal from **c** to **d** shifted the vortex shedding frequency away from the natural frequencies of the retaining wall, which removed the gate vibrations on that weir.

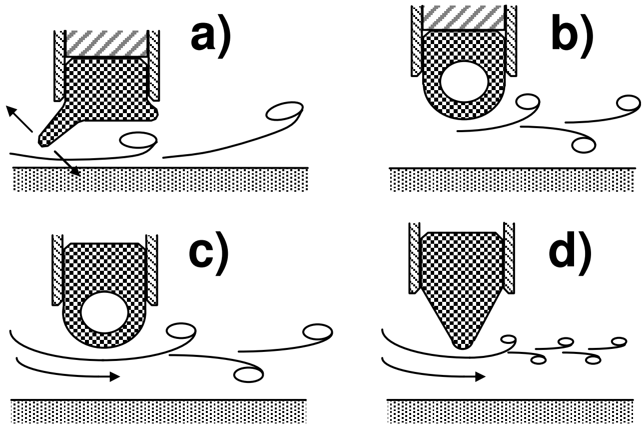


Fig. 18. Solution to the vibration problem on the Haringvliet Barrier (**a** → **b**) and on the Hagestein Weir (**c** → **d**)

- Pointed, linear and surface contacts – when referred to element rather than system level – have a different mechanical character and require different materials. As mentioned, most pointed and linear contacts are Hertzian, which classifies them as elastic. Surface contacts are seldom purely elastic – they usually are elastoplastic, viscoelastic etc. These differences can be significant e.g. for system geometry, local and global load distribution, rheological changes etc.

- Choosing the location and the character of gate supports involves an assessment of the civil structure (e.g. lock crown) load bearing capacity. In this respect, it can be advisable to spread the gate reactions or – contrary – to concentrate them in order to optimize the scope and the costs of the civil works. This is particularly important in renovation projects.

3.3. Fixities of gates under bidirectional hydraulic loads

3.3.1. Bidirectional loads on different gate types

In the complex waterway system of the Netherlands, the water levels on both sides of navigation locks can take reversible positions, i.e. high water drops and low water rises, so that the gate hydraulic load takes an opposite direction. This phenomenon is in fact also common in other countries, in particular in coastal areas. It may be caused by the tide, storm surges, winds in large lake areas, flooding rivers etc. Reversible hydraulic loads require a bidirectional gate service which, in turn, introduces a number of specific contact problems. In recent years, much new experience has been acquired in handling such cases on the Dutch lock gates. In this section, some technical developments are evaluated comprising gate system modifications, structural and mechanical provisions and the related contact problems. The author has been involved in research, design and construction of a number of innovative lock gate projects in this field in the Netherlands.

Some types of lock gates are better suited to bear hydraulic loads in any of the two directions than the other. For a vertical lift gate (see section 2.3.2) or a rolling gate (see section 2.3.3) such an operation presents little problem, while a mitre gate (see section 2.3.1) or a single-leaf gate is usually considered to be fit only for a unidirectional service. This does not, however, make the choice simple because the gates which are fit for a unidirectional service, have a number of other practical advantages. A brief evaluation (Table 5) of the three gate types mentioned above shows that, under usual conditions, the mitre gates deserve preference for lock widths of about 8 until 24 m.

Table 5. Global evaluation of the three most common gate types

Gate type Criterion	Mitre gate	Vertical lift gate	Rolling gate
Construction costs	good	fair	poor
Navigation conditions	good	fair	good
Operation & maintenance	good	good	fair
Lock lay-out conditions	good	good	poor
Aesthetics	good	poor	good
Environmental impact	good	fair	fair
Global	**good**	**fair**	**fair**

Moreover, in nearly all cases of double-sided service there is one dominant water head direction - in respect of size as well as frequency. This makes the objections against the types like mitre gates less substantial. Therefore, it is repeatedly suggested in the Netherlands that the engineers adapt the mitre gates and the single-leaf gates for a double-sided service. The response to this call is not always enthusiastic - there is also a considerable opposition to it. Particularly controversial is adapting the mitre gates. Structural engineers used to say that “nature itself holds water on a mitre gate”. The fact is that the high water level on the pointed side (see Fig. 3a) causes not only bending moments but also compression in the gate. This helps to prevent the leakage and it increases the stability of the entire system. The pressure of a natural element, water, takes in a sense care of its own control. When set in the opposite direction it – on the contrary – tends to open the gate and destabilize the system.

Therefore, there is some truth in the argument that letting a mitre gate (to less extend also a single-leaf gate) bear a reverse, so-called “negative”, load is structurally not logical – or even violent towards the nature. Yet, the call for such solutions is growing – and the development of technology pushes out the feasibility frontiers. A number of projects employing “negatively” loaded mitre and single-leaf gates have been realized in the Netherlands in the recent decades. There are good and bad experiences in this field. In the next three sections of this chapter, some most instructive examples are given, followed by a general discussion focusing on the involved contact problems. The evaluation of diverse system performances is based on the author's engineering practice and his interviews with operation and maintenance personnel in the Netherlands [38].

3.3.2. Locking single-leaf gates – systems and performances

While mitre gates are known in navigation since the early Italian renaissance, the single-leaf gates belong to the oldest types, and originate probably in China about the beginning of our era [39]. This type of gates is less used nowadays but it has kept a certain attraction for narrow, not very intensively navigated locks. Under normal conditions, the hydraulic load pushes the gate towards its frame, what gives it good support and helps to prevent the leakage. This is a valuable advantage, although there is no leaf compression as in a mitre gate. Under reverse load a single leaf gate tends to open, what must obviously be prevented.

An example of a single-leaf gate locking is a bolt device resembling a conventional door lock. On the Yacht Lock in the Krammer (Fig. 19) two such devices on a gate have been installed – the low and the high one, both driven by hydraulic cylinders. The horizontal cylinders drive the bolts into the recess sockets; and the vertical cylinders insert safety pins to secure their position. That lock is only navigated by recreation vessels which draw maximal 1.9 m. Therefore the designers had little concern for ship collisions, malfunctions under water and difficult access for maintenance. The lock is in operation since the end of 1980's and there have been no serious maintenance problems since then. Moreover, there is also no significant leakage, although the fall ("positive" and "negative") frequently exceeds 2.5 m. Instead of a bolt lock, a hook device can be used, as applied to the gates of the Linge Harbor Lock in Gorinchem (Fig. 20). Also this lock is used by recreation vessels only, but the machinery driving the hook is located in a machine room and is, therefore, collision-free. When the gate closes, the machinery holds the hook in an extended, lifted position. Then the hook is lowered, grips the gate and pulls it towards its frame. This puts the edge seal under compression, which seals some deflection resulting from reverse hydraulic loads. It is difficult to apply such a device under water, therefore only one hook on a gate has been provided – on the top girder. The result is a significant warp angle and large gaps under reverse loads. The existing seals do not in fact prevent the leakage. Despite this disadvantage, the lock operator is satisfied with the device, especially with its high reliability and easy access for inspection and maintenance.

A conclusion to be drawn from the last two examples is that a well sealed, collision-resistant single-leaf gate should have a two-level locking device, preferably linked together and driven from a dry place. This has, e.g., been done on the Bergsche Diep Lock near Tholen (Fig. 21). The item linking the two locking levels is there a short frame hinged to the crown wall. When the gate closes, the frame free end is driven towards the gate free post, what locks the gate. This device holds reverse loads resulting from the water heads similar to those in the Krammer Yacht Lock. The leakage is insignificant and no big maintenance problems have been reported so far. Similar locking frames have been applied in the Nieuwe Statenzijl Lock gates near Groningen. While there are still some electro-mechanical drive components in the Bergsche Diep locking frames, the locking frames in the Nieuwe Statenzijl Lock are driven by entirely hydraulic devices. Also there, the gate locking takes place at two levels – under and above water. However, all the machinery is hooked to the frame top member what keeps it dry and accessible for maintenance.

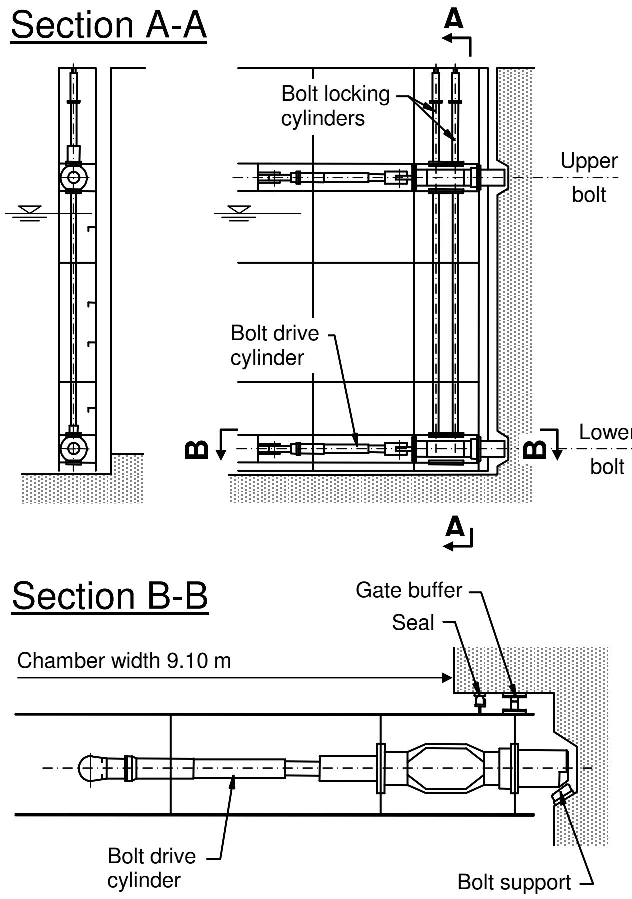


Fig. 19. Gate locking in the Yacht Lock in the Krammer

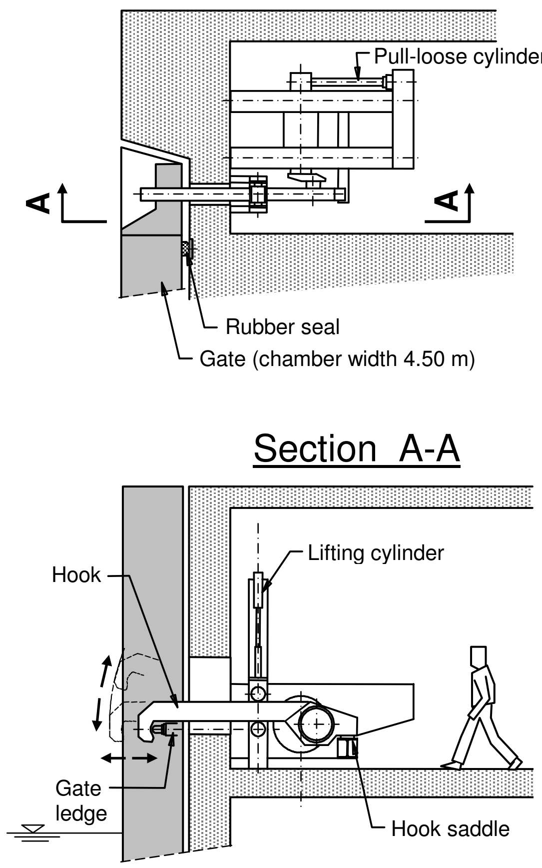


Fig. 20. Gate locking in the Linge Harbor Lock in Gorinchem

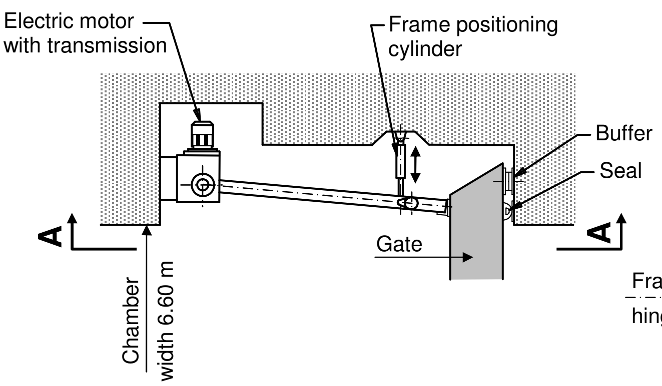
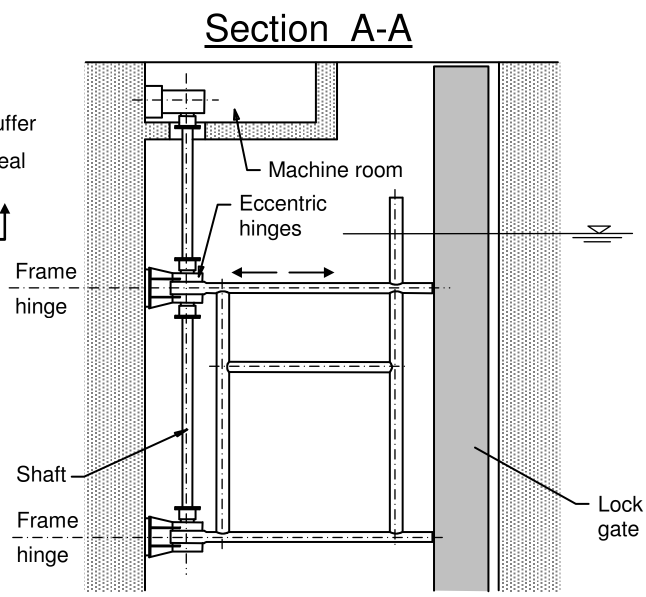


Fig. 21. Gate locking frame in the Bergsche Diep Lock near Tholen



3.3.3. Locking mitre gates – systems and performances

A traditional solution to the problem of reverse mitre gate load is to put two gates at each lock crown, pointing in opposite directions. One of them bears then always "positive" load, i.e. on the pointed side; and the other gate remains unloaded. However, such a solution requires more space and it drives the costs up, which may spoil the evaluation presented in Table 5. Attempts to let a single mitre gate hold the load from two sides have, therefore, been made since long. One of the first ideas was to lock the front posts of the gate leaves to each other, e.g. by a vertical pin. The pin could be driven manually, by an electric screw jack, or by a hydraulic cylinder. The first device of this type, driven by a hand winch, was installed in 1939 on the Queens Lock gate in Vreeswijk [18]. More engineers followed this idea since then (Fig. 22) but the performances of such locking devices remained poor. The system was very vulnerable to deformations, geometrical divergences of the gate contact line etc. It also required large clearances in the pin sockets, which resulted in mechanical failures and large leaks. Such devices are not favored in the Netherlands nowadays.

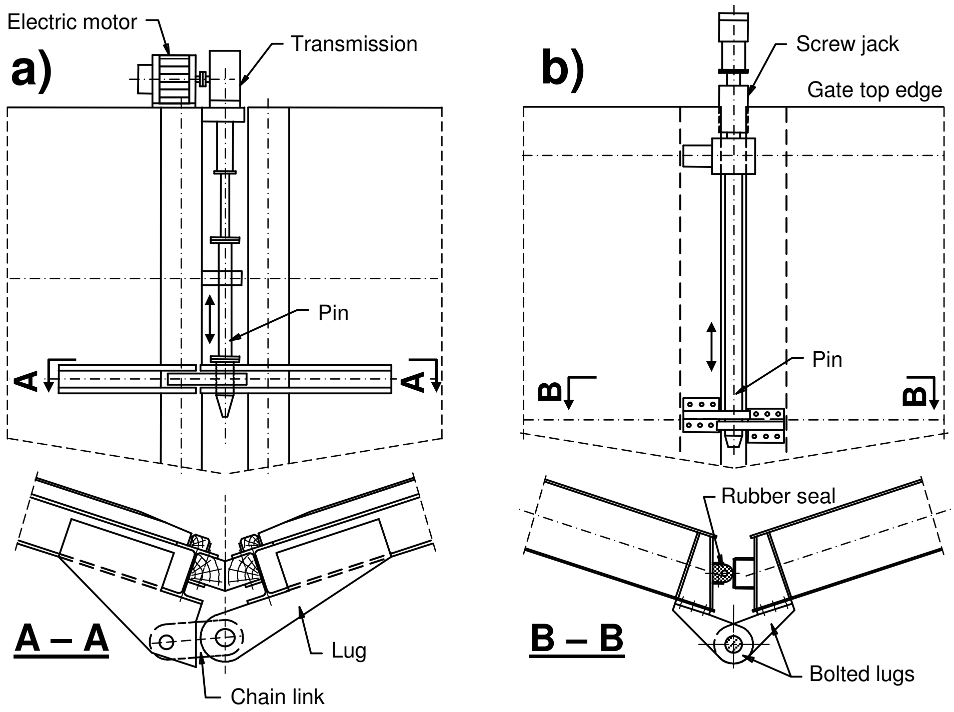


Fig. 22. Mitre gate front post locking: **a)** Queens Lock gate in Vreeswijk (present device); **b)** canal locks in Haandrik and Aadorp.

A quite different idea was to install a locking device on the gate operating machinery rather than on the gate itself. The result is that the machinery must then be capable to bear hydraulic loads next to the loads which set the gate in motion. An early example of this idea is a locking device on Panama wheels used, e.g., in the Schie Canal lock in Schiedam (Fig. 23). That device is mounted on a Panama wheel pinion shaft. It consists of a ratchet coupling driven by a jack. The entire machinery and the gate drive arms are heavily oversized in order to sustain loads from the "negative" water head which in this case can approach 2.0 m. The risk of a ship running into a drive arm is small on that lock because the arms are high above water. According to the lock operator, the system performs quite well although the reverse load does not frequently occur, and when it occurs it causes a considerable leakage. As known, Panama wheels are not used in new projects any more. The collected experience is, therefore, primarily interesting in adaptations of the existing, old lock gates.

There is also a solution in which only the gate drive arms (and not the operating machinery) bear reverse hydraulic loads. An example is the gates of the Merchants` Lock in Den Helder (Fig. 24). The lock has a double mitre gate at each crown. Therefore, the reverse hydraulic load presents little danger. The reason why the gates have been designed for a double-sided service is the so-called “haul waves” or “seiches” which reach considerable heights at that location. The drive arms are gear racks driven by electro-mechanically powered gear wheels. When the gate closes and the drive arm moves out, a locking beam is lifted to support the foot of the arm. In this position, the arm can receive compression from the possible reverse load, and pass it on through the beam to the solid crown. The lock gates are installed in the years 1980’ and the system has been performing well since then. It should, however, be mentioned that there are barely “negative” falls larger than 1.0 m at that location.

Instead of drive arms, one can use separate compression rods to lock a mitre gate. This solution has, e.g., been applied during the renovation of the Merwede Lock in Gorinchem (Fig. 25) and the Large Lock in Vianen. New lock gates received there additional locking bars located in the motion planes of the drive cylinders. The system is designed to bear “negative” falls up to 2.0 m which, however, do not often occur. Therefore large leaks have been taken for granted. Under extreme “negative” water heads, the leakage in low parts of the gate (mainly due to warp angle) is so high that the divers sent to measure the openings could not approach them for security reasons. Yet, except for some mechanical problems at starting, the entire devices have been performing well until now.

In the years 1990-2000, a number of large navigation locks in the Netherlands were scheduled for reconstruction or had to be constructed anew. In all of them, the selected gate type was mitre gate. The engineers (the author among them) had to face a growing demand to apply that gate type in such a way that it could bear hydraulic loads in both directions: the dominant load on the pointed side and the less frequent but also significant reverse load on the concave side. The main objective was to win more space for vessels in lock chambers within limited areas, and to reduce the number of mitre gates into a half of that in the conventional arrangement with double gates. The result of this demand is shortly discussed in the next section. However, the first step was to evaluate the performances of the existing systems in this field – and to draw the conclusions. The main conclusions were as follows:

- Mitre gate is and remains a gate predestined to bear unidirectional loads, i.e. on the pointed side. It performs poor under reverse loads. Nevertheless, it can be used to carry bidirectional loads when the loads on the reverse, concave side are incidental and/or significantly smaller.

- Letting a mitre gate bear reverse loads brings radical changes to its structural system and introduces new contact problems. Crucial is the gate locking device, which is not needed under unidirectional loads. Such a device can be installed on the gate leaves or on the drive system.

- Locking the gate leaves can be realized in a number of ways, e.g. by hooking the front posts to each other, using bracing bars etc. Practical applications prove, however, that the performances of such solutions remain poor. The systems produce large leakage and are vulnerable to malfunctioning.

- Locking the drive system can also be realized in various ways, e.g. by locking the drive machinery (e.g. Panama wheels) itself or only the drive arms. The existing applications of this idea are – in general – more successful than in case of the gate leaves locking.

- Considering the significant development of hydraulic drive technology and digital control systems in recent decades, it is fair to assume that locking a (hydraulic) drive system is the most promising option to follow in prosperous bidirectional mitre gate projects.

An example in support of the last conclusion can be the hydraulic drive system of the Hartel Canal Barrier, briefly discussed in section 2.3.2. The gate drive cylinders of that barrier are locked under full load in stand-by position. No performance problems have been reported so far.

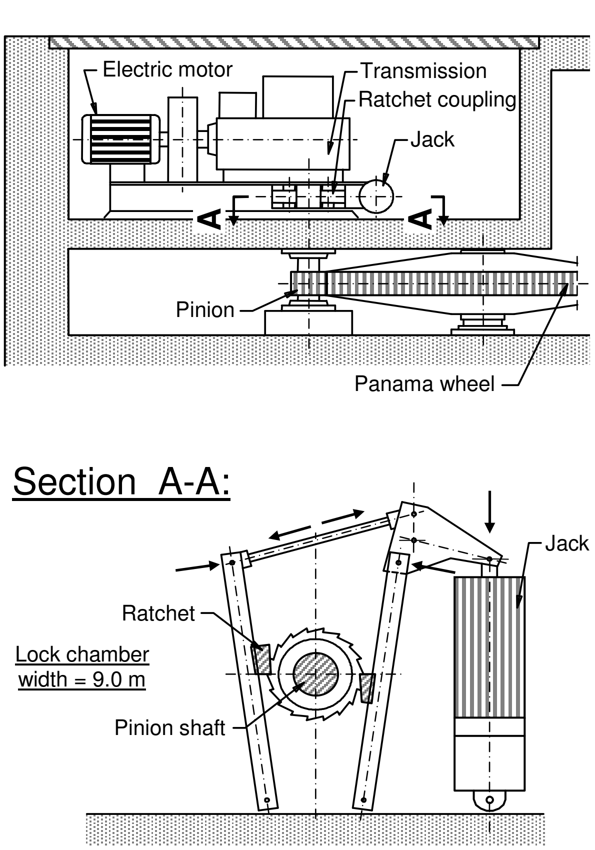


Fig. 23. Gate locking in the Schie Canal Lock in Schiedam

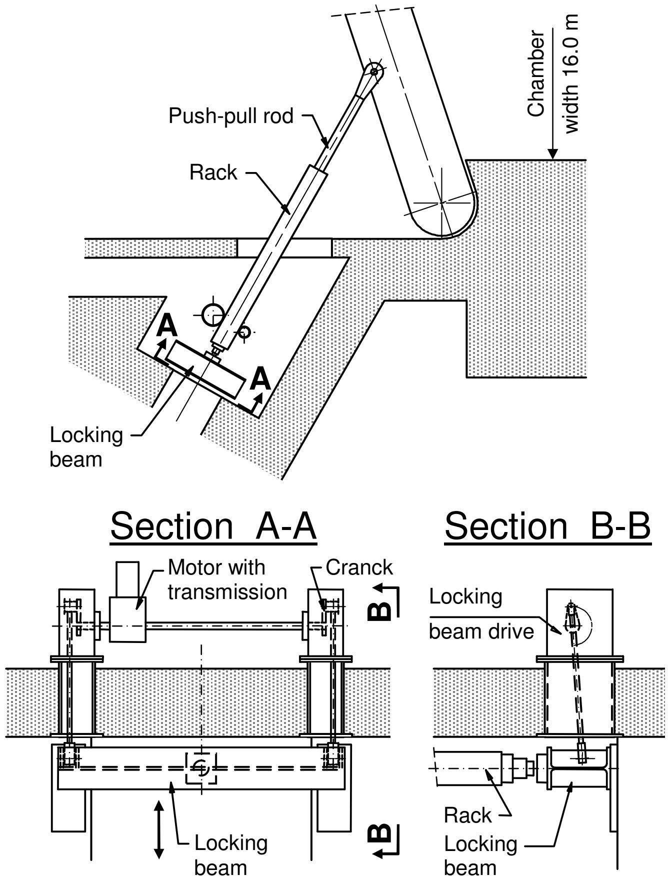


Fig. 24. Gate locking in the Merchants´ Lock in Den Helder

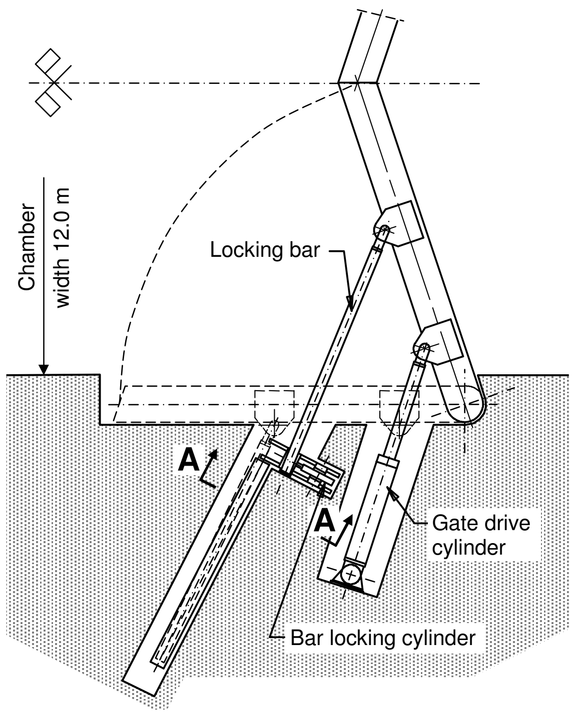
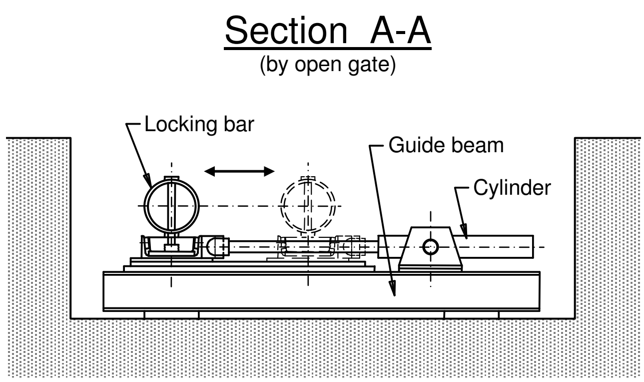


Fig. 25. Gate locking in the Merwede Lock in Gorinchem



3.3.4. New tendencies, new challenges

As the hydraulic drive technology develops very fast, more and more engineers prefer it above the electro-mechanical drives. New developments open new possibilities – it is not a problem any more to lock a drive cylinder and let it carry a significant, long lasting force resulting from a reverse hydraulic load, or a prestression force covering such a load. Based on this idea, three large projects have been realized in the Netherlands in the recent years. These projects are:

- Reconstruction of the Orange Locks in Amsterdam;
- Reconstruction of the Small and the Southern Lock in IJmuiden;
- Construction of the “Naviduct” (lock on an aqueduct) in Enkhuizen.

The gates used in all these projects are mitre gates suited for bi-directional service. Some most essential details are presented in Table 6. For comparison a recent “conventional” lock project - with mitre gates carrying loads in only one direction - has been added in Table 6:

- Construction of the Second Lock in Lith on the Meuse.

The author was lead engineer for gates and related structures in all these projects except the IJmuiden locks. The comments in this section reflect his preliminary studies, structural analyses and practical experiences during construction and the first periods of operation.

The choice for a gate with a drive cylinder as locking device has considerable structural consequences for the entire system. The first decision to be made concerns the gate response to hydraulic loads. As discussed in section 2.3.1, this response can, in general, be realized in three ways (see Fig. 4):

- through gate hinges;
- through gate heel post lining;
- through gate heel post saddles.

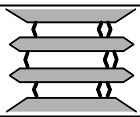
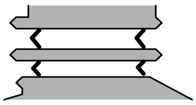
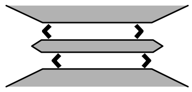
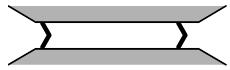
The first choice leads to the so-called *fixed* rotation points; the second and the third to the *free* rotation points. Both terms should be understood in geometrical, not mechanical sense: *Fixed* rotation points have practically no clearances and “feel” directly any gate load. *Free* rotation points are constructed with fair-sized (about 10÷20 mm) clearances which give the gate leaves a small sag in open position, as discussed in section 3.1. Load on the pointed side lifts the front posts a little which removes the sag. The clearances are such that the rotation points become then released and the reactions are passed to the heel post lining or saddles. This helps to seal the gate under unidirectional, so-called “positive” load, like in the Lith lock. Under reverse load, however, it does just the opposite – it produces leakage gaps. Therefore, two of the three bidirectional gate projects from Table 6 are constructed with *fixed* rotation points. The reason why *free* rotation points have been applied in the IJmuiden locks is that large leakage under reverse, so-called “negative” loads has been considered acceptable there.

Leakage is, however, not the only contact issue in support of the *fixed* rotation points in bidirectional gate service. The other two arguments are:

- The advantages of hinge relief and reaction passage to heel posts do not apply to “negative” loads. The gate hinges can not be spared from carrying those reactions – and must, therefore, be oversized anyway. There is then less to win in passing “positive” loads through the heel posts.
- When – in particular – gate leaves with drive arms are applied (which should be recommended, see below), the loads on the top hinges are during opening such that they drive the heel posts towards their contact surfaces in the lock crown. Large clearances of *free* rotation points would cause then unfavorable contact and wear of the heel post lining.

Observe in Table 6 that the only bidirectional gates with *free* rotation points – those of the IJmuiden locks – are driven by hydraulic cylinders hooked directly to the top girders, the same way as in conventional, unidirectional gates in Lith. In both other two projects (Amsterdam and Enkhuizen), drive arms (see Fig. 1 in section 1.1) have been applied in combination with *fixed* rotation points. The reason why drive arms are recommended rather than a direct drive connection is an increased reliability requirement of the drive itself. Its task covers now also the gate locking, the failure of which can be quite harmful. Using drive arms removes the drive cylinders from the zone of possible ship collisions, which improves that reliability. In addition, the cylinders are better accessible for maintenance, less exposed to pollution, weather degradation etc. which further decreases the probability of their failure.

Table 6. Comparison of four mitre gate lock projects

	Orange Locks in Amsterdam	**Southern and Small Lock in IJmuiden**	**’Naviduct’ in Enkhuizen**	**2nd Lock Lith on the Meuse (for comparison)**
Lock chambers	3	2	2	1
Gates per chamber	3	2	2	2
Chamber widths	14, 18 & 14 m	18 & 11 m	2 x 12.5 m	18 m
Usable lengths	62, 82 & 62 m	2 x 111 m	2 x 125 m	200 m
Layout of gates				
Type of operation	lock between canal and lake	lock between sea and canal	lock between two lakes	lock on a navigated river
Flow directions	⇄	⇄	⇄	←
Gate load character	bidirectional	bidirectional	bidirectional	unidirectional
Gate design falls: primary, reverse	2.10 m primary 1.00 m reverse	4.30 m primary 1.30 m reverse	3.20 m primary 1.00 m reverse	5.55 m primary no reverse
Single leaf weight	250, 300, 250 kN	800 & 400 kN	each 220 kN	450 kN
Response to water pressure	through gate bearings	through gate side posts	through gate bearings	through gate side posts
Vertical support location	top bearing	bottom pivot bearing	bottom pivot bearing	bottom pivot bearing
Gate drive	hydraulic, to gate drive arm	hydraulic, to gate top girder	hydraulic, to gate drive arm	hydraulic, to gate top girder
Retaining plate position	upstream (primarily)	upstream (primarily)	downstream (primarily)	downstream
Leakage tightness	low, few seals required	low, few seals required	high, extensive sealing	high, yet no seals required
Filling/emptying system	gate sluices, two per leaf	gate sluices, two per leaf	gate sluices, one per leaf	gate sluices, two per leaf
Chamber condition during installation	’wet’, bottom too weak	’wet’, bottom too weak	’wet’ or ’dry’	’wet’ or ’dry’
Maintenance cycle	10 - 12 years	10 years	16 years	12 -16 years
Design life cycle	40 years	50 years	50 years	50 years
Construction year	1997-2000	2000-2001	2001-2002	1998
Engineered by	Haskoning BV, Nijmegen/NL	Bouwdienst RWS, Zoetermeer/NL	Bouwdienst RWS, Zoetermeer/NL	Bouwdienst RWS, Zoetermeer/NL
Constructed by	HSM bv in Schiedam/NL	Victor Buyck nv in Eeklo/B	Bergum Staalbouw in Bergum/NL	Genius Vos bv in IJmuiden/NL

Locking the gate by drive cylinders obliges the engineer to consider new loading cases in gate design. Following is a brief indication of some hydraulic aspects and new gate loads. For the space reasons, the discussion does not cover cylinder loads, control system requirements etc., which must obviously be considered as well. More details on the design approach to these problems in the projects from Table 6 can be found in [2], [28] and [40]. In chapter 4 of this thesis, a more detailed approach to gate contact loads is presented. When compared to the classical engineering practice, the new gate loads vary not only in respect of size and location but also in respect of character. Classical gate engineering was rooted in static structural analysis, while diverse details of bidirectional systems (e.g. drive couplings, cylinders, hinges, other contact components, locking devices etc.) require dynamic analysis.

A particularly important field of dynamic analysis is fatigue. In order to reduce the leakage under reverse loads, it is usually not enough to lock the drive cylinders – the engineer should also use them to produce some prestression in the gate. As the reverse loads are difficult to predict, there will usually be one option left: prestressing the gate on every closure. This and the hydraulic load build-up determine two poles of a so-called *stress range*, which causes fatigue. Of course, some components are more exposed to fatigue loads than the other. Special attention should be paid to drive connections, top girders, top hinges and the vicinity of those components.

Another already mentioned problem is the leakage. It is caused by hinge clearances and gate deflections under “negative” load. The gate responds elastically to hydraulic loads. When edge linings are of hard material, such as wood, hard synthetics etc., gap openings cannot be prevented. This happens also when a soft (e.g. rubber) seal works only in one, “positive” direction. Obviously, the extensive leakage continues as long as the gate bears “negative” fall. By high water heads (> about 1.0 m), flow velocities in leakage gaps are high as well. This results in considerable volumes of leaking water, which can hinder the locking of vessels.

The leak restrictions mentioned above apply to lock projects as whole. However, strong leakage flow can present a problem to the gate itself. High flow velocities through long gap openings are perfect conditions to produce gate vibrations. The vibrations occur in particular when a gate edge is not stiff or when a rubber seal is applied bridging only a part of the gap. Such vibrations are unpleasant for the personnel. They also cause an early machinery damage, control system malfunctions and fatigue of the gate structure. The best cure against vibrations is stiff gate edges, well closing seals and seals which are short in the direction of the flow. The place of flow departure from the structure must have a sharp edge. A good cure is also to make the downstream side of the gap narrower than the upstream side, so that the greatest flow velocities appear on the downstream side. Two well proven solutions to vibration problems are shown in section 3.2 (see Fig. 18). More details about vibration prevention can be found in e.g. [36] and [41]. However, most of the known preventive methods do not work when the flow assumes reverse direction. The design effort should, therefore, be focused on flow prevention, short intervals of risky flows etc., rather than shaping the flow exposed components. A brief discussion on flow prevention and examples of gate sealing are given in section 3.4 of this thesis.

Another flow problem concerns the lock leveling sluices. For space and costs reasons, sluice openings in the gate are usually preferred to feed culverts in the Netherlands. The sluices are usually situated on the upstream side of the gate. In the downstream direction the sluice openings become wider and on the downstream side the so-called flow-break beams are installed. The result is that the filling flow enters the lock with moderate velocity, spread equally across the chamber. The flow loads on vessels in the chamber are limited. In addition, the discharge flow is well spread when leaving the lock. However under reverse loads this arrangement produces just the opposite: strong jets by the openings and whirlpools aside. The flow loads on vessels in the chamber increase. The jets down the lock attack bottom reinforcement. For these reasons, the lift velocity (often also the lift height) of the sluices should in some cases be decreased, what gives longer filling and discharge times. One can also apply valves of other type than sluices, increase their number and spread them better across the gate. An ultimate solution is moving vessels further from the upper gate, or reconsidering the construction of culverts.

3.3.5. Concluding remarks on gate locking

In conclusion of section 3.3.3, short evaluation has been given leading to the selection of gate drive cylinders as locking devices. An important advantage of this system when compared to double gates or other locking devices is a considerable reduction of system components. The gate cylinders combine the function of a drive and a locking device, therefore no additional structural or mechanical components are required. There are, however, significant differences when compared to a conventional gate that bears loads only on one side. The most important differences are as follows:

- The drive cylinders are heavier and they meet higher requirements;
- The reliability (in particular: contact) requirements for each gate are higher;
- The gate control system performs more tasks (locking) and is therefore more complex;
- The gate itself is heavier due to higher and more complex loads;
- The dimensional tolerances are narrower in order to keep the leakage down;
- More gate details are subject to fatigue loads and require fatigue analysis;
- Precautions against vibrations and unfavorable flows (e.g. through sluice openings) are required.

It should not be forgotten that letting a mitre gate bear reverse loads is contradictory to the very concept of that structure. Therefore it is not true that (as one might suppose) gate locking on drive cylinders spares the designer one gate per crown. The three recent double-sided lock gate projects discussed in this section show in fact no spectacular costs reduction in comparison to the option with double gates per crown. More significant is the space winning and cost reduction due to shorter crowns. It is also expected that the maintenance costs will decrease, as there are less components to be maintained. In particular, the costs of coating – which are significant for steel gates [42] – will be reduced. These advantages will probably continue to be favored in harbors and other urban areas where there is a dominant load direction and the reverse loads are clearly smaller. If space is not a problem and the difference between the loads in both directions is small, a solution with two mitre gates per crown (or another gate type) shall be preferred. Other locking systems – e.g. presented in sections 3.3.2 and 3.3.3 – will probably keep their attraction for single-leaf gates, but loose it gradually for mitre gates.

3.4. Gate tightness – linings and seals

As discussed in section 3.3, gate leakage presents a particularly difficult problem for mitre gates under reverse hydraulic loads. However, it should be prevented in any gates – and also under unidirectional loads. Leakage is in fact (after load distribution) the most significant criterion in design of gate contact components. The main reasons to prevent leakage in hydraulic gates are as follows [38]:

- As mentioned in section 3.3.4, heavy leakage may cause flow in the lock chamber, which can disturb the vessel locking, e.g. by delaying it, hindering the mooring etc.
- When the water storage capacity of the lock downstream basin is small and the leakage volumes high, the water level down the lock may rise too quickly.
- For the locks connecting basins of salt and fresh water, it is important that no large quantities of salt water penetrate into the hinterland. Special care should be taken in the neighborhood of drinking water inlets, unique nature areas etc.
- The lock bottom can be subject to erosion under strong leakage flows. It should be avoided that leakage and not the regular water levelling determine the scope of bottom protection.
- Large leakage on one gate can make it impossible to bring water on both sides of the other gate to the same level during locking. This hampers the gate motion by opening and exposes the vessels to sudden flow loads.
- Flows through narrow gaps are known to be the source of vibrations. As already mentioned (see section 3.3.4), gate vibrations can hurt people, machinery and cause gate fatigue damage.
- Leakage flows suck floating rubbish, wood, ice etc. into the gaps. When the gate opens, those objects can cause damage to edge post linings, seals or other components.

The leakage restrictions in gate projects depend strongly on the situation. If no salt penetration is allowed, the sealing must be almost perfect. If the lock connects two large basins containing water of the same quality, the leakage restrictions can be milder depending on the required sailing conditions, operation convenience, bottom condition etc.

The author's experience from a number of projects is that compromising on leakage prevention is a common practice when time or money become critical. That is a wrong practice. Indeed, tight gates require high construction accuracy (particularly in civil works) and – sometimes – additional precautions like seals, both of which cost effort and money. However, letting a gate leak shifts the problem to the maintenance by causing vibrations, damage by floating debris, ice etc., which is not proper.

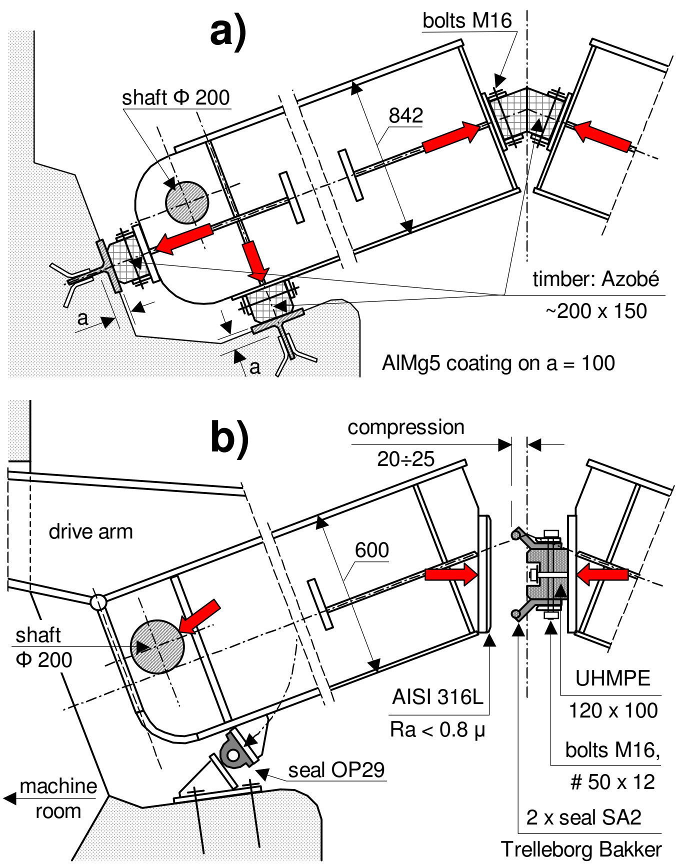


Fig. 26. Mitre gate lining and seals in:
a) Lith Lock on the Meuse [2];
b) Naviduct in Enkhuizen [43].

In Fig. 26, two realized examples of mitre gate sealing are presented, both from the author's engineering practice. These examples can be seen as representing two opposite approaches to the problem of gate sealing. Let us consider case (a) first, in which the sealing has been realized by the same contact components which provide the load transfer from the gate to the lock crown. These components are edge post linings, made traditionally of hard timber[1)]. Timber, when installed within dimensional tolerances, fits soon well in the gate frame, adjusting its surface to the contact irregularities. When that timber has good mechanical properties (in particular the bending strength and the elastic modulus), it can perfectly combine the functions of load bearing and sealing. Below are some main mechanical properties of a number of timber species which can be considered for hydraulic gate linings or entire gates (Table 7) [44]. These properties can vary from the data in other sources. They were determined by a leading Dutch research institute TNO, partly on behalf of the projects under the author's supervision [29]. Soft timber, e.g. pine wood, is not applicable for hydraulic gates. Nevertheless, it can be used to seal the contacts of compound timber sections where load bearing is performed by another, harder timber. The softest in Table 7, which can fulfill both tasks – sealing and load carrying – is oak wood. It performs well, assuming there is no high compression stress and a good, free of longitudinal split, timber batch is delivered. There are some good experiences with Polish oak for this purpose in the Netherlands. American oak is, in general, less durable and therefore less favored.

Table 7. Mechanical properties of some timber species for hydraulic structures

Property → **Timber species ↓**	**Origin**	**Density** [kg/m^3]	**Bending strength** [N/mm^2]	**Modulus of elasticity** [N/mm^2]
Angelim vermelho	Brazil	1086 (5%)	78.8 (21%)	16000 (11%)
Azobé	Cameroon	1050 (7%)	101 (15%)	18600 (15%)
Basralocus	Surinam	939 (11%)	58.0 (33%)	17200 (30%)
Cumaru	Brazil	1078 (5%)	102 (21%)	18300 (16%)
Denya	Ghana	991 (8%)	75.7 (16%)	17000 (30%)
European oak	Poland	885 (7%)	42.0 (16%)	9300 (18%)
Karri	South-Africa	924 (8%)	62.0 (20%)	15500 (17%)
Massaranduba	Brazil	1100 (4%)	110 (14%)	24700 (35%)
Nargusta	Bolivia	742 (9%)	73.9 (22%)	19900 (22%)
Piquia	Brazil	940 (5%)	63.0 (14%)	18600 (31%)
Robinia	Hungary	740 (6%)	66.0 (24%)	15200 (13%)
Vitex	Solomon Isl.	908 (10%)	58.0 (18%)	13100 (16%)

Note: Values (_%) represent the coefficients of variation, i.e. the ratios of standard deviations to mean values.

Species like *Angelim vermelho* and *Cumaru* are tropical, hard timbers from the Amazonian forests. They are nowadays available from forest managed in a sustainable way and should bear the so-called FSC (Forest Stewardship Council) certificate – the most reliable certificate in this matter. This certificate has not yet been granted e.g. to any *Azobé* supplier. That timber species, growing in Cameroon and neighboring countries, gives no confidence of being harvested in a sustainable way. Therefore, the purchasing of this species should not be advised, despite very good mechanical properties.

The bending strength values in Table 7 are not design values. They are obtained from tests on beams of about 150 mm section depth, moisture content of 10 ÷ 15% and with no correction for sample size, moisture content etc. The elasticity moduli are determined along the grain. The values across the grain (which are particularly interesting for gate lining) are about $^1/_{12}$ to $^1/_{10}$ of these values, which is a good approximation for all hardwood species.

Let us now consider case (b) from Fig. 26, in which the sealing and the load bearing functions are split and performed by different components. The edge post linings are now of UHMPE (Ultra High Mo-

---

[1] The used tropical timber, Azobé, is in short supply from sustainable forests. Its application should, therefore, be limited. Another project engineered and directed by the author – new gates for Lock III in the Wilhelmina Canal – proves that there are timber species equivalent to Azobé not only for the lining but for entire gates [29].

lecular Polyethylene), material showing good mechanical properties under moderate load. The seals are rubber profiles with vulcanized polyethylene contact strips in case of slide contacts. The latter minimizes the friction and wear of seals, providing the opposite surface is smooth. The gate leaf compression is entirely transferred by the front post lining and two hinges. This system is effective for a moderate hydraulic load which, however, can change its direction. The double front post seal could have been reduced to a single one (on the "negative" load side), if there was no risk of its excitation by unsealed gap flows under "positive" loads. This applies also to the bottom edge seal (not shown in the figure), which has an identical cross-section as the front post seal.

High quality polyethylene can theoretically sustain higher compression than timber, providing proper measures (e.g. stiff casing) are taken to manage its viscoelasticity. If – as in this case – such measures are not taken, the compression stress must be kept low to avoid deformation under long-lasting loads. Laboratory investigations performed under author's supervision (for details see section 6) resulted in selecting the following design mechanical properties (in the sense of Eurocode 1) of UHMPE for the applications in hydraulic gate design (Table 8):

Table 8. Mechanical properties of polyethylene (UHMPE)

Property	**Unit**	**Value**	**Examples, comments**
Density $\boldsymbol{\rho}$	kg/m^3	940	slightly higher by soot addition
Max. compression: stationary, short	N/mm^2	15.0	obstacle, ship collision, wave etc.
Max. compression: stationary, long	N/mm^2	5.0	weight, lasting hydraulic load etc.
Max. compression in slide contacts	N/mm^2	3.0	hydraulic load initiation, guides and hinges during gate motion etc.
E modulus by short-lasting load	N/mm^2	~ 1000	indication, viscoelasticity
E modulus by long-lasting load	N/mm^2	~ 200	indication, viscoelasticity
Collapse temperature	°C	130	loss of mechanical properties
Wear factor *k*, rolled steel roughness	mm^2/N	$18.0 \cdot 10^{-9}$	in temperature << 130 °C
Wear factor *k*, roughness $R_a < 0{,}8\mu m$	mm^2/N	$8.0 \cdot 10^{-9}$	in temperature << 130 °C
Friction coefficient $\boldsymbol{\mu}$	-	0.15 ÷ 0,20	normal temperature, no lubrication
Thermal expansion coefficient $\boldsymbol{\alpha}$	1/°K	$2.0 \cdot 10^{-4}$	~10 x higher than metals!

Note: The investigations have been performed on specimens of UHMPE received from Hostalen 412 processing.

Obviously, more materials than timber and polyethylene can be considered for hydraulic gate linings. There are both good and bad experiences in the Netherlands with such contacts as: steel – (reinforced) rubber, steel - bronze, stainless steel – stainless steel, concrete – timber, stainless steel – composite etc. The scope of this thesis does not allow a detailed discussion of all these contacts. Instead of that, some concise, practical engineering advices are given in conclusion:

- Avoid gate leakage. Even when there are no operational objections, it still causes misery.
- Define and do not exceed dimensional allowances – in gates as well as in their contact frames.
- If possible, choose robust contacts. Beware of heavy operational, weather and other conditions.
- Avoid or minimize maintenance. There will be a scarce and very limited possibility to do it.
- Do not hesitate to use timber. It is not old-fashioned. It can be a perfect, environmentally the best sustainable material. Take care that it bears the FSC certificate.
- If high dimensional accuracy is required (e.g. by reversible hydraulic loads), let the load bearing and the sealing be performed by different components.
- Prefer simple synthetics (polyethylene) in complex contacts, but study carefully their properties.
- Try to avoid or minimize friction and lateral loads on lining and (rubber) seals.

3.5. Guiding and maintaining gate contacts

The last concise advice from section 3.4 can, in fact, be seen as an engineering principle. Gate linings and seals perform well when loaded perpendicular to the contact surface. Friction and lateral loads (i.e. loads in the contact surface) are known to cause wear, excessive deformations, serious disturbances or even collapse of the entire gate supporting system. This problem must be considered in all gate positions, which means that it can – in general – be split into the three following questions:

1. How to avoid or manage lateral actions on lining in gate open position;
2. How to avoid or manage such actions during gate motion;
3. How to avoid or manage such actions in gate closed position.

The first two questions are of particular interest for vertical lift gates and rolling gates. The linings of single-leaf and mitre gates are usually not exposed to lateral loads in those positions. The third question is relevant for all gate types – especially for the mitre gates.

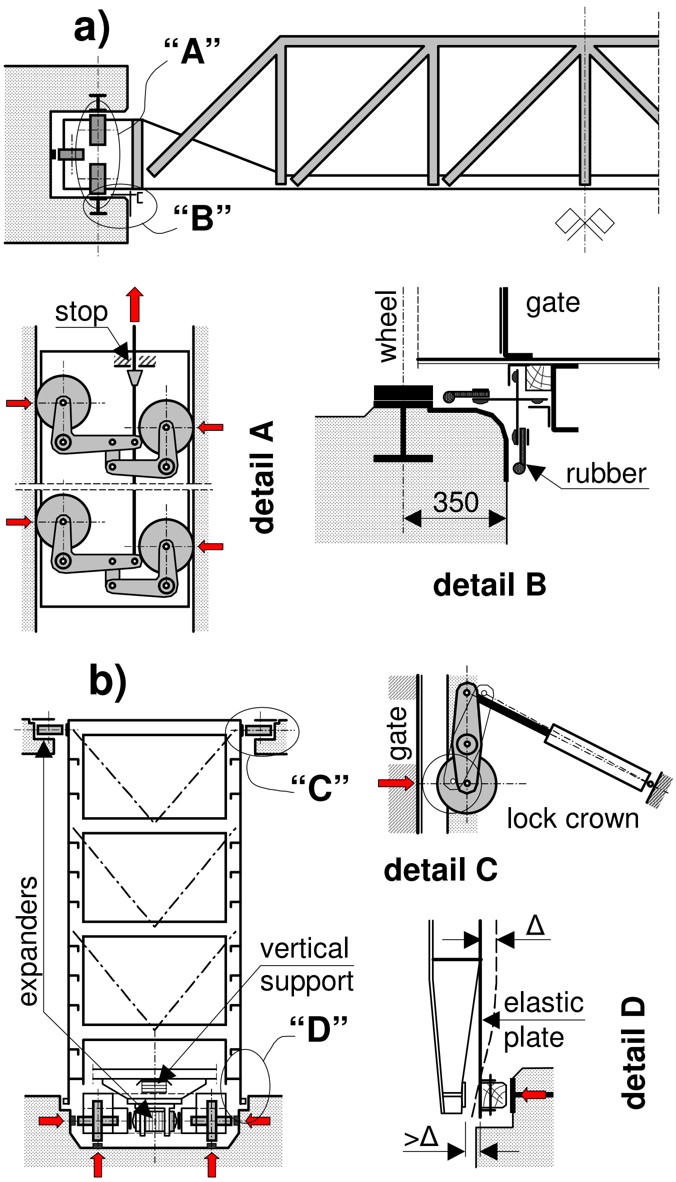


Fig. 27. Contact guiding and sealing in:
a) vertical lift gate (e.g. St. Andries [1]);
b) rolling gate (e.g. Hansweert [45]).

It is principally better to eliminate lateral loads and friction than to manage them. In Fig. 27, some ways to do it for vertical lift gates (a) and rolling gates (b) are presented. These examples present gates capable of carrying loads in any of the two directions. Gates carrying loads in one direction present a smaller problem. The solution to it can be deduced from the details in Fig. 27. The main idea is the same for vertical lift gates and rolling gates. It can be put as follows: Bring the gate, before closing, in a position giving sufficient clearance on contact lining and seals during motion. The devices realizing this idea are guide wheel expanders. There exist various types of such expanders. Most representative are perhaps a double-sided mechanical expander (detail "A") and a hydraulic jack expander (detail "C"). The first expander works – simply speaking – in a manner similar to a toy known as "puppet on a string". Its ingeniousness is that it does not require a drive. The gate lifting force expands the guide wheels itself. Naturally, this force needs to be limited, e.g. by a stop, otherwise the device would clamp the gate. When the distance between guide rails is large, wheel lever arms can be replaced by a system of ropes and pulleys, which is e.g. done sometimes in large rolling gates [11]. In new projects, however, hydraulic technology is usually preferred, which leads to expansion devices similar to the one shown in detail "C".

While the guide wheels (optionally: slide pads) help to avoid lateral loads and friction, the gate seals prevent the leakage. In the examples presented in Fig. 27, the seals become effective under hydraulic loads, which is the most logical arrangement for a gate. Nevertheless, as men continue to substitute the nature by own products, it is possible that also the seals will have their own (e.g. pneumatic) drives in the future. So far, no such ideas have been realized. It is the hydraulic load build-up which moves the seals towards their contact surfaces and puts them there under pressure closing the possible gaps. In order to let this movement take place, the seals must be sufficiently flexible. While in mitre gates this flexibility can entirely be obtained in seal compression (compare Fig. 26 b), in the rolling and vertical lift gates this will usually not be enough. The gaps to be bridged are too wide. Therefore, deflections of other structural components must contribute to bridging these gaps. In detail "B", a long vertical member of a cross-shaped section with low torsional rigidity does this task. In detail "D", the flexural elasticity of a retaining plate bottom strip (so-called "resilient plate") provides the same effect. In the latter case, the gap to be sealed is not only large but also variable because it must cover the deflection Δ of the entire gate under hydraulic load. The resilient plate deflection should also be limited inwards to ensure that a pressure difference on both sides of the plate (caused e.g. by waves in gate open position) does not bend it too far.

The most favored materials for gate seals are timber (if some leakage is acceptable) and rubber (for a perfect leakage tightness). Combinations of both materials in compound linings are practiced as well. In such cases, rubber fulfils usually the sealing function while timber bears the loads. A good guide to rubber seal design, containing a number of practical solutions from Italy, is given in [46]. In addition, a wide range of rubber seals as well as an expertise in their applications can be obtained from different suppliers, e.g. Trelleborg Bakker [47]. For the sake of completeness, the indicative properties of rubber are given below (Table 9). The values have been compiled from the data in [46] and [47], i.e. they do not originate from the tests directed or initiated by the author.

Table 9. Comparative properties of natural end synthetic rubbers

Property	**Unit**	**Natural rubber**	**Neoprene**	**Styrene-Butadiene**
Density **ρ** of base elastomer	kg/m^3	930	1230	940
Tensile strength, new	N/mm^2	10.3 ÷ 27.5		
Tensile strength, aged	% of new	min. 80%		
Elongation at break, indicative	%	400 ÷ 800		
Hardness range (durometer method)	° Shore A	30 ÷ 90	40 ÷ 95	40 ÷ 100
E modulus (strip, free bending)*	N/mm^2	4.0	4.5	4.5
Friction coefficient **μ** dry, indicative	-	0.9	0.8	0.8
Abrasion resistance	relative	excellent		
Oil resistance	relative	poor	good	bad
Resistance to weathering	relative	poor	excellent	good
Low temperature resistance	relative	excellent	good	good

*/ These values are indicative. The elasticity modulus of rubber depends on many factors, e.g. section shape, load character and range etc. Proper supplier's graphs should be used in detailed engineering.

Note that the rolling gate from Fig. 27 (b) has central supports allowing for lateral movements with respect to the wheel units. Thanks to this arrangement, almost no gate hydraulic loads are passed to vertical wheels and their rails, which results in about equal wheel loads. The gate lateral position below is entirely controlled by expanders of the (horizontal) bottom guide wheels. This arrangement is considered nowadays to give the best solution to the problem of wheel and rail wear. However, it has only been practiced since the end of 1970's, which is not long in hydraulic engineering. It took some generations of engineers to duly recognize the contact problems of rolling gates, while other structural problems of such gates have always drawn sufficient attention.

In recent decades, there is a tendency to replace rolling contacts by sliding contacts – in both vertical lift and rolling gates. Combinations of high quality materials available nowadays, such as UHMPE and stainless steel, allow for low wear and friction in such contacts. As result, slide guiding devices require in general less maintenance than the conventional guiding wheels. However, the practice shows that slide guides remain vulnerable to impurities such as sand and gravel, rough weather, temperature etc. In author's opinion, based on long engineering and field experience, slide guides should certainly be preferred in gates of relatively low operation frequency, e.g. the Hartel Canal Barrier (Fig. 28). Gates frequently operated (e.g. in navigation locks) can better preserve the rolling contacts, unless thorough precautions are taken to isolate the slide contacts. As slide contacts have linear character, they shall usually be extended over the whole edge post lengths, so that no additional seals are required. This, in turn, allows removing the expansion devices. The entire system becomes then deeply integrated and, therefore, much simpler.

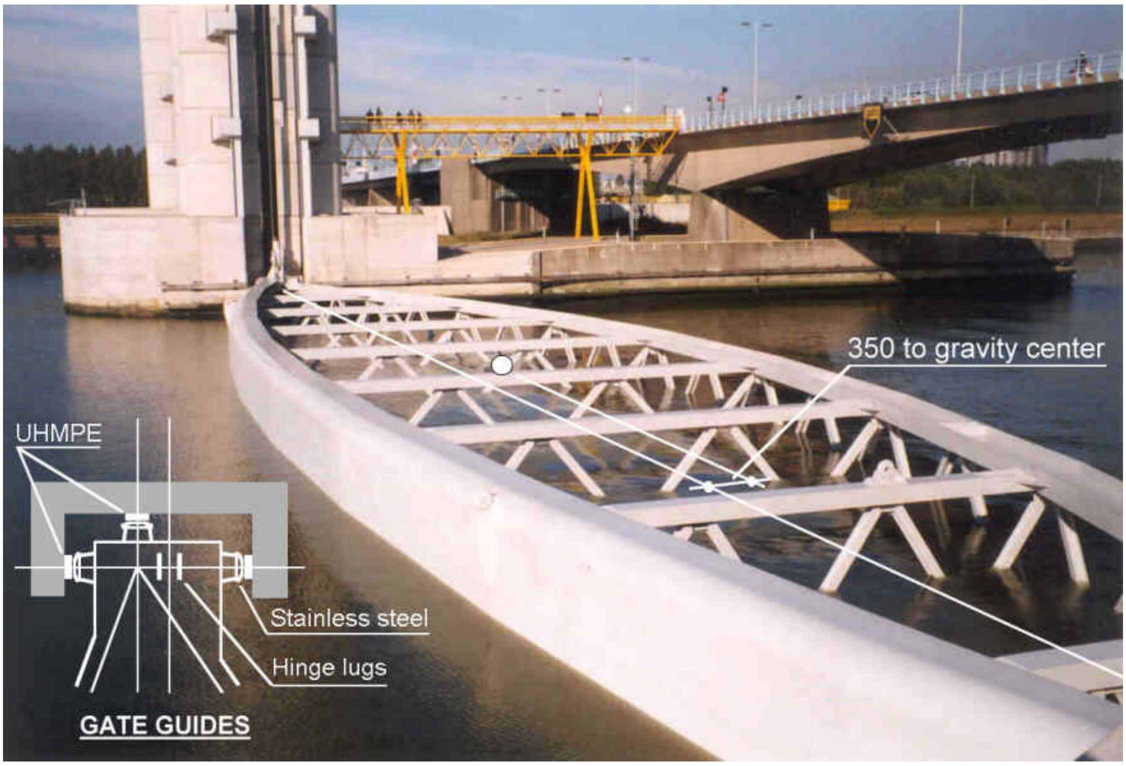
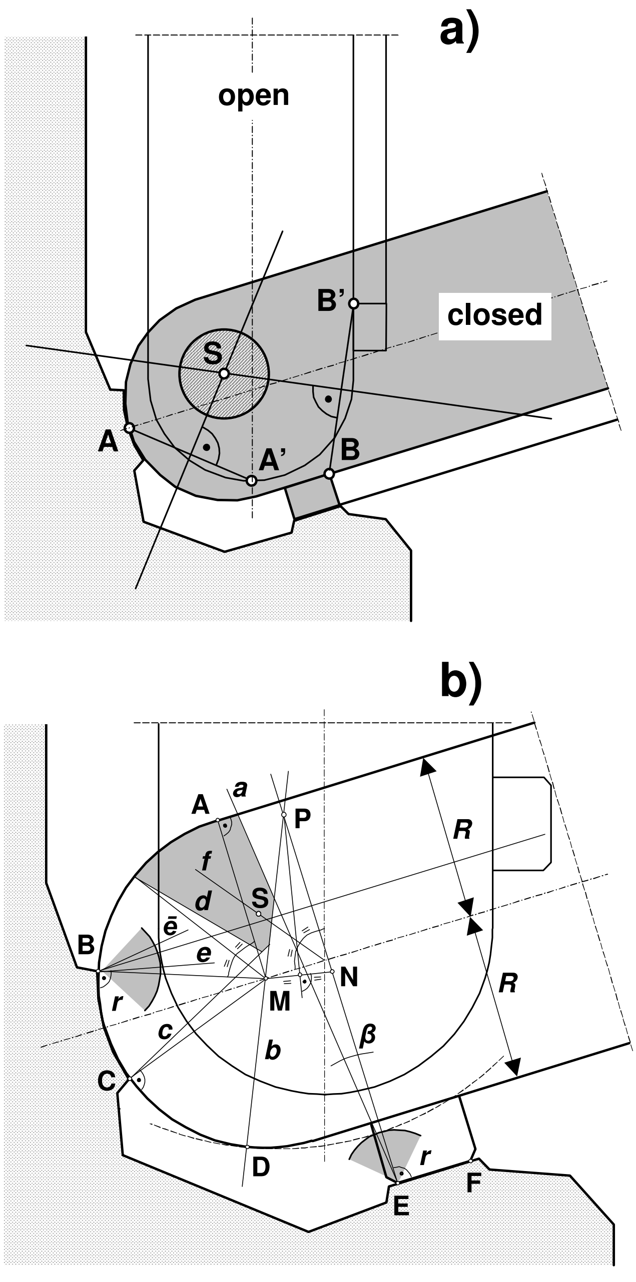


Fig. 28. Slide guiding of the Hartel Canal Barrier near Rotterdam

The latter does not mean that there is no problem of slide contact loads. These loads must definitely be limited – not only due to friction and wear but also to avoid the creep of slide guides. This is particularly important in vertical lift gates, which – in lifted position – pass a significant overturning moment to their guides and towers. A good way to solve this problem is to construct the gate in such a way that its center of gravity lies not far from the plane of suspension. On the other hand, a certain eccentricity of this center of gravity is advisable in order to make sure that the guide clearances do not cause gate fluttering under wind loads. The gates of the Hartel Canal Barrier, designed by the author, have both the guide clearance of 20 mm and the gravity center eccentricity of 350 mm: the "large" Southern Gate on the rear chord side, and the "small" Northern Gate on the retaining wall side. This results in moderate overturning moments in the lifted position, ensuring at the same time that the fluttering does not take place before wind force 8, Beaufort [48].

Observe that both examples in Fig. 27, as well as the gates of the Hartel Canal Barrier, employ natural forces such as gravity and hydraulic loads to expand and seal the gates (first two examples) and to obtain the optimal guide reactions (third example). This approach can be seen as representing a certain design philosophy. It recognizes, in short, the conformity with natural laws and forces as an ultimate assessment criterion of engineering; and is restrained in excessive employment of forces and energies of man-made devices. According to this view, nature ought to be respected – not subjugated.

In single-leaf and mitre gates, guiding gate contacts presents – in principle – a smaller problem. As the only gate movement is rotation about its fixed edge, there is no need to guide it or to protect the seals during motion. The top and the bottom hinges provide sufficient control of this movement. The problem of gate guiding appears only at the very moment of closing, when the heel post lining and/or seal come in contact with the lock crown wall. As already discussed, this contact should – if possible – be perpendicular, i.e. generating no friction or other lateral loads.



The latter is, unfortunately, only possible for seals, see e.g. Fig 26 b. The contact planes of heel posts and their linings are determined by hydraulic load rather than the gate motion geometry. Therefore, the engineer will try to make sure that:

- closing and opening are geometrically possible, i.e. there is enough space for a free rotation of all contact points;
- the angle of heel post approach to (= departure from) its buffer surfaces is as large as possible, in any case larger than 0°, in order to avoid friction;
- gate opening activates gaps wide enough to discharge water driven into the recess.

There exist geometrical methods to determine the position of the gate rotation axis in accordance with those directives. Most of them are founded on craftsmanship. They, regretfully, become forgotten, as craftsmanship does not always go along with modern technology. In Fig. 29, two such methods are presented. The first (a) is very simple. It can be applied when the gate boundary stands (open and closed) have already been determined; and the care has been taken that the heel post does not stuck or rub against its buffers. In that case, one can arbitrary choose two points **A** and **B** of the heel post section, then draw symmetry lines between their positions in the closed and open (**A’** and **B’**) stand. Intersection of those lines gives the gate rotation center **S**.

Fig. 29. Selection methods of a mitre gate rotation center

The second method (b) is slightly more complex, but it allows determining a whole range of possible positions of the rotation center **S**. This can be very useful, if only because the position obtained from method (a) can be inconvenient for some (e.g. constructive) reasons. Moreover, method (b) does not require any prior determination of the gate open position – it generates a range of such positions. Starting from the gate closed position, here is a step by step description of this method:

- Draw lines perpendicular to contact surfaces in all characteristic points of the heel post contact (**B**, **C** and **E**). The gate in Fig. 29 will open if the rotation center lies clockwise from those lines.
- To provide gaps for water discharge from gate recess during opening (and for water supply during closing) chose a gap width ***r*** and draw circles of the required free space around **B** and **E**.
  A practical condition for ***r***, well proven by experience, is:
$$r \quad \geq \quad \begin{cases} 0.2 \cdot R \\ 50\ mm \end{cases}$$
- Set the distance ***R + r*** on the perpendicular drawn from **E**. Connect the received point **N** with the center **M** of the heel post rounding. Draw a perpendicular in the middle of **MN** and determine the intersection **P** with the line **EN**.
- Reach from **P** the farthest point of the rounding **D** and check if it remains outside ***r*** in E by gate opening. If not, rearrange the position of contact **EF**.
- To avoid that the highest point **A** of the rounding hits **B** during gate opening, draw a line dividing the angle **AMB** into half. Find its intersection with the circular edge.
- The above does not prevent rubbing against the buffers. To avoid that, draw the lines ***a***, ***c***, ***d*** and ***e*** at an angle ***β*** to the lines drawn before – on the clockwise side, as shown in the drawing.
  A well proven "craftsman's" condition for ***β*** is:
$$tg\,\beta \quad \geq \quad 0.10$$
  It originates from wooden gates (and/or linings) and buffers of natural stone. It can be slightly modified when other material combinations are used presenting smaller (or bigger!) wear problem. However, the author does not advice to deviate much from this value.
- The gate rotation center **S** must lie inside the polygon drawn by the lines ***a***, ***b***, ***c***, ***d*** and ***e*** (here outside the polygon). Select the most convenient location of **S** and draw the gate in open stand.

The procedure described above applies to wooden as well as steel or other gates. If the contact **BC** is not – as drawn – cylindrical but plane (which is usually the case in steel gates), the line perpendicular to it will be parallel to the gate system axis. The line ***e*** at an angle of ***β*** will then take the position $\bar{e}$. We see that it will then co-define the area of the possible gate rotation center in Fig 29.

3.6. Time, temperature and otherwise determined phenomena

One of the properties of hydraulic gate loads is their dual character. There can be long periods (weeks, months, years) of high and quite constant loads, which we tend to consider static. On the other hand, there are also long periods when those loads vary from zero to the maximum value up to some 30 ÷ 40 times a day. Such loads should be considered dynamic. This duality is particularly visible in gates of navigation locks. High frequency of locking in top navigation seasons intersperse which long closures outside the seasons, during maintenance, waterway renovations etc.

This has significance for gate contacts. Such contacts are not only vulnerable to load ranges and histories, but also – and especially – to geometrical distortions caused by different loads. In this section, we shall ignore the distortions of civil structures housing the gate (lock crowns, sills, weir pillars etc.) and concentrate on the distortions of the gate itself and its contact components in particular. Load history plays here a prominent part. For space reasons, some relevant phenomena will only be introduced and illustrated by field examples, without going into details. Those phenomena are:

- Plastic deformations and relaxation;
- Creep, viscoelastic and other non-elastic deformations;
- Temperature;
- Wear and decomposition;
- Corrosion, weathering and biological processes;
- Fatigue.

a) Plastic deformations and relaxation

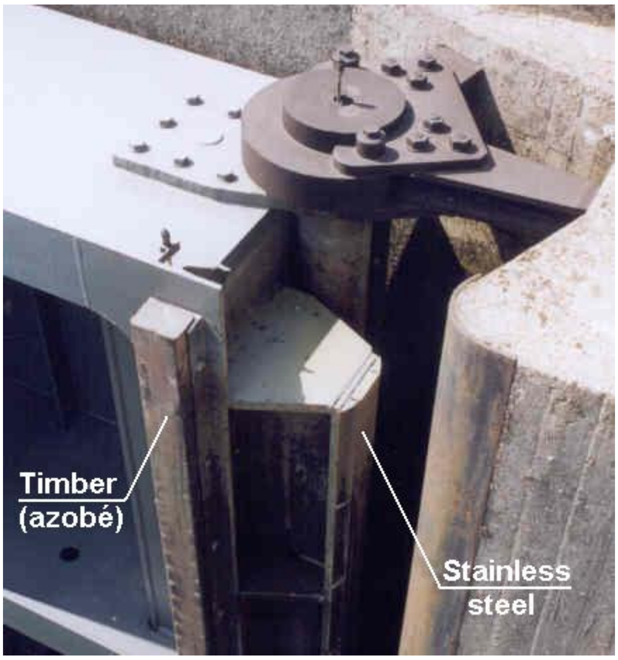
In hydraulic steel structures, we usually do not allow any plastic deformations. This applies also (and particularly) to gate contact components of steel, as shape stability of those components is crucial to maintain the desired contact character. Another reason is that we do not want any stress relaxation or material hardening (loss of its ductility) in contact components. Therefore, the design of such components proceeds entirely in the serviceability limit state in the sense of Eurocode 3 [27].

This does not always apply to soft alloys like bronze, aluminum bronze or brass. In this case, the engineer will often try to employ the (local) deformations of such alloys for sealing the contact or equally distributing its load over a certain area. The system geometry will not suffer from it if those alloys are applied locally, embedded or well fixed in the steel structure.

Contact sealing and load distributing can still better be done by synthetic materials which, in general, have lower modules of elasticity and coefficients of friction. Under high and long lasting load, however, these materials can simply become extruded from the contact area. This does not happen when synthetic material is reinforced, e.g. by polyester or other fibers, perpendicularly to the load direction. The result is an anisotropic material which easily deforms in the direct contact area but still maintains its overall shape. Such materials were introduced in gate bearings in the Netherlands, based on investigations directed by the author. The details are presented in chapter 6 of this thesis.

b) Creep, viscoelastic and other non-linear deformations

Assuming that a steel gate works entirely in the elastic stress-strain range, there will be neither creep nor other non-elastic deformations. This changes, however, when load is passed through other materials of a lower elastic (proportional) limit; or through materials showing other stress-strain behavior, e.g. viscoelasticity. Mechanically, there is not much difference between creep and viscoelasticity, although the nature of both is quite different. Both phenomena cause a gradual change of dimension in the load direction. However, creep will usually appear when the material becomes heavily loaded, e.g. wooden floor loaded close to its bending strength. Viscoelasticity appears under any load, e.g. table-leg print on a vinyl floor, although its effect by low load can often be ignored.



An example of contact distortion by both creep and viscoelasticity is the behavior of the mitre gates in the Maasbracht and Born locks on the Juliana Canal. Both locks consist of more chambers, 16 m wide, with downstream gates bearing a constant head of 12 m, which is the highest in the Netherlands. The gates were designed with stainless steel to stainless steel contacts for the heel post reactions in the planes of gate leaves. For the smaller, perpendicular reactions, hardwood linings of *azobé* were designed (Fig. 30). However, already during construction *azobé* was replaced by oak wood which has twice as low strength and modulus of elasticity, see Table 7 in section 3.4.

Fig. 30. Heel post lining of the lock gates in Maasbracht and Born

After a few years, the gates appeared to pass a substantial part of their reactions to hinges instead of the linings. As those hinges were subject to excessive wear (for other reasons, see section 7.1), the result was a total damage of contact bushings of the bottom pivots every 6 to 8 years. The problem was, unfortunately, not correctly diagnosed and the renovation of the lock in Maasbracht in 2002 made it still worse: Stainless steel strips on one of the gates were replaced by UHMPE. Within a few weeks divers recorded that the bottom pivots carried again hydraulic loads. The author's investigation [50] prevented further execution of that project and led to restoring the design solution. In this case, the problem was caused by the creep of timber and the viscoelastic deformation of UHMPE.

c) Temperature

In hydraulic gate engineering (and contact engineering in particular), temperature can – in general – be an issue in the two following ways:
- affecting mechanical or other properties of applied materials;
- causing thermal expansion.

Under normal circumstances (for exceptions see e.g. section 2.5.2), the first way should not present a problem for steel gates, nor for their steel contact components. It can, however, be a problem if other (contact) materials are used. In particular, synthetic materials are in general vulnerable to the changes of temperature. These materials have usually an amorphous or only partly crystalline character, which is not thermostable. E.g. UHMPE looses entirely its mechanical properties in the temperature of about 130°C, see Table 8. Other synthetics show a similar behavior. Although there is no risk that weather might drive material temperature so far, it can – under some circumstances – be exceeded due to the warmth generated by friction. The engineer should take care that this does not happen, e.g. by minimizing the friction, providing proper cooling etc.

The second way – thermal expansion – may become considerable if the thermal expansion coefficient α [1/°K] is high, e.g. for synthetic gates, and when the gate system is very vulnerable to dimensional allowances, e.g. wide mitre gates. The combination of both is not very likely, therefore we shall ignore this case. Nevertheless, thermal expansion of contact components can be an issue in detailed design. An example is the UHMPE bottom lining of maintenance bulkheads for two projects of the author's engineering practice: the 2nd Lock Lith on the Meuse and the "Naviduct" in Enkhuizen [2]. The bulkheads, 3 to 4 m high, are piled on each other in chamber vertical slots to bear the entire water pressure when maintenance is performed in the chamber or on the gate. Each bulkhead foot is made of UHMPE profiles which are delivered in the length of 6.0 m. Assembly joints are, therefore, inevitable not only due to thermal expansion. With a thermal expansion coefficient **α** from Table 8 and a 20°K maximum temperature drop between manufacturing and operation, we receive 24 mm shrinkage on every 6.0 m. This would cause a considerable leakage, not favored by the maintenance crews. In order to avoid it, a small UHMPE key plate is plugged in the assembly joint, as shown in Fig. 31. In this case (Naviduct), it is plugged tightly, but it another (Lith) it has been put with large clearances, which is sufficient too as hydraulic load will always press it to one side and close the gap.

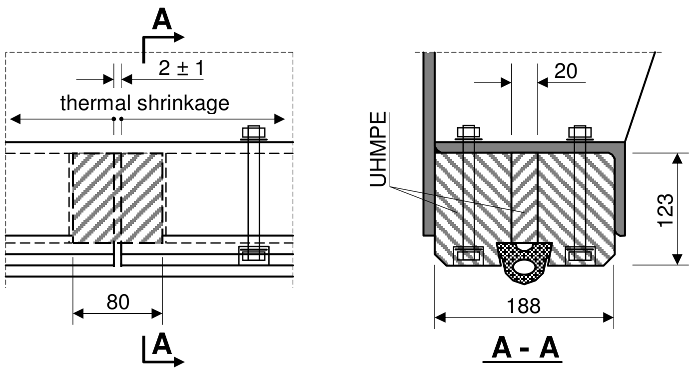


Fig. 31. Leak protection for a polyethylene profile joint

A remarkable detail is that the condition of bolts does not suffer from this thermal shrinkage, although the bolt holes have not been widened. One can probably attribute this to load relaxation caused by local viscoelastic deformations of polyethylene.

d) Wear and decomposition

Wear in gate contact components becomes a problem when the contact surfaces undergo mutual lateral displacements, i.e. sliding. As discussed in sections 3.4 and 3.5, the engineer should try to avoid such situations. This is, however, not always possible. Moreover, sliding is a normal operation condition for some details or types of gates. The main conditions which generate sliding are the two following:

- gate opening and closing;
- gate hydraulic loads.

The first condition is rather obvious. Wear due to gate opening and closing is one of the main factors determining the gate service life or its maintenance regime. This problem is further discussed in sections 5 and 6. We often do not realize, however, that also the gate loaded position – which seems motionless – produces wear. True, the slide motion caused by contact gap closing or elastic deformation is then small, but the contact loads are usually much higher than by opening and closing.

An interesting example of wear caused by hydraulic loads is the condition of gate bottom edge seals in the Hagestein Weir on the Rhine, as observed in 2003 during the renovation of all gate seals. This project, engineered and directed by the author (see also Fig. 18 in section 3.2), had to be executed in a very short time in winter when the two so-called visor gates were lifted allowing the discharge of large water masses. Under normal conditions, the gates are lowered to hold the fall of some 3.0 m. In order to manage the vibration problem [51], one gate was usually kept down on the sill while the opening of the other gate was double high. Since the gates are flexible (they carry basically only radial loads in the form of circumferential tension) and the arch span is large (54.0 m), some lateral movements of gate bottom edge are inevitable. The closed gate bottom edge seal was, therefore, subjected to lateral loads. This caused excessive wear. In Fig. 32 we see the disassembly of the old rubber seal in progress (a) and a close-up (b) of the same seal on the vessel deck. Observe the clear tracks of wear on the seal in front and the decomposition of the three seals behind it.

Obviously, decomposition is particularly imminent if anisotropic materials are used in gate contacts, e.g composites, materials with welded, glued, vulcanized etc. seams. More and more modern contact solutions apply such materials. Using them should be encouraged but the engineer must fully be aware of their properties. As hydraulic construction projects are complex and expensive, it pays always back to employ proper expertise or to let a problem be individually investigated.

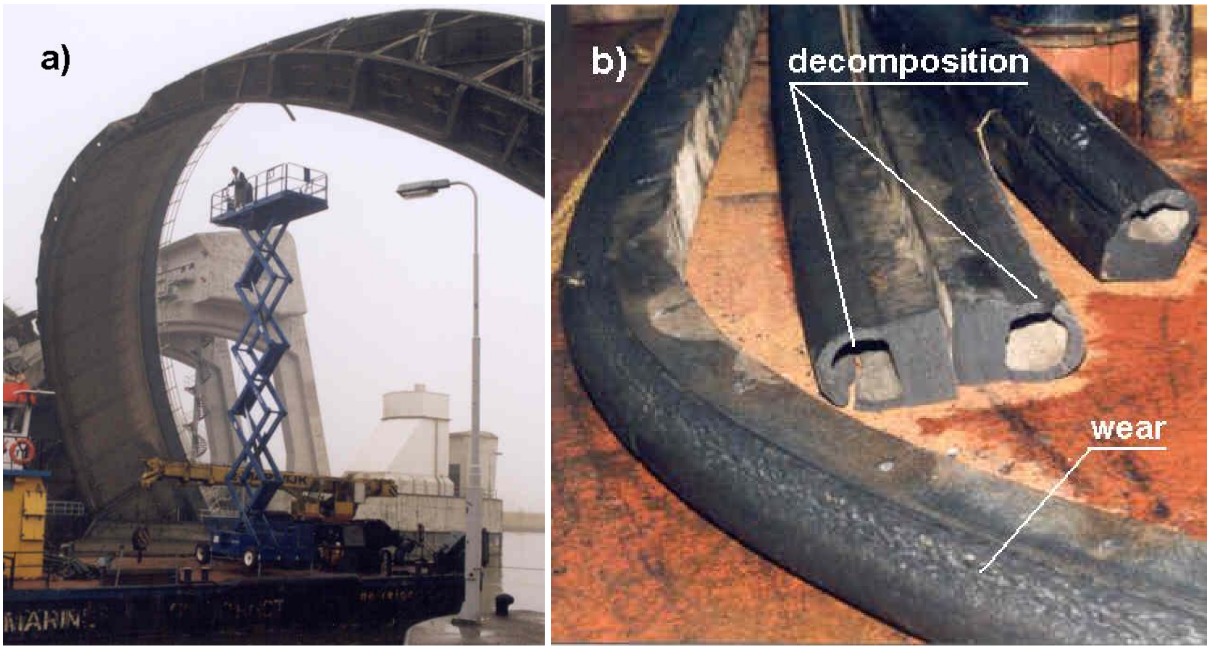


Fig. 32. Bottom edge renovation of the Hagestein Weir:
a) rubber seal disassembly;
b) removed seal sections on the barge deck.

e) Corrosion, weathering and biological processes

Corrosion can in fact be seen as a form of weathering, but let us distinguish both phenomena. While corrosion primarily affects the surface condition, weathering will penetrate deeper affecting also e.g. mechanical properties of contact materials. It should be obvious that both – surface condition and mechanical properties – are of crucial importance in hydraulic gate contacts.

Corrosion has many different forms [42] and should particularly be controlled in heavy industrial and maritime environment. There exists an extensive literature on this subject, therefore it does not have to be discussed here. It shall only be emphasized that especially synthetic materials require smooth contact surfaces of steel or other components. In the Netherlands, stainless steel to be applied in hydraulic gate contacts should, in general, have grade 316L or better.

Weathering covers material deterioration due to e.g. temperature, frost, ultraviolet rays, ozone etc. In this group, special attention should be paid to rubber seals (aging), chemically less stable alloys and synthetics, composites, items of compound sections etc. The engineer must also be a biologist or have an open attitude in this field. He/she should know e.g. that a pile worm appears only in salt water, before refusing a timber species in his/her fresh water project for this reason. It may also be worth to know which moulds under which conditions may attack a structure, on which surfaces shellfish vegetates, what attracts birds and sea life etc.

f) Fatigue

We used to associate fatigue phenomenon with metals. In this view, fatigue can be a considerable issue in hydraulic gate metallic contacts and the components holding the contact materials[1)]. Until short, fatigue was seldom considered in hydraulic gate engineering. Attention to this problem was only paid in projects of exceptional significance, like the Eastern Scheldt Storm Surge Barrier [52]. The load variation causing fatigue was considered to represent wave loads. This practice changed in the Nether-

[1)] This discussion is limited to contact related items. The fatigue of other structure falls beside the subject.

lands with the introduction of mitre gates bearing loads in both directions, especially the type with drive cylinders carrying “negative” hydraulic load. As explained in section 3.3.4, such gates must be prestressed on every closure, which produces fatigue loads. The first projects employing complete fatigue analyses were the reconstruction of the Orange Locks in Amsterdam and construction of the Naviduct in Enkhuizen, the first supervised and the second directed by the author [2].

An effective way to eliminate or reduce fatigue loads is prestression or – still better – post-tensioning[1]. With respect to gate contacts, this method shall be advised for all components which receive variable tensile loads. It not only prevents fatigue, but also takes care that no concrete cracks or gaps under foot plates become open. This, in turn, provides a better dimensional stability of the contact and extends its service life. The condition is that the prestressing force must be higher than the frequently appearing tensile load.

In Fig. 33, the anchor post-tensioning of a mitre gate top hinge ring is presented. At first, the anchors are stretched as shown up in photograph (a). Under the round anchor nut down in the same photograph, we see a coupling block with holes for fitted bolts of the two horizontal socket plates. These holes are bored to size after post-tensioning of the anchors. Then the ring (here split in two for the lack of space) is assembled by means of fitted pins, as shown in photograph (b).

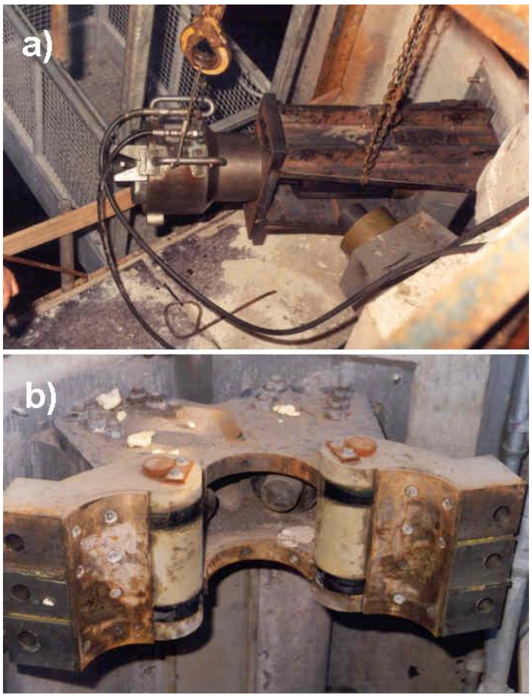


Fig. 33. Top hinge ring of the Middle Lock in IJmuiden
a) post-tensioning of the ring anchors;
b) ring in assembled position.

Post-tensioning of such crucial details is a good measure against fatigue only when the anchors have a sufficient length to guarantee a stable, permanent tension – preferably some 2÷3 m. This is often difficult to reach, so that the gate engineer will have to negotiate it (sometimes make a compromise) with the lock chamber designer. The author’s experience is that compromising on this issue does not pay.

[1] “Prestression” means here applying tensile force before the concrete is poured; “post-tensioning” means applying tension to steel after the concrete cures.

4. LOADS ON GATES IN CONTACT AREAS

4.1. Gate load assumptions - general

The design practice of lock, weir and barrier gates in the Netherlands is usually based on probabilistic load analysis and, to less extend, probabilistic strength definition. Neither hydrotechnical steel structures nor their loads are subject to a national code, as it is e.g. in Germany [53]. Particularly important for a steel gate engineer are the general code for load and deformation analysis [54] roughly complying with Eurocode 1 [55] - and the codes covering design rules for steel structures [56] to be compared with Eurocode 3 [27]. Direct applications of the Eurocodes keep growing. It can be expected that the national codes will not be used any more after some years.

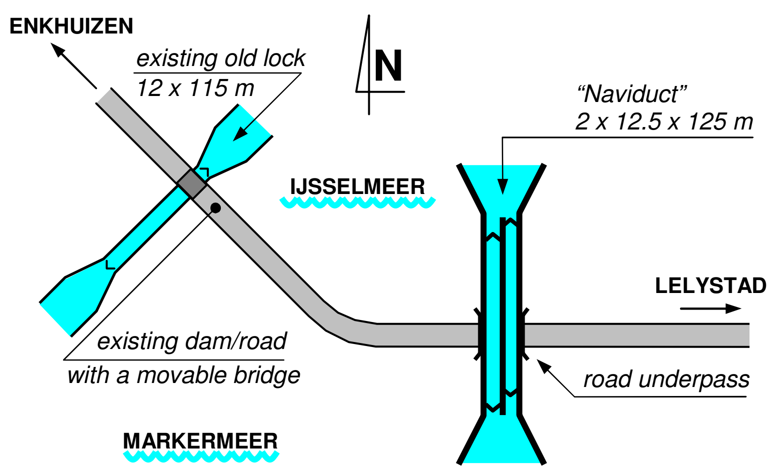
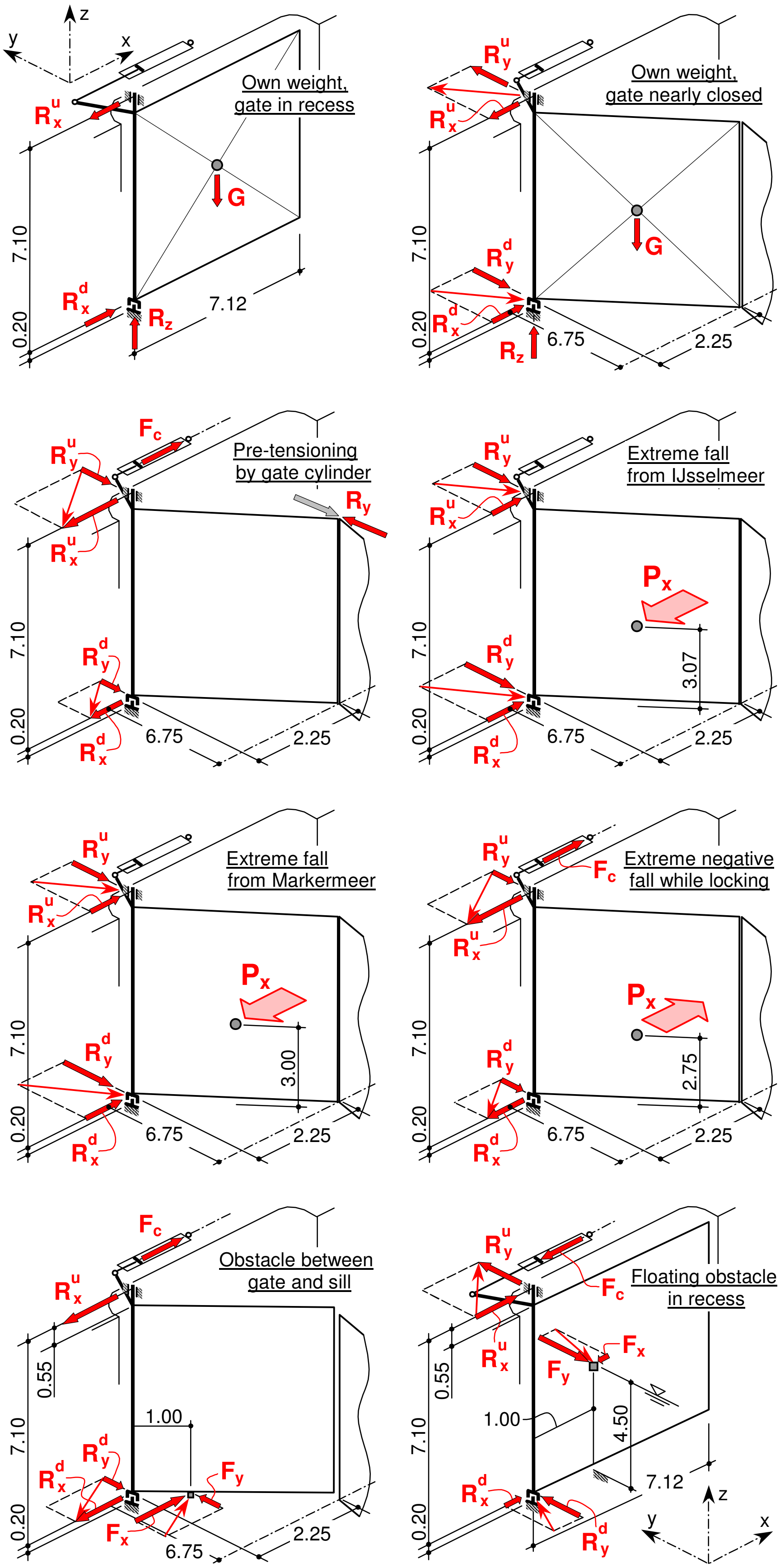


Fig. 34. Naviduct Enkhuizen – project lay-out

Let us consider the design load assumptions in author's recent gate project of the Naviduct in Enkhuizen. It is a complex project due to bidirectional loads, see section 3.3.4. A schematic lay-out of it is shown in Fig. 34. The hydraulic loads result here from wind driving water up in one lake (IJsselmeer or Markermeer) and down in the other [43] along the dam dividing the lakes. Both lakes originate from closing the Dutch internal sea, (Zuiderzee) in the 1930's.

Fig. 35. Naviduct Enkhuizen – one of the mitre gates

In Fig 35, one of the four mitre gates (still without a walkway) is shown during the contact accuracy tests on the site. The Naviduct was set "dry" for this purpose.



The gate response to the most relevant single loads (*actions* in the sense of Eurocode 1, *Einwirkungen* in DIN 19704) is shown schematically in Fig. 36. Here is a short discussion on the single loads:

- Own weight is rather obvious. All installed weights must be considered, e.g. also gate drive machinery. Buoyancy does not make part of this load but of a proper hydraulic load.
- Pre-tensioning by gate cylinder takes place in two steps: 490 kN on every closure, 900 kN when the fall exceeds about 0.4 m. It prevents opening of the reverse loaded gate.
- Variable walkway load is an incidental load by maintenance or operation personnel, here assumed as 3.0 kN/m^2.
- Maximal hydraulic load was defined as having a legally limited probability of occurrence (see section 4.2). It comprises a water head of 3.2 m and a 0.9 m high wave, reflection not included. It may occur on any side: the IJsselmeer or the Markermeer.
- The maximal 'positive' and 'negative' water head during locking was limited to 1.0 m here. Above this water head, the locking holds up – and both chambers of the lock operate as a barrier.

Fig. 36. Gate of Naviduct Enkhuizen – some loading cases.

- Ice load was estimated as 50 kN/m horizontally on normal water level, and 10 kN/m vertically. Ice thermal expansion as well as impoundage had both been considered. These loads shall be higher in countries of lower winter temperatures, e.g. Poland or Scandinavia.
- Stream load by a leaving ship was computed using normative vessel data (here the RHK ship) and a propeller distance of 5.0 m to the gate. It resulted in a load of 97 kN, 2.5 m under the normal water level. Proper analysis methods can, e.g., be found in [57]. This load was significant in combination with the 'negative' hydraulic load, to test the gate stability in closed position.
- Loads resulting from obstacles were considered in the three following cases:
  - obstacle between gate and sill;
  - obstacle on the bottom in gate recess;
  - floating obstacle in gate recess.

  In all cases, a distance of 1.0 m between the obstacle and the gate rotation axis was assumed[1)]. In both boundary zones of 10° of the gate rotation angle, the cylinder oil pressure was limited to about ¼ of the oil pressure in the middle zone, in order to avoid overdimensioning or damage.
- Failure of drive control was estimated to take place with a probability of $2 \div 5 \cdot 10^{-4}$ (once on 5000 to 2000 gate movements). It results in an uncontrolled full-speed smash of a gate leaf against its sill or recess wall. Considered are the inertial loads of the gate and the attached water mass.

The last three loads were considered to have low probabilities of becoming exceeded, which classify them as making part of so-called *accidental* (Eurocode 1) or *außergewönliche* (DIN 19704) loading combinations. More about this subject can be found in section 4.3 of this thesis. Observe, however, that most loads named above have, in fact, been specified in a probabilistic way – i.e. by a load level and its probability of occurrence. This is necessary in order to link them to the reliability requirements resulting, e.g., from a fault tree – see section 2.4.1 of this thesis. A complete discussion of this matter goes beyond the scope of this thesis. In the following section, the probabilistic approach to extreme hydraulic loads will be introduced as an example.

The discussed single loads do not comprehend all possibilities. A number of other loads were not numerically considered; nevertheless precautions had been taken to avoid or to minimize any resulting damage, distortion etc. This group comprises e.g.: transport and installation loads, vessel collisions, various maintenance handlings, vibration excitations in a flow, sabotage etc.

[1] This is one of the so-called "Ypey values". Mr. E. Ypey was a leading engineer of Rijkswaterstat in the 1970's and 80's. Asked by a young colleague which obstacle distance is appropriate, he simply said "Just take one meter". Since then it became more or less a standard in the Netherlands.

4.2. Stochastic model of hydraulic loads

The design hydraulic loads for the Naviduct were determined in a statistical way. Prior to the project design, water level was permanently monitored on both crowns of the existing old lock (see Fig. 34). The measurements lasted 15 years[1)] and were then statistically compiled to produce so-called probability density functions. These functions and the knowledge of the physical processes during storm allow for statistical extrapolation into far future. In the Netherlands, a special computer program RIEMANN [59] is used for this task, performing the integration of the probability density functions; and computing the probabilities of occurrence of the diverse water levels z_m outside the gate.

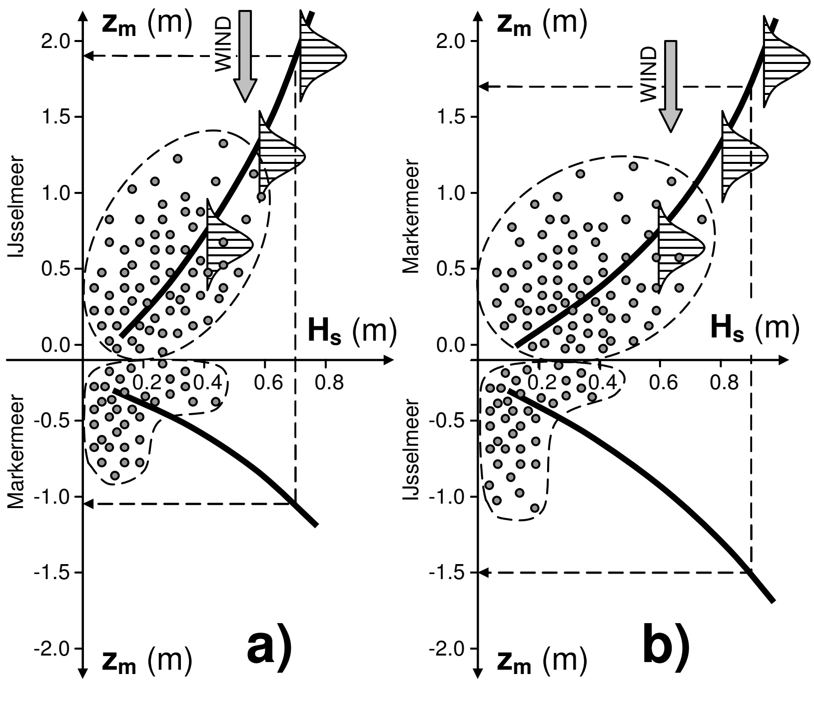


Fig. 37. Hydraulic loads on the Naviduct gates in a barrier operation, measured results (illustratively) and computed extrapolations
a) by North winds – from the IJsselmeer;
b) by South winds – from the Markermeer.

We shall focus on the way in which the maximal hydraulic loads are determined. The extreme water head under locking conditions was deterministically set at 1.0 m. This occurs about once a year and lasts a few hours, which represents an acceptable locking hold-up.

In Fig. 37, extrapolations computed from the measured data are schematically shown. Obviously, the most critical (damming-up) winds are here from the North and South directions, see Fig. 34. Not surprisingly, a strong correlation between the water levels of both lakes was observed by those winds.

Along with the water levels, the wave heights were measured. Also here a strong correlation between the water level on the windward side and the significant wave height[2)] $\boldsymbol{H_s}$ on that side was observed. Waves on the leeward side appeared to be small and quite insignificant for the gates – also due to the damping in prosperous lock chambers. Up in Fig. 37, we see an extrapolation of the relation between the storm water level z_m and the wave energy (here represented by $\boldsymbol{H_s}$) – both on the windward side. This extrapolation is partly statistical and partly based on the knowledge of the physical processes involved. There is a statistical relation between the significant wave height $\boldsymbol{H_s}$ and the design wave height $\boldsymbol{H_d}$, based on the Rayleigh distribution. Dependent on the desired probability $\boldsymbol{P}$ that no actual wave height $\boldsymbol{H}$ exceeds $\boldsymbol{H_d}$, this relation can be put as follows [25]:

[1] In statistical sense, this is not a long period. However, it was considered sufficient due to the local significance and limited environmental risk of the project. For comparison: Load determination for the Eastern Scheldt Storm Surge Barrier was based on 68 years of permanent water level registration [59].
[2] Significant wave height is a statistical mean height of the highest third part of all observed waves.

$$H_d / H_s \quad = \quad \begin{cases} 2.00 & for \quad P(H > H_d) = 0.60 \\ 2.25 & for \quad P(H > H_d) = 0.10 \\ 2.50 & for \quad P(H > H_d) = 0.01 \end{cases} \qquad 4.1$$

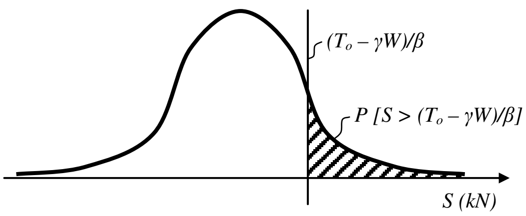
In the Dutch engineering practice, the middle relation is usually followed, provided that $\boldsymbol{H_d}$ shall still be increased by a so-called reflection coefficient. This gives a link between $\boldsymbol{H_s}$ and the wave load $\boldsymbol{W}$ for every static load $\boldsymbol{S}$ – represented here by a water level difference on both sides of the Naviduct.

Once the relation between $\boldsymbol{z_m}$ and $\boldsymbol{H_s}$ had been determined, it was sufficient to investigate one of these stochastic variables, in this case $\boldsymbol{z_m}$. In Fig. 37, the conditional probability density functions of $\boldsymbol{z_m}$ have been given for a number of levels in this relation. The total load $\boldsymbol{T}$ can, in general, be defined as:

$$T \quad = \quad \beta \cdot S + \gamma \cdot W \qquad 4.2$$

We are interested in the probability of $\boldsymbol{T > T_o}$, but assuming that $\boldsymbol{W}$ is a quasi-deterministic, and $\boldsymbol{S}$ is a stochastic variable we shall, in fact, be concerned about the probability of:

$$\beta \cdot S \quad > \quad T_o - \gamma \cdot W \qquad \text{or:} \qquad S \quad > \quad \frac{T_o - \gamma \cdot W}{\beta} \qquad 4.3$$



Graphical interpretation of this problem is shown in Fig. 38. The probability in question results from integration of the probability density function $\boldsymbol{f_S(S)}$:

$$P\left(S > \frac{T_o - \gamma W}{\beta} \right) \quad = \quad \int_{S > (T_o - \gamma W)/\beta} f_S(S)\, dS \qquad 4.4$$

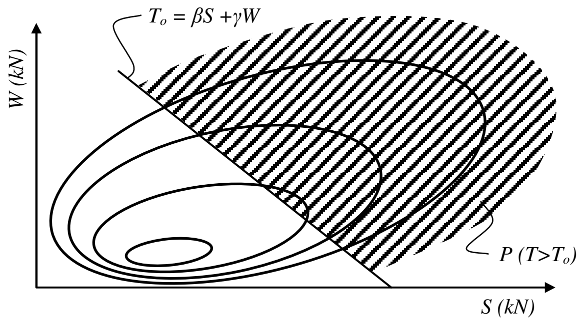
Fig. 38. Probability density function of static load $\boldsymbol{S}$

In this case, no special studies were required to take account of local factors, such as shape of banks, mooring facilities, navigation channels, wave breaking structures etc. The engineers were lucky, they could profit from good hydraulic resemblances to the conditions of the existing old lock, on which the actual measurements had taken place. This will not be possible in a number of other projects. If a project is large and the local conditions complex, there will often be no other way than to use physical gate model investigations in support of numerical simulations.

Another favorable factor in this project was the strong correlations between both:

- the water levels on the windward and on the leeward side;
- the water level on the windward side and the windward wave heights.

These correlations will be weaker in barrier, lock or weir gates closing access to large water basins (seas), or on inland waterways exposed e.g. to flooding, dry seasons etc. In such cases, unconditional two- three- or more dimensional probability density functions shall be introduced, which makes their integration more complex. An example is the Eastern Scheldt Storm Surge Barrier – a gigantic land protection project that introduced probabilistic design in hydrological engineering in the Netherlands. In that project, the correlation between the static load $\boldsymbol{S}$ and the wave load $\boldsymbol{W}$ was very weak. After all, an extreme storm surge results not only of the wind action in the area (producing waves) but also of the wind set-up in other areas, astronomical tide etc. – the phenomena that have no links to local wave heights. The probability of exceeding a specified load $\boldsymbol{P\ (T>T_o)}$ had, therefore, to be found by integration of a two-dimensional probability density function $\boldsymbol{f_{S,W}(S,W)}$ over the area where $\boldsymbol{T>T_o}$. Using the same general formula for $\boldsymbol{T}$ as in (4.2), we obtain:



$$P(\beta S + \gamma W > T_o) \quad = \quad \int\limits_{\beta S + \gamma W > T_o} f_{S,W}(S,W)\, dS\; dW \qquad \ldots\ 4.5$$

This is graphically presented in Fig. 39, showing the "vertical projection" of the problem. The integration result is now a volume (not an area as in Fig. 38) under the marked part of $\boldsymbol{f_{S,W}(S,W)}$.

Fig. 39. Two-dimensional probability density function of static load ***S*** and wave load ***W*** [58]

Using two- or more-dimensional probability density functions increases the number of required data and the computation time. On the other hand, it shifts the problem approach into a (in statistical view) higher level. Here, the following comment can be placed: As the nature often offers partial correlations between stochastic variables, the analysts get usually some space for a personal choice of the approach strategy. In general, this strategy will lie between the following two extremes:

- Purely statistical approach – tending to consider every value as being stochastic, and to neglect or underestimate the correlations as "impurities" of the analysis;
- Purely deterministic approach – tending to see values as computable results of correlated processes; and ignoring the deviations ("exceptions prove the rule").

There is no guidance saying which (mix) of the two is better. Instead of seeking guidance, we should primarily focus on the problem itself while selecting the approach strategy. It is always advisable to find and to use all relevant relations between the variables under consideration; but it is also advisable to recognize and to take account of their stochastic character.

The discussed probabilistic load model, along with a proper fault tree analysis (compare section 2.4.1) produced the following extreme hydraulic loads for the Naviduct gates [60], [61] (Table 11):

Table 11. Extreme hydraulic load conditions for the gates of Naviduct Enkhuizen

	High water on the IJsselmeer side	High water on the Markermeer side
Probability of occurrence	$1{\cdot}10^{-4}$ a year	$1{\cdot}10^{-3}$ a year
Windward water level	NAP +1.90 m	NAP +1.70 m
Windward significant wave $\boldsymbol{H_s}$	0.70 m	0.90 m
Wave period/length $\boldsymbol{T_p/L_o}$	2.2 sec. / 7.7 m	2.5 sec. / 10.0 m
Leeward water level	NAP -1.05 m	NAP -1.50 m

The reason why higher probability of occurrence was specified for high water on the IJsselmeer side, was a legal regulation recognizing that side as falling under the standards of country protection against the sea [62]. The Markermeer side had a status of an inland inundation prevention. Yet, it was that side which generated higher loads for dimensioning of gates and the gate contact components. This can be seen as one more argument in support of the stochastic load analysis.

4.3. Load analysis and loading combinations

Having determined the single loads and their probabilities of occurrence (in complex projects also e.g. the probability density functions), the next step is to define the design load combinations. Below is a short discussion on the load combinations as defined for the Naviduct gates, see Table 10.

In the first column of Table 10, all relevant single loads are listed. The next columns of that table represent the design load combinations [2], [43]. The combinations are obtained by multiplying the representative values of the single loads by load ('action') factors. The values of some most crucial load factors have been received in a reliability analysis covering probabilistic definition of actions and their effects in various combinations. In the sense of Eurocode 1 [55] or DIN 19704 [53], these factors combine, therefore, the meaning of the following three normative factors: the partial load factor γ, the partial safety factor γ_M and the combination factor ψ.

Table 10. Design loads, load combinations and load factors for the gates of Naviduct Enkhuizen

Combination / Single load	A	B	C	D	E	F	G	H	I	J
Self weight	1.20	1.20	1.20	1.20	1.00	1.00	1.00	1.00	1.00	1.80
Pre-tensioning by gate cylinder	-	1.20	1.20	1.20	1.00	-	-	1.00	1.00	1.80
Variable walkway load	1.50	1.50	1.50	1.00	1.00	-	-	-	-	-
Max. hydraulic load, storm	1.25	-	-	-	-	-	-	-	-	-
Max. locking fall - positive	-	1.50	-	1.00	-	-	-	0.50	-	-
Max. locking fall - negative	-	-	1.50	-	1.00	-	-	-	0.50	-
Load by ice	-	-	-	1.50	-	-	-	-	-	-
Stream from a ship propeller	-	-	-	-	1.00	-	-	-	-	-
Obstacles	-	-	-	-	-	1.00	-	-	-	-
Failure of drive control	-	-	-	-	-	-	1.00	-	-	-

A complete discussion on these load combinations goes beyond the scope of this thesis. Below are some comments in regard to the approach of Eurocode 1 and the new DIN 19704. In fact, both codes were not rooted in the engineering practice at the time of this particular design. Therefore, the comments represent rather a conversion effort than an application guideline of the two codes.

- Load combinations **A** through **D** represent *persistent and transient situations* (Eurocode 1) or *Grundkombinationen* (DIN 19704) with regard to the ultimate limit state. The factor of 1.20 for unfavorably acting self weight and gate pre-tensioning results from the Dutch code [21]. The factors for the hydraulic load (in particular 1.25 for the maximal hydraulic load) and ice load result from reliability analysis.
- Load combination **E** represents an *accidental situation* (Eurocode 1) or *Außergewönliche Kombination* (DIN 19704) with regard to the serviceability limit state. It gives an indication about the gate tightness when a ship's propeller increases the 'negative' hydrostatic load, but it presents no further structural problem.
- Load combinations **F** and **G** are *accidental situations* (Eurocode 1) or *Außergewönliche Kombinationen Fall 3* (DIN 19704) with regard to the ultimate limit state. The Dutch design practice allows for a limited damage in these situations, as long as the locking can continue. Therefore a load factor of 1.00 has been chosen.
- Load combinations **H** and **I** determine the design stress variations for fatigue analysis. As already mentioned, the gate is pre-tensioned by drive cylinders on every closure. The fatigue load has

conservatively been chosen as 50% of the largest hydrostatic load during locking. The actual pre-tensioning is usually smaller. Therefore, this load was meant to cover all other load variations for fatigue as well. In a more complex approach, probability density functions can be applied.
- Load combination **J** is not easy to classify within the existing codes. Yet, it appears physically on every closure. Therefore, the designers felt that it should be considered. The factor 1.80 has in this case arbitrarily been chosen as a product of 1.20 (unfavorable effect according to [21]) and 1.50 (all-over load factor for a safe distance to the yield stress).

These are, basically, all load combinations considered for each Naviduct gate as a whole. In addition, particular gate components may, obviously, be subject to other loads. E.g., sluice drive couplings must bear the maximal loads from sluice jacks, flow spoiler beams in sluice openings – dynamic flow loads, walkway banisters – normative handrail loads, etc. Also here, appropriate load combinations should be defined. The combination factors should be estimated following, basically, the same rules as discussed in this section.

Finally, there is a group of load combinations resulting from the unusual character of gate service. It often requires some imagination to define and to quantify them. E.g., the Hartel Canal Barrier – shown from the back in Fig. 40 – has been designed to allow the flow of about 3 m above the top edge, under extreme storm conditions (probability $1{\cdot}10^{-4}$ a year). Such conditions have never been recorded in Rotterdam. However, one can imagine, that water will carry various objects which might damage the back trusses (see photo) when falling across the retaining wall. A load model, assumed by the author in this case, was derived from a cargo container.

Fig. 40. Hartel Canal Barrier in stand-by position

Once the gate system has been chosen and the design loads specified, the gate structural analysis is a matter of skills in mechanics, and a proper use of computer programs. The common strategy is “from rough to fine”: At first, the system geometry including contact areas is determined. Then the cross-sections of main load bearing components are estimated – usually by computing some simple beam or grid models. This leads to more sophisticated models and more detailed FEM-calculations. In case of the Naviduct gates, the detailed solutions were obtained using the Finite Element System DIANA [63]. Some specific problems, e.g. computing the leak opening under ‘negative’ loads, were modeled separately and investigated using the author’s own developed software DISCO, as enclosed to this thesis. A similar approach was used, e.g., for the Hartel Canal Barrier. There, the structural system, the supports and principal cross-sections were computed using DISCO[1)]; while the final details were shaped using the DIANA software.

[1] Gate design of the Hartel Canal Barrier was supported by investigations on physical models. DISCO was also used to provide the necessary input for those investigations [64].

4.4. Character and distribution forms of contact loads

4.4.1. Some theoretical background

Having defined the gate loads and analyzed its numerical model, we usually receive a computer output describing the behavior of the structure in terms of displacements, internal loads, support reactions, stresses etc. The most relevant for this thesis are the support reactions. Continuing to use mitre gate as an example, we shall now focus on load distributions within the contact areas.

In section 3.2, distinction has been made between pointed, linear and surface contacts. However, it has also been noted that classifying a contact into one of those groups depends on the level on which the problem is considered. We are now leaving the system level – on which the loads were viewed in the first three sections of this chapter – and going down to the component level. On this level, the contact loads can usually be considered as distributed over a certain area. The form, sizes and character of load distribution in that area depend, in general, on the following factors:

- Geometrical arrangements within the contacting components and their vicinity;
- Mechanical material properties of those components and their vicinity;
- Direction, size, character, duration etc. of the contact loads;
- Other factors, e.g. temperature, moisture, pollution, presence of lubricants etc.

Load distributions in contact areas are – similarly to load distributions in entire structures – functions of deformations. Alike the deformations of entire structures, the deformations in contact zones can be of different types. In view of this thesis, the most relevant types are:

- elastic;
- elastoplastic;
- plastic;
- viscoelastic.

Theoretical discussion on these types of contact deformations, including model description, formulas etc., can be found in the literature about contact mechanics, e.g. [33], [34], [35], [65]. The intention of this section is to help recognizing these types in hydraulic gate contacts; and to present some simple, workable load distribution models for them. The short theoretical background in this subsection is a selection of some known concepts in this field, meant only as an introduction to the two following, gate-oriented subsections.

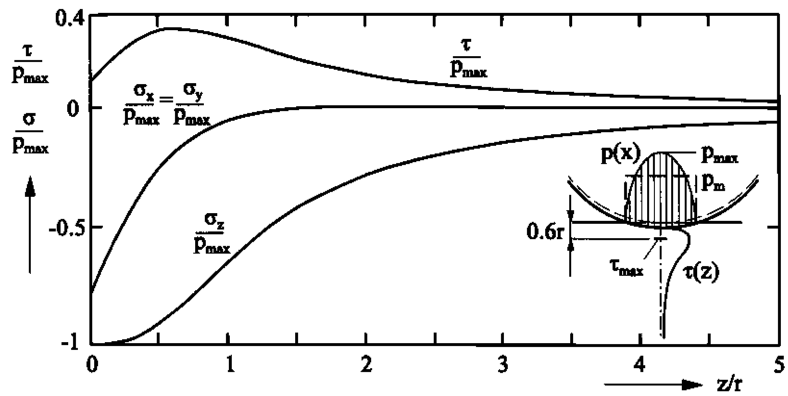


Fig. 41 presents a distribution of principal stresses:
$\sigma_x = \sigma_y$ across the direction of contact load **p**,
σ_z in direction of load **p**,
τ_z shear in direction of **p**,
in an elastic sphere to plane contact, with radius **r** of the circular contact area.

Fig. 41. Sphere to plane contact, stress distribution [34]

A similar but two-dimensional ($\sigma_y = 0$) distribution appears in cylinder to cylinder [33] or cylinder to plane contacts. Observe that the normal stresses $\sigma_x = \sigma_y$ and σ_z are the highest on the contact surface and exactly in the middle of the contact circle (in cylinder contacts: strip). The shear stress τ_z reaches its maximum at the depth of:

- for sphere to plane (or sphere) contacts: $z = 0.63\,\mathbf{r}$;
- for cylinder to cylinder (or plane) contacts: $z = 0.78\,\mathbf{a}$, where 2**a** is the contact strip width.

At this level, plastic deformations will first appear. The critical value of τ_z by which this happens, τ_c, depends for metals on their yield stress R_m or the $R_{p0.2}$ value:

$$\tau_c \quad = \quad \begin{cases} 0.5\, R_m \quad or: \\ 0.5\, R_{p0.2} \end{cases} \qquad 4.6$$

As the contact is elastic, the stress distribution in Fig. 41 follows directly from the Hertz' theory [35]. The formulas of this theory are widely known and do not need to be discussed here. The fact is, however, that the relative straightforwardness of the Hertz' equations made them one of most misused tools in engineering in the past century. Also today, despite the growing possibilities of finite element methods (FEM), the Hertz' formulas are often used beyond their validity range. Therefore, it is good to remind the basic assumptions of the Hertz' theory, e.g. after Johnson [33]:

1) Each solid body can be considered as an elastic half-space.
2) Contact surface is continuous and much smaller than the contacting bodies.
3) Contact strains are small.
4) Contacting surfaces are frictionless.

We shall violate all these assumptions in hydraulic gate contacts. This is not wrong as long as the impact of those violations is recognized and correctly quantified in the analysis. The first to violate is the assumption of elastic half-spaces. As mentioned above, gate contacts are not necessarily elastic. Even when elastic materials are used, there will often be elastoplastic and plastic contact zones. Such zones are usually indicated on a σ - ε diagram in structural mechanics. In contact mechanics, however, the load bearing areas are usually not constant, as e.g. the sectional areas in 'classical' structural analyses. Therefore, it is more convenient to use a $\bar{F}$ - $\bar{p}_m$ diagram, where:

$$\bar{F} \quad = \quad \frac{F}{F_1} \qquad 4.7$$

is the ratio of the contact force F to the maximal force F_1 which does not cause plastic deformation;

$$\bar{p}_m \quad = \quad \frac{p_m}{p_c} \qquad 4.8$$

is the ratio of the mean surface pressure p_m to its critical value p_c, by which $\tau_z = \tau_c$.

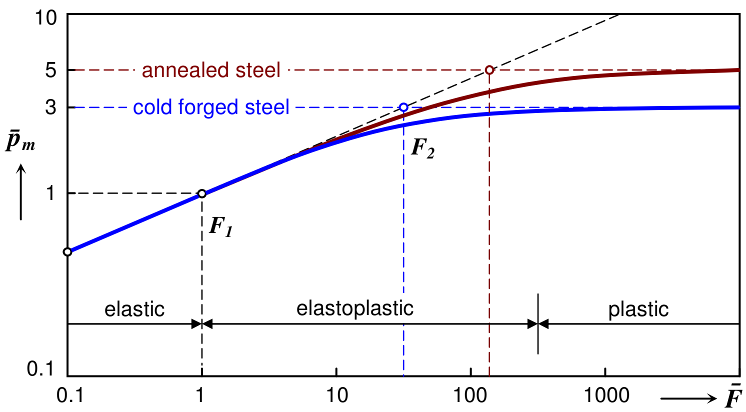


Fig. 42. Contact deformation diagram for two groups of steel

An example of the $\bar{F}$ - $\bar{p}_m$ diagram is presented in Fig. 42 [34]. It gives an indication about the behavior of two groups of steels often used in contact items of hydraulic gates:

- cold forged steel and
- steel hardened by annealing.

The three behaviour types – elastic, elastoplastic and plastic – can easily be recognized, though their borders are not sharp.

The diagram in Fig. 42 refers to circular (spherical) contacts, but the material behavior in strip (cylindrical), elliptical or other contacts will be similar. Using the relations from [65] and (4.6), we obtain:

- for circular contacts: $\tau_{\max} = 0.338 p_{\max} = 0.506 p_m \ , \quad p_c = \dfrac{0.5}{0.506} R_{p0.2} \approx 1.0 R_{p0.2}$ 4.9
- for strip contacts: $\tau_{\max} = 0.304 p_{\max} = 0.387 p_m \ , \quad p_c = \dfrac{0.5}{0.387} R_{p0.2} \approx 1.3 R_{p0.2}$ 4.10

Note that the two graphs from Fig. 42 have their asymptotes. Those asymptotes reflect, in fact, the hardness $\boldsymbol{H}$ of the softer contact material. For $\boldsymbol{p_m} = \boldsymbol{H}$, we obtain:

- for circular contacts:

$$\bar{p}_m = \frac{H}{p_c} \approx \frac{H}{1.0R_{p0.2}} \approx \begin{cases} 3 & \textit{for cold forged steel} \\ 5 & \textit{for annealed steel} \end{cases}, \qquad \text{as shown in Fig. 42.} \qquad 4.11$$

- for strip contacts:

$$\bar{p}_m = \frac{H}{p_c} \approx \frac{H}{1.3R_{p0.2}} \approx \begin{cases} 2.5 & \textit{for cold forged steel} \\ 4 & \textit{for annealed steel} \end{cases}. \qquad 4.12$$

Obviously, the hardness $\boldsymbol{H}$ must in those estimations be put in the same stress units as $\boldsymbol{p_c}$ and $\boldsymbol{R_{p0.2}}$, e.g. 2000 MPa (N/mm^2) and not 200 HB.

Other character of deformations, thus also contact load distributions, appears by viscoelastic materials. In hydraulic gates, these are primarily polimere contact materials. The most characteristic differences between elastic, viscoelastic and viscous behaviour are summarized below (Table 12):

Table 12. Main features of elastic, viscoelastic and viscous behavior

Elastic	Viscoelastic	Viscous
• material holds applied stress	• material deforms but retains part of stress	• material deforms, no stress retained
• deformations immediate	• immediate and delayed deformations	• deformations delayed
• time independent response to loads	• part of response dependent on time	• entire response dependent on time
• "memory" by load release	• partial "memory" by load release	• no "memory" by load release
• example: steel, rubber	• example: polyetylene	• example: oil, water

Johnson [33] discusses various mathematical models of viscoelastic behavior. The most relevant for hydraulic gate contacts will be his "delayed elasticity" model. Below (Fig. 43) are Johnson's pathes of creep $\boldsymbol{e}$ and stress $\boldsymbol{\sigma}$ as functions of time $\boldsymbol{t}$ for this model, slightly modified in order to take account of load application time. As load build-up takes usually a certain time in hydraulic gates, this modification will be significant for this thesis.

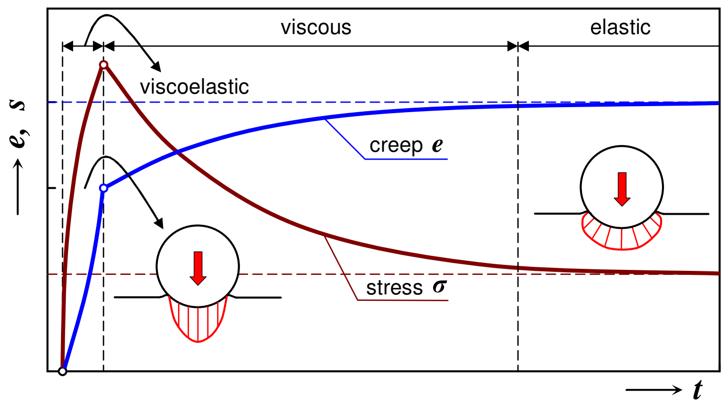


Fig. 43. Contact deformation diagram for two groups of steel

The range division into viscoelastic, viscous and elastic is author's own, and it is only based to the time criterion. The author agrees that other or no division will be possible when other criteria are considered, e.g. response distribution (sketched in Fig. 43).

Alike in Fig. 42, the two graphs in Fig. 43 have their asymptotes. They represent respectively maximal deformation including creep, and minimal residual stress – both as limit values when $\boldsymbol{t} \to \infty$. For an engineer, however, the intermediate values will be of great importance. While Johnson [33] introduces exponential functions for the range $0 < t < \infty$, various polymere suppliers give rather empiric formulas to estimate those intermediate values. E.g. from the data of the German chemical concern Hoechst [66] – one of the world's largest polymer suppliers – the following formula for the creep ε_c of UHMPE[1)] can be derived:

$$\varepsilon_c = \quad p \cdot (0.50 + 0.1 \cdot \log t) \qquad 4.13$$

where:

ε_c	creep in percents of compressed thickness	[%]
p	mean compressive stress	[N/mm^2]
t	(sum of) load bearing period(s)	[min].

An almost identical formula can be derived from proper American publications in this field, e.g. [67]. Laboratory tests performed by TNO, a leading Dutch research institute, show that this formula represents a rather careful estimation covering wide range of applications, i.e. also the situations in which the material is free to expand laterally to the load direction. When applied in hydraulic gate contacts, a part of the lateral expansion will usually be held back e.g. by a low thickness to width ratio or a casing. Therefore, the following modified formula was proposed for hydraulic projects [68]:

$$\varepsilon_c = \begin{cases} 0.5 p \cdot (0.25 + 0.1 \cdot \log t) & \textit{in oblong contacts} \\ p \cdot (0.25 + 0.1 \cdot \log t) & \textit{in square or round contacts} \end{cases} . \qquad 4.14$$

This formula applies to uncased material. In situations where UHMPE is cased, ε_c will be still smaller. Like most empiric formulas, also these formulas are only valid in a certain range (author's estimation: up to about p = 100 N/mm^2). They also do not account for, e.g., specimen size proportions, partial relaxation by interim load release, temperature etc. Therefore, practical applications of these and similar other formulas should, in general, be limited to estimations in preliminary design. In detailed design, it is advisable to study the behavior of contact components using a FEM or other model which – in any case – reflects the actual geometry and stiffness of contact components. A good tool for this task is the author's computer software, DISCO, which is included to this doctoral thesis.

Finally, it should be mentioned that there are still other forms of inelastic behavior than discussed in this section. Non-isotropic materials like composites, laminates, timber, heavy coated (e.g. by stellite or ceramic layers) metals will all show deviations from the models presented above. The same applies to materials of nonlinear elastic behavior (e.g. concrete, some kinds of rubber), weather beaten items, materials in stage of decomposition, fragmentation etc. Not all deviations from linear elastic behavior are unfavorable in hydraulic gate contacts. Some of them (e.g. fiber reinforcement in composites) will, in fact, be very welcome. In chapter 6 of this study, the results of laboratory investigations on different gate hinge materials are presented. The investigations, initiated and supervised by the author, resulted in a number of valuable data for gate contact design and engineering.

---

[1] Ultra High Molecular Polyethylene, here delivered under the name Hakorit® or Hostalen® GUR.

4.4.2. Elastic contacts - examples

In general, an engineer will aim at having only elastic behavior in hydraulic gate contact components. An exception is the ultimate limit state, where exceeding the elastic range can sometimes be an option. In the serviceability limit state, elastoplastic range shall not be favored, let alone the plastic range. A number of reasons can be given in support of this view – here are only three of them:

- The entire gate design is, as a rule, elastic in serviceability limit state. This traditional approach is justified by both the dynamic character of water as loading medium and the economical and other importance of hydraulic gates.
- In risk analyses, it is in most cases preferable to choose a damage mechanism in which the internal gate components collapse prior to its supports (contact components). This leads to a less serious damage and easier damage repair. Gate contacts should, therefore, have larger safety margins than the gates themselves.
- Most hydraulic gates, their contacts in particular, are subject to fatigue. This can result from gate operation (e.g. locking), character of hydraulic loads (e.g. waves) or other reasons (e.g. vibrations). Fatigue loads can not be tolerated outside the elastic range.

Having stressed the importance of elastic contact design in hydraulic gates, one can now differentiate this position. First, is should be noted that all contacts on asperity level (see section 3.2) are plastic anyway. Plasticity on this level – to some extend also on segment level – will even be favored. It smoothes the asperities which reduces friction, wear, warmth generation etc. An example is wooden post linings – leaking in the first weeks after renewal and regaining their tightness afterwards.

In the group of elastic contacts, we shall have a whole range of metal-to-metal as well as non-metallic contacts, the later low loaded in order not to exceed the elastic range. In mitre gates, e.g., such contacts will frequently be applied in (see also Fig. 1):

- top and bottom hinges;
- gate sluice guides (see Fig. 44);

and less frequently but not unusually in:

- heel post linings (e.g. Fig. 30);
- front post linings.

In Fig. 44, manufacturing of gate sluices for one of the author's projects is shown. In this case, the sluice guides consist of UHMPE strips in guide channels, and machined stainless steel strips on sluice posts; as sketched on the photograph. The polyethylene strips may here as well be replaced by, e.g., bronze or cast iron as long as no excessive friction or wear occurs. Important is that the behavior of this contact remains elastic. These sluices will soon be lifted about 30 times a day – each time under hydraulic load of 5 m. Therefore no plastic or other behavior causing residual contact deformations will be acceptable.

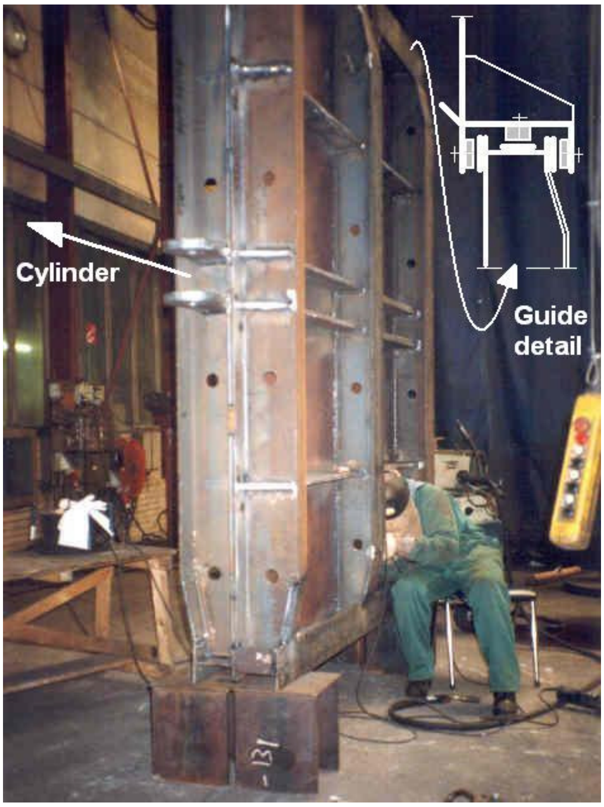


Fig. 44. Manufacturing of sluices for the gates of the 2nd Lock Lith on the Meuse

An interesting detail is here that the importance of contact issues has correctly been understood and implied in the manufacturing. Observe that two sluices have been fixed to each other, retaining plates inside. The welding takes now place in the middle of the compound section. The heat input is, therefore, symmetrical which allows avoiding warp distortions. These sluices will certainly comply with the very narrow dimensional tolerances in the guiding channels, which gives sufficient confidence that their contacts will indeed be elastic.

Fig. 45 presents a few other examples of elastic contacts, this time in mitre gate hinges. The combination of contact materials used in the top hinges is here in both cases as follows:

- hinge shaft: forged steel 42CrMo4;
- collar ring bush: aluminum-bronze CuAl10Ni5Fe4.

In the bottom pivot hinges, there is a slight difference between both projects. The gates of the Middle Lock in IJmuiden (left) have caps of manganese cast steel GS-X120Mn12, material known from very low wear parameters, in both pivot heads pivot shafts (see also Fig 14 in chapter 2). In the Lith Lock gates (right), this has been modified into the combination of:

- pivot head cap: refined cast steel 34CrNiMo6;
- pivot shaft cap: manganese cast steel GS-X120Mn12.

Fig. 45. Mitre gate top and bottom hinges in:
left: Middle Lock in IJmuiden; **right**: 2^{nd} Lock Lith on the Meuse.

The advantage of this modification, which was in fact the first of this kind on the Dutch waterways, will be presented in the chapter 5. At this moment we should notice that the contact loads in all four details in Fig. 45 are elastic. This does not mean that they are all Hertzian. One can observe that all Hertz assumptions are, in fact, violated here, i.e.:

- The contact bodies have limited depth and can hardly be considered as elastic half-spaces.
- Due to the small radii difference of contacting surfaces, these surfaces are not much smaller than the contacting bodies.
- The contact strains are not small, though – on component level at least – elastic.
- The contacting surfaces are not frictionless.

The engineering of these details will, therefore, for a big part be based on suppliers data and the confidence which the engineer has in them. The known European suppliers of bronze bearings are e.g. SKF and PAN®. The latter, operating from Mannheim, Germany, gives also an extensive design data on a variety of bronze alloys and their applications [69]. Gate contact details showing better confirmation with the Hertz theory are all wheel-to-rail contacts. These contacts we shall mainly see in rolling and vertical lift gates. Also all saddle-to-heel post contacts (e.g. gate type c in Fig. 4) are usually Hertzian. Good analyses and calculation examples for these contacts are given by Schmauβer [70] and Erbisti [46]. Not surprisingly, just these types of contacts are better theoretically elaborated and standardized today than the contacts like in Fig. 45.

Note that the collar ring bushes up in Fig. 45 do not cover the whole circumference but only its outer part. This is still better visible on the photograph in Fig. 46, showing a collar ring of the old gates in the Orange Locks in Amsterdam (now replaced by the new gates, see data in Table 6).This is possible because the horizontal reaction on the ring can only come from the gate own weight. All these gates represent the system of so-called "free" rotation points, in which the hinges do not bear hydraulic loads, see also Fig. 15 in chapter 3. The bronze bushing extends here over an angle of about 120°. The entire gate rotation angle is about 72°. Preserving some margins in boundary positions, we see that the engineer expected the actual contact over an angle of no more than about 30°.

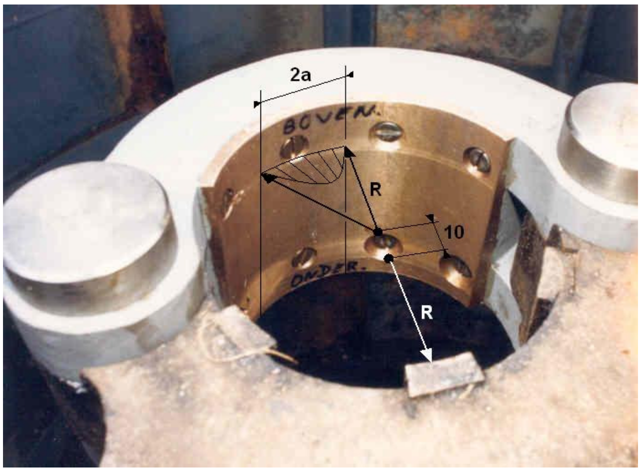


Fig. 46. Collar bronze bushing of an old gate in the Orange Locks in Amsterdam.

This contact angle is still large when compared to the Hertzian assumptions, but necessary to keep the contact stress low. It is usually achieved by making the radius of the inner bushing only 0.5 ÷ 1.0 mm larger than that of the shaft cross-section. The shaft backward movement under hydraulic loads (see Fig. 15 c) is enabled by moving the rear half-circle 5 ÷ 10 mm backwards, as sketched on the photo. In this example, bronze vertical pads are used to bound the shaft rear space. In the IJmuiden gates (left in Fig. 45), this task is done by two horizontal strips. In the Lith gates (right in Fig. 45), no items of this kind are provided – the collar ring itself restrains the shaft rear space. In that solution, no eccentricity of the two half-circles is applied. The aluminum-bronze lining extends there over an angle of almost 180° to compensate for a loss of shaft guidance.

Still more complex are the arrangements for elastic load distributions in mitre gate bottom pivots. The complexity of problems in those hinges was a reason of the author's idea of a suspended gate. Therefore, the bottom hinge loads and arrangements are discussed in section 7.1 of this thesis.

4.4.3. Inelastic contacts - examples

At this moment we do not consider contacts on asperity level, which are always inelastic. In several cases, inelasticity offers interesting solutions on the component level as well. Fig. 47 presents a lock chamber set "dry" by means of maintenance bulkheads. Each bulkhead consists here of two damming slabs placed atop each other in vertical grooves provided in the chamber walls. The contact between both slabs is sealed in the way presented earlier in this study (see Fig. 31 in chapter 3). The bulkhead contacts in chamber slots have, however, not been sealed although the slot surfaces are bare concrete. At the moment when this photo was taken, the hydraulic load on the other side was about 4.50 m of water column. Yet, no leakage can be observed. This is achieved by deliberately allowing for inelastic deformations of polyethylene contact lining, see detail drawn up on the photograph. As result, the material follows all irregularities of the concrete surface, which prevents the leakage [61].

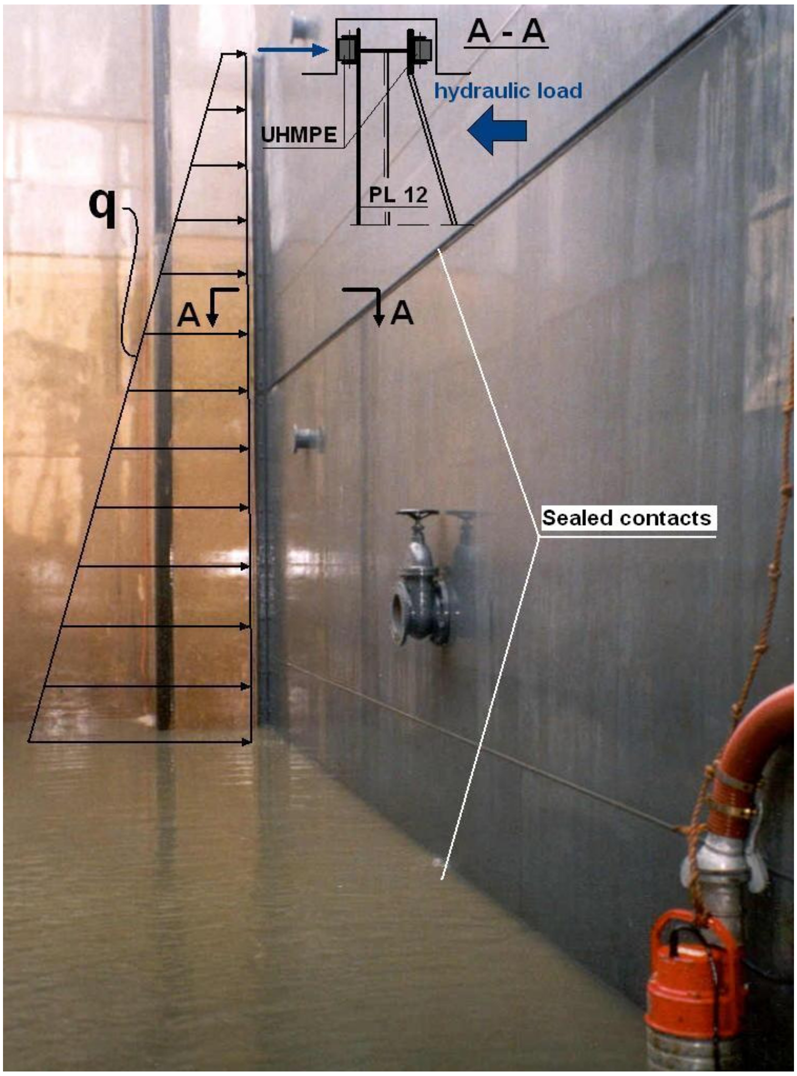


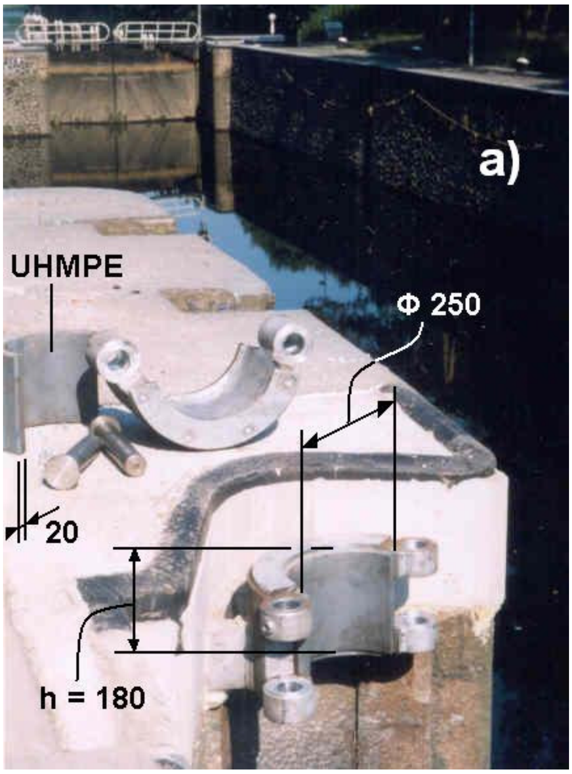
Fig. 47. Bulkhead for Naviduct Enkhuizen

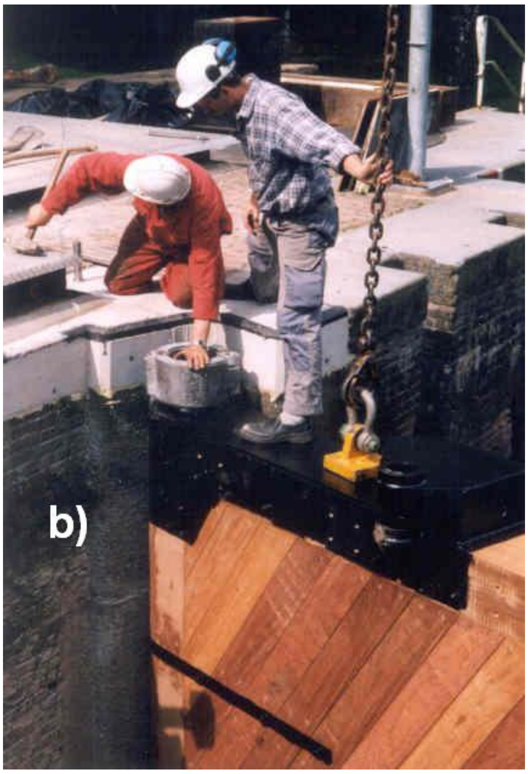
The bulkhead slabs in Fig. 47 are in fact of the same structural system as the gate sluices from Fig. 44 – including the contact arrangements. Yet, comparing the two proves the significance of contact load character for the engineering of entire structures. Such a comparison is presented in Table 13.

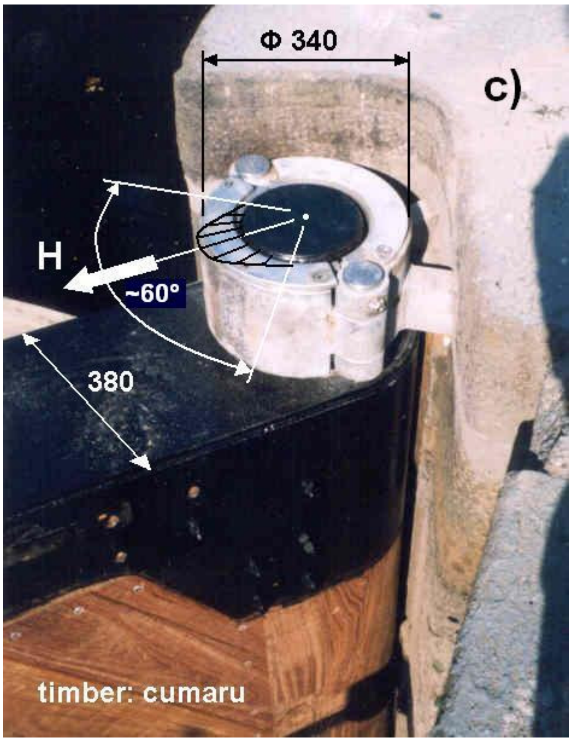
Table 13. Main contact related differences between sluice and bulkhead engineering

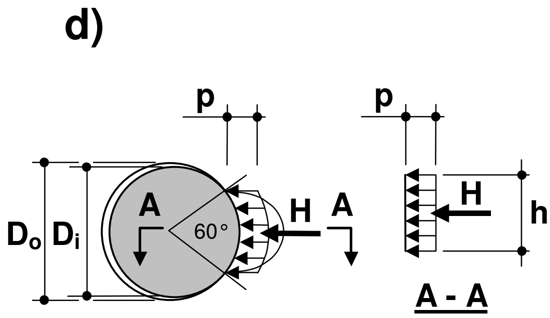
Property	Difference		Reasons
	Sluices	Bulkheads	
Contact response character	elastic	inelastic	• dynamic/static contact loads, • yes/no contact friction
Rigidity of structural system	stiff	flexible	• high/low support accuracy, • yes/no flow loads (vibrations)
Contact precision requirements	strict	mild	• yes/no vulnerability to warp, • yes/no slide contact
Effective leakage tightness	poor	high	• low/high contact compression, • high/low system rigidity

Inelastic behavior can – to some extend – also be favored in components bearing dynamic contact loads, as well as in slide contacts. For mitre gates, e.g., growing popularity of such contacts can be observed in gate hinges as result of a series of investigations performed under author's leadership in the years 1995 – 2000 (see chapter 6 of this thesis). A recent example of gate hinges with inelastic contact behavior is the author's design of the new wooden gates for Lock III in the Wilhelmina Canal in Tilburg [71]. Assembly of the gate top hinge is presented below (Fig. 48).









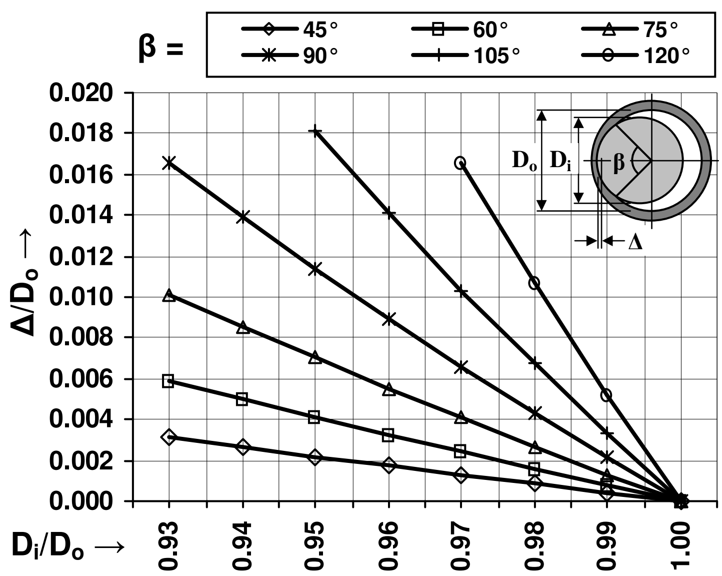
$$p \approx \frac{6 \cdot H}{\pi \cdot D_i \cdot h}$$

Fig. 48. Gate top hinge in Lock III (Tilburg) in the Wilhelmina Canal.
- **a)** hinge assembly;
- **b)** gate installation;
- **c)** contact load distribution;
- **d)** simplified estimation of contact pressure.

The lock in this example has a chamber of a so-called "bayonet type", with the 8.20 m (between the rotation axes) wide gates over a half of the lock width, see photo (a). The operational hydraulic load is here 5.0 m of water column, which is much for wooden gates. This load is, however, passed through the gate heel posts. It does not rest on the hinges which carry only the gate own weight and the walk-way load. These loads are not big. Thanks to the large vertical distance between the hinges (~6.50 m), they also produce small horizontal reactions $\boldsymbol{H}$. These favorable circumstances enabled the author to use viscoelastic material, UHMPE, in both hinges. The resulting dimensions are shown in photo (a). Photo (b) shows the collar ring locking – done by driving specially coated pins into the half-ring lugs. In photo (c), we see the assembled hinge and the contact load distribution drawn on it. Note that the hinge diameter is here comparable with the gate leaf thickness. The collar is also remarkably high when compared, e.g., to the collars from Fig. 45. These large sizes were necessary to keep the contact pressure within the limits acceptable for polyethylene, see Table 8 in chapter 3. The model used to estimate the mean contact pressure is sketched in part (d) of Fig. 48.

Obviously, the model of contact pressure from sketch (d) is very simplified. It does not, e.g., account for tangential stress in UHMPE, certainly present in this detail. This and other simplifications were considered acceptable due to a number of additional safety measures applied for this detail. The two most significant measures were:

- Limited bushing thickness of 20 mm in combination with large contact areas restricts tangential deformations of UHMPE.
- In order to prevent material extrusion in vertical direction, raised collar edges are constructed, see upper half-ring in photo (a).



The angle of load distribution $\boldsymbol{\beta}$ was estimated as 60°. The estimation was made using the program DISCO, in a way which will be discussed further in this thesis. However, it can be observed that the analysis is not sensitive to this estimation. Increasing $\boldsymbol{\beta}$ results in a larger contact area and a lower mean pressure $\boldsymbol{p}$. The system is, in a sense, self-stabilizing. Fig. 49 shows geometrical relations between the maximal bushing compression $\boldsymbol{\Delta}$ and the ratio of shaft to collar diameters $\boldsymbol{D_i/D_o}$ for a range of distribution angles $\boldsymbol{\beta}$. The diagram in this figure can be useful to estimate dimensional proportions in a hinge.

Fig. 49. Bushing compression $\boldsymbol{\Delta}$ for a range of load distribution angles $\boldsymbol{\beta}$.

The most usual $\boldsymbol{D_i/D_o}$ ratios are:

- for gates with "free" rotation points: $\boldsymbol{D_i/D_o} = 0.94 \div 0.96$;
- for gates with "fixed" rotation points: $\boldsymbol{D_i/D_o} = 0.99 \div 1.00$.

In the first case, the maximal contact load angles of about 45° ÷ 60° will usually be acceptable, resulting in compression $\boldsymbol{\Delta}$ of about (0.002 ÷ 0.004) $\boldsymbol{D_o}$. In the second case, the maximal contact angles of about 90° ÷ 120° can be accepted, resulting in compression $\boldsymbol{\Delta}$ of about (0.001 ÷ 0.002) $\boldsymbol{D_o}$. These compressions **Δ** can usually be considered correct for UHMPE, if the angle assumptions of these ranges give acceptable mean contact pressures ***p*** (see Table 8 in chapter 3).

In the project from Fig. 48, the hinge maximal horizontal load was ***H*** = 37 kN. The geometrical relations for the top hinge and its feasibility control (not the final detailing!) were as follows:

$$D_i = 200, \quad D_0 = 210, \quad \frac{D_i}{D_0} = \frac{200}{210} = 0.952\,,$$

assumed $\beta = 60°$, from diagram in Fig. 49 → $\dfrac{\Delta}{D_0} = 0.0039$.

$\Delta = 0.0039 \cdot 210 = 0.82$ mm (4% of thickness), considered acceptable. … O.K.

Contact pressure: $p = \dfrac{6 \cdot 37000}{\pi \cdot 200 \cdot 180} = 2.0$ N/mm^2 < 3.0 N/mm^2 (see Table 8). … O.K.

Some other aspects of inelastic (in this case viscoelastic) contact load distribution will be discussed using different cases in chapters 5, 6 and 7. For now, a substantial difference in the approach to elastic and inelastic contacts should be noticed:

- In elastic contacts, the designer is primarily concerned about the contact stresses. The contact geometry is considered to be more or less stable (Hertzian theory).
- In inelastic (particularly viscoelastic) contacts, the contact geometry is variable. Controlling this geometry is the designer's primary concern. The contact stress is a secondary issue.

4.4.4. Load modeling at different contact levels

In sections 4.4.1 through 4.4.3, the mutual relation between the character (elastic, plastic, viscoelastic etc.) and the distribution of contact loads is discussed. It has also been pointed out that classifying the contact as carrying pointed, linear or surface load depends on the level of the contact analysis. For the sake of completeness, it shall be noted that the relation between the analysis level and the load model goes further than the load distribution forms mentioned above. In can, e.g., also determine the number and the directions of contact loads.

A typical example of a very significant difference between contact loads on the system level and on the component level is the load modeling on a mitre gate bottom pivot, as described in section 5.2.2. Insufficient consideration to this difference was, in fact, the reason of many improper designs and – in consequence – maintenance problems in the Netherlands. Another range of differences appear after moving to the segment and asperity level. These phenomena are discussed in section 5.1 of this thesis. The reader is encouraged to consult both sections for more details in this matter.

4.5. Static and dynamic contact loads, fatigue

In the discussion on gate load character and distribution in section 4.4, no impact of load variation has been considered. In physical sense, however, gate contact loads (including the gate own weight!) – are usually variable. The reason why they, in most cases, can be considered static is that the external load variations are slow enough to let the contact reactions be in static equilibrium with those loads. When this is not the case and the external load variations are fast, the system will generate inertial forces. The resulting contact loads must then be considered dynamic. In hydraulic gates, this happens, e.g., in the following situations:

- Fast opening and closing, particularly when attached water masses are involved;
- Opening or closing with a control system malfunction, e.g. an unsynchronized mitre gate closing;
- Wave impact (not the semi-static wave load);
- Vessel or other floating object collision;
- Flow induced gate vibrations.
- Stick-slip behavior during gate motion.

The detailed discussion on these cases goes beyond the scope of this thesis. The discussion on proper (elastic as well as inelastic) contact impact loads can, e.g., be found in Johnson's [33]. One of the conclusions of Johnson's discussion is that even the impacts of small velocities ($\boldsymbol{v} \approx 0.14$ m/s) cause some plastic deformations in steel contacts. This conclusion is particularly significant in contact analyses on component, segment and asperity level (see Fig. 17 in chapter 3) and will still be quoted further in this thesis in relation to the so-called "thread shaped" wear.

Although gate contact loads can usually be considered static, some phenomena of these load variations become more and more significant nowadays. One of such phenomenon is fatigue. In traditional, static analysis of gate structures, little consideration was given to the number of load cycles. This applied also to contact components. E.g. for a lock gate steel contact component with the required service life of 15 years and the equivalent constant amplitude stress range $\Delta\sigma_{E.2} = 120$ N/mm^2, the following estimation according to Eurocode 3 [27] will be quite common in the Netherlands:

Number of stress cycles: $N = 15\,years \cdot 360\,days \cdot 20\,lockings = 108\,000$,

partial load safety factor for fatigue: $\gamma_{Ff} = 1.00$ (according to [27], § 9.3.2),

partial strength safety factor for fatigue: $\gamma_{Mf} = 1.15$ (as advised e.g. by Schmaußer [70]).

$$N > 2 \cdot 10^6 \cdot \left[\frac{36/\gamma_{Ff}}{\gamma_{Mf} \cdot \Delta\sigma_{E.2}} \right]^3 = 35\,506\,\text{cycles} \quad \rightarrow \quad \text{fatigue assessment required.}$$

Nevertheless, this difference is not large in the sense of fatigue load assessment, which partly justifies the traditional approach. The situation changed with the development of hydraulic drive technology. Unlike electro-mechanical drives, the hydraulic cylinders proved to be capable of delivering forces of any size with moderate energy inputs. The engineers profited from this by decreasing the arms of drive forces, prestressing the gates to make them suitable for bidirectional service (see section 3.3.4) etc. In the gates of the Second Lock Lith on the Meuse, the drive cylinders are hooked up in the distance of only 1/5 of the gate leaf length from the rotation axis – while the usual distance for mechanical drives is about 1/3 of that length. Such measures required a thorough and differently focused approach to the fatigue problem. Drive forces and not the hydraulic loads produced now (locally) the largest constant amplitude stress range $\Delta\sigma_{E.2}$. Increasing this stress range to, e.g., 150 N/mm^2 results in:

$$N > 2 \cdot 10^6 \cdot \left[\frac{36/1.00}{1.15 \cdot 150} \right]^3 = 18\,179\,\text{cycles}, \quad \text{which makes the problem more serious.}$$

Fig. 50 shows the detail of drive cylinder lug for a gate of the Second Lock Lith under construction. Note that the lug plate – in its central part 100 mm thick – is not welded to the flange of the top girder, but it runs through this flange and is integrated in the girder web. This is done in order to minimize fatigue risk. For the same reason, the welds of the lug plate to the cylinder arm ring are fully penetrated. Weld toes in the vicinity of this detail are – as shown on the photograph – grinded, which is also a measure to improve the fatigue strength. The size of both the ring and the lug plate gives an impression of the expected gate drive forces.

Fig. 50. Gates of the Second Lock Lith – lug plate detail during manufacturing

A special, very dangerous dynamic contact load is a so-called "hydraulic downpull force" [41]. An example of this phenomenon has already been shown in chapter 3 (Fig. 18 a). The hydraulic downpull force becomes induced by a flow through narrow gaps. When the flow loads tend to open the gap, this force can remain static, which usually presents a minor problem. However, when the flow loads tend to close the gap and/or when the system elasticity allows for gap width oscillations, the pulldown force tends to excite heavy gate vibrations which alternately close and open the gap. This, in turn, can cause a sort of contact creep, resulting in an internal load build-up and – finally – a collapse of the gate.

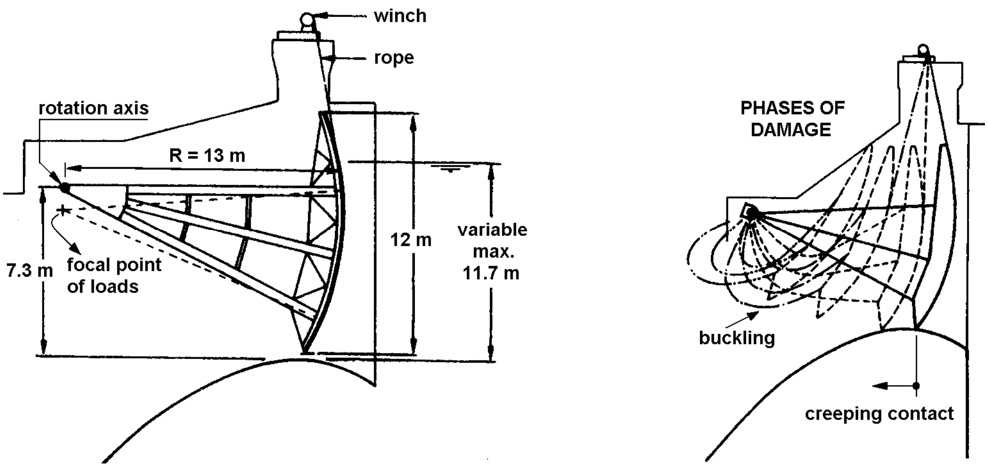
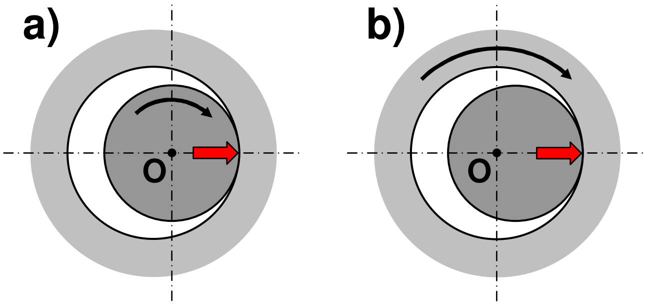


Fig. 51. Contact creep and damage of the Wachi-Dam tainter gate in Japan.

An example of this damage mechanism is the collapse of the Wachi-Dam tainter gate in Japan in 1976 [73], shown schematically in Fig. 51. In the Dutch Haringvliet Barrier (Fig. 18 a), the heavy downpull vibrations were caused by a small object (possibly of steel) laying on the sill, which gave the critical gap width. Lifting the gate and cleaning the sill removed the problem. No significant contact creep or other damage to the gate occurred [36], [74]. Nevertheless, creeping contacts are yet another example supporting the opinion that gate contact issues should be considered in very early stages of the gate design (already by system definition) – and not only at the stage of detailing. As stated in chapter 1, this opinion makes the main thesis of this study.

4.6. Stationary and moving contact loads

The contact load models discussed until now implied an assumption that both contacting bodies do not change their mutual position, or that the changes of this position are insignificant. In other words, the discussed contacts were considered to be stationary. In fact, all examples of gate contacts from section 4.4 (with the exception of Fig. 47) do not comply with this assumption – they are moving contacts. So far, this incompliance was only covered by assuming lower contact compression for moving (in particular sliding) contacts, see e.g. Table 8 in chapter 3. Now we shall take a closer look at it.



For clarity reasons, the following comment ought to be made first: In tribology, the term "stationary contact" is used sometimes, e.g. [34], to distinguish the cases in which the surfaces in contact increase their conformity due to wear, from the cases where this does not take place. Fig. 52, (a) represents the first case and (b) the second – provided the shaft wears slower than the ring.

Fig. 52. Conformable (a) and unconformable (b) contact

We shall not use the term "stationary contact" in this sense. The phenomenon mentioned above will be referred to as conformable and unconformable contacts (author's terms). The term "stationary contact" represents a mutually motionless contact in this thesis.

Motion can, in general, mean mutual displacement or rotation of contact surfaces. We shall accept the Johnson's definition that the displacements produce sliding and the rotations rolling contacts [33], although it is not accurate (E.g. torque rotation will produce spinning, which has – in tribological sense – more features of sliding than of rolling). Both sliding and rolling involve the presence of tangential loads, which we have ignored until now. Of course, these loads are usually much higher in sliding than in rolling, but their presence is essential in both, otherwise no motion occurs (except for some purely theoretical, special cases). Fig. 53 presents a photoelastic stress exposure in a contact without (left) and with (right) tangential force[1)] [34]. One can observe that the main stress trajectories resume a different pattern. In particular, the extreme shear stress τ_{max} moves now closer to the contact surface. As we remember from section 4.4.1, this stress appears at the depth of 0.63 **r** (for spherical) and 0.78 **a** (for cylindrical) stationary contacts.

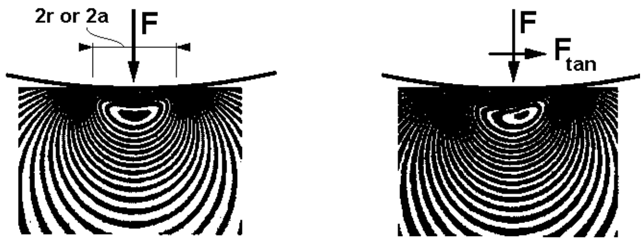


Fig. 53. Stress trajectories with and without tangential force

When the shear stress moves closer to the contact line, the same will happen with the maximal Huber – Von Mieses stresses [76], which means that the initial plastic deformations will now – so to say – come up to the surface and be no longer protected by an elastically behaving material layer. In most metallic contacts, this happens already by the ratio of:

$$\frac{F_{tan}}{F} > \sim \frac{1}{9}$$ [34], which is usually lower than the coefficient of friction.

[1)] In tribology, the two cases in Fig. 53 are also used to distinguish the so-called "pure rolling" from "rolling with traction". As the entirely "pure" rolling exists only in theory, this distinction will not be made here.

This, obviously, has severe consequences for the load bearing capacity of contact items, their service life, maintenance requirements etc. A detailed analysis of tangential loads in both sliding and rolling contacts can, e.g., be found in [33]. At present, it is important to realize that these loads can present a major problem in hydraulic gates, see Fig. 54. In general, the engineer will choose between the three following strategies to deal with these loads (in the sequence of preference):

- eliminating;
- decreasing;
- maintaining.

Fig. 54. Top hinge collar ring of the old Orange Locks in Amsterdam damaged by wear

Eliminating:

This strategy will not always be technically feasible because the appropriate tangential motion makes usually an essential system requirement. Yet, it is advisable to consider it first. The ideas can, in general, be generated in the two following directions:

- eliminating tangential motion;
- eliminating the contact.

An example of this strategy can be the contact guiding and sealing of the vertical lift and rolling gates as shown in Fig. 27 in chapter 3. In both gates, the seal contact during motion has been eliminated by the action of expansion devices. This contact takes only place under sufficient hydraulic load, which – in turn – can only appear in the stationary, closed position. It is a very effective solution but its initial costs are rather high due to the complexity of additional devices.

Another, quite spectacular example of this strategy is the principle of so-called hydrostatic bearings, as described in sections 2.2.3 and 5.5. In these devices, pumping water under the bearing pads releases the contact by maintaining a water film, a fraction of a millimeter thick, which separates the contacting bodies. As far as known, this principle has only been applied in rolling gates but it can – under favorable conditions – be used in other types of gates as well.

Decreasing:

This strategy is usually easier to realize than the first one, but it is not as efficient. It is also not as reliable, because its basic idea is to manipulate friction which is – in author's opinion – one of the least controllable system parameters under the field conditions of a hydraulic gate. The idea's can be found here in more directions, but the most promising ones are:

- replacing sliding by rolling;
- low friction contact materials;
- lubrication.

The two latter directions require no comment. An example of the first one is the modification of an unconformable contact from Fig. 52 (b) in the way as shown in Fig. 55. Letting the shaft slide in a well fitting bushing decreases the sliding contact stress, while the high stress on the ring surface goes now along with rolling.

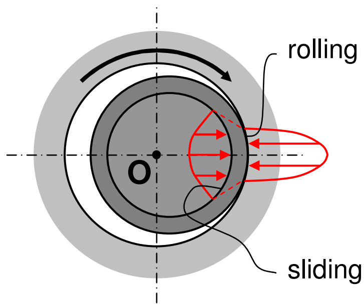


Fig. 55. Shaft in a bushing

The described principle can, in fact, be a solution to the problem of mitre gate top hinge wear, like the case shown in Fig. 54. It has recently been developed by an author's colleague [75], and successfully applied in the renovation of the Southern and Small Lock in IJmuiden which both have the gates with the so-called "free rotation points", see Fig. 15 in chapter 3. Precautions have been taken to let the friction between the shaft and the bushing be much lower than between the bushing and the ring. So far, the devices show no maintenance or other problems.

Maintaining:

The last solution to the tangential contact load problem is to accept the gradual deterioration of contact components, maintain them (inspections, cleaning, lubrication if required) and take care of their timely replacements. It can be an acceptable solution in case of low navigation intensity through the lock or, e.g., an easy withdrawal of a weir gate from service. The latter usually happens when a weir consists of several gates in a row. Removing one gate at a time does not put the entire weir out of service. In general, however, this strategy will not be advisable, because the costs of removing a gate for maintenance and bringing it back afterwards are high.

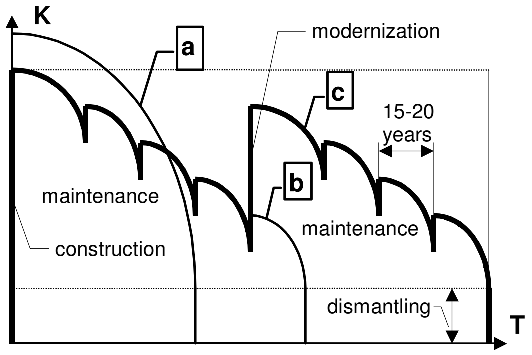


Fig. 56. Three maintenance strategies

The most logical approach is to aim at providing the contact components with a service life equal to the maintenance cycle of the gate. Fig. 56 presents three maintenance strategies of a gate (also applicable to a weir, lock etc.), as a relation between the time **T** and the costs (construction, decapitalizing, …) **K** [77]. These strategies are:

a) no maintenance;
b) periodical maintenance;
c) periodical maintenance + modernization.

We see that, with the exception of the strategy (a), there will be obvious moments when the contact components should be exchanged – namely during major maintenance works. The field practice in the Netherlands is that the frequency of those works is once in every 15 ÷ 20 years, but it can be different (e.g. frequenter) in other countries. It is usually not an easy task to engineer all the gate contact components in a way which guarantees such a service life. Yet, the engineer should certainly aim at doing that. The involved maintenance and other costs justify these efforts.

5. ANALYSIS OF SELECTED CONTACT PROBLEMS

5.1. Contact phenomena on segment and asperity level

The contact loads, as discussed until now, referred primarily to the system and component level. At those levels, we considered contact loads as pointed or continuously (often equally) distributed over a line or an area. The direction of those loads was perpendicular to the contact surface, or oblique if also tangential loads were present. In case of distributed loads, this direction was – alike the size – equally or in another way continuously distributed over the contact line or surface. Both the size and the direction could directly be derived from the equilibrium conditions of the system[1)].

All these assumptions must be put aside when the segment and asperity levels are concerned, compare Fig. 17 (a), (b), (c) and (d) in chapter 3. The main differences in comparison with the system and component level are then as follows:

- The contact surface is no more continuous. The actual contact covers usually a small fraction of the so-called nominal contact area; and is split up into a number of small asperity contacts.
- The size of asperity contact loads is irregular and does not follow the distribution of component contact loads. In general, it can be considered as a stochastic value with a mean (component load divided by a number of asperities in contact) and a standard deviation.
- The direction of asperity contact loads is also irregular and does not – as on component level – result from the global equilibrium conditions. It can better be considered as a stochastic value in a way similar to the size of these loads.
- The division into elastic and inelastic contacts is on the segment and asperity levels less useable than on system and component level. E.g. in metals, all contacts on asperity level are plastic.

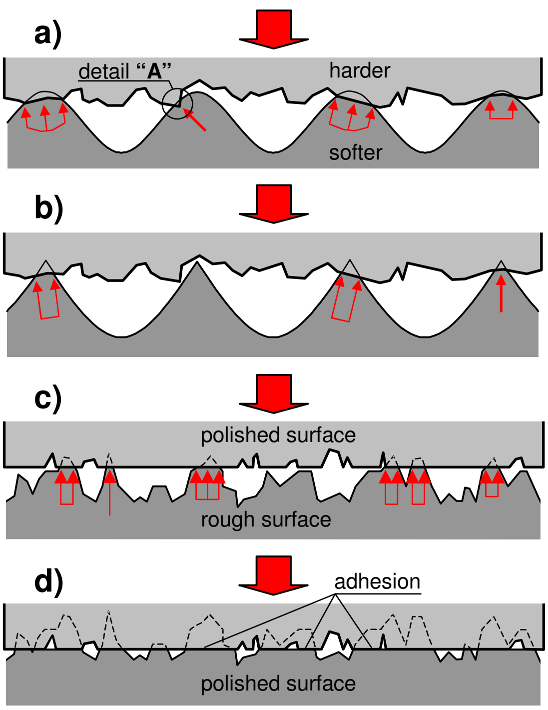


Fig. 57. Contacts on segment level, examples (enlarged: l/h ≈ 10/500x)

In a general case, when the distribution and the size of asperities are random, there will be no correlation between different parameters of asperity contacts, as shape, area, load size, load direction etc. In many forthcoming situations, however, some correlation can be traced, e.g. as result of component surface processing or machining. Some examples of this are presented in Fig. 57. If the surface of one of the two solids is plastically worked, it may have a wavy profile, as shown in sketch (a). In that case, there will be some correlation between external load and – at least – the number, location and shape of the asperities in contact. Obviously, this correlation will be much stronger when both surfaces are worked in the same way. The same happens in machined contacts, e.g. like sketched in (b), although the probability of contact on every wave top may then be different (lower in the sketch). Observe that in both cases the asperity contacts must also carry tangential loads to satisfy the equilibrium conditions. This, as we know, brings the plastic deformations closer to the contact surface – see discussion in section 4.6.

[1] Unless otherwise mentioned, the term "system" refers to a structural system in this study. Other systems, e.g. loading, drive, contact, lubrication or flow systems will be referred to using fully comprehensive terms.

Considering the above, an engineering assessment of the cases (a) and (b) will be that they are both quite "messy". This is already clear for the stationary position, not to speak about the motion. In order to regain control over the contacts, we shall first aim at bringing all asperity contact surfaces into one plane – normal to the direction of the external load. This can e.g. be achieved by polishing the contact surface of the harder (in Fig. 57 the upper) material. As polishing does not actually remove all surface cavities but it brings their number and size to an acceptable minimum, the polished surface will look like the one sketched up in (c). When this surface is brought in contact with a rough surface of a softer material, it will cause yielding of its asperity tops until the asperity contact responses come to equilibrium with the external load. As drawn, these responses follow now indeed the direction of the external load; but they are still very fragmentary and cover only a fraction of the nominal contact area. A way to change this is to polish the contact surface of the softer material as well, as drawn in (d). Only then the actual contact surface will cover large parts of the nominal contact area. In case of, e.g., metallic contacts and very fine polished surfaces, there can even occur adhesion caused by molecular attraction between both solids. This, in turn, is not favored – particularly in moving contacts – which makes us consider the lubrication [78], other (e.g. non-metallic) contacts, another gate system etc.

As soon as the two solids begin to slide over the contact surface, the material of the deformed asperity tops will depart and fall out or start filling the cavities. We will usually welcome this process as it smoothes the contact, reduces its friction and leads to more conformity between the contact loads on the component and segment level. A known example is the running-in period of a car engine, which – if properly controlled – increases its performances. In hydraulic gates, an additional advantage of this process can be the increased water tightness. However, this process does not always work to the advantage of the structure. An example is the thread-shaped wear on mitre gate pivot bearings. Let us move to asperity level and consider the asperity contact marked as detail "A" on Fig. 57. If the hardness relations are as indicated, this asperity contact will initially look like in Fig. 58 (a). If these relations are opposite, i.e. if the lower solid is harder, this contact will look like in the sketch (b) of that figure. Large plastically deformed zones occur each time in the softer material and can easily be distinguished in both sketches.

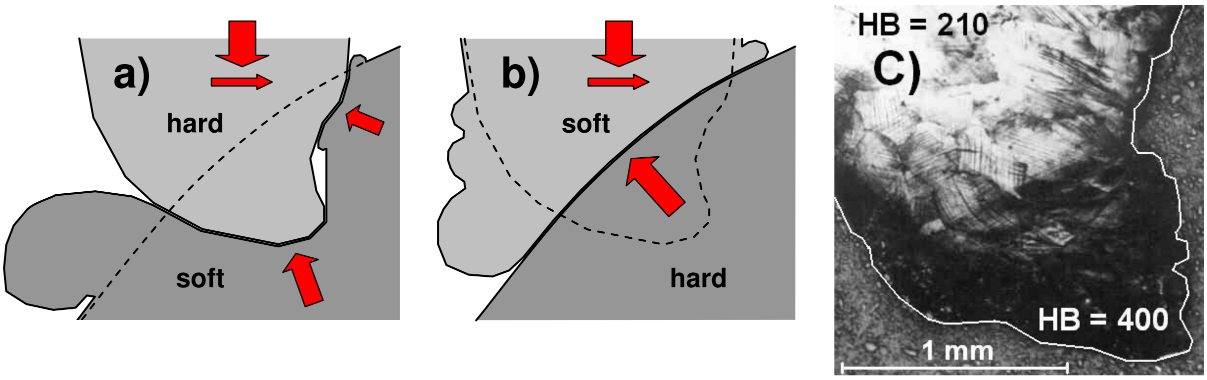


Fig. 58. Variants of asperity contact for detail "A" from Fig. 57

Several metal alloys used in hydraulic gate contacts show, however, a hardening behavior under strain. Photograph (c) in Fig 58 shows a section through one of many asperity peaks in a thread-shaped wear profile on a mitre gate bottom pivot. The author's investigation of this phenomenon included hardness measurements by a Vicker's 2.0 N micro pyramid indenter and (as a verification) a 50 N pyramid indenter [49]. Two "thread" peaks were investigated in details. The mean results of micro measurements (confirmed by random 50 N punch measurements) are shown in Table 14.

Table 14. Vicker's hardness distribution for the "thread" peak from Fig. 57 (c)

Distance crest - foot along centerline [mm]	0.00	0.20	0.80	1.50	2.00
Vicker's hardness HV [daN/mm^2]	435	370	320	270	210

The considered material was manganese cast steel G-X120Mn12, which is indeed known for its strain-hardening. We can observe the austenite γ structure of this material, with – within the crystals – many parallel dislocation planes as result of strain. The strain hardening was one of the main causes of the phenomenon known as “thread shaped wear”, discussed further in sections 5.2.2. and 7.1 of this study.

Strain-hardening is one of many contact phenomena which cause and effects can be investigated not sooner than on asperity level. It is not the intention of this thesis to discuss all the hydraulic gate contact phenomena on this level. Their theory does not, in the main, depend on the application field; and can be found in proper publications, e.g. [33], [34], [78], [79]. We shall confine ourselves to naming the most significant phenomena in this field. This is done in Table 15, apart for the metal-metal and polymer-metal contacts. The author is aware that exceptions can be found within this division. E.g., steel contacts with very soft metals (lead, tin) or with rubber will not comply with the characteristics in Table 15. Nonetheless, it seems helpful to give a condense, systematic overview of the phenomena on asperity level, typical for hydraulic gate contacts. This overview can be used as a check list for further study, e.g. in the publications mentioned above.

Table 15. Contact phenomena on asperity level for metals and polymers

Phenomena types		Metal-metal contacts	Polymer-metal contacts
Stationary		• Asperities generate tangential loads • Plastic punching/crushing • Actual contact surfaces small • Molecular adhesion • Low water tightness	• Asperity tangential loads ignorable • Viscoelastic deformations • Actual contact surfaces large • No molecular adhesion • High water tightness
Motion related	Mechanical	• Surface asperities smoothed • “Running-in” period • Strain hardening (in some alloys) • High friction (usually) • Stick-slip behavior • Primarily adhesive wear • “Thread” on wear surface	• Surface asperities compressed • No “running-in” period • No strain hardening • Low friction (usually) • No or little stick-slip • Primarily abrasive wear • Smooth wear surface
	Thermodynamic	• Asperity flash temperatures • High heat generation • Heat resistance • Good heat conduction • Low thermal expansion	• Whole surface bulk temperature • Low heat generation • Heat sensitivity • Bad heat conduction • High thermal expansion

We see that the asperity level features of both groups of contacts in Table 15 are in many respects opposite to each other. These groups include the most frequently used contacts in hydraulic gates. Other contact types, e.g. timber-metal, rubber-metal, timber-stone etc. can be characterized in a similar way, which has been omitted for space reasons. Also those contacts are, however, subject to very different phenomena in both qualitative and quantitative sense. A conclusion to be drawn at this moment is that the selection of contact materials is an issue of utmost importance in contact engineering in general – and in hydraulic gate contacts in particular.

5.2 Problems of pointed contacts in mitre gate hinges

5.2.1. Wear in collar rings – problems and solutions

In a conventional arrangement, mitre gate collar rings make part of the gate top hinges. As shown in Fig. 4 (e) and (f) in chapter 2, this arrangement can be changed. So far, there are three major locks or lock complexes in the Netherlands, where system (e) from Fig. 4 has been applied – with gate leaves supported vertically at their top hinges, and the collar rings below. The system (f) of gate suspension [6] waits still for its world first realization. The three locks of system (e) are:

- Barrier Lock in the Merchants' Harbor in Vlissingen;
- Eastern Lock in Groningen;
- Orange Locks in Amsterdam (3 chambers).

Fig. 59 shows components of the collar ring hinge in the third of these locks: the ring (in this case on gate leaf, i.e. opposite to the sketch in Fig. 4 e) and the shaft. The first photograph has been taken after 6 years of operation, the second during construction. Observe the space under the shaft bottom lug, denouncing that the hinge carries (as marked) only the horizontal loads. The applied contact materials are:

- Ring: composite Feroform[1)] T814 (phenolic resin with PTFE addition, reinforced by polyester fibers);
- Shaft: stainless steel AISI 316 L, Ra < 0.8 μm.

It can be noted that the smoothed surface in the ring covers only a certain angle, as the gate rotation angle is limited. Further, no significant wear has been detected in this hinge. Note also that the smooth contact surface does not resemble the thread-shaped wear in metallic contacts, which confirms that the characterization in Table 15 has been correct. An important detail is the care which has been taken here not to injure the collar polymer bushing during the gate installation. The machined pilot cone with rounded edges decreases the risk of denting or stripping the soft bushing.

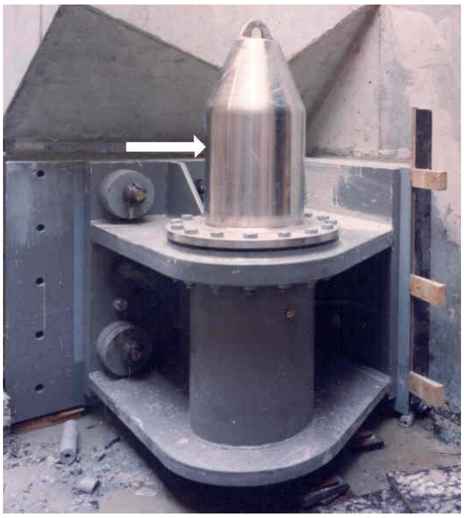


Fig. 59. Collar ring (above) and shaft (below) of the Orange Locks gates bottom hinge, Amsterdam.

In this case, the problem of collar ring wear has successfully been solved. The hinge is entirely maintenance free and ecologically favorable, as it requires no lubrication. This is particularly important due to the submerged location which limits the inspection and maintenance possibilities. The diameter and height or the ring are large and comparable to the dimensions from Fig. 48, which keeps the contact pressure low – in this case under 30 N/mm^2.

Based on the tests performed under the author's directives [49], the design contact pressures and other specifications for the Feroform T814 composite were assumed as presented in Table 16. These values differ in several cases from the supplier's data. The main reasons were: larger safety margins required and lower performances measured under hydraulic gate conditions. Therefore, both the supplier's data and the author's investigation results are presented.

[1] The name Feroform is a trade name of Tenmat® Inc. and covers a whole range of composite contact materials. In the USA, the Feroform T814 is better known under the name Tenmat T814.

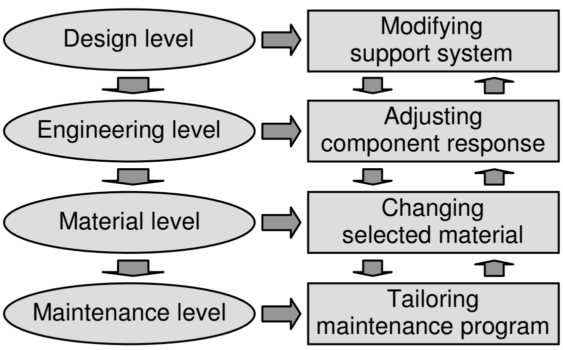
Table 16. Principal design specifications for Feroform T814 composite in hydraulic gate bearings

<table>
<tr><th rowspan="2">Property</th><th rowspan="2">Indication</th><th rowspan="2">Unit</th><th colspan="3">Design value</th></tr>
<tr><th>acc. to supplier</th><th colspan="2">author’s tests</th></tr>
<tr><td>Density ρ</td><td>in dry condition</td><td>kg/m³</td><td>1.25</td><td colspan="2">1.31</td></tr>
<tr><td>Compressive strength</td><td rowspan="2">measured on projected bearing areas (high!)</td><td rowspan="2">N/mm²</td><td>320</td><td colspan="2" rowspan="2">not tested</td></tr>
<tr><td>Shear strength</td><td>95</td></tr>
<tr><td rowspan="2">Friction coefficient μ</td><td>laboratory tests</td><td rowspan="2">-</td><td>0.04 ÷ 0.10</td><td colspan="2">0.09 ÷ 0.10</td></tr>
<tr><td>design recommended</td><td>no data</td><td colspan="2">0.20</td></tr>
<tr><td>Temperature range</td><td>incl. friction heat</td><td>°C</td><td>-20 ÷ +120</td><td colspan="2">-20 ÷ +100</td></tr>
<tr><td rowspan="2">Elasticity modulus E</td><td>3 mm thick samples</td><td rowspan="2">N/mm²</td><td rowspan="2">no data</td><td colspan="2">1.0 ÷ 1.6 · 10³</td></tr>
<tr><td>12 mm thick samples</td><td colspan="2">0.8 ÷ 1.4 · 10³</td></tr>
<tr><td rowspan="2">Design compression, stationary contact</td><td>smooth distribution</td><td rowspan="2">N/mm²</td><td>240</td><td rowspan="4">for gate contacts</td><td>120</td></tr>
<tr><td>peak shaped</td><td>200</td><td>100</td></tr>
<tr><td rowspan="2">Design compression, contact in motion</td><td>smooth distribution</td><td rowspan="2">N/mm²</td><td>60</td><td>30</td></tr>
<tr><td>peak shaped</td><td>50</td><td>20</td></tr>
<tr><td rowspan="2">Wear factor k</td><td>roughness Ra ≈ 0.8 μm</td><td rowspan="2">mm²/N</td><td rowspan="2">no data for gate type operation</td><td colspan="2">3.5 · 10⁻⁹</td></tr>
<tr><td>roughness Ra ≈ 1.6 μm</td><td colspan="2">5.0 · 10⁻⁹</td></tr>
<tr><td>Water absorption</td><td></td><td>%</td><td>0.35</td><td colspan="2">0.5 ÷ 0.8</td></tr>
<tr><td>Thermal expansion α</td><td></td><td>1/°K</td><td>4 · 10⁻⁵</td><td colspan="2">not tested</td></tr>
</table>

There exists a range of commercially available composite materials which can be used as bushings in hydraulic gate hinges. Feroform T814 is only an example. Another successfully tested (see chapter 6) but not yet used by the author material is e.g. Thordon SXL. Comparative tests on a group of such materials were, e.g., also carried by Powertech Labs (Canada) in cooperation with the US Army Corps of Engineers. Those tests included the following materials [80]:

- Kematics (Karon V);
- Deva Glacier (Deva strip);
- Erma Werke (Fiberglide);
- Thordon Bearing (Thordon TRAX XL, SXL and HPSXL);
- Tenmat (Feroform T12 and T814);
- Lubron Bearing (Lubron TF);
- Orkot (TLM/A/S);
- Polymer Corp. (Delrin AF 100).

Naturally, proper selection of contact materials is not the only solution to the collar ring wear problem. Another solution can be a change of the way in which the component responds to its load. An example of such a change is shown in Fig. 55 in chapter 4. Three strategies to deal with the contact problems caused by moving loads (thus also the wear) are named there: eliminating, decreasing and maintaining. Now it is time to split the second strategy into two: decreasing by component modification or by another material selection. In general, we can then seek the solution on four levels (Fig 60).



This flow chart resembles in its upper part the contact levels as defined in chapter 3 (see Fig. 17). The comments in that chapter apply, therefore, also to this approach.

Fig. 60. Four project-oriented levels of solving contact problems

5.2.2. Wear on bottom pivots – problems and solutions

Obviously, the approach levels to contact problems from Fig. 60 apply not only to collar rings but also to all other contacts in hydraulic gates. Let us now consider the wear of a mitre gate pivot support. As a matter of fact, this support presents usually a more serious problem than the collar ring hinge. There are two main reasons for that, i.e.:

- Pivot hinge is usually a bottom support of a gate leaf (system (d) in Fig. 4). Its inspection and small maintenance can, therefore, only be carried out by a diver, which restricts the scope of work. Any major work requires a navigation stop and setting the lock crown dry.
- Pivot hinge carries not one (as the collar ring) but two reaction components: the horizontal reaction $\mathbf{R_h}$ and the vertical reaction $\mathbf{R_v}$ (see e.g. Fig. 15 in chapter 3). Combining these two reactions in one hinge increases the wear risk tremendously, which will be proved in this section.

The engineering of gate bottom pivots was in the Netherlands (and is often still) traditionally based on contact loads resulting directly from the global load equilibrium, as presented in Fig. 4 and 15. This means that the contact loads during gate motion were, basically, assumed as follows (compare Fig. 4 d through f in chapter 2):

- Vertically: $V = R_z = G$;
- Horizontally: $H = R_h = \dfrac{G \cdot a}{h}$.

This assumption is only correct for the system (f), not for the systems (d) and (e). Let us consider the pivot loads during gate motion on the component level instead of the system level. In the side view in Fig. 61 we see not only the system external forces ***V*** and ***H***, but also an additional horizontal force $\boldsymbol{H_1}$. This force emerges as result of the friction under the actual support center S which will always show a certain eccentricity from the rotation axis. After all, the rotation axis is not fixed due to the hinge clearance, and the sphere radii of the pivot and its cap are similar in order to keep the Hertz stress low. The top friction $\boldsymbol{H_1}$ must be in equilibrium with the contact force on cylindrical surface $\boldsymbol{H_c}$ and the system external load ***H***, the latter lying slightly out of the gate plane due to the action of the rotating moment ***M***. As result, the actual contact load $\boldsymbol{H_c}$ on cylindrical pivot surface can, in fact, be much higher than the system horizontal force ***H***.

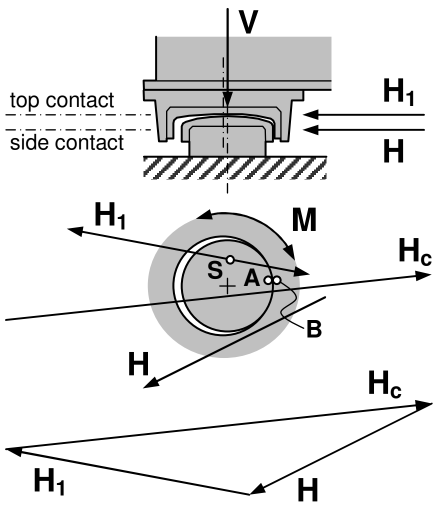


Fig. 61. Equilibrium of loads on a mitre gate pivot hinge during motion

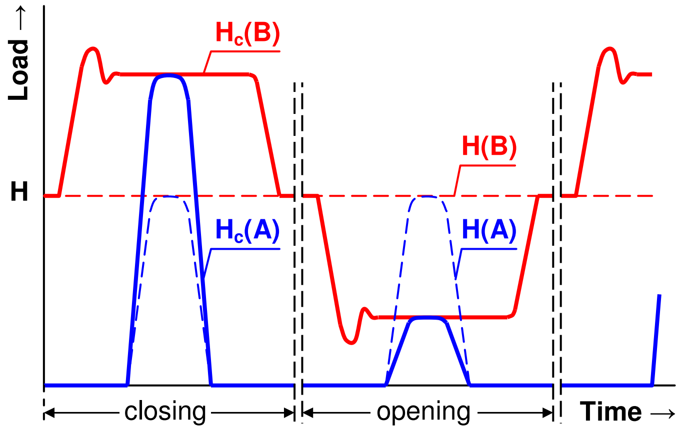
Moreover, as the rotating moment ***M*** takes alternate direction by gate closing and opening, the friction force $\boldsymbol{H_1}$ will accordingly change its sign. In consequence, also the resulting contact pressure $\boldsymbol{H_c}$ will resume a more variable character than when only the system level loads are considered. Let us choose two points within the pivot cylindrical contact zone:

- Point A – on pivot shaft, fixed in the chamber bottom;
- Point B – inside pivot cap[1)] under the gate leaf.

Point A becomes loaded only within a quite narrow sector of the gate motion angle. Point B bears permanently contact loads, though the size of these loads varies. We shall now consider the variations

[1] In Dutch technical literature known as pivot shoe (*taatsschoen*), which descends from wooden gates where this detail was made of iron and was indeed shaped like a shoe heel.

of the contact normal force only, leaving the tangential force aside. Those variations are schematically shown in Fig. 62. The indication of closing and opening is incidental – the probability that an opposite situation takes place is the same. The small hysteresis at the beginning of gate motion is caused by the transition from static to dynamic friction atop the pivot.



We see that the cylindrical surface actual contact load $\boldsymbol{H_c}$ shows indeed considerably stronger variations than the system horizontal load $\boldsymbol{H}$. This applies to points A and B alike, i.e. to both surfaces of the contact. This conclusion is of great importance for the analysis of wear, surface fatigue (fretting), friction, possible strain hardening, heat generation, and other aspects determining the hinge service life.

Fig. 62. Variation of horizontal contact load in a gate pivot hinge

If no load analysis on component level (like the one shown above) is performed, the result is usually an excessive wear as shown in Fig. 63. These particular samples of pivot shaft and "shoe" caps come from a rather small gate of the Sea Lock in Muiden near Amsterdam. More dramatic is, e.g., the situation on all navigation locks in the Meuse constructed before the Second Lock Lith. The wear of pivot caps proceeds there so fast that they actually burst sometimes after about eight years of service [81]. What makes the matters worse in the Netherlands, is that both caps have – until recently – always been manufactured of the same material: manganese cast steel. As shown in section 5.1, this is a strain-hardening material, which is the primary (not the only) reason of the thread-shaped wear, clearly visible in Fig. 63. The "author's" gates of the Second Lock in Lith were, in fact, the first to break this tradition by using two different steel grades for both components, see details in chapter 6.

Fig. 63. Wear of the pivot shaft and "shoe" cap in the Sea Lock gates in Muiden.

Other possible material selections for the gate pivot hinges – proven as favorable in the author's and his colleagues' engineering practice – are e.g.:

- Fiber reinforced composite from the group mentioned in 5.2.1 as bushing and cap in a "shoe" – and machined stainless steel as a shaft cap (example: gates of the Naviduct Enkhuizen [43]);
- If large dimensions are acceptable: Plain, isotropic polymer (e.g. UHMPE) as a "shoe" cap – and machined stainless steel as a shaft cap (example: Lock III gate in the Wilhelmina Canal [29]);
- If small dimensions are prefarable: High-tech isotropic polymer alloy (e.g. Thordon SXL) as a "shoe" cap – and machined stainless steel as a shaft cap (encouraging test results [49]),

Alike the collar rings, the pivot wear problem is solvable in more ways than only by proper material selection. We shall keep in mind the flow chart from Fig. 60 when seeking a solution to this problem. Particularly interesting is here the highest, design level in that chart. It will be proved in chapter 7 that there is a system offering a feasible, structural solution to the phenomenon of contact load "growth" on component level, as discussed above. This system is the suspension gate idea.

5.3. Linear contact through gate post lining (case Naviduct)

The main reason why attention should be paid to the wear of gate hinges is that it has impact on the way in which the gate responds to hydraulic loads, i.e. on the gate effective structural system. This argument does not apply to all types of gates in equal measure. E.g. mitre gates are very sensitive to any change of hinge clearances; single leaf gates are less sensitive; flap and tainter gates still less sensitive. Therefore, the design requirements concerning gate hinge wear will not be equally sharp for all types of gates.

In case of edge post linings, there are not one but two essential reasons why attention should be paid to their geometry distortions:

- impact on the effective structural system of the gate;
- impact on the gate water tightness.

What endangers the gate geometry, is not only the wear (although it will be a major concern e.g. for guide linings of vertical lift gates), but also the lining deformation under compression. In hinge bushings, the deformation plays usually a minor role because bushings are much thinner than post linings, which is why their compression generates less geometry distortions.

Let us consider a case from the author's design practice, in which the lining compression was an issue of major concern for both reasons mentioned above. This case is the gates of the Naviduct Enkhuizen. A photograph of one of these gates is shown in Fig. 35 in chapter 4. The detail of edge post lining is shown in Fig. 26 (b) in chapter 3. Here, an additional reason to prevent the leakage was the risk of seal vibrations in a flow, which might excite vibrations of the entire gate.

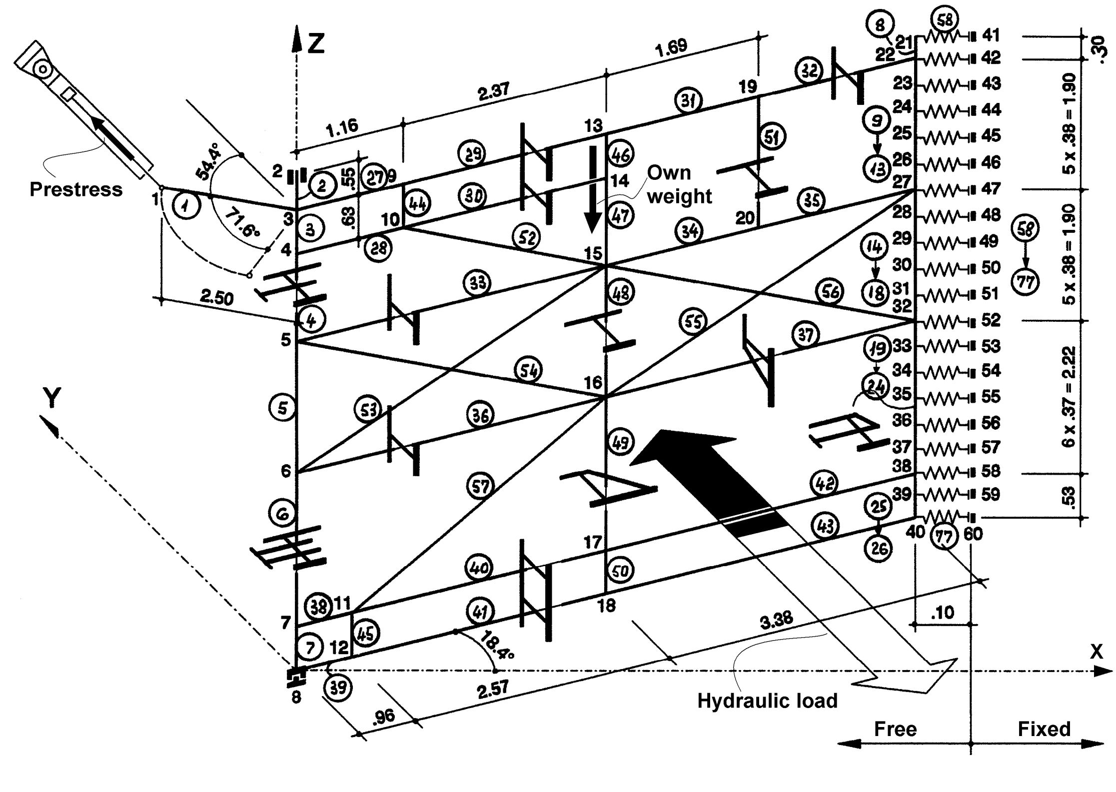


Fig. 64. Structural analysis model for the mitre gates of Naviduct Enkhuizen

Therefore, an analysis of possible gap openings was performed. Fig. 64 presents the gate model, which is a 3D frame, free to rotate about the global Z-axis, loaded by a 'negative' hydraulic load (here in the positive Y-direction) and prestressed by the gate drive cylinder. The gate front post lining is simulated by a series of elastic members (no. 58 ÷ 77), called here 'springs'. Using a conventional, linear analysis program does not give a satisfactory solution in this case. Such a program computes compressive as well as tensile reactions along the gate front post lining (nodes 41 ÷ 60), instead of gap openings. In fact, we do not know beforehand where the lining compression ends and the gap begins. The author takes the liberty to call this category of problems *discontinuous* which primarily refers to the physical (not mathematical) discontinuities of contacts[1)]. The discussed problem can be solved using a program capable of determining the actual contact zone; and of adjusting the analytical model respectively. Such a program, developed by the author and based on his original algorithm, is DISCO [83].

That program, attached to this thesis, allows for conditional definition of the joint degrees of freedom (DOF's) including all displacement and rotation components, e.g. (Fig. 65):

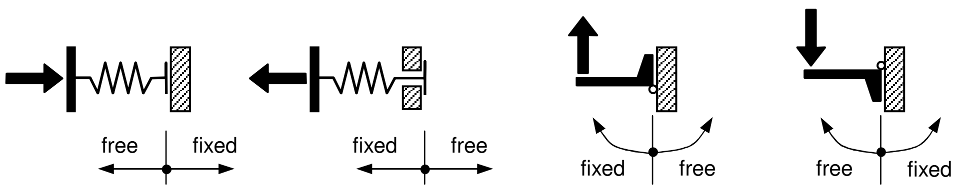


Fig. 65. Two examples of conditional DOF fixities

In the considered model, such conditional DOF's exist in:
- joint 8: with respect to displacements in the Z-direction;
- joints 41 ÷ 60: with respect to displacements in the X-direction.

Input of the conditional DOF's proceeds in DISCO using unique joint type numbers which represent the combination of joint discontinuous fixities in all DOF's. The details are discussed in the appendix to this thesis. For now on, it should be noted that the total numbers of possible joint types, i.e. joint fixity combinations (in 6 DOF's: 3 displacement and 3 rotation components), are:
- in continuous models: $N = 2^6 = 64$;
- in discontinuous models: $N = 2^{2 \cdot 6} = 4096$. 5.1

In Table 17, some excerpts of the discontinuous joint input data are given (/ = free, # = fixed).

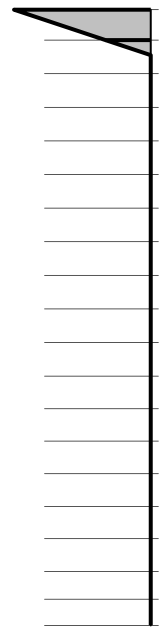
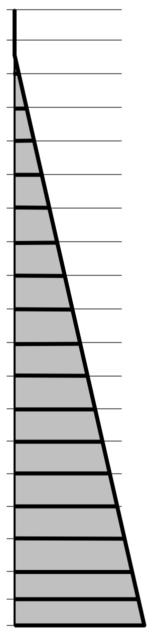
Table 17. Excerpts of discontinuous joint fixity input for the model from Fig. 64

Joint coordinates					Joint fixities					
Joint	Type	X (m)	Y (m)	Z (m)	-DX+	-DY+	-DZ+	-AX+	-AY+	-AZ+
1	1	-2.033	1.455	6.550	/ /	/ /	/ /	/ /	/ /	/ /
2	3841	0.000	0.000	7.100	# #	# #	/ /	/ /	/ /	/ /
3	1	0.000	0.000	6.550	/ /	/ /	/ /	/ /	/ /	/ /
8	3969	0.000	0.000	0.000	# #	# #	# /	/ /	/ /	/ /
…	1	…	…	…	/ /	/ /	/ /	/ /	/ /	/ /
41	1028	6.657	2.181	6.850	/ #	/ /	/ /	/ /	/ /	# #
42	1028	6.657	2.181	6.550	/ #	/ /	/ /	/ /	/ /	# #
…	1028	6.657	2.181	…	/ #	/ /	/ /	/ /	/ /	# #
59	1028	6.657	2.181	0.265	/ #	/ /	/ /	/ /	/ /	# #
60	1028	6.657	2.181	0.000	/ #	/ /	/ /	/ /	/ /	# #

[1] The author admits that his use of the term *discontinuous* instead of *nonlinear* has been criticized by some theoreticians (e.g. reviewers of Int. Journal for Numerical Methods in Engineering [82]), as it does not quite comply with the mathematical definition of discontinuity. Yet, he is convinced that it better reflects the engineering view as it is focused on the physical character of the phenomenon in question.

In this particular case, the computed lining compression zone was quite small [84]. In fact, only the two top springs appeared to carry compression; the remaining discontinuous spring supports became released and showed a gap varying from 0.2 mm at node 44 to 7.0 mm at node 60. Obviously, the actual front post gap is double as wide due to the symmetry. In Table 18, the computed lining reactions and half-gap widths are shown – numerically and in a graph[1)]. The gap width has here an almost linear distribution, with a very small progression towards the bottom.

Table 18. Discontinuous contact output for the front post lining from Fig. 64

Joint	Reaction RX(kN)		Displacement DX(mm)	
	Numerical	Graphical	Numerical	Graphical
41	-206.5835		0.0000	
42	-70.5846		0.0000	
43	0.0000		-0.2432	
44	0.0000		-0.6550	
45	0.0000		-1.0668	
46	0.0000		-1.4789	
47	0.0000		-1.8914	
48	0.0000		-2.3042	
49	0.0000		-2.7169	
50	0.0000		-3.1295	
51	0.0000		-3.5419	
52	0.0000		-3.9541	
53	0.0000		-4.3623	
54	0.0000		-4.7806	
55	0.0000		-5.2038	
56	0.0000		-5.6268	
57	0.0000		-6.0444	
58	0.0000		-6.4513	
59	0.0000		-6.7377	
60	0.0000		-7.0240	

This analysis (shown here in excerpts) made it possible to control the gate contact behavior during the entire design process[2)]; and to 'tailor' the measures preventing the leakage under 'negative' hydraulic loads. Those measures comprised finally the following:

- Extending the front posts 0.5 m above the gate top girders (visible in Fig. 35) in order to get the prestressing force inside the contact zone, instead of at its edge;
- Widening the UHMPE lining in the top zone to twice a size of the lining below;
- Bringing the gate hinge clearances down to the necessary minimum;
- Applying rubber seals as shown in Fig. 26 (b);
- Imposing sharp dimensional tolerances upon the gate and lock crown construction.

This example proves that it is possible, advisable, and it does not have to cost much effort to consider gate contact issues at all stages of the gate design – i.e. not only at the stage of detailed engineering. Recommending such an approach is the main objective of this thesis.

[1] Only the front post lining is shown. The sill lining gap was also considered but it did not require discontinuous modeling because no response was expected there.
[2] One can observe that the retaining plate in Fig. 64 is still on the (predominately) upstream side. The decision to put it on the downstream side (irrelevant for gap computation) was taken later, compare Fig. 35.

5.4. Examples of surface contact problems

5.4.1. Wear in a gate ball hinge (case Orange Locks)

In section 5.2 (particularly 5.2.2), it was shown that the so-called contact level has a great impact on analysis results. We have seen that the contact load on a pivot cylindrical surface can, e.g., grow double when the problem is approached on the component instead of the system level. A correct choice of the analysis level does not, however, guarantee correct results. An important issue is also the selection of analysis method. An example in this matter is the malfunctioning of the gate top hinges in the Orange Locks in Amsterdam. As mentioned in section 5.2.1, the top hinges of these gates carry both the horizontal ***H*** and the vertical ***V*** loads. This is shown in the upper photograph in Fig. 66, taken directly after the gate installation (walkways do not cover the hinge yet). Fig. 13 in chapter 2 presents the same detail pictured later in a side view, while Fig. 11 shows the moment of gate installation.

An unusual feature of this hinge is that, with a more or less constant vertical load ***V*** (own weight), it actually needs high horizontal load ***H*** to perform properly. This has been underestimated in detailed engineering, with the result that the ratio ***H***:***V*** ≈ 1:1.5 during gate motion, while an opposite ratio would have been more proper. To make things worse, the lock owner did not lubricate the hinges 6 years long, believing incorrectly that they were entirely maintenance free. The result was that the gate leaves (totally 18, see Table 6 in chapter 3) began to settle and load the bottom hinges (Fig. 59) vertically, that could obviously not be tolerated[1)].

Satisfactory analysis of this problem is not possible on the system level. The engineer must go down to the component, and then to the segment level. On the first of these levels he will find a ball bearing of Europe's wellknown bearing manufacturer, loaded in a way as shown down in Fig. 66. The outer ring support drawn in the right section is, obviously, present along the whole circumference. We see that the entire gate weight rests actually on the lower polyamide ring, well encased to sustain high compression. The horizontal load 'drags' this compression to one side of the ring.

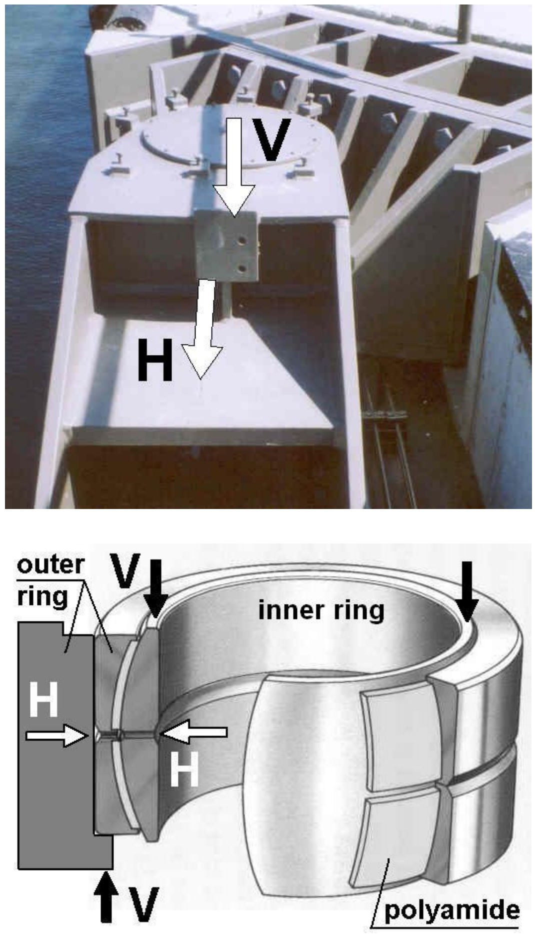


Fig. 66. Gate top hinge and the ball bearing of the Orange Locks in Amsterdam

Having observed that, the question is if the actual distribution of compression stresses – in particular in the left down segment of polyamide ring in Fig. 66 – allows for this particular loading combination. A mistake, often made by this group of problems, is superposition of the ring stresses from both the horizontal (here radial) load ***H*** and the vertical (here axial) load ***V***. Superposition is not the correct approach here because the actual contact (i.e. the compression zone) does not continue over the whole surface of both polyamide rings, but covers only a variable part of it, dependent on the size and the direction of the resultant load. In this sense, the problem is *discontinuous* and can, therefore, better be approached using appropriate computer software, e.g. DISCO.

[1] For space reasons only the main causes of damage are mentioned in this discussion.

Invalidity of superposition methods should be stressed here because it not only applies to this example but is, in fact, one of the fundamental features of contact mechanics. Let us, therefore, consider what happens when the actions of the vertical load **V** and the horizontal load **H** become superposed. An effort to do that is made in Fig. 67, showing the outlines of pressure figures during this procedure.

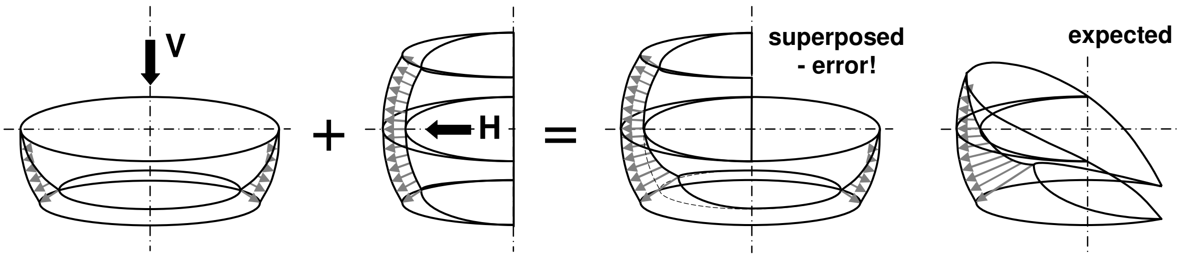


Fig. 67. Ball hinge problem – invalidity of the superposition approach

We see, e.g., that the contact pressure up-left remains the same as under the horizontal load, while it is obvious that this pressure will probably drop to zero as result of the vertical load. The same applies to the contact pressure down-right that will certainly decrease as result of the horizontal load. The actual pressure figure will look more like the one drawn in the last sketch, resulting in a significantly higher extreme compression than the superposed figure. Therefore both loads **V** and **H** must be analyzed in one loading case, e.g. using the DISCO analysis model as follows (Fig. 68):

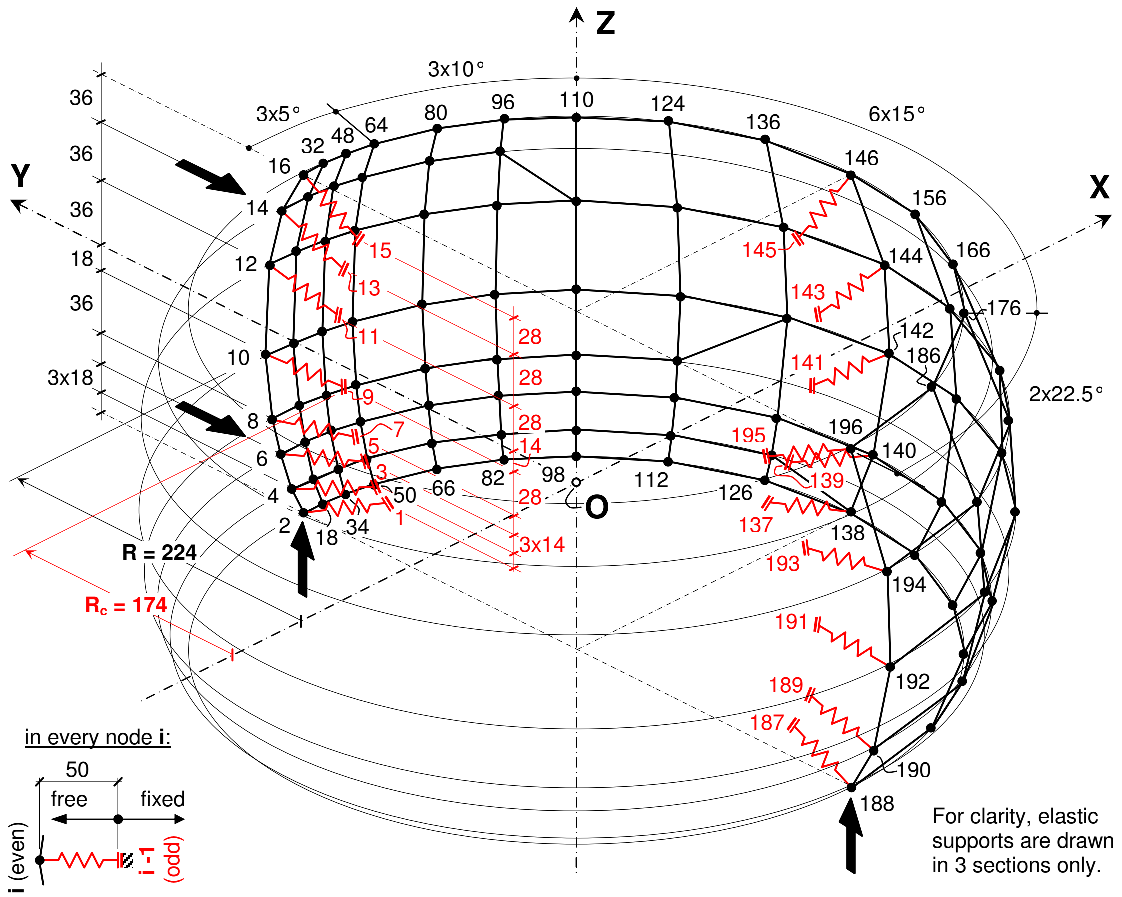


Fig. 68. Ball hinge computer model for the problem shown in Fig. 66

As DISCO is a medium size program accepting only the input of linear elements, the outer ring has been modeled as a spherical network of rigidly connected members. The member stiffness in all local directions can be input to simulate the actual ring stiffness. However, in this case very high stiffness can as well be assumed to show no significant ring deformations, as we do not expect the ring to deform but the polyamide. Having an idea about the most critical segment of the contact zone (Fig. 67), we shall use fine network of members low on the compression side – and a large-darned network on the opposite side. We shall also take advantage of the system symmetry in the modeling.

In each node of the outer ring network, an elastic radial support member is attached to simulate the polyamide response. All these members are directed towards the ball center. Their length has been set at 10 times the polyamide thickness, which – in turn – is compensated by increasing their ***EA*** stiffness 10 times. This is done for more numerical precision within a uniform format of coordinate input. Care has been taken to let the joint numbering run in the direction resulting in a small band matrix width [85]. For the sake of convenience, the numbering is chosen in such a way that all even numbers represent the network nodes; and all odd numbers represent the fixed ends of their supporting members. These fixities are discontinuous. As DISCO has been programmed to accept input in the right-handed orthogonal coordinate system (not in radial coordinates), we shall have a whole range of joint fixity combinations (joint types) here. Some examples are given in Table 19.

Table 19. Excerpts from discontinuous joint fixity input for elastic supports from Fig. 68

Joint coordinates					Joint fixities					
Joint	Type	X (mm)	Y (mm)	Z (mm)	-DX+	-DY+	-DZ+	-AX+	-AY+	-AZ+
1	3712	0.000	152.381	-84.000	# #	# /	/ #	# #	# #	# #
15	3776	0.000	152.381	84.000	# #	# /	# /	# #	# #	# #
97	2688	107.750	107.750	-84.000	# /	# /	/ #	# #	# #	# #
109	2752	107.750	107.750	84.000	# /	# /	# /	# #	# #	# #
137	2176	152.381	0.000	-84.000	# /	/ /	/ #	# #	# #	# #
145	2240	152.381	0.000	84.000	# /	/ /	# /	# #	# #	# #
167	2432	107.750	-107.750	-84.000	# /	/ #	/ #	# #	# #	# #
175	2496	107.750	-107.750	84.000	# /	/ #	# /	# #	# #	# #
187	3456	0.000	-152.381	-84.000	# #	/ #	/ #	# #	# #	# #
195	3520	0.000	-152.381	84.000	# #	/ #	# /	# #	# #	# #

The output confirms the expectation as drawn in the last sketch in Fig. 67. At the time of writing this thesis, that particular problem was still under discussion between the concerned parties. Due to the sensitivities involved, no numerical details are presented here. One can, however, observe that a relatively small contact item can – if not properly engineered or maintained – be a reason of very serious malfunctioning, endangering the stability of an entire gate system. The repair costs will certainly be high in this case, as the 18 gate leaves must one by one be disconnected from hydraulic and other systems, lifted out and partly disassembled for it. This could have been avoided if sufficient consideration on component and segment level was paid to this contact problem during engineering.

5.4.2. Ball hinge Φ 10.0 m of the New Waterway Barrier

Another example of ball hinge contact – but of a quite unique scale – is the support hinge of the New Waterway Barrier[1)] in Hoek van Holland. The barrier, constructed in the 1990's, is a "big brother" of the Hartel Canal Barrier, which has globally been presented in sections 2.3.2 and 3.5. Both structures are storm surge barriers protecting the Rotterdam harbor and its hinterland against the intrusion of sea waters. The New Waterway is the first, main entrance to the harbor; the Hartel Canal is the second.

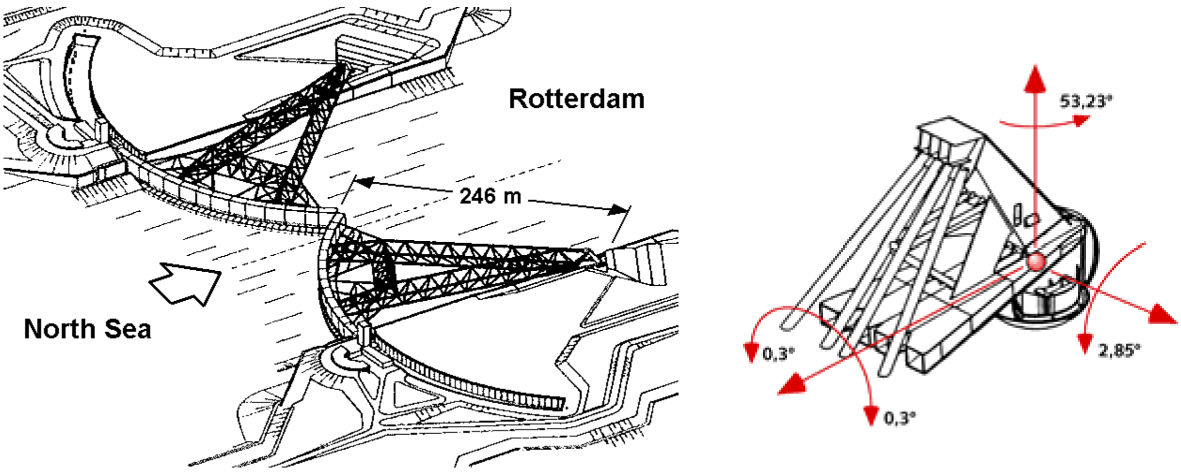


Fig. 69. The New Waterway Barrier and the support hinge of its sector gate

Fig. 69 presents a general view of the barrier and a close-up of the gate hinge with its rotation components about the system axes. With its diameter of 10.0 m, this is the largest ball hinge ever made by a man. Also its design loads are quite unique, namely [86]:

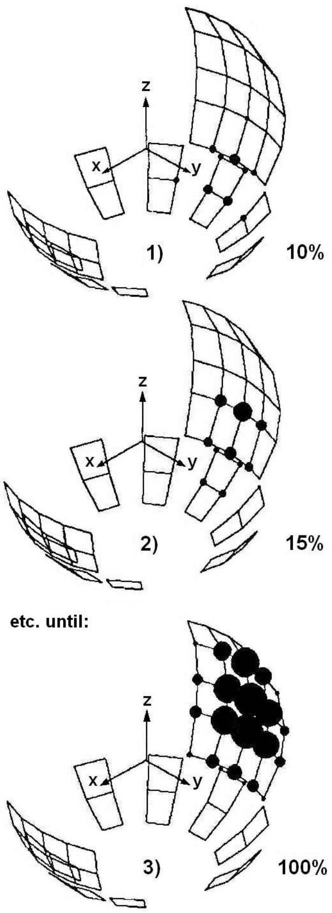
- Horizontal reaction to extreme 'positive' water head: 300 000 kN;
- Horizontal reaction to extreme 'negative' water head: 60 000 kN;
- Vertical reaction (mainly own weight): 40 000 kN;
- Lateral horizontal reaction (wind, inertial loads, …): 20 000 kN.

Despite these immense figures, there is a remarkable analogy between this hinge and the much smaller top hinges of the Orange Locks discussed in section 5.4.1. In both cases, the attention of the engineers was focused on the hinge operation under extreme hydraulic loads, which is more or less stationary (see discussion in 4.6). Yet, in both cases it went wrong due to the much lower but frequent loads during gate opening and closing - comprising little hydraulic load, but acting on contacts in motion.

The hinge itself is a large structure occupying a specially conditioned building and consisting of cast iron spherical shell elements, machined and assembled with radial dimensional tolerance of ± 0.3 mm. This precision was necessary due to the relatively thin slide layer applied here, that can not redistribute loads from surface roughness. The ball bedding consists of a number of separate segments – smaller in the bottom zone and large in the heel zone, which results from the load proportions mentioned above. The difference between the diameter of ball and its bedding is 40 mm which is small for a diameter of 10.0 m. This small difference and the carefully chosen stiffness relations within the hinge produce a sufficient actual contact area under operation loads. Once the gate is closed, the water head build-up changes the resulting hinge load direction from vertical into (in extreme case) almost horizontal. This moves the ball from the bottom to the heel bedding, increasing at the same time the contact pressure. This mechanism, pictured schematically in Fig. 70, has been studied in details using a large, powerful

[1] The New Waterway Barrier is also known under the name the Maeslant Barrier; the Hartel Canal Barrier is also known as the Europoort Barrier.

software system ANSYS®. Alike DISCO, ANSYS® enables contact discontinuity modeling, but based on another programming approach employing contact elements instead of discontinuous joints.



The ANSYS® results have been visualized (using another software) in Fig. 70 for three stages of the hydraulic load built-up: 10%, 15% and 100% [88]. We can see that the bedding response not only grows but also clearly changes its direction. Note that the middle nodes of the bottom bedding pads are loaded the heaviest at stage (1), very little at stage (2) and not at all at stage (3). This confirms what has already been mentioned in section 5.4.1: One should not apply the method of superposition in contact mechanics.

Some engineers, e.g. [89], distinguish in this matter difference the so-called "conform" or "disperse" contacts with equal curvatures of both solids – and other forms of contacts. According to their view, the method of superposition would still be applicable within the first group. The author strongly disagrees with it. Such approach ignores the fact that contact loads produce strain. No matter which strain behavior the contacting solids show (elastic, plastic, viscoelastic, …), as long as there is relation between load and load bearing surface[1)] no method of superposition should be applied.

As mentioned, the originally applied contact slide system between the ball and its bedding was thin. It comprised the following layers [88], applied on both the ball and the bedding surface:
1. Molybdenum sulfide (MoS_2) ground coat layer of 20 μm;
2. Teflon (PTFE) based top coating layer of 20 μm.

Fig. 70. Contact load growth in the hinge of New Waterway Barrier

This slide system did not work satisfactory. After some 5 years of service, covering test closures only, the system began to show severe wear damage. It should, however, be noted that the contact is here – also under daily conditions – not stationary. Due to the thermal expansion of truss arms (by supported retaining wall) or changes of wave level in gate docks (by floating retaining wall), the contact surfaces are in continuous slow motion or – in any case – receive varying tangential loads. At the time of writing this thesis, the original surface coating has just been replaced by a new system. That system introduces some geometrical modifications, allowing to use UHMPE pads cased in carbon fiber reinforced bands. It is too soon to talk about field experiences yet, but the designers hope to have solved the wear problem. Their hope is particularly based on performed calculations, other successful applications of UHMPE, and a series of laboratory tests performed for this repair. The author of this thesis is not directly involved in the hinge repair. The reported technical details come from his colleagues.
This case is a yet another example showing that not the extreme high loads but typical contact issues have caused damage. As such, it confirms the main thesis of this study that contact problems should be given a more prominent place in hydraulic gate design. The proposed new approach to these problems has been sketched in section 1.2.

[1] It is technically possible to eliminate this relation within a certain range, e.g. by contact prestression.

5.4.3. Drive arm connection of the Orange Locks gates

The cases discussed until this moment represent contacts between gates and their surrounding, usually the civil structures of lock crowns, weir or barrier piers etc. Underexposed remain the internal contacts between the gate components. There are some objective reasons for that, e.g.:

- Structural components of modern hydraulic gates are usually fixed together (e.g. by welding) in such a way that there is no question of contact in the sense as discussed in this thesis;
- Exceptions, such as rolling gate elastic supports to wheel units, guides of water leveling devices (sluices) in gates etc. usually represent isolated, special problems that concern only gate engineers and have no impact on other participants of the project.
- Bolted (in old structures riveted) connections, e.g. assembly joints, are traditionally the domain of structural engineering and not of contact mechanics. The latter is usually seen as making part of mechanical engineering.

Nonetheless, some typical contact problems are frequently experienced in internal joints, supports, restrains etc. between various gate components. This is a logical consequence of the fact that gates are structures in motion, which distinguishes them from most other civil engineering structures, see discussion in section 3.1. Therefore, gate engineering should also comprise some elements of mechanical approach, in particular the consideration to contact phenomena.

A painful example of that is the series of damages of drive arm connection in the Orange Locks gates in Amsterdam. These lock gates, with technical data as shown in Table 6 (see chapter 3), are driven by hydraulic cylinders hooked to drive arms. The arms are bolted to the gate leaves at the level of their top girders (Fig. 71). Bolted connections have here been chosen for assembly reasons – a permanent (e.g. welded) joint would make the gate installation almost impossible.

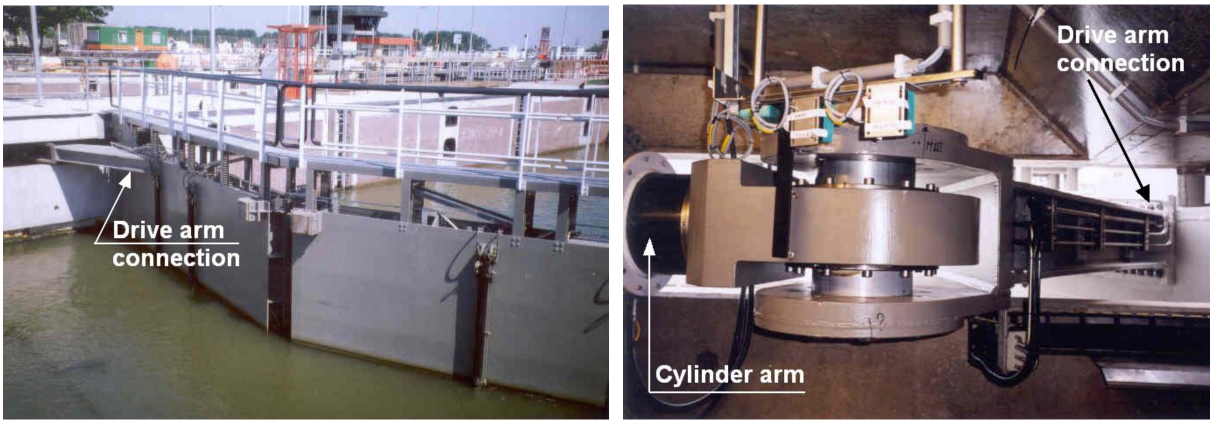


Fig. 71. One of the Orange Locks gates (left) and its drive connection (right)

It already became clear during gate testing that the drive arm connection was too weak. Although the engineer presented calculations showing no bolt overload, the bolts kept breaking under cylinder tension – starting from the drive side (right photo) towards the gate middle. As usually, a number of reasons contributing to the damage were found, e.g.:

- Flange surfaces were not machined (standard in structural engineering), showed large deviations and provided only partial contact along the drive arm connection.
- Bolts were not sufficiently tightened and practically not pre-tensed.
- Control system was malfunctioning and produced repeating, high cylinder loads.

The main reason was, however, an incorrect approach to the bolted joint analysis. This approach – not unusual in steel structures – assumed a compression point close to the far end of the bolted connection, and a linear distribution of bolt tension from that point towards the gate rotation axis. Looking at the dimensional proportions in Fig. 72 (a), we see however that there is no ground for such approach, because the connection is too long to assume that the contact surfaces will remain flat after deformation. Only in that case the assumed approach could have been justified.

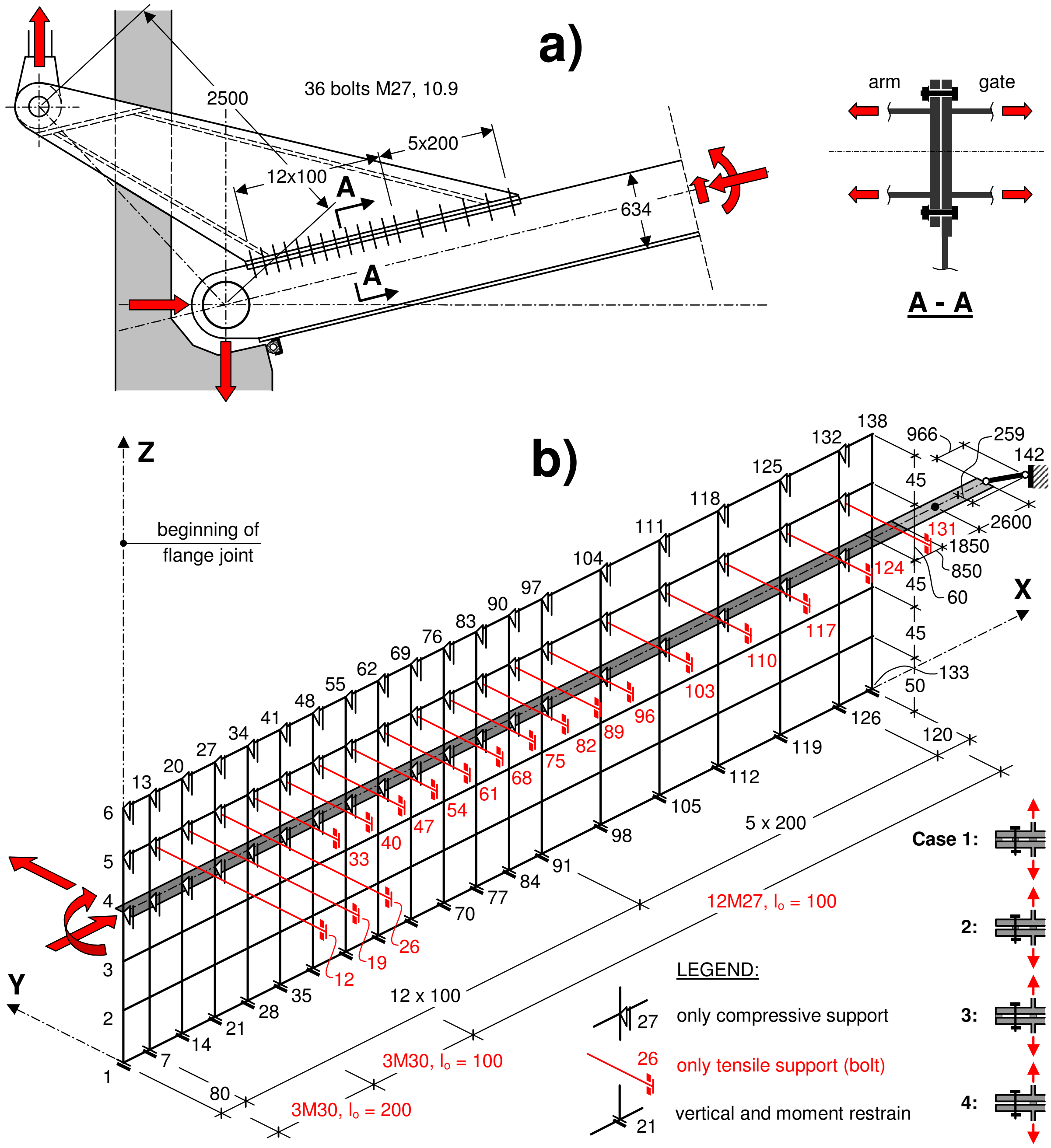


Fig. 72. Orange Locks: drive arm connection (a) and DISCO analysis model for the repair (b) [90]

The question is now: If the model of linear bolt tension distribution is incorrect, what is the correct model then? The answer is again to find in the basic property of contacts – their discontinuity. We can observe that the flexural stiffness of both connected items (especially locally in the vicinity of bolts, but also in global cross-sections) is quite similar. Let us assume that it is equal. This entitles us to consider the nominal contact plane a symmetry plane. Another symmetry plane runs horizontally through the middle of the two box sections. Under these assumptions, a DISCO model like in Fig. 72 (b) can be built. It comprises only one (here upper) row of bolts, the half of the flange height and the half of the box section flexural stiffness assigned to the members at the web height. Member stiffness plays here an important role and must be determined quite accurate, unlike in the example in section 5.4.1.

The analysis was performed after deciding that continuous flange contact should be restored by pad welding and machining in one of the ways marked as "case 1 ÷ 4" in Fig. 72 (b). The model presented in this figure shows in fact "case 1", but switching to another case is easy in DISCO – it only requires changing some joint type numbers. Some examples of the applied joint types, i.e. joint discontinuous fixity combinations, are presented below (Table 20). The technique of joint type determination is described in the program manual attached to this thesis.

Table 20. Excerpts from discontinuous joint fixity input for the model from Fig. 72 (b)

		Joint coordinates			Joint fixities					
Joint	Type	X (m)	Y (m)	Z (m)	-DX+	-DY+	-DZ+	-AX+	-AY+	-AZ+
1	253	0.000	0.000	0.000	/ /	/ /	# #	# #	# #	/ /
6	525	0.000	0.000	0.245	/ /	# /	/ /	/ /	# #	/ /
11	513	0.080	0.000	0.200	/ /	# /	/ /	/ /	/ /	/ /
12	497	0.080	-0.170	0.200	/ /	/ #	# #	# #	/ /	/ /
13	513	0.080	0.000	0.245	/ /	# /	/ /	/ /	/ /	/ /
130	513	2.280	0.000	0.200	/ /	# /	/ /	/ /	/ /	/ /
131	497	2.280	-0.095	0.200	/ /	/ #	# #	# #	/ /	/ /
132	513	2.280	0.000	0.245	/ /	# /	/ /	/ /	/ /	/ /
133	253	2.400	0.000	0.000	/ /	/ /	# #	# #	# #	/ /
138	513	2.400	0.000	0.245	/ /	# /	/ /	/ /	/ /	/ /

Take special notice of the displacement fixities in the Y direction. We see that the nodes on all contact lines are modeled as supports that can only carry compression, while the bolt anchorages (by symmetry the middle sections) are modeled as supports that can only carry tension. Both bolt arrangements before (Fig. 72a) and after (Fig. 72b) the repair were analyzed. Under extreme cylinder load, the computed distribution of flange gap and bolt tension were as shown below (Fig. 73).

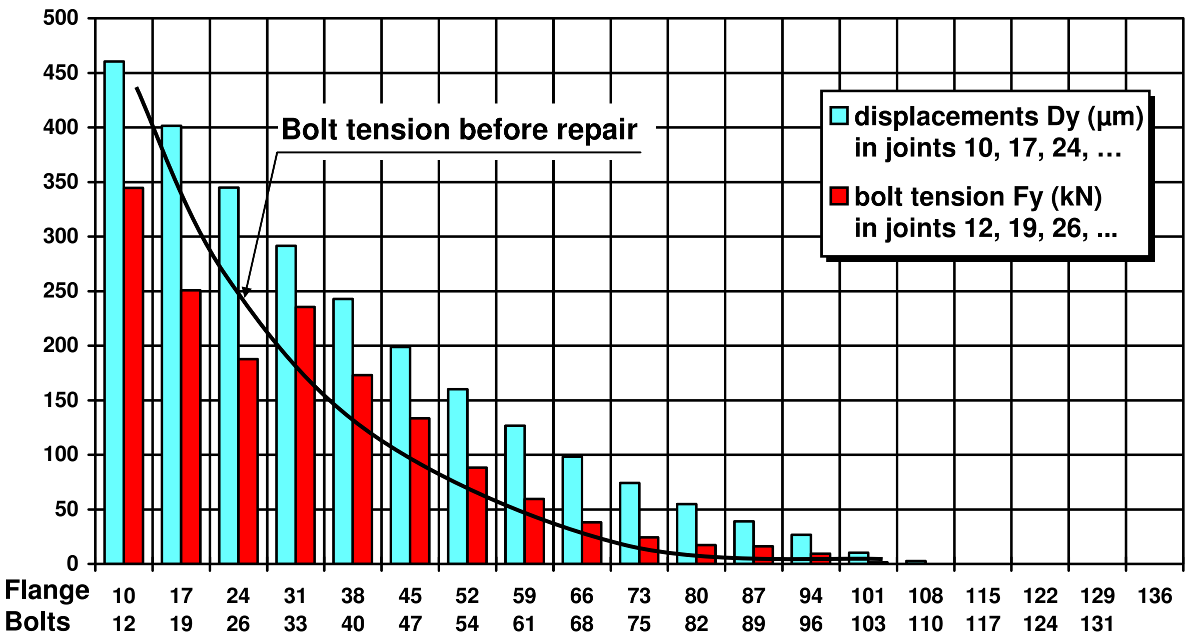


Fig. 73. Distribution of flange gap and bolt tension for the model from Fig. 72 (b)

Observe the strongly nonlinear distribution of the computed bolt tension – with a peak on the left side bolt. Note also that a long right side of the bolt group does not, in fact, carry any tension which means that the remaining left side receives still higher loads. This explains the damage of the connection. It also shows clearly the way to repair it, which is to strengthen the left side bolts and – if possible – to redistribute the peak bolt tension onto the bolts behind. The first was reached by changing 6 bolts in a row into M30; the second by extending twice (using high washers) the length of the first 3 bolts in a row. Note that the second measure decreased, indeed, the peak tension, which is to see in the diagram back leap when passing from short into long bolts.

In view of contact behavior, an interesting question was which of the contact cases (1 ÷ 4 in Fig. 72 b) offered the best solution. The numerical results of this investigation are shown in a diagram in Fig. 74. We see that there is practically no difference for the bolt peak tension. Significant differences appear only in the middle and low tension zone. These differences are to explain by the interference of flange contact forces, while there is no flange contact any more in the highest tension zone. One can conclude that by lower cylinder loads these differences will also appear in the highest tension zone. This makes cases 2 and 4 more favorable than 1 and 3. Such a conclusion should not be surprising, as it is known in other fields of engineering, e.g. flanged pipeline connections in the process industry. It is especially significant for connections bearing fatigue loads which, in fact, is also the case here.

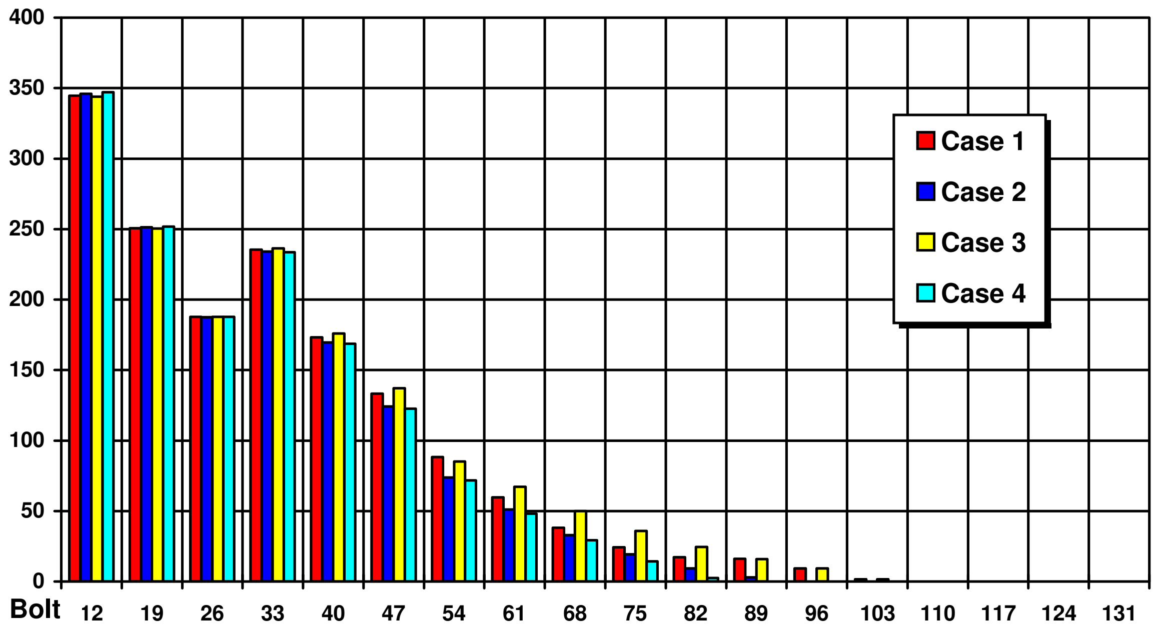


Fig. 74. Bolt tension (kN) distribution in four contact cases for the model from Fig. 72 (b)

The general conclusions to be drawn from this example can be as follows:

- Alike the gate external contacts, the engineering of its internal contacts requires thorough attention – also when those contacts are stationary or are usually not discussed in contact mechanics, e.g. bolted, riveted, pinned, clamped or other joints with loose connectors.
- An important issue in the analysis of such contacts is the (local) stiffness of contacting components. This issue can be crucial in selection of the analysis model. Limited stiffness can, e.g., be a reason of nonlinearities in contact load distribution, producing unfavorable load peaks.
- When modeling an internal contact problem, sufficient attention must be paid to its discontinuities. Contact discontinuities exist – and are significant – also in bolted or other connections which are considered as having equal strength to the sectional strength of the connected components.

5.5. Dealing with some complex and special contact cases

The contact examples discussed until now could (more or less accurately) be simulated in numerical models and then analyzed and engineered using the computer output. This will not always be possible, anyway not without support of other investigation methods. The reasons for that can be as follows:

- too complex contact mechanisms;
- contact parameters outside the practiced range;
- new, little known contact materials;
- innovative physical or geometrical arrangements;
- special, not dealt with yet contact requirements, etc.

There is always some degree of subjectivity in classifying a contact as “complex” or “special”. We shall not try to resolve it, as it usually has a positive impact on the engineer’s approach. Instead, a brief presentation of two contact examples will be given, in which the numerical analysis was supported by other methods.

Fabric folding in an inflatable dam (case Ramspol Dam)

In the late 1990’s, the first inflatable dam project was realized in the Netherlands – the Ramspol Dam. Yet, it was at once the largest dam of this type in the world. It comprises 3 inflatable gates, all 80 m long (at water level), 8.30 m high, designed to carry a water head up to 4.40 m [91]. The dam works as a barrier in case of heavy storms, closing a pass to the Ijsselmeer – a large lake originating from the Dutch sea drying projects in the 1930’s. Fig. 75 presents a general view with a cross-section of one of the gates (left) and the phases of the gate folding in bottom recess (right).

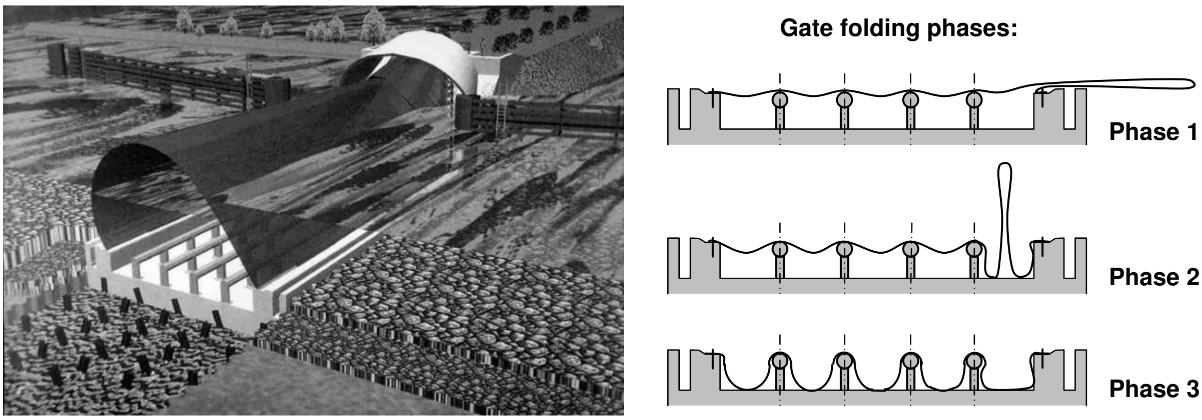
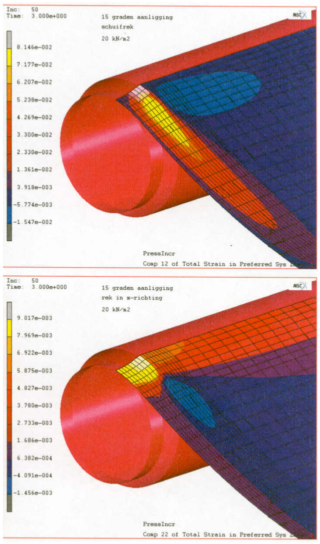


Fig. 75. Ramspol Dam: gate closed position (left) and phases of gate folding (right)

The gate material is a rubber-coated, multi-layer nylon fabric. It is just its folding (in reverse sequence also unfolding) which has been one of the main concerns for the designers. Note that the gates become filled with water (about ⅔) and air (⅓) when operating. After the storm has passed, the water masses are not driven towards the gate any more, the levels at both sides become almost equal and the barrier can be opened. Opening proper valves gives a pressure difference of about 2 m across the fabric. This “squeezes out” the inner space, brings the fabric to the bottom and makes it move from right to left, as sketched in Fig 75. The roller supports provide an almost frictionless fabric positioning until phase 3. From that moment there is a friction between the fabric and the recess bottom. Due to the complexity of this and other friction problems, the scarcity of reliable data etc., the fabric behavior in recess was subject to model investigations carried for this project. The risks of distortions and early damage could be brought back to acceptable sizes in this manner. Despite that, some local fabric damages occurred



during the first tests. They were caused by improperly machined, sharp edges of roller supports. These edges were smoothed away and no distortions have been observed since then. In the fabric behavior analysis, complex FEM models were built, using structural analysis software like ANSYS® and MARC®. In these programs, the fabric was not only modeled using surface elements; also its thickness was simulated in a number of element layers. The analysis had a quite unique character due to the so-called bifurcation phenomenon, which allows for different shapes of equilibrium under the same loads. The computed results (e.g. Fig. 76) made it possible to define the significant fabric shapes, internal loads, stresses in contact zones on rollers, tensile anchorage reactions etc.

Fig. 76. Ramspol Dam: Samples of computed stress visualizations of shear (above) and tension (below) in the fabric

Hydrostatic feet of a sliding gate (case New Orange Lock)

In order to increase the capacity of the Orange Locks in Amsterdam, a new, 24 m wide navigation lock was constructed in the early 1990’s. The lock gates are of a sliding type. This choice was motivated by less maintenance requirements than by the rolling gates. The total weight of a single gate is about 2000 kN, but the operational vertical load does not exceed 500 kN thanks to the buoyancy tanks. Nevertheless, this load was still too high for the designers to let the gates slide with no additional measures. In order to reduce the friction (and by that also the wear), the so-called hydrostatic bearings were applied [20], here to be called hydrostatic feet.

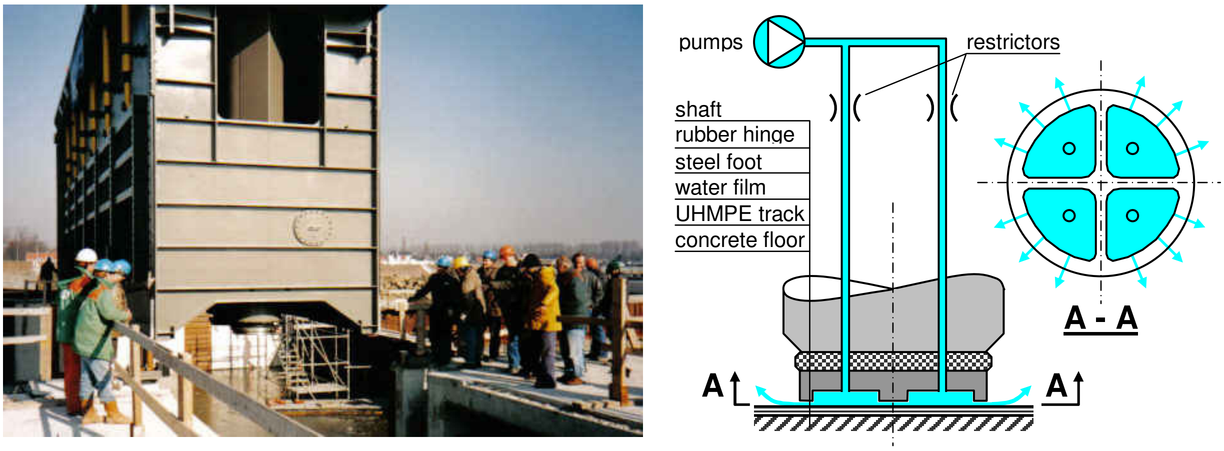


Fig. 77. Hydrostatic foot of the New Orange Lock gates in Amsterdam

The gates were installed using a heavy floating crane. In the photograph in Fig. 77, we can just see one of the two hydrostatic feet. The way in which this device works, has schematically been sketched next to the photograph. The system uses water from the lock. That water passes filters at first to remove any particles larger than 0.1 mm, that might cause problems in the foot. Then it is pumped till the pressure gets large enough to create a nominal flow gap of at least 0.12 mm underneath. Each of the four foot chambers (see section A-A) has its water supply with a restrictor, so that there is not much relation between the chamber pressures. This increases the system stability.

The question is now how high the restricted water pressure p_1 must be to provide the required bearing capacity of $\boldsymbol{F}$. We shall consider this question for a single circular chamber, as drawn in Fig. 78. This consideration is based on the approach published in [20], with some minor corrections. An approach assuming linear instead of logarithmic pressure distribution in the water film zone [34] is also possible but will not be used here as it represents an underestimation of $\boldsymbol{p_1}$.

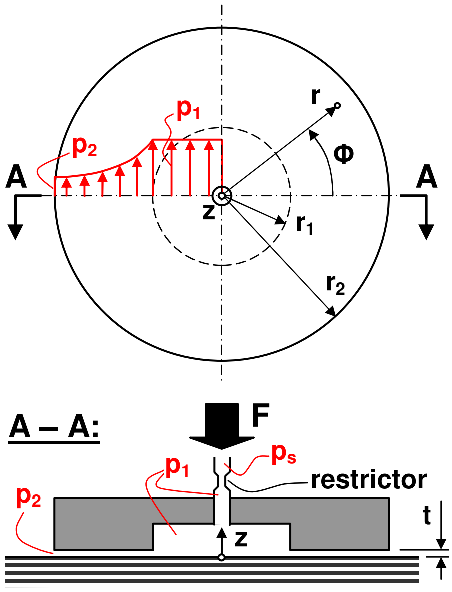


Fig. 78. Hydrostatic bearing, principle

From the equations of laminar flow, the following pressure $\boldsymbol{p}$ and radial flow velocity $\boldsymbol{v}$ can be derived for a point at the distance $\boldsymbol{r} \le \boldsymbol{r_2}$ from the center[1]:

$$p = \begin{cases} p_1 & for\ r \le r_1, \quad otherwise: \\ p_2 + & (p_1 - p_2) \cdot \dfrac{\ln(r/r_2)}{\ln(r_1/r_2)} \end{cases} \qquad 5.2$$

$$v = \begin{cases} \approx 0 & for\ r \le r_1, \quad otherwise: \\ \dfrac{p_1 - p_2}{2 \cdot r \cdot \eta \cdot \ln(r_2/r_1)} \cdot (t \cdot z - z^2) & , \end{cases} \qquad 5.3$$

where η is the so-called dynamic viscosity, for water about 0.001 N·s/mm^2 (Pa·s), depending mainly on pressure and temperature [34].

The load bearing capacity of this device is obtained by integration of the pressure $\boldsymbol{p}$ from (5.2) over the total area of the circle $\boldsymbol{r_2}$. The result of this integration is:

$$F = \ (p_1 - p_2) \cdot \pi \cdot \frac{r_2^2 - r_1^2}{2 \cdot \ln(r_2/r_1)} = \ const \cdot (p_1 - p_2) \qquad 5.4$$

By integration of the velocity $\boldsymbol{v}$ from (5.3) over the circumference of the circle $\boldsymbol{r_2}$, we obtain the flux $\boldsymbol{\Phi}$ (flow volume per time unit) as follows:

$$\Phi = \ \frac{F \cdot t^3}{3 \cdot \eta \cdot (r_2^2 - r_1^2)} = \ const \cdot F \cdot t^3 \qquad 5.5$$

This will let us choose the pump capacity, taking – obviously – account of the restriction. We see that the water film thickness $\boldsymbol{t}$, in the third power in (5.5), has a tremendous impact on this choice. Therefore we shall rather choose small values of $\boldsymbol{t}$, taking care that the slide surface of the hydraulic foot is smooth and large enough not to cause severe damage e.g. by emergency closing without pressure.

The theory of the four-chamber foot is, in fact, much more complex, although the principles are the same. This, and the innovative character of the New Orange Lock gates, made it necessary to complete thorough laboratory tests before a “go” decision could be taken for this project. Alike the Ramspol Barrier, the New Orange Lock gates combine the know-how of analytical (in Ramspol numerical) approach and extensive material and model investigations.

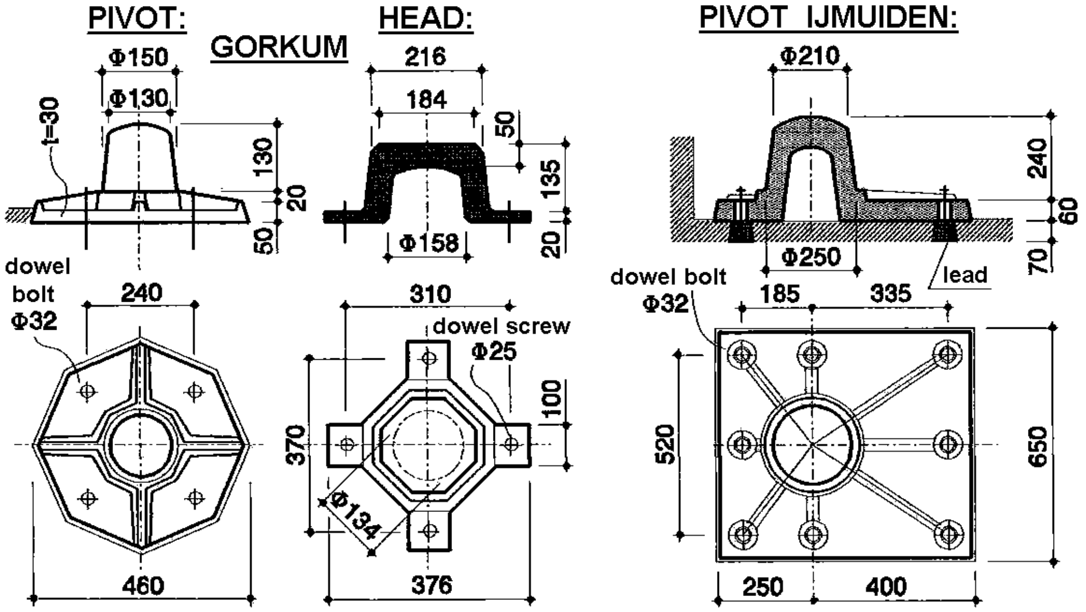
[1] We assume in this example that the film thickness $\boldsymbol{t}$ is very small, which allows us to ignore boundary effects.

6. LABORATORY INVESTIGATIONS OF GATE HINGE MATERIALS

6.1. Some historical background, “thread” forming

Between the early 1950’s and the beginning of 1980’s, the waterways of West Europe experienced a steady growth of navigation. One of the results was an increasing number of ship passages a day. The engineers were also under the demand to construct faster moving lock gates, which would increase the locking frequency. This seemed easy because improved (mechanical) and new (hydraulic) drive technologies offered still higher speeds and forces.

The negative result was, however, an excessive hinge wear due to the high loads and load frequencies on gate hinges. The biggest problem was the mitre gate bottom pivots, with their difficult accessibility for maintenance. Navigation locks and weirs are structures of long service life, so the technology of this detail dated often back to the end of 19^{th} century. The contact materials were e.g. phosphor bronze, cast iron or cast steel, as shown in the two examples in Fig. 79 [81].



Constructed in ~1880, totally under 6 gate leaves.
Drawn are pivots and heads on the canal side.
Material: phosphor bronze (pivots and heads).

Constructed in 1893. From late 1950's gradually replaced - the last in 1992.
Material: cast steel, machined.

Fig. 79. Typical mitre gate bottom pivots from the end of 19^{th} century in the Netherlands

A solution to the pivot wear problem was in the first instance sought in wear resistant materials. Such a material, well proven e.g. in mining and quarry machines, was manganese steel. Bottom pivots with manganese steel caps on both the shafts and the heads soon became a standard solution in Dutch and other lock gates. This solution proved, however, not to be as wear resistant as it was supposed to be. After some years of operation, manganese steel caps began to show a very nasty form of wear, called popularly “thread” forming (Fig. 80). The course of the wear process was also quite unfavorable: It usually lasted a few years before it initiated; but once it started, it seemed to accelerate – so that there was often no time for waiting with the repair till the scheduled gate maintenance works[1)].

[1] These and the following notes are collected by the author from lock operators and maintenance personnel. They represent field experiences and have not been systematically investigated or recorded by means of regular measurements. Nevertheless, they are reliable due to the high conformity between the reports from different regions.

The problems started always on the cylindrical contact surface, as shown in Fig. 80 (a), see also the photograph in Fig. 63 in chapter 5. The typical "thread" pattern in natural size is to see in Fig. 80 (b). From a number of specimens examined by the author, a conclusion can be drawn that the wear course was far from uniform and the grooves had a strong tendency to grow deeper. In the last stadium, if the contact caps had not been replaced by then, the groves appeared also on the spherical top surface. It lasted not long then before one of the caps – usually the pivot cap – fell into pieces, see Fig. 80 (c), which made further gate operation impossible.

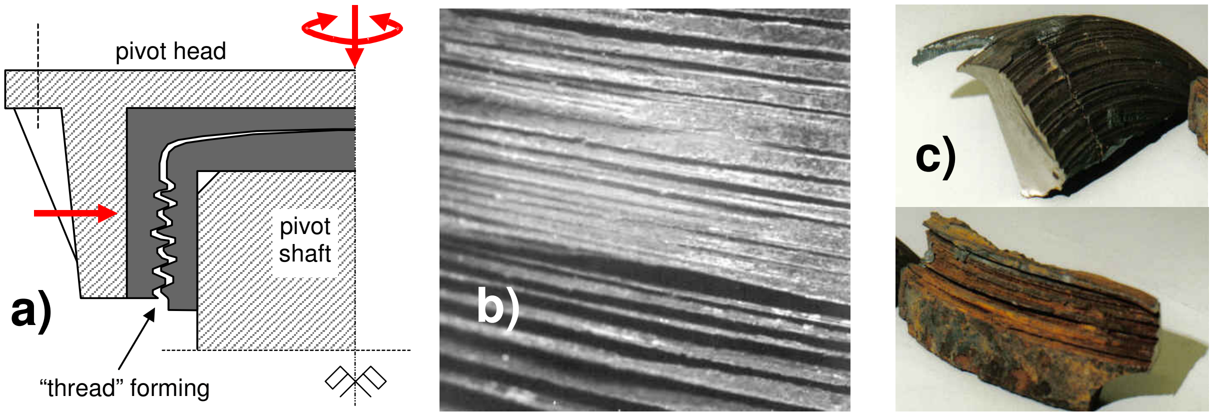


Fig. 80. "Thread" forming on a mitre gate bottom pivot:
a) location and loads,
b) "thread" section in natural scale.
c) grooves on a disintegrated cap.

The process described here is not quite new in contact mechanics. Its course and characteristics are similar to the phenomenon called "galling". This phenomenon appears e.g. on heavily loaded, not lubricated, rotating shafts in lugs or bushes of the same material. It has particularly well been studied in some fields of industry, like metal cutting, bar drawing and deepdrawing [92]. Additional factors in the discussed case are a very slow motion velocity (stimulating stick-slip) and a strain-hardening behavior of manganese steel. Some details of this will still be discussed in the following sections.

Other unfavorable property of this process was that many gates (not all) showed a sort of "climbing" behavior. In particular, the heavily loaded gates in the Meuse and in some large canals had a tendency to gradually creep up. This process could last weeks or months and drive a gate leaf some 20 ÷ 50 mm up. It was followed by a sudden fall, perceptible as a dull rumble by the lock personnel. Obviously, it was not only unpleasant for people (lock operators and vessel crews) but also harmful for drive installations, the control systems etc. The nature of this phenomenon was a mystery for maintenance crews, as the gates in question were quite heavy (40 to 60 tones a leaf), had no buoyancy tanks, so that there seemed to be no physical reason for driving them up.

The authors study on the gate "climbing" phenomenon started from inventorying it and seeking relations with gate structural systems and loads. This resulted in the following observations:

- All gates suffering from the "climbing" phenomenon were of the so-called "free hinged" type, i.e. type (b) or (c) from Fig. 4 in chapter 2 – working as discussed in section 3.1. There was no report of "climbing" (also not upon author's inquiry) on gates of the "fixed hinged" type from Fig. 4 (a).
- The "climbing" appeared only in gates controlling relatively constant, medium till high (3 ÷ 12 m) water heads. This situation is typical for canalized rivers in the Netherlands.
- The phenomenon appeared primarily in gates of intensively navigated locks, i.e. with an average number of lockings a day larger than about 20.
- No "climbing" was recorded in a gate having its retaining plate on the downstream side. The retaining plate was always on the upstream side in the recorded cases.
- In all cases of gate "climbing" there was also a record of the "thread" forming on pivots.

- Further, no relation could be established between the degree of “thread” forming and the gate “climbing”. The latter could appear by deep and shallow groves alike.

These relations could not be statistically proved because no measurements of “climbing” frequencies, heights etc. had been held. Moreover, the population of observations was small and not free of subjectivities, as some lock operators were more concerned about the problem than the other. Nonetheless, they indicated the direction of further investigation. In particular, the relation with the retaining wall position was remarkable.

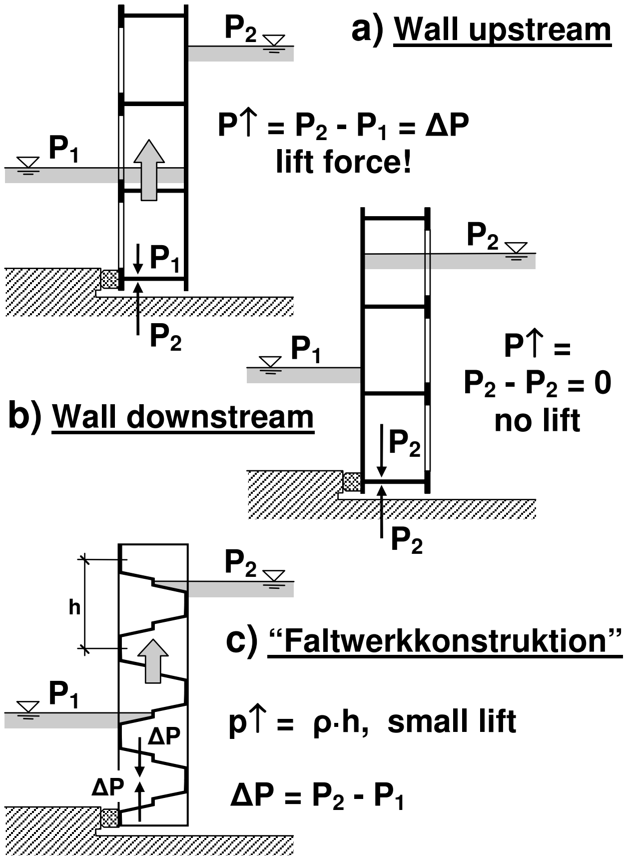


Fig. 81. Retaining plate positions in a mitre gate

In Fig. 81, some typical arrangements of the retaining plate position are presented [2]. The upstream position (a) was the most frequently used in the Netherlands before the author’s investigation, but the downstream position (b) was also not unusual. The third arrangement (c) represents a German technology [70], [93] using large cold-formed sections and aimed primarily at saving welding costs. It has not yet been used in the Netherlands.

Note that the gate in case (a) receives lift force by every closure. This force originates from the water pressure difference below and above the bottom girder. A simple calculation proves that the size of this force is comparable to the gate own weight. If this system had, e.g., been chosen for the Lith Lock gates (leaf length 10.5 m, water head 5.0 m, gate thickness as in Fig. 26), it would give:

$$\Delta P = 9.81\cdot(0.84+0.15)\cdot 10.5\cdot 5.0 = 510\ kN,$$

which is more than the gate leaf own weight of 450 kN (see table 6 in chapter 3).

This problem does not exist in case (b) that produces no lift force (to neglect pressure difference on the gate sill lining). In case (c) there is a lift force, but of a much smaller size than in case (a).

The process of gate “climbing” will further be discussed in chapter 7. At this moment we shall confine ourselves to concluding that we have found a force capable of driving this process, that might explain the relation between the gate “climbing” and the position of the retaining plate. Whether this force actually drives the phenomenon, is still a question as there are also arguments against such a hypothesis. One of them is that the gate water head growth during locking should lead to contact release on pivot cylindrical surface. All gates suffering from the “climbing” were, after all, of the “free hinged” type.

6.2. Purpose and scope of investigations

The contact wear problems described in section 6.1 can (and should) be approached on different contact levels, as discussed in section 3.2, namely:

a) system level;
b) component level;
c) segment level;
d) asperity level.

To leave no doubt: It is not a matter of choosing one of the four ("or-or approach") but of following all of them ("and-and approach"). This should not withhold the engineer from "tuning" his/her approach to the needs. E.g., when the problem concerns a new design, we shall usually be free to approach it at the system level. When, on the contrary, existing structures are involved, we might have to accept their systems the way they are, and seek solutions at the lower levels.

The first mentioned strategy will be discussed in the next chapter. The second was, in fact, the case by the author's early involvement in the problem of gate hinge wear. There were numerous reports of excessive "thread" shaped wear, including or not the gate "climbing" phenomenon. For obvious reasons, changing existing gate systems was not a welcome solution. Moreover, geometrical relations within the existing structures drew limits to component modification possibilities. The customers' preference was a relatively small, local modification, easy to realize during maintenance service and within the geometry of the existing structure. This determined the direction of investigations to large extend. The purpose was – in short – to find contact materials performing better than the manganese steel, under the same loads and (as far as possible) within the same geometrical conditions.

The investigations comprised – in general – the following steps:

1) Problem inventory (globally discussed in section 6.1);
2) Exploration of market, literature, design practice in related fields etc.;
3) Selection of materials and material combinations for further investigations;
4) Laboratory research and tests of the selected material combinations;
5) Analysis of results, conclusions and recommendations.

As there was little (in later stage none) financing available for the investigations as such, the research work was mostly performed within a number of large construction projects, in which the gates and related structures fell under the author's supervision. Those projects profited directly from the investigation results. The most important of those projects were the following:

- Construction of the Second Lock in Lith on the Meuse;
- Reconstruction of the Orange Locks in Amsterdam;
- Construction of the "Naviduct" (lock on an aqueduct) in Enkhuizen;
- Middle gate of Lock III in the Wilhelmina Canal in Tilburg.

Due to the character of this financing, the investigations were carried on in a number of series, starting in 1995 and ending in 2000. The laboratory part (step 4) was each time performed in the Mechanical Research and Failure Analysis Laboratory, Schielab BV in Breda, under the author's supervision. The detailed research and test results are recorded in four reports, [49]. In general, the laboratory investigations covered the following research and tests of the selected material combinations:

- Visual inspection prior to tests, including microscope recording of material structure;
- Determination of basic properties (e.g. material composition, density, surface condition);
- For metals: Hardness measurement before and after the tests on both surface and crystal level, using the Vicker's pyramid indenters of, respectively, 50 and 2 N (micro-hardness).
- Preparation of specimens for wear tests; and performing the tests under the conditions which simulate hydraulic gate service (dry and wet), see section 6.3.
- Continuous measurements of friction coefficients, warmth generation, stick-slip behavior and other significant parameters during the wear tests.

- Determination of the material specific wear factors during and after the tests, based on the specimen weight measurements.
- Microscope recording of the material structure, surface condition etc. after the tests.
- Processing and presentation of test results in four reports [49].

Fig. 82 presents some equipment used during the tests. The micro-hardness measurements were conducted using a microscope controlled Vicker's 2 N pyramid indenter, as shown in the photograph (a). It enabled very precise, local hardness measurements, on the level of the material crystalline structure. This was particularly desired in order to assess the significance of alloy (especially manganese steel) strain-hardening behavior for the wear process.

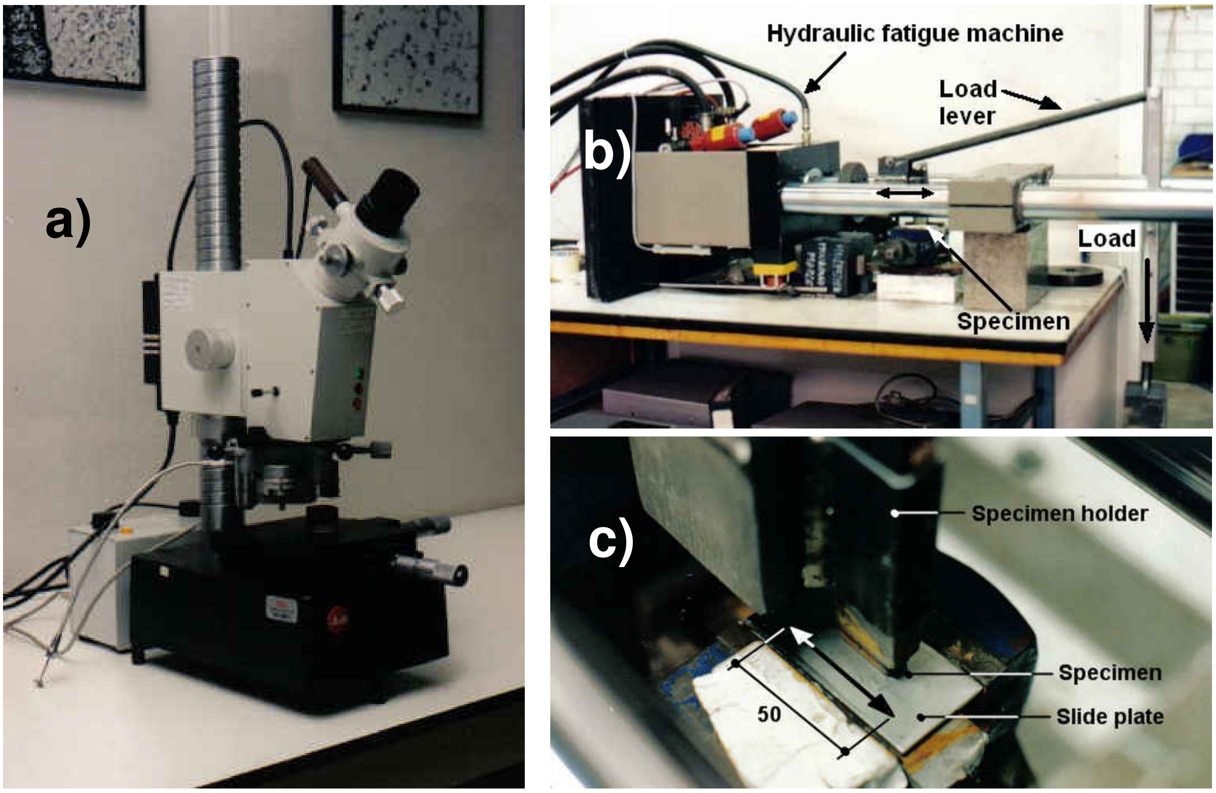


Fig. 82. Some research and testing equipment used during investigations:
a) Vicker's micro-hardness indenter, with microscope control;
b) Fatigue test machine adapted for wear tests;
c) Detail of wear test station in the machine from photograph (b).

The wear tests were carried on using a fatigue machine with a load lever and wear station especially designed for these tests, see photographs (b) and (c). The load lever (see photograph (b)) was a simple device enabling the application of any desired contact compression during testing. The parameters of motion were chosen in such a way that a great degree of similarity to actual mitre gate pivot conditions was maintained. In particular, the contact materials were set in a uniform, oscillatory directed motion. This was, in fact, quite new at that time, as all other comparable tests were carried – as far as known – under the single-sided motion conditions, e.g. [80], [94]. The oscillating direction of contact motion was in this case an essential requirement in order to preserve the representative character of the tests.

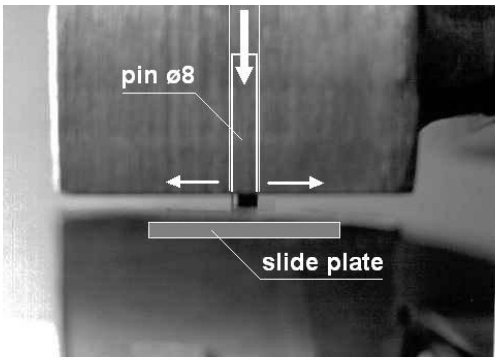
The tested materials included, in the first series, a number of metal-metal combinations. In the following series, the synthetic contact materials (plastics) were in majority – monolithic and fiber reinforced alike. The full list of tested materials, their basic technical specifications etc. will be presented further in this chapter.

6.3. Model description and research parameters

As mentioned, the intention of the investigations was to simulate the actual conditions of a mitre gate hinge as close as possible. Therefore, the investigations do not pretend to give an absolute performance evaluation of the tested contact materials. They represent such an evaluation for one particular application only. Possible similarities with other applications are for readers' assessment.

An effort has been made to test all the selected materials in exactly the same way. This appeared to be feasible in regard of test parameters (loads, motion velocities, numbers and amplitudes etc. of motion cycles), but not in regard of specimen sizes. For a number of reasons (e.g. big differences between the elasticity modulus ***E***), different specimen forms were chosen for metals and synthetic materials (plastics) or composites, that is (Fig. 83):

- Metals: pin of a circular section 8 mm dia.,
- Plastics: plate 20 x 10 mm glued to a steel connecting piece.



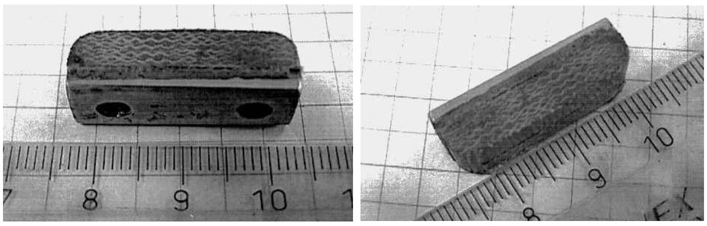


Fig. 83. Specimens of tested materials:
Left: metal pin in a holder during testing;
Above: composite glued to a steel connector.

One of the problems to solve was how to simulate the extremely low slide velocities (about 2÷4 mm/s) that appear in actual gate hinges. Proper simulation of these velocities was important for two reasons:

- In situations with friction, slide velocity has direct impact on warmth generation. Warmth, in turn, can bring significant change to mechanical properties of the materials in question, in particular the synthetic materials. In gate hinges, the low slide velocities usually prevent that effect.
- There is often a relation between slide velocities and stick-slip behavior which, in turn, increases both friction and wear. Low slide velocities generate usually more stick-slip, reducing the service life of the device.

Obtaining such low slide velocities was not a technical problem but a practical one. These velocities would require very long test periods. After completing some estimations and primary tests, the compromise was found comprising the following conditions:

- The slide distance was set at 50 mm, as indicated in Fig 82 (c), which gave a full oscillation slide length (there and back) of 100 mm.
- The motion oscillation frequency of was set at 0.2 Hz. By the periodic slide length as above, the motion velocity is then 20 mm/s, i.e. about 5÷10 times faster than in actual gate operation.
- Despite the increase of slide velocity, a single test of each specimen (with interim examinations) lasted some 3 days when tested by one shift a day; and 1½ day when tested by two shifts a day. The investigations were, therefore, very time-consuming.
- In all tests with synthetic materials, specimen temperature was constantly controlled by a thermocouple at a close distance (about a millimeter) to the contact plane[1)].

[1] In general – in dry as well as in wet conditions – no significant temperature increase was observed during the testing. The temperatures stabilized below 40°C. This can probably be explained by a local character of friction and high cooling capacity of the surrounding. In a few cases, additional cooling by a fan was applied.

- The test contact load was 8 N/mm^2, uniform for all materials. Additionally, most specimens were also tested under the contact load of 16 N/mm^2. Due to the different contact surface, the compressive force on synthetic specimens was higher than on metal specimens.
- The test duration was set at 15 000 load oscillations for each specimen, which represents about 4 years of gate operation with an average intensity of 10÷12 closings and openings a day. Under field conditions, this is about the time when the wear clearly begins to manifest itself.
- The testing took place in "dry" as well as in "wet" conditions. In the second case, a raised edge was built around the slide plate from Fig. 82 (c) in order to hold water.

The material selection for the tests was preceded by a global estimation of their fitness for application in hydraulic gate hinges. Since the tests were to be time-consuming, there was every reason to include only the most promising material combinations in the test program. The preferences which have been followed in this selection are explained in the following section of this thesis. Beside them, the author made contacts with specialists in other fields of technology, where he expected similar problems. As mentioned in section 6.1, this method had also been followed in the early 1950's. It resulted in the selection of manganese steel contact caps for gate bottom pivots, due to the positive experiences with this material in mining and quarry machines. The question was, how to avoid the same mistake now.

Learning from mistakes is one of the most important and at the same time least respected principles in engineering. Perhaps because it usually sounds easier than it really is. In order to answer the question stated above, one should go back to the 1950's and ask – with the present knowledge – what the engineers of then had forgotten or failed to consider. The answer can, in short, be as follows:

- The selection of manganese steel was correct at first sight. This material is indeed wear resistant. However, wear resistance is not an absolute property but it depends on the contact character. This character is quite different in mining and quarry machines than in gate hinges.
- There was no ground for making both contacting items of the same material. This is not the case in mining or quarry machines either. In contrary, it is known that such arrangements produce the surface damage known as 'fretting' [33], [95].
- The phenomenon of strain hardening was insufficiently considered (perhaps also little known at that time). Otherwise the "thread"-shaped wear could have been foreseen.

Having learned this, we shall now try to avoid a similar mistake by seeking examples in other fields of technology. A way to do it is, e.g., to seek examples where the wear is under control and – at the same time – the wear mechanisms resemble that of a hydraulic gate hinge. A brainstorm session would probably be a good approach here. In this particular case, it had not been held but the following examples came into mind:

- bearings of heavy cranes operating at a limited rotation angle;
- rudder bearings of large ships;
- gate bearings of floating or other docks in shipyards;
- bearings of movable (e.g. bascule or draw) bridges;
- bearings of some devices in the heavy industry.

The most interesting from this list proved to be bearings of large ship rudders. Other devices offered better maintenance accessibility (cranes), operated at significantly lower frequencies (dock gates) or under different surrounding conditions (industry). The scope of this thesis does not allow for a comprehensive presentation of ship rudder bearings, but one recent design will be presented, because this stage of horizontal exploration (author's term) is important in the presented analysis method[1)]. This design is the rudder of ms. JOWI, an inland container ship (134 m long, 17 m wide, 4 600 t DWT) [97], shown in Fig. 84. The rudder bearings operate since 1998 with no significant wear[2)].

[1] In author's opinion, many research institutions and individuals tend to skip this "horizontal exploration", and enter the stage of analytical solution too soon. This is not good for the research quality. It also produces a *Tower of Babel* situation [96], in which we all talk without listening to (at the end even without understanding) each other. In this section, the attention is drawn to learning from each other and from each other's mistakes.

[2] All Information about these rudder bearings is received from Mr. Aad Kok, Maprom Engineering, Dordrecht.

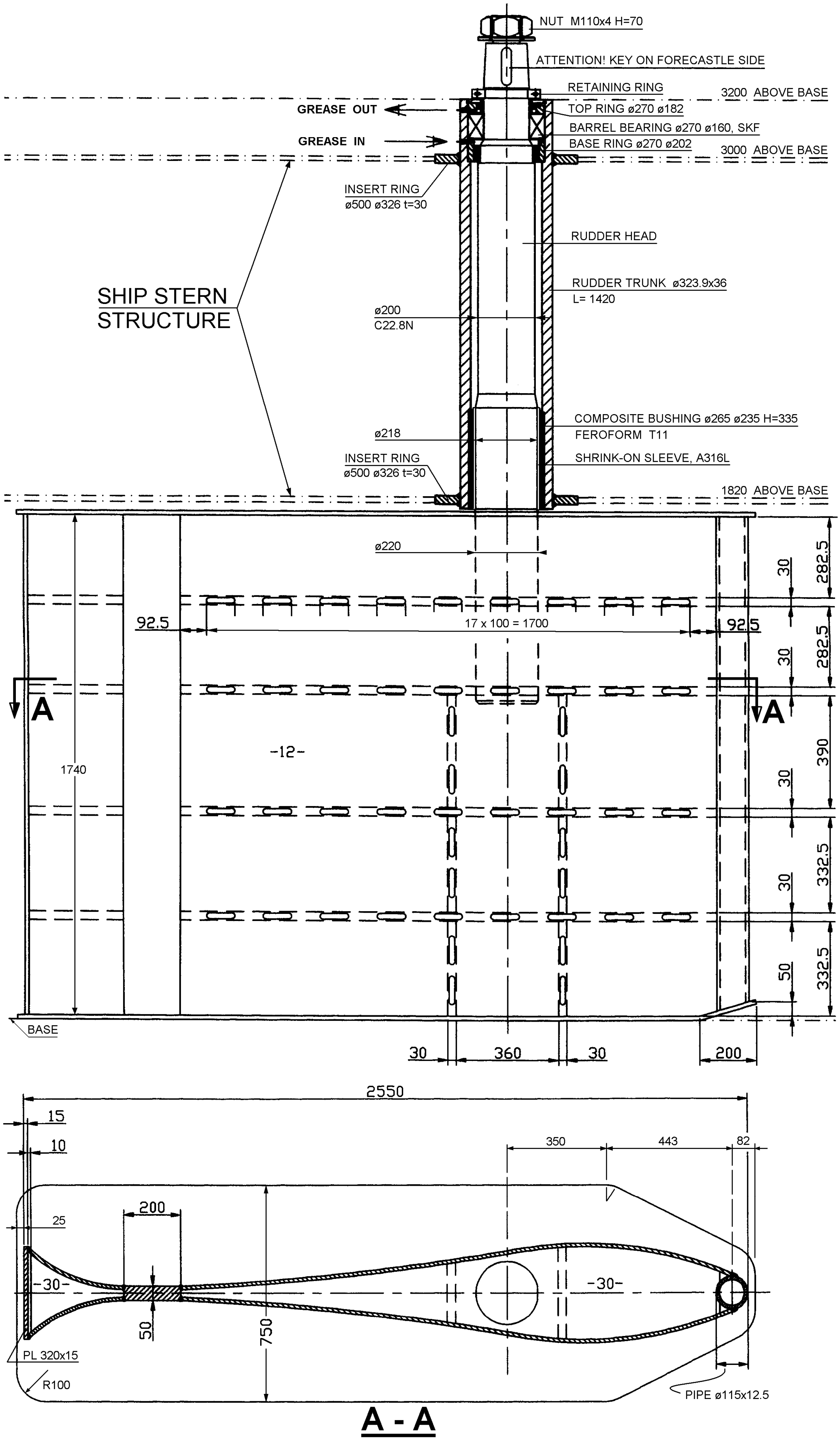


Fig. 84. Ms. JOWI – rudder and its bearings (courtesy Maprom Engineering, Dordrecht)

When taking a closer view at the development of rudder bearings in shipbuilding, one can observe that also this process is, in many respects, comparable to what hydraulic gate bearings have gone through. For a long time, exotic timber was used in these bearings – with jacaranda wood (Brazilian rose wood) as the most favored sort. The industrial revolution introduced different kinds of greased metal-to-metal bearings; and the modern times brought high quality synthetic materials and composites. As the maintenance possibilities of rudder bearings (especially at high seas) and hydraulic gate bearings are about equally limited, the engineers from both fields can learn much from each other[1]. This applies in particular to the countries where shipbuilding still has a strong economical position, e.g. Japan, Korea and China in Asia, Poland in Europe.

The rudder from Fig. 84 represents the type where the vertical reaction (mainly rudder own weight) is carried by the top hinge – comparable to some extend with gate type (e) from Fig. 4 in chapter 2. On closer investigation, one will find more similarities between the rudder types and the mitre (or single-leaf) gate types. The regulations of the Lloyd's Register of Shipping [98] distinguish, e.g., three basic types of rudders with respect to their bearings, as shown below (Fig. 85). The reader will easily find a corresponding gate type in Fig. 4 for each of these rudders.

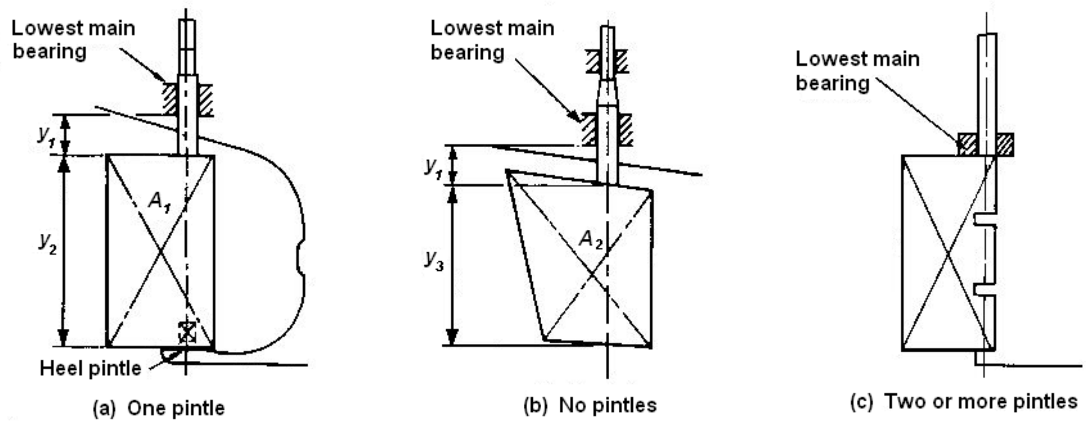


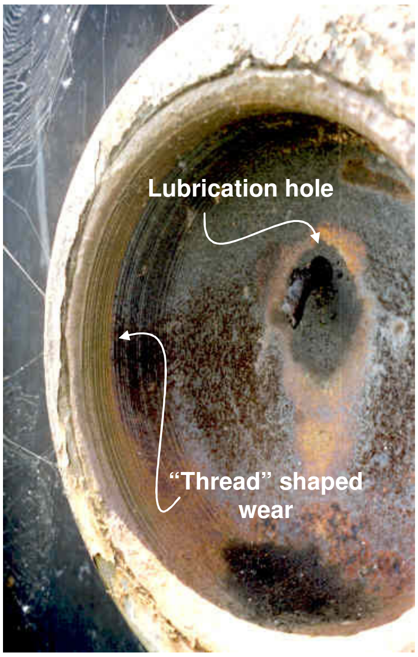
Fig. 85. Types of rudder bearing arrangements according to the Lloyd's Register of Shipping [98]

The Lloyd's Register of Shipping contains also a number of simple formulas, limits for maximum contact pressure in rudder bearings etc., which might be used as estimations in primary gate hinge design. In a similar way also other technical fields can be explored, which has in fact been done prior to starting the test program. This will not be discussed any more for space reasons. As shown further in this chapter, the presented rudder design (Fig. 84) employs a composite material Feroform® (in the U.S. known as Tenmat®), that has been included into the test program as well – although of another grade number. We see that exploring other, related fields of engineering can be an important support in contact design. In a similar way, other materials and material combinations have been selected for the tests. A full list of these combinations is presented in Table 21, further in this chapter. Some details about the material origin, structure and composition are given in section 6.5.3.

[1] Perhaps not coincidentally, the world largest mitre gates (width 42.7 m) are still the gates of the Portbury Lock in Bristol, originally designed by Isambard Kingdom Brunel – the same man who designed the great steamers of the XIX century like *ss. Great Britain* and *ss. Great Western*. In fact, those gates enabled Brunel launching his steamers in the docks of Bristol [99].

6.4. Why to refrain from lubrication, general material preferences

With the exception of water, no other means of lubrication were tested. The ground for such approach is that there is a clear tendency to refrain from lubrication for environmental reasons on one hand, and for accessibility reasons on the other hand. Lubrication proves also to be less effective in hydraulic gates than in other mechanical devices. This is primarily caused by a limited significance of dynamic lubrication (so-called "squeeze film" effect [34]) due to extremely low motion velocities. Another reason is very high contact loads. Nevertheless, lubrication is still used in gate hinges, especially in older structures. The reader interested in this subject is encouraged to consult specialized literature, e.g. [78], [100], [101], as the discussion of it falls beyond the scope of this thesis.



The photograph in Fig. 84 is a good example of lubrication ineffectiveness in a conventional gate pivot bearing. It shows a pivot head cap of manganese steel in a reserve gate of the Lock Born on the Meuse (Dutch province of Limburg). This cap has operated about 5 years. It can be observed that the lubrication could not prevent the cap wear. In this particular example, the lubrication has been applied in a little professional way – with no sealing or lubricant ducts to the contact zone. Moreover, no measures have been taken to prevent environmental pollution. In extenuation, one must agree that this detail is very difficult to seal, due to the large hinge clearances in this so-called 'free-hinged' gate (type (b) in Fig. 4). Lubricating this detail was probably the lock owner's act of despair in the hope that it would decrease the wear problem.

Fig. 84. Ineffective lubrication of a pivot contact zone in gates of the Born Lock on the Meuse, Limburg

Professionally applied or not, lubrication remains little effective in hydraulic gate hinges. This applies also to so-called maintenance-free bearings with thin, low friction running layers of, e.g., PTFE. That can be seen in the following example (Fig. 85). It represents a ball bearing of a drive cylinder hooke-up hinge to the gates of the Houtrib Locks in Lelystad. The bearing location is to see in photograph (a) – along with the cylinder arm jaw end. Photograph (b) shows an entirely new bearing; photograph (c) presents a bearing after 3÷5 years of service.

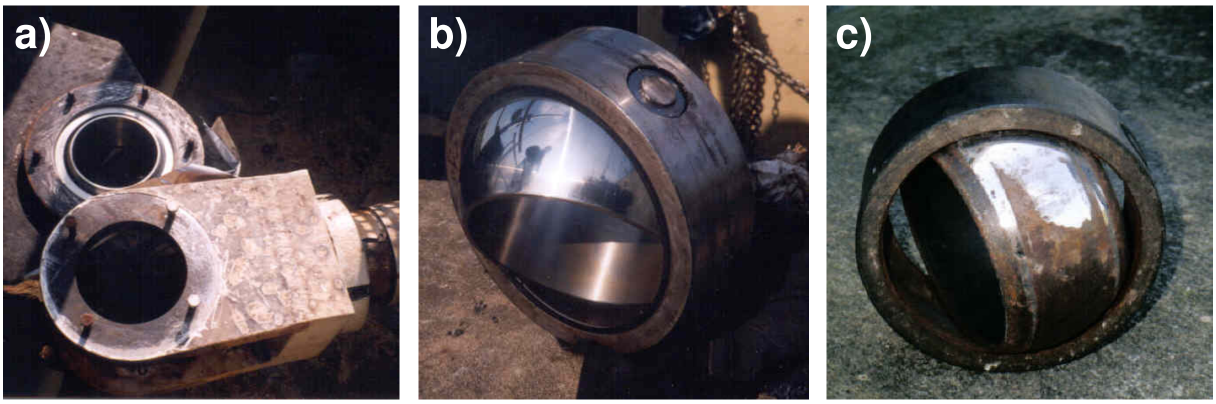


Fig. 85. Ineffective lubrication of a cylinder arm ball hinge in gates of the Houtrib Locks in Lelystad **a)** bearing location; **b)** new bearing; **c)** bearing after 3÷5 years of service

The bearing shaft has a diameter of Φ160 mm. The contact surfaces of the bearing are: hard chromium layer on the ball; and PTFE composite in the ring. Although the contact loads are much lower than on gate support hinges, we see that the chromium layer wears up within only a few years of service[1)]. The PTFE layer is, obviously, also worn up by then. Also here, the main reason of wear is – supposedly – the very low slide velocity. Only in this case it probably generates stick-slip behavior instead of limiting the effectiveness of dynamic lubrication, as in the first example.

The presented examples are two of many to support some general preferences in the engineering of hydraulic gate contacts. These preferences can also be traced in the selection of material combinations for wear tests discussed in this chapter. The most important of these preferences are as follows:

- Lubrication should – if possible – be avoided. The reasons for that are its generally small effectiveness and the resulting environmental pollution.
- Utmost care is advised when using thin contact layer technologies. This applies to running layers such as PTFE, as well as to hard counter surface layers such as chromium.
- Recommended are robust arrangements applying thick contact material layers and not vulnerable to pollution, moisture, dimensional, thermal or other distortions, etc. – even at the cost of more friction or less geometrical precision.
- If serially produced bearings are used, the wear figures from manufacturer's catalogue are usually too optimistic. This does not necessarily mean that they are colored. The gate operation conditions are usually harder than in other application fields of those bearings.
- It is – in general – better to take account of some contact wear in hydraulic gate design than to aim at eliminating this wear entirely. There is little reason for a perfect precision of gate motion, but there is a reason for its long, maintenance free operation.

These preferences should, obviously, be seen as reflecting the "state of the art" in the time in which this thesis has been written, rather than as undisputable recommendations. They should never refrain the engineer from following technological developments and trying to take profit of them in hydraulic gate design. It should also not be forgotten that gate operation conditions can substantially differ per project. In lock gates of wide, deep and intensively navigated Dutch canals, the wear problem will have quite different dimension than in gates of tourist canals, e.g., in Scotland or in Polish Masuria. An example is a top hinge of the gate to a prestigious Scottish hydraulic structure – the Falkirk Wheel, Fig. 86. The contact in that hinge, pictured even in a logo of the canal authority, takes place between steel and timber! That arrangement, totally unacceptable in the Netherlands, can still comply with the "fitness for purpose" principle in case of very low intensity of locking.

Fig. 86. Outport of the Falkirk Wheel in Scotland (left) and a top hinge of the gate to it (right)

---

[1] Field experiences quoted in this section are collected by the author from regional Water Management Authorities in Limburg and the IJsselmeer Area (the Netherlands) and in Scotland.

6.5. Research results, summary

6.5.1. Specific wear factors

For space reasons, we skip in this section the measurements of lower significance (density, chemical analyses etc.), and concentrate on wear related properties. The first of these properties is the so-called specific wear factor ***k*** [mm^2/N], which is defined by the formula (6.1) as follows:

$$k = \frac{S}{L \cdot p} \quad \text{,where:} \qquad 6.1$$

L = totally covered slide distance [mm] in a considered period, e.g. for a life cycle of 16 years: 16 years · 365 days · 20 lockings · swing angle 71° · π/180° · radius 120 mm = 1.7·10^7 mm;
p = surface pressure [N/mm^2], mean over the specimen contact surface;
S = wear thickness [mm], mean over the specimen contact surface.

The following specific wear factors ***k*** have been found for the tested material combinations (Table 21):

Table 21. Wear factor ***k*** for gate hinge shafts and bushings

Pivot (top hinge) contact material			**Wear factor *k* [mm^2/N]**	
Test	**Slide plate: pivot (ring)**	**Specimen: head (shaft)**	**Slide plate: pivot (ring)**	**Specimen: head (shaft)**
A	Manganese steel G-X120 Mn12	Manganese steel G-X120 Mn12	$2.1 \cdot 10^{-9}$	$10.3 \cdot 10^{-9}$
B	Ditto	Ditto with hardened surface	$2.1 \cdot 10^{-9}$	$9.6 \cdot 10^{-9}$
C	Ditto	Refined steel 34 Cr Ni Mo6	$1.5 \cdot 10^{-9}$	$2.4 \cdot 10^{-9}$
D	Refined steel 34 Cr Ni Mo6	Manganese steel G-X120 Mn12	$1.8 \cdot 10^{-9}$	$2.0 \cdot 10^{-9}$
E	Ditto	Refined steel 34 Cr Ni Mo6	$4.2 \cdot 10^{-9}$	$3.8 \cdot 10^{-9}$
F	Ditto	Case hardening steel 20 Mn Cr5	$1.9 \cdot 10^{-9}$	$6.2 \cdot 10^{-9}$
G	Aluminum-bronze, bronze etc., greased	Refined steel 34 Cr Ni Mo6	$\sim 12.0 \cdot 10^{-9}$	$\sim 1.5 \cdot 10^{-9}$
$H_{0,8}$	Stainless steel 316L, roughness R_a = 0,8 µm	Feroform T814, Fibre reinforced composite	$0.2 \cdot 10^{-9}$	$3.5 \cdot 10^{-9}$
$H_{1,6}$	Ditto but roughness R_a = 1,6 µm	Feroform T814, Fibre reinforced composite	$0.3 \cdot 10^{-9}$	$5.0 \cdot 10^{-9}$
$I_{0,8}$	Stainless steel 316L, roughness R_a = 0,8 µm	Polyethylene UHMPE	$0.1 \cdot 10^{-9}$	$0.5 \cdot 10^{-9}$
$I_{1,6}$	Ditto but roughness R_a = 1,6 µm	Polyethylene UHMPE	$0.1 \cdot 10^{-9}$	$25.0 \cdot 10^{-9}$
$J_{0,8}$	Stainless steel 316L, roughness R_a = 0,8 µm	Railko RG2, fibre-reinf. phenolic resin	$0.1 \cdot 10^{-9}$	$4.0 \cdot 10^{-9}$
$J_{1,6}$	Ditto but roughness R_a = 1,6 µm	Railko RG2, fibre-reinf. phenolic resin	$0.1 \cdot 10^{-9}$	$25.0 \cdot 10^{-9}$
$K_{0,8}$	Stainless steel 316L, roughness R_a = 0,8 µm	Thordon SXL, high polymer composite	$0.1 \cdot 10^{-9}$	$0.7 \cdot 10^{-9}$
$K_{1,6}$	Ditto but roughness R_a = 1,6 µm	Thordon SXL, high polymer composite	$0.1 \cdot 10^{-9}$	$5.4 \cdot 10^{-9}$
L	Chromium plated steel, roughness R_a < 0,8 µm	Polyamide with PTFE and glass fiber (dry!)	$\sim 0.3 \cdot 10^{-9}$	$\sim 4.0 \cdot 10^{-9}$

Notes to Table 21:

1. The testing was focused on gate bottom pivots. Column “pivot” represents the slide plate material; column “head” represents the specimen material. The results are, however, also usable for the top hinge situation, which is referred to as “ring” and “shaft”.
2. Chemical and crystalline structure analyses were performed for all tested metal alloys, prior to the testing. All tested alloy constitutions were in accordance with appropriate standards.
3. If not stated otherwise, the specimens and slide plates initial surface roughness was Ra ≤ 0.8 µm. In case of synthetic specimens, the slide plates were machined to receive the desired roughness.
4. Tests G and L were not carried out. As the wear behavior of bronze and polyamide is quite known, the ***k*** factors have been estimated from the published data, respectively [102] and [94]. The impact of alternating slide direction was roughly estimated by increasing the ***k*** factors twice.
5. Most tests were performed at two levels of contact pressure ***p***: 8 and 16 N/mm^2. A fair linear relation between ***p*** and the wear ***S*** was found, confirming the correctness of formula (6.1). In case of some differences, mean values are reported in Table 21.
6. The results in Table 21 are derived from “dry” tests. With the exception of polyamide and Railko, no significant differences were encountered between the “dry” and “wet” tests. The “wet” tests of polyamide result in about 10 times higher wear factors [94]. The “wet” test of Railko resulted in a twice higher wear factor. The latter is taken into account by reporting a mean value in Table 21. The first is not taken into account; applying polyamide in “wet” operation is an error.
7. Although the mean values showed little difference, the dispersion of “wet” test results was considerably higher than in the “dry” tests. This applies in particular to composite materials. The reason was moisture absorption, difficult to eliminate in specimen (interim) weight measurements.
8. Stick-slip behavior of various intensity was encountered in practically all metal-to-metal tests. While testing synthetic materials (tests **H ÷ L** in Table 21), stick-slip was only recorded in tests $\mathbf{J_{0.8}}$ and $\mathbf{J_{1.6}}$ (during whole tests); and $\mathbf{H_{1.6}}$ (by temporary temperature increase). $\mathbf{J_{0.8}}$ and $\mathbf{J_{1.6}}$ were also the only tests where significant temperature increase (above 40°C) was measured.

The specimen wear was measured not only at the end, but also at regular intervals during the test. The following general regularity could be observed:

- All metal-to-metal tests showed little differences between the initial, the middle and the late wear measurements. Also, no regularity could be traced in the observed small differences.
- All tests of synthetic materials showed, on the contrary, strong wear correlation with the moment of measurement. One could clearly distinguish an “initial phase” of higher wear and an “operation phase” of lower wear.

In Fig. 87, cumulative wear graphs are presented for the considered synthetic materials, on slide plates with the $\boldsymbol{R_a}$ roughness of respectively 0.8 and 1.6 µm[1)]. We can distinguish the two phases mentioned above. It has been observed that the mechanism of the initial phase can vary for various materials. E.g. in case of Thordon SXL, the gradual wear decrease resulted from the fact that cavities in the slide plate became filled by particles of the worn material – an effect comparable to self-lubrication. No such effects took place in case of, e.g., Railko RG2. There, the gradual wear decrease resulted entirely from the slide plate “polishing” during the test. The two cases are clearly discernible on the microscope wear track photographs of both slide plates, see Fig. 88. The plates were made of the same material and had, initially, identical surface condition. Of course, intermediate and other wear mechanisms are also possible. Moreover, it has been observed that a slight change of testing conditions (e.g. temperature, specimen fixity) can cause switching from one wear mechanism to another. Correct recognition of potential wear mechanisms is, therefore, very important in contact engineering. In regard of hydraulic gates, we have seen this in some of the cases discussed in chapter 5.

[1] With the exception of polyamide, all graphs are based on numerical values as measured and reported in [49]. The wear graph for polyamide is derived from the final value of ***k*** as reported in [94] (see note 4 on this page) and is, therefore, somewhat hypothetical.

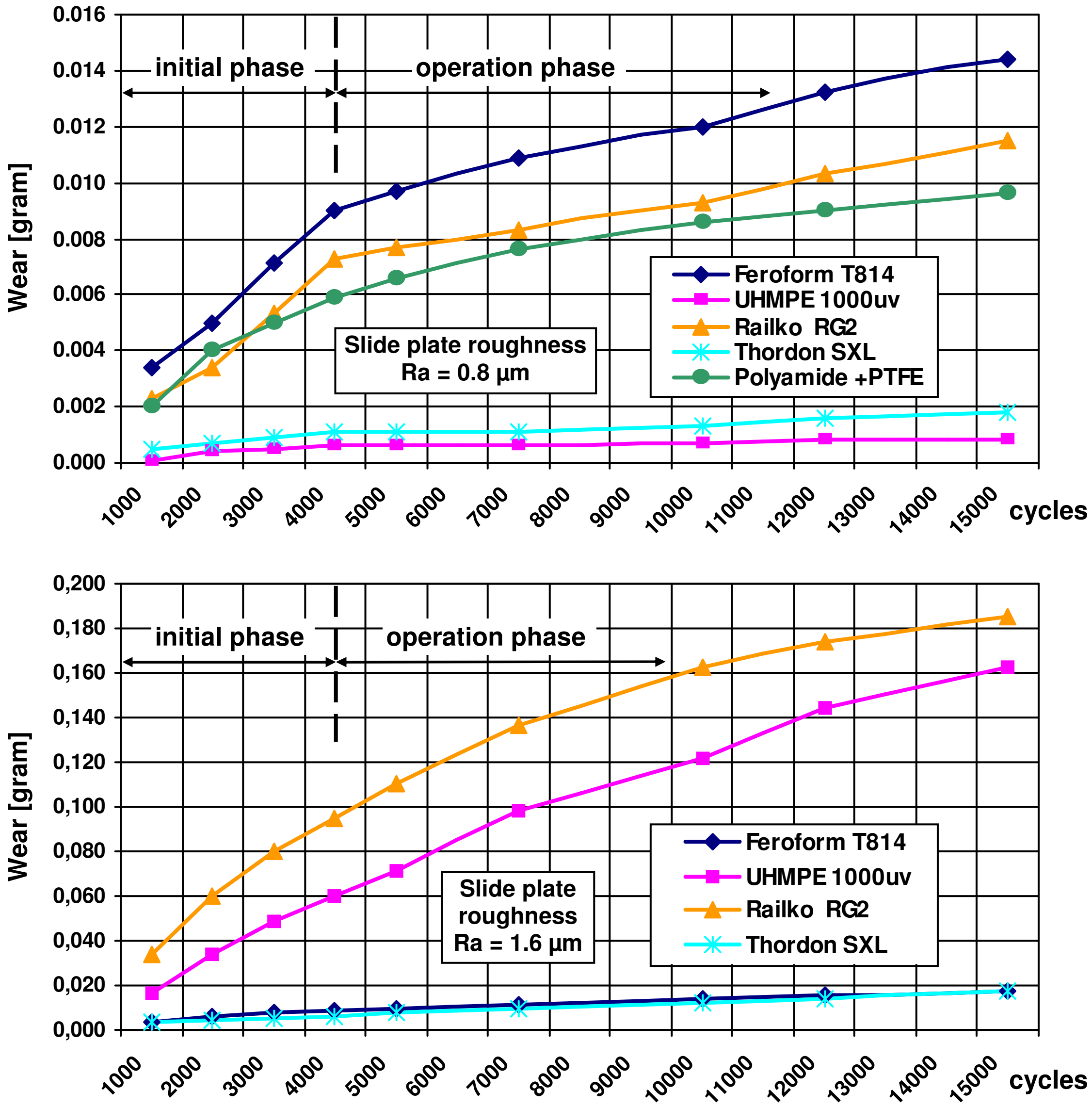


Fig. 87. Cumulative wear of synthetic materials on slide plates of different initial roughness

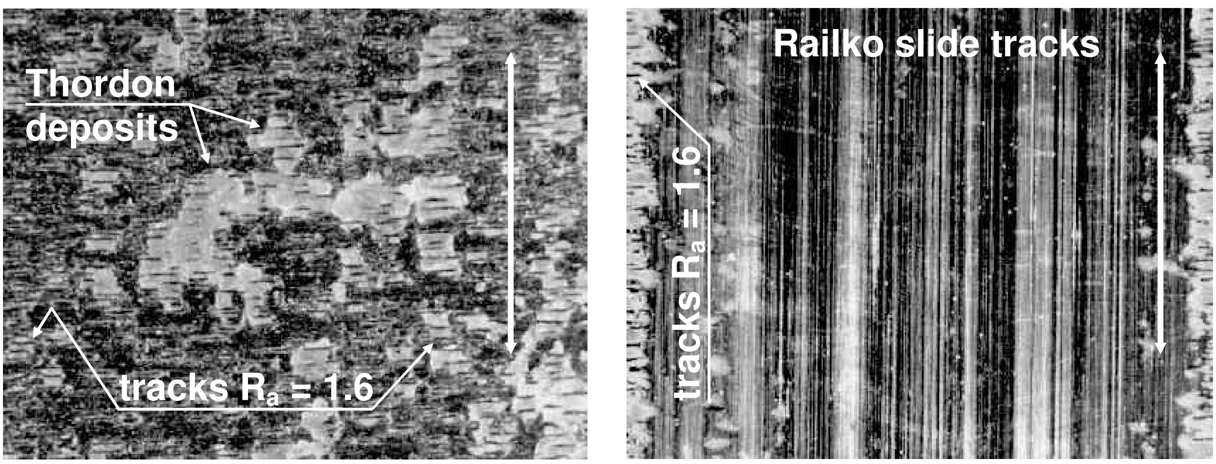


Fig. 88. Tracks on stainless steel slide plates: left Thordon, right Railko (10 x enlarged), [49]

6.5.2. Friction coefficients

Simultaneously with the wear tests, the friction coefficients were measured. Friction as such is not a critical parameter in hydraulic gate design, as it plays a minor role in required drive capacities, resulting hinge reactions etc. Exceptions are gates where sliding instead of rotation is a dominant motion, e.g. some types of rolling and vertical lift gates, sluices etc. Nevertheless, friction is usually strongly correlated to other parameters that are crucial for gate performances and its service life, like e.g. wear, contact heat generation, mechanical properties of contact materials, some forms of fatigue loads etc. Therefore, friction is a very important indicator in gate contact design.

The measurements were carried on continuously, using a traction dynamometer mounted between the machine arm and the specimen holder (Fig. 89, left). The force variation was recorded on graph paper, using an analog graph writing device. An example of this force recording – here in one of the steel-to-steel wear tests – is presented in Fig. 89, right.

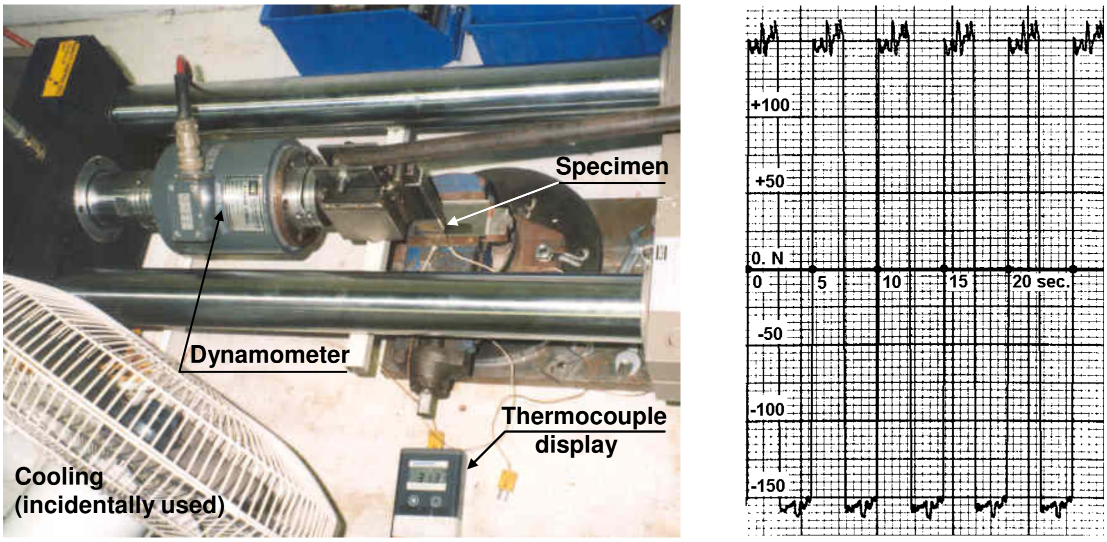
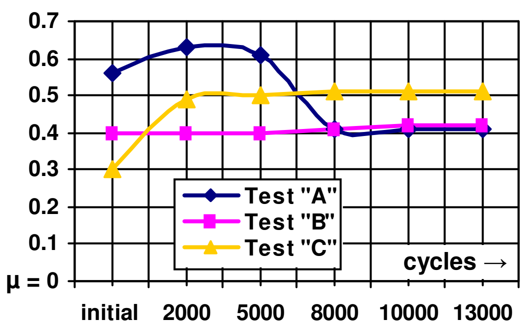


Fig. 89. Wear test with friction measurements: left testing table, right friction force record (example)

The friction coefficient showed, in general, some dispersion within the same tests. This dispersion was higher in all metal-to-metal tests – and lower in the tests of synthetic materials. In was especially high in the first phase (0 ÷ 5000 load cycles). Despite the same initial roughness of all contact surfaces, the friction coefficients varied then between 0.30 ÷ 0.65. Later, they stabilized in the range of 0.40 ÷ 0.50. The differences within this tendency are shown on the graph in Fig. 90 for the first 3 contact material combinations from Table 21.



A. Manganese steel pin
B. Ditto but with hardened surface
C. Refined steel pin

against manganese slide plate.

The most remarkable friction force course was that of test **A**, showing high and increasing values in the first phase, then strongly decreasing and stabilizing at a moderate level. Comparison to test **B** allows a conclusion that the surface strain hardening has taken place in that first phase.

Fig. 90. Global variation of friction coefficient during testing

Although this “spontaneous” strain hardening affects the friction coefficient, it seems to have little effect on the wear, see the values in Table 21. Considering the much higher contact stress in a prototype situation, one may conclude that strain hardening proceeds there very soon, so that it makes no difference whether the material surface is strain pre-hardened or not. Another conclusion is that the relation between friction coefficient and wear is not as strong as one might suppose. We see that the test **C**, which has ended with the highest friction coefficient, shows in Table 21 the wear of only a quarter of that of tests **A** and **B**. It has been known before that the materials of the same composition – which is the case in tests **A** and **B** – are very sensitive to wear, e.g. [34], [95]. Now we see how strong this effect is for manganese steel contact caps in hydraulic gate pivots. Despite the high friction coefficient, it would be a much better choice to change the material of one of these caps into refined steel.

Interesting is also the course of the friction force during a single load cycle. This course showed remarkable differences with respect to both the tested materials and the moment of recording within the test. Fig. 91 illustrates these differences in, respectively, tests A and B as described in the preceding figure. This time, it focuses on the tops of the load cycle graphs. The moments of recording represent in both cases respectively: the initial cycles, 5000 cycles and 13000 cycles. The friction coefficients measured at those moments are reported on the graphs.

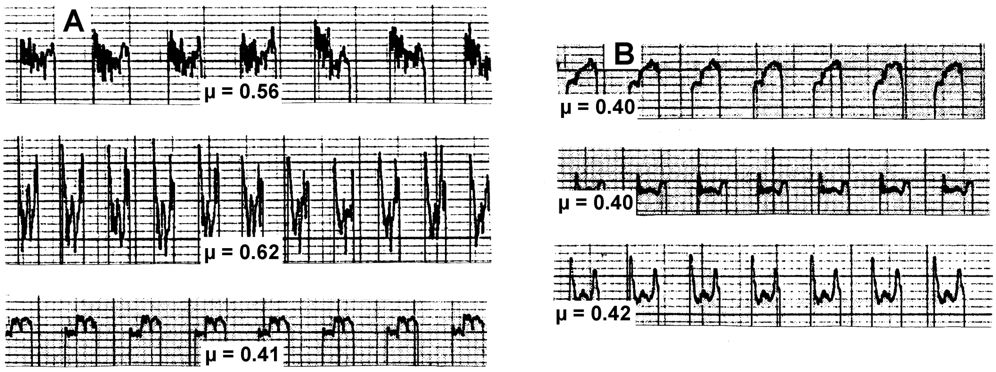


Fig. 91. Variation of friction force in single load cycles during testing

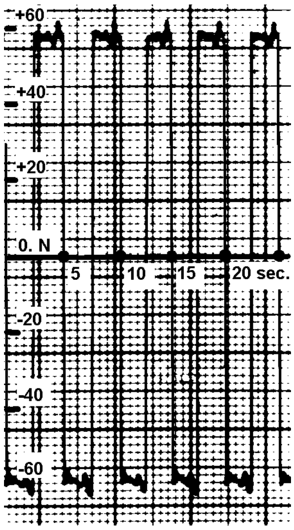
Leaving a detailed explanation of the friction mechanisms involved to a tribologist, we can observe two global regularities. The first is that high friction (e.g. in the first two graphs of test **A**) goes along with high instability of that friction in a single load cycle[1)]. As the reported values of $\boldsymbol{\mu}$ are cycle mean values, we can estimate the extreme deviations from these values as follows:

⇒ <u>Test **A**:</u>	$\mu = 0.56 \pm 0.05$	⇒ <u>Test **B**:</u>	$\mu = 0.40 \pm 0.03$
	$\mu = 0.62 \pm 0.10$		$\mu = 0.40 \pm 0.02$
	$\mu = 0.41 \pm 0.02$		$\mu = 0.42 \pm 0.05$

Other tests, not shown for the space reason, confirm this observation. The reason of this regularity is a stick-slip behavior during each single traction course and (especially) a passage from static to dynamic friction at both ends of each course.

Another observation is that the last graph in test **A** shows a very remarkable similarity to the first graph in test **B**. Knowing that the pin contact surface in test **B** has been strain pre-hardened while the strain hardening of the pin in test **A** took place during testing, we can now issue the following hypothesis: Tribological behavior of metallic contacts has a periodical character, especially traceable in materials of strong strain hardening properties. This means also that the second part of the graphs in Fig. 90 does not, in fact, represent a stabilized situation. If the tests lasted long enough, periodical increases and decreases of friction would probably be found. As mentioned, the friction coefficient is an important indicator in hydraulic gate contacts, which makes this hypothesis quite significant.

[1] In the middle graph of test **A**, the paper roll motion has been slowed down which may be a little confusing.



In the group of non-metallic, synthetic materials, the measured friction coefficients were 2.5 ÷ 5.0 times lower than in the group of metallic contacts. Moreover, the friction courses in single load cycles were (with an exception of tests **J**) quite stable, showing little or no stick-slip effects. Similarly, no considerable differences between static and dynamic friction were observed. The momentary friction at each turn of the machine arm was practically the same as in the middle of a single stroke. An example is the friction record of test $\mathbf{I_{1.6}}$ shown in Fig. 92. For better readability, the vertical scale has been increased 2½ times here in comparison with the graphs of a steel-to-steel test from Fig. 89. Despite that, little variation of the friction force can be observed.

Fig. 92. Friction force record for a synthetic material (test $\mathbf{I_{1.6}}$)

The mean friction coefficients received during testing are put together in Table 22. They may differ from manufacturer's data, various publications or other records. Those differences result from the test method (see sections 6.2 and 6.3), selected to closely simulate the service of hydraulic gates.

Table 22. Friction coefficients $\boldsymbol{\mu}$ measured in the tests as in Table 21

	Pivot (or top hinge) bearing material		**Friction coefficient**
Test	**pivot (ring)**	**head (shaft)**	
A	Manganese steel G-X120 Mn12	Manganese steel G-X120 Mn12	0.506
B	Ditto	Ditto with hardened surface	0.407
C	Ditto	Refined steel 34 Cr Ni Mo6	0.471
D	Refined steel 34 Cr Ni Mo6	Manganese steel G-X120 Mn12	0.516
E	Ditto	Refined steel 34 Cr Ni Mo6	0.533
F	Ditto	Case hardening steel 20 Mn Cr5	0.567
G	Aluminum-bronze, bronze etc. greased	Refined steel 34 Cr Ni Mo6	~ 0.300
$\mathbf{H_{0,8}}$	Stainless steel 316L, $R_a = 0.8$ µm	Composite Feroform T814	0.150
$\mathbf{H_{1,6}}$	Ditto but $R_a = 1.6$ µm	Composite Feroform T814	0.150
$\mathbf{I_{0,8}}$	Stainless steel 316L, $R_a = 0.8$ µm	Polyethylene UHMPE	0.160
$\mathbf{I_{1,6}}$	Ditto but $R_a = 1.6$ µm	Polyethylene UHMPE	0.300
$\mathbf{J_{0,8}}$	Stainless steel 316L, $R_a = 0.8$ µm	Composite Railko RG2	0.550
$\mathbf{J_{1,6}}$	Ditto but $R_a = 1.6$ µm	Composite Railko RG2	0.315
$\mathbf{K_{0,8}}$	Stainless steel 316L, $R_a = 0.8$ µm	Composite Thordon SXL	0.340
$\mathbf{K_{1,6}}$	Ditto but $R_a = 1.6$ µm	Composite Thordon SXL	0.190
L	Chromium plated steel, $R_a < 0.8$ µm	Polyamide/PTFE composite	~ 0.200

Alike the wear, also friction showed no significant differences between the "wet" and "dry" tests. The correlation with slide plate roughness was, however, less clear. Some composite materials showed less friction on rough than on smooth plates. This can probably be explained by manufacturers' strategy to use "lubricating" additives (e.g. PTFE) that fill cavities in the counter material, decreasing the friction. Most of those composites show some wear in an initial operation period; but little wear afterwards. Engineers must be aware of that and not allow other lubrication on such contacts – as this may "wash" the cavity fillings away.

6.5.3. Changes to material structure

It is not the purpose of this thesis to analyze the impact of friction and wear on the microstructure of tested materials in their contact zones. Such an analysis, interesting as it is, belongs to the domain of material engineering, which is not the main subject of this thesis. For the sake of completeness, some data on microstructural effects and processes must, however, be reported. Following are microscope photographs of some specimens contact surfaces after testing, with short comments.

Manganese steel:

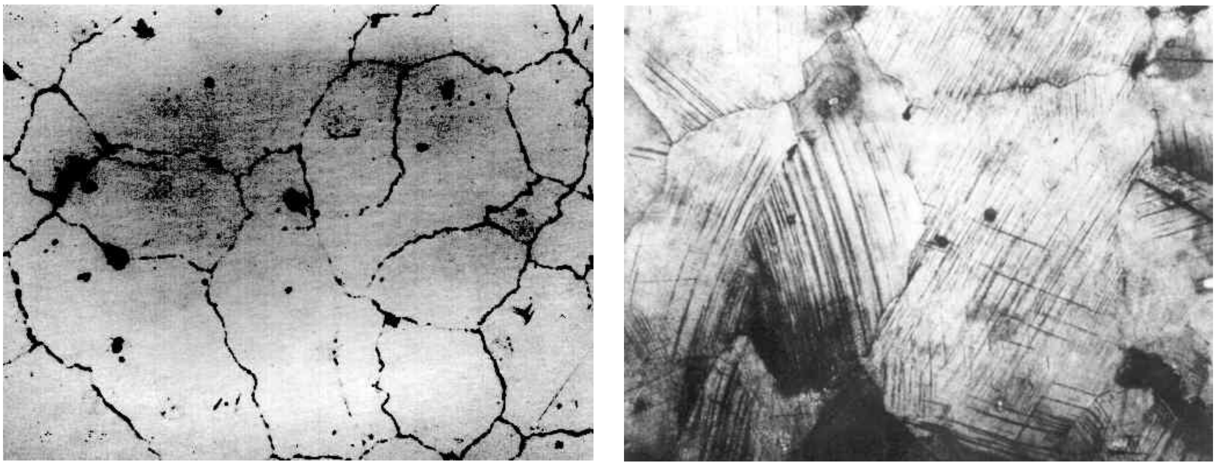


Fig. 93. Manganese steel crystalline structure far from (left) and on (right) the deformed surface, respectively ~80 and ~160 x enlarged, [49]

These photographs are made from a sample of a damaged pivot cap. We see a clear difference between the strain-free and the deformed crystals. In the first case, no track twinning through the crystals can be seen, despite good etching. In the second case, very clear parallel twinning planes are visible (with local lateral micro-cracks). Although a similar deformation mechanism can be observed in most steel alloys, it is exceptionally strong here. It explains, in fact, the strain-hardening property of manganese steel, a discussion of which falls – however – beyond the scope of this thesis.

Some other metallic alloys:

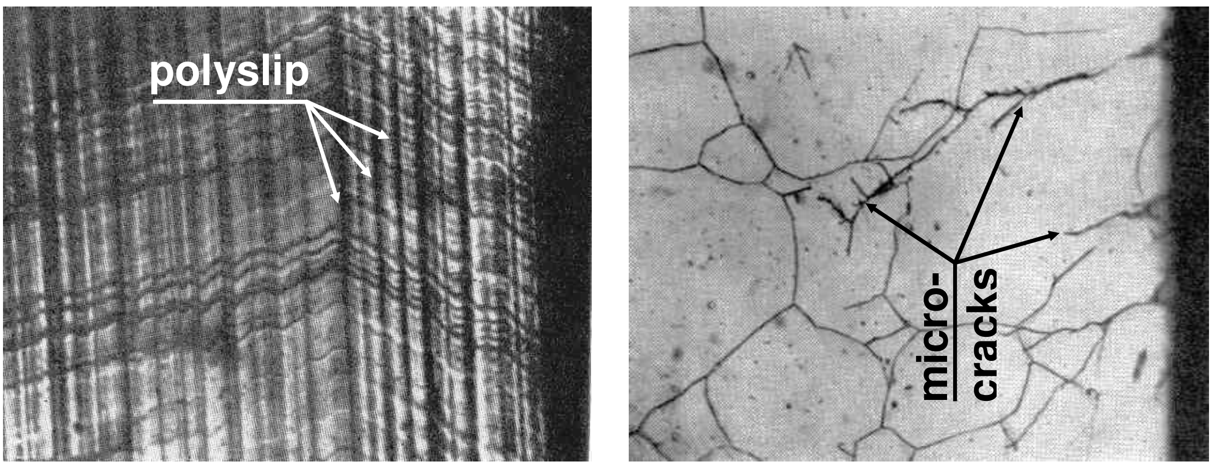
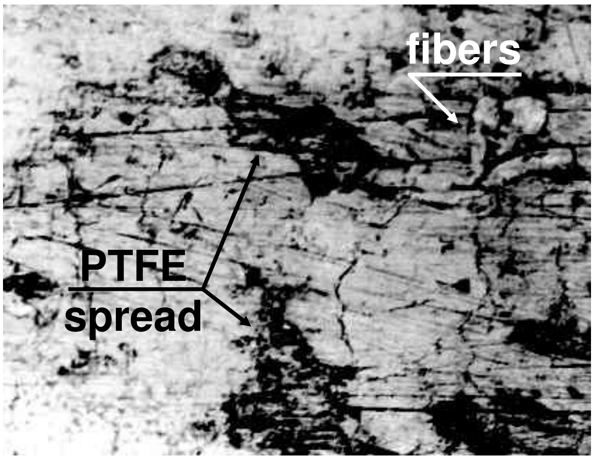


Fig. 94. Aluminum-copper (left) and stainless steel (right) crystalline structure shaped by fatigue, respectively ~800 and ~200 x enlarged, [103]

From all performed metal-to-metal tests, the combination of manganese steel and refined steel showed the lowest wear (tests **C** and **D** in Table 21). This is further discussed in section 6.6. In view of the material structure, other metallic alloys are now interesting, i.e. the group of bronze, aluminum-bronze, aluminum-copper etc. and the group of stainless steels[1)]. No microscope photos of these materials have been made during investigations, but their surfaces resembled the structures shown in Fig. 94. The left photograph has been taken after 105 000 load cycles [103], which is exactly the desired service life in our considerations, see section 4.5. One can see the characteristic deformation of a single crystal, with many parallel slip planes (polyslip) and no micro-cracks. This denounces a very good ductility of that alloy. Quite opposite is the structure of the stainless steel alloy from the right photo. There, the fatigue load produced no slip but micro-cracks through the crystals. That alloy is not ductile at all; it is but brittle.

Feroform (Tenmat®) T814 composite:

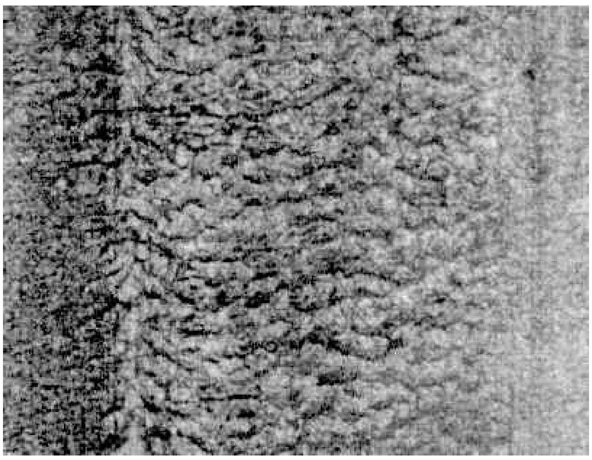


The American manufacturer Tenmat® is present on the market with a range of composite contact materials known either under the company name or, in Europe, under the name Feroform. These materials have made a name e.g. in automobile, process and offshore industry. Formerly containing asbestos (Ferobestos), they now have other reinforcing additives. Feroform T814 uses phenolic resins with an addition of PTFE as a matrix and polyester fibers as reinforcement.

Fig. 95. Feroform T814 structure after the wear test, ~40 x enlarged, [49]

In Fig. 95, we see that the phenolic resin matrix covers still almost the whole contact surface after the wear test. The fibers can only incidentally be spotted. There are some tinny surface cracks in the matrix, caused possibly by a local warmth impact, but they do not look serious enough to fear material decomposition. The photograph shows also that a small addition of PTFE (here only a few percent of the matrix volume) can give a very significant reduction of friction. The reason is that the PTFE particles become spread over a much larger surface than what might be expected from their contents rate. Feroform T814 is certainly a well engineered contact material.

Polyethylene UHMPE 1000 uv:



Ultra **H**igh **M**olecular **P**oly**e**thylene is supplied by a number of companies, the largest of which in Europe is Hoechst AG of Germany. Polyethylene is, as known, a thermoplastic material, which indicates that its thermal behavior will be opposite to that of, e.g., the (thermosetting) resin matrix in Feroform. This is visible in Fig. 96. Instead of the surface cracks, that we have spotted in Fig. 95, we now see characteristic "tufts" of the worn surface material.

Fig. 96. UHMPE structure after the wear test, ~40 x enlarged, [49]

[1] This is a generalization for the sake of space. Alloy properties in both groups can, in fact, significantly differ.

These "tufts" (or – locally – "scale") remain attached to material for some time, which improves its abrasion resistance – provided that the surface of counter-material is smooth. One can trace this property to the very large molecular weight of UHMPE, ranging from $3.5 \cdot 10^6$ to $6 \cdot 10^6$ g/mol [67], which gives the molecules containing about $2.5 \cdot 10^5$ to $4.3 \cdot 10^5$ CH_2 units in a chain. If the surface of the slide track is rough, however, the "tufts" are cut away and the wear process accelerates dramatically. We can observe it by comparing the wear graphs of UHMPE in Fig. 87.

Railko RG2 composite:

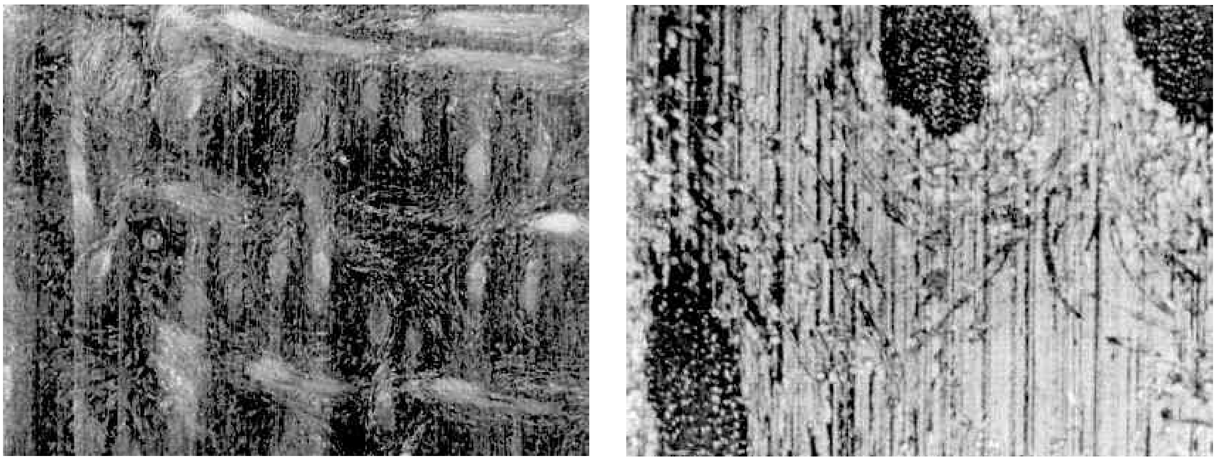
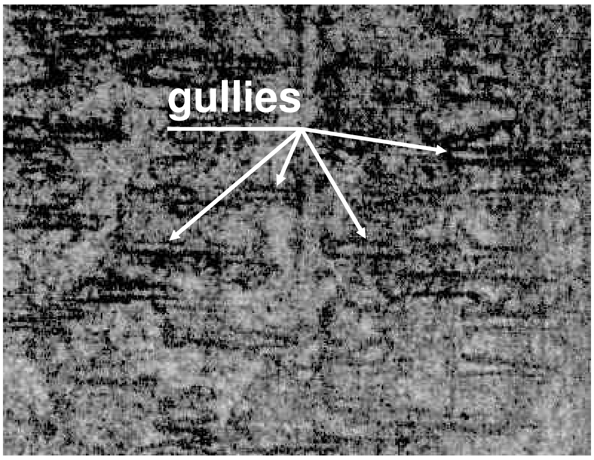


Fig. 97. Railko RG2 structure after the wear test, left ~10 x and right ~50 x enlarged, [49]

Alike Feroform, also Railko is commercially available in a number of grades. The RG2 is composed of phenolic resin matrix and aramid fiber reinforcement. Instead of PTFE, the manufacturer uses here graphite as a self-lubricating additive. Railko is a product of a British company of the same name, that earned its reputation as supplier of the railway and automobile industries, marine and shipbuilding.

Fig. 97 presents the material structure after testing on a $R_a = 1.6$ µm slide plate. We have seen in Fig. 87 that Railko specimens did not perform well in these tests, showing excessive wear – while the wear on Ra = 0.8 µm slide plates was quite acceptable. The photographs give more insight into the mechanism of the first tests. The matrix is severely worn and shows no tendency to form stable slide areas (like in the Feroform or Thordon tests) despite the addition of graphite. The aramid fibers are broken in the slide plane (right photograph), which denounces their brittleness and produces an opposite effect to what we have seen in the UHMPE tests.

Thordon SXL:



Thordon SXL belongs to a family of contact materials supplied by the Canadian company Thordon Bearings Inc. The manufacturer is cautious not to disclose the details about the composition of this material; informing only that it is an elastometric polymer alloy. Tracing the composition was also not the purpose of the current tests. The reports of test performed by third parties [104] indicate, however, that the material is "impregnated with a liquid lubricant", which is an exceptional feature in this investigation.

Fig. 98. Thordon SXL structure after the wear test, ~40 x enlarged, [49]

Impregnation means that there must be some kind of porosity and, indeed, we can see in Fig. 98 small gullies on the surface of a worn Thordon specimen. In all the performed Thordon tests, the gullies ran across the slide direction, but it has not been investigated whether this was a coincident or regularity. The presence of gullies suggests that they might have contained liquid lubricant as mentioned in [104], but there is no information about how it penetrated there, how the gullies came into being etc. Known is, however, that this trybological system works. Thordon specimens showed perfectly low wear on slide plates R_a = 0.8 µm and quite good on slide plates R_a = 1.6 µm. An interesting detail is also that the material deposits on slide plates (see left photo in Fig. 88) caused a significant decrease of the friction coefficient. Consequently, the friction on rough plates was almost twice lower than the friction on smooth plates, see data in Table 22.

Fiberglass reinforced polyamide with PTFE:

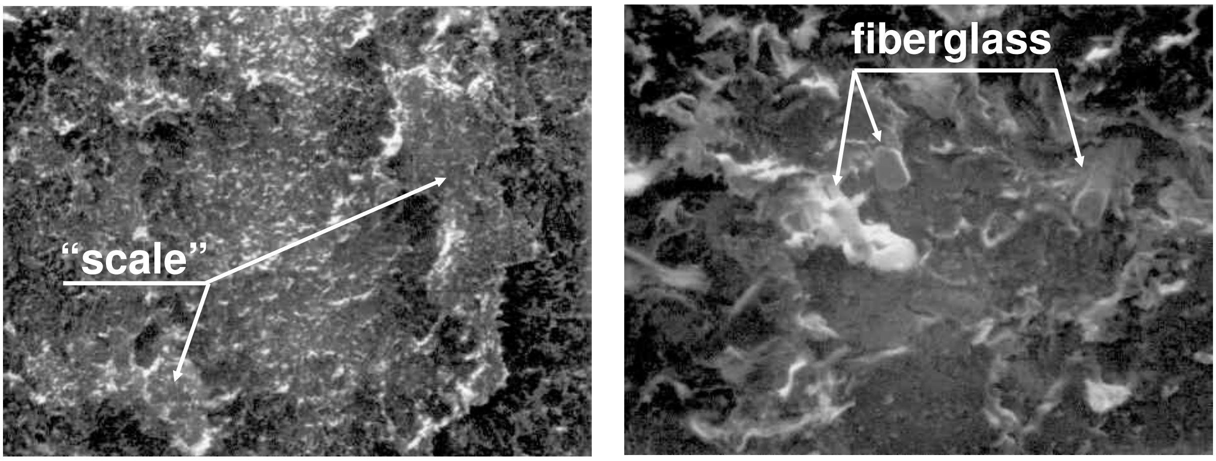


Fig. 99. Polyamide structure from a gate worn bearing, left ~50 x and right ~400 x enlarged, [89]

Polyamide (nylon) is known for its water absorption which significantly changes the mechanical properties of this material. In the case discussed in section 5.4.1, we have seen that this can cause serious damage. Manufacturers applying this material tend to call it maintenance free, which is somewhat misleading. Polyamide may not need lubrication to limit the friction, but it certainly needs it not to allow the moisture come through.

From the photographs in Fig. 99, we can conclude that the wear mechanism of polyamide resembles to some extend that of UHMPE. The difference is that the slide surface scales rather than grows covered by "tufts" of long polymer chains. In this particular example, water penetrated into the bearing, which accelerated the scale-shaped wear. It is possible that the wear of dry material would show a different form. In the right photograph, some single glass fibers are visible, running in rather random directions through the specimen. One can assume that the uncovering of those fibers caused some wear of the inner ring (see Fig. 66 in chapter 5), which had indeed been noticed in this case. The growing roughness of that ring wore, in turn, more polyamide, which accelerated the deterioration process.

6.6. Discussion, conclusions and recommendations

6.6.1. General, classification of tested materials

In order to draw some general conclusions from the performed investigation, one must classify the investigated contact materials into groups. A comprehensive classification is impossible here due to the diversity of alloys, composites, structure arrangements etc. on the market. We shall, therefore use a simple classification, as shown in Fig. 100. The roughest simplification is that the division is focused on one of the two contact materials, while the second (sometimes also the third, e.g. lubrication) is, obviously, also significant in contact behavior. If not otherwise specified, we shall assume that this second material is steel for metallic contacts and stainless steel for non-metallic contacts. Non-metallic contacts are here contacts in which at least one of the two contacting materials is not metal.

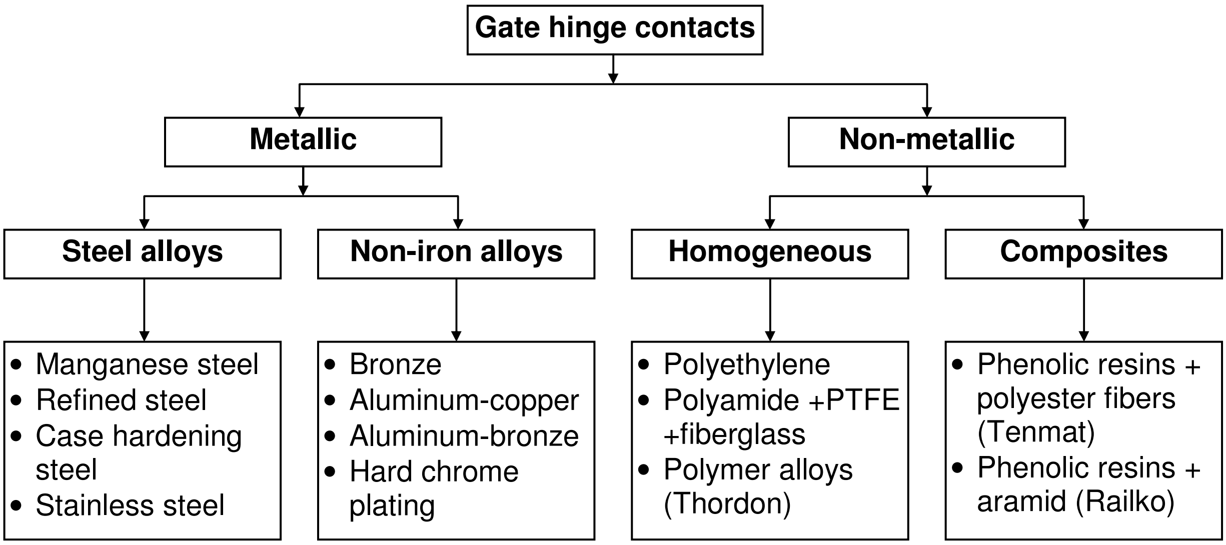


Fig. 100. Simple classification of the investigated contact materials

Another disputable division is that into homogeneous and composite materials, as the first can consist of more components and be, in that sense, composites as well. A typical example is polyamide with a PTFE additive and fiberglass reinforcement. The reason why it has been classified as homogeneous is that both PTFE and fiberglass are in this case spread random through the material batch, so that the material remains isotropic. This can not be told about composites with fiber reinforcement in the form of unidirectional ropes or fabrics. Only such materials will be classified as composites here.

6.6.2. Metallic versus non-metallic materials

On the ground of performed investigations, the following conclusions can be drawn regarding the selection of metallic or non-metallic contact material for a hydraulic gate hinge:

- The technology of metallic contacts has a much longer history than that of non-metallic contacts. As a consequence, the first is better proven, standardized and rooted in the engineering practice. This minimizes the risks and generates confidence. The technology of non-metallic contacts is younger and has a potency to reach performance levels unavailable for metallic contacts. The involved risks are, however, greater as the rooting in standards and the confidence are smaller.

- Also the mechanical behavior of metallic contacts conforms better to the existing theoretical models. In particular, the Hertzian theory offers a fair estimation of contact stresses which, in turn, can be used to generate analytical formulas for, e.g., wear – based on the test results. The mechanical behavior of non-metallic materials lies usually outside the validity range of the Hertz' formulas and is theoretically more complex.

- A weak point of metallic contacts is their demand for lubrication. The investigations confirmed generally poor performances of unlubricated contacts of this group. The derived wear factors were not only higher than in a number of non-metallic contacts but they also applied to both contacting materials. The wear of non-metallic contacts appeared usually only on the side of the non-metallic (synthetic) material, which is of great importance for maintenance reasons.

- The demand for metallic contact lubrication generates the needs for monitoring, accessibility, measures to protect the environment, more maintenance etc. The importance of these factors in engineering assessments is steadily growing – for both economical and operational (safety, ecology) reasons. In this view, non-metallic contacts will probably be granted more confidence in the future. The maintenance intensive metallic bearings, as the one in Fig. 101, belong to the past.

Fig. 101. Bearing of the Rhine weir visor gate in Hagestein

- A great majority of commercially available non-metallic contact materials are synthetic materials. Other materials from this group (e.g. organic or ceramic) are – in general – exceptional and have little significance for hydraulic gate hinges. Those materials are, however, frequently applied as additives to modify mechanical or other properties of the basic synthetic material. Typical examples are organic fibers, fiberglass and graphite.

- Both thermoplastic and thermosetting synthetics can be used in hydraulic gate hinges. A common property distinguishing them from metallic materials is their sensitivity to temperature. Metallic contact materials have – in general – more stable structures and are less sensitive to the warmth generated by friction. On the other hand, synthetics offer more possibilities to limit the friction.

- So far, synthetic contact materials can carry lower contact stresses than appropriate metal alloys. However, the traction properties (wear, friction) of those materials are better, which has been confirmed by the current investigations. A general conclusion is that metallic materials are preferable in heavily loaded contacts with little or no traction (e.g. vertical lift or tainter gate bearings), while non-metallic materials are preferable in contacts with intensive traction.

- Metallic contact materials have – in general – much higher elasticity modules than synthetic materials. In the so-called conform contacts, metals will pass their loads over through a small – and synthetics through a large contact surface. In order to reach that larger surface, the latter must undergo strain. As result, metals perform better in contacts where large clearances are required. For synthetics, this can often be compensated by increasing the bushing diameter and height.

- Although the investigation was focused on hydraulic gate hinges, the results are – to some extend – also useful for other gate contacts, e.g. mitre gate contact posts, hinges of gate drives, vertical lift or rolling gate expanding devices etc. It may, however, be necessary to consider still other materials in such cases, e.g. ceramics, timber, elastomers etc.

- Due to the higher contact stress capacities, metallic contacts are often better suited for renovations of existing gate hinges. Lowering the contact stress in order to apply synthetic materials requires usually more space for a hinge, which is a difficult demand in an existing gate. Nevertheless, there have also been successful realizations of hinge renovations using synthetic materials, see e.g. Fig. 102 further in this chapter.

6.6.3. Steels and non-iron alloys

In the group of non-iron alloy contacts, much information could be traced in the existing literature and in other investigation reports, e.g. [102], [105]. Based on this information and the results of the current investigations for steel contacts, the following conclusions can be drawn regarding the selection of a steel or non-iron metallic contact in a gate hinge:

- Whatever the choice may be, one should never apply exactly the same material on both sides of the contact. Such arrangements proved to result in highly unfavorable wear forms of both abrasive and adhesive type. The results of the current investigations confirm this conclusion. Compare the high wear of double-sided manganese steel contacts (tests **A** and **B**) and double-sided refined steel contact (test **E**) with the lower wear of divergent material contacts in Table 21. More confirmation has been found in field experiences, e.g. with double sided stainless steel contacts.

- No clear correlation has been found between the wear results and the friction coefficients measured during the tests. In particular, the high wear of manganese steel contacts went along with the friction coefficients of the same range as the lower wear of other steel contacts. This does not exclude the existence of a certain correlation in cases when the wear mechanisms are better comparable, e.g. when no strain-hardening appears.

- In metallic contacts, both contact sides are potentially subject to wear. The engineer ought to consider which of the two should wear faster, in view of available maintenance possibilities. In mitre gate bottom pivots, e.g., this should be the cap in a pivot head (“shoe”), as it is easier to replace it when the gate leave is hoisted up for a maintenance service. Allowing the pivot shaft cap to wear faster would be an obvious design error.

- Regarding the bottom pivot situation, the best result in terms of wear gave the combination of manganese steel G-X120 Mn12 in the pivot shaft cap, and refined steel 34 Cr Ni Mo6 in the pivot head (“shoe”) cap. The head cap wear was only ¼, and the shaft cap wear ¾ of the double-sided manganese steel contact wear. This arrangement was later applied by the author in the gate hinges of the Lith Lock on the Meuse [2], [28]. No wear problems have been reported there yet.

- While engineering metallic contacts, one should not only consider the nominal material hardness but also the possibility of strain-hardening during operation. The investigations confirmed various field observations reporting that the impact of strain-hardening is not always positive. When the contact materials were different (e.g. test **C** and **D** in Table 21), the wear of both strain-hardening and the other material was low. When the contact materials were the same (tests **A** and **B**), the wear of both materials was high.

- The investigation results allowed formulating a hypothesis that the wear of metallic contact has a cyclic character. In short, it claims that the surface material – before getting detached – adapts its structure and properties to the contact loads, in which stage the friction actually decreases. Then it detaches as result of fretting fatigue [33], which increases the friction and marks the beginning of a new adapting phase. A strong indication of this phenomenon has been found in the behavior of manganese steel specimens. Other metals may possibly behave in a similar way.

- Using non-iron metallic contacts (bronze, aluminum-bronze etc.) decreases the friction and offers some more corrosion protection, but it does not – in general – decrease the wear. Since friction, as such, is a minor problem in gate hinges, the main advantage of non-iron alloys is that they allow guiding the wear into that contact side which we want to be worn, and sparing the other one. This can, however, also (often better) be done by synthetic materials. The applications of bronze, aluminum bronze and the related alloys will likely decrease in the future for this reason.

- Stainless steel performs well in corrosion exposed contacts with materials of low hardness and elasticity modules. Special care must, however, be taken in salt water exposures and in environments poor in oxygen, due to the risks of – respectively – chloride and bacterial corrosion. Field experiences (e.g. in linings of Born and Maasbracht Lock gates, Fig. 30) and microscope analyses (e.g. Fig. 94) indicate that stainless steel performs badly in metal-to-metal contacts, showing high wear and the risk of intercrystalline brittleness.

6.6.4. Homogeneous synthetics versus composites

Based on the results of the current investigations for the contacts of synthetic materials to (stainless) steel, the following conclusions can be drawn regarding the selection of a homogeneous synthetic or a composite in a hydraulic gate hinge:

- At the time of writing this thesis, the commercially available contact materials of the homogeneous synthetics group were all thermoplastic, while nearly all composite contact materials were based on thermosetting resins. The nature of this division is, in the first instance, technological: It is easier to impregnate fiber reinforcement with thermosetting resins than to bring it into thermoplastic polymers. However, this may change in the future resulting in a supply of, e.g., fiber reinforced thermoplastic materials, interesting for hydraulic gate contacts.

- The investigations have proved that the relation between the wear and the counter surface roughness is for synthetic materials much stronger than for metals. A double roughness increase (from R_a = 0.8μm to R_a = 1.6 μm) resulted in about 10 or more times wear increase of the synthetic material. An exception was the Feroform composite showing only a slight wear increase. From the homogeneous synthetics, the wear of Thordon was the lowest due to the thoroughly engineered wear mechanism, see comment below.

- The investigations have shown that different wear mechanisms of synthetic materials are possible, and that the actual wear strongly depends on those mechanisms. In most cases, abrasive wear was dominating, resulting in relatively high specific wear factors $\boldsymbol{k}$. In case of Feroform (composite), the abrasion was soon reduced due to the forming of large PTFE spreads. In Thordon (homogeneous material), an adhesion of the worn material to the counter surface filled its grooves, reducing the roughness and the further wear.

- An obvious distinction of homogeneous synthetics in relation to composites is their isotropy. It is advantageous in cases when the contact stress direction on a segment level (see section 3.2) is variable. When that contact stress direction does not vary much, the anisotropy of composites can prove more advantageous.

- Similar preferences can be formulated with respect to the stress size variations. Homogenous materials are less vulnerable to unidirectional varying stresses. Frequent and short stress cycles can even be welcome, as they reduce the viscous deformations. Composites show usually less viscous behavior (contraction strain being held by reinforcement), but they are more vulnerable to fatigue caused by frequent stress cycles.

- The investigations have confirmed that composites can, in general, bear higher contact loads than homogeneous synthetics. Their permissible contact stresses approach the level of about 50% of those for metals. For homogenous synthetics, this level lies between, roughly, 10% (polyethylene) and 25% (polyamide, Thordon)[1)]. These estimations are based on the behavior under compression with traction in a hydraulic gate hinge, as recorded during the presented investigations.

- As mentioned in 6.6.2, synthetic materials are, in general, less suited for renovations of existing, metallic gate contacts. Due to the lower design contact stresses, the space demands for synthetic materials are difficult to meet. Nevertheless, there exist successful realizations of gate replacements using synthetic contact items within the size limits of the old, metallic contacts. Fig. 102 presents an example from the author's design practice [71]. The old cast iron pivot support has been given a stainless steel cap, providing larger contact areas. This, in turn, enabled the application of a polyethylene cap in the new pivot head. While writing this thesis, the hinge is 4 years under operation and no noticeable wear has been reported.

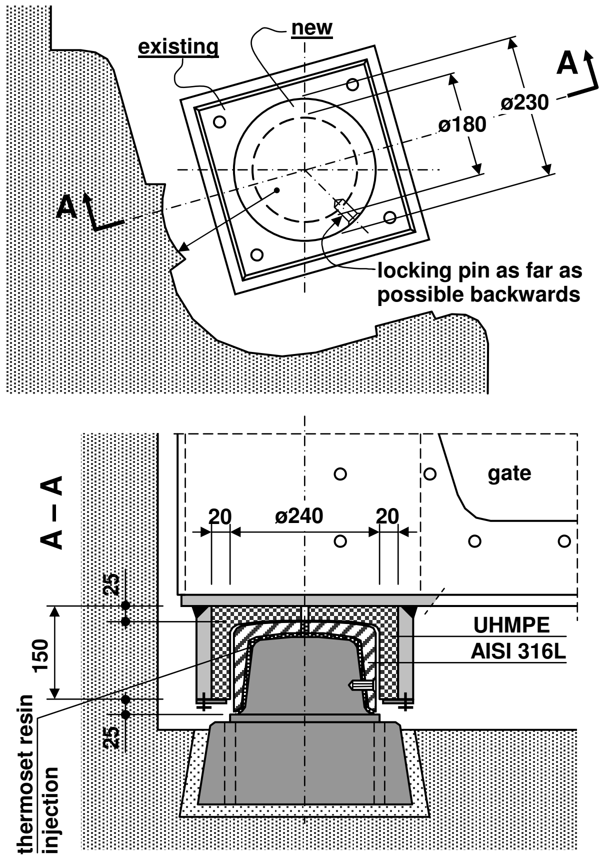


Fig. 102. New bottom pivot of Lock III in the Wilhelmina Canal in Tilburg

- Both homogeneous synthetics (mostly thermoplastic) and composites (mostly thermosetting) are sensitive to temperature variations. Their behavior in very low temperatures is less significant, as gates are usually not moved in times of heavy frosts. Particularly critical are high temperatures, generated by friction. Composites offer, in general, better than homogeneous materials possibilities to preserve contact stability under these temperatures.

- The investigations have shown that the friction coefficient of synthetic materials is, in general, lower than of metals, but shows still large dispersion – for different synthetics as well as different operation phases of the same material. There is no rule saying which of the two – homogenous or composite synthetics generates more friction. In both groups, high and low friction has been encountered. The highest friction, combined with stick-slip behavior, has been observed in the wear tests of the Railko composite.

- In the group of composites, the tests have proved superiority of some fibers, additives etc. above the other. E.g. flexible (polyester) fibers and a PTFE additive performed better than, respectively, stiff (aramid, fiberglass) fibers and a graphite additive. These assessments are not, however, definitive and can change as result of technological developments in the future.

---

[1] By perfect casing and smooth counter material surface, all these estimations can be significantly increased.

7. THE SUSPENSION GATE IDEA

7.1 Disadvantages of pivot supported gates

The discussion in the preceding chapters was focused on handling gate contact problems, in particular the deformations and the wear. Returning to the main thesis of this study, as formulated in chapter 1, we can place this discussion in the last three project phases from Fig. 2, emphasizing the design phase. The definition phase, which is one level higher, was mainly considered in terms of gate type selection, i.e. a contact related gate choice for particular design conditions, from a range of the known types. It is time now to take a broader look. We have seen that there are different measures, in the field of contact material selection, dimensioning etc., to handle the hydraulic gate contact problems. But we have also seen that gate contacts, in particular the hinges, are subject to engineer's continuous concern, certainly in mitre gates – the most frequently used gate type on navigated waterways. The question which arises now is whether another, more radical solution to the gate hinge problems can be found.

Before answering this question, it is good to see where the current hinge solutions originate. They all make use of two (exceptionally more) hinges – the top and the bottom hinge – one of which (usually the bottom hinge) bearing the vertical and the horizontal load, and the second hinge bearing only the horizontal load. The vertical load passage takes place on a pivot shaft fixed to the lock crown (mostly the bottom), through a pivot head fixed to the gate. This arrangement may seem obvious today, but it has not existed always in mitre gates. The early gates of this type, as well as the older single-leaf gates, employed an opposite arrangement of the vertical load passage, see Fig. 103. The wooden heel post was manufactured with a short octagonal extension, on which a bronze cap was mounted. The cap rotated in a socket, also of bronze, fixed in a hard wooden or stone block of the lock floor. The contact spheres of the cap and the socket were – as we would say today – non-conforming, which is also contrary to the current arrangements. The reason was that such an arrangement could longer be operated without cleaning, as sand deposits were the main problem of these solutions. We see that turning this arrangement upside-down was, in fact, a revolutionary idea. It did not only allow to handle the problem, but it eliminated that problem entirely. In this chapter, we shall take a similar approach to the current problems of the mitre gate contacts.

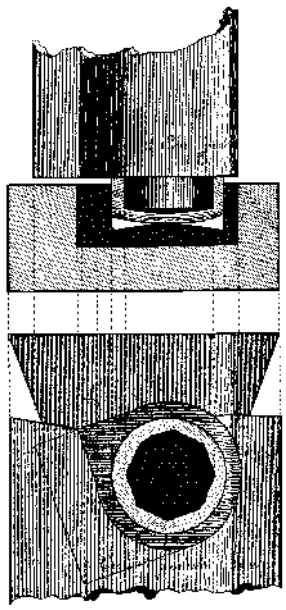


Fig. 103. Bottom hinge of an old (XVII century) gate in the Sea Lock in Muiden near Amsterdam [106]

The reason to assume this approach is author's conviction, based on historical view and current design experience – that the traditional pivot and collar ring system approaches the end of its technological development. This conviction is also supported by a morphological survey of the problem, presented in section 7.2. Although new contact materials, high-tech bearings etc. bring some improvements, they increase the costs, introduce new risks and demands (concerning smoothness, temperature, moisture) and do not follow the idea of simple, robust solutions any more. The repairs of such contact arrangements can be very complex, costly and often only possible by calling in the suppliers service (see e.g. the case in section 5.4.1), which puts the gate owner in a vulnerable position.

In the group of "self-engineered" metallic or simple synthetic contacts, the dependency on supplier's terms is, in general, smaller. There is, however, not much unexplored space for new ideas in that group any more. Also here, modifying the (metal) alloys helps to improve the wear resistance and to direct the wear to the easier replaceable part of the contact, but it does not actually stop or spectacularly decrease the wear. The only measure which causes such a decrease is intensive lubrication, which should be avoided for both environmental and maintenance reasons. An exception in this group is the contact arrangements employing polyethylene UHMPE, the material showing very good traction properties – provided it is well cased, its contact stresses are small and both the temperature and the smoothness of the counter-material are very well controlled. These conditions can be met in some projects (e.g. Lock III in the Wilhelmina Canal, see Fig. 48 and 102), but by far not in all. Therefore, composites are usually better suited for gate hinge contacts at present.

The main disadvantage of pivot supported gates is the wear as result of the combination of horizontal and vertical (radial and axial) load in one hinge[1)]. Although the other hinge – bearing only horizontal load – is also exposed to wear, the field experiences show that both the size and the control difficulty of the problem are there less dramatic. An additional disadvantage is that the discussed load combination usually acts on the bottom hinge (gate types (a) through (d) in Fig. 4), because that arrangement is constructively simpler and easier in installation than the system with vertical load on a top hinge (gate type (e) in Fig. 4). In this way, the main contact problem becomes hardly accessible for maintenance, which, as such, is not a logical arrangement.

One should also realize that turning the arrangement from Fig. 103 upside-down, revolutionary as it was, had a price. It introduced an additional reaction component from the bottom hinge – the moment. As the gate horizontal reaction acts now above the bottom, there is always an eccentricity to the center of bottom response, tending to overturn the pivot. In order to prevent that, the pivot shaft must make part of a heavy, anchoring structure, preferably of cast steel, approaching the size of a man (Fig. 104). The horizontal reaction and its moment can then be passed on the lock floor through the "wings" on a pivot core.

Fig. 104. One of the bottom pivots in Naviduct Enkhuizen [43] before installation

Obviously, the casted structures of this size and form are not cheap. They also require deep, solid and heavily reinforced chamber floors in the vicinity of the pivots. The cost impact of these reinforcements is usually more than local, as they also affect the required excavation depth, cofferdam strength, possible measures against "piping", a so-called "quick condition" [107] etc. To put it briefly, searching a solution which might eliminate the bottom pivots is certainly worth an effort.

[1] See discussion in section 5.2.2 and in particular Fig. 61 for more details to support this opinion.

7.2. Genesis and mechanism of a suspension gate

In order to find a new, better support system for a structure like a hydraulic gate (or, in fact, to find an innovative solution to any other technical problem), the designer may try different strategies, which can – in general – be divided into the two following groups [108], [109]:

- Discursive methods: focused on systematizing the existing know-how, evaluating it in view of the given problem – and a systematic, methodical selection of solutions;
- Intuitive methods: focused on provoking spontaneous idea generations, not necessarily based on the existing know-how, in a rather free or very gently controlled way.

The methods of both groups require assuming a certain distance to the problem at first, in order not to fall back on the existing solutions. In the case under consideration, a good approach is the method of so-called *morphological survey*. The first step in this method is to anatomize the function of the prosperous device into some simple partial functions. Seeking a device to replace gate pivot bearings, the following partial functions can be defined (the numerical values are exemplary):

1. Carrying a vertical load of V = 300 kN, spinning over the rotation angle of 71.5°;
2. Carrying a horizontal load of H = 150 kN, sliding over the same rotation angle;
3. Incidentally carrying a stationary horizontal load of H = 1000 kN in boundary positions;

The first two partial functions result from normal operation conditions, with load proportions typical for a gate of the *free-hinged* system (type (b) in Fig. 4). The third function results from incidental obstacles on the bottom during the gate motion. In case of the *fixed-hinged* gates (Fig. 4 (a)), it also results from the hydraulic load in closed position, which is not an incidental load any more.

Having defined the partial functions, we can generate a number of operation modes that realize these functions. The result is a collection of those modes, like the one shown in the table below (Fig. 105):

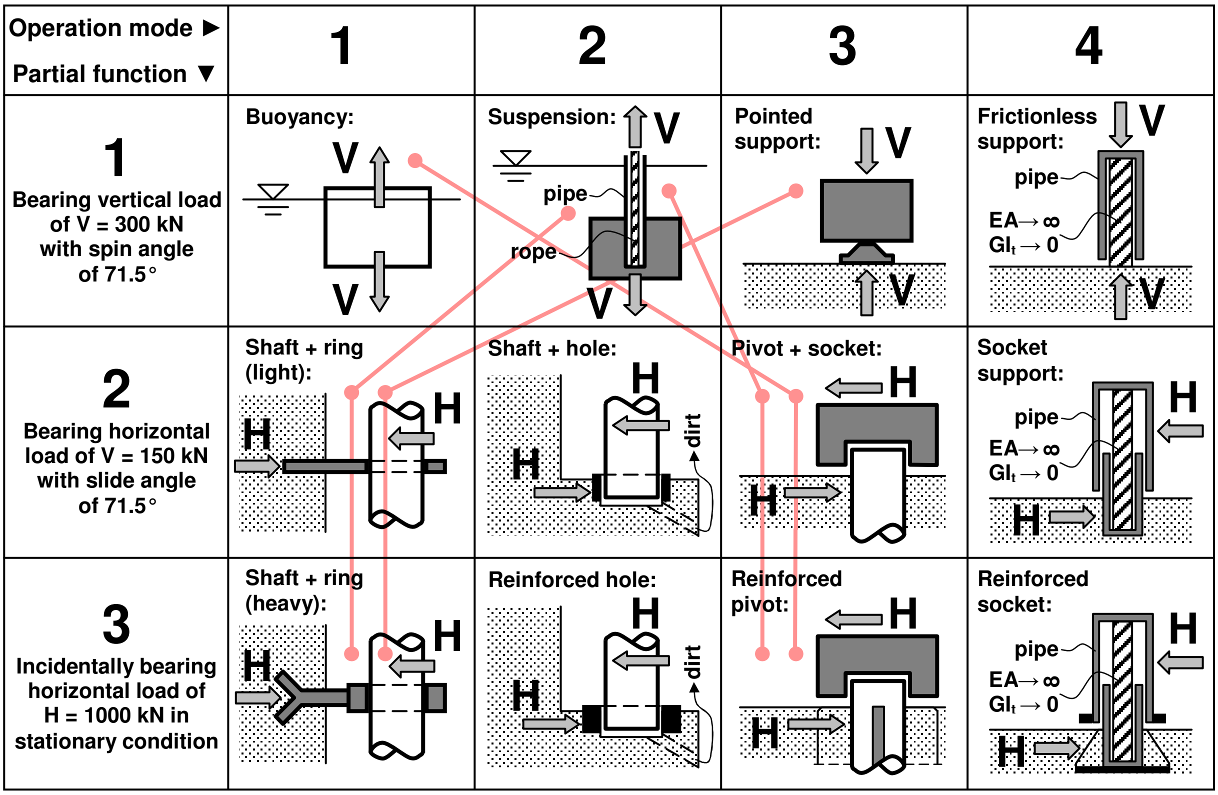


Fig. 105. Morphological survey matrix for a device to replace a gate pivot bearing, example

The most obvious combinations (called *structures* in design methodology) of operation modes for the defined partial functions have already been set in columns in Fig. 105. Other structures are, however, also possible. Some of them have been marked with crosswise paths. Below is the list of structures which have been found worth considering [81]. The selection is rather arbitrary at this stage.

Structure 1 = 1.1 + 2.1 + 3.1;
Structure 2 = 1.2 + 2.2 + 3.2;
Structure 3 = 1.3 + 2.3 + 3.3;
Structure 4 = 1.4 + 2.4 + 3.4;
Structure 5 = 1.1 + 2.3 + 3.3;
Structure 6 = 1.2 + 2.1 + 3.1 (possibly better than structure 2);
Structure 7 = 1.2 + 2.3 + 3.3;
Structure 8 = 1.3 + 2.1 + 3.1.

For space reasons, we shall confine the assessment to the first four structures. The assessment method is basically the same as in case of the gate type selection, see sections 2.1 and 2.2 of this thesis. Five following criteria will be considered:

1. **Reliability**, weight factor = 0.2: The main issue is here the predictability of performance, not the performance as such. E.g., a battery which runs empty after a month, is perfectly reliable if this is known before and if every specimen keeps working a month long.
2. **Service life**, weight factor = 0.3: The question here is how long a device is going to work with no significant maintenance, and what its total service life will be.
3. **Maintenance**, weight factor = 0.2: Not the frequency (as that is criterion 2) but the scope of required maintenance is important here. Also the issues like accessibility, maintenance duration, navigation or traffic disruption due to maintenance etc.
4. **Initial costs**, weight factor = 0.2: Includes construction costs and the costs of entire replacements during the service life. Not the spare part replacement, as that is criterion 3.
5. **Environment**, weight factor = 0.1: Environmental impact (energy consumption, pollution, other degradation) of the entire life cycle, i.e. raw material winning, processing, manufacturing, maintenance works and utilization after the service life.

The final assessment matrix is presented in Table 23.

Table 23. Assessment matrix for the first four structures in morphological survey from Fig. 105.

		Structure			
Criterion	Weight factor	**1**	**2**	**3**	**4**
1. Reliability	0,20	5,0	7,0	9,0	4,0
2. Service life	0,30	7,0	8,0	8,0	5,0
3. Maintenance	0,20	6,0	9,0	7,0	6,0
4. Initial costs	0,20	7,0	7,0	8,0	6,0
5. Environment	0,10	8,0	8,0	7,0	7,0
Total score	1,00	6,50	7,80	7,90	5,40

The evaluation rating in Table 23 was based on simple estimations, experience and comparisons to the existing structures in other fields of engineering. The critics would say that it is still partly arbitrary, which indeed is true. However, it has an important advantage – it makes the assessment transparent. This transparency discloses both the strong, quantifiable and the weak, arbitrary components of the designer's selections. In author's opinion, it is just that property – the transparency – that makes such assessments desired components of public construction projects in our post-modern societies.

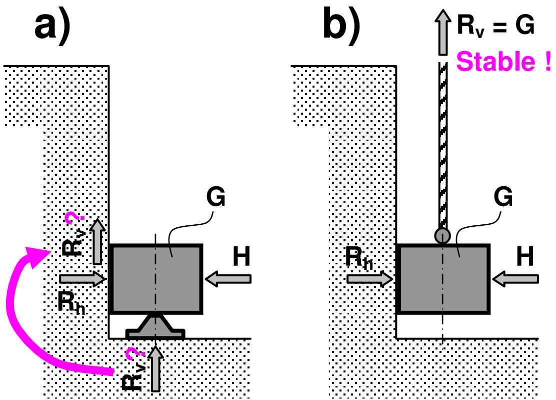
The assessment in Table 23 produced two winners with almost identical total scores:

Structure 3 which is, in fact, the conventional solution with a bottom pivot;
Structure 2 or the version 6 or 7, further to be called a suspension gate.

One can observe that the strongest attribute of structure 3 is its reliability that, obviously, is based on the existing field experience with that structure. Structure 2 scores lower in that criterion and costs slightly more due to some research and development costs, but it still ends up with an equal final rating thanks to the expected maintenance advantages. The conclusion is that structure 2 has more development potency. The first realizations will certainly increase its reliability and reduce the initial costs (no R&D any more) making it the winner of the future assessments.

The claim that significant maintenance advantages can be expected when passing from structure 3 to structure 2, is grounded on the two following arguments:

- Structure 2 removes the combination of horizontal and vertical (radial and axial) system loads in one hinge. That combination has been recognized as the main reason of excessive wear causing the current maintenance problems, see discussion in sections 5.2.2 and 7.1.
- Structure 2 removes (or significantly decreases) the variation of vertical load in the system. The mechanism of that phenomenon is explained below. As discussed in section 6.1, the field survey shows a correlation between the vertical load variation and the so-called gate “climbing” behavior. This behavior accelerates the wear and causes severe other maintenance problems.



The advantage of little or no vertical load variation in structure 2 results from the elastic response to this load. Let us consider a solid of a weight ***G***, pushed against a vertical wall by a force ***H*** and supported on a rigid saddle (a) or elastically suspended (b), see Fig. 106. Let us assume that the solid – for whatever reason – undergoes an upward displacement of a fraction of a millimeter[1)]. In case (a), the support is then released and its vertical reaction moves as a shear to the contact surface with the wall. In case (b), no change appears because a fraction of a millimeter is insignificant for a suspension length of a few meters.

Fig. 106. Disadvantage of a rigid support (a) compared with an elastic suspension (b)

If the opposite happens, i.e. if the solid moves downward a fraction of a millimeter, the saddle reaction in case (a) grows out of control and the suspension reaction in case (b) remains, again, the same. When looking at contacts on the segment level (see section 5.1), we have seen that the contact equilibrium is a result of several asperity contact loads. If some asperities are cut off, released or loaded higher – e.g. by the growing tangential load (here force ***H***) – this equilibrium becomes disrupted. Therefore, there is a reason to assume that fractional vertical displacements indeed take place on gate supports.

Naturally, in order to take full profit of the suspension gate idea, the suspension member (hanger) must be rather long – e.g. a few meters – otherwise its tensile elasticity may be limited, or it may receive significant stresses from the torque moment as result of the gate leave swing angle of ~71.5°. This will further be discussed in section 7.4. The hanger cross-section must also have a small torsional rigidity, i.e. one can better choose a rope, chain or package of flats than, e.g., a pipe section for it. Despite these conditions, the range of possible suspension gate types and arrangements is quite broad, what will be shown in the following section.

[1] By this example, the author aims to convince the readers of not necessarily mechanical background, who might be involved in a suspension gate selection. The discussion is, therefore, narrative rather than mathematical.

7.3. Possible sub-types and arrangements

Having proved an advantage of the suspension gate idea [1)] theoretically, we can now give it a form. As mentioned in the previous section, more types of such gates are possible. We shall consider the three basic types, as drawn below (Fig. 107):

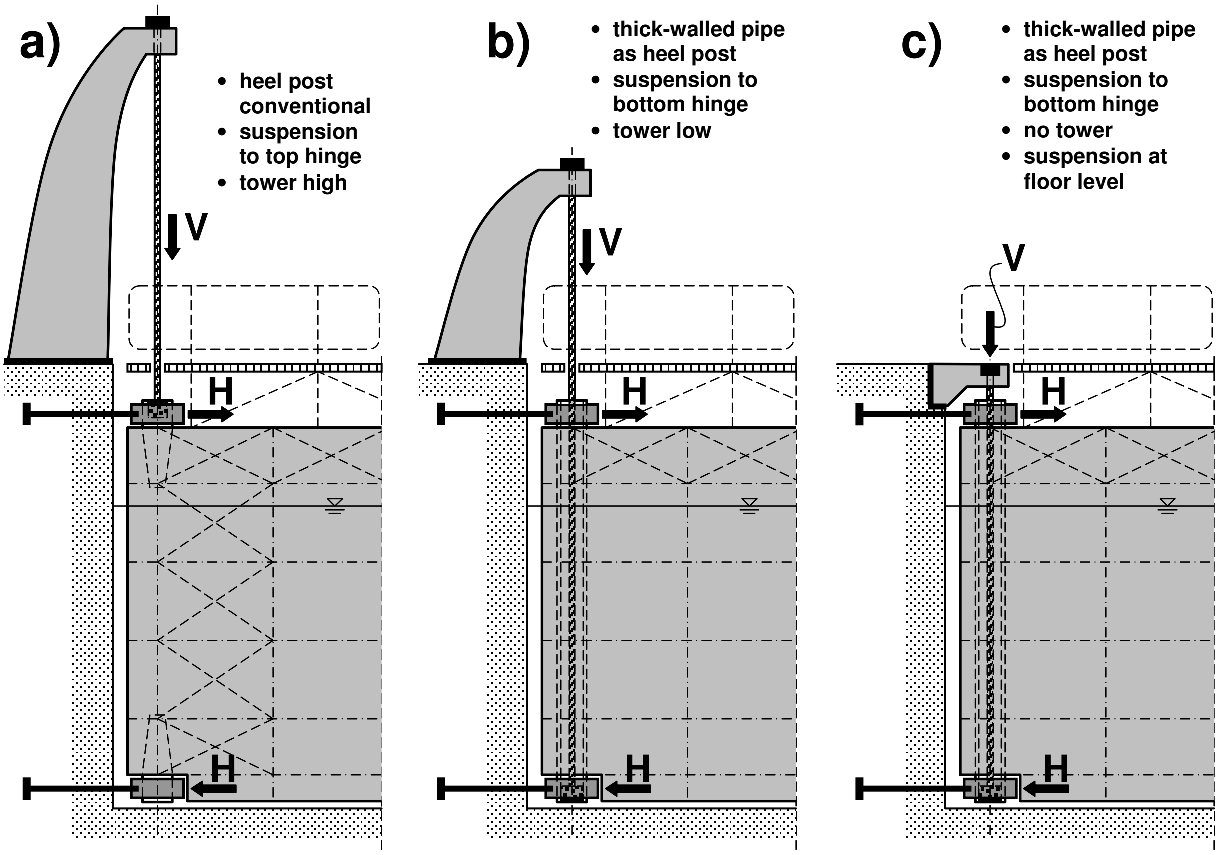


Fig. 107. Three basic types of a suspension gate

In all the three types, the vertical load is passed outside the gate hinges, which – as already discussed – is the main advantage of this structure. The component passing this load, hanger, is a steel rope, cable, chain or another tensile member of small torsional rigidity. It runs along the gate rotation axis and is hooked or anchored to the top hinge shaft in type (a), or the bottom hinge shaft in types (b) and (c). In case of the bottom hinge anchoring, a thick-walled pipe is used as the heel post core member, but an open profile can also be considered. As the hanger must have a proper length, the only way to provide it in type (a) is to give it a suspension point high above the chamber top floor. This requires a tower of the height comparable to the height of the gate leaf. In type (b), such a tower can be much lower – e.g. about 1½ man size for aesthetic and practical reasons (walkway). In type (c), which may be less suited for low but heavy gates, no tower is required. The author's personal opinion is that this type should be less favored aesthetically, as it camouflages the real mechanism of the gate. Nevertheless, it may e.g. be preferred in case of pedestrian traffic over the gate. An advantage of the thick-walled pipe in the heel posts of types (b) and (c) is its torsional rigidity, that might – by thorough design – make the bracings in the gate side fields unnecessary.

---

[1] As mitre gate alternative support systems are quite new, there is still some confusion in terminology. The term "suspension gate" is used sometimes to refer to the gates of type (e) from Fig. 4, i.e. with vertical supports at top hinges. The author opposes that. As supporting a bridge at the level of the girder upper chord does not make it a suspension bridge, rising a gate support in the same way does not make it a suspension gate.

The relative advantages and disadvantages of the three types of a suspension gate from Fig. 107 can globally be summarized as follows:

a) Suspension from high tower

Advantages:

- No thick-walled pipe required, conventional heel post arrangements possible;
- High suspension towers aesthetically favorable (a clear and appealing entrance marking);
- Hanger entirely above water – less corrosion, easy inspection and maintenance;
- No heel post pipe – no issue of inaccessible space inside, corrosion, dewatering etc.;
- Solid hinge shafts allow applying smaller size bearings – no space problems.

Disadvantages:

- Torsional bracings required in the flange plane of the gate fields neighboring the heel post;
- High (~ 6 m) towers are additional cost items, possibly more expensive than pivot cores;
- Limited hanger length in case of tower height limits – less choice of hanger section/material;
- Hanger can be an obstacle for pedestrians: locally wider walkways required;
- Although outside the navigation profile, more chance of ship collision that in type (c).

b) Suspension from low tower

Advantages:

- Torsional bracings in heel post fields unnecessary thanks to the thick-walled pipe;
- Low suspension towers aesthetically still to be favored (appealing entrance marking);
- Large hanger length available – low torsional stress and many choices in cross-section;
- Hanger condition still better controllable than in type (c), but less than in type (a);
- A very integrated design, e.g. heel post pipe = torsional stiffener = hinge shafts.
- Possibly favorable concrete compression from tower around the gate hinge anchors

Disadvantages:

- Special arrangements (e.g. pipe) for the hanger required, conventional solution not applicable;
- Low (~ 3 m) towers still cost money: less than high towers, possibly the same as pivot cores;
- If hanger (partly) in pipe, difficult access for inspection and maintenance;
- If pipe in heel post is used, attention required to corrosion and dewatering (frost);
- Although outside the navigation profile, more chance of ship collision that in type (c).
- Hanger can be an obstacle for pedestrians: local walkway widening required;

c) Suspension from floor level

Advantages:

- Torsional bracings in heel post fields unnecessary thanks to the thick-walled pipe;
- Eliminating towers saves money – the cheapest of the three, and cheaper than bottom pivots;
- Limited hanger length available – little choice in its cross-section and material;
- No obstacle for pedestrians on walkway over the gate, no risk of ship collision to tower;
- A very integrated design, e.g. heel post pipe = torsional stiffener = hinge shafts.

Disadvantages:

- Special arrangements (e.g. pipe) for the hanger required, conventional solution not applicable;
- No suspension towers, structure aesthetically not to be favored (less readable);
- If hanger entirely in pipe – almost no access for inspection and maintenance;
- If pipe in heel post is used, attention required to corrosion and dewatering (frost);
- Very compact design, space problems possible, special care to assembly required.

The character of this thesis does not allow for a discussion about details which still require consideration, e.g. walkway arrangement in the vicinity of the hinge, dewatering (or not) of the heel post pipe, corrosion protection of the hanger etc. All those details must be thoroughly engineered still, but there is ground to state that they are solvable. There exist quite simple solutions to similar problems in other hydraulic structures and other fields of engineering. The feasibility of entirely new aspects (like, e.g., torsion of heavily tensed hangers) will be discussed in section 7.4.

Three-dimensional visualizations of a suspension gate in a mitre gate chamber and two single-leaf gate chambers are presented in, respectively, Fig. 108 and 109.

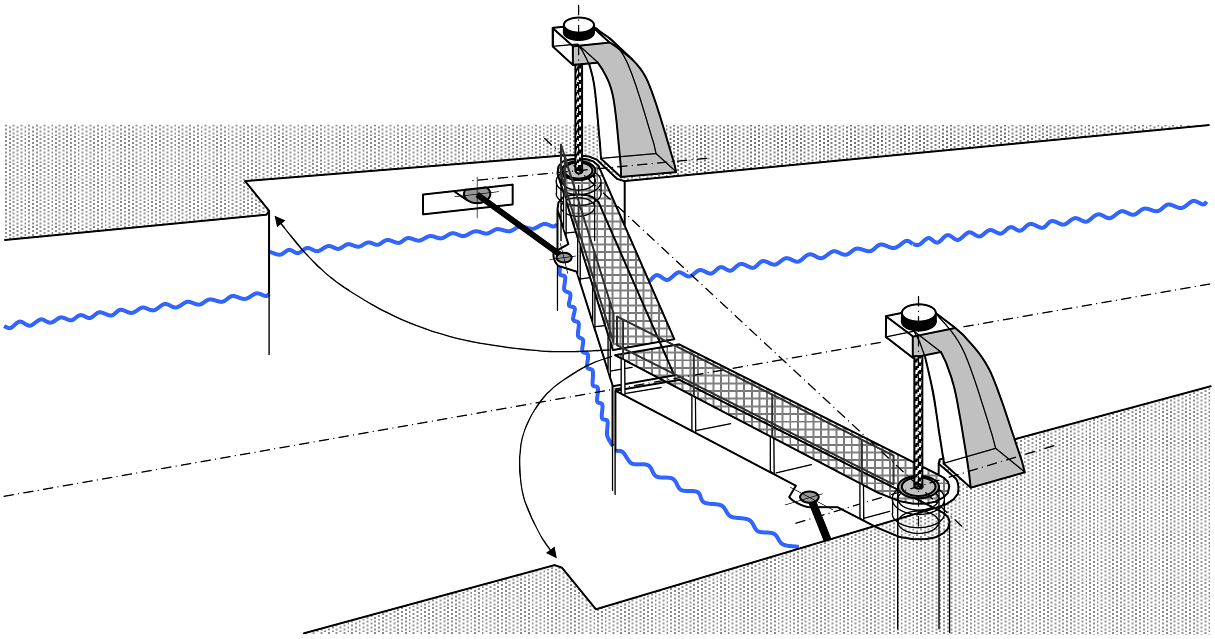


Fig. 108. Suspension gate as a mitre gate

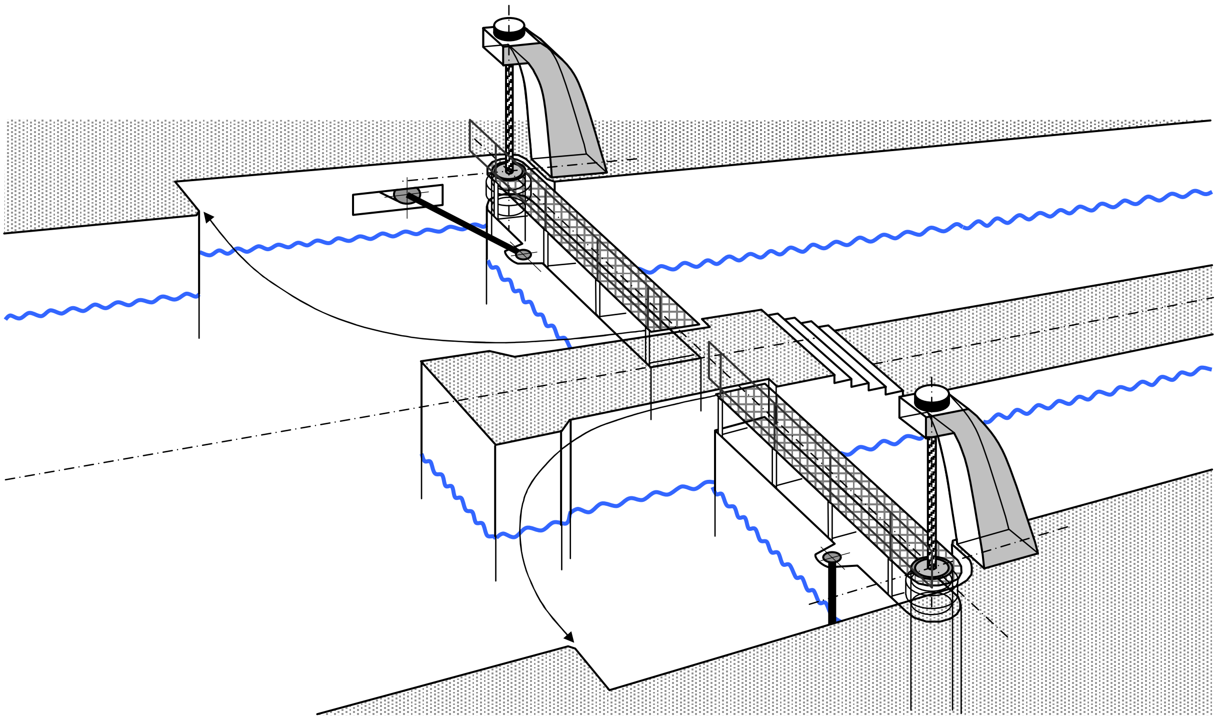


Fig. 109. Suspension gate as a single-leaf gate

The sketches in Fig. 108 and 109 are meant to give a general impression, not a detailed solution. E.g., the walkways will in both cases probably need widening and an overlap section in the vicinity of the suspension, which has not been drawn. In the Netherlands, walking over lock gates becomes gradually less important nowadays because most gates (even entire locks) are remote controlled. There is usually no personnel to make use of the walkways, except periodical inspections and maintenance activities. The policy in that matter is, however, disputable[1)] and it may be different in other countries. Nevertheless, one should not think that the hangers running through the walkways form an insurmountable problem. Proper walking passage can easily be provided.

Suspension gate creates a possibility to give a navigation lock a remarkable, very expressive image – well tuned with the function of the lock. Also that aspect has not been worked out in Fig. 108 and 109. Especially the suspension towers, when thoroughly shaped, can give a harbor or an inland navigation lock an individual, recognizable landmark. This architectural effect can be traced back in the classical harbors (e.g. Piraeus, Carthage, Alexandria), the entrances of which were often marked by lofty towers [110], [111], serving a number of purposes like:

- Navigation: marking the harbor entrance;
- Aesthetics: distinguishing the harbor and giving it a safe, guarded image;
- Defense: enabling to span chains at night in order to prevent enemy intrusion.

In the present post-modernity, such towers can also combine a number of functions, e.g. in the field of communication (radio, radar), surveillance (cameras), management (navigation signals) etc. Of course, care should be taken to avoid a “Christmas-tree effect” destroying the architectural value of towers.

A more detailed discussion on the suspension gate aesthetics falls outside the scope of this thesis. Let us conclude it by noting that the idea has been submitted by the author for aesthetical assessment by Zwarts & Jansma, a renowned Dutch architects team. Prof. M. Zwatrs described a suspension gate as “a possible enrichment of a lock sight” [112].

Within the author’s employer institution – the Civil Engineering Department of the Dutch Ministry of Transport, Public Works and Water Management – the suspension gate idea has been proposed for the two following navigation lock projects until now:

1. Reconstruction of the Orange Locks in Amsterdam (idea of Fig 108);
2. Construction of the “Naviduct” in Enkhuizen (idea of Fig. 109).

In both these projects, other – less innovative – gate types were finally chosen despite enthusiastic reactions within the project teams. The background of those decisions was, generally, not technical. In the first project, a third-party engineering consultant was contracted. He showed little appreciation for creativity. In the second project, the idea of two single-leaf gates in a crown (Fig. 109) was finally dropped for two staggered mitre gates, see gate layouts in Table 6. This would increase the number of towers per crown into four; and decrease the aesthetical advantages. In both projects, the factor that probably also played a role was a relative conservatism of the deciding individuals.

Since the completion of those projects, no other suitable opportunity occurred in the Netherlands for the construction of a suspension gate. The idea is, therefore, still waiting for its first realization.

[1] Personnel reduction or elimination on navigation locks and weirs has a number of negative effects. It does not, e.g., take account of the social function of lock personnel for both the vessel crews and the local population [77].

7.4. Short feasibility study

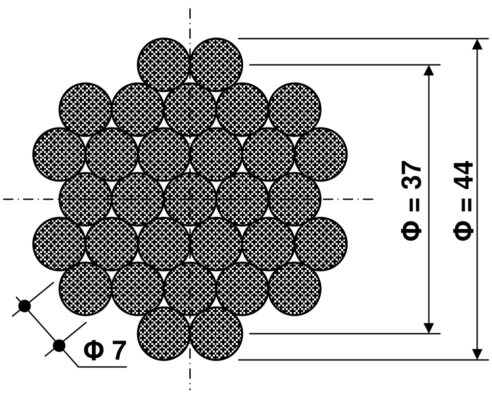
For a feasibility study, we choose a quite heavy single-leaf gate (as its rotation angle is larger than that of a mitre gate leaf) with the following parameters:

- Vertical hanger load: $\boldsymbol{V}$ = 400 kN;
- Horizontal hinge reaction: $\boldsymbol{H}$ = 400 kN;
- Hanger torque length: $\boldsymbol{L}$ = 10.0 m;
- Operation torque angle: $\boldsymbol{\Theta}$ = +45° ÷ -45° (gate installed in the middle stand).

7.4.1. Torsional suspension - cable

We shall confine ourselves to suspension members of steel although other than steel materials, particularly carbon fibers, become increasingly interesting for this application in recent years. Carbon fibers win more and more confidence in post-tensioning or reinforcing of bridges. Promising in this field are, e.g., the studies of K. Bergmeister and U. Meier [113], [114] in Europe.

There is a range of steel sections which can be considered for a suspension gate hanger. Mechanically, such sections must have two main properties: high tensile strength and low torsional rigidity. The type of section that very well answers this requirement is a cable consisting of parallel strands, of the type as used in post-tensioning concrete or in cable stayed bridges. Left- or right-lay rope can be considered as well, but an ordinary-lay rope (with left and right laid wires) seems a less favorable choice, as its torsion will cause an unequal stress distribution between the wire layers.



Take, e.g., a parallel wire strand 31ø7 mm, as drawn in Fig. 110, made of high tensile strength steel with tensile strength in the range of 1600 ÷ 1800 N/mm [115], [116], [117]. It gives the strand a minimum breaking load of 1900 kN. Assume conservatively a safety factor of 4.0[1]. The unity check for tensile strength is then:

$$\frac{4.0 \cdot 400.0}{1900} = 0.84 \quad < \quad 1.00 \qquad \ldots\text{OK.}$$

Fig. 110. Cross-section of the exemplary strand

The torque angle **Θ** gives both the shear and the normal stress in the strand wires. At first, the shear stress from single wire torsion will be controlled:

$$I_t = \frac{\pi \cdot d^4}{32} = \frac{\pi \cdot 7.0^4}{32} = 236\,\text{mm}^2$$

$$M_t = \frac{\Theta \cdot G \cdot I_t}{L} = \frac{45 \cdot \pi \cdot 0.81 \cdot 10^5 \cdot 236}{180 \cdot 10000} = 1500\,\text{Nmm}$$

$$\tau = \frac{M_t \cdot d}{2 \cdot I_t} = \frac{1500 \cdot 7.0}{2 \cdot 236} = 22.2\,\text{N/mm}^2$$

Unity check: $22.2/(0.58 \cdot 1600) = 0.024 \quad << \quad 1.00$ …OK.

[1] Careful assumptions are justified in feasibility studies. An additional reason in this case is strength reserve for torque and the resulting fatigue load. For comparison: Safety factors for the same strands in suspension or cable-stayed bridges are usually in the range of 2.0 ÷ 2.5.

This strength control is sufficient for the middle wire, but it may be questioned for the outside wires. These wires bear also normal stresses as result of the entire strand torsion. The outside wires assume then a spiral line. Concentrations of those stresses appear at both ends, where the spiral line must again asume a straight, vertical position due to the torque fixity. This is a so-called second-order problem, in which the wire deformation generates additional load components and stresses. Moreover – due to its slenderness, the wire falls not entirely within the beam theory. We shall first present the theoretical solution[1)] to this problem and then the numerical calculation.

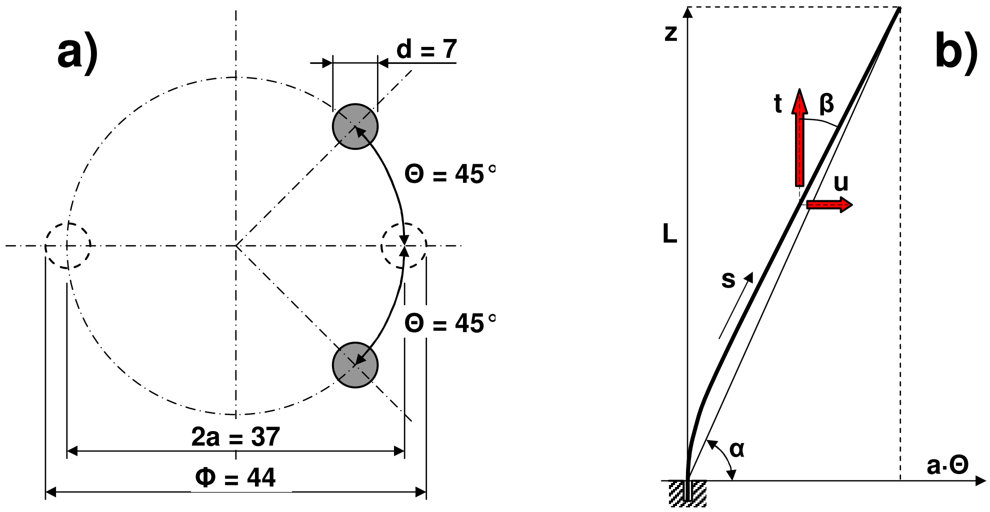


Fig. 111. Second-order bending of a wire in the outer layer

As the wire local angle ***β*** to the vertical is small, we can consider the wire plane development instead of the spiral line. If N is the total number of wires in a strand then each wire of the outer layer carries a vertical force ***t*** and a horizontal force ***u***, the latter holding up the torque angle **Θ**. These forces are:

$$t = \frac{V}{N} \;, \qquad u = t \cdot \frac{a \cdot \Theta}{L} \tag{7.1}$$

The wire angle to the vertical is ***β = β(s)***, where ***s*** is the local coordinate along the wire curve. Except for the two boundary zones, where the wire is fixed and its flexural stiffness plays a role, we have:

$$\beta \approx \alpha = arc\tan\left(\frac{u}{t}\right) = arc\tan\left(\frac{a \cdot \Theta}{L}\right) . \tag{7.2}$$

From the differential Bernoulli's equation for a bended member [118], we have:

$$EI \cdot \frac{\partial^2 \beta}{\partial s^2} = t \cdot \sin\beta - u \cdot \cos\beta = n \cdot \sin(\beta - \alpha) \;, \tag{7.3}$$

where: $n = \sqrt{t^2 - u^2} = \dfrac{t}{\cos\alpha}$.

[1] The author wishes to express his gratitude to dr. S.W. Rienstra and dr. J. Molenaar of the Eindhoven University of Technology, who helped him in finding this theoretical solution, see "Acknowledgements".

After the first integration of equation (7.3), we obtain:

$$\frac{EI}{2}\cdot\left(\frac{\partial\beta}{\partial s}\right)^2 = C - n\cdot\cos(\beta-\alpha)\ , \qquad 7.4$$

where $\dfrac{\partial\beta}{\partial s} = \beta'$ is the wire curvature.

When $\boldsymbol{s} \to \infty$, then $\boldsymbol{\beta} \to \alpha$ and $\boldsymbol{\beta'} \to 0$. This allows determining the constant: $\boldsymbol{C} = \boldsymbol{n}$. Therefore:

$$\frac{EI}{2}\cdot(\beta')^2 = n\cdot[1-\cos(\beta-\alpha)] = 2\cdot n\cdot\sin^2\left(\frac{\beta-\alpha}{2}\right)\ ,$$

$$\beta'(s) = 2\cdot\sqrt{\frac{n}{EI}}\cdot\sin\left(\frac{\alpha-\beta}{2}\right)\ . \qquad 7.5$$

After the second integration, we obtain:

$$\beta(s) = \alpha - 4\cdot\arctan\left[\left(\tan\frac{\alpha}{4}\right)\exp\left(-\sqrt{\frac{n}{EI}}\cdot s\right)\right]\ , \qquad 7.6$$

$$a\Theta(s) = \int_0^s \sin\beta(s')\,\partial s'\ , \qquad 7.7$$

$$z(s) = \int_0^s \cos\beta(s')\,\partial s'\ . \qquad 7.8$$

The last two equations represent the coordinates of the developed wire line. The maximal curvature of this line appears in the origin of these coordinates and can be determined from (7.5) as follows:

$$\beta'_{\max} = \beta'(0) = 2\cdot\sqrt{\frac{n}{EI}}\cdot\sin\left(\frac{\alpha}{2}\right) = 2\cdot\sqrt{\frac{t}{EI}}\cdot\frac{\sin(\alpha/2)}{\sqrt{\cos\alpha}}\ . \qquad 7.9$$

When – as in our case – the angle $\boldsymbol{\alpha}$ is very small, the equation 7.9 can be simplified to:

$$\beta'_{\max} \approx \sqrt{\frac{t}{EI}}\cdot\alpha = \sqrt{\frac{t}{EI}}\cdot\frac{a\cdot\Theta}{L}\ . \qquad 7.10$$

This curvature determines the extreme bending moment $\boldsymbol{M_{max}}$ in the wire:

$$M_{\max} = EI\cdot\beta'_{\max}\ . \qquad 7.11$$

The equations (7.10) and (7.11) can, obviously, also be used to determine the maximal curvature and bending moment in all other wires of the strand. The only parameter which changes then is the wire radius $\boldsymbol{a}$. One can also consider using, e.g., a bundle of Freyssinet-type strands [116], [119]. It should be recommended then to use a parallel bundle of coiled strands, and not the way around (coiled bundle of parallel strands) – anyway no coiled bundle comprising left- and right-coiled strand layers. In the latter, the strands are subject to reverse vertical length variations under the torque angle, which may spoil the uniform tensile load distribution assumed in formulas (7.1).

Having solved the problem theoretically, we can compute the numerical values of maximal additional stresses in the hanger section from Fig. 110. From (7.1), the tensile force $\boldsymbol{t}$ per wire is:

$$t = \frac{400 \cdot 10^3}{31} = 12900 \text{ N.}$$

The wire flexural rigidity ***EI*** is:

$$EI = 2.1 \cdot 10^5 \cdot \frac{\pi \cdot 7^4}{64} = 2.475 \cdot 10^7 \text{ Nmm}^2.$$

The curvature $\boldsymbol{\beta'_{max}}$ in the strand fixity section is, according to (7.10):

$$\beta'_{\max} = \sqrt{\frac{12900}{2.475 \cdot 10^7}} \cdot \frac{18.5 \cdot 45 \cdot \pi}{10000 \cdot 180} = 3.317 \cdot 10^{-5} \text{ mm}^{-1}.$$

The wire maximal bending moment from (7.11) is then:

$$M_{\max} = 2.475 \cdot 10^7 \cdot 3.317 \cdot 10^{-5} = 821 \text{ Nmm.}$$

This gives the extreme additional normal stress $\boldsymbol{\sigma_{max}}$ from the wire bending:

$$\sigma_{\max} = \pm \frac{821 \cdot 32}{\pi \cdot 7^3} = \pm 24.4 \text{ N/mm}^2.$$

This stress is only about 1.5% of the wire tensile strength of 1600 ÷ 1800 N/mm^2. The shear stresses will, therefore, also be marginal. There is no point in further analysis. Hanger static as well as fatigue strength are both easily solvable issues in case of the cable option.

7.4.2. Torsional suspension – chain or packed flats

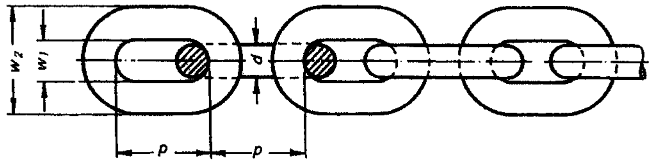
Chains are not in large demand in structural engineering any more, but they are still widely used in old hydraulic gates. Moreover, they continue playing a role in navigation and special maritime operations – a role which has given them some emotional value in that branch. Chains hold anchors (Fig. 112), help in a salvage of sunk or endangered ships etc. Chains are also very expressive items. As navigation is what lock gates are primarily built for, one may consider referring to those emotional and aesthetical values by using chains as hangers of a suspension gate.

True, a chain is as strong as its weakest link, while cable strength is usually a sum of the strengths of its wires. This cliché example from the theory of probability does not, however, take account of the common supply conditions. The truth is also that all chains are factory tested nowadays to the tensile load of 2÷2.5 x SWL (Safe Working Load). The actual break loads are usually about 4÷5 x SWL [120]. This makes chains not less reliable than strands or cables. One can continue weighting the two against each other, e.g. by assessing the risk of a link replacement against a wire replacement, but this goes beyond the scope of a feasibility study.

Fig. 112. Chain of a ship anchor

Table 24. Commercially available chains, example [120]

THIELE ALL0Y STEEL CHAIN
(GRADE 80)



Nominal thickness (mm) d	±	Inner length (mm) p	±	Inner width (mm) w_1 min.	Outer width (mm) w_2	w_2 max.	Safe Working Load (tons)
6	0,2	18	0,5	8	21	21,6	1,12
7,2	0,2	21,8	0,6	9,45	24,5	25,2	1,5
8	0,3	24	0,7	10,8	28	28,8	2
10	0,4	30	0,9	13,5	35	36	3,15
13	0,5	39	1	17,5	45,5	46,8	5,3
16	0,6	48	1,4	21,5	56	57,6	8
18	0,9	54	1,6	24,3	63	64,8	10
20	1	60	1,8	27	70	72	12,5
22	1,1	66	2	29,5	77	79,2	15
26	1,3	78	2,3	35	91	93,6	21,2
28	1,4	84	2,5	37,8	98	100,8	25
32	1,6	96	2,9	43,2	112	115	31,5
36	1,8	108	3,2	48,5	126	130	40
40	2	120	3,6	54	140	144	50
45	2,3	135	4,1	61	157,5	162	63
50	2,5	150	4,5	67,5	175	180	80
56	2,8	168	5	75,6	196	201,6	100

There are more chain types which can be used as a suspension gate hanger. We shall consider the simplest one, as drawn up in Table 24. The chain SWL's available in that table vary up to 1000 kN, which is 2.5 time as high as the $\boldsymbol{V}$ = 400 kN in this study. The most obvious selection is the chain of the outer width w_2 = 126 mm, with the SWL = 400 kN.

$$\frac{V}{SWL} = \frac{400}{400} = 1.00 \qquad \ldots\text{OK.}$$

There is practically no chain torsion or other load within the considered geometrical conditions. Therefore, no further control is required.

One can probably consider it a disadvantage that the chain solution does not really eliminate the twist slip friction under vertical load. That friction exists still, but the twist angle of 45° is spread over a large number of link contacts. The author does not expect it to be a significant problem.

The last possibility to be considered here is a hanger made of packed flats. There are a number of steel grades satisfying the requirements of such a hanger. An unusual requirement is that the flats must be able to undergo some mutual slide displacements due to the hanger torque. The engineer will possibly like to have their surfaces machined or, in any case, free of mill scale. This is a usual requirement for, e.g., railway wagon springs, as the one drawn in Fig. 113. The existing experience with such springs can also be a model to generate other requirements, e.g. concerning corrosion protection, steel grade selection[1)], design stresses etc.

Because the dominating hanger load is tension, not torsion, we first consider an ordinary structural steel solution, using flats of steel grade Fe 510 according to the Eurocode 3, [27], with the yield stress of f_y = 355 N/mm^2. Like in the cable solution (section 7.4.1), we assume a high all-over safety factor in order to cover a wide range of design conditions in this feasibility study, here SF = 2.0.

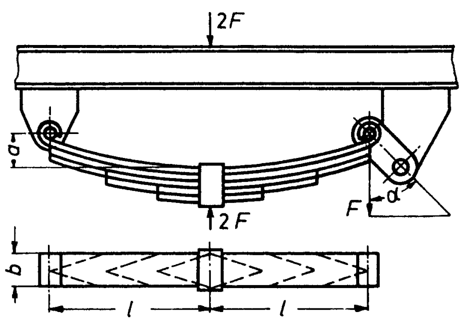
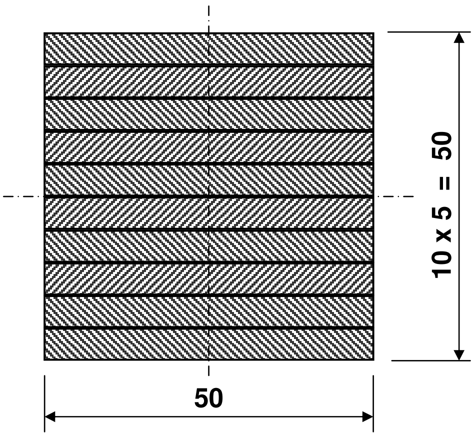


Fig. 113. Spring support of a railway wagon

The hanger cross-section should be as compact as possible, because the farer from its centerline, the higher shear and normal stresses from torsion will be. Let us take a pack of 5 x 50 mm flats, at this

[1] In Europe, spring steels of grades 65 Si 7 and 66 Si 7 (acc. to German DIN-codes) are commonly used here.

stage without dimensional corrections for (e.g. graphite) greasing, possible zinc coating etc. This gives a cross-section as shown in Fig. 114.



Load ***V*** gives the following normal stress ***σ***, followed by its unity check:

$$\sigma = \frac{400 \cdot 10^3}{10 \cdot 50 \cdot 5} = 160 \text{ N/mm}^2 ,$$

$$\frac{SF \cdot \sigma}{f_y} = \frac{2.0 \cdot 160}{355} = 0.90 < 1.00 \qquad \text{...OK.}$$

Fig. 114. Cross-section of a flat pack hanger

The axial torsion $\boldsymbol{M_t}$, the resulting shear stress ***τ*** in flats 50x5, and its unity check are:

$$M_t = \frac{\Theta \cdot G \cdot I_t}{L} = \frac{45 \cdot \pi \cdot 0.81 \cdot 10^5 \cdot 1956}{10000} = 12440 \text{ Nmm} ,$$

$$\tau = \frac{M_t}{W_t} = \frac{12440}{391.2} = 31.8 \text{ N/mm}^2 ,$$

$$\frac{SF \cdot \tau}{0.58 \cdot f_y} = \frac{2.0 \cdot 31.8}{0.58 \cdot 355} = 0.31 < 1.00 \qquad \text{...OK.}$$

Unlike the normal stress ***σ***, stress ***τ*** has an alternating character, that can eventually cause fatigue. The value of this stress is, however, too small for that. Also the bending stress as result of torque in both outer flats is small. The computed extreme values of this stress are:

- ***σ*** ≈ 5.5 N/mm² from linear approach (only bending due to Θ·a);
- ***σ*** ≈ 17.7 N/mm² from non-linear approach (non-axial tension, as in Fig. 111).

These stresses are so small that there is no reason to doubt about the feasibility of the flat pack option for a suspension gate hanger. Additionally, as the assumed material in this test is structural steel, there is a wide range of other, higher steel grades which can be considered for this application.

7.4.3. Gate bearings

The large diameter of thick-walled pipe in the heel posts of the suspension gate makes it possible to use homogeneous synthetic contact materials in gate hinges. These materials can usually bear low contact loads but they are isotropic and give little or no risk of delaminating, aging or other damage. We shall consider hinge bushing of polyethylene UHMPE in this feasibility study. The fact that this material can successfully be used in both bottom and top hinges, has already been proved by the author in practice, see hinge details of the Lock III gate in the Wilhelmina Canal in Tilburg (Fig.48 and 102). The design loads assumed in this feasibility study are, however, much higher than in the Tilburg lock gate. They intend to cover a wide range of possible projects.

Let us assume the structural steel heel post pipe of an outside diameter Φ356 mm (14”) and the wall thickness t = 32 mm (1¼”). At both ends of that pipe we shall put shrink-on sleeves, 12 mm thick, of stainless steel AISI 316L according to the US codes or 18Cr6Nixxx according to the European norm [121]. We have seen in Fig. 84 that such sleeves perform well in rudder bearings. This gives the hinge shaft outside diameter of Φ380 mm. The inside diameter can still house all the three optional hanger types, as considered in sections 7.4.1 and 7.4.2. As both (the top and the bottom) hinges bear the in our case same horizontal load H = 400 kN, we shall assume that they are identical at this stage. Possible modifications due to different assembly or maintenance conditions can be introduced later on.

Further geometrical arrangements of the hinge can, e.g., be assumed as drawn in Fig. 115.

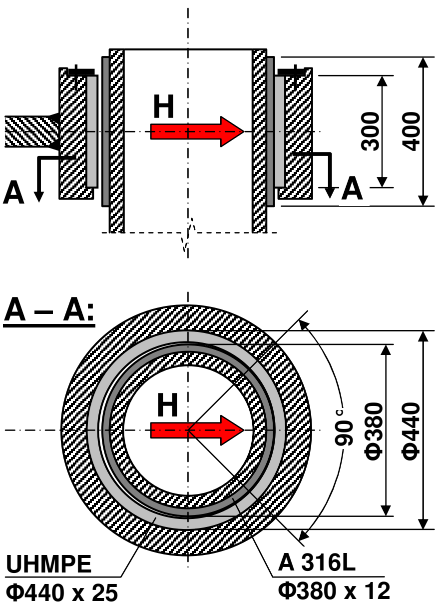


Fig. 115. Suspension gate bearing

The relatively large contact areas of UHMPE in relation to its thickness and the good incasing of this material entitle us to increase the design contact stress in Table 8 (chapter 3) from 3 N/mm^2 to $\boldsymbol{f_d}$ = 5 N/mm^2. An additional argument for this is that no visible wear has been observed yet in the hinges of the Lock III gate of the Wilhelmina Canal[1]. The hinge clearance will be assumed as 10 mm, which is much and covers also the so-called 'free-hinged' gates, i.e. type (b) from Fig. 4. The actual contact angle $\boldsymbol{\beta}$ can now be estimated as 90°, which is larger than in the Lock III gate due to the relatively smaller clearance. We shall substitute the non-linear pressure distribution by an equal distribution, as done earlier in Fig. 48 (d). These assumptions give us the following required height of the UHMPE bushing:

$$h_{req} = \frac{4 \cdot H}{\pi \cdot f_d \cdot \Phi} = \frac{4 \cdot 400 \cdot 10^3}{\pi \cdot 5.0 \cdot 390} = 261.2 \text{ mm},$$

assumed: $\boldsymbol{h}$ = 300 mm.

As the assumption of $\boldsymbol{\beta}$ is no more than an "engineering guess", it is advisable to check whether it still gives an acceptable bushing compression **Δ**. This compression is a function of time for viscoelastic materials (see formulas 4.13 and 4.14 in chapter 4), but a compression below some 5% of the bushing thickness can certainly be accepted as long as it does not disturb the geometry of the system. It will be checked now using the diagram from Fig. 49:

$$\beta = 90°, \qquad \frac{D_i}{D_o} = \frac{380}{390} = 0.975 \qquad \Rightarrow \qquad \frac{\Delta}{D_o} = 0.002\,,$$

$$\Delta = 0.002 \cdot D_o = 0.78 \text{ mm} \ < \ 0.05 \cdot 25 = 1.25 \text{ mm} \qquad \ldots\text{OK.}$$

The last parameter to be checked is the bushing wear $\boldsymbol{S}$. From the formula (6.1), we have:

$$S = L \cdot p \cdot k \text{ [mm]}\,, \qquad 7.12$$

where:

L = total slide distance to cover during the bushing service life; let us take:
20 years · 365 days · 20 lockings · swing angle of ¼π · radius of 195 mm = 2.24·10^7 mm;

p = mean contact pressure, here 4.35 N/mm^2;

k = specific wear factor, k ≈ 0.5·10^{-9} mm^2/N from test results in Table 21.

For the considered hinge, (7.12) gives:

$$S = 2.24 \cdot 10^7 \cdot 4.35 \cdot 0.5 \cdot 10^{-9} = 0.05 \text{ mm} \qquad \rightarrow \text{ negligible.}$$

[1] This is an "engineering approach" of seeking the limits of feasibility in both the theory and field experiences.

These results prove that the assumed gate bearing type is easily feasible for a suspension gate. We see that low contact stresses have been obtained in the bushing of UHMPE, which is a quite soft material. Therefore, a wide range of other synthetic materials can as well be applied in the suspension gate bearings. An additional advantage is that these are all maintenance-free or maintenance-saving materials, which decreases both the costs and the environmental impact of such device. This also goes well along with the aim to solve the current maintenance problems of gate hinges, see section 7.1. This aim is the main purpose of the suspension gate idea.

7.4.4. Assembly, installation and maintenance

Hydraulic gates are in most cases entirely manufactured at construction yards, shipped or floated to the sites and – thereupon – installed in definitive locations. The latter is usually a very well planned operation that must be completed within a day (at most a few hours); and is in fact quite spectacular. Both gates of the Hartel Canal Barrier were, e.g., shipped to the site location at night, and installed in the early morning hours (Fig. 116) in order to disturb the navigation in the Rotterdam harbor area as little as possible [8], [40].

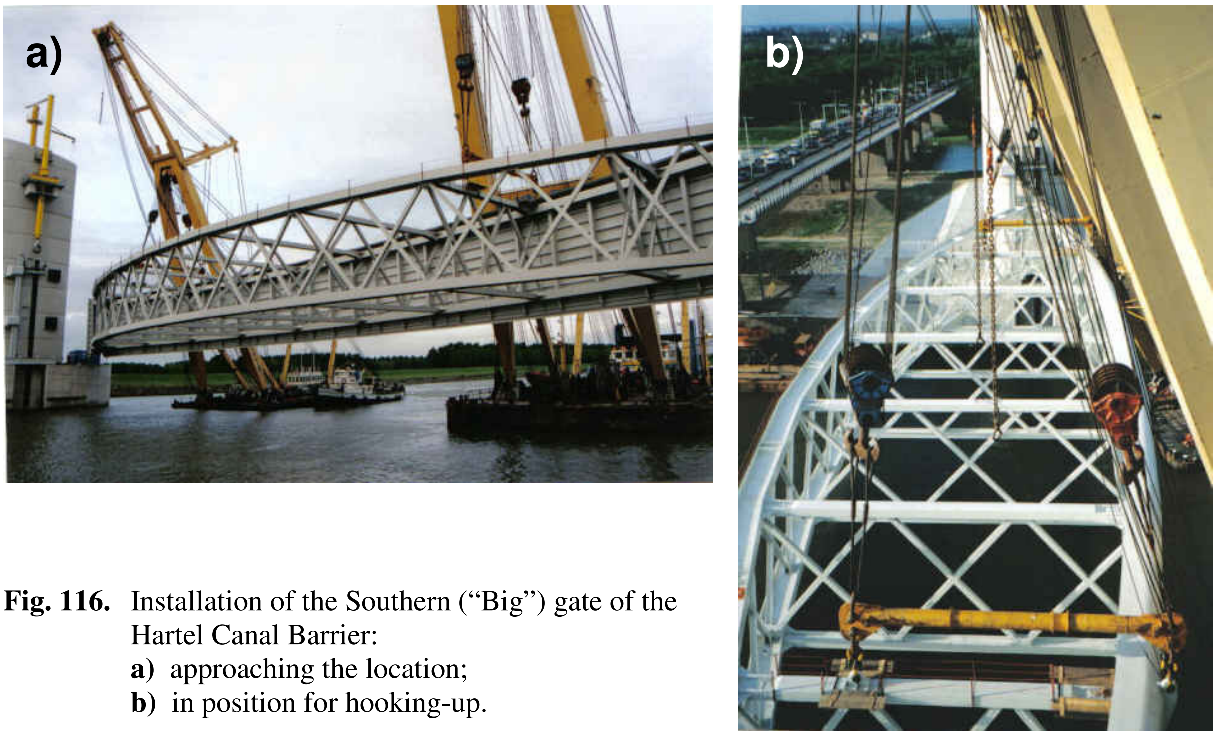


Fig. 116. Installation of the Southern ("Big") gate of the Hartel Canal Barrier:
a) approaching the location;
b) in position for hooking-up.

Other than navigation reasons for a fast installation of hydraulic gates are, e.g.:
- Utmost attention and discipline required – men can not hold it for long;
- Required hold-up to almost all other works – expensive when lasting long;
- Expensive heavy (floating) cranes and other equipment required;
- Attracting spectators and media – disturbing and dangerous if not properly guided[1)];
- Risk of changing weather conditions, tidal flows in sea harbors, etc.

Therefore, we shall forget in this study all installation methods which require a longer time than a few hours. This means that the gate and its suspension must be fully prefabricated when approaching the

[1] …but also entitled to be there. This subject falls beyond the scope of the thesis.

site. Depending on the hanger length and material, precautions may be required to keep the hanger in vertical position at that moment. This can be obtained, e.g., by a temporary column fixed to the gate top girder, an additional small derrick ashore or an extended spreader beam with a suspension lug. In a similar way we can find more solutions to other installation-related problems. A tool to assess them is again a morphological survey, as already introduced in section 7.2. In this case, the selection matrix can be, e.g., as drawn in Fig. 117. Let us narrow the considerations down to the partial functions which are new in relation to conventional gate installation. We can distinguish thee such functions:

- The hanger must be ready to suspend the gate directly when approaching the location;
- The tower must be ready to take the hanger load over when approaching the location;
- Both hinges must enable an easy and quick coupling of the heel post shaft.

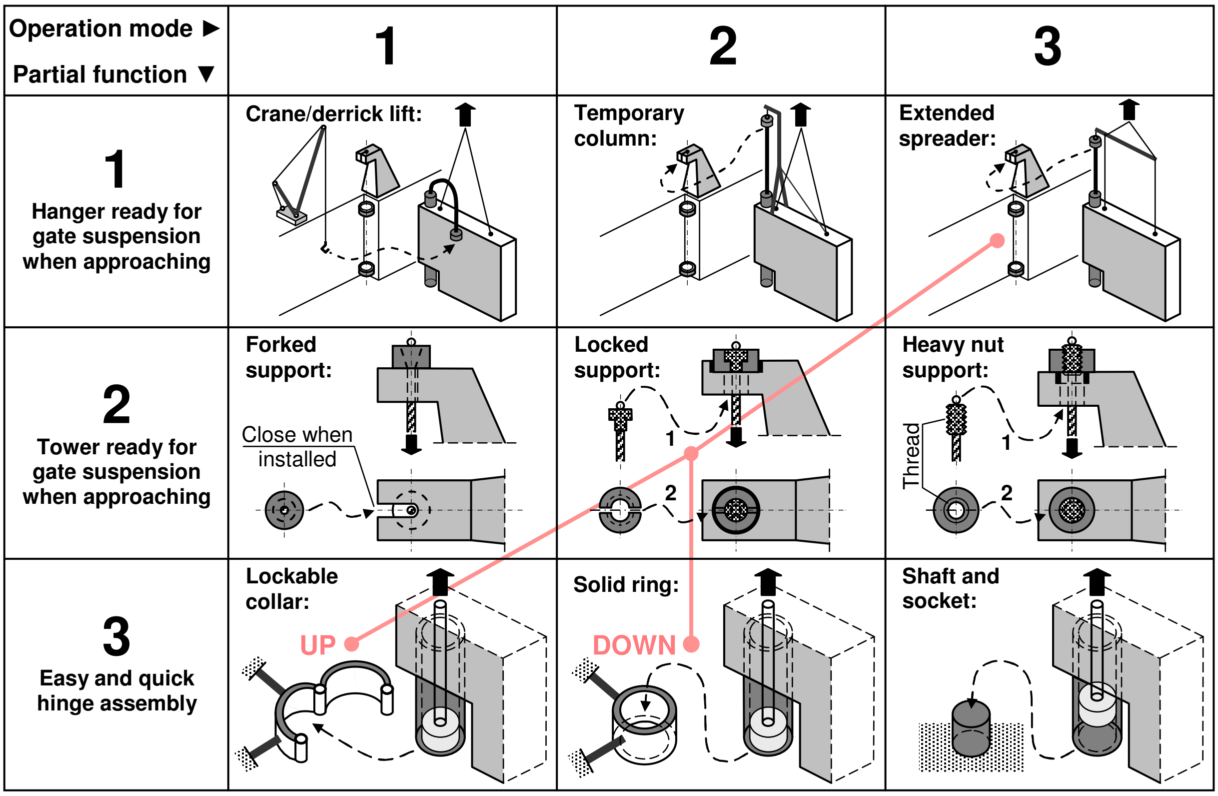


Fig. 117. Morphological survey matrix for an installation method of the suspension gate

The matrix in Fig. 117 does not pretend to comprise all possible operation modes. E.g., the modes that make use of a temporary gate support to the chamber bottom have been omitted for both the time and the costs reasons. A light bottom construction is, after all, one of the suspension gate advantages. The evaluation and the final design of the gate installation method strongly depend on local conditions. We shall not complete it now for this reason. One of the many possible results ("structures") is marked in Fig. 117. In this example, different operation modes in the top and bottom hinges have been chosen. The lockable top hinge results in less vertical space requirements during assembly. The hardly accessible bottom hinge is, to the contrary, of the solid type fearing the difficult locking under water.

The problems with that locking, caused mainly by rust, have also been encountered on the top hinges, but the conditions to manage them there are better because no divers work is required. These problems are not easy to solve due to the combination of two following factors:

- High and varying contact stresses on locking pins;
- Close tolerance pins required.

In consequence, much effort is usually required to remove the pins after some years of operation, often resulting in a pin damage. A solution, successfully introduced by the author in two projects (Lock III in the Wilhelmina Canal [29] and Naviduct Enhhuizen [43]), is the pins covered by spray-fused (SF) nickel 40, 1 mm thick [122]. The lockable collar ring of the Lock III gate hinges, including the pins, is shown in Fig. 48. The lockable outer ring of the Naviduct gate hinges is shown below (Fig. 118).

Fig. 118. Lockable collar ring of the mitre gates in the Naviduct Enkhuizen
left: ready for gate coupling;
right: during gate installation.

Though the suspension gate is a new type of structure, the operation modes of all the partial functions in Fig. 117 are not new. We see that similar or identical installation procedures are quite common in hydraulic gate projects. An important conclusion for this thesis is that there exist a number of proven installation possibilities for the suspension gate. The feasibility of this type of structure is, therefore, also proved with respect to its execution and exchange in case of ship collision, maintenance or the application of new coating.

Another new aspect concerning maintenance is the corrosion of the hanger. Let us assume that the pipe housing it is open to water intrusion from rain, wave spray, condensation etc. Although removing this water is possible (e.g. by air compression into the pipe), it may still be inconvenient. The question is whether dewatering or other corrosion protection of the hanger is necessary. This question has been studied by the author with respect to both salt and fresh water. The corrosion progression for construction steel used in this study was [123]:

- in fresh water: 0.012 mm/year;
- in salt water: 0.120 mm/year;

Assuming a double value for fresh water (even in costal areas water in the pipe will mostly be fresh), the hanger cable as in section 7.4.1 and its service life of 25 years, the section reduction will be, [6]:

- when the entire surface of all wires in a strand corrodes : 33%;
- when only the outside surface of the outer wires corrodes: 9%.

The actual corrosion will lay in between, probably closer to the second value, which can be explained by chemical processes, in particular the low oxygen content of water. Obviously, the surface reduction will be lower in other sections due to the lower total circumferences. It means that a strand oversize of some 15÷20% will be sufficient, otherwise hot dip-zinc coating, synthetic sleeve or another protection should be considered. Anyhow, hanger corrosion is not a matter of feasibility for the suspension gate.

7.5. Gate costs and concluding remarks

The idea of suspension gate was also studied and compared to conventional gates in terms of costs. All involved disciplines (steel structures, civil works, mechanical devices) were considered, as well as all project phases (design, construction, maintenance). This study was carried on in the early stage of the project Naviduct Enkhuizen, when the intended solution comprised single-leaf gates (Fig. 109), [6]. In the total construction costs, the differences between conventional and suspended gates were small and could be summarized as shown in Table 25:

Table 25. Construction cost indices for a suspension gate (types referring to Fig. 107)

Conventional gates	**Suspension gates**		
	Type (a)	**Type (b)**	**Type (c)**
reference gate costs 100 %	costs higher: 101.0 %	costs equal: 100.0 %	costs lower: 98.9 %

This estimation did not cover the engineering costs. For all the three suspension gate types, those costs were expected to be slightly (~ 1% of the gate construction costs) higher than for conventional gates. There was a controversy whether those costs should be counted, because some more engineering effort in case of a suspension gate represented also an investment in knowledge that could be considered an additional value. Nevertheless, the differences in construction costs in Table 25 remain also small after the inclusion of the engineering costs.

A comparison of the maintenance costs gives, to the contrary, a significant difference. The suspension gate with polyethylene hinge bushings appears to be about 40% cheaper in maintenance than the conventional gate. As maintenance costs are spread over the gate entire service life of some 50 years, we should capitalize them back to the time of project execution before adding to the construction costs. This results in the following comparison[1)] (Table 26):

Table 26. Construction and capitalized maintenance cost indices for a suspension gate

Conventional gate, only construction	**Conventional gate, with maintenance**	**Suspension gate, with maintenance**		
		Type (a)	**Type (b)**	**Type (c)**
reference gate costs 100 %	total gate costs: 126.5 %	total gate costs: 116.9 %	total gate costs: 115.9 %	total gate costs: 114.8 %

The conclusion of this cost comparison is that the suspension gate is not significantly more expensive than a conventional mitre or single-leaf gate in regard of the construction costs. However, it is significantly cheaper in regard of the maintenance costs. This makes the difference in the total (construction + capitalized maintenance) costs of about 10÷12% to the advantage of the suspension gate. As the cost difference is not high, this advantage does not necessarily apply to every lock gate project. In general, the total costs of suspension gates will clearly be lower in case of high water heads and intensive navigation – and comparable in case of small hydraulic loads and incidental locking.

In recapitulation, the following general conclusions concerning the suspension gate idea can be drawn:

- The presented idea offers a structural solution to the problem of wear and geometry distortions resulting from the combination of horizontal and vertical (radial and axial) load in one hinge. This solution is found by letting the vertical load be taken up by a tensile suspension member outside the gate hinges. This removes the first cause of the current problems.

[1] The yearly interest rate was assumed to be 3% in these estimations.

- The presented idea removes also the second cause of the current problems, which is the instability of the vertical load response by different system components. The ability of this load is obtained by elastic – instead of rigid – response in a long suspension member.

- The suspension gate idea has been developed from a systematic inventory and analysis of field problems. Its basic concept was received using a so-called morphological survey method. Therefore, the idea and its components have a verifiable character and can reliably (in quantifiable terms) be compared to other hydraulic gate arrangements.

- There are three main types of a suspension gate possible, as presented in section 7.3. These types comprise different hanger, heel post and suspension point arrangements. The advantages and disadvantages of each of these types have globally been presented, but they also strongly depend on the local conditions.

- One of the advantages of the discussed gate is a very remarkable, expressive aesthetical effect of the suspension towers. This effect will, presumably, especially appeal to the vessel crews and passengers, as it spectacularly accentuates the lock entrance and makes the gate system communicative. Obviously, thorough shaping and landscaping is required to take full profit of this effect.
- Potential disadvantage in the form of an obstacle in the walkway over the gate can e.g. be solved by a section overlapping the crown floor in the vicinity of the hanger. This may be desired in suspension gates of types (a) and (b) from Fig. 107, if the walkway passage is – indeed – significant. The gates of type (c) do not have such an obstacle.

- The feasibility study of the suspension gate proves that all the requirements for that structure can be realized within the commercially available technology. This includes a number of suspension arrangements (high, low or no tower), suspension media (cable, chain, packed flats), hinge bushing materials (UHMPE, other synthetics and composites) etc.

- The feasibility study proves also that there are no significant installation or maintenance problems when choosing a suspension gate. The morphological survey approach to gate installation results in a number of possible installation procedures, at no more effort than by conventional gates. Also the matter of hanger corrosion is easily manageable and does not affect the gate feasibility.

- Although cost estimations strongly depend on local specifications and economical relations, an effort has been made to compare the costs of a suspension and conventional gate for a realized lock gate project in the Netherlands. The results show basically the same construction costs in both cases, while the maintenance costs of a suspension gate are significantly lower.

This page is deliberately left blank.

8. CONCLUSIONS AND RECOMMENDATIONS

8.1. Concluding remarks on the significance of contact engineering

The aim of this study was to emphasize the importance and to propose a framework for the analysis of contact related problems in hydraulic gates. The author approached this task with a large number of practical cases and solutions collected from his work in design, research, engineering and management of hydraulic gate projects. While systemizing this material, his conviction of the insufficient attention to the contact problems in the current practice grew stronger. This thesis, as presented in chapter 1, claimed both more weight and space for the contact related issues in design processes. It also pleaded for breaking with the conventional, discipline-orientated approach to these issues, claiming that the hydraulic gate contacts must be seen as more than a matter of detailed engineering. They must be considered significant already at the stage of gate type selection; recognized as co-determining the entire structural systems of gates, the types of their drives etc. Also in the last phases of projects – the realization and the operation phase (the latter not always seen as a project) – gate contacts deserve more attention than what they usually receive nowadays.

A thesis formulated in this way can hardly be proved by processing numerical data from experimental or other research. This study contains, therefore, little equations and complex mathematics, which may be surprising in a doctoral thesis. The applied research method included mainly collecting, systemizing and analyzing of the relevant field experiences; followed by a reasoned synthesis of conclusions. In addition, a program of laboratory investigations was carried on, focused on the aspects of different materials behavior in hydraulic gate hinges. The results of these investigations should, however, only be seen as one of the supports – not the main subject – of this thesis.

The question whether the submitted thesis has been proved can not be answered by adducing new derived formulas, measured or computed results, or in another “hard” manner. An answer to it depends on the cogency of the quoted arguments. The author hopes to have convinced the reader by presenting a range of correlations between the contact issues and the performances of hydraulic gates as a whole. As this thesis has a deliberately interdisciplinary character, it will possibly not satisfy the professionals who expect to deepen their specialization in a single discipline. It does not, e.g., go very deep into all relevant aspects of contact engineering. However, it shows the relations of this engineering with other disciplines involved in hydraulic gate projects. The purpose of this is double: On the one hand it aims to encourage the contact engineers to interfere in more aspects of hydraulic gate projects; and on the other hand it tries to make other participants of those projects aware of the significance of gate contact problems. The author believes that this strategy has more chance of success in putting the contact engineering in a position recommended in chapter 1, than only striving for more perfection in theoretical contact models or in the contact technology.

The growing specialization in construction disciplines, welcome as it is, carries also a trap: It increases the distance between the disciplines and makes the communication more difficult. This strengthens the position of the leading parties in a project; and weakens the positions of other participants. It too often leads to a situation in which contact specialists claim to have foreseen poor performances, but received no attention. This, in turn, is too often seen as a matter of pure communication (with all grotesque consequences of that, like calling on communication advisers etc.) – with no elements of power contest. The most straight way to get out of this trap is to revaluate the significance of contact related problems – and to do it by the own strength of the involved groups of professionals. The author of this doctoral thesis hopes to have contributed to this goal.

8.2. Some technological conclusions and recommendations

Different chapters and sections of this study have already been provided with proper conclusions and recommendations. In this section, only some very general conclusions and recommendations are repeated, followed – if required – by references to other sections for details.

- Different examples and analyses of this study demonstrate that gate contact issues should already be considered at the stage of project specifications, as they codetermine the gate type selection. Therefore, it is recommended that the requirements concerning gate contacts make part of those specifications or can be derived from other requirements. Examples of contact related requirements at the stage of gate type selection are given in section 2.1.

- Hydraulic gates of any type can still have different support and guide systems, locking devices, drives etc. These arrangements are all, in fact, contact provisions. Their selections, locations and designs must, therefore, take into account the requirements of both the gate systems as a whole and the contact assemblies as the "front line" components. Section 2.3 contains guidelines in this matter for the three most frequently used gate types: the mitre, the vertical and the rolling gates.

- When the decision about gate type selection has been taken, the requirements concerning contact arrangements can further be specified and systemized. This includes, in particular, the functional reliability requirements in terms of probability of failure. Examples of these and other requirement specifications at that stage are given in sections 2.4 and 2.5.

- Hydraulic gates are structures that assume not only variable positions but also variable structural systems in diverse operation stands. As result of that, there is usually a large diversity of contact areas and contact loads. Examples of this diversity are given in section 3.1 for the mitre and the rolling gates. It is important that all occurring contacts are analyzed as such in the design.

- The analysis of hydraulic gate contacts can be carried on at different levels. This thesis proposes an object-orientated level definition (section 3.2), that slightly differs from the definition quoted in tribological literature. The reason is that contacts are claimed here to have a much wider than only tribological significance. Four contact analysis levels are proposed: the system, the component, the segment and the asperity level.

- In the recent decades, a new group of complex contact problems frequently manifests itself in the Netherlands. These problems are introduced by a tendency to let the gates carry hydraulic loads in alternating directions. In particular, the mitre and the single-leaf gates are hardly suited for this task and require additional provisions. Overviews of these provisions and the author's own experiences in this field have been presented in sections 3.3 and 3.4.

- One of the most significant recommendations concerning the hydraulic gate contacts is to avoid or to minimize the lateral loads on contacting solids. Diverse considerations and constructive solutions in this field for the vertical lift, the rolling and the mitre gates – mainly but not exclusively from the author's practice – are presented in section 3.5.

- Not only the load size, direction and distribution are significant in gate contacts, but also the load history. This includes the phenomena like relaxation, creep, viscoelasticity, thermal behavior, corrosion, contact fatigue, wear etc. A full discussion of these phenomena goes beyond the scope of this thesis, but a global presentation is included in section 3.6.

- Contact design loads follow, in general, from the design loads and load combinations for the gate as a whole. A systematical determination of the gate design loads is presented in sections 4.1 ÷ 4.3. However, the representative load combinations for gate contacts are often not the same as for other components of the gate structure. It may also be required to consider additional loads and load combinations in order to determine the representative load combinations for the gate contact components.

- An important stage in every contact load definition is the determination of the load distribution model. This model depends on the deformation character (e.g. elastic, elastoplastic, plastic, viscoelastic), as well as the contact geometry (e.g. conforming, nonconforming) and the load course (e.g. static, dynamic, stationary, moving). Some theoretical background and practical examples in this matter are presented in sections 4.4 ÷ 4.6.

- Unlike the rest of a gate structure, the contact components can not usually be designed on the base of stress and strain analysis alone. Additional contact phenomena must be considered, such as: strain hardening, friction, abrasion, adhesion, heat generation, stick-slip behavior etc. An introductory discussion on these and other phenomena in hydraulic gates is given in section 5.1.

- The phenomena mentioned above can hardly be considered on the system or the component level. It is necessary to go down to the segment or the asperity level when investigating their nature. The system level division into pointed, linear and surface contacts does not apply to the other levels any more. There also emerge interesting contrasts between the contact phenomena in e.g. metallic and synthetic materials.

- A particularly unfavorable contact case in hydraulic gate hinges is the combination of horizontal (radial) and vertical (axial) load in one hinge. Different examples of analyses and practical solutions of this and other cases in realized projects are presented in sections 5.2 ÷ 5.5. In a number of these analyses, the author's computer program "DISCO" for structures with discontinuous support conditions has been used.

- The wear problems with, in particular, mitre gate hinges inspired the author to perform a series of laboratory investigations and tests on the behavior of different materials in those hinges. The investigations were preceded by an inventory and analysis of the problem, including a survey of relevant solutions in other technological fields, e.g. by ship rudder bearings. The conclusions of this survey and the program of the investigations are discussed in sections 6.1 ÷ 6.4.

- The investigations mentioned above generated results covering wear factors, friction coefficients, data about roughness influence, heat generation, influence of moisture etc. – on a wide range of contact material combinations including metallic, synthetic and composite materials. They also enabled to determine the wear mechanisms of those materials. As the test parameters were derived from the actual gate hinge operation, the results are indicative for the design of hydraulic gate hinges. These investigation results are discussed in sections 6.5 and 6.6.

- The current problems with hydraulic gate hinges can be (more or less successfully) managed by geometrical and/or material modifications – but they can also be structurally solved. A way to do it is the idea of a suspension gate. In that gate, the vertical load is transferred to an elastic, tensile member outside the gate hinges, which avoids combining this load with the horizontal load in one hinge. The genesis of a suspension gate is discussed in sections 7.1 and 7.2.

- There are, basically, three types of a suspension gate possible, as shown in section 7.3. The feasibility study presented in sections 7.4 and 7.5 proves that all the components and arrangements of this structure can be realized within the existing technology; and do not require more effort than in case of a conventional gate. The construction costs of a suspension gate are the same, and the maintenance costs are lower than those of a conventional gate.

8.3. Areas of further research, anticipation of developments

In the Dutch province of Limburg – with important waterways to Belgium, France and Germany – all lock and weir operation distortions were set in a data base and sorted by the author's request. The data base covered a period from January 1999 till April 2004. Only the distortions resulting in a significant operation break were considered. As there are large lock and weir complexes in that province, with a great diversity of hydraulic gates, the results can be considered representative not only for the whole country but also internationally. The global figures [124] were as follows (Fig. 119):

- total number of operation distortions: 1267;
- herein due to electrical or control failures: 1024;
- the rest, generally labeled "mechanical": 223.

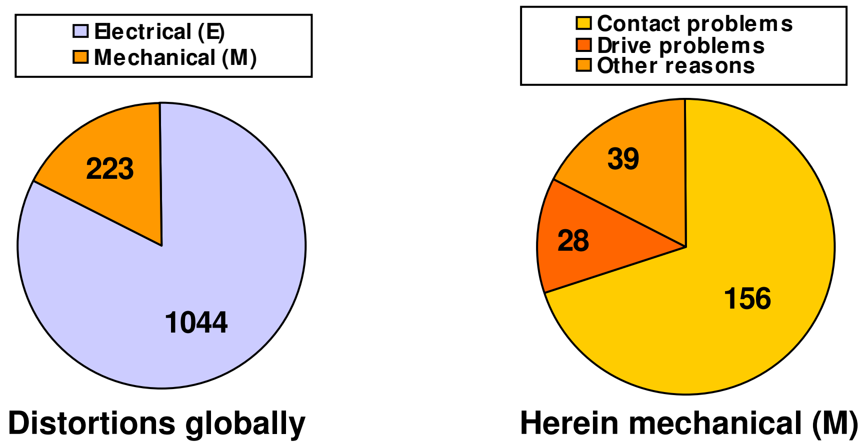


Fig. 119. Global pie-charts of hydraulic gate operation distortions on waterways in Limburg
left: split into electrical and mechanical distortions;
right: split of mechanical distortions by their nature.

The electrical and control system failures, alarming as they are, fall beyond the scope of this thesis. For some 60 ÷ 80% of the remaining 223 "mechanical" distortions, however, the contact problems can be blamed. There was further no structural failure due to the stress or strain excess outside the gate contact areas, even not after some ship collisions that had, in fact, taken place in the considered period. The exact percentage of the contact related distortions is difficult to draw due to complexity of some reasons, nevertheless the quoted figures are still remarkable.

These results indicate that we should revaluate the significance of the contact problems, which has already been claimed in this thesis. The author does not plead for doing it at the cost of structural analysis as a whole. That analysis is and should remain the engineer's core activity. Nevertheless, some parts of it, e.g. peak stress computing using very fine mash models, can be given some less attention making place for more thorough contact analyses. Also, more significance, budget and effort can be given to further research of contact phenomena. During the work on thesis, the following areas of prosperous research in this field came in sight:

- further investigation of the relations between contact behavior and the performances of hydraulic gates as a whole – preferably in terms of service life.
- further development of theoretical contact models in general – and the models with high contact loads and low traction velocities in particular;

- development of low-maintenance and maintenance-free (in particular lubrication-free) contact arrangements and materials, focused on the operating conditions of hydraulic gates;
- development of reliable tools to quantify some time-related phenomena, such as corrosion, aging, decomposition, weathering, creep, relaxation etc. in hydraulic gate contacts.
- more standardization in general – and the standardization of wear and other contact performance tests in particular, focused on the applications in hydraulic gates.

The recommended position of contact design and engineering in gate projects – as presented in Fig. 2 (chapter 1) – will eventually be reached one day. It will happen as result of the shortcomings and failures in projects where the contact issues are given insufficient consideration. The reason why it has not happened yet, can partly be found in the fact that contact mechanics is much younger than the mechanics of structures. The Hertz formulas, that gave birth to it, date from 1881 [35], while, e.g., the Hooke's law, that can be considered the beginning of modern structural mechanics, dates from 1660 [125] – not to mention structural engineers of the ancient Rome or the middle ages [126]. Another (somewhat embarrassing) reason is possibly that the subjects of contact engineering are much smaller and, therefore, less spectacular than those of structural engineering.

We can wait until life itself corrects this situation, or help it happen. In the first case we shall be subjects, and in the second – the co-steersmen of this process. Hydraulic gate engineering has (perhaps due to the small market) always been open to other disciplines. It is, e.g., not incidental that ship rudder bearings are used as example in this thesis. This gives the confidence that the proposed revaluation of contact-related problems can actually be done under the own steam of hydraulic engineers.

This page is deliberately left blank.

BIBLIOGRAPHY

[1] *Postema J.A., Schiphorst M.F.A., Van der Schrier W.*: Sluizen, Kanalen en Havens – Weg- en waterbouwkunde, deel II, Uitgevers-Mij "Kosmos", Amsterdam-Antwerpen, 1956;

[2] *Daniel R.A.*: Mitre gates in some recent lock projects in the Netherlands. „Stahlbau", Nr 69, Heft 12, Dezember 2000, p. 952-964.

[3] Standard test method for galling resistance of materials – ASTM G98-89. Technical report, ASTM, Philadelphia, 1989.

[4] *Hokkirigawa K., Kato K.*: An experimental and theoretical investigation of ploughing, cutting and wedge formation during abrasive wear. "Tribology International", No. 21(1), 1988, p. 51-57.

[5] *Daniel R.A.*: A multi-criteria assessment. Report of the PIANC – AIPCN Work Group 26 "Movable Weirs and Storm Surge Barriers" (draft, final version in progress), Brussel, publication scheduled for 2005.

[6] *Daniel R.A., Van As J., Donkers A.L.J.M., Mönch A.P.* : Hangdeur als onderhoudsvrij alternatief voor conventionele sluisdeuren, internal study (not published), Bouwdienst Rijkswaterstaat, Utrecht 1996.

[7] *Daniel R.A.*: Niektóre tendencje w budownictwie hydrotechnicznym. „Inżynieria i Budownictwo", nr 8/2002, p. 405-412.

[8] *Daniel R.A.*: Hartelkering – Schuiven met mogelijkheden. "Bouwen met Staal", nr. 130, mei/juni 1996, p. 38-45.

[9] *Starke W-D., Wolff R.*: Das Emssperrwerk und seine Verschlüsse. „Stahlbau", Nr 69, Heft 12, Dezember 2000, p. 974-980.

[10] *Josephus Jitta J.P.*: Sluizen en andere Waterbouwkundige Kunstwerken in en langs Kanalen, De Erven van F. Bohn N.V., Haarlem 1947.

[11] *Remery F.J., Verlint D.H.*: Renovatie van de bewegende delen van de Noordersluis te IJmuiden, "Otar", nr. 12/1996, p. 429-439.

[12] *Rogge und Mitarbeiter*: Die neuen Ostseeschleusen des Keiser-Wilhelm-Kanals, "Zeitschrift für Bauwesen", 10-12 Heft, 1923, p. 266-291.

[13] *Glerum A., Vrijburcht A. and others*: Ontwerp van Schutsluizen (Design of Navigation Locks) – Part 1 & 2, Bouwdienst Rijkswaterstaat, Utrecht 2000.

[14] *Schroeter P.*: Neuere Entwicklungen beim Bau groβer Schiebetore am Beispiel der Schleuse der 4. Hafeneinfahrt Wilhelmshafen, "Bautechnik", 42/1965 Nr. 10/11.

[15] *Duuring P., Rothilde C.*: Les portes d'ecluses maritimes Belges – De sluisdeuren der Belgische zeesluizen, Extrait des "Annales des Travaux Publics de Belgique" No. 3/1988.

[16] *Dubois J., Bontron G., Roert J.*: Les travaux de la nouvelle Écluse Maritime du Havre, Annales de l'Institut Technique du Batiment et des Travaux Publics, Supplément N° 299, Novembre 1972.

[17] *Goetinck R.*: L'écluse de Berendrecht – The Berendrecht Lock – De Berendrecht Sluis, Ministère des Travaux Publics, Sint-Niklaas, 1985.

[18] *Josephus Jitta J.P.*: Automatisch werkende afdrukinrichting voor schuifdeuren (in plaats van roldeuren) van schutsluizen, "De Ingenieur" jrg. 84, nr. 3, 21 januari 1972, p. A43-A56.

[19] *Norfolk R.N.*: The development and use of hydrostatic bearings to support large lock caissons, "PIANC Bulletin" no. 30, Volume 1, 1978, p. 3-6.

[20] *Van Tol R.A.G.*: Hydrostatische lagers Nieuwe Oranjesluis – Gedragen door water, "Land + Water" nr. 5, mei 1992, p. 58-63.

[21] Consorzio "Venezia Nuova": Alloggiamento Porta Lato Mare – progetto definitivo, version of March 2004, (final design drawings, not published).

[22] *Ros D.*: Glijdende ondersteuningen van UHMPE – Eenvoudiger ontwerp en minder onderhoud, "Land + Water" nr. 1/2, februari 1999, p. 26-27.

[23] *Ang A.H.S., Tang W.H.*: Probability Concepts in Engineering, Planning and Design, Vol. II: Decision, Risk and Reliability, J. Wiley & Sons, New York, 1984.

[24] *Van der Horn B.A., Braam H., Dijkstra O.D., Van Manen S.E.*: Inventarisatie van bestaande probabilistische methoden, report ECN-C-92-062 by Energieonderzoek Centrum Nederland, Petten, oktober 1992.

[25] TAW Leidraad Kunstwerken, publication of Technical Advice Commission for Hydraulic Structures, Rijkswaterstaat DWW, Delft, mei 2003.

[26] *Vrijling J.K.*: Design of Concrete Structures – Probability design method, Proceedings of the Delta Barrier Symposium "Eastern Scheldt Storm Surge Barrier", Rotterdam, 13 – 15 October 1982.

[27] ENV 1993-1-1, Eurocode 3: Design of Steel Structures – Part 1-1: General rules and rules for buildings, Brussel, April 1992, with official amendments up to the date of this thesis.

[28] *Daniel R.A., Peters D.J.*: Tweede Sluis Lith en renovatie Oranjesluizen. Sluisdeuren op maat – traditioneel of innovatief. „Bouwen met Staal", nr 151, november/december 1999, p. 30-37.

[29] *Daniel R.A., Brekoo A., Mulder A.J.*: Nieuwe materialen voor oude sluis – Innovatie met respect voor oude kennis. „Land+Water", nummer 11, november 2001, p. 36-38.

[30] *Daniel R.A.*: Construction material for a bridge with regard to the environment. „Bautechnik", Nr 80, Heft 1, Januar 2003, p. 32-42.
[31] *Daniel R.A.*: Wybór materiału budowlanego pod względem ekologicznym na przykładzie konstrukcji mostowej. Materiały XLIX Konferencji Naukowej KILiW PAN i KN PZITB „Krynica 2003", tom V, p. 75-91, Warszawa-Krynica, wrzesień 2003.
[32] Recommandations pour la Justification des Structures Metalliques Mobiles en Site Aquatique, Report STCPMVN (CETMEF-VNF), Notice STC-QG N° 98.02, Paris, Décembre 1998 (mise en forme 2004).
[33] *Johnson K.J.*: Contact Mechanics, Cambridge University Press, Cambridge, 2003.
[34] *Van Beek A.*: Tribologie – Levensduur en Prestatie, published on authors own, Eindhoven, 2001.
[35] *Hertz H.R.*: Über die Berührung fester elastischer Körper. "J. Reine Angew. Math.", Nr. 92 (1881), S. 156-171.
[36] *Kolkman, P.A., Jongeling T.H.G.*: Dynamisch gedrag van waterbouwkundige constructies, Deel A: Constructies in stroming, Rijkswaterstaat, Delft, 1996.
[37] *Daniel R.A.*: Trillingsanalyse Stuw Hagestein - report TSH-D-01100, Bouwdienst Rijkswaterstaat, Zoetermeer, 15 februari 2002.
[38] *Daniel R.A., Vrijburcht A.*: Tendencies in design of lock gates under alternating hydraulic loads, PIANC-AIPCN Bulletin N° 117 - 2004, International Navigation Association, Brussels, September 2004.
[39] The International Canal Monument List, part II - Individual Structures, Internet address: www.icomos.org/studies/canals2a.htm, update 23-06-2000.
[40] *Daniel R.A.*: Zamknięcia śluz i jazów na przykładzie doświadczeń holenderskich, wykład gościnny na Wydziale Budownictwa Wodnego i Inżynierii Środowiska Politechniki Gdańskiej, 30 maj 2003.
[41] *Lewin J.*: Hydraulic gates and valves in free surface flow and submerged outlets, Thomas Telford Publications, London, 1995.
[42] *Daniel R.A., Willems M.H.M.*: Tweede Sluis Lith en renovatie Oranjesluizen. Conservering – aandacht blijft geboden. „Bouwen met Staal", nr 151, november/december 1999, p. 40-43.
[43] *Daniel R.A., Donkers A., De Rijk M.C.*: Naviduct Krabbersgat in Enkhuizen. Sluisdeuren naar een hoger niveau. „Bouwen met Staal", nr 175, december 2003, p. 12-17.
[44] *Van de Kuilen J-W.G., Ravenshorst G.J.P.*: Bending strength and stress grading of (tropical) hardwoods, Workshop Probabilistic Modeling in Reliability Analysis of Timber Structures, Zurich, October 2002.
[45] Rijkswaterstaat Directie Bruggen: Schutsluis Hansweert – Gebruikershandleiding, version of June 1989 (final design and maintenance report, not published).
[46] *Erbisti P.C.F.*: Design of Hydraulic gates, A.A. Balkema / Swets & Zeitlinger Publishers, Lisse, 2004.
[47] Trelleborg Engineering Systems: Rubber Seals catalogues, Trelleborg-Bakker B.V., Riddekerk, also: www.trelleborg.com.
[48] *Daniel R.A., Leendertz J.S.*: Geïntegreerd ontwerp van de hefschuiven Hartelkering. „Civiele Techniek", nummer 4/1994, p. 9-14.
[49] *Schepers E.G, Haarman W.*: Repports on tribological investigation of some material combinations for lock gate bearings (supervised by R.A. Daniël, Bouwdienst Rijkswaterstaat): DRA-R-95002, -96001, -97006 and -00010, Schielab, Breda, 1995-2000.
[50] *Daniel R.A.*: Expertise report DMN-N-02002, Advies Renovatie benedendeuren Sluis Maasbracht, Bouwdienst Rijkswaterstaat, Zoetermeer, 3 juni 2002.
[51] *Daniel R.A.*: Report TSH-D-01100 - Trillinganalyse Stuw Hagestein (Vibrations of the Hagestein Weir, Analysis), Bouwdienst Rijkswaterstaat, 15 februari 2002.
[52] *Ypey E.*: Design of gate structures, in "Eastern Scheldt Storm Surge Barrier" – Proceedings of the Delta Barrier Symposium, Rotterdam, 13-15 October 1982.
[53] DIN 19704: Stahlwasserbauten – Teil 1: Berechnungsgrundlagen, Teil 2: Bauliche Durchbildung und Herstellung, Berlin, Mai 1998.
[54] NEN 6702: Structural design rules – Loadings and deformations TGB 1990 (with appendices), Delft 1997.
[55] ENV 1991-2-1, Eurocode 1: Basis of design and actions on structures – Part 2-1: Actions on structures – Densities, self-weight and imposed loads, Brussel, February 1995.
[56] NEN 6770: Steel structures – Basic requirements and basic rules for calculations of predominantly statically loaded structures TGB 1990 (with appendices), Delft 1997.
[57] *Pilarczyk K.W.*: Costal Protection, A.A. Balkema, Rotterdam – Brookfield, 1990.
[58] *Vrijling J.K.*: Design of concrete structures – Probability design method, in "Eastern Scheldt Storm Surge Barrier" – Proceedings of the Delta Barrier Symposium, Rotterdam, 13-15 October 1982.
[59] *Van Manen S.E., Houben R.J.*: Gebruikshandleiding programma RIEMANN – version 7, Vakgroep Risico Analyse, Rijkswaterstaat Directie Sluizen en Stuwen, 11 januari 1990.
[60] Rijkswaterstaat Directie Flevoland: Projectnota Krabbersgatsluis, Lelystad, september 1994.
[61] *Daniel R.A.*: Naviduct Krabbersgat te Enkhuizen – Ontwerpnota Waterkerende Staalconstructies, report KRB-NS-3007 (as built, not published), Bouwdienst Rijkswaterstaat, Zoetermeer, 15 september 2003.

[62] Ministerie van Verkeer en Waterstaat (Ministry of Transport, Public Works and Water Management): Hydraulische randvoorwaarden voor Primaire Waterkeringen, own publication, Den Haag, 1996.

[63] TNO Building and Construction Research: DIANA User's Manual – Introduction and Utilities, Release 7, TNO, Delft, 1998.

[64] Van Driel G., De Jong R.J.: Europoortkering met open Beerdam, Stormvloedkering Hartelkanaal - trillingsonderzoek met behulp van een sectiemodel, WL rapport Q1500, Delft, 1993.

[65] *Timoshenko S.P., Goodier J.N.*: Theory of Elasticity, 3rd edition, Mc Graw Hill, New York, 1982.

[66] Catalogue "Kunststoffe Hoechst – Hostalen® GUR (PE-UHMW)", Hoechst Aktiongesellschaft, Frankfurt am Main, not dated.

[67] *Stein H.L.* (Ticona LLC): Ultra High Molecular Weight Polyethylene (UHMWPE), "ASMInternational", Materials Park, Ohio, 1999.

[68] *Ros D.*: Waarom ontwerpen met kunststoffen – De kunst van het benutten van geode eigenschappen, „Land+Water", nummer 1/2, januari 1999, p. 22-24.

[69] Catalogue "PAN Bronzen leisten immer relativ mehr…", PAN-Metallgesellschaft, Mannheim, not dated.

[70] Schmauβer G., Nölke H., Herz E.: Stahlwasserbauten – Kommentar zur DIN 19704, Ernst & Sohn, Berlin, 2000.

[71] *Daniel R.A.*: Wilhelminakanaal Sluis III – Ontwerpnota Vervanging Middendeuren Sluis III, report WIL-D-00100 (not published), Bouwdienst Rijkswaterstaat, Zoetermeer, 30 juni 2000.

[72] *Bignonnet A.*: Improving the fatigue strength of welded steel structures. Steel in Marine Structures - Proceedings of the 3rd International ECSC Offshore Conference, Delft, June 15-18, 1987, Elsevier, Amsterdam – New York, 1987, p. 99-118.

[73] *Ischi N., Imaichi K., Hirose A.*: Dynamic instability of tainter gates. Practical Experiences with Flow-Induced Vibrations – Proceedings of the IAHR/IUTAM Sumposium in Karlsruhe, 1979, Springer-Verlag, Berlin – Heidelberg – New York, 1980.

[74] *Daniel R.A.*: Haringvliet Tainter Gate Barrier, project review. In appendix to "Movable Weirs and Storm Surge Barriers" – report of the PIANC International Commission WG26, Brussels 2005.

[75] *Remmerswaal G., De Rijk M.C.*: Ontwerpberekeningen sluisdeuren voor de Zuider- en de Kleine Sluis In IJmuiden, projectcode 1291B, (not published), Bouwdienst Rijkswaterstaat, Zoetermeer, februari 1996.

[76] Huber M.T.: Stereomechanika techniczna, PWN, Warszawa, 1958 (theory of combined stresses originally published in "Czasopismo Techniczne", Lvov, 1904).

[77] *Daniel R.A.*: Wybrane holenderskie doświadczenie w modernizacji infrastruktury komunikacyjnej. Materiały XLIV Konferencji Naukowej KILiW PAN i KN PZITB „Krynica '98", tom II, p. 89-103, Poznań-Krynica, wrzesień 1998.

[78] *Van Leeuwen H.*: Filmsmering – een inleiding in de natte tribologie. Lecture notes from the PATO courses "Tribotechnology", Eindhoven University of Technology, Eindhoven, October 2002.

[79] *Van Heijningen G.J.J.*: Handboek Werktuigbouwkundig ontwerpen & construeren. B8720: Tribotechniek: Wrijving, slijtage en smering, Kluwer ten Hagen & Stam, Den Haag, augustus 1999.

[80] *Palylyk R.A., Franklin D.E., Jones J.A.*: Comparative testing of greasless bushings for hydro units, "Hydropower & Dams", Issue Two, 1996, p. 64-66.

[81] *Daniel R.A.*: Scriptie "Materiaalkeuze voor taatsopleggingen in sluisdeuren", Stichting Post-Tertiair Onderwijs, Hogeschool Utrecht, februari 1993.

[82] *Lewis R.*W.: Response to paper submission "DISCO – A Simple Iterative Algorithm for Discontinuous Linear Structures", 23 March 1998; also R.A. Daniel's reaction of 8 April 1998 (in author's receipt).

[83] *Daniel R.A.*: DISCO - … (enclosed to this thesis).

[84] *Daniel R.A.*: Naviduct Krabbersgat – Detailberekeningen Sluisdeuren, report no. KRB-SS-322, Bouwdienst Rijkswaterstaat, Utrecht, september 1997.

[85] *Rakowski G. e.a.*: Mechanika Budowli z elementami ujęcia komputerowego, Arkady, Warszawa, 1984.

[86] *Berenbak J., De Vries A., Aantjes A.*: Maeslantkering – De ontwikkeling van het scharnier, „Bouwen met Staal", nr. 101, juli/augustus 1991, p. 37-44.

[87] *Van Stekelenburg G.*A.M.: Sectordeuren beschermen Rotterdam tegen hoogwater – Het bolscharnier, „Bouwen met Staal", nr. 135, maart/april 1997, p. 18-20.

[88] *Kerstens J.G.M., Timmerman G.K., Pollemans P.J.Th.*: Maeslantkering Nieuwe Waterweg – Gestructureerde berekeningsaanpak …, „Bouwen met Staal", nr. 121, november/december 1994, p. 42-48.

[89] *Slot H.*: Onderzoek naar de oorzaak van korte levensduur van de bovenlagers in de Oranjesluizen (investigation supervised by R.A. Daniel), TNO rapport nr. 42/04.012267, Eindhoven, november 2004.

[90] *Daniel R.A.*: Renovatie Oranjesluizen – Controleberekeningen Draaiarm Sluisdeuren, reports no. ROS-D-S-C-99003 and ROS-D-S-C-00001, Bouwdienst Rijkswaterstaat, Zoetermeer, Dec. 1999 / Jan. 2000.

[91] *Meuleman W., Dries H., Jansen P.*: Unieke balgstuw keert stormvloed, "Civiele Techniek" no. 4 (2001), p. 11-16.

[92] *De Rooij M.B.*: Tribological aspects of unlubricated deepdrawing processes, Ph.D. Thesis, University of Twente, FEBO druk BV, Enschede, 1998.

[93] *Wagner R.*: Anforderungen und Lösungen bei Wasserbauwerken, "Mitteilungsblatt der Bundesanstalt für Wasserbau", Nr. 78, 1998.

[94] *Mens J.W.M., Gee A.W.J.*: Friction and wear behaviour of 18 polymers in contact with steel in environments of air and water, "Wear", No. 149 (1991), p. 255-268.

[95] *Johnson K.L.*: Energy dissipation at spherical surfaces in contact transmitting oscillating forces, "Journal of Mechanical Engineering Science", No. 3 (1961), p. 362.

[96] *Elishakoff I.*: Three faces of uncertainity – Editorial, "Computers & Structures" No. 67 (1998), p. 1-2.

[97] Maprom Engineering BV and Breko Machinefabriek BV: Design of the inland container ship ms. JOWI, drawing 9706-000: Rudder, Dordrecht/Papendrecht, September 1998.

[98] Lloyd's Register of Shipping: Rules and Regulations for the Classification of Inland Waterway Ships – Ship Control Systems (Part 3, Chapter 12) – Section 2: Rudders.

[99] Pugsley Sir A.: The works of Isambard Kingdom Brunel, Institution of Civil Engineers, London, 1974, also: The International Canal Monument List – Part II, www.icomos.org/studies/canals2a.htm.

[100] *Linke H.*: Stirnradverzahnung – Berechnung·Werkstoffe·Fertigung, Carl Hanser Verlag, München/Wien, 1996.

[101] *Klaver P.*: Olie & transmissies – Technische leergang, Delta Press BV and Castrol Nederland BV, Amerongen/Voorburg, 1993.

[102] *Ros D.*: Triboregister – Wrijvingscoëfficiënten en slijtfactoren, Min. van Verkeer en Waterstaat, Bouwdienst Rijkswaterstaat, Zoetermeer, juni 1995.

[103] *Drewnowski S.*: Formy złomów I zniszczeń elementów konstrukcji metalowych, Wydawnictwo Arkady, Warszawa 1969.

[104] Louisville District Corps of Engineers: Observations of Bearing Performance on Olmstead Dam Prototype Site (not published), October 7, 1996.

[105] *Honselaar A.C.M.*: Tribologische eigenschappen van metaal/metaal en kunststof/metaal combinaties, (investigation by the direction of D. Ros) TNO rapport nr. 96Mi/00678/HON, Apeldoorn, oktober 1996.

[106] *Van der Horst T., Schenk J.*: Theatrum Machinarum Universale, Petrus Schenk, Amsterdam, 1736 (new eddition by T. Wever BV, Franeker, 1981).

[107] *Bowles J.E.*: Foundation Analysis and Design, McGraw-Hill Book Company, New York - St. Louis - San Francisco etc., 1968.

[108] *PahlG., Beitz W.*: Konstruktionslehre – Handbuch für Studium und Praxis, Springer-Verlag, Berlin-Heidelberg, 1977 (Polish edition "Nauka Konstruuwania" by W.N.T., Warszawa, 1984).

[109] *Riksen J.*: Design process, lectures from the course "Material Selection for Designers" (in Dutch, author's notes), Post-graduate Education Institute (Stichting PTO-U), Utrecht, 1992-1993.

[110] *Hammond N.G.L., Scullard H.H.*: The Oxford Classical Dictionary (entry "Harbours"), Oxford University Press, New York, 1976.

[111] *Lehmann-Hartleben K.*: Die Antiken Hafenanlagen des Mittelmeeres, "Klio", Beiheft 14 (1923).

[112] *Zwarts M.*: Letter to project team "Naviduct", Abcoude, 1 July 1996 (in author's files).

[113] *Bergmeister K.*: Vorspannung von Kabeln und Lamellen aus Kohlenstoffesern, "Beton- und Stahlbetonbau" Nr. 94 (1999), Heft 1, p. 20-26.

[114] *Meier U.*: Composite Materials in Bridge Repair, "Applied Composite Materials, No. 7 (2000), p. 75-94.

[115] Catalogue «NEW-PWS» , Nippon Steel Corporation catalogue no. C0339, Tokyo, September 1988.

[116] Catalogue "Freyssinet STAY CABLES", Freyssinet Information, February 1995.

[117] *Westerhoff D.*: Open Spiral Strands and Full-Locked Coil Ropes, Thyssen Draht AG, Düsseldorf, 1991.

[118] *Frish-Fay R.*: Flexible Bars, Butterworths, London, 1962.

[119] *Guyon Y.*: Limit State Design of Prestressed Concrete – Volume 1: The Design of the Section, Applied Science Publishers Ltd., London, 1972.

[120] Catalogue "THIELE Anschlagketten und Einzelteile – Güteklasse 8", THIELE Kettenwerke GmbH & Co. KG, Iserlohn-Kalthof, 2002.

[121] EN 10088: Stainless Steel – Part 1, List of Stainless Steels, August 1995.

[122] Stellite - Properties of Deloro Stellite alloys, brochure DS-43 of Stellite Division of Cabot Corporation, Kokomo, Indiana (USA), undated.

[123] Empfehlungen des Arbeitsausschsses "Ufereinfassungen" – Häfen und Wasserstraβen, EAU 2004, Ernst W. + Sohn Verlag, Berlin, 2005.

[124] *Boland R.W.M., Van der Varst T.G.*: Onderzoek storingen aan sluizen (Investigation on lock distortions), by author's request (not published), Roermond, May, 2004.

[125] *Koiter W.T.*: Inleiding tot de Leer van Stijfheid en Sterkte, Epsilon Uitgaven, Utrecht, 1985.

[126] *Głomb J.*: Pontifex Maximus – Ponad przestrzenią i czasem, Wydawnictwo Politechniki Śląskiej w Gliwicach, Gliwice, 1997.

ENCLOSURES

1. *Daniel R.A.*: Computer software "DISCO – Analysis of Structures with Continuous and Discontinuous Support Conditions", version 4/04, Gdansk, April 04, 2005.

   The software is delivered in a set containing:
   - Reference and Operation Manual;
   - one 3½" diskette named 'DISCO' and containing:
     - system files in directories DISCO and DANCE;
     - data files in directories CBE, DBE, CPT, DPT, CGR, DGR, CPF, DPF, CST, DST, CSF, DSF.

   This software constitutes a tool that helps analyzing a wide range of contact problems, including the problems discussed in this thesis. It is, however, a stand-alone software package that can be operated with no relation or reference to this thesis.