# Comparison of two barriers of gate systems
# Hydrodynamic study

**Technical Document**

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# ABSTRACT

Protection of the lagoon of Venice against highest tides is a major objective for the Municipality of Venice. Design of a gates system has been selected and construction has been engaged since two years. The gates system is composed of a barrier of elementary gates which can be closed to maintain the maximum allowable water level inside the lagoon.

A key point of the project is the hydrodynamic behaviour of both an elementary gate and a gates barrier through which water circulation could be possible even with sea states less severe than the maximum design condition. The objective of the present study is to compare the dynamic behaviour of two gates barrier systems based on a different elementary gate design.

The main differences between the two gate barriers are the basic principle of the gate and its orientation of within vertical :

- the MoSE gates contrast the difference of levels with the gate buoyancy. The gate is inclined to the lagoon
- the Gravity gates contrast the difference of levels with the gate weight. The gate is inclined to the open sea.

The case study refers to the Malamocco inlet. Each barrier is composed by 20 gates of 20m large pined at the bottom level. Comparison will be concerned performance of, first, a single gate (2D and 3D analysis) and then a complete barrier (3D analysis).

The document describes the:

- Methodology, assumptions and numerical tools used for comparisons
- Comparison of the numerical tools used and existing bibliography
- Input data: environmental conditions to consider, gates characteristics
- Analyses performed and main results
- Comments on the main results : gates motions and loads transferred to the foundation.

Main conclusions:

<u>Methodology</u>

The methodology, numerical assumptions and tools used for the analysis represent the most advanced state of the art in the non linear hydrodynamic modelling and multi-body interaction in waves. Specific task on the matter has been given to professor B. Molin of Marseille University. For the response of the gate barrier, the results achieved by professor B. Molin (Ref.4), with linear analysis, are in agreement with the results published by professor C.C. Mei (Ref.5, 6).
For a full understanding of the dynamic behaviour, both an approximate linear analysis and subsequently non-linear calculations that represent the effective mechanical model of the gates and of the barrier have been performed.

<u>Isolated gate</u>

- The comparison between linear and non-linear calculations shows that non-linear hydrostatic effect has a major influence both for MoSE and Gravity gates. Then conclusions are derived from non-linear calculations performed for two spectra having Hs=3.2m and Tp=9.3s and 8s.

- Considering the 1000-years wave conditions, Hs=3.2m, Tp = 9.3s. Gravity gate leads to 10% to 20% larger oscillation angles compared to MoSE gate. Vertical force at the pined point is reduced for Gravity gate and horizontal components are similar for the two design. Mean drift imposes a modification of the mean inclination less than 4°: down-lift for MoSE and up-lift for Gravity.
- For the MoSE gate, for the lowest wave peak period, an unstable behaviour has been observed depending on the significant wave height Hs. A specific analysis has been followed for Tp=8s, decreasing Hs. The limit of stability has been found for Hs=2.0m. For larger value the gate oscillates between the two unstable equilibrium inclinations with amplitudes not compatible with the geometry of the inlet mouth and that cannot be represented with the state of the art of modelling and analysis. Occurrence of unstable behaviour is very sensitive to the mass distribution (and ballast).

| | | Fx (N) | | Fz (N) | | Total | Pitch (°) | |
|---|---|---|---|---|---|---|---|---|
| | | Min | Max | Min | Max | Max | Min | Max |
| Tp=8.0 | Mose NL | UNSTABLE BEHAVIOUR — NON REALISTIC RESULTS | | | | | | |
| Tp=8.0 | Gravity NL | -7.82E+05 | 7.40E+05 | -4.78E+05 | 4.74E+05 | 9.17E+05 | -8.0 | 8.5 |

To achieve readable results with Hs=3.2m, for an academic exercise, it has been imposed an additional quadratic damping corresponding to 15% of critical damping (added to wave radiation damping) which seems quite larger that real viscous flow could do.
The results obtained are in the table:

| | | Fx (N) | | Fz (N) | | Total | Pitch (°) | |
|---|---|---|---|---|---|---|---|---|
| | | Min | Max | Min | Max | Max | Min | Max |
| Tp=8.0 | Mose NL | -1.86E+06 | 1.53E+06 | -9.47E+05 | 7.71E+05 | 2.09E+06 | -17.9 | 18.9 |

The obtained values can not be compared with Gravity NL.
As matter of fact, for systems such as the MOSE gate, where the viscous damping is determinant, it is very difficult to define a mathematical model that can represent the real behaviour of the unstable gate. In these cases there is also the difficulty to utilize scaled model testing results that follow the Froude similitude and not the Reynolds one for the viscous forces, and therefore the forced dumped behaviour during the tests, does not permits a correct dynamic behaviour of the model and, as consequence, it is not possible the direct transfer of measured data to the real prototype.

Gate barriers

- The comparison of the behaviour for MoSE and Gravity barriers has been done tacking into account the hydrodynamic interactions between the gates; to avoid enormous calculation difficulties, primarily due to the already experienced dynamic instability of MoSE gate, a linear elastic spring has been assumed (linear analysis).
- The analysis of the barriers has been performed, including hydrodynamic interactions between the 20 gates and assuming 2 meters difference between sea-side and lagoon water levels. No-symmetric waves field is obtained by modelling the boundary walls of the barrier and a small wave incidence.
- Hydrodynamic interactions have a major influence on the global behaviour of the barrier. Then tentative to define natural periods seems quite unrealistic as hydrodynamic coefficients are too sensitive to the relative motions between gates induced by waves.
- For wave periods corresponding to the 1000-years conditions (Hs=3.2m, Tp=9.3s), limited absolute rotation angles are obtained close to those obtained for an isolated gate but higher for MOSE gates (see point 6.3.1) and with larger difference in the phases between adjacent gates.

The relative rotation angles increase to 10° for the Gravity gate and to 25° for the MoSE gate. For larger wave periods a "snake" behaviour is obtained with large rotation angles.

- Loads at the pined point take similar values as for an isolated gate.
- The linear analysis of the gate barrier has shown that their interaction greatly influence the relative motions between adjacent gates and does not introduce sub-harmonic response of on the gate behaviour and on the barrier.
- As conclusion of the study a non linear analysis of the two gate barriers has been performed for the starting condition of the closure of the inlet mouth for the spectrum Hs = 3.2m, Tp = 8 sec. A simple configuration composed of two moving gates close to the channel wall has been considered. The non linear analysis of the behaviour of the two gates has demonstrated that the presence of the wall influence the dynamic behaviour of the gates adjacent the inlet mouth for both the gates MoSE and Gravity. In particular the dynamic behaviour of the first MoSE gate is regular and is possible its modelling, but the adjacent gate shows also in this case an irregular behaviour with not reliable results. The same analyses performed for the Gravity gate show a regular dynamic behaviour of the two gates with reliable results. Based on these results it has been deducted that is useless to continue the analysis of the whole MoSE barrier, being impossible its modelling with the mathematical models existing in the state of the art, and not to continue the analysis for the Gravity gate barrier as it is impossible a comparison between the two solutions.
- The results achieved show that, for the project of the system for the closure of the inlet mouths, it is necessary to perform the non linear analysis of the whole barrier, and in particular the results achieved for the Gravity solution with the isolated gate and the couple of gates adjacent the inlet mouth wall, show that it is necessary to run a 3D analysis of the whole barrier. Simplification with 2D model or with limited number of gates do not represent the real dynamic behaviour of the gate barrier.

General Comment

- The comparisons of the two isolated gates with dynamic analysis using linear hydrostatic spring leads to similar behaviour with larger motions for the Gravity gate but larger vertical loads for the MoSE gate for the extreme wave conditions Hs = 3.2m and Tp = 8sec and 9.3sec. With the effective non linear hydrostatic spring the behaviour of the two gates is significantly different, MoSE gate shows an unstable behaviour not only with maximum design spectrum Hs = 3.2 m, Tp = 8 sec but also with less severe sea states.
- The linear analysis out-phase motions shows, for both barriers, relative angle between adjacent gates, limited to 10° in the 1000-years sea-sate. Higher relative angles are obtained but only for wave periods larger 13s (not in the range of the incoming wave periods)
- The unstable behaviour, induced by non linear hydrostatic spring, is obtained for the MoSE gate for steep waves, i.e. Tp=8s corresponding to Tz=7.5s. and Hs>2.0m. A preliminary sensitivity analysis shows that instability is highly sensitive to the gate mass and inertia, the wave energy distribution and to the fluid flow damping. This is of particular interest because during the wave measuring campaign at the installation site of the barrier of approx. 4 years at the Malamocco inlet there is evidence of at least one storm with Hs = 2.5 and Ts = 7.5 sec corresponding to a Tp = 8 sec has occurred at site.
- Due to the limited scope of the work of the present analysis using the state of art in hydrodynamic modelling, these are the achievable results, a deeper analysis on the damping mechanism taking place between a set of gates, could be required to better define limits and range of the instability occurrence.

- In any case the chaotic response with high dynamic amplification of the oscillations of the MoSE gate that are not compatible with the geometry of the inlet mouth as drawn in the final design and cannot be analysed with the modelling technique possible with the present state of the art, for several working conditions still remain.
- The utilization of structures dynamically unstable to the waves action has no examples in the marine and offshore engineering and therefore the state of the art does not permit to define a reliable dynamic behaviour of the gate and consequently a reliable design of the connection system of the MOSE gate to the foundation base. In addition it has to be considered that, in presence of such amplification of the gate oscillation, the formation of gates barrier should lose the efficiency as barrier against the tide differential level.
- The Gravity gate does not show unstable behaviour induced by the non-linear hydrostatic spring for the design sea states.
- The proximity of the MoSE gate to the mouth inlet wall introduce significant variations in the added mass and in the radiation matrices keeping the gate out of the instability, but it is not sufficient to influence the dynamic behaviour of the second gate as shown for case 3. This confirm that the chaotic response, when exists as for the MoSE gate, it is introduced by the gate into the whole barrier and not viceversa: if the gate is stable the barrier does not introduce instability or sub-harmonics as demonstrated with the linear analysis of the complete gate barriers.
- The dynamic behaviour of the two Gravity gates close to the mouth inlet wall is confirmed to be regular.
- Based on the above results obtained for the MoSE gate, that is the impossibility to perform its dynamic analysis, and considering that the scope of this study is not to perform the design of the gate system but only to perform the dynamic analysis and to compare the different dynamic behaviour of the two gate concept, it has been decided not to perform the non linear dynamic analysis of the whole barrier also for the Gravity gate as it is not possible to compare a stable system with an unstable one:
  - → the stable system can be analysed with standard techniques considering non linear dynamic behaviour of multi-bodies interacting with wave, and it is possible to achieve realistic and reliable results for a proper design.
  - → the unstable system cannot be analysed even using the most advanced non linear simulation software available in the market place and therefore it is not possible to achieve reliable results for a proper design.
- In addition to the comparison of the dynamic behaviour in waves of the two gates, there is evidence that with respect to tide variation, MoSE gate requires an active control system of the water ballast to maintain the design working condition, while Gravity gate does not need it.

**Key Words**

**Venice lagoon, Gates system, Hydrodynamic analysis**

# TABLE OF CONTENTS

## 1 CONTEXT AND OBJECTIVES

Protection of the lagoon of Venice against high increase of sea level is a major objective for the Municipality of Venice. Design of a gates system has been selected and construction has been engaged since two years. The gates system is composed of a barrier of elementary gates which can close to maintain a maximum water level inside the lagoon.

A key point is the hydrodynamic behaviour gates barrier corresponding to the elementary gate design within water circulation could be possible through the barrier even if maximum waves conditions occur. The objective of the present study is to compare the dynamic behaviour of two gates barrier systems based on a different elementary gate design.

The main differences between the two systems are the basic principle of the gate and its orientation of within vertical :

- the MoSE gates contrast the difference of levels with the gate buoyancy. The gate is inclined to the lagoon
- the Gravity gates contrast the difference of levels with the gate weight. The gate is inclined to the open sea.

The case study refers to the Malamocco inlet. Each barrier is composed by 20 gates of 20m large pined at the bottom level. Comparison will be concerned performance of, first, a single gate (2D analysis and 3D analysis) and then a complete barrier (3D analysis).

Performance are defined as :

- Motions of an elementary gate : stable behaviour, motion amplitude
- Load induced on the gate articulation system and on the foundation
- Capability to avoid water propagation through the barrier related to the global "snake" behaviour
- Wave elevations induced in the lagoon if the barrier acts as a wave-maker

The present design basis document describes the :

- Methodology, assumptions and numerical tools used for comparisons
- Input data : environmental conditions to consider, gates characteristics
- Analyses performed and main results obtained
- Comments on the main results : gates motions and load transferred to the foundation.

## 2 REFERENCES

Ref.1 "Metocean report" – Extraction – 25/09/2002
Ref.2 "Study specifications"
Ref.3 Design Drawings of Mo.S.E. (Progetto definitivo)
Ref.4 Autocad Model of the Gate "Paratoia a Gravità"
Ref.5 "Hydrodynamic analysis of the Venice gates – Part I and II", B. Molin
Ref.6 "Numerical solution for trapped modes around inclined Venice gates", C.Y. Liao, C.C. Mei, JWPCOE , October 2000
Ref.7 "Natural modes of mobile flood gates", CG.L. Chiang, C.C.Mei, AOR, August 2003

# 3 ENVIRONMENTAL CONDITIONS

The gates barrier is closed in severe environmental conditions leading to prevent high water in the Venice lagoon due to a large increase of the water level at the sea side. The objective is to maintain a maximum water level of 15m at lagoon side in any conditions.

The most severe working conditions of the gates barrier system is governed both by the maximum tide and by the wave conditions:

- water depth on the open sea side: 15m at the closure of the gate barrier and 17m with the maximum design tide (design tide = 2m)
- 1000-year waves conditions to be considered (extract from the metocean report):
  - → zero-up-crossing period: Tz=7.5s s (corresponding Tz=7.5s)
  - → Significant wave height: Hs=3.2m
  - → JONSWAP spectrum with $\gamma$ adjusted to fit the Tp/Tz ratio
  - → Wave direction: assumed perpendicular to the gates barrier.

Comment :

- The metocean specifications does not give indication on the peak period Tp to be related to Tz. Then a range of Tp = 8.0s to 9.3s has been selected to cover the expected sea-states, adjusting for each Tp the $\gamma$ parameter to fit Tz.
- Unidirectional waves will be considered in the first step of the analysis considering that the barrier is located in channel delimited by two parallel walls. In fact the right and left boundaries of the channel are not identical, inducing a non-symmetrical wave flow.
- A critical point to assess is the capability of each design to avoid any water propagation through the barrier as the gates could move with different phase lags. Then a little wave heading and/or waves spreading will be considered for the analysis of the muti-gates configuration to reproduce the effect of the non-symmetrical wave flow
- Steady waves could be also taking place:
  - → between the two boundaries (walls): due to the channel width and water depth, the lateral modes excited by in-coming waves would be rapidly damped.
  - → in front of the barrier: combination of in-coming, reflected waves and radiated waves induced by the gates motions

# 4 GATES SYSTEM DESCRIPTION

## 4.1 GLOBAL CONFIGURATION

The “Bocca di Malamocco” configuration will be considered. The 20 gates, of 20m width each, are distributed between the 2 walls of a channel open to the sea at its upstream entrance. Width of the channel is then 400m.

Gates are not linked together which means that each gate is free to rotate even if its own hydrodynamic response is affected by the global motion of the barrier and by the other gates.

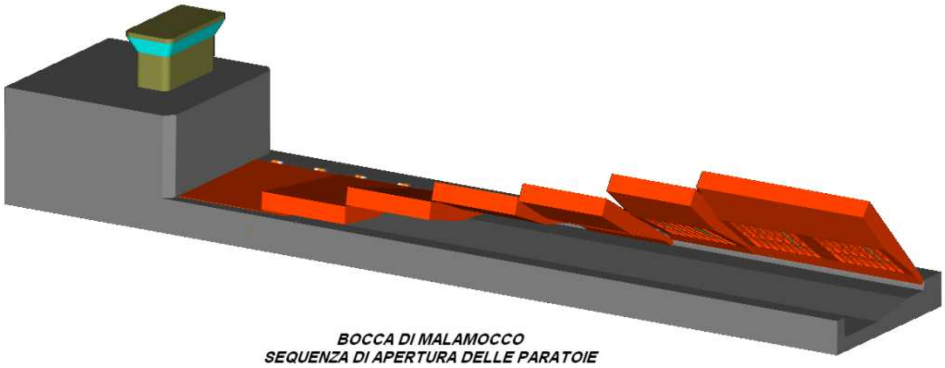
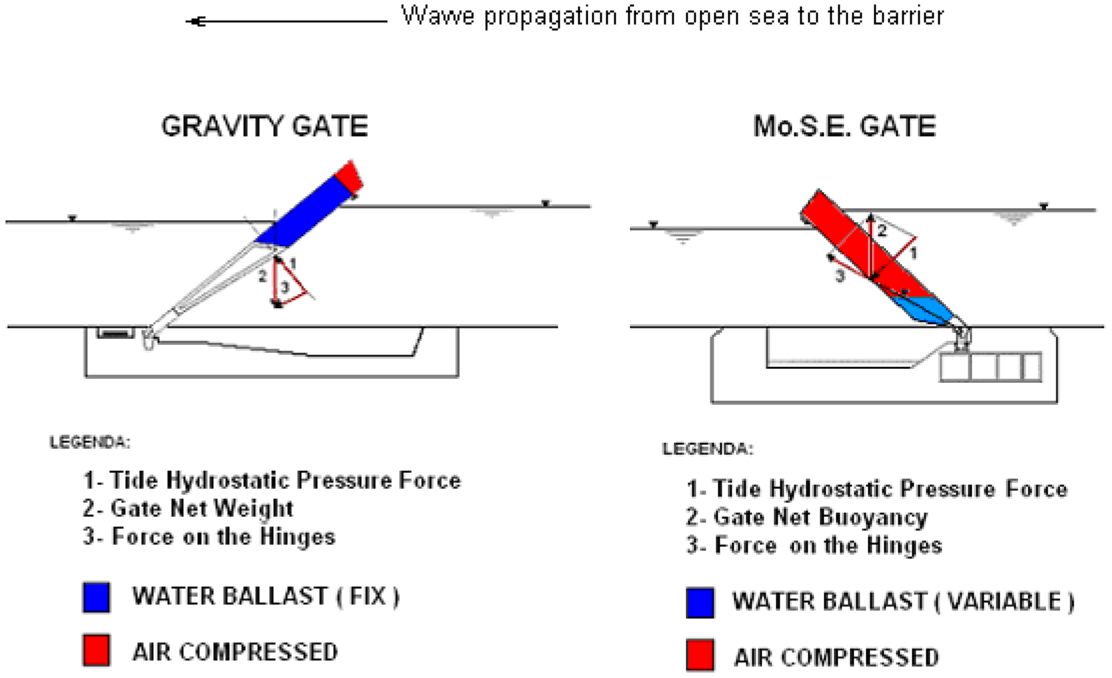



*Figure 1 - Example of half of the barrier configuration using the gravity gates design*

## 4.2 GATES DESCRIPTION

### 4.2.1 General arrangement and principle

General schemes of the gates are given on Figure 3.

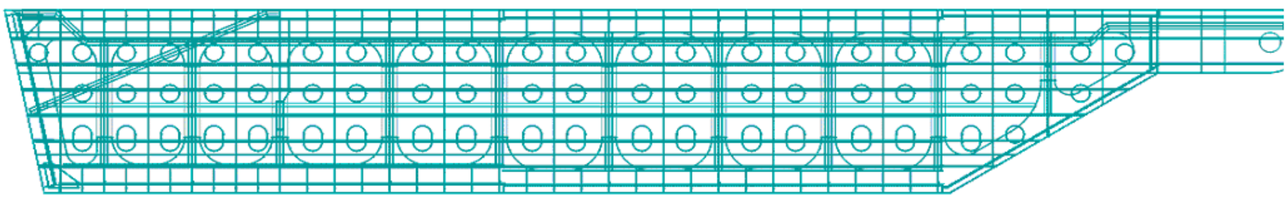



MoSE gate (or buoyant gate)

The gate is composed of a steel hull partially filled with water and compressed air. The working inclination (45° to the laguna side) is given by the buoyancy moment corresponding to the water level difference between the sea level and the water ballast level inside the Gate. Internal water level is adjusted as function of the tide differential level to provide the proper buoyancy insuring the required constant inclination. An active control system is required to maintain the specified inclination by adjusting the water level in the internal tank (ballast).

The gate is articulated on a sea floor concrete base which is shaped to integrate the gate in its removing position. Gate is raised by ballasting operation and is deployed by de-ballasting with compressed air. In absence of mass characteristics of the gate, autocad model has been done, a section is reported below.

In working position buoyancy induces up-lift load on the articulation fitting and on the concrete base.

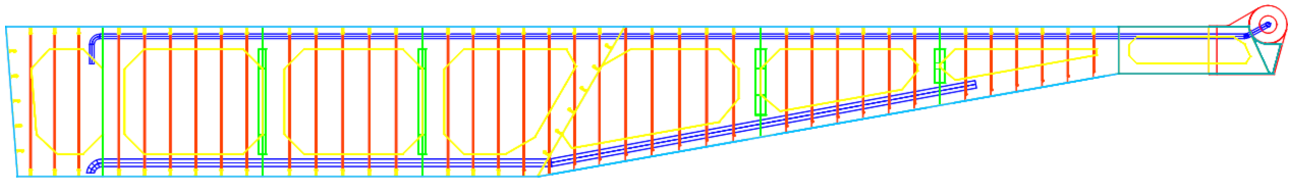


Gravity gate

The gate is composed of a steel reinforced structure, articulated at the sea floor level and a tank (ballast) completely filled with water and a supporting manoeuvring tank on top.

The working inclination (at start 32° to the open sea side) is given by the weight (water ballast + structural weight) moment. The manoeuvring tank is initially de-ballasted to provide the required inclination and stability independently of the tide. The maximum inclination, obtained for the maximum tide, is close to 46°.

Gate is raised empting only the manoeuvring tank. No active control system is required to maintain the specified water level in the internal tank. Section of the autocad model is shown below.
In working position water ballast induces down-lift load on the articulation fitting and on the steel base.



### 4.2.2 Gates characteristics

The following table provides the main characteristics of each gate design. Values are referred to a frame centred at the articulation point and are given for the mean working position of the gates for 15m water depth on the lagoon side and 15m to 17 m on the sea side.

Main dimensions:

| Gate | Gravity | MoSE |
|---|---|---|
| Total length | 31.5 m | 29.6 m |
| Total width | 20 m | 19.9 m |
| Tank width | 3.8 m | 4.5 m |
| Tank length | 16.1 m | 26 m |
| Total structural mass | 236.15 tons | 257.88 tons |
| Total mass in start working conditions | 1469.80 tons | 1767.00 tons |
| Total mass in max. working conditions | 1469.80 tons | 1079.40 tons |
| Working inclination / horizontal | ÷ 46° to sea side | 45° to lagoon |

Stability curves for the two designs are provided in appendix. It could be concluded that hydrostatic restoring moment is highly non-linear and non symmetric around the working inclination, i.e. up and down rotations are anticipated quite different.

Based on these data rotation stiffness, tentative to derive resonance periods are made with free oscillations tests (decay curve) for an isolated gate and from RAOs for the multi-gates configurations. Quite different results are obtained depending on the considered configuration: 2D isolated gate (or all gates of the barrier moving in phase), 3D isolated gate, 2D multi-gates (including hydrodynamic gate interactions). The reason is in the high sensitivity of hydrodynamic coefficients (added mass) to the configuration. It can be noticed also that high variation of added inertia with oscillation period could lead to different resonance period, even if linear hydrostatic stiffness is considered. The following Table give the range of values obtained :

| Configuration | 2D isolated | 3D isolated | 2D multi-gates |
|---|---|---|---|
| Gravity gate | 11s to 12s | > 18s | 4s < < 15s |
| MoSE gate | 5s to 6s | > 14s | 4s < < 15s |

Lower values are obtained for a pure 2D gate and larger values are obtained for a 3D isolated gate for which 3D wave radiation is dominant. In fact the multi-gates reality included the two “extreme” conditions depending how adjacent gates are moving and the response depends mainly on the number of the gate that in this analysis are the same.

Range of periods of resonance must be compared to the peak period of the 1000-years sea-sate, i.e. Tp=9.3s - 8s for Tz=7.5s. In any case the natural period of the isolated Gravity gate are higher and outside the range of periods of the design spectra with significant energy. As wave radiation damping is generally high for small period, it is anticipated that occurrence of “pure” resonance will be small.

When several gates are considered moving, each gate motion induced excitation on the others leading to a set of near field modes. Semi-analytical solution derived for a set of inclined articulated flat plates gives response for periods from 4s to 15s (see results given by Li & Mei confirmed by Molin in the present study). However it will be shown hereafter that motions amplitude are less than 10° for wave periods lower than 12s.

“Pure” resonance is defined as resonance obtained from a standard linear mechanics, i.e. balance between inertia and linear hydrostatic stiffness. Non-linear component could lead to “indirect” resonance as the well-known “Mathieu instability”.

# 5 METHODOLOGY AND ASSUMPTIONS FOR ANALYSIS

## 5.1 GATES BEHAVIOUR AND EFFICIENCY IN WAVES

Wave action induces dynamic rotation of the gates around their hinge points. Several kind of behaviour have to be considered :

- Dynamic rotation at the wave frequency, which induces, radiated waves inside the lagoon (similar to a wave maker). This effect could be predicted using classical linear diffraction / radiation analysis (wave excitation load and added mass), including hydrostatic loads and gate inertia. Boundary conditions are not the same for all the gates of the barrier depending on their location from the walls of the channel. Then each gate moves with its own phase which leads to a "snake" behaviour or an "erratic" behaviour of the barrier. Gates are not connected together which could induce fluid flow passing through the barrier (through the gates spaces) depending of difference in amplitudes and phases of adjacent gates.
- Interaction between in-coming waves and reflected waves could induce trapped modes (steady wave fields) which could lead to harmonic excitations at frequency close to the natural period of the gates. Corresponding response is well estimated using a near field diffraction
- In case of large rotation amplitude hydrostatic restoring moment becomes non-linear and could lead to unstable response (like parametric resonance).
- Transverse steady waves could also occur between the walls of the channel which could induce additional out of phase excitations on the gates. However the channel is 400meters width and the corresponding first modes have largest wavelengths than the in-coming waves. Then this effect could be neglected.

The present study is focused on the influence of these physical phenomena on the gate barriers behaviour both with Gravity and MoSE elementary gates.

Comparisons are provided for the following design parameters :

- Maximum absolute amplitude of rotation of a gate along the barrier
- Relative rotation amplitudes between two adjacent gates
- Induced forces and moment at the pin level

The analysis will be performed for the two extreme working conditions: at closure of the barrier (w. d. 15 m) and at the maximum expected tide (w. d. 15 m lagoon side, 17 m sea side).

## 5.2 NUMERICAL MODELLING

The global approach is based on existing hydrodynamic tools :

- Fully 3D radiation / diffraction method :
  - First wave excitation loads and added mass are computed with the 3D linear wave diffraction code Diodore (potential flow theory solved by a standard panel method in frequency domain). Mean wave loads and wave frequency components are derived for a range of wave periods
  - The water channel bottom is firstly considered flat in the diffraction analysis. Upstream and downstream water depth are assumed equal for wave loads prediction.
  - Added mass and wave loads are transferred to a time domain mechanical DeepLines model including exact gate inertia and hydrostatic loads taking into account the difference in upstream / downstream water levels.

- Time domain simulations are performed in irregular waves to obtain the angular motion around the static equilibrium position. A pure pined condition is assumed at the bottom level (no friction at the hinges).
- Both linear and non-linear hydrostatic stiffness are considered imposing in the time domain model a non-linear restoring moment derived from the static analysis. The goal of the linear approach is to understand the influence of different parameters affecting the dynamic of the gate barrier. The goal of the non-linear approach is to simulate a more realistic dynamic behaviour of the gate system (motions and loads) and to check possible occurrence of parametric resonance.
- Several configurations are analyzed depending on the gates configuration and location considered : an isolated gate, an isolated gate moving close to a channel wall, set of gates moving in phase between the channel walls.

- 2D semi-analytical model :
  - the specific aspects of the gate barrier configuration are included : the water level may be different on the two sides of the barrier, the barrier is considered as a multi-mobile flap with hydrodynamic interactions between the gates
  - each gate is modelled as an inclined thin plate, but with a correct the correct mass and buoyancy
  - angular motions, loads and corresponding phase are computed for each gate of the barrier in frequency domain (RAOs).

Gate moving with significant amplitude induces vortex shedding on its sides leading to viscous/drag damping in the rotation motion. This damping can be easily estimated using existing data for drag loads on a plate for an isolated gate. An estimation of drag damping is included in the models even if wave radiation damping is dominant.

A set of validation tests have been performed before starting the study:
- comparison between 2D semi-analytical method with the 3D numerical tool Diodore for an infinite width gate
- comparison of the 2D semi-analytical method with results provided by Li & Mei for a set of vertical flat plates.

Comparisons have been focused on the hydrodynamic loads: added inertia, damping and wave diffraction. Results are provided in appendix only for verification of the software used for the analysis.

# 6 GATES SYSTEM RESPONSE

## 6.1 PRELIMINARY HYDRODYNAMIC ANALYSIS

The analysis follows two main stages:

- Dynamic analysis of an isolated gate for the 2 designs
- Dynamic analysis of the global barrier configurations corresponding to the two gate designs

However a preliminary analysis has been performed for different configurations for a better understanding of gate systems response (illustrations are provided in appendix) :

- Hydrostatic loads :
  - mean gate inclination is highly sensitive to the CoG and CoB locations. Accurate buoyancy meshing of the hull has been done to obtain the correct inclination in the working conditions (2 meters difference in water levels). For the MoSE gate, fitting the ballast mass has been also needed.
  - Non-linear GM curve is not symmetric (or anti-symmetric) around the mean inclination which means that “going-down” and “going-up” motions are of different behaviours.
- Added inertia and radiation damping :
  - Large variations with the motions period (and then with the wave period) are obtained which leads to difficulty to estimate a natural period in a classical way.
  - Both added mass and damping are different for a pure 2D gate and an isolated 3D gate. This means that the motion amplitudes of a full “in-phase” set of gates is quite different that an isolated gate or a “out-of-phase” set of gates.
  - For a multi-gates configuration, hydrodynamic interactions between gates governed the added mass and damping.
- Hydrodynamic interactions leads to gates motions with different amplitudes and phases along the barrier, between “in-phase” and out-of-phase” depending on the wave period :
  - For small wave periods some “erratic” behaviour is obtained but with small angular amplitude
  - For long wave periods a “snake” behaviour is obtained with as large amplitudes as wave period is close to natural periods of the gates
  - Most of the gates “resonance” or, better, response periods in the barrier appears in the range of 12s to 18s, i.e. outside of the wave spectra which limits the occurrence of large angular amplitudes (the instability is not considered in this type of analysis).

## 6.2 DYNAMIC ANALYSIS OF AN ISOLATED GATE

Results obtained for 3D isolated Gravity and MoSE gates are compared. The meshes of the gates used for diffraction radiation analysis are given in appendix.

Time domain simulations have been done with DeepLines for the 1000-years irregular waves conditions assuming wave direction perpendicular to the barrier. In a first step hydrostatic stiffness is assumed linear (valid only for rotation angle smaller than around 5°). As large rotation amplitudes have been obtained, calculations including the non-linear hydrostatic restoring moment have been performed.

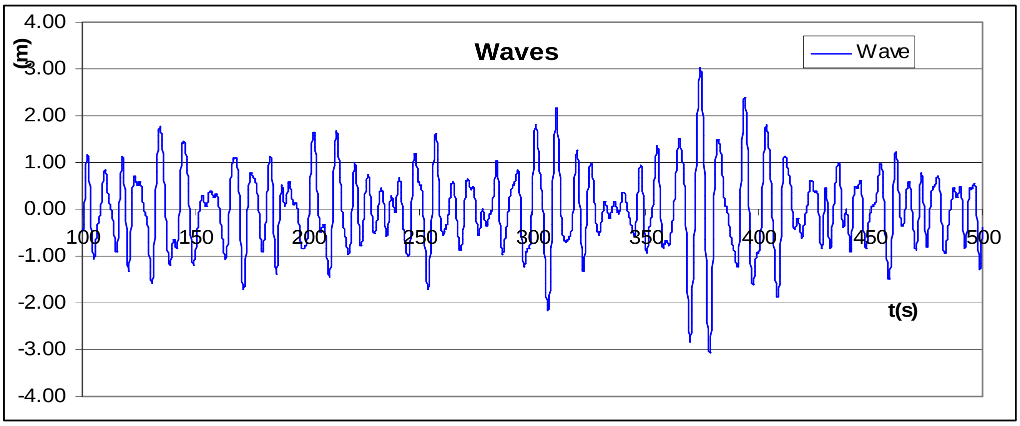
### 6.2.1 Linear hydrostatic assumption

Time duration is close to 1200 sec. centred on the maximum 3hr-wave height to be sure that the maximum values of angular motion and forces are encountered. A ratio of Hmax/Hs = 1.8 has been imposed.

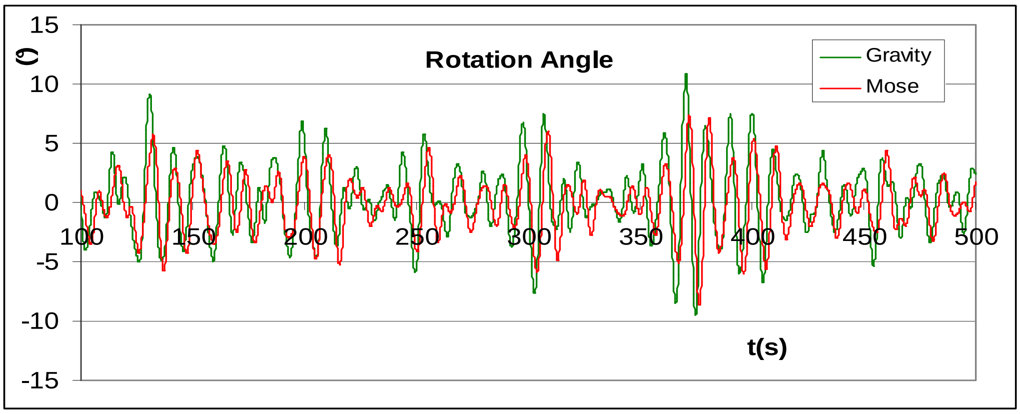
The following Table summaries the results obtained for Hs=3.2m and Tp=9.3s, considering linear hydrostatic stiffness. Only drift and dynamic components corresponding to wave excitation are given.

| Variable | Unit | Min | Tz | Max | Mean | Std dev. |
|---|---|---|---|---|---|---|
| **MOSE** | | | | | | |
| Force global Z | N | -4.29E+06 | 9.306 | -7.40E+05 | -2.36E+06 | 5.77E+05 |
| Force global X | N | -1.42E+06 | 10.743 | 1.10E+06 | -8.23E+04 | 3.96E+05 |
| Global Force | N | 4.52E+06 | | 1.33E+06 | | 7.00E+05 |
| Pitch | deg. | -8.617 | 10.827 | 7.819 | -45.08 | 2.785 |
| **GRAVITY** | | | | | | |
| Force global Z | N | -2.54E+06 | 10.378 | 1.61E+05 | -1.18E+06 | 4.43E+05 |
| Force global X | N | -8.61E+05 | 8.772 | 9.06E+05 | 5.33E+04 | 2.89E+05 |
| Global Force | N | 2.68E+06 | | 9.21E+05 | | 5.29E+05 |
| Pitch | deg. | -9.524 | 10.397 | 10.825 | 46.32 | 3.337 |
| Wave elevation | m | -3.07 | 9.50 | 3.02 | -0.002 | 0.807 |

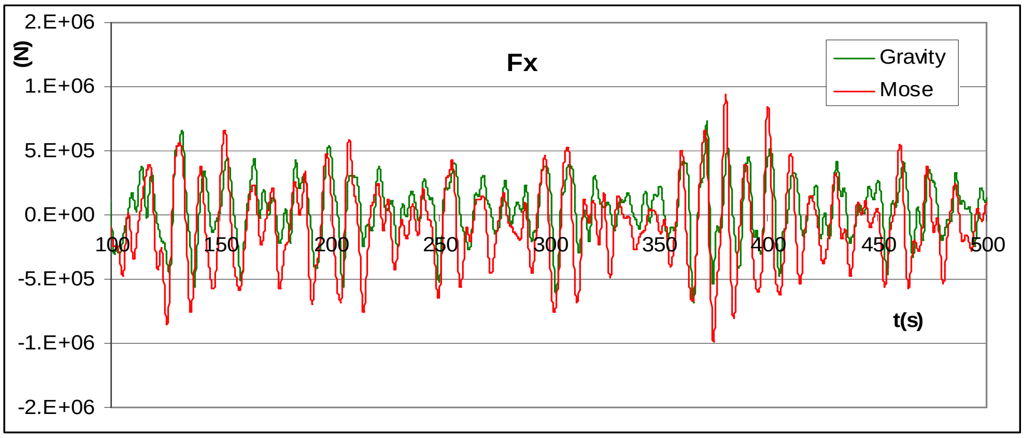
The results show a better compliancy of the Gravity gate i.e. a larger amplitude for the pitch that correspond to a drastic reduction of loads at the pined point)
Time series of the dynamic component (the first 100sec. to 500sec. including Hmax) and response spectra are compared hereafter considering a linear hydrostatic restoring moment.

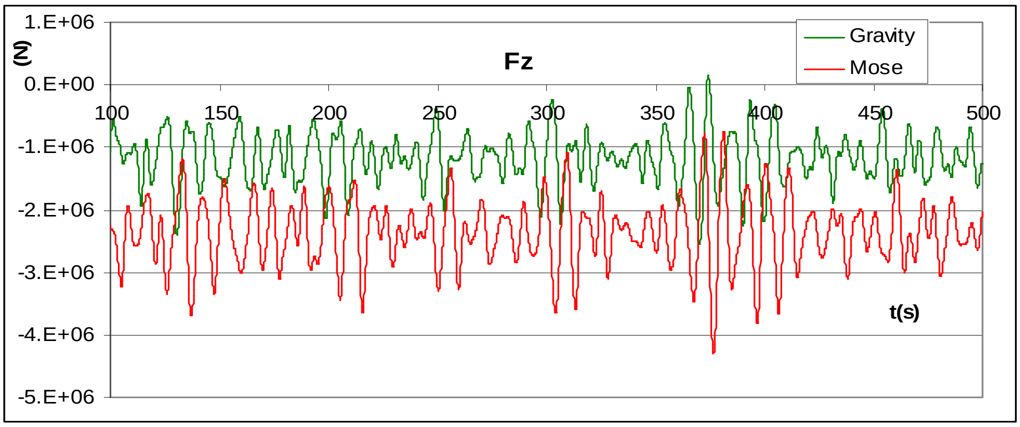



Rotation angle is given around the static mean inclination for each gate



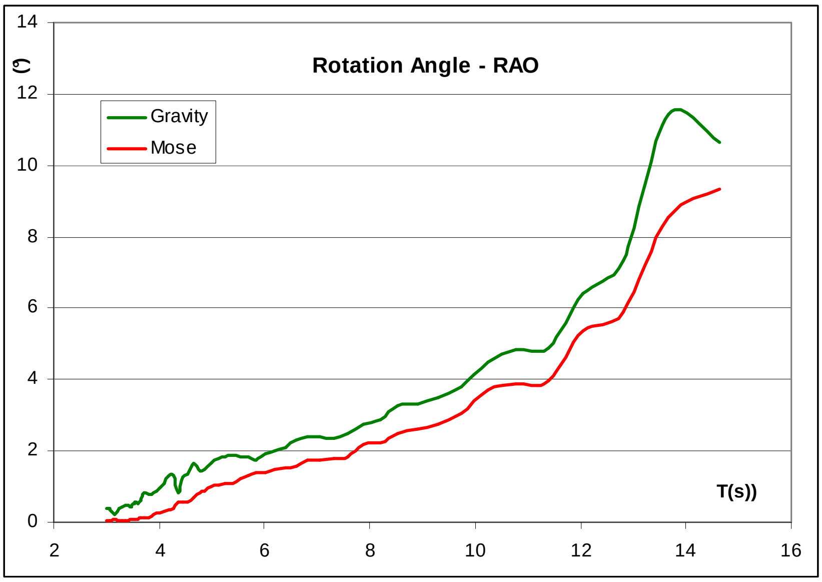
Dynamic loads at the pined point on the foundation :




Even if rotation amplitude of the Gravity gate is larger than the amplitude of the MoSE gate, vertical force is smaller, mainly the mean wave drift force.

From cross correlation analysis of the time series of rotation angles and wave elevation, RAOs have been derived which clearly show 10% larger amplitude for the Gravity gate all other the period range.




The same conclusion is derived hereafter for the multi-gates configuration.

### 6.2.2 Effect of non linear hydrostatic stiffness

For rotation amplitude larger than 5° it is expected that the variation of flotation and submerged volume of gate have an influence on the hydrostatics.

Calculations have been performed for the 1000 years conditions with two sea spectra having the same Hs = 3.2 m and two peak periods: Tp = 9.3 sec and 8 sec.

**For the larger peak period, Tp=9.3s**, comparisons of results obtained for Gravity gate and MoSE gate are provided hereafter (only "dynamic" component induced by waves) :

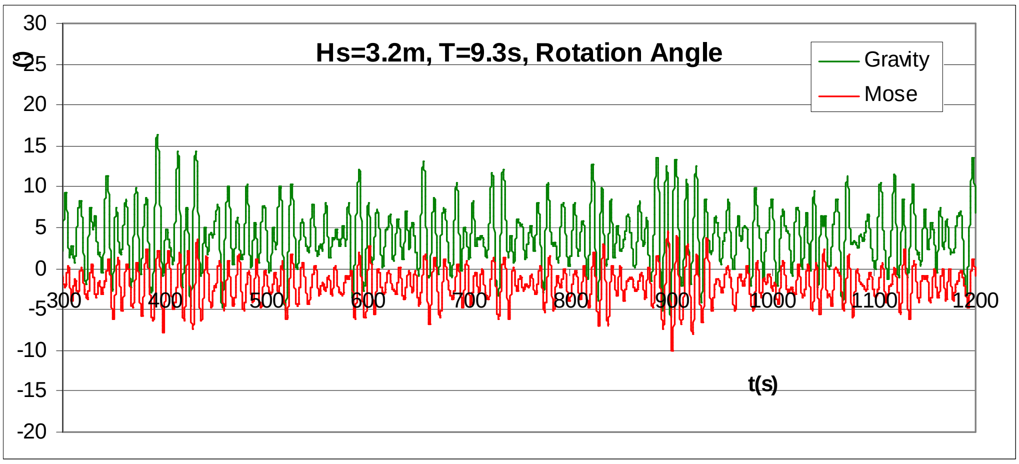
| | Fx | | Fz | | Total |
|---|---|---|---|---|---|
| **Force (N)** | Min | Max | Min | Max | Max |
| MoSE Lin | -1.33E+06 | 1.18E+06 | -1.93E+06 | 1.62E+06 | 2.34E+06 |
| MoSE NL | -7.55E+05 | 5.61E+05 | -3.51E+05 | 4.02E+05 | 8.33E+05 |
| Gravity Lin | -7.79E+05 | 9.89E+05 | -1.78E+05 | 2.52E+06 | 2.71E+06 |
| Gravity NL | -1.04E+06 | 1.23E+06 | -4.55E+05 | 4.94E+05 | 1.32E+06 |

Non linear hydrostatic component slightly decreased the loads compared to linear calculations. This reduction plays in favour of the MoSE gate.

**Considering the smaller peak period, Tp=8s**, similar results can be provided only for the Gravity gate, as instability occurs for the MoSE gate. The Gravity gates show lower loads for Tp=8s than for Tp=9.3s, even if rotation angle is quite similar.

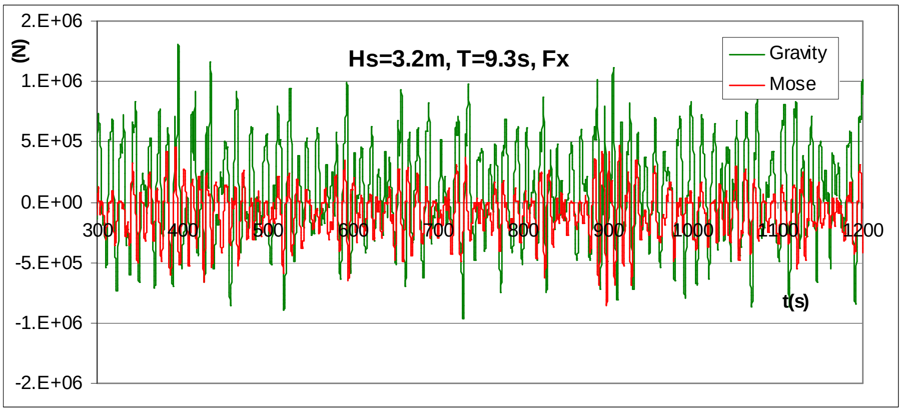
| | | Fx (N) | | Fz (N) | | Total | Pitch (°) | |
|---|---|---|---|---|---|---|---|---|
| | | Min | Max | Min | Max | Max | Min | Max |
| Tp=9.3 | Gravity NL | -1.04E+06 | 1.23E+06 | -4.55E+05 | 4.94E+05 | 1.32E+06 | -8.11 | 6.49 |
| Tp=8.0 | Gravity NL | -7.82E+05 | 7.40E+05 | -4.78E+05 | 4.74E+05 | 9.17E+05 | -7.96 | 8.51 |

*Rotation angle for Tp=9.3s*

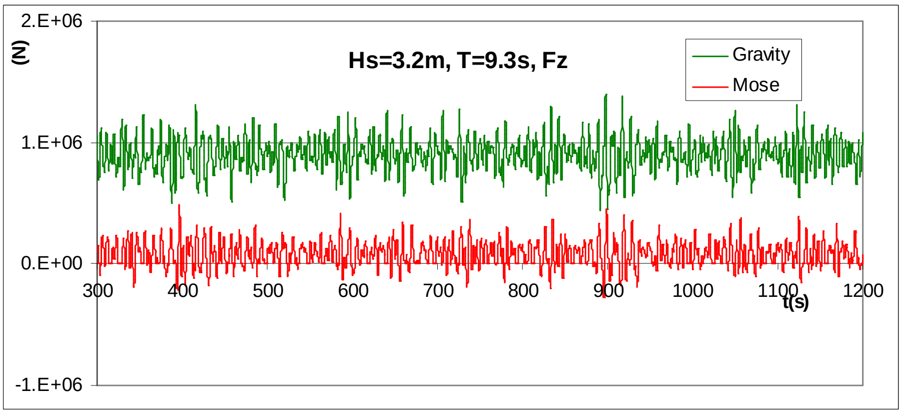



Mean inclinations are obtained : 2° down-lift for the MoSE gate and 4° up-lift for the Gravity gate. Down-lift reduces the free-board of the gate barrier, up-lift increase the free-board.
Dynamic components are quite similar for the two gates with a maximum amplitude of 10°.

*Horizontal loads at the pined point:*



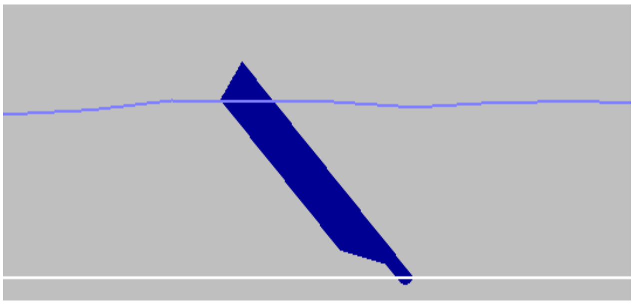

Maximum force is comparable to the linear result even if contributions of mean component and dynamic component are quite different.
*Vertical loads at the pined point:*

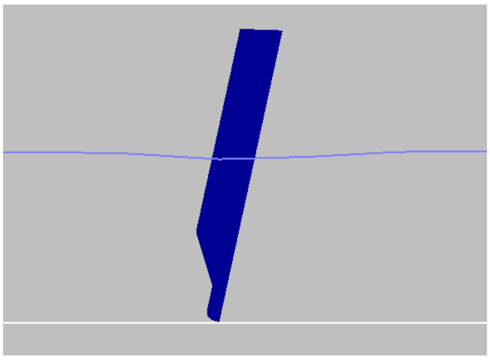


Both mean component and dynamic component are quite different compared to the linear calculations. Dynamic component is drastically reduced.

For the lower peak period the Gravity Gate shows a better response with respect to the larger peak period, the occurrence of instability for **the MoSE gate has been found**. Based on these results a sensitivity analysis to the significant wave height conditions has been performed for the MoSE gate. The following conclusions have been obtained:

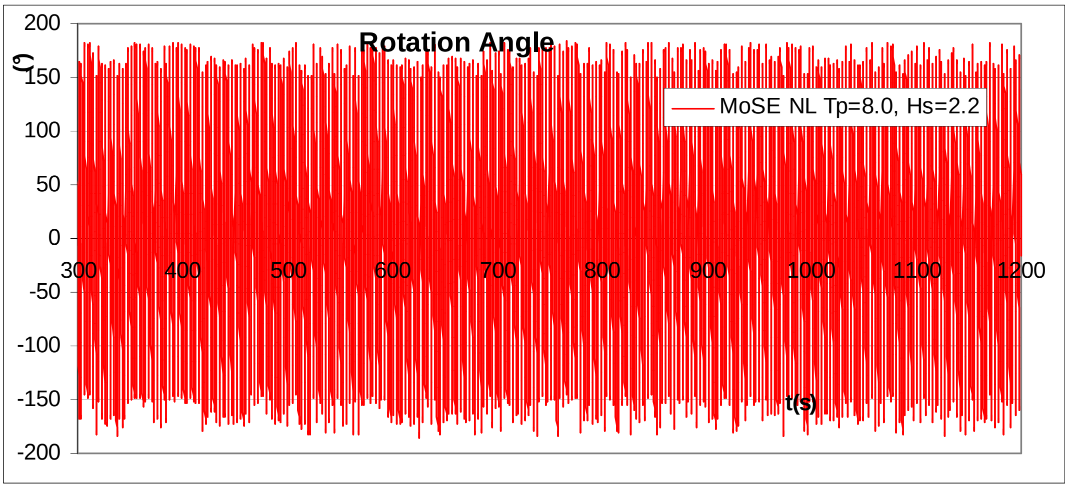
- Taking Hs=3.2m and Tp=8s leads to an unstable (chaotic) behaviour with large unrealistic motions and loads. Viscous damping has been added to wave radiation damping to reduce this effect (see here-after).
- The sensitivity analysis has demonstrated that the maximum value of Hs giving stable response has been found close to Hs=2.0m. For Hs < 2.0m maximum rotation angle is lower than 6° around the working inclination. For Hs > 2.0m very large rotation amplitude (larger than 30°) are taking place around both the working inclination and an another inclination of the gate close to 10° towards the waves (see following figures).



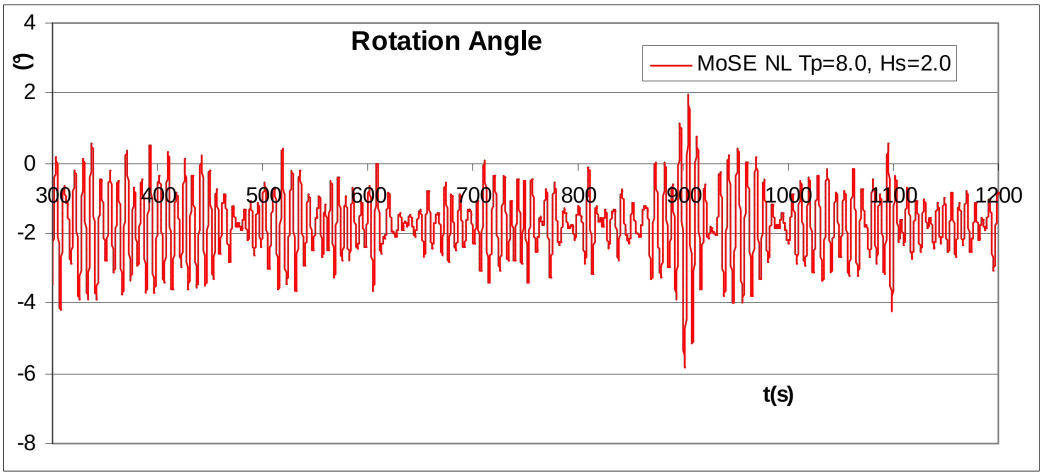


*Mean inclination of the Mose gate – Tp=8.0s*
*left: Hs=2.0m, right: Hs=2.2m*

*MoSE Gate – Tp=8.0s, Hs=2.2m – unstable response*

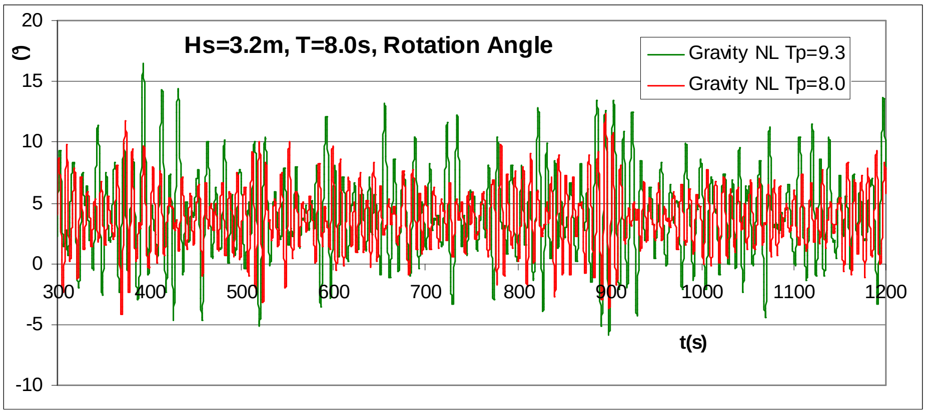


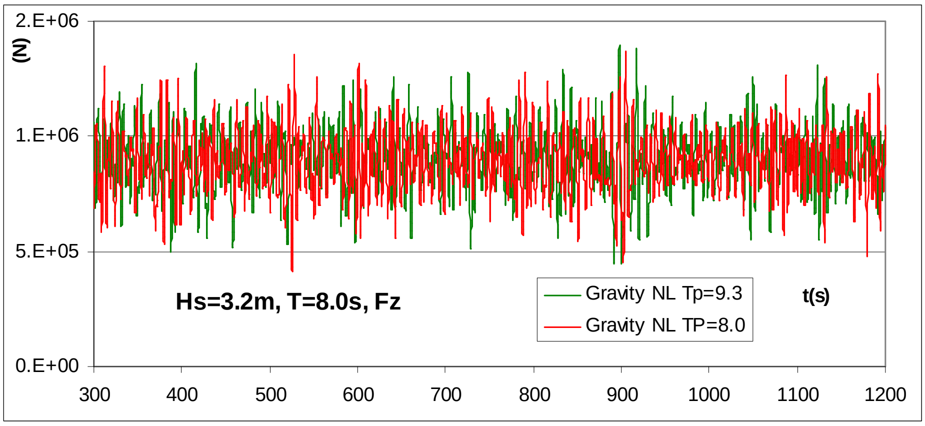
*MoSE Gate – Tp=8.0s, Hs=2.0m – stable response*

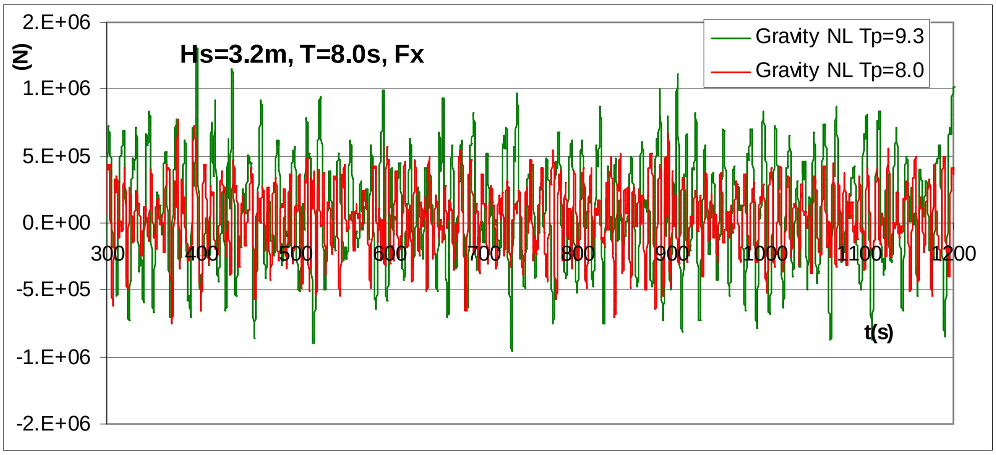



- For the same peak period **Gravity gate** has a quite good response to Hs=3.2m with lower rotation angle and similar loads than for Tp=9.3s (see hereafter). Maximum wave height is obtained at t=900s.

*Gravity Gate – Tp=8.0s, Hs=3.20m - Rotation angle and load components at the pined point*

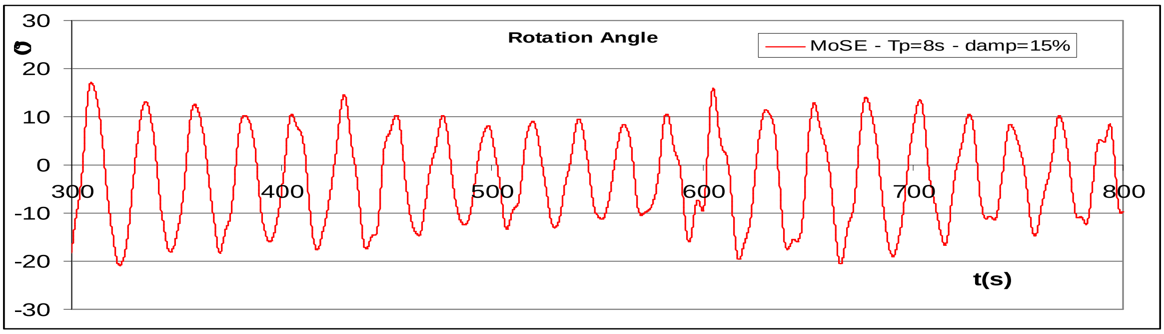





**Viscous damping influence on instability of the MoSE gate**

Following these last results sensitivity of the unstable behaviour of **the Mose gate** to damping has been analysed. Taking Hs=3.2m, stable response is obtained imposing a quadratic damping corresponding to 15% of critical damping (added to wave radiation damping) which seems quite larger that real viscous flow could do. Results are given hereafter :

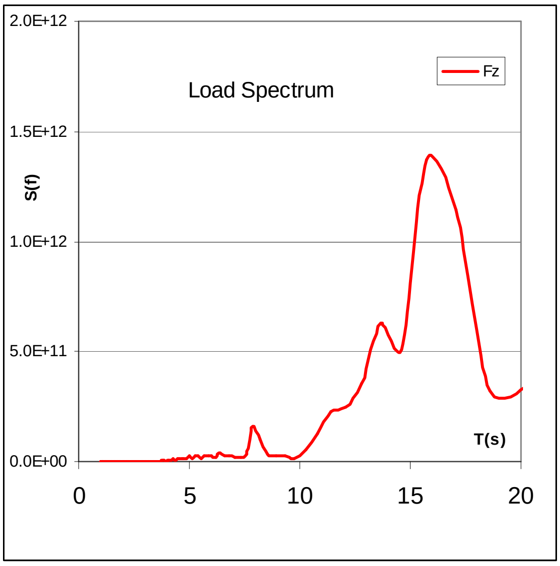


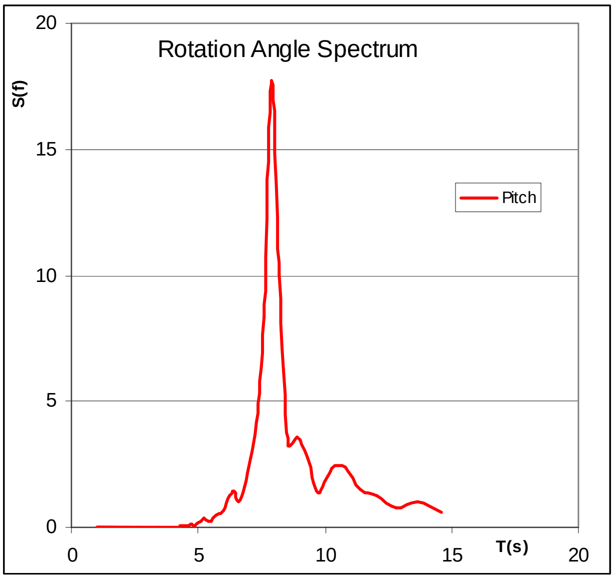

Rotation angle and loads at the pined point appears larger than hose obtained for the Gravity in the same waves conditions. The following table compares the dynamic component issued for each parameter :

| | | Fx (N) | | Fz (N) | | Total | Pitch (°) | |
|---|---|---|---|---|---|---|---|---|
| | | Min | Max | Min | Max | Max | Min | Max |
| Tp=8.0 | Mose NL | -1.86E+06 | 1.53E+06 | -9.47E+05 | 7.71E+05 | 2.09E+06 | -17.9 | 18.9 |
| Tp=8.0 | Gravity NL | -7.82E+05 | 7.40E+05 | -4.78E+05 | 4.74E+05 | 9.17E+05 | -8.0 | 8.5 |

Note: the values related to MoSE gate are not directly comparable with the values of the Gravity gate, where only wave radiation damping has been considered for the Gravity gate (viscous damping ignored).

*MoSE gate - Load and pitch spectra for Tp=8s and additional damping*




As it could be observed on the load spectrum that most of the energy is taking place at resonance period of the gate and not at the wave periods even if pitch reacts at the wave periods. It seems that instability is reduced but not completely “killed”. It confirms that an isolated MoSE gate remains unstable for Hs starting from 2.2m (and Tp=8s).
The artificial additional damping introduced in this simulation, can be compared (only qualitatively) to the artificial damping that the gate experience in a model scale simulation that shadows the real dynamic behaviour of the gate.

## 6.3 DYNAMIC ANALYSIS OF THE GATE BARRIER

In this section we compare the performances of the MoSE and Gravity gate barriers taking into account hydrodynamic interactions between gates. For consistency reason an linear hydrostatic spring is assumed first. Then non-linear behavior of is analyzed for two gates close to the channel wall.

### 6.3.1 Working conditions (linear response)

**In a first step**, we focus on the 15 m – 17 m cases, where they have nearly equal inclinations.

Calculations have been performed for a set of 20 identical gates of 20 meters width each. Water level on each side correspond to the maximum tide (15m and 17m). Mean inclination of gates corresponds to the working position, i.e. 46° to the seaside for Gravity gate and 45° to the lagoon for the MoSE gate.
Motions have been derived for a range of wave periods corresponding to the 100-years wave spectrum, i.e. from 3s to 15s.

In pure theory trapped modes and "snake" behaviour along the barrier is not occurred for wave perpendicular to the barrier. Then a wave incidence is imposed only initiate the multi-gates response. In pure theory, for a wave field perpendicular to the barrier and for symmetric boundary walls, all the gates will move with the same phase (behaviour close to a 2D isolated gate. In reality non symmetric wave field is expected (walls configuration, small incidence of wave, non 2D wave diffraction, …). Then relative motions between adjacent gates will take place. In simulation an artificial non symmetric effect must be imposed : different starting conditions for each gate along the barrier, small in-coming wave field incidence.

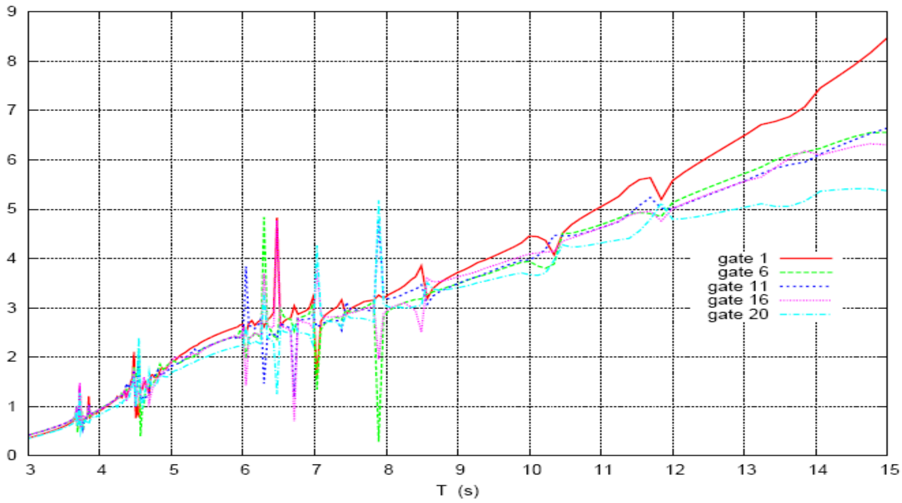
Details on the theoretical method and validation are given in Reference (B. Molin). Comparisons have been done with the previous 3D calculations for an isolated gate (both Gravity and MoSE) to confirm consistency of the results.

Looking to the maximum values of the absolute motions and of the corresponding loads along the barrier, similar with values are obtained comparing to the behaviour of an isolated gate, even if significant variation are obtained along the barrier.

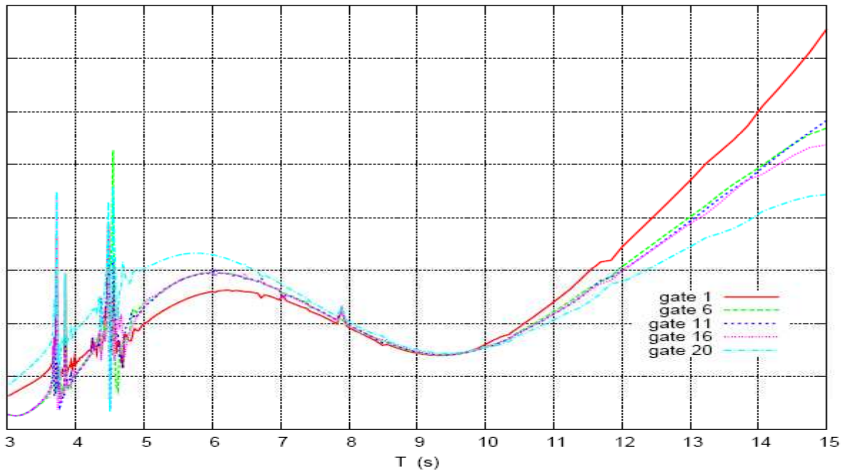
Then the analysis has been mainly focused on the relative motions between adjacent gates. Rotation amplitudes (transfer function) around the working inclination are given on the following figures for different wave periods:
- in red the amplitude of each gate
- in green the corresponding phase

The following comments can be derived from these results:
- maximum relative motions could be larger than 20° in the 1000-years conditions (out-of-phase motions)
- MoSE gate barrier is more sensitive to interactions effects, relative motion going up to 25° compared to 10° for the Gravity gate barrier
- For larger wave periods, greater than 12s, a "snake" behaviour is obtained depending on the starting conditions of the gates close to the walls and peak. Peak resonance could be observed, mainly for a the MoSE gate barrier.

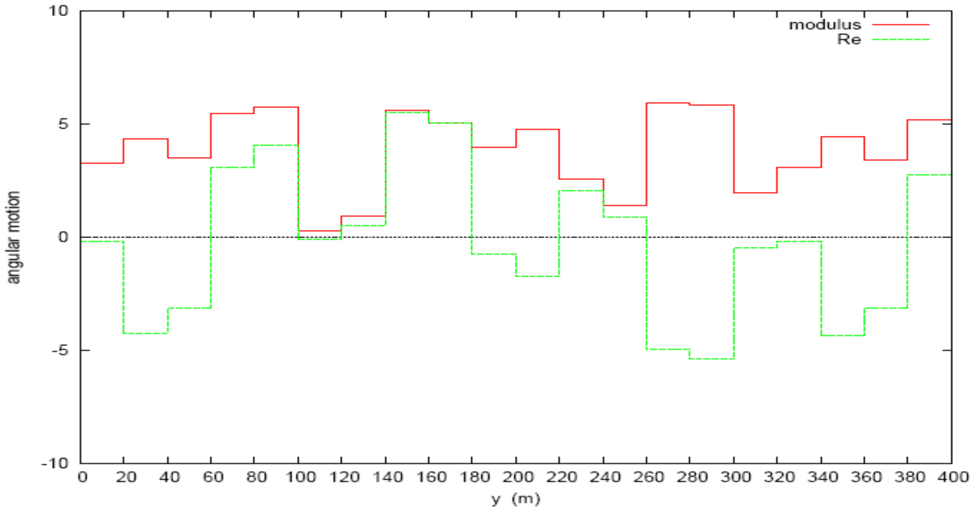
## Gravity gate



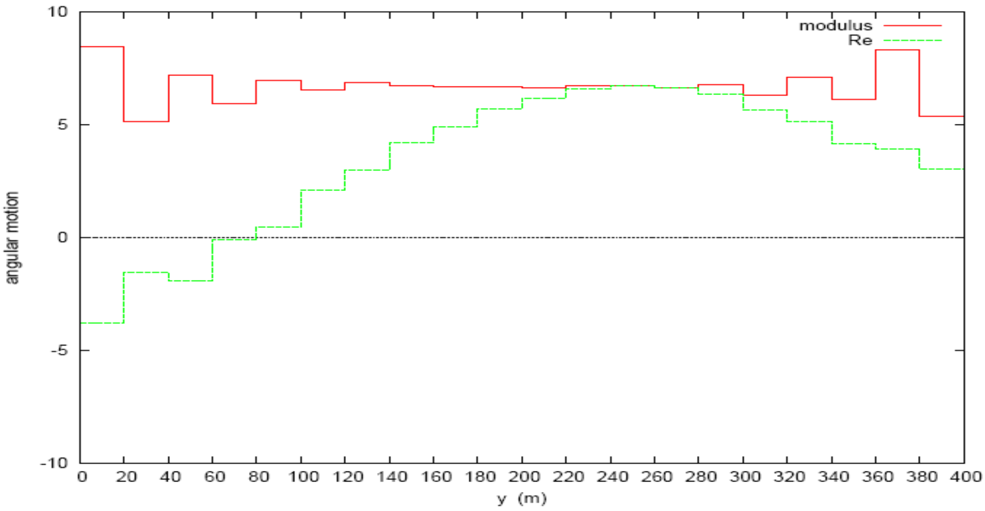

*Gravity gate barrier – working condition – RAOs of Angular motion*




*Gravity gate barrier – working condition*
*RAOs of Horizontal load at hinge point*

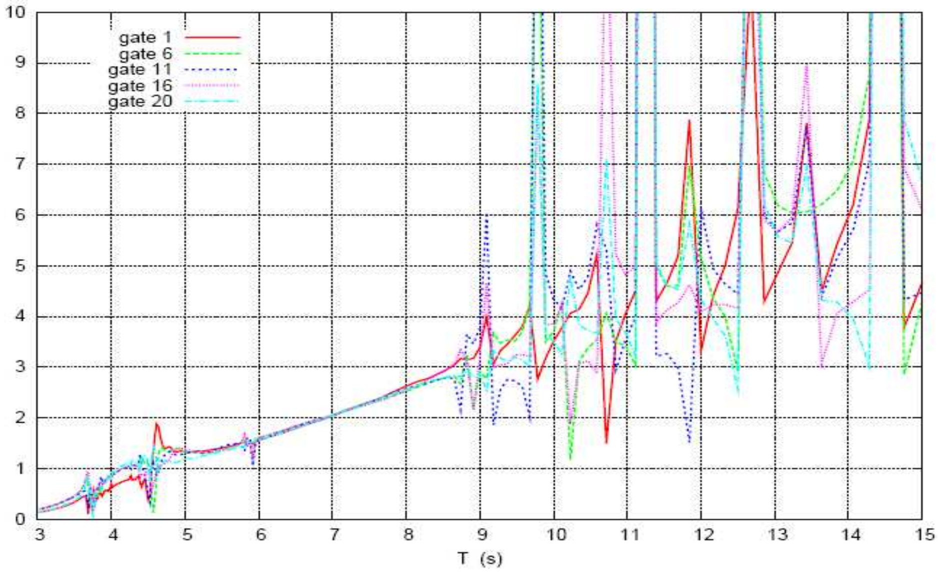



*Angular motion along the barrier – T=7.9s*

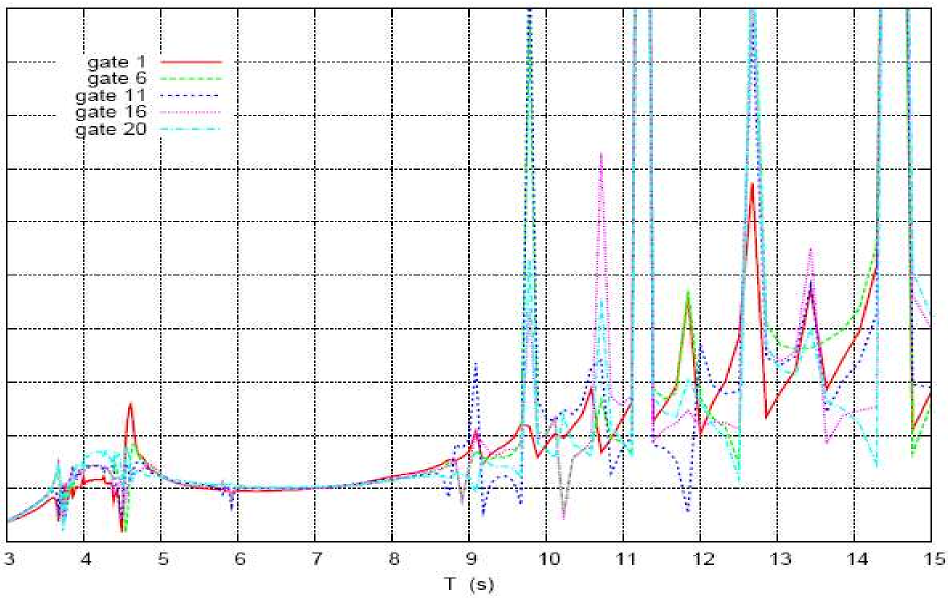



*Angular motion along the barrier – T=15s*

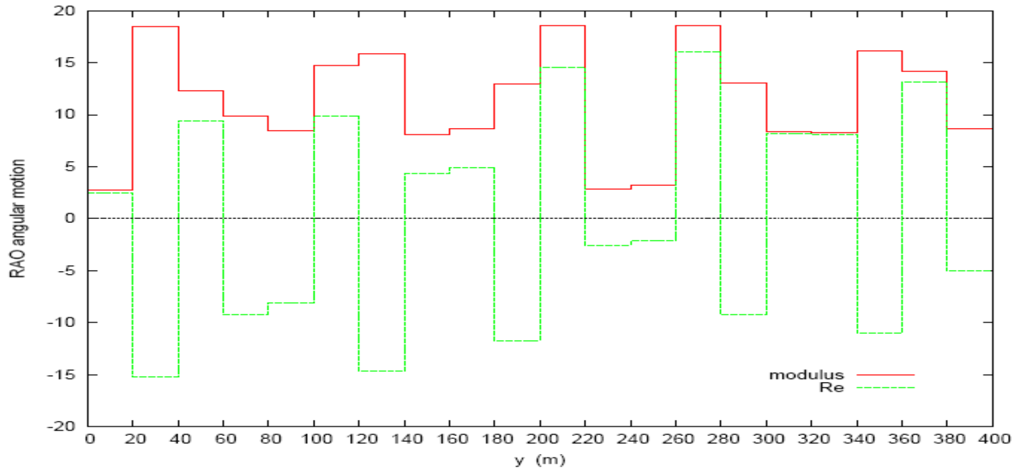
**<u>MoSE gate</u>**



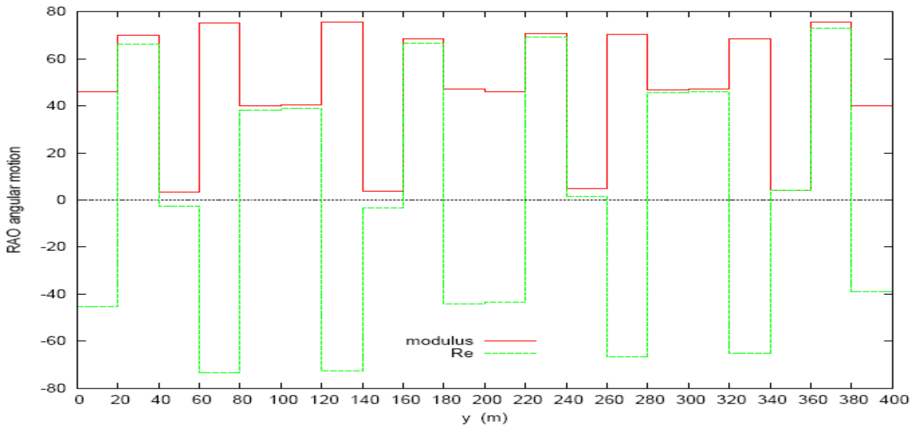

*MoSE gate barrier – working condition – RAOs of Angular motion*




*MoSE gate barrier – working condition*
*RAOs of Horizontal load at hinge point*




*Angular motion along the barrier – T=9.8s*




*Angular motion along the barrier – T=11.25s*

Comments on the results obtained :

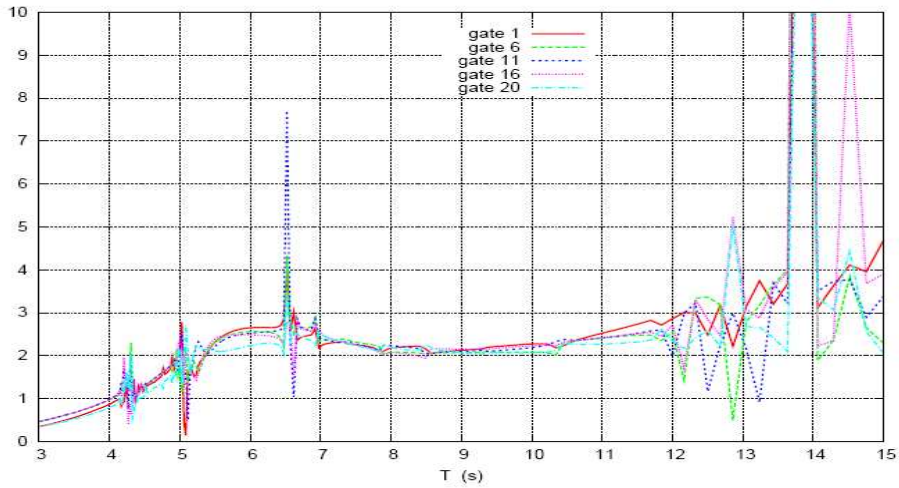
- Lower resonance periods are obtained due to interactions between gates. Due to larger stiffness and smaller mass and added inertias, the MoSE gate has much lower resonance periods than Gravity gate
- Interactions are clearly appearing on the motions. However the radiation damping is so high that no peaks can be seen at the resonance periods in the angular response.
- Both concepts have very similar RAOs of the angular motion which are also similar to those obtained for an isolated gate modelling the real gate shape (2D or 3D). Interactions have a major effects for periods larger than 11sec (out of range of the wave periods) and only for the MoSE Gate
- “out-of-phase” motions between two adjacent gates are clearly occurred with a relative rotation of 5° to 20° depending of the wave period (in the 1000-years wave periods range). This effect is quite chaotic for period lower than 10s regarding gate motion along the barrier and much important for the MoSE gate. For larger period a “snake” behaviour is observed like a multi-flaps wave maker.
- Considering the RAOs of the dynamic loads at the hinge point, they are somewhat smaller with the Gravity gate than with the Mose gate. In the multi-gates case, both gate barriers exhibit

peaks in the response that look like resonance. The peaks that appear in the low period range are very narrow and not very high, so they should not be of concern in irregular seas where the wave energy is distributed in the frequency domain.

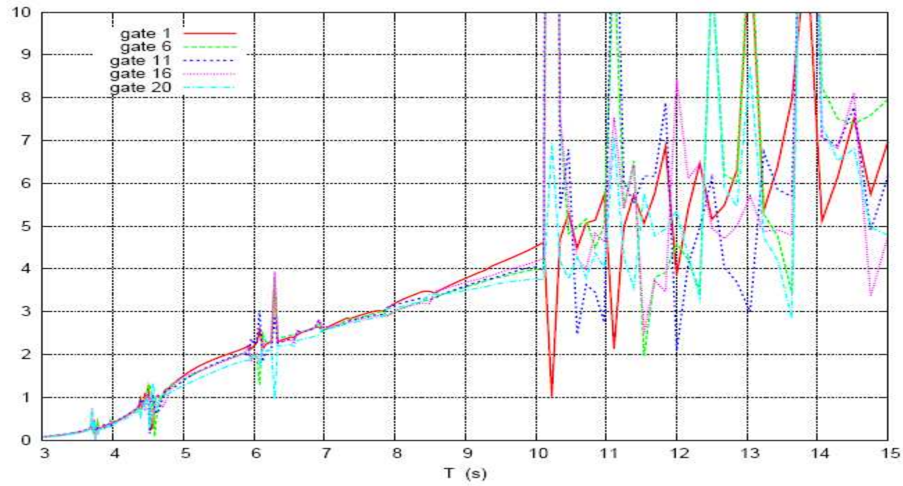
- Other peaks, wider and higher, appear in the high period range, beyond 9s, with the Mose concept. They do not appear with the Gravity concept in the 15 m – 17 m configuration. It looks like the Gravity concept is thus superior to the MoSE concept.
- However the occurrence of these peaks is very sensitive to the mass and to the stiffness of the system. We have repeated calculations, with the MoSE concept, with the hydrostatic stiffness divided by two. It can be seen that the resonant peaks beyond 11s have disappeared. Not only the peaks have disappeared but the RAO has decreased in the low period range, due to the lower stiffness. The resonant peaks have moved to lower wave periods. The small peaks at 3.7, 4.6 and 6 s have not moved. They are not related to the stiffness and natural frequencies of the individual gates. It is likely that these peaks are associated with other kinds of resonance, like trapped waves along the gate barrier. The calculation with reduced stiffness has been performed for academic consideration considering that the MoSE gate stiffness depending on its geometry and weight/buoyancy distribution (box shaped working as reverse pendulum) is derived from the "progetto definitivo" and it is considered the best design achievable for the buoyant concept.

### 6.3.2 Starting conditions (linear response)

In **a second step** starting conditions have been analyzed taking a 15m water depth on both sides of the barrier. Similar results have been obtained :

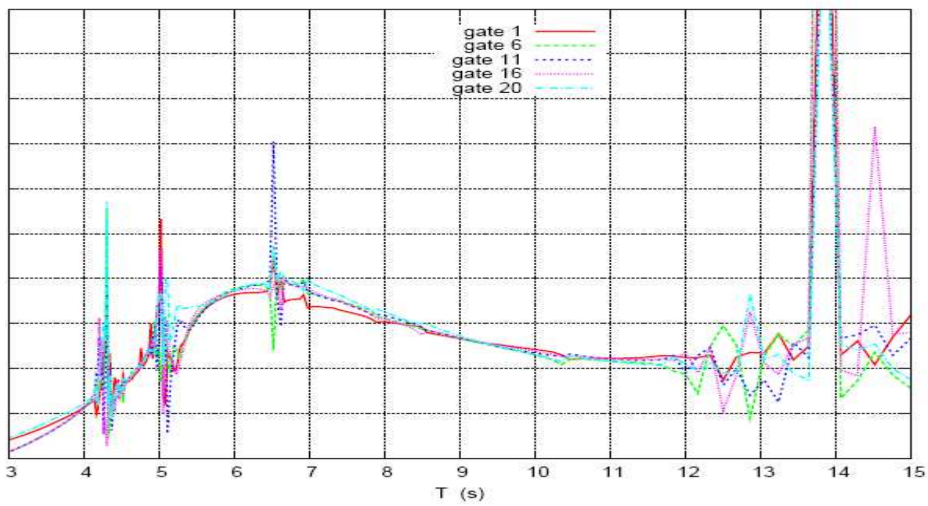



*Gravity gate barrier – starting condition – RAOs of Angular motion*

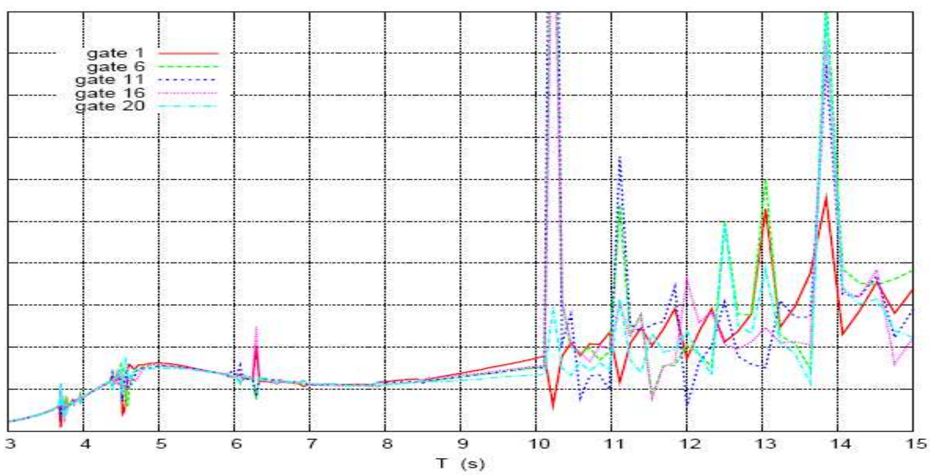



*MoSE gate barrier – starting condition – RAOs of Angular motion*

As in working conditions motions RAOs are quite larger for the MoSE gate with also larger “out-phase” relative rotations between adjacent gates.




*Gravity gate barrier – starting condition – RAOs of Horizontal load*




*MoSE gate barrier – starting condition – RAOs of Horizontal load*

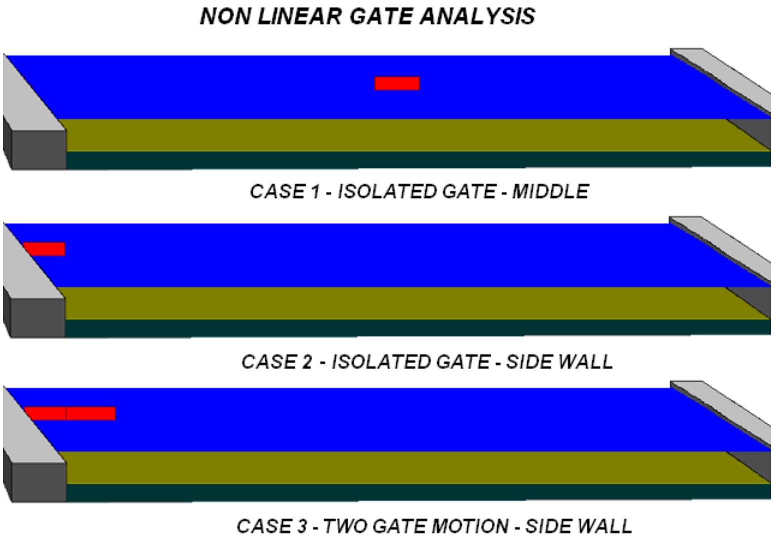
Even if peak of load RAOs is larger for Gravity gates than for MoSE gates, these RAOs lead to similar maximum load for the two gates.

### 6.3.3 Starting conditions (non-linear response)

Even if modeling the non-linear behavior of a multi-bodies configuration in pure resonance is now possible with an advance software, such as DeepLines used for this analysis, difficulties arise in front of :

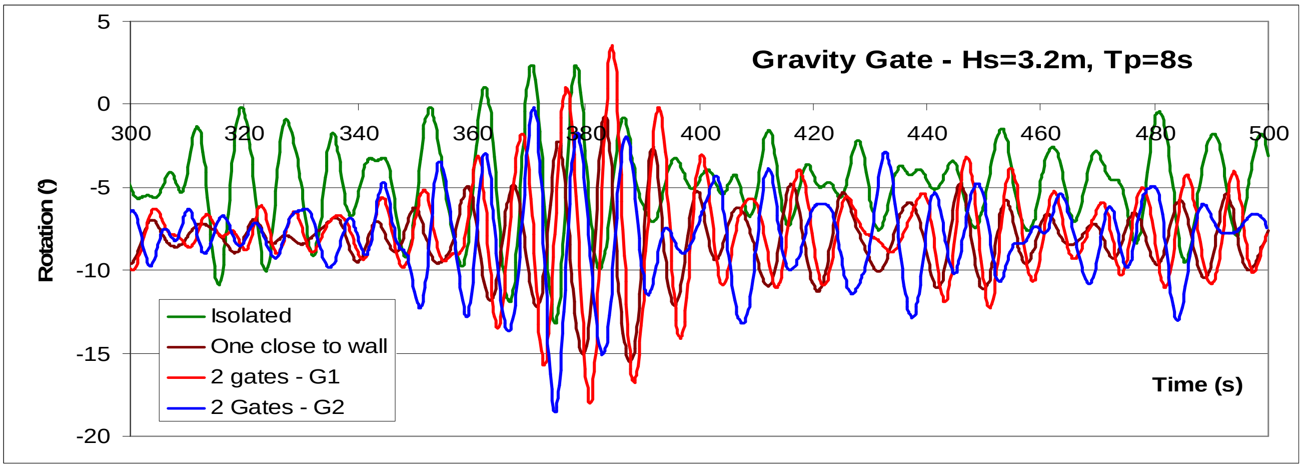
- In case of occurrence of unrealistic large motions of gates, characterized by the presence of super- harmonics and/or sub-harmonics (dynamic instability according to Mathieu definition), as observed for one MoSE isolated gate in working conditions, there are limitations for their numerical simulation.
- Very large calculation times required to take into account hydrodynamic interactions between all the gates of barrier, both for preliminary hydrodynamic calculations and for time domain analysis of the response, and there are not previous experience available that allow to validate the results of the analyses.

Alternative retained here is to simulate only two moving gates located at an extremity of the channel. An intermediate configuration has been also analysed composed of an isolated gate moving close to the channel wall (see illustrations hereafter). The more severe sea-state condition, Hs=3.2 m, Tp=8 sec, have been imposed. As chaotic (super- harmonic and sub-harmonic) behaviour has been obtained for the MoSE gate, wave height has been reduced to Hs=2.2m to confirm the "stable" sea-sate limitation derived in the working conditions.

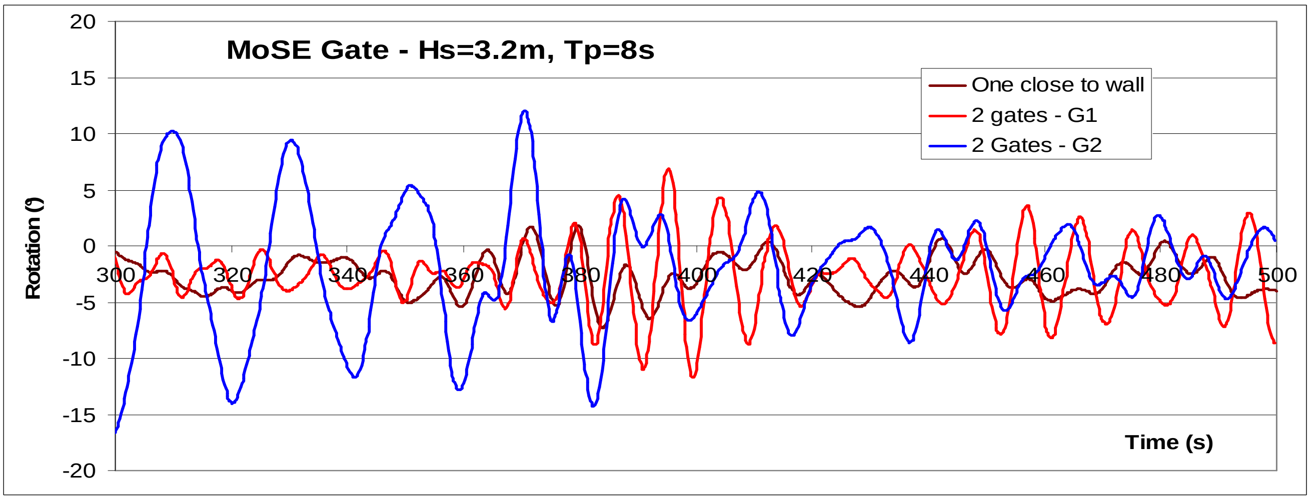



*Configurations considered for starting conditions analysis*

Simulations have been performed in irregular waves on 500 seconds (close to 80 wave periods). Viscous damping is not included assuming that radiated waves compose the most important part of the energy dissipation. The following graphs clearly confirm the workability of the Gravity gate and the instability of MOSE gate, excepted for the gate close to the channel wall.




*(a) Gravity Gate – Maximum wave height correspond to t=370 sec.*




*(b) MoSE Gate*

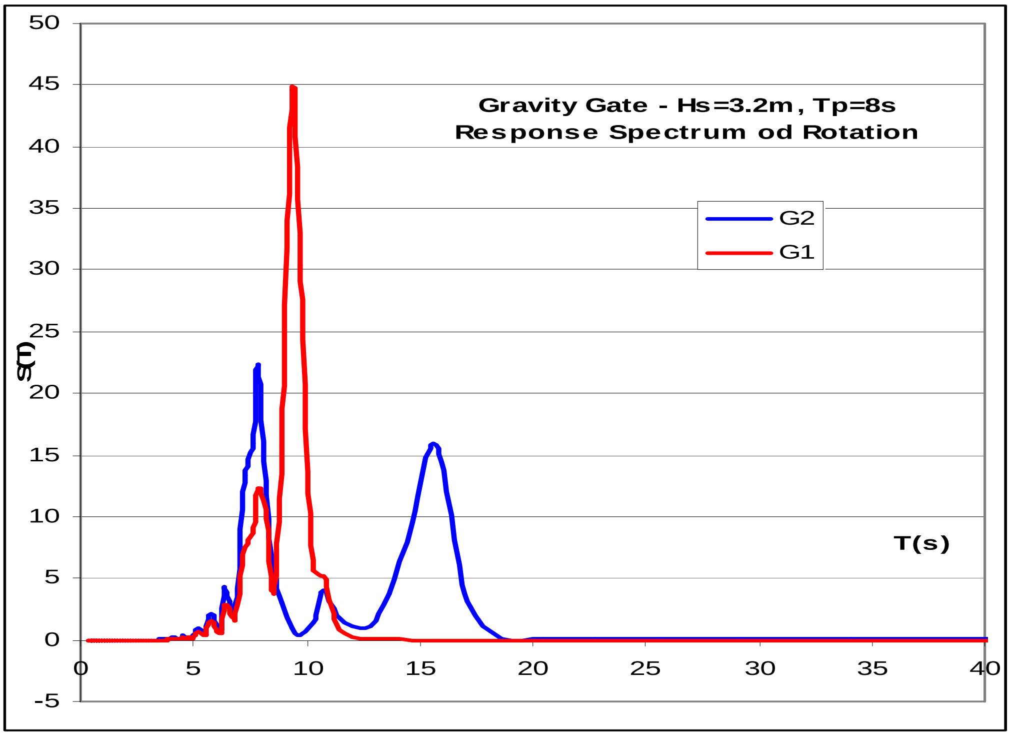
Statistics of results are provided in the flowing tables (removing the first 100 seconds of the simulation corresponding to the transient part).

| **Gravity** | Case 1 | Case 2 | Case 3 / Hs=3.2 | | Case 3 / Hs=2.2 | |
|---|---|---|---|---|---|---|
| **Pitch (°)** | | | Gate 1 | Gate 2 | Gate 1 | Gate 2 |
| Max | 13.1 | 7.3 | 11.2 | 7.8 | 7.7 | 5.4 |
| RMS | 3.1 | 1.8 | 2.6 | 2.4 | 1.8 | 1.6 |

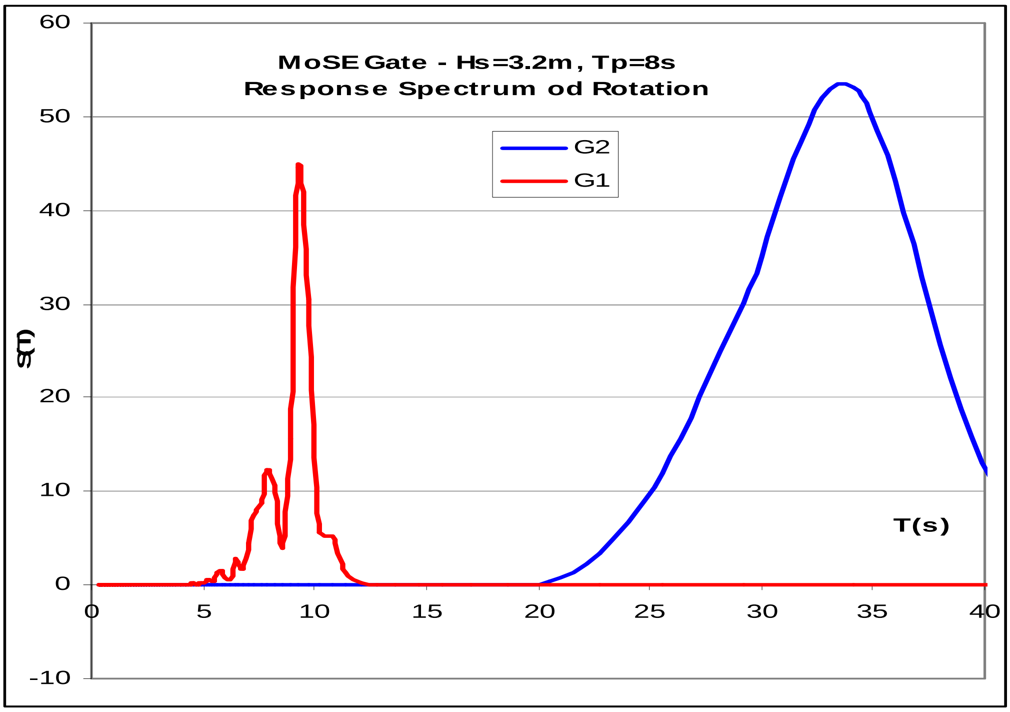
| **MoSE** | Case 1 | Case 2 | Case 3 / Hs=3.2 | | Case 3 / Hs=2.2 | |
|---|---|---|---|---|---|---|
| **Pitch (°)** | | | Gate 1 | Gate 2 | Gate 1 | Gate 2 |
| Max | 179.0 | 4.3 | 6.8 | 11.9 | 6.5 | 7.6 |
| RMS | 24.9 | 1.5 | 3.1 | 5.4 | 1.8 | 3.1 |

*Statistics of simulations in starting conditions (referring to the mean values)*

Going deeper in the physical analysis of sub-harmonic phenomena, energy spectra of the response have been issued for the two gates (Case 3). Wave peak energy is close to a circular frequency 0.8 rad/s.

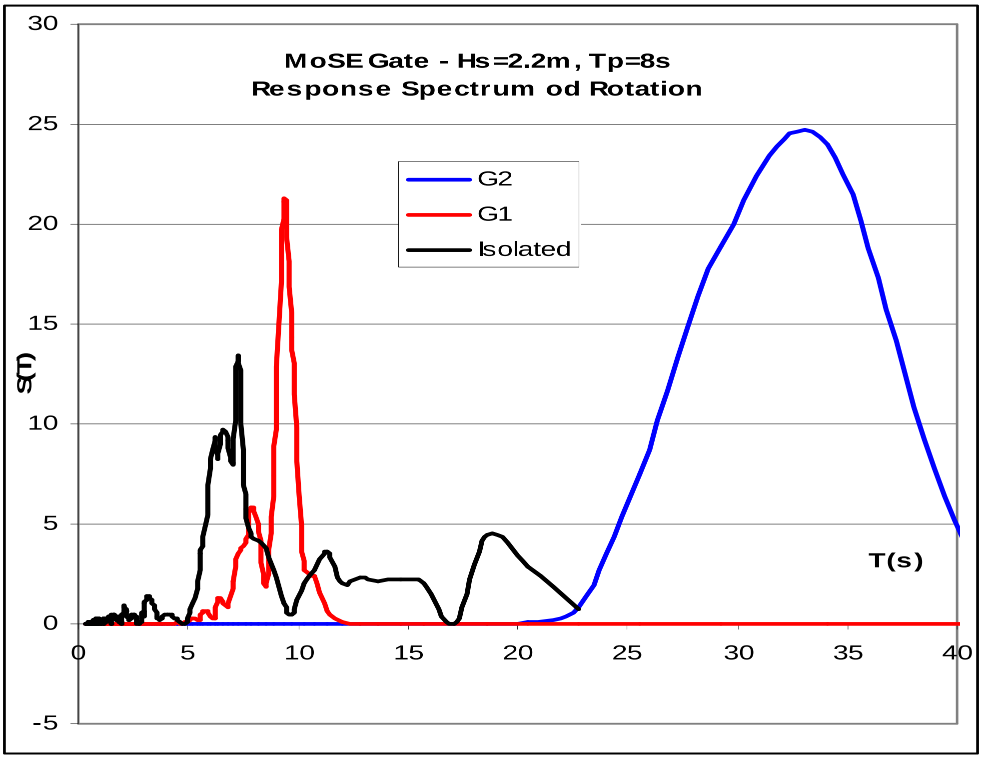



*(a) Gravity Gate – Spectrum of Rotation – wave peak period =8sec.*




*(b) MoSE Gate – response spectrum divided by 100 for G2*

Similar analysis has been done for the MoSE gate in the different configurations and for lower wave conditions, Hs=2.2m and Tp=8sec., in the way to identify effect of added mass on the sub-harmonic and super-harmonics which could excited by wave loads.

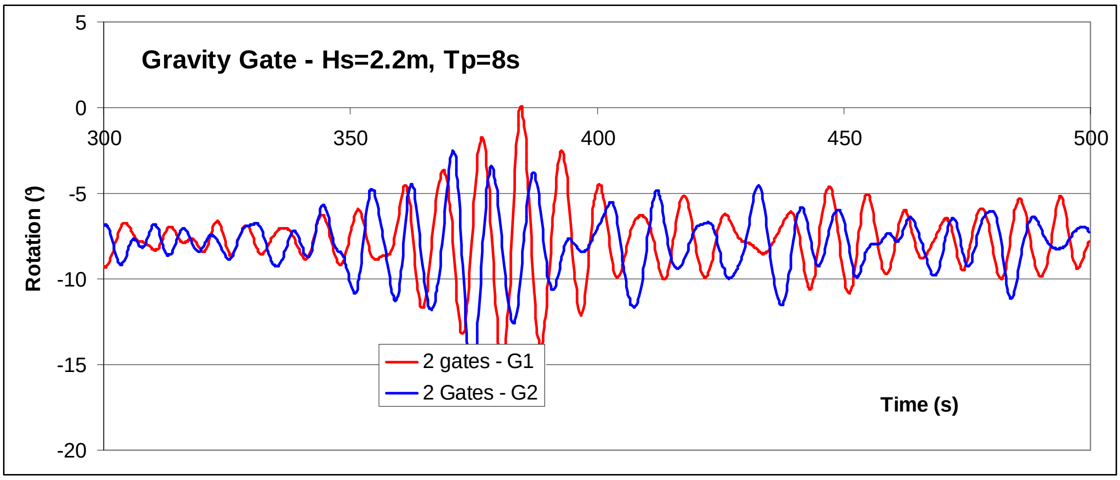



*MoSE Gate – starting conditions in a moderated sea-sate*

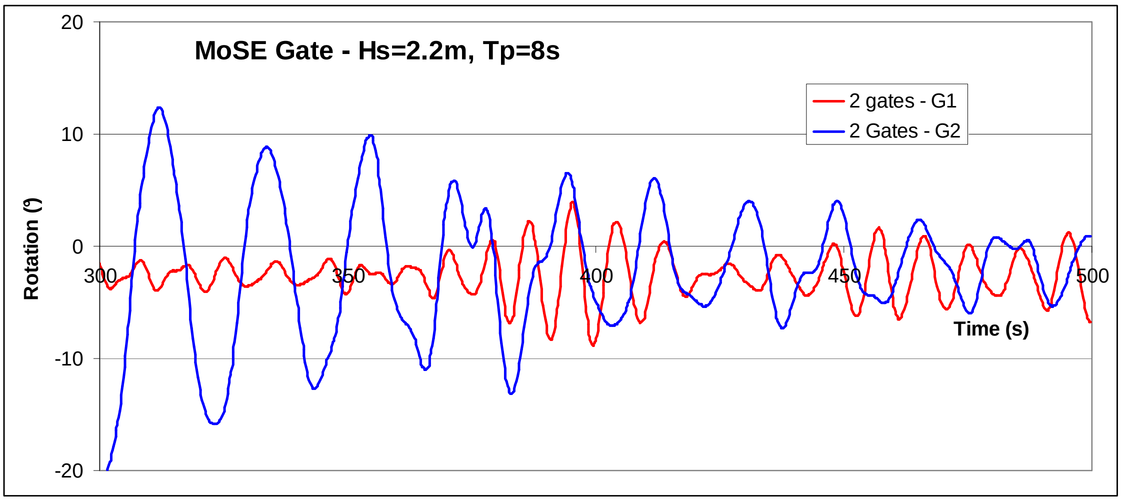
Comments:

- Super-harmonics are observed for the external gate (G2) both for Gravity and MoSE designs which is not the case for gate immediately close to the inlet wall (G1). However super-harmonic period is not the same for the two gates: twice the wave peak period for the Gravity gate compared to four time the wave peak period for the MoSE gate.
- Looking to the MoSE gate response in a moderated wave conditions show the influence of added mass which different for an isolated gate and several gates influencing by the channel wall. Both super-harmonics and sub-harmonics occurrence is observed for the isolated gate
- The super-harmonic response appears more critical for the MoSE because its period corresponds to a very low wave radiation damping. It is clearly shown both on the time series and on the spectrum (divided by 100 on the graph for G2).
- The super-harmonic response of the Gravity gate seems to be the normal response spectrum at the natural frequency of the gate.
- The reason why no sub-harmonic occurs for the gate close to the wall (G1) is to be found in the increase of the gate added mass induced by the wall.
- Looking to the Gravity gate results, it is clear also that mean drift moment is modified by the wall effect, increasing the mean drift loads. Hydrodynamic interactions have also a great influence of the rotation amplitudes depending on the configuration analysed.

Additional calculations have been performed with Hs=2.2m in the way to confirm the sea-sates limitations leading to stable response of an isolated MoSE gate obtained in working conditions. Results are provided in the preceding table and on the graphs provided hereafter.



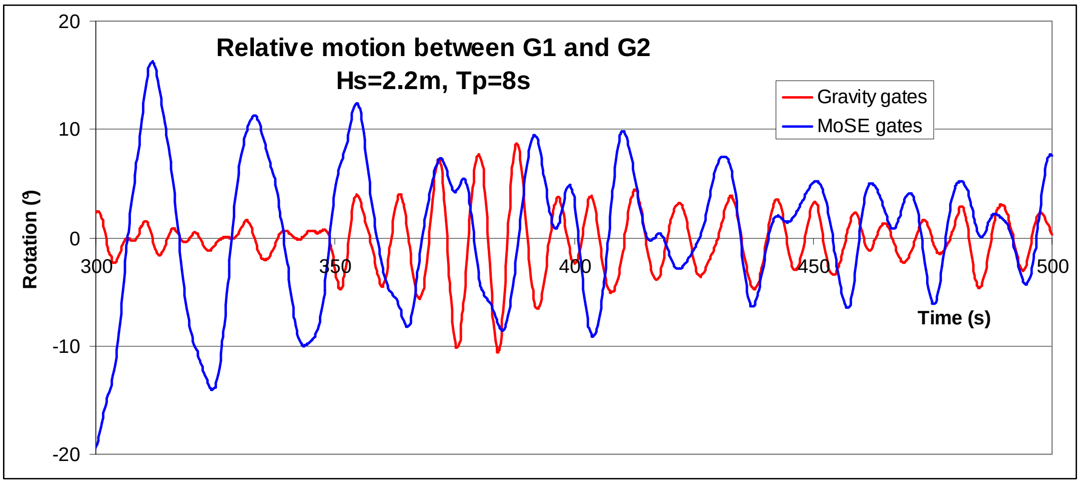

*(a) Gravity gate*




*(b) MoSE gate*

<u>Comments</u>:

- If the super-harmonic component remains dominant for the MoSE gate (external gate G2), its amplitude is reduced compared to Hs=3.2m
- The maximum relative motions between the two gates is 10° for the Gravity gates and to 20° for the MoSE gates (see time series hereafter).




In conclusion of this part, the proximity of the gate to the mouth inlet wall introduce significant variations in the added mass and in the radiation matrices keeping the gate out of the instability, but it is not sufficient to influence the dynamic behaviour of the adjacent gate as shown for case 3. This confirm that the instability, when exists as for the MOSE gate, it is introduced by the gate into the whole barrier and not viceversa: if the gate is stable the barrier does not introduce instability or sub-harmonics.

## 7 CONCLUSIONS

Protection of the lagoon of Venice against high increase of sea level is a major objective for the Municipality of Venice. Design of a gates system has been selected and construction has been engaged since two years. The gates system is composed of a barrier of elementary gates which can close to maintain a maximum water level inside the lagoon.

A key point is the hydrodynamic behaviour of both an elementary gate and a gates system through which water circulation could be possible even with sea states less severe than the maximum design conditions. The objective of the present study is to compare the dynamic behaviour of two gates barrier systems based on a different elementary gate design.

The main differences between the two gate barriers are the basic principle of the gate and its orientation of within vertical :

- the MoSE gates contrast the difference of levels with the gate buoyancy. The gate is inclined to the lagoon
- the Gravity gates contrast the difference of levels with the gate weight. The gate is inclined to the open sea.

The case study refers to the Malamocco inlet. Each barrier is composed by 20 gates of 20m large pined at the bottom level. Comparison will be concerned performance of, first, a single gate (2D and 3D analysis) and then a complete barrier (3D analysis).

The document describes the :

- Methodology, assumptions and numerical tools used for comparisons
- Input data : environmental conditions to consider, gates characteristics
- Analyses performed and main results
- Comments on the main results : gates motions and loads transferred to the foundation.

Main conclusions :

<u>Methodology</u>
The methodology, assumptions and numerical tools used for the analysis represent the most advanced state of the art in the non linear hydrodynamic modelling and multi-body interaction in waves. Specific task on the matter has been given to professor B. Molin of Marseille University. For the response of the gate barrier, the results achieved by professor B. Molin (Ref.4) are in agreement with the results published by professor C.C. Mei (Ref.5, 6).

<u>Isolated gate</u>

- Comparing linear and non-linear calculations shows that non-linear hydrostatic effect has a major influence both for MoSE and Gravity gates. Then conclusions for an isolated gate are derived from non-linear calculations.
- Considering the 1000-years wave conditions, Hs=3.2m, 9.3s, Gravity gate leads to 10% to 20% larger rotation angles compared to MoSE gate. Vertical force at the pined point is reduced for Gravity gate and horizontal components are similar for the two design. Mean drift imposes a modification of the mean inclination less than 4° : down-lift for MoSE and up-lift for Gravity. Maximum rotation angle, including mean value, is less than 15°.

- For the lowest wave peak periods, unstable behaviour of the MoSE gate could be observed depending on the significant wave height Hs. A specific analysis has been followed for Tp=8s, increasing Hs. The limit of stability has been found for Hs=2.0m. For larger value the gate oscillates between the two unstable equilibrium inclinations: the working position (-46°) and an inclination towards the sea-side (7°). Occurrence of unstable behaviour is very sensitive to the mass distribution (and ballast), i.e. 10 tons is sufficient to move from a stable to an unstable motion.

<u>Gate barriers</u>

- The linear analysis has been performed for a set of gates, including hydrodynamic interactions between the 20 gates and a 2 meters difference between sea-side and lagoon water levels. No-symmetric waves field is obtained by modelling the boundary walls of the barrier, a small wave incidence.
- Hydrodynamic interactions have a major influence on the global behaviour of the barrier. Then tentative to define natural periods seems quite unrealistic as hydrodynamic coefficients are too sensitive to the relative motions between gates induced by waves.
- For wave periods corresponding to the 1000-years conditions (Hs=3.2m, Tp=9.3s), limited absolute rotation angles are obtained (close to those obtained for an isolated gate) but with difference in the phases between adjacent gates. The relative rotation angles could be increase to 10° for the Gravity gates and to 25° for the MoSE gate. For larger wave periods a "snake" behaviour is obtained with large rotation angles. Loads at the pined point take similar values as for an isolated gate.
- The non linear analysis done for the gates configurations in starting conditions (cases 1 and 2 has shown that both for the position of the gate midway and close to the inlet wall, MOSE gate has a chaotic dynamic behaviour and therefore it is useless to perform this analysis for the entire MOSE barrier being this not possible for the mathematical model available at the present state of the art. The Gravity gate shows a regular dynamic behaviour. Results of the calculation for case 3 demonstrate that the interaction between the two adjacent gates still present the instability of the MoSE gates, while the behaviour of the Gravity gates is regular.
- Considering the different results obtained for the isolated Gravity gates (cases 1 and 2) and for the two adjacent Gravity gates (case 3) it can be concluded that for the correct calculation of the entire gate barriers it is necessary to perform a non linear 3D analysis.
- For a more comprehensive evaluation it has also been performed the dynamic analysis for the two adjacent gates with the wave spectrum Hs=2.2 m and Tp=8 sec both for MoSE and Gravity gates. The analysis has been performed with the same coefficient for the quadratic damping and without any additional artificial dumping, and also in this case there is a confirmation of the chaotic response of MoSE gates, and of the regular behaviour of the Gravity gates.

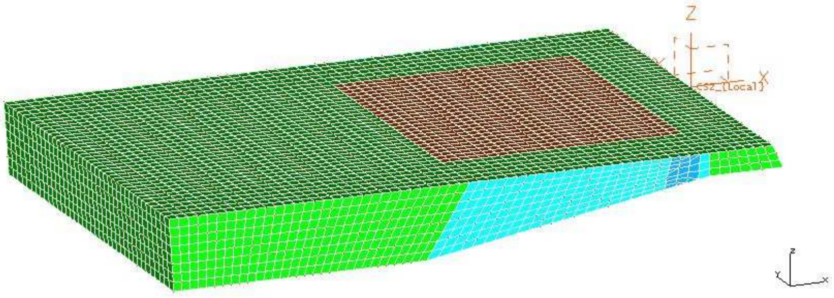
<u>General</u>

- Using the state of art in hydrodynamic modelling, the comparisons of the two gates designs with dynamic analysis using linear hydrostatic spring leads to similar behaviour with larger motions for the Gravity gate but larger vertical loads for the MoSE gate for the extreme wave conditions Hs = 3.2m and Tp = 8sec and 9.3sec.
- Both Gravity and MoSE gates have non linear hydrostatic spring constant, and therefore a non linear analysis is necessary.
- With the effective non linear hydrostatic spring the behaviour of the two gates is significantly different, MoSE gate shows an unstable behaviour not only with maximum design spectrum Hs = 3.2 m, Tp = 8 sec but with less severe sea states.

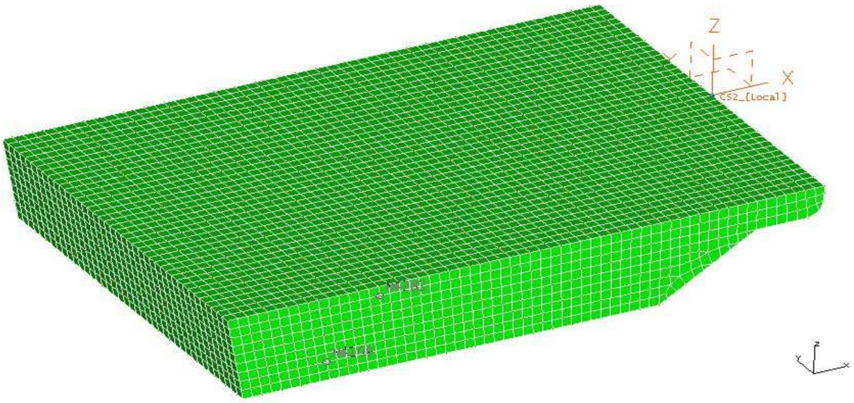
- With linear analysis out-phase motions could induced relative angle between adjacent gates, limited to 10° in the 1000-years sea-sate. Higher relative angles are obtained but only for wave periods larger 13s (not in the range of the incoming wave periods)
- The unstable behaviour, induced by hydrostatic, is obtained for the MoSE gate for steep waves, i.e. Tp=8s corresponding to Tz=7.5s. and Hs>2.0m. A preliminary sensitivity analysis shows that instability is highly sensitive to the gate mass and inertia, the wave energy distribution and to the fluid flow damping. This is of particular interest because during the measuring campaign at the installation site of the barrier of approx. 4 years at the Malamocco inlet there is evidence of at least one storm with Hs = 2.5 and Ts = 7.5 sec corresponding to a Tp = 8 sec has occurred at site. Due to the limited scope of the work of the present analysis using the state of art in hydrodynamic modelling, these are the achievable results, a deeper analysis could be required on the damping mechanism taking place between a set of gates to better define limits and range of the instability occurrence. In any case larger motions of the MoSE gates have a great impact on the efficiency of the barrier against the difference of tide level.
- The Gravity gate does not show unstable behaviour induced by the non-linear hydrostatic spring for the design sea states.
- Based on the above results obtained for the MoSE gate, that is the impossibility to perform its dynamic analysis, and considering that the scope of this study is not to perform the design of the gate system but only to perform the dynamic analysis and to compare the different dynamic behaviour of the two gate concept, it has been decided not to perform the non linear dynamic analysis of the whole barrier also for the Gravity gate as it is not possible to compare a stable system with an unstable one:
  - → the stable system can be analysed with standard techniques considering non linear dynamic behaviour of multi-bodies interacting with wave, and it is possible to achieve realistic and reliable results for a proper design.
  - → the unstable system cannot be analysed even using the most advanced non linear simulation software available in the market place and therefore it is not possible to achieve reliable results for a proper design.
- In addition to comparison of the dynamic behaviour in waves of the two gates, there is evidence that with respect to tide variation, MoSE gate requires an active control system of the water ballast to maintain the working condition, while Gravity gate does not need it.

# 8 APPENDIX 1 : WAVE LOADS FROM PANEL METHOD

## 8.1 3D MESH OF AN ISOLATED GATE



*Mesh of the "Gravity gate"*



*Mesh of the "MoSE" gate*

## 8.2 3D WAVE LOADS TRANSFER FUNCTIONS

All results are provided in a separated report
Separated reports issued by B. MOLIN (Ecole Centrale Marseille - consultant of Principia) describe the theoretical method used and the numerical analyses of the multi-gates configurations.

Videos of simulations are also provided in a joint DVD