THE DYNAMICS OF THE VENICE GATE BARRIERS AND THE EXTREME EVENT OF NOVEMBER 22nd, 2022

Paolo Sammarco, University of Rome Tor Vergata, sammarco@ing.uniroma2.it
Piera Fischione, University of Rome Tor Vergata, piera.fischione@uniroma2.eu
Alessandro Romano, Roma Tre University, alessandro.romano@uniroma3.it
Giorgio Bellotti, Roma Tre University, giorgio.bellotti@uniroma3.it
Sergio Dalla Villa, Consorzio Venezia Nuova (CVN), Sergio.DallaVilla@consorziovenezianuova.com

The design and construction of the most complex storm surge defense system ever made, i.e. the four systems of floating gates at the inlets of the Venice Lagoon (also known as the Mo.S.E. project), took more than forty years since its ideation. The entire spectrum of the fields of Coastal, Civil and Environmental Engineering has been challenged by this project, with contributions from an unprecedented number of national and international research institutions, design and construction firms. One of the many significant challenges has been the modelling of the complex hydrodynamic behavior of the floating gates in waves and current. Investigation was conducted by analytical, numerical and experimental means. Experimental set-up covered vertical and inclined gates in 2D wave flumes, in 3D wave tanks, and the whole four barriers and inlets in 3D layouts; scales ranged from 1:64 to 1:10. Gates were subjected to regular and irregular waves, linear and nonlinear, combined with currents. Each of the three main phases of work of the barrier gates, i.e. lifting, oscillating around the design angle and lowering, have been studied, tested, designed and engineered.
Linear and nonlinear response of the gates to waves attack have been studied, both experimentally and theoretically. Monochromatic waves induced not only a synchronous response, but also a subharmonic response with specific out of phase patterns, also subjected to modulational chaos (Mei et al 1994, Sammarco et al 1997a, b). These modal oscillations were shown to be resonantly excited through a mechanism similar to the excitation of edge waves on a beach. Real sea state conditions and viscous dissipation attenuated the phenomena. Panizzo et al (2006) analyzed the experimental data of the full 3D model of the Chioggia inlet and gate barrier via E.O.F. analysis and showed that in storm condition the patterns and frequencies of a sub-set of the N-1 natural modes (N being the number of gates – see Li & Mei 2003) can be synchronously and subharmonically excited, together with the spatially and synchronously in-phase motion. Questions arose during the testing and design phases, whether the occurrence of nonlinear responses and the measure of the natural modes' periods were affected by the scale of the models. So, the model tests data in scale 1:60, 1:30 and 1:10 were thoroughly compared (CVN report 2003) to reveal that no significant trends could be observed, e.g. the measure of the first natural mode period, in which the neighboring gate oscillates out of phase, showed substantial stability of its value.
The complex response of the gate system became a kernel in the design of the gates, which included an articulated feedback control system that regulates the air inflow in each single gate in order to maintain the design angle during storm surge and wave attack.

The first raising of the system in real necessity occurred in 2020. From 2021 on the Mo.S.E. has been "called on duty" several times. Since then the time series of angles, waves, current and levels have been monitored. The appropriateness of the design and construction of the Mo.S.E. system is proved by its mint operations and functioning and by the numbers of extreme flood events that were spared to the Lagoon in the last 2 years.
Now, in this new phase of Operations and Maintenance some questions still remain open. Were the natural modes' periods and patterns of the actual barriers (scale 1:1) properly predicted? Do these natural modes manifest themselves in a manner similar to that revealed by the analytical theories and the experimental testing? Do the actual ballast water, water level differences (sea vs lagoon), actual real sea state in front of the barrier, structural details of the gates, viscous dissipation and friction, all combine to alter the periods of the natural modes and the likelihood of being excited? Considered that in the first two years of operation no unpredicted response was ever observed, that oscillation amplitudes have been always below the envelope of predictions, what is the role played also by the feedback control system?
To answer all these questions an additional complex network of measuring devices of the main parameters has been designed and is currently being deployed by the CVN. However, the first and foremost scientific question which is the determination of the actual values of the natural modes poses technical difficulties hard to overcome, at least at a first glimpse. Indeed, in all the model experimental tests the floating gates were arranged fixed in an initial position according to the spatial distribution of the natural modes and then released: the following relatively persistent oscillations could be measured to give the actual value of the natural period, including the effect of the model scale viscous effect. See for example the 1:10 model test arrangement in Voltabarozzo (Padua, Italy) in Figure 1.

Figure 1 – Chioggia gates experimental model test of the natural period of mode 1 (1:10 scale); gates are displaced by magnets.

A similar approach cannot be pursued for the Lagoon inlets actual barriers as it poses safety risks that cannot be overcome. However, an ad-hoc procedure of the raising of the gates has been conceived and will be highlighted in the present contribution. This safe procedure could yield the desired information with a high degree of approximation.

The benefits of the Mo.S.E. already surpassed the costs when on November 22nd, 2022, the raising of the gates halted outside the Lagoon the highest storm surge event since 1966, which would have caused invaluable damages, beyond economic appraisal. We present a walk through this storm event and highlight the features of the complex gate barriers' response, by analyzing and interpreting the recorded data.

First the water levels. Figure 2 shows the water level outside the lagoon (black) compared to the synchronous ones inside the Lagoon (green), for the Lido Inlet. The water level at Punta della Salute would have otherwise reached 1.84 m above sea water level (wetting of San Marco Square starts at 0.80 m), yet it remained below about 0.80 m in the whole Lagoon. No flooding occurred.

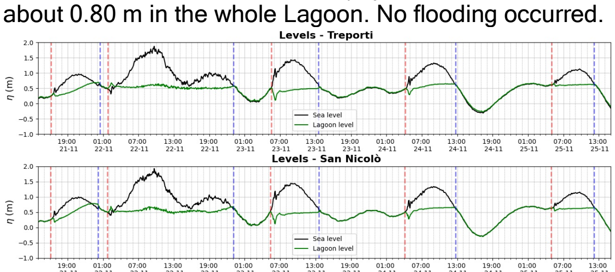

Figure 2 - Tides levels at the inlets (black) and inside the Lagoon (Green)

While the most severe storm surges are associated with South-East winds (Scirocco), the same winds do not generate high waves that can propagate through the inlets. The other way around for North-East events (Bora). During the November 22nd storm the already persistent Sirocco winds first significantly raised the storm surge levels, then relatively quickly rotated towards North-East (Bora) forcing water waves at the barriers of significant wave height up to 1 m. The rotation of the wind direction can be appreciated in the polar plot of Figure 3.

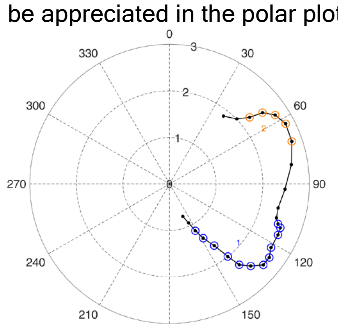

Figure 3 – Counterclockwise rotation of the wind direction on November 2022 (ERA 5 dataset - points are every hour from 2 am to 11 pm)

The time series of the angular position of each gate of the four barriers (Lido Treporti, Lido San Nicolò, Chioggia and Malamocco) sampled at the frequency of 1Hz were analyzed and compared with the wave height time series from four ADCP, each centrally located at about 100 m from the gates' common axis of rotation.

Figure 4, in each of the three rows, shows for each of the three most energetic empirical modes: modal shape, energy content and oscillation amplitude spectrum. The first row highlights the persistence of a long period (about 1800 s) in phase oscillation, due to excitation of long period oscillation of the whole canal. The second and third rows resemble the modal shape of Mode 17 and 16 with two frequency components: the main period of the excited mode (75 s) and the energy pertaining to the synchronous oscillation with the wave spectrum (6-10 s).

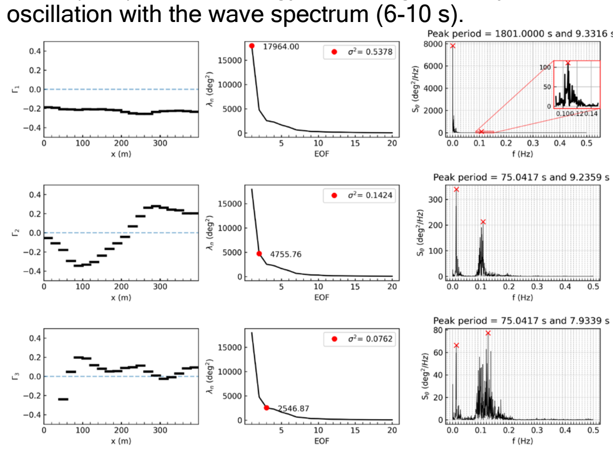

Figure 4 - EOF analysis of the San Nicolò barrier gate oscillation.

These observations were confirmed also by the comparison of the frequency spectra of each single gate with wave motion, where several energy components are present (see Figure 5 – gate 11 of San Nicolò barrier). With an overall very limited angular oscillation about the mean, frequency distributions suggest spurious synchronous and subharmonic modal oscillation, long period channel oscillation, all superposed. Data also show that the shorter period waves (T<3 s - typically reformed by wind action on the inlet surface) do not affect at all the gate oscillations.

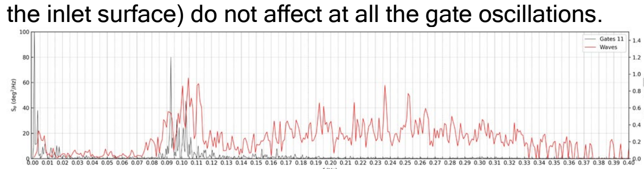

Figure 5 - Gate oscillation (black) and wave motion (red) spectra for Gate 11 of San Nicolò barrier.

REFERENCES

Mei C.C., Sammarco P., Chan E.S., Procaccini C. (1994) Subharmonic resonance of proposed storm gates for Venice Lagoon. Proc. Royal Society of London, A, Vol. 444, pp 257-265.

Sammarco P., Tran H.H., Mei C.C. (1997a) Subharmonic resonance of Venice gates in waves. Part 1. Evolution equation and uniform incident waves. Journal of Fluid Mechanics, Vol. 349, pp. 295-325.

Sammarco P., Tran H.H., Gottlieb O., Mei C.C. (1997b) Subharmonic resonance of Venice gates in waves. Part 2. Sinusoidally modulated incident waves.
Journal of Fluid Mechanics, Vol. 349, pp. 327 359.

Li G. & Mei C.C. (2003). Natural modes of mobile flood gates. Applied Ocean Research, 25(3), 115-126.

Panizzo, A., Sammarco, P., Bellotti, G., & De Girolamo, P. (2006). EOF analysis of complex response of Venice mobile gates. Journal of waterway, port, coastal and ocean engineering, 132(3), 172-179.

CVN Report B.06.53A_R016 (2003). Studio sugli effetti scala nelle prove in modello fisico delle paratoie.