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**DESIGN OF RIVER NAVIGATION WEIRS AND FLOOD PROTECTION  
BARRIERS<sup>1</sup>**

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## 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.

## 2. GATES OF MOVABLE WEIRS AND BARRIERS

Case studies of each of the following gates are included on the WG26-CD /Directory A1/. [1]

- Arch or visor gates: An arch gate is a three-hinged arch that spans from abutment to abutment across the waterway. Fig. 1 shows one of 3 lock gates constructed as flood protection measures from storm surges for the city of Osaka.



Fig.1

Aji River Barrier (Japan)

- 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.

- 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. Fig. 2 shows the Ramspol barrier. These 3 inflatable fabric bellows barriers with a width of 60m, provide 2.7m of flood protection from inland river flood waters.



Fig. 2

Ramspol Barrier (The Netherlands)

- 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.

- 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. Fig. 3 shows the 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.



Fig. 3

Thames River barrier (UK)

- Sector gates-vertical axis: Those 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. Fig. 4 shows the Maeslant Storm surge barrier. The gate is made buoyant when it is moved by locomotive engines on each shore. The gates pivot on specially fabricated spherical bearings.



Fig. 4

Maeslant Storm Surge Barrier (The Netherlands)

- 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 designed to span across the opening or between intermediate posts that can be installed at intervals across the opening.

- 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. Fig. 5 shows an innovative concept (not built) 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.

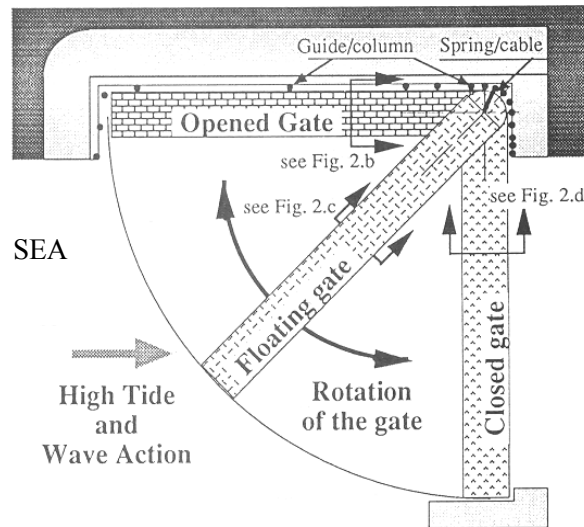


Fig. 5

Antwerp and Rotterdam swing barrier (Belgium & The Netherlands)

- 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.

### 3. DESIGN PROCEDURE

The design procedure 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 safe, 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 coastal 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.

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. 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.

#### 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.

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.

Table 1  
Simple and qualitative analysis

Option Criterion	Mitre gate (a)	Mitre gate (b)	Vert. lift gate (c)	Herein: ++ very good;
Total costs	-	--	+	

Operation	+/-	+/-	++	+ good; +/- fair; - poor; -- bad
Navigation	+/-	+	-	
Maintenance	+/-	+	+	
Environment	+	+	++	
Aesthetics	+	+	-	
<b>Total</b>	<b>+/-</b>	<b>+/-</b>	<b>+</b>	

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?”.



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.

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.
- 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 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**

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.

## 5. DESIGN CONSIDERATIONS (PARAMETERS AND CRITERIA)

### 5.1. STRUCTURAL CONSIDERATIONS

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.

→ *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),
- 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, transient situations, accidental situations.

→ *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. 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.

### **5.3. FOUNDATION AND CIVIL ENGINEERING**

The 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. 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. SAFETY, RELIABILITY AND RISKS**

- 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: 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, ...

- 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.

- 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. 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 mutual dependency and succession of failure mechanisms is important.

## **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.

- Aesthetics: For any major structure, we would recommend that an artistic impression should be commissioned to create a “vision” of the possible options.

### 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. 6 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.

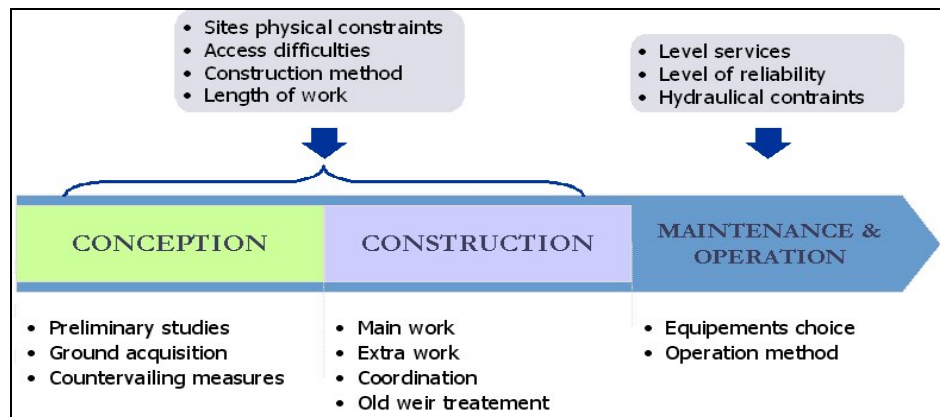


Fig. 6

Steps of a weir project (Conception-Design, Construction, and Operation and Maintenance)

## 6. DESIGN AND ASSESSMENT TOOLS

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).

## 7. PREFABRICATION TECHNIQUES

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 (see Fig. 7). 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.

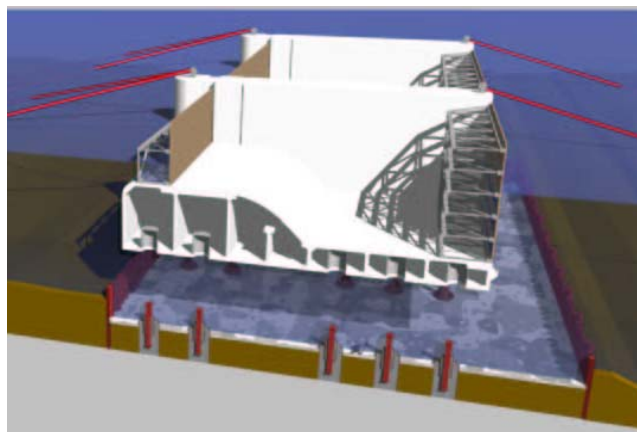


Fig. 7

Braddock Lock & Dam Tainter Gate Bay Float in Segment (USA)

## 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.

### REFERENCE

- [1] 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).

## SUMMARY AND KEY-WORDS

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.

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