2D flood barrier oscillation in severe sea conditions

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The MoSE (Experimental Electromechanical Module) flood barrier is now working to protect Venice from very high tides. It is a system of 78 flap gates that close the three inlets to the lagoon when the tide exceeds 1.10m. It has been raised for the first time on Saturday, October 3rd 2020, during storm Alex. It was the first time that the system was protecting the city from high tide flooding after the previous year event, when the worst floods in 50 years left St Mark's square submerged under a meter of water in November 2019.

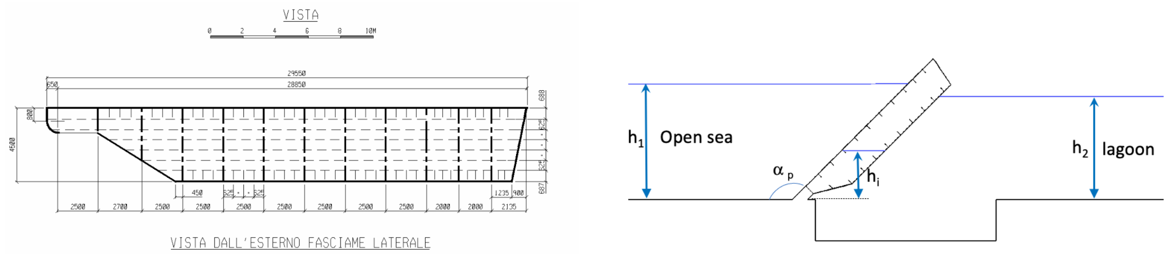

Figure 1: Left: Sketch of the MoSE layout with main dimensions; right: definition of the main variables in the raised conditions.

Each flap is a part of a dam that separates the lagoon from the open sea. The metal box-like structure of the dam is shown in the left of figure 1 in its rest position; it is 20 meters wide and between 18 and 29 meters long depending on the local water depth. The flaps are connected to a concrete foundation with hinges. When the tide is low, the gates are filled with water and rest in their concrete bottom housing. When the tide rises, air is pumped inside the box, the flap rises up to an angle α_p with respect the open sea. The ballast water is reduced so that it has a water height h_i with respect to the sea bottom, this is a function of the weight of the metal box and of the difference of water height between open sea (h_1) and lagoon (h_2). For the deepest inlet, the flap inertia is 1074400kNm2, its mass is 3161kN and a CoG is 16.23m away from the in hinge in the horizontal direction and -1.28m in the vertical direction.

Besides the technical and economic difficulties in building such an infrastructure, other aspects delayed the opening of the barrier, in particular the fears of unstable behaviors of the structure to the incoming waves. The feared instabilities were both in 2D and 3D. According to [1], 2D large oscillations could take place for incoming waves with period of oscillation close to the resonance period. In this work, a fully non linear viscous solver OpenFOAM is applied to verify these conditions. The results show that the non linear interaction of the waves with the flap gate can largely influence the oscillation, limiting its amplitude. Furthermore, the effect of the sloshing of the ballast water is considered, to determine if it can be destabilizing. The calculated eigenfrequency of the sloshing in the flap is lower than the characteristic wave periods of the area so that the sloshing has weak stabilizing effects. This work does not addresses the 3D instabilities highlighted in [4], they could take place in the longitudinal direction and cause neighboring gates oscillations in opposite phase but it paves the way for future full 3D viscous non linear studies.

External problem First, the interaction of the flap gate with the incoming regular waves is addressed. The amount of ballast water left inside the gate is such that the angle α_p is equal to 135^o

when the water level in the open sea is $h_1 = 17m$ and $h_2 = 15m$ in the lagoon, *i.e.* there is a 2m tide. In this paragraph, the ballast water inside the gate is considered frozen so that its inertia moment does

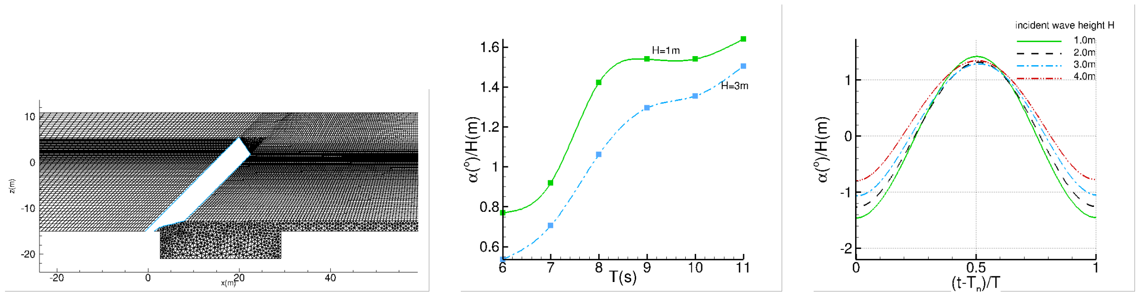

Figure 2: Left: details of the mesh around the flap gate; Center: Angular oscillation response as a function of wave period and height; Right: time history of flap oscillation as a function of the wave height for a wave period $T = 8s$.

not vary during the oscillations. This allows meshing of only the outer domain as plotted in the left panel of figure 2. The mesh is refined close to the free surface and both structured and unstructutred strategies are used. Particular attention is paid to the region where the hinge is located, because the mesh deforms with the angular motion of the gate and clustering of cells have to be avoided.

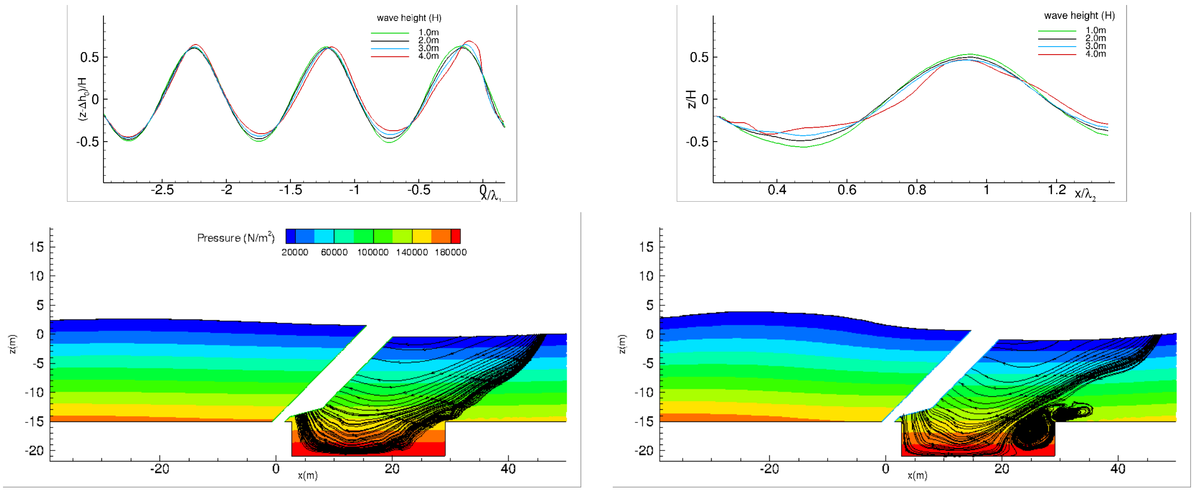

Figure 3: Top: Free surface on the windward and leeward side of the flap gate at $(t - t_n)/T = 0.9375$ $(T = 8s)$. Bottom: pressure and streamlines for the same time instant with wave height $H = 1m$ on the left and $H = 3m$ on the right.

The central panel of the same figure shows the RAO for different wave heights H. For larger waves, the variation of the angular motion is less than proportional to H even though the resonance frequency is unaltered. The right part of figure 2 highlights that the variation is mainly taking place for negative values of the angle of oscillation of the flap, that is the oscillation towards the open sea is relatively reduced for higher waves.

Figure 3 shows some features of the flow for the time instant when the flap is rotating towards the open sea. Its top part shows the wave elevation made non dimensional by the wave height for the windward and leeward side of the flap for four wave heights. The waves become steeper for increasing H, the interaction with the top right corner of the flap generates small oscillations in the downwind waves but the wave shapes variations do not justify the large changes in the flap position history. However, the bottom part of the same figure shows the effect of the interaction of the downwind wave with the step made by the housing of the gate in rest conditions. There, the generated vorticity is larger with increasing H, dissipating larger values of energy that would have been used for the righting of the flap on a flat bottom. Other smaller sources of vorticity are the bottom and top right corners of the gate. The vorticity generated in those corners also contributes to the reduced rightening effect.

Internal problem The moving ballast water that fills the gate could also have an influence on the rotation of the flap. For this reason, here the sloshing effects are taken into account first from a theoretical point of view and then numerically.

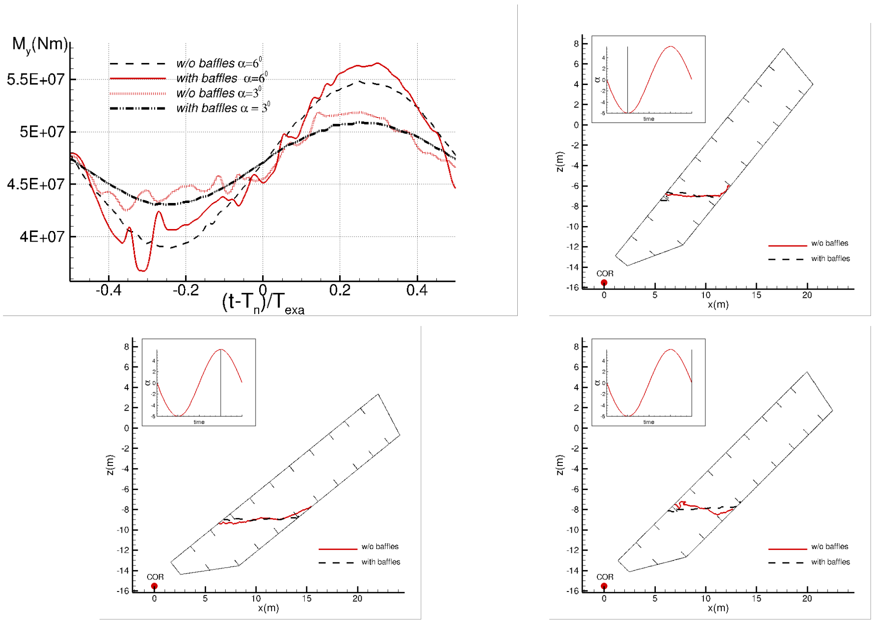

Figure 4: Oscillation of the gate with $T = 8s$ (length of the gate in the longitudinal direction of 20m). Top-left: Angular moment history in one period for two different amplitudes of oscillation with and without baffles. The other panels refer to the free surface deformation with and without baffles for an amplitude of oscillation $\alpha_o = 6^o$

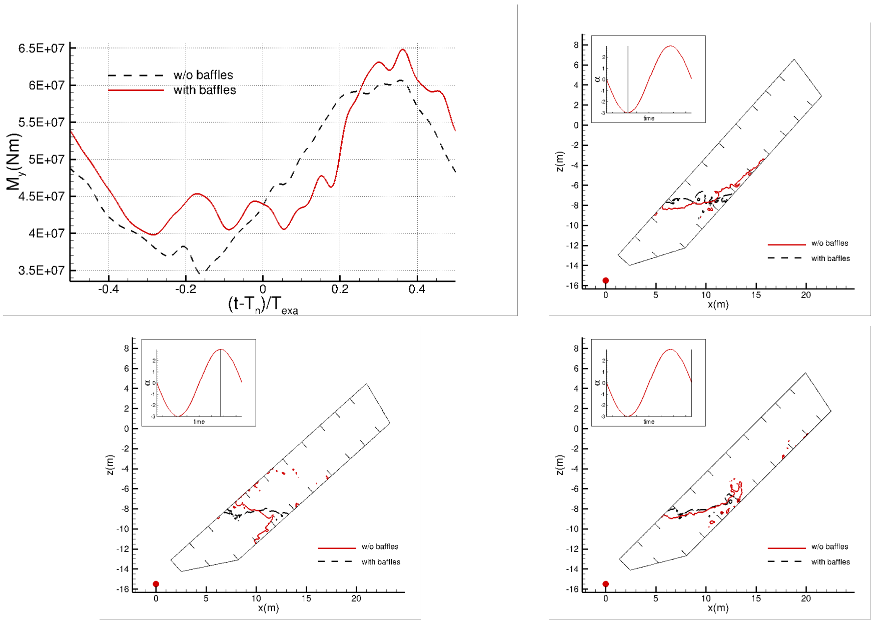

Figure 5: Oscillation of the gate with period $T = 3.5s$ and amplitude $\alpha = 3^o$ (length of the gate in the longitudinal direction of 20m). Top-left: Angular moment history in one period of oscillation with and without baffles. The other panels refer to the free surface deformation with and without baffles at three different time instants.

Because the shape of the internal part of the gate is not classical (neither a parallelepiped nor a cylindrical shape), the eigen-period cannot be calculated through analytical methods as in [3] but a semi-analytical strategy is used as described in [2]. For a gate in the same conditions of the previous paragraph, it is possible to find an eigen-period of sloshing $T_{sloshing} = 3.26s$. This is a linear approximation and does not take into account the structural stiffeners that appear in a 2D section of the gate as baffles. For this reason, numerical calculations were carried out with OpenFOAM both for smooth walls and in presence of baffles, to understand the importance of their presence on the flow.

Figure 4 shows the moment around the longitudinal axis due to the internal fluid under forced oscillations with period $T = 8s$ with and without baffles. When the walls of the gate are straight, even for a period so far from the natural one, the free surface impacts against the inclined walls and causes large local oscillation of the moment. However, when baffles are considered, the moment is changing mildly as the free surface is almost always flat as shown in the other panels of fig. 4, where the free surface deformation is sketched in three positions corresponding to the maximum tilting on the right, on the left and in the neutral position. Similarly, figure 5 shows the moment and the free surface deformations for a forcing period $T = 3.5s$, very close to the resonance period. The oscillation of the moment is larger and local peaks appear also in the case with baffles. In fact, the free surface breaks in both the analyzed cases, even though, in the case without baffles, the motion of the tongues of water along the inclined wall is so violent to produce also a large phase shift of the moment with respect to the case with the structural stiffeners.

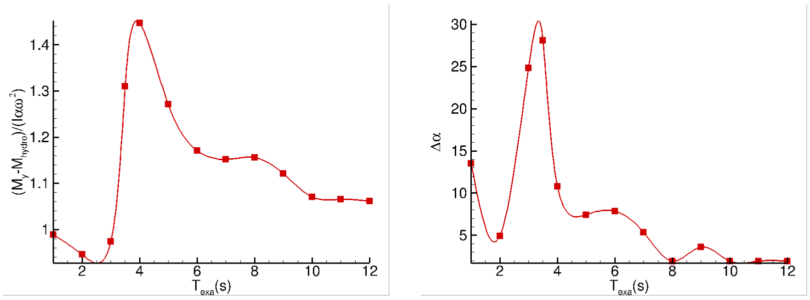

Figure 6: Added inertia and phase shift due to the sloshing calculated for an angle of oscillation $\alpha = 3^o$

Figure 6 shows the added inertia and phase shift due to the sloshing in a gate with baffles, they are obtained forcing the oscillation of the gate with amplitude $\alpha = 3^o$ and several forcing periods. The figure shows that up to $T = 3s$ the sloshing has a weakly unstabilizing effects; the maximum stabilizing effect is around the natural period of sloshing but it decays quickly for higher periods of oscillation. The same figure also highlights a damping effect due to the phase shift that disappears for periods of oscillation larger than $10s$.

Conclusions This work highlights the importance of the non linear interaction of the waves with the sharp corners either of the gate itself or of the bottom for the external problem and of the baffles for the internal one. Moreover, it shows that for some periods of the incoming wave the sloshing effects can be easily modeled with a negative restoring force but for shorter waves a full simulation of the internal and external problem needs to be run.

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