31st PIANC Congress
Estoril, May 2006
Portugal

Design of Movable Weirs and Storm Surge Barriers

Rigo Philippe, University of Liege, ANAST-FNRS, Belgium, ph.rigo@ulg.ac.be,
Abdelnour R. (Can); Bulckaen D., Hiver J-M. (BE); Daniel R. (NL); Chapital L., Daly F., De La Personne C., Lagache A. (FR); Dixon J, Wilkes D. (UK); Kupsky M. (Cz); Meinhold W. (DE); Miller D., Stockstill R. (USA); Nagao T., Kawana F. (Jap); Perillo G. (It); Sarghiuta R. (Ro); *Members of the PIANC- INCOM WG26*

ABSTRACT

The PIANC InCom-WG26 has performed a comprehensive review (state of art) of the modern technologies, design tools and recent researches used to design and build structures controlling water level and flow in rivers, waterways and ports (for navigation & flood protection). This includes:

- Gates controlling water level and flow in rivers (even not navigable) and waterways (lifting gate, tilting gate, radial gate, sector, etc.; designed in one piece or with an upper flap, ...). They are the **MOVABLE WEIRS.**
- Gates controlling water level and flow in estuaries with regards to high tides and storms (lifting gate, articulated, tilting, rolling, floating, sliding, etc.). They are the **FLOOD BARRIERS** or the **STORM SURGE BARRIERS.**

SOMMAIRE

Le groupe de travail InCom-WG26 de l'AIPCN présente dans son rapport un état de l'art actualisé relatif aux techniques modernes de conception et de dimensionnement des ouvrages hydrauliques de régulation des niveaux et des courants des rivières et voies navigables (y compris les zones portuaires), à des fins de navigation ou de protection contre les inondations.

Parmi ces ouvrages on distingue :

- les barrages mobiles destinés au contrôle des niveaux et des débits dans le biefs (navigables ou non) : vanne levante, clapet, segment, secteur, .. conçus en une ou deux pièces, les barrages gonflables, ...
- les portes marées tempêtes destinés, de façon similaire, au contrôle des niveaux et des débits dans les estuaires.

KEYWORDS : Movable weirs, storm surge barriers, hydraulic structures

1. INTRODUCTION

The aim of the WG (Working Group) was to conduct a comprehensive review (state-of-the-art) of the modern technologies, design tools and recent research used to design and build structures controlling water level and flow in rivers, waterways and ports (for navigation & flood protection).

The WG considered regulatory structures such as:

- Gates controlling water level and flow in rivers (even non navigable) and waterways (lifting gate, tilting gate, radial gate, sector, etc.; designed in one piece or with an upper flap). These are referred to as WEIRS.
- Gates controlling water level and flow in estuaries with regards to high tides and storms (lifting gate, articulated, tilting, rolling, floating, sliding, etc.). These structures are referred to as BARRIERS.

The WG Report focuses on the following aspects:

- List of the recent movable weir and barrier projects (<u>Project Reviews</u>), presentation of their concepts and innovations, and the driving forces considered for selecting these particular designs (Section 2.1).
- A <u>terminology review</u> of the technical terms and names used to define weirs and barriers (Section 2.2)
- <u>Design Procedure</u> for the design of weirs and barriers (Section 3).
- A review of the various <u>multi-criteria assessment</u> approaches that can be used to select the most relevant designs (Section 4). List of criteria for weirs and barriers, are proposed.
- Technical considerations including environmental, economic and safety aspects, for design, construction, maintenance and operation (Section 5).
- Structural considerations on various gate-types with an advantage-disadvantage comparison (Section 5.1).
- Technical background required to perform hydraulic and flow analysis of various gate types (Section 5.2)
- Interaction between foundation and weir/barrier structure (Section 5.3).
- Control procedures of the gate operations and their maintenance (Section 5.4)
- Survey of the temporary closure systems used for inspection and maintenance (Section 5.5).
- State-of-the-art on the risk-based design methods. With applications to navigation weirs and flood barriers (Section 5.6)
- Interactions between the technical aspects of a weir/barrier design with environmental and aesthetic aspects (Section 5.7)

- Procedure to assess the global construction cost of a weir at the design stage (Section 5.8).
- Design assessment tools for preliminary and detailed design stages (Section 6 and Annex A of the report).
- Prefabrication techniques (Section 7),
- Codes, rules and standards: at national and international level; including the use of the semi-probabilistic Eurocode format (Section 8)
- An extensive list of relevant technical books, web sites, and guidelines (Section 10)

Additional information has been saved on a companion CD-ROM (attached to the PIANC hardcopy report). This CD includes:

- About 50 Project Reviews of movable weirs and storm surge barriers with various flat, radial, lifting, sector, inflatable... gates
- Various additional information about WG26 report including a survey of maintenance bulkhead types.
- Various technical guidelines such as:
  - PIANC's "Illustrated Technical Dictionary" (Locks, Gates, Dewatering services and Protection from Ship Impact).
  - "Design of Mobile and Marine Metallic Structures using the Limit States and Partial Safety Factor Concepts" (France) & "ROSA 2000: Guidelines for the limit state design of harbour and waterways structures"
  - Movable Weirs (Guide du chef de projet - VNF)
  - Inflatable Weirs (BAW, Germany)
  - Maintenance bulkhead types (survey) and some technical reports are also given.
  - Examples of rehabilitation Weirs
  - Flood Protection in UK (Environment Agency)
  - Environmentally Considerate Lubricants (UK)

2. GATES OF MOVABLE WEIRS AND BARRIERS

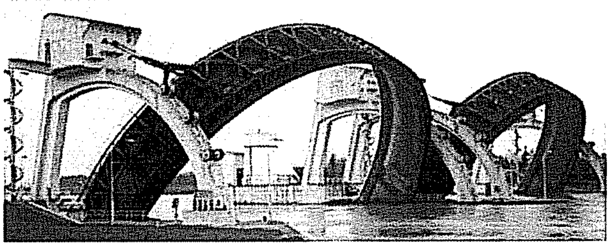
Representative samples of each gate type included in this document are summarized in this section. Case studies of each of these gates are included on the WG26-CD /Directory A1/. The case studies include a more complete description of the gate, foundations, abutments, operating characteristics and, where available, cost. Photographs and select engineering drawings are also presented for many of the gates.

A. ARCH or VISOR GATES

An arch gate is a three-hinged arch that spans from abutment to abutment across the waterway. It is hinged at the abutments and rotates upward for storage and downward to close the channel.

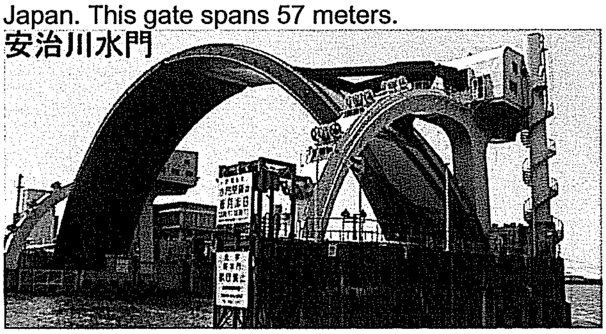
A.1 Rhine Visor Weirs

These double visor gates each span 54 meters and are used to control flow for power generation and navigation. This is one of 3 weirs of similar construction on the Rhine River.


Hagestein, The Netherlands (~1960)

A.2 Aji River Barrier

This is one of 3 lock gates constructed as flood protection measures from storm surges for the city of Osaka, Japan. This gate spans 57 meters.



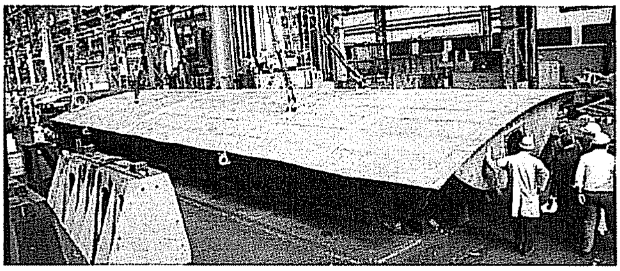
Osaka, Japan, 1970

B FLAP GATES

Flap gates are hinged along the upstream edge of the gate and attached to a sill foundation. They are stored submerged and flat to the bottom. To close the flow, the downstream edge is rotated upward.

B.1 Lagan Weir (Storm surge barrier)

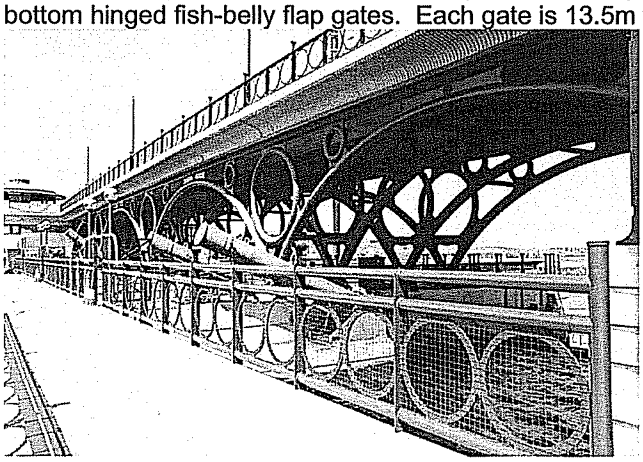
The barrier is composed of 5 Fish Belly, bottom hinged, flap gates. Each gate is 20m wide by 4.5m tall. These gates are used for flood control and to improve water quality.



Belfast, Northern Ireland, 1994

B.2 Tees Barrage (Tidal weir)

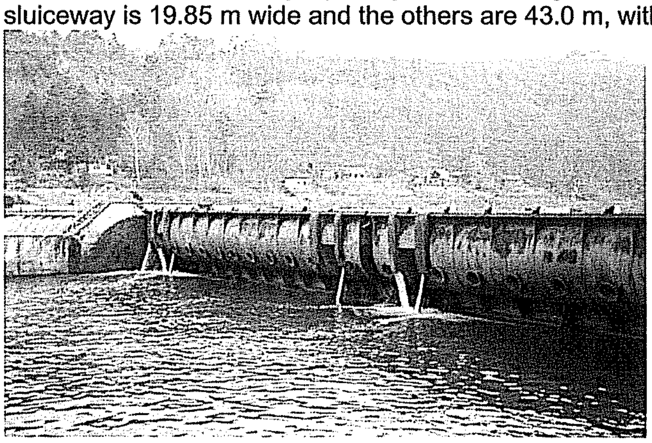
This barrage was established to improve water quality and to provide flood protection. The barrage has 4 bottom hinged fish-belly flap gates. Each gate is 13.5m wide by 8m high.



Stockton on Tees/Teesside, UK, 1995

B.3 Libcice-Dolany (river navigation weir)

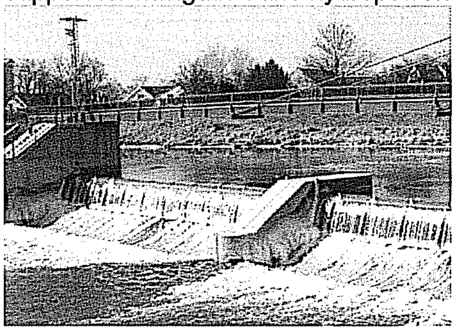
The three sluiceway openings serve navigation and hydropower interests on the Vltava River. The right sluiceway is 19.85 m wide and the others are 43.0 m, with a control height of 3.3m.



Libcice, Vltava River, Czech Republic, 1989

B.4 Veseli (24m long)

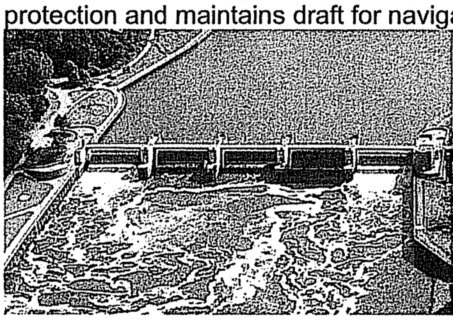
The weir Veselí consists of two 24.4 m wide hollow flap gates with a 1.4 m control head. The dam provides support for navigation and hydropower. A fish ladder is also provided.



Veseli, Morava River, Czech Republic, 2002

B.5 Bremen Weser Weir (navigation weir)

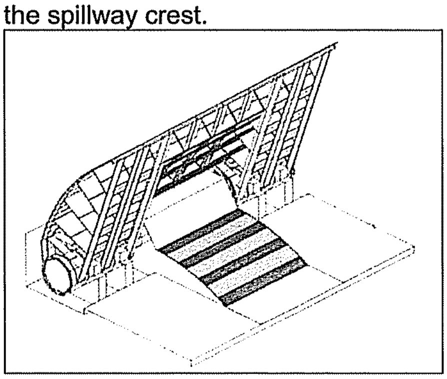
The five fish belly flap gates span 31 m and provide a control height of 3.8m. The weir provides for flood protection and maintains draft for navigation.



Bremen, Germany, 1993

B.6 Torque-tube at Montgomery Dam

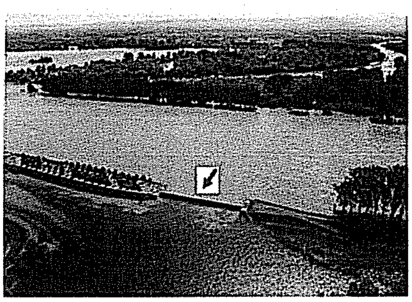
The project consists of a navigation lock, a 91.4-m-wide controlled navigation pass spillway with 10 torque-tube gates, and a 61.0-m-wide fixed uncontrolled overflow spillway. Each gate is 9.1 m wide and rises 3.96 m above the spillway crest.

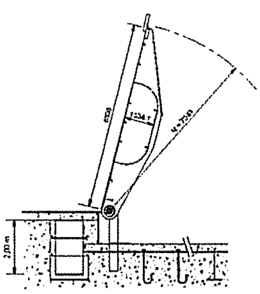


Desha County, Arkansas, USA, ~2004

B.7 Sauer Closure Gate

The goal of this project is the protection of cities and lands against flood created by the river Rhine. There is a single flap gate of 7.04 m high by 60 m long.

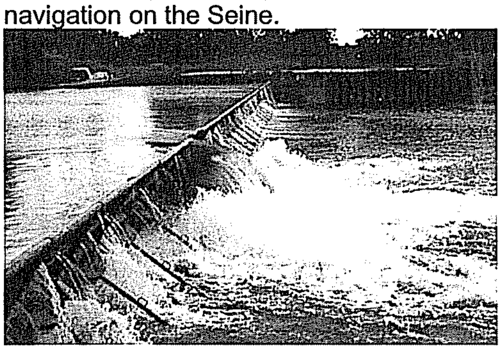




Sauer Flood Barrier – Munchhausen, France, 1993

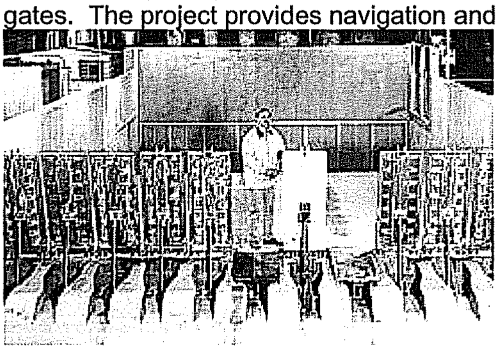
B.8 Denouval Wicket Gates

These 30 wicket gates dam a river width of 70 m. Each wicket has a height of 3.3 m and a width of 2.5 m. The gates are hydraulically operated and can be placed in one of four possible positions. The gates facilitate navigation on the Seine.


Andresy, Seine River, France, 1980

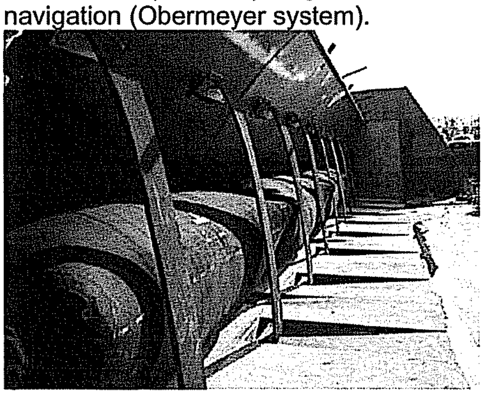
B.9 Olmsted Wicket Gates

The navigable pass section of the dam will be 420-m long with 140 x 2.95-m wide, boat-operated steel wicket gates. The project provides navigation and flood control.


Olmsted, Illinois, USA, Estimated 2009.

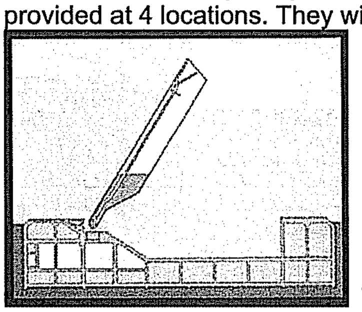
B.10 Sinnissippi Dam

The dam has three 16m (48-foot) long and four 32m (96-foot) long pneumatically operated hinged-leaf gates and a 168m (504-foot) long conventional concrete ogee spillway and provides for flood protection, hydropower and navigation (Obermeyer system).


Sterling – Rock Falls, Illinois, 2002

B.11 Mose Buoyant Flap Gate

These oscillating buoyant retractable floodgates will provide flood protection to Venice. 78 flood gates will be provided at 4 locations. They will vary in width from 3.6m to 5m and the length will vary from 18 to 28m.

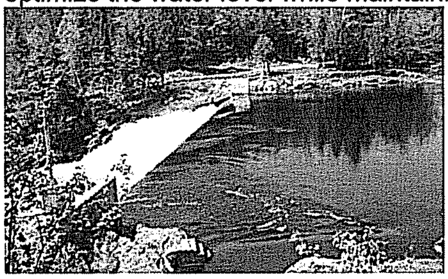

Venice, Italy (planned project)

C INFLATABLE WEIRS

These are operable weirs that are composed of long bladders, secured to a bottom foundation. The weir is raised by inflating the bladders with air or water.

C.1 Canadian Inflatable Weir

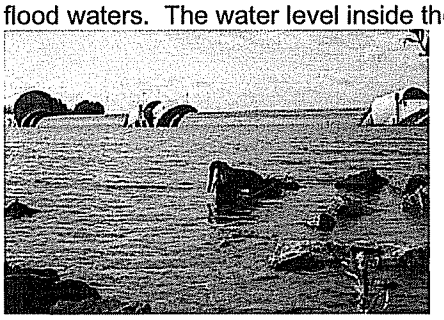
An inflatable weir was built upstream of a fall, downstream from a power plant intake structure, to control and optimize the water level while maintaining a minimum flow over the weir at all times.



Chute Bell, Rivière Rouge, Québec, Canada, 1994

C.2 Ramspol Barrier

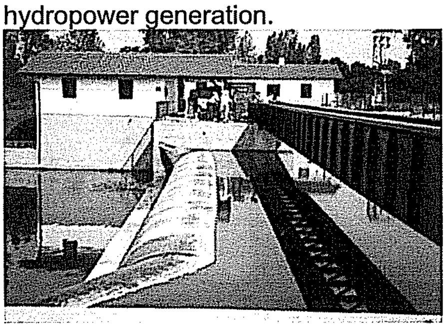
These 3 inflatable fabric bellows barriers with a width of 60m, provide 2.7m of flood protection from inland river flood waters. The water level inside the barrier matches the tail-water, the level above this is air supported.



Kampen, the Netherlands, 2002

C.3 Pocaply Inflatable Weir

This rubber dam is 21m wide with a design height of 1.6m. It is water filled and provides a pool for hydropower generation.



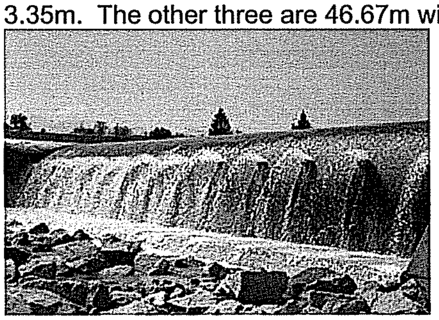
Pocaply, Loucna River, Czech Republic, 1998

C.4 German Inflatable Weir Reference Document

This pdf document shows a presentation on the operation and design of inflatable weirs (BAW, Germany).

C.5 Rubber Dam at the river Lech

This dam provides a pool for hydropower. Four sections are used, one with a width of 26.65m and a height of 3.35m. The other three are 46.67m wide by 1.25m high.



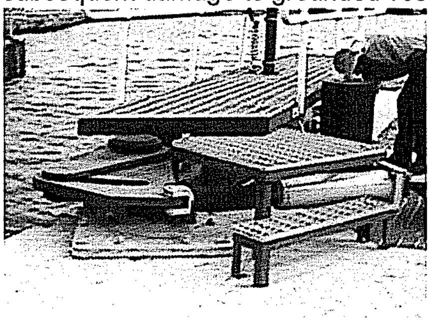
Füssen, Germany, 2001

D MITER GATES

Miter gates are typically used for navigation locks rather than flood control. However, they are used at Goole to prevent the harbour draining if the canal wall collapses.

D.1 Goole Caisson

These gates are closed if a breach in the canal wall occurs. This prevents the harbour from draining with subsequent damage to grounded vessels.

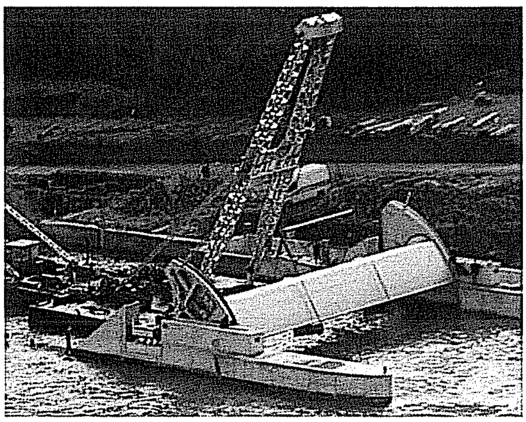

Goole, Great Britain, 2002

E RADIAL GATES

A Radial or Tainter gate has a skin plate mounted on an open structural steel frame supported by strut arms at each side of the gate. The strut arms extend to trunnion bearings mounted on abutment walls on either side of the gate opening. Radial gates may have the trunnion bearing either upstream or downstream and the gates may be stored submerged and raised to close flow or stored overhead and lowered to close flow.

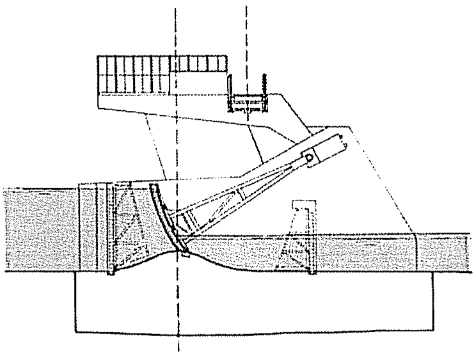
E.1 Upper Meuse

This project will rebuild a number of locks and dams on the upper Meuse River to improve navigation and power generation. These radial gates have an upper flap that allows more economical and precise flow control.


Upper Meuse Basin, Belgium, 1985-95

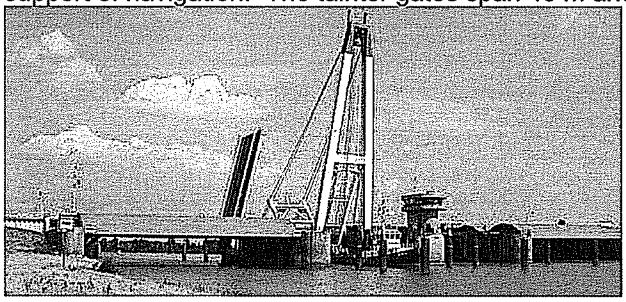
E.2 Steti Radial Gates

The weir is provided with seven sluiceway openings, two are fixed, two are locked by a steel radial gate, and three openings are locked by a steel radial gate with a control flap. 4.4m of control height is provided.


Steti, Labe River, Czech Republic, 1972

E.3 Stör Storm Surge Barriers

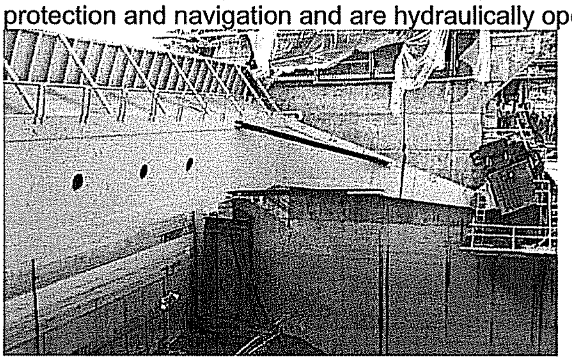
Double Tainter gates are provided on each side of two lock chambers to provide redundant flood protection in support of navigation. The tainter gates span 43 m and are 13 m high.



Federal State Schleswig-Holstein, Germany, 1974

E.4 Braddock Dam

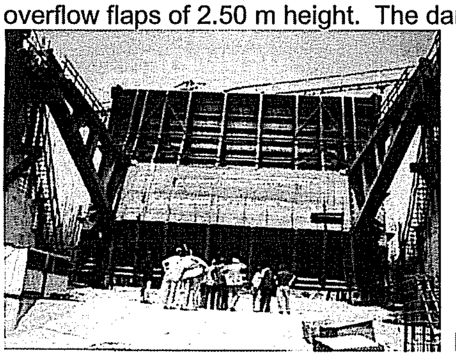
The 4 radial gates are 33.53m long with a total damming height of 6.4m. The gates are used for flood protection and navigation and are hydraulically operated.



Braddock, PA, USA, 2003

E.5 Iron Gates

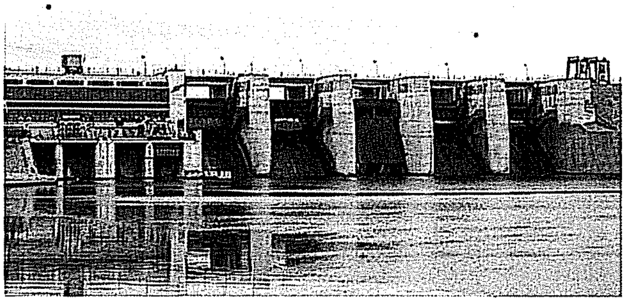
The two spillway dams on each river branch with seven 21m wide gates, three of which are equipped with overflow flaps of 2.50 m height. The dams are used for navigation and power generation.



Danube, Romania and Yugoslavia, 2000

E.6 Olt River Lower Course

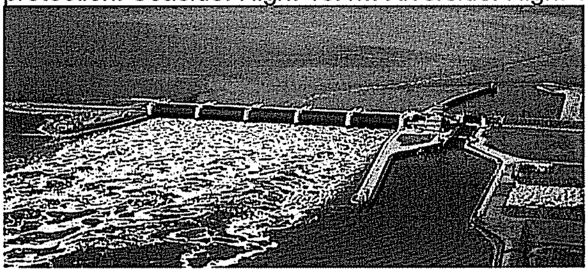
Five dams were constructed in 13.5m steps along the Olt River to provide for hydroelectric power generation. Each of them consist of a gated dam with 5 openings of 15 m each. The gates are radial gates with flaps.



Olt River – lower course, Romania, 1990

E.7 Eider Barrage (storm surge barrier)

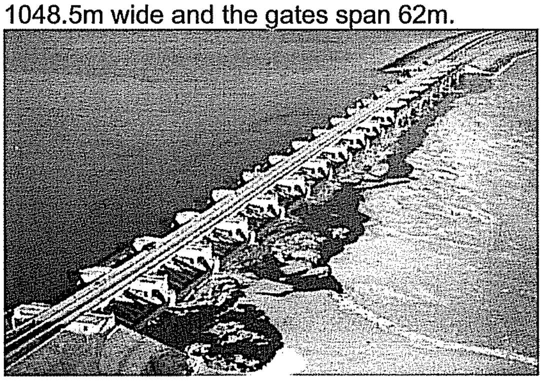
The floodgate section consists of five 40m wide spillways. Each opening has two radial floodgates for double protection. Seaside: High: 10.1m Riverside: High: 11.10 m



Schleswig-Holstein/Nordfriesland, Germany, 1973

E.8 Haringvliet Storm Surge Barrier

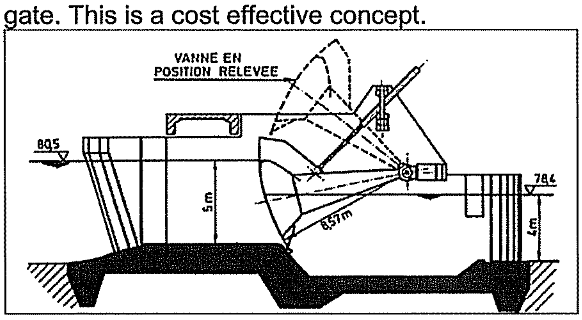
This flood control structure provides two rows of 17 seaside and 17 riverside radial gates. The barrier is 1048.5m wide and the gates span 62m.



Hellevoetsluis, The Netherlands, 1970

E.9 Radial Gate with Under and Overflow

This gate concept has not yet been implemented, but would allow fine control of flow by lowering the gate and allowing surface flow over the top or would provide for high discharges and passage of sediment by raising the gate. This is a cost effective concept.



Upper-Meuse, Belgium (not built)

E.10 Prefabricated Floating Weirs - Innovative Concept

A series of 9 prefabricated navigation control weir sections are constructed in 4 floating sections that are transported afloat to the site and placed on a prepared foundation. Elements are made of aluminium to float in shallow water (60cm) steel can also be used. The structure (30m long, 29.5m wide and 7.6m high) includes 2 radial gates of 12m. The infill concrete is reinforced with steel fibbers rather than traditional rebar. This facilitates underwater placement.

The concept was developed for the Sambre river, Belgium, (not yet built).

F ROLLING or TROLLEY GATES

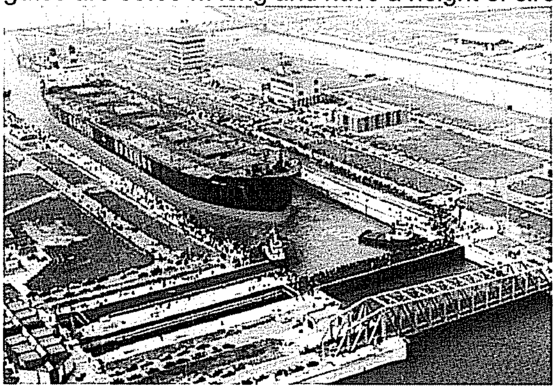
Rolling and Trolley gates are closure panels stored adjacent to the waterway. They are rolled into position in anticipation of a flood event. Rolling gates are bottom supported and trolley gates are top supported.

F.1 Selby Lock Rolling Gate

This flood control gate is stored in a slot at the side of the waterway and is winched across the canal. The gate is 6.4m wide, 3.85m high and 0.35m deep. It is partially buoyant and seals to a timber sill.

F.2 Berendrecht Flood Control Rolling Gate

These rolling lock gates are used to provide navigation access through a flood control barrier. The gates are buoyant and supported by a submerged trolley on the leading edge and an above water trolley on the aft end. The gates are 69.69 m long and have a height of circa 22.60 m. The average width is 9 m.



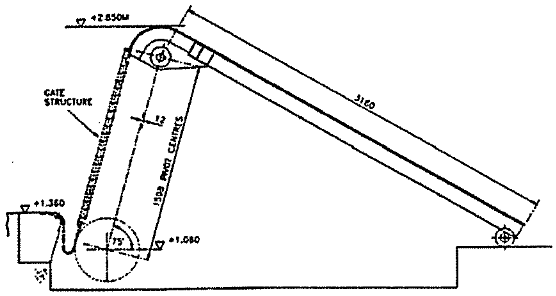
Antwerp, Belgium, 1989

G ROOF or BEAR TRAP GATES

Bear trap gates are not as common today as in years past. A bear trap gate is constructed of two leaves that slide over one another and seal together. They are stored on the bottom of the waterway. Typically water is allowed to enter the space beneath the gate and the upstream water pressurizes the space beneath the leaves and the gate leaves rise to block the flow.

G.1 Tees Barrage Bear Trap Gate

This bear trap gate is 5.950 m wide. The upstream leaf is 1.598 m centre to centre and the downstream leaf is 3.160m. The gate is used to control flows for white water canoe and kayak recreation.



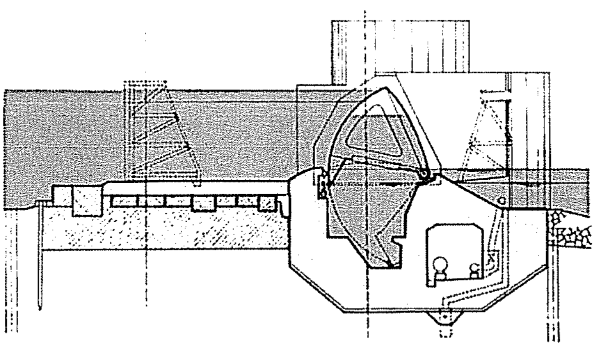
Tees, United Kingdom,1984

H SECTOR GATES - HORIZONTAL AXIS

Horizontal axis sector gates are circular sections hinged on the downstream side with a skin plate on the upper 2 sides. A horizontal axis sector gate rotates in a vertical plane about a horizontal axis. When lowered the upper skin plate of the gate coincides with the overflow section of the sill. Rotating or Rising sector gates are included here also. These gates provide skin plates on a segment of a circular arc and are supported at the sides of the spillway.

H.1 Roudnice

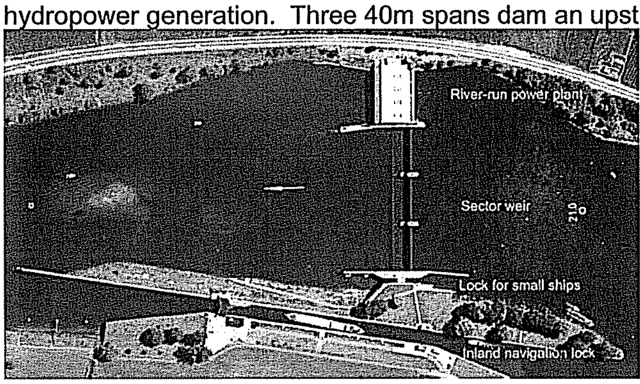
These gates are used for navigation and irrigation. Three sluiceways of the same clear width of 54.05m span the river with a dam height of 2.70 m



Roudnice, Labe River, Czech Republic, 1972

H.2 Mosel River Weir Lehmen (Navigation Weir)

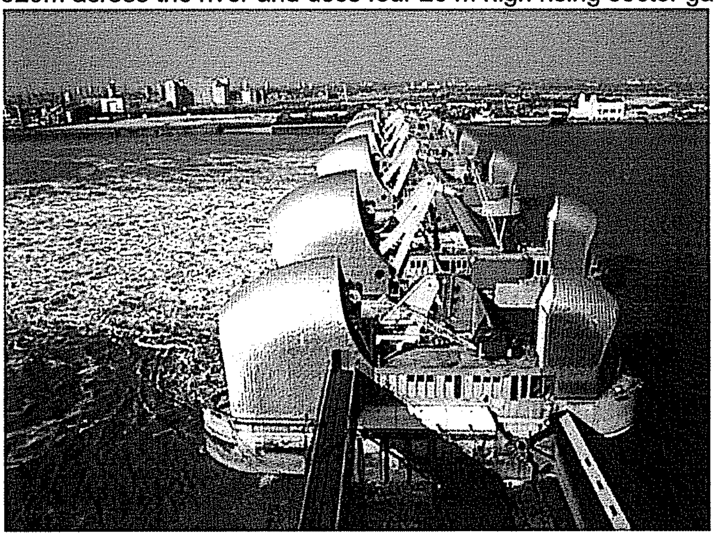
Eleven of the 14 weirs built on this section of the Mosel use sector gates to control flows for navigation and hydropower generation. Three 40m spans dam an upstream head of 5.4m.



Mosel river, Germany,1963

H.3 Thames River Barrier

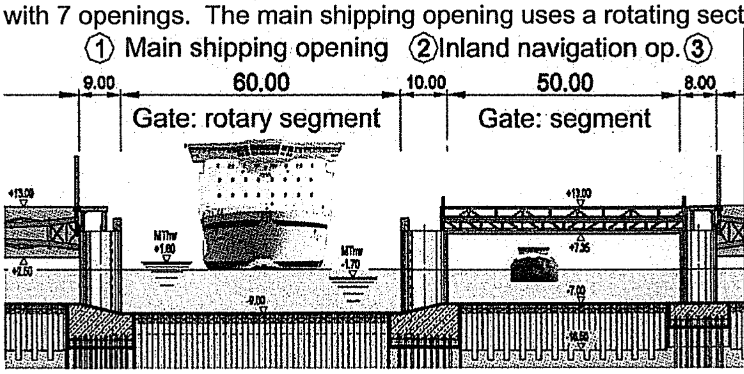
This massive flood protection barrier protects London from flooding on the river Thames. The barrier extends 520m across the river and uses four 20 m high rising sector gates that span 61m.



London, United Kingdom, (1982)

H.4 Ems Barrier

The Ems barrier provides flood protection and supports navigation, it has a length of 476m between bank lines with 7 openings. The main shipping opening uses a rotating sector gate.



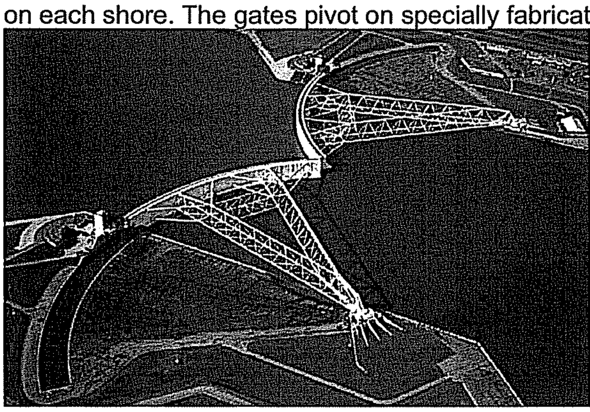
Ems river, Germany, 2002

I SECTOR GATES - VERTICAL AXIS

Vertical Axis Sector Gates are circular sections supported on a vertical hinge at the center of a circular arc. The skin plate is only on the face of the circular arc. Because the hydraulic thrust is directed radially inward toward the vertical axis there is very little unbalanced load and they can be opened and closed with differential head across the gate.

I.1 Maeslant Storm Surge Barrier

This flood protection barrier spans 360m. The gate is made buoyant when it is moved by locomotive engines on each shore. The gates pivot on specially fabricated spherical bearings.



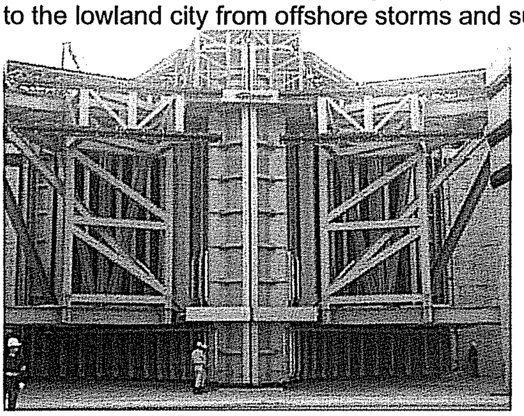
Hoek van Holland, Netherlands, 1997

I.2 Maeslant Barriers – Alternative designs

This paper discusses the alternatives to the sector gates finally selected for the Maeslant barrier. A pneumatic tumble gate, a segment gate, hydraulic tumble gate, sliding gate, boat gate and floating sector gates are discussed.

I.3 Amagasaki lock gate

These Vertical axis sector gates provide 17m wide lock access for navigation while providing flood protection to the lowland city from offshore storms and surges.



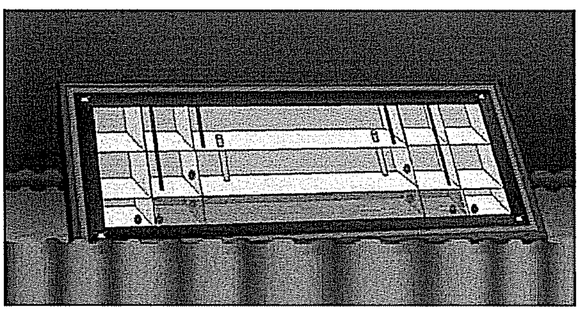
Amagasaki City, Japan, 2003

J STOPLOGS and BULKHEADS

Stop Logs and Maintenance bulkheads are typically constructed with a pair of horizontal trusses supporting a vertical skin plate on one face. They are stored separately from the gate opening and lifted into place by an overhead or mobile crane. They are designed to span across the opening or between intermediate posts that can be installed at intervals across the opening. They may extend vertically from the sill to the top in one piece or smaller units may be stacked and seal against one another to close the opening.

J.1 Kentucky Lock Floating Caisson

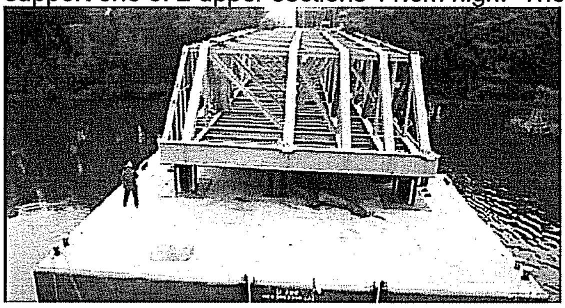
This floating gate is used to dewater lock chambers for maintenance. The bulkhead is towed from one site to another as a barge. It is then filled with water in a sequence to rotate it vertically, move it into position, and lower it into final position. The gate is 34.3m wide and 9m high with a depth of 3.2m.



Locks on Tennessee & Kentucky Rivers, USA, 1969

J.2 Olmsted Maintenance Bulkheads

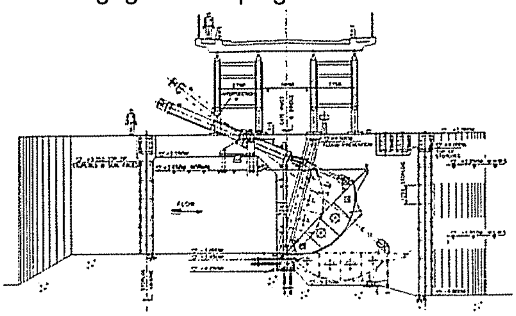
Four bulkhead sections were built to allow maintenance dewatering of the locks and radial gates. The bulkheads are stacked to meeting varying site conditions. Two lower sections 3.4m and 5.5m high are designed to support one of 2 upper sections 11.6m high. The bulkheads span 34.1m.



Olmsted, Illinois, USA, 2004

J.3 Tees Stoplog

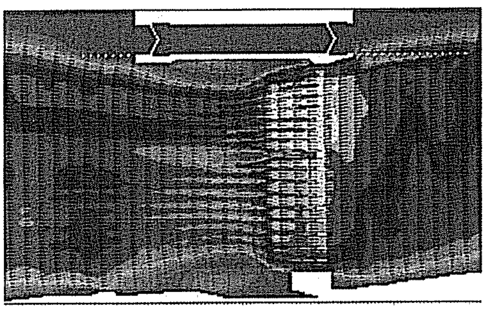
Thirteen stoplogs, 1.25 m high, close an opening 13.89m wide. Eight are used on the downstream side of a gate bay and 5 are used upstream. They are placed with a crane and a lifting beam that will automatically engage or disengage the stoplogs.



Stockton on Tees/Teeside, UK, 1995

J.4 Murray River Stop Logs

These stop logs are used in support of navigation and flood control. They resist heads varying from 4.5 to 6m



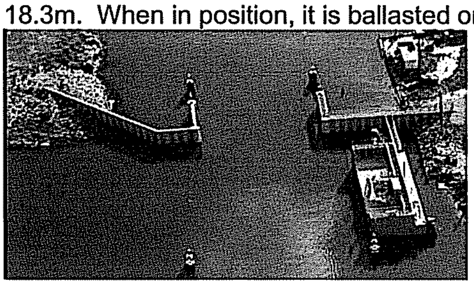
Between Adelaide and Mildura, Australia, ~ 2000

K SWING GATES

A swing gate is stored on one side of a waterway and pivots about a vertical axis to close against abutments on either side of the waterway. A Swing Gate may be buoyant to reduce hinge and operating forces.

K.1 Bayou DuLarge Barge Gate

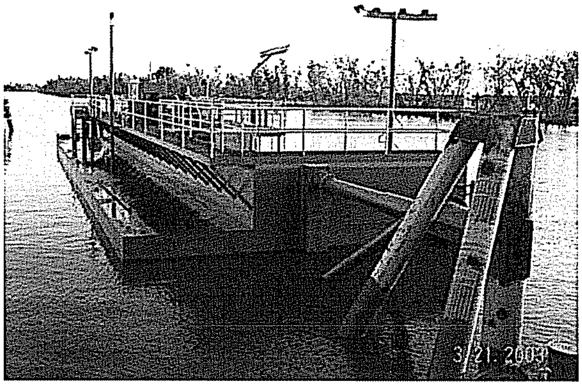
This flood control barrier is made buoyant and floated into position by winches in advance of a flood. It spans 18.3m. When in position, it is ballasted onto the sill and has a height of 6.25m.



Bayou DuLarge, Louisiana, USA, 1996

K.2 Bayou Lafourche Barge Gate

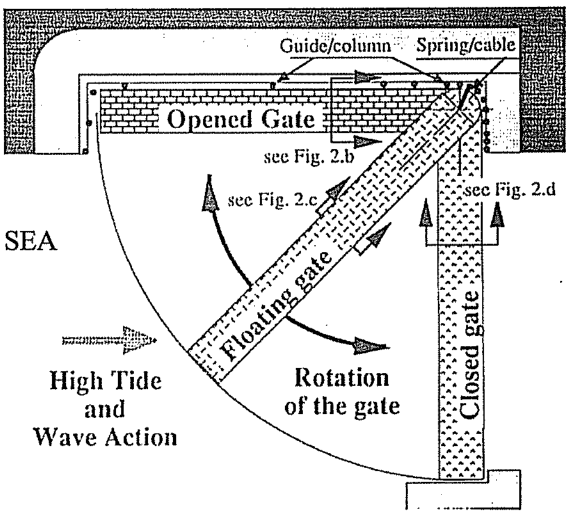
This flood control barrier is similar to Bayou DuLarge. It spans 22.9m and has a depth of 3m with a water-tight parapet extending up an additional 1.5m.



Bayou Lafourche, Louisiana, USA

K.3 Antwerp and Rotterdam Swing barriers

This innovative concept of floating rotating barrier was developed for closure of large spans (up to 400m) without any limitation on draft or air clearance, during construction or operation.



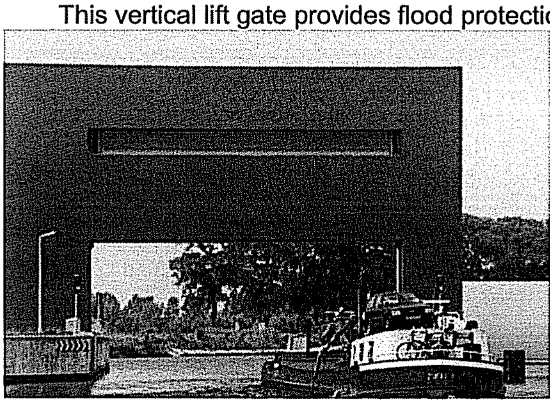
Project in Belgium and The Netherlands (not built)

L VERTICAL LIFT GATES

Vertical lift gates are raised and lowered vertically. They may be stored underwater and raised to close flow, or stored above a channel on towers and lowered to close flow.

L.1 Beernem Weir

This vertical lift gate provides flood protection and is 8.05m high and 17.9m wide.



Beernem, Flanders, Belgium, 1998

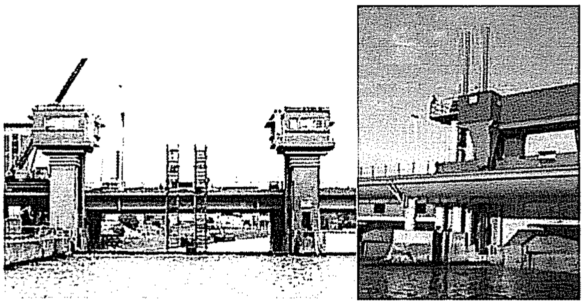
L.2 Hartel Canal Barrier

This large storm surge barrier consists of two lens-shaped vertical lift gates with spans of 98m and 49.3 m with a height of 9.3m. To facilitate water storage the gate never fully closes and at high flood stages the gates are overtopped.

Spijkenisse, Netherlands, 1996

L.3 Ivoz-Ramet

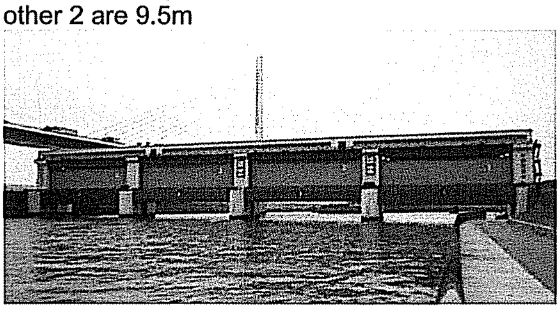
This is a nice example of a rehabilitated weir.



Liege, Meuse River, Belgium, 2000-2001

L.4 Kamihirai Gate

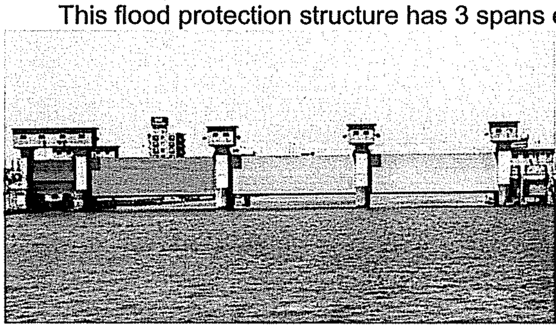
These 4 gates are closed in advance of a flood event. Each gate is 30m wide, 2 gates are 9.2m high and the other 2 are 9.5m



Tokyo, Japan, 1990

L.5 Shinanogawa River Gate

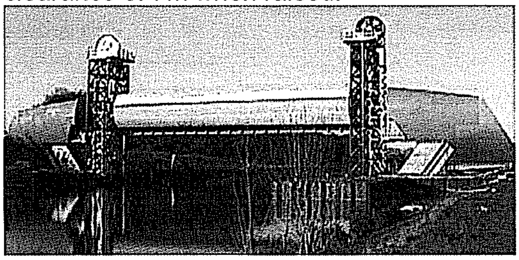
This flood protection structure has 3 spans each 30m wide with a height of 24.5m.



Niigata prefecture, Japan, 1974

L.6 Blanc Pain

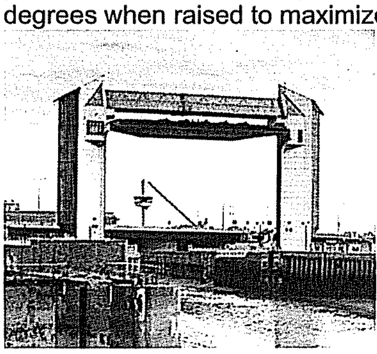
This emergency lift gate protects the 73m high shiplift at Strépy and the surrounding countryside from a flood event in the event of riverbank or structural collapse. The gate closes a channel width of 32.4m and has an air clearance of 7m when raised.



La Louvière, Canal du Centre, Belgium 2003

L.7 Hull

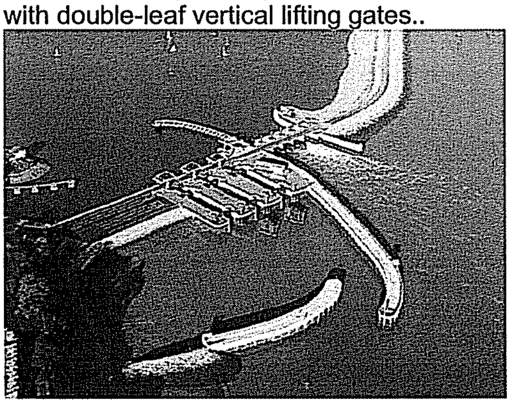
The flood protection barrier is a vertical lift gate which provides a 30 meter wide navigation opening and provides 6.3 m of flood protection. The gate is designed to be aesthetically pleasing and the gate rotates 90 degrees when raised to maximize navigation clearance and minimize visual impact.



Hull, UK, 1979

L.8 Cardiff Bay Barrier

Cardiff Bay Barrage is a tidal exclusion barrier designed for flood control with 5 sluices (9m wide x 7.5 m high) with double-leaf vertical lifting gates..

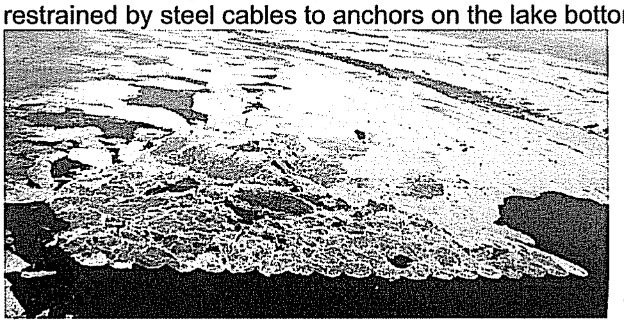


Cardiff Bay, UK, 1998-99.

M UNCLASSIFIED GATES

M.1 Ice Boom - Lac St. Pierre

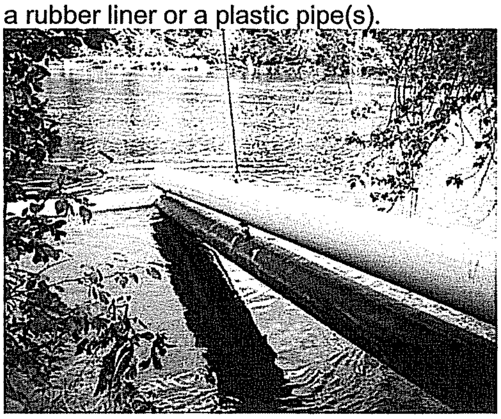
This floating structure protects a major shipping channel from closure by ice. The floating boom segments are restrained by steel cables to anchors on the lake bottom.



Trois Rivières, Québec, Canada, 1994

M.2 Curtain Barriers – Temporary

This curtain barrier was designed to create a headloss and temporarily force the diversion of the flow away from a tributary. The barrier consists of a long steel pipes with a curtain attached to the bottom. The curtain can be a rubber liner or a plastic pipe(s).



Laboratory test and the field deployment of a curtain, 2004.

3. DESIGN PROCEDURE

This section provides a summary of the design procedures (Figure 3.1) of the controllable weirs and gate structures essential for safe operation under environmental or other loading conditions expected during its operational life.

The design procedure (Fig 3.1) of movable gates and barrier structures includes a number of steps and associated parameters, which includes:

- Site Parameters, as the selection of the site, depends on several factors (called here parameters).
- Required Information such as bathymetry, water discharge, wind magnitude, ... and Loads that are necessary for technical analysis at concept development and later for the weir structure design.
- Navigation and Operational Requirements such as debris flow protection, navigation safety, sedimentation ... that correspond to the user requirements to have save, efficient and reliable operations of the weir.
- Design Criteria that help the development of a preliminary analysis by assessing the degree of applicability of each type of structure to the proposed project site.

4. GATE SELECTION PROCEDURE

4.1 Multi-criteria assessment

Both river movable weirs and costal barriers are structures that have great economical, environmental, and other impacts to large areas. The weir and the barrier projects usually affect many people in many different ways, varying from the safety of their homes to the nature of their means of income. The processes, which generate these effects, are often complex, and can be short-term (e.g. immediate solution to flood problems) as well as long-term (e.g. agricultural, ecological, or even climatic changes).

A gate type selection is a significant part of these processes. There are far-reaching consequences of choosing one gate type above another. Though gate type selections usually take place when the global project requirements are known, they can still affect such principal issues as:

- Weir/gate location – as not all gate types are suitable for all locations;
- Waterway navigability – as the gate type selected may promote or halt navigation.;
- Flooding risk – as not all gate types are equally stable, watertight etc.;
- Water flows, bottom and shore erosion – as different gates give different flow patterns;
- Water ecosystem – as not all gate types allow, for example, for a fish passage;
- Local economy – as gates can provide one kind of work and/or destroy another;
- Local energy balance – as gates can be suitable for energy generation or not.

It should, therefore, be clear that the gate type selection is a matter of engineering, economy, politics, or any other privileged discipline, and its people. It is, in fact, a matter of the entire communities living or having other interests in the areas in question. These communities and areas can be very large. In extreme cases, different interests in this matter result in international disagreements. For practical reasons, the gate type selection is usually made by the engineers. They should, however, be aware of all different interests involved; and seek a balance between those interests. The gate type selection can be assisted using multi-criteria assessment methods.

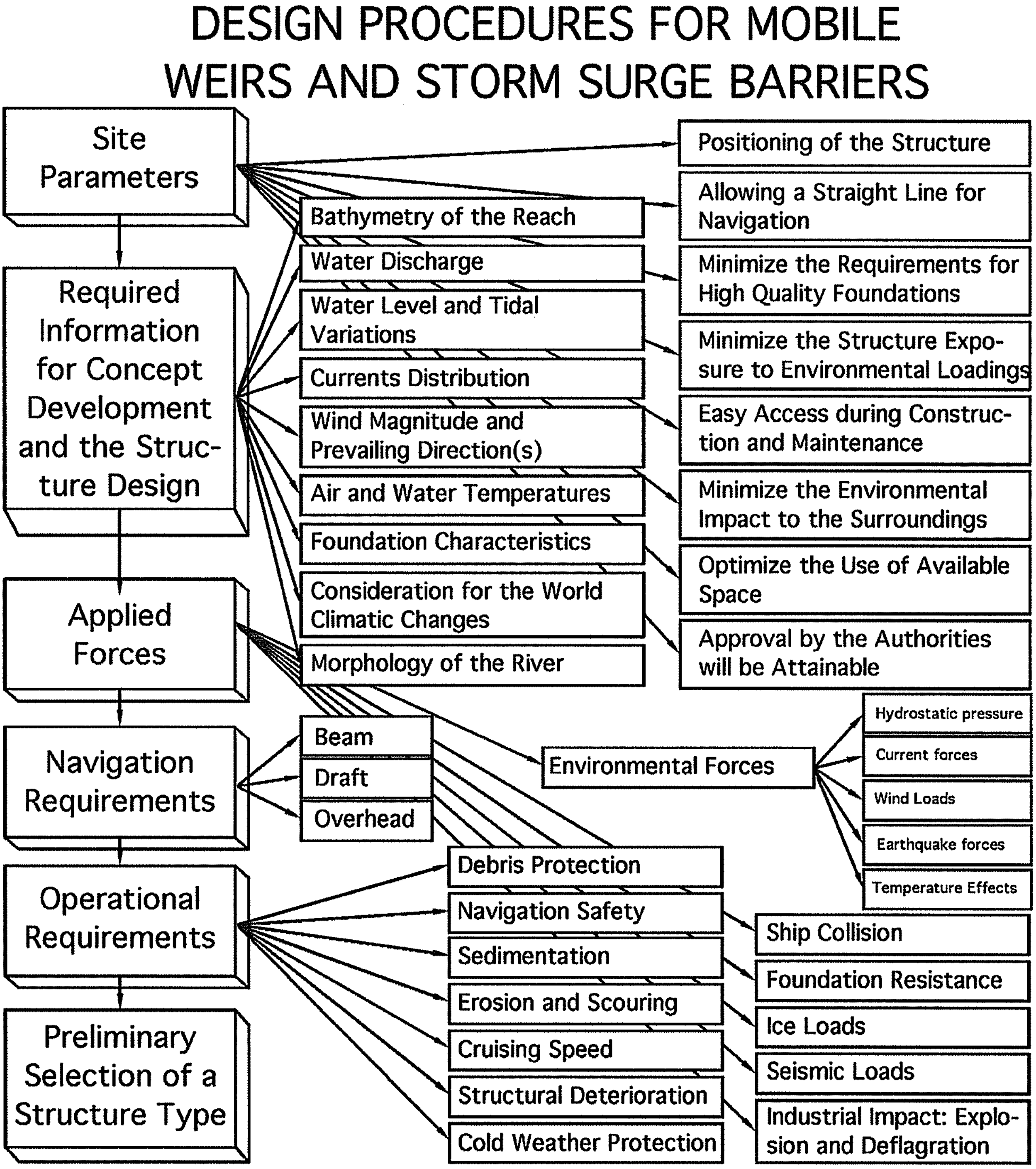


Figure 3.1: Design procedure for Controllable Weirs and Gate Structures

4.2 Method of qualitative assessment

In general, a multi-criteria analysis is a procedure which should result in a matrix in which different options are evaluated with respect to different criteria, see Table 1. Completing such an analysis means - simply speaking - giving values to the matrix elements.

The two main questions of a multi-criteria gate type assessment are:

1. How and in which units to measure the scores of gate types in each criterion?
2. How to convert these scores to the same units in order to make a total assessment?

The simplest solution is to ignore these questions by using qualitative descriptions with no quantitative values.

Option / Criterion	Mitre gate (a)	Mitre gate (b)	Vert. lift gate (c)
Total costs	-	--	+
Operation	+/-	+/-	++
Navigation	+/-	+	-
Maintenance	+/-	+	+
Environment	+	+	++
Aesthetics	+	+	-
Total	**+/-**	**+/-**	**+**

Herein:
++ very good;
+ good;
+/- fair;
- poor;
-- bad

Table 1: Simple and qualitative analysis

Such an analysis is entirely based on subjective judgments of a person or a team. As the matrix contains no numerical values, there is practically no way to verify the performance assessments of the gate types considered. Nevertheless, this simple method can be considered sufficient in a number of situations when, e.g.:

- There is no time to perform a better, quantitative analysis.
- The analyzed case is rather simple. It may be efficient then to make a simple, qualitative assessment; and decide later whether more effort should be expended on gate selection.
- The customer has already made a choice and he does not want any discussion about it. Yet, he appreciates some kind of "educated justification" in case he is asked to give an account of it. If this does not conflict with the engineer's ideas, he may do it.

The last situation shows that the method of qualitative assessment is manipulative. In general, one is advised to lay it in the hands of more specialists, if possible from different organizations, profiles, etc. However, this method can delay progress. A correct, quick assessment is often preferable to long discussions, which can result in a general impotence to get anything done.

4.3 Methods of quantitative assessment

In order to provide a better, traceable gate type assessment, answers must be found to the 2 previous questions: "How and in which units to measure the scores?" and "How to convert these scores to the same units?".

These answers are not easy, as the gate performances can clearly be quantified in some criteria (e.g. costs in euro), less clearly in other ones (e.g. navigation in ship passages) or not at all in still other ones (e.g. aesthetics or environment).

As far as is known, there are two strategies to deal with this problem:

- Expressing everything in terms of costs (in currency units);
- Performance rating and the use of weighting factors.

An argument for the first strategy is that project costs are always one of the most important selection criteria – and this criterion is certainly the best quantifiable. As this criterion often dominates the analysis, the idea is to give values in currency units to gate performances in all other criteria as well. Such an approach answers both questions from the beginning of this section. In support of this strategy, some other criteria – like maintenance or operation – can indeed be measured in currency units to some extent. The maintenance and operation costs over the entire service life must first be capitalized, then added to construction costs.

Despite the clearly defined, recognizable measure unit (money), this approach has a number of disadvantages:

- Not all criteria can be quantified in currency units.
- Strict financial assessment in maintenance and operation says little about e.g. inspection conditions, risks and obstructions due to maintenance, ease of operation, safety for operation personnel, etc.
- The owner always wants his costs accurately counted. The costs of other parties are often underestimated.
- This can be considered morally controversial, e.g. with respect to human life, irreversible damage to the environment, etc.

4.4 Performance rating with weighting factors - general

As mentioned above, another assessment strategy is to use performance ratings with weighting factors. Such a strategy does not make use of measure units from any single criterion, but it introduces its own measuring system which is applicable to all the criteria. Usually, a rating scale, for instance from 0 to 5 points, is assumed to quantify gate performances in each single criterion. Higher marks usually represent better scores, although reverse systems (the higher, the worse) are also possible. In the WG26 report, a decimal scale with a progressive performance rating is discussed.

In general, the rating of gate performance takes place in one of the two following ways:

- For quantifiable criteria: Measure the gate performances in quantity units of a criterion (e.g. in money for the costs criterion); choose a rating range covering the performance range; and convert the measured values to the rating system.
- For not-quantifiable criteria: Allow a representative group of specialists rate the gate performances subjectively; ask them to come up with a consensus or mean scores.

4.5 Performance rating – criteria clusters

It is obvious that different projects require different systems of criteria and their weighting factors. Therefore, it was not the intention of the WG26 report to establish a uniform system, for all weir and barrier projects, apart from locations, local conditions, preferences, etc. Nevertheless, it can be helpful to have an example of such a system when approaching the question of gate assessment. In this sense, as an example – not as advice, two systems of hypothetical gate criteria are given, one for a weir and one for a barrier project (see Table 2).

In both cases, the criteria are clustered in a relatively small number of main criteria, which, in turn, cover a number of sub-criteria. The sub-criteria have been selected taking the following principal guidelines into account:

- There is no doubling of issues between the criteria. Every relevant issue is represented in only one (sub-) criterion.
- Each sub-criterion is more or less independent. There is no or little correlation between the criteria. In case some correlation cannot be avoided (e.g. service life and maintenance), a clear division between the domains of the sub-criteria can be drawn.
- The proposed criteria and weighting factors reflect the average views in the so-called "industrially developed" countries.

Table 2. Indication of gate assessment criteria for weir and barrier projects

Criteria	Weir projects		Barrier projects	
	W.f.	**Sub-criteria**	**W.f.**	**Sub-criteria**
Generalized costs	0.30	Initial costs (engineering, land purchase, construction etc.);	0.15	Initial costs (engineering, land purchase, construction etc.);
		Periodic costs (inspections and maintenance);		Periodic costs (inspections, testing and maintenance);
		Operation costs (personnel, energy, facilities, etc.);		Operation costs (personnel, energy, facilities, etc.);
		Costs of dismantling / modernization after service life;		Costs of dismantling / modernization after service life;
Reliability	0.15	Sensitivity to malfunctions, human errors, ship collisions;	0.25	Failure chance to close, when closed and loaded, to open;
		Vulnerability to foundation distortions, vibrations, bottom erosion, earthquake, etc.;		Vulnerability to foundation distortions, bottom erosion, earthquake, etc.;
		Vulnerability to sediments, ice, debris, algae etc.;		Sensitivity to malfunctions, human errors, ship collisions;
Operation	0.15	Capacity and accuracy of river control in all seasons, operation vulnerability to calamities;	0.15	Convenience and clarity of procedures, especially under extreme conditions;
		Convenience of operation, procedure clarity;		Unavailability for operation due to maintenance;
		Unavailability for operation due to maintenance;		Construction time, especially in reconstruction projects;
		Construction time, especially in reconstruction projects;		Sensitivity to technological aging, patented technology etc.
Navigation	0.10	Construction impact on navigation conditions;	0.15	Free navigation width, overhead space and depth;
		Maintenance impact on navigation conditions		Clarity of navigation regulations during closing and opening;

		Navigation safety and convenience (distances, currents etc.)		Construction impact on navigation conditions;
		Disturbances to maneuvering, radar signals etc.;		Maintenance impact on navigation conditions;
Maintenance	0.05	Maintainability (not in terms of costs!) of all areas and details	0.05	Compliance with ban on maintenance in stormy seasons;
		Access to maintenance sensible components		Maintainability (not in terms of costs!) of all areas and details
		Maintainability under operation conditions		Access to maintenance sensible components
		Health and safety of maintenance crews		health and safety of maintenance crews
Environment	0.15	Operation impact on eco-system (vegetation, wide life etc.);	0.10	Required area, construction impact on eco-systems;
		Environmental “footprint” of materials (pollutions, energy consumption);		Environmental “footprint” of materials (pollutions, energy consumption);
		Environmental impact of gate construction and maintenance (e.g. painting, lubrication);		Residual environmental impact of storm surge passage;
		Possibility of winning “clean” (water) energy;		Environmental impact of gate maintenance (e.g. painting, lubrication);
Social impacts	0.10	Aesthetics, harmony with landscape, local culture etc.;	0.15	Aesthetics, harmony with landscape, local culture etc.;
		Daily impact on local community (jobs, economy, transport, agriculture, social contacts);		Daily impact on local community (economy, transport, agriculture, social contacts);
		Noise (water flow, machineries, maintenance vessels, etc.)		General image, feeling of safety for the local community;
		Tourism, sport and recreation benefit, science and technology popularization effect;		Tourism, sport and recreation benefit, science and technology popularization effect;

In conclusion, gate type selection is an important stage in a barrier or weir project. The operational, financial, and other consequences of this selection are often more important than the detailed engineering. It is, therefore, advisable to give thorough consideration to the gate type selection. The WG26 report gives some background information and a review of existing assessment methods in this field. General advises are:

- There are always a number of criteria to be considered in gate type selection. These criteria are, however, different for every individual project. Therefore, it is not advisable to standardize them, neither to establish strict procedures to be followed in this matter. Nevertheless, every effort should be made to get a clear, well-balanced inventory of all criteria significant to a particular project.
- A multi-criteria gate type selection can be performed in one or more phases. The first takes place when there is a general understanding about significant criteria and suitable gate types – and when the numbers of both are not large. This happens often in small projects. In large projects, the chance of it is usually small. A better strategy then is to make a selection in two or more phases, focusing still deeper on the crucial criteria.

5. DESIGN CONSIDERATIONS (Parameters and Criteria)

5.1 Structural Considerations

The aim of this section is to give an overview about the gate structural aspects and to survey the advantages and disadvantages of the structural aspects of the various gate-types for their intended purposes. These advantages-disadvantages will vary according to how closely the gate type matches its expected uses.

The WG26 report first presents the Main Steps of a Structural Design, and then present 3 additional areas of consideration for gate selection:

- Structural Characteristics of various gate-types
- Analysis of specific constraints and functions
- The Typical Structural concerns (problems, malfunctions) that may occur in movable weirs,

Finally the report compares the advantages and disadvantages of the design, construction, maintenance and operational characteristics for 5 major gate types. The typical range of operation and use are provided to assist the designer in selection of the most appropriate gate type for a specific application.

The main steps of design are described:

→ *Global and geometric design*

The geometric characteristics of the gate have to be optimized using hydraulic and structural considerations in order to:

- Transmit the loads to the civil work,
- Improve hydraulic efficiency,
- Avoid vibrations,
- Control deflections,
- Resist torsion and bending forces,
- Minimize weight (for movable gates),
- Simplify fabrication,
- Provide corrosion protection,
- Simplify maintenance (access to different parts),
- Guarantee long service life.

→ *Determination of characteristic actions (Design loads)*

- Hydraulic (static and dynamic),
- Operating (reaction to the hydraulic loads),
- Accidental (induced for instance by hoisting devices that are not synchronized),
- Deadweight,
- Friction,
- Ice and debris,
- Other actions: earthquakes, waves, wind, blast, etc.

→ *Structural analysis*

In order to calculate the strengths in the structure, it is necessary to analyze:

- Stresses in the fixed and operable structural elements of the gate,
- Forces transmitted to the foundation or supporting structures,
- Reaction forces on hinges, trunnions, rails,
- Deformations, etc.

→ *Load cases*

Different load cases have to be determined for:

- Permanent situations (typical case: normal water levels),
- Transient situations (typical cases: maintenance…),
- Accidental situations (typical case: floating debris chock, malfunction of hoisting device…).

→ *Verifications*

The designer has to form combinations (with partial factors applied to the actions) in order to make the verifications for all the load cases and for various limit states (serviceability, ultimate limit…).

→ *Design of operating equipment*

Attention must be paid to design seals and hoisting devices.

→ *Catastrophic events*

For catastrophic events, failure mechanisms should be designed to provide an orderly reduction of forces and to minimize the costs of repair.

5.2 Hydraulic and Flow considerations

This section evaluates various gate configurations from a hydraulic perspective. The discharge characteristics are quantified in terms of discharge coefficients (where available), that is, the head/discharge relation. Vibration tendencies that may be associated with the gate geometrical configuration or seal locations are identified. Gate performance in regards to their ability to control flow/pool by throttling flow is compared. Some gate types lend themselves to simply a fully open or fully closed operation. Another issue that can be important is the speed of gate operation. What type of gates can be opened or closed rapidly relative to other choices. Venting of the lower nappe of the jet is required for certain types of gates to avoid harmful vibrations. A gate's efficiency at passing floating material such as ice and debris can be an important project consideration. Wider gates are more efficient at passing floating material and are better at avoiding jams of floating material between piers. Effects of high tailwater, potential for unusual hydrodynamic loads, and potential for problems associated with sediment accumulation are also addressed.

A list of hydraulic performance evaluation metrics is provided in the WG26 Report. Each of the gate types is described in terms of these metrics. Any appurtenances that should be avoided (e.g. a seal location) or included (e.g. air vent for nappe aeration) are also mentioned.

5.3 Foundation and Civil Engineering

This subtask intends to emphasize the main aspects of foundations and civil works related to movable weirs and storm surge barriers. Their foundation shall be designed to be safe against loads transmitted from the weirs and barriers body, to possess the required water tightness against seepage flow.

The selection of the most appropriate foundation type is largely based on the site geology, the available geologic and geotechnical information, as well as the performance requirements of the foundation. The type of structure should also be considered. The final decision on the foundation type will affect the total project cost. Foundation investigations and field data are required to assess whether or not a safe and economical structure can be built at a selected site. Especially, in a seismic environment and in locations where differential settling is expected will affect the foundation design. Therefore, foundation investigation is one of the most important issues at the design stage.

5.4 Control, Operation and Maintenance

This section investigates the control systems used on the Movable Weirs and Barriers reviewed by the WG. The investigation should enable an informed decision on the advantages and disadvantages of the various systems in use and assist in the selection of a control system for a new construction.

As well as the control functions of the mechanical, electrical and computer systems the investigation shall include the controls imposed on the operation by statutory bodies.

The investigation considers operational aspects including the manning implications of the systems adopted and the method to isolate the gate for maintenance.

5.5 Temporary Closure Arrangements

It is important to separate "maintenance closure" from "emergency closure" and "site construction closure" systems. The WG26 report mainly deals with maintenance closure, but in some case site construction closure systems can be quite similar to maintenance closure. The "Pallet Barrier" is probably the best example.

Typically, emergency closure systems are vertical-lift gates that remain suspended. They are expensive systems. Few emergency systems were considered in the WG's Project Reviews (Blanc-Pain Gate in Belgium and the Hartel Canal in the Netherlands).

A *bulkhead* is a vertical partition used to seal off one space from another, capable of withstanding the differential head without significant deformation or leakage. Bulkheads are a variation on Stoplogs and are generally one piece construction rather than sectional or modular. There are several devices capable of being deployed to be a temporary closure. A few common examples are:

- Stoplogs
- Needles
- Cofferdams
- Caissons
- Air or water bags
- Palets
- ....

5.5 Safety, Reliability and Risks

WG26 presents, as example, an approach for risk analysis for storm surge barriers.

Definition of failure

In the reliability assessment of storm surge barriers, safety against flooding is the central point. Therefore, failure can be defined as "not fulfil anymore the function of retaining the high water levels".

Failure mechanisms (Fig 5.1)

The state of failure can be reached in various ways, called "failure mechanisms". For a surge barrier, main failure mechanisms can be (as example):

- Overflow or overtopping by waves
- Loss of stability or loss of strength
- Failure of the closure operation of the gates.

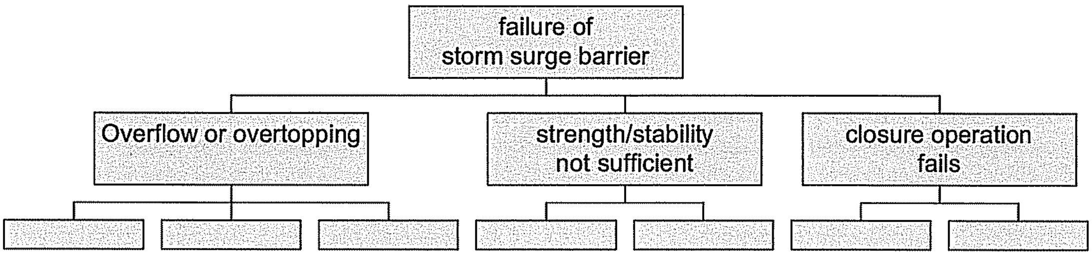


Fig. 5.1: Failure Mechanisms tree of a storm surge barrier

Fault and event trees

The ways in which failure can be reached, can be shown systematically in a fault tree. The top event is failure. In the branches of the tree, it is shown which chain of events (from bottom up) can give rise to the top event. In this way, insight is created in sometimes very complex systems.

The relationship between the elements in the fault tree has to be such that they can provoke the "higher" situated event. The top event has to be a clearly defined event and can only be one state of failure. When constructing a fault tree, it is important to consider systematically all parts of the structure, and to take into account effects of order of appearance of the events and effects of time. Therefore, it is advisable to construct first event trees, permitting to analyse chained events.

Methods of calculating reliability

A fault tree analysis consists of a qualitative and a quantitative part. The qualitative part analyses how the structure can fail. In the quantitative part, each event is given a probability of occurrence, and the probability of the top event is calculated.

For quantitative analysis, two approaches are possible:

- Bottom-up: the probability of failure of each element is determined, next it is verified if the top event satisfies the imposed reliability criteria,
- Top-down: an allowable failure rate of the top event is fixed. On the basis of maintenance reasons, the allowable failure rate of the components and mechanisms is fixed. Next, the design is made and it is verified if the allowable failure rate of the top event is satisfied. If not, the design is adapted.

The top-down approach is mostly used in hydraulic engineering.
When calculating probabilities of failure (Fig 5.2), mutual dependency and succession of failure mechanisms is important.

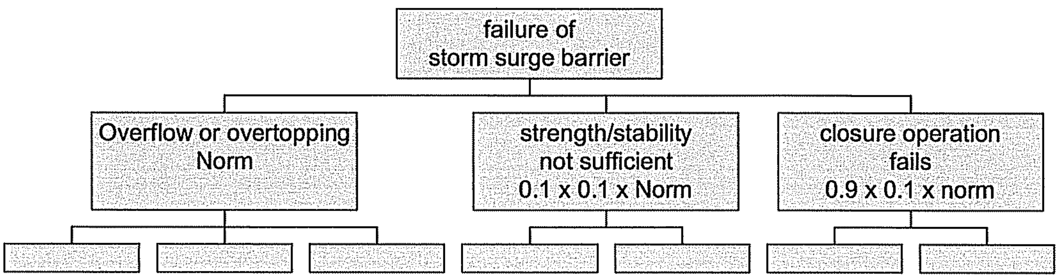


Fig. 5.2: Probability of failure of the Fault and event tree of a storm surge barrier

5.6 Environmental Impacts and Aesthetics

➔ Environmental Impacts

It is recommended that clients, designers and planning authorities are mindful of the "*whole life cycle*" impact of their projects – it would be unfortunate if a chosen design was resource effective at the building stage, but proved resource intensive during operation and posed major wastage and impact at decommissioning.

Similarly, it is important to consider the "*whole environmental footprint*" of the project and not just factors relevant to the site of construction and operation. For example, avoid specifying timber or stone from sources which are not sustainably managed and/or require transport over large distances; instead, use more innovation in the specification and seek out managed, local sources of materials.

As with so many designs and conceptual processes, recognise that achieving high standards of environmental acceptability is an iterative process – allow one good idea to lead into another.

Environmental headings that must be considered include:

- Storage and handling of all materials;
- Construction materials;
- Materials, resources and energy required to operate;
- Impacts, particularly waste streams at times of major overhaul, e.g. removal and surface preparation from old paint, especially over water.

➔ Aesthetics

By its very nature, aesthetics is very subjective. Perhaps any system of classification could be under three broad headings:

- Poor or negative impact,
- Average or acceptable,
- Good or with added value.

For any major structure, we would recommend that an artistic impression should be commissioned to create a "vision" of the possible options. These artistic impressions will have many purposes including:

- Evaluation of options and optimising the preferred solution,
- Satisfying the expectations of client, stakeholders or the planning authority,
- Used as a visual and conceptual guide for the design team.

It is often wise to include structural and landscape architects as part of the design team.
Installations in urban sites or sites visited by a large number of people for recreation (sailing, walking, cycling, bird watching, etc.) may warrant closer attention to aesthetics than installations rarely seen by others.

5.7 Cost (Construction, Maintenance and Operation)

Global cost for construction of a navigation weir is related to the site's physical constraints (geology, hydraulics, sediments science, aesthetics, etc.) and to the adopted weir type (flap gates, sills, etc.). Fig. 5.3 shows the different steps of a weir project including Conception, Design, Construction, and Operation and Maintenance.

But to obtain a real estimation, the operation and the maintenance cost should also be taken into account. These costs depend on the expected safety level. That is what is called **"global cost".**

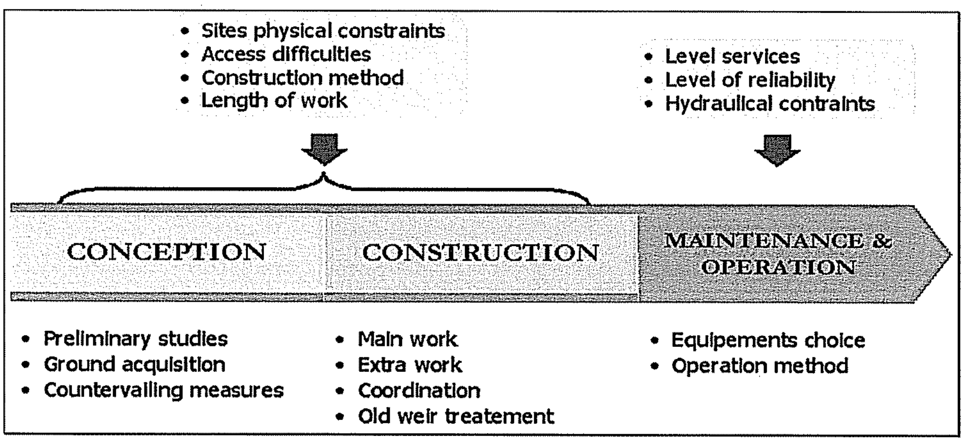


Fig. 5.3: Steps of a weir project (Conception-Design, Construction, and Operation and Maintenance)

6. DESIGN AND ASSESSMENT TOOLS

This section presents design and assessment tools currently used in standard practice for the design of movable weirs. Also, new trends in the use of advanced analysis are introduced.

The tool review focuses on the standard design tools used nowadays by engineers in the current practice of designing movable weirs and barriers. It also surveys the engineer's needs for specific and advanced tools taking into account, the design requirements that become more and more demanding (economic, technical, and environmental aspects).

In the report, the design tools are categorized according to the different technical problems that an engineer faces during the design of a movable weir/barrier:

(1) CAD software for project drawing and plans,
(2) EARLY DESIGN tools including optimisation capability,
(3) HYDRAULIC: Flow pattern and discharge assessment,
(4) PHYSICAL MODELS in laboratories,
(5) LOADS assessment including dynamic water pressure, wind, wave, tide, snow, ice, etc.,
(6) Strength assessment of STEEL structures,
(7) Strength assessment of CONCRETE structures,
(8) Strength assessment of FOUNDATIONS,
(9) Static and dynamic FLOATING STABILITY assessment,
(10) FINANCIAL assessment,
(11) Other specific tools and software (RISK assessment, ENVIRONMENTAL assessment, GIS, etc.).

Tools, specificities and user requirements are discussed in relation with the tool purposes. For each technical problem, the WG proposes a list of relevant tools with, if possible, recommendations and reference to previous experiences (with links to project reviews). According to the design stage (preliminary design stage, detailed design stage) specific problems with their associated assessment tools are discussed like structure optimization, cost assessment, nonlinear behaviour, large deflection, shock and impact, etc.

7. PREFABRICATION TECHNIQUES

Flood control projects have traditionally been constructed in cofferdams. This allows traditional construction methods and equipment as well as conventional quality control inspections and measures to be used. The cost of this method is high; it requires the temporary construction of a large cofferdam that serves no final purpose and needs to be removed after construction. There is the risk of overtopping and potential damage to work in progress as well as delays to construction for demobilization, flooding, cleanup and start up efforts.

Prefabrication has long been used on flood control projects for various gate components. Typically the steel gates themselves and their operating components are fabricated offsite and then placed by crane.

Improvements in technology and engineering knowledge have increased the viability of prefabrication. It is now possible to completely construct hydraulic structures without a cofferdam. Foundation can be prepared "in-the-wet" by floating construction equipment that prepares the river bottom and supporting structures from the surface. Templates or guide structures that extend above the water surface can provide great accuracy in placement.

Shells for the substructure and/or superstructure are constructed offsite, transported via a navigable waterway to the site and set in place, see Fig. 7.1.

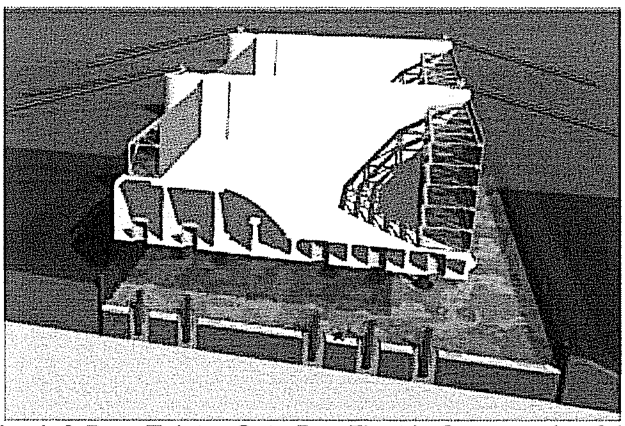


Fig. 7.1: Braddock Lock & Dam Tainter Gate Bay Float in Segment (prefabricated civil works)

The structure is then filled with concrete to complete the structure and join it to the foundation. If necessary, the gate openings can be closed with bulkheads and dewatered for installation and final adjustment of the gates.

A prefabricated gate foundation structure is typically built as a shell structure fabricated of reinforced concrete. Steel or aluminium plate can also serve this purpose but are not as common.

In-the-Wet construction allows rapid completion of construction, minimizes disruption to existing river traffic, and has less environmental impact than conventional techniques.

8. CODES, RULES and STANDARDS

8.1 Application of New Standards to Hydraulic Structures

The development of new standards (like Eurocodes) based on limit states and partial factors format, has been focusing on the need to express harmonized design standards in practical terms. So far, hydraulic structures have been mainly designed using different rules according to the relevant part of the structure (structural vs foundation design) that leads to tricky situations when different formats are used simultaneously.

On the other hand, several actions [static and dynamic water pressure, waves, currents, ... as well as actions due to vessels (berthing, mooring) and to port activities (live loads, cranes, equipments...)] fall out of the scope of existing standards, which are mostly devoted to buildings and bridges (wind, snow, exploitation loads, traffic actions). To overcome this problem, some aspects of the semi probabilistic format were developed, by unifying the «*source factors*» and by diversifying the «*model factors*». The most important issues to be addressed when developing a limit states verification format are then: partial factors, characteristic values for actions with emphasis on water actions, assessment of safety level, and calibration procedures.

9. CONCLUSIONS & RECOMMENDATIONS

The WG has investigated a variety of projects and concludes that much knowledge and information particularly relevant to the design of movable weirs is available, but not being taken advantage of. We hope that this report will enable designers of future projects to take advantage of that knowledge and information, leading to improvements in design and economies in construction.

As it was stated that the '*design of movable river weirs is a conservative world*', the WG recommends:

- **About Innovation**
  The Public Administrations, who are usually the weir owners and managers, should leave more room for innovation and new concepts.
- **About Prefabrication and Standardisation**
  Prefabrication usage that closely relates to standardisation should be investigated, as it is a source of savings, fast construction, and friendly environment construction modes.
- **About Temporary Closure Devices**
  Temporary closure devices and maintenance bulkheads must be considered as a key issue of an efficient design.
- **About Design Procedure and Multidisciplinary team**
  It is now time to integrate the traditional weir design procedures with risk assessment, maintenance and control, codes and standards (Eurocodes), and design concept (limit states and partial safety factors).
- **About Computational Tools**
  We should promote the development and use of specific computational tools for preliminary design. Advanced analysis can now be performed at the early design stage to show the feasibility of new innovative concepts. Optimisation can also be performed at the early stage, as it can induce large savings. Delaying will reduce the potential benefits.
- **About Gate type selection and About Multi-criteria Analysis**
  Gate selection is an important stage in a barrier or weir project. The operational, financial, and other consequences of this selection are often more severe than are the detailed engineering.
- **About Maintenance and Standardisation**
  Maintenance is one on the major hidden issues of a weir design. Maintenance must be considered at the early design stage in order to reach a high efficiency/cost ratio and a high operational standard.
- **About Floating Structures**
  Designing movable a structure as floating structures should be used more as it usually leads to simple, cheaper, and more reliable structures.
- **About Control of Operation**
  The philosophy "Keep it Simple" is always good, but not always realisable!
- **About Risk Based Design**
  Risk analysis is now an accessible tool for the design of weirs and barriers. It is particularly useful when failure may induce important damages to nature, cities, and the human lives.
- **About Environmental Impact and Aesthetics**
  It is recommended that clients, designers, and planning authorities be mindful of the "*whole life cycle*" impact of their projects.

REFERENCE

- INCOM WG26 Report (2006), "Design of Movable Weirs and Storm Surge Barriers", Report of the INCOM-WG26 , http://www.pianc-aipcn.org , Publ. PIANC, Brussels, January 2006, 124p (and CD-Rom).