## MODELLING THE CAISSON PLACEMENT AT THE CHIOGGIA INLET, VENICE

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In the summer of 2014 Strukton Immersion Projects has placed the foundation caissons of the Venice flood barrier in the Chioggia inlet to the Venice Lagoon. The caissons were loaded by currents and waves during placement. Before the placement, physical model tests were performed in a wave-current basin to optimize the placement procedure, and to determine the line force and pontoon motions. This paper describes the model setup, tests that were performed, the results and the implications for the placement procedure. Also the experiences during actual placement are discussed.

*Keywords: Venice; flood barrier; physical modelling; immersion; caisson; MOSE; Chioggia*

### INTRODUCTION

In the summer of 2014 Strukton Immersion Projects (SImP) has placed the foundation caissons of the Venice flood barrier in the Chioggia inlet, see Figure 1. The Chioggia inlet is one of three tidal inlets to the Venice Lagoon, which can be closed by the flood barrier. The caissons can be loaded by currents and waves during placement. Prior to placement, the immersion process of the caissons was studied in a physical model at Deltares. This paper describes the model setup, the tests that were performed, the results, and the implications for the placement procedure. Also some experiences during the actual placement are mentioned.

The aims of the study were:

- Determination of governing line forces.
- Determination of the pontoon and caisson movements.
- Optimization of immersion operation.
- Determination of window of workability.

**Figure 1. Golia pontoon placing a gate caisson for the Venice flood barrier at the Chioggia inlet.**

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## BACKGROUND ON VENICE FLOOD BARRIER

Around 1990 the design of the Venice flood barrier was completed. The project is also referred to as the MOSE project, after the name of a protoytype experimental setup of the gates (MOdulo Sperimentale Elettromeccanico).

The barrier consists of 20 m wide steel gates that are resting on the sea floor in large concrete caissons. When the barrier should be closed, air is pumped in the gates. The gates float up and close the tidal inlets. A head difference of up to 2 m can be maintained. The principle of the barrier is shown in Figure 2. In total over 1500 m of gates will be placed in the three inlets to the Venice Lagoon.

In 2003 the construction was started. First the inlets were 'paved', including the construction of trenches for the gate caissons, breakwaters, revetments, bed protections, ship locks, and beach nourishments. In 2013 the caisson placement started at the Lido inlet, and in 2014 the caisson placement for the Chioggia inlet was performed. The barrier is expected to be operational around 2017.

The present paper deals with the placement of the concrete gate caissons in which the gates will be placed. Placement for the Chioggia inlet was executed by Strukton Immersion Projects in the period of June to August in 2014.

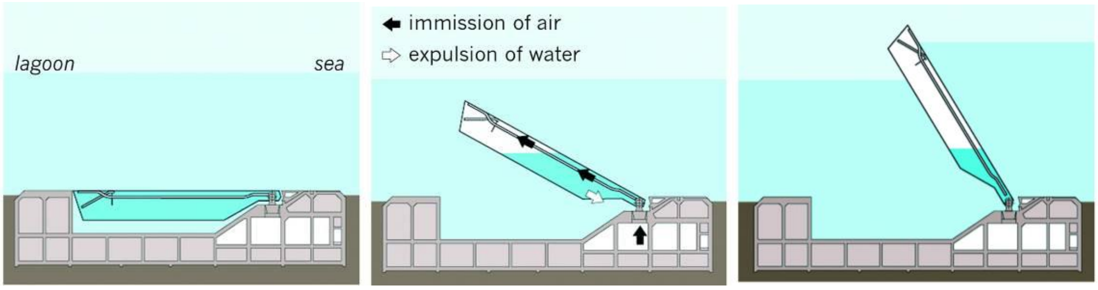


**Figure 2. Principle of Venice flood barrier (source: Magistrato alle Acque di Venezia - Consorzio Venezia Nuova)**

In total eight caissons were placed in the Chioggia inlet for the foundation of the storm surge barrier. The gate caissons will hold the bottom-hinged gates of the Venice Barrier. The shoulder caissons were placed at the banks. These shoulder caissons are emerged and represent the fixed vertical channel sides near the gates. Six gate caissons were placed in a trench that spanned the inlet, see e.g. Figures 2 to 4. The channel width is 360 m, which constitutes the deepened trench in which the caissons are placed and fixed shores.

**Figure 3. Gate caisson (middle) and shoulder caisson (right) ready for placement.**

The gate caissons are 60 m long (along trench), 46 m wide (perpendicular to trench), and 11.5 m high, see Figure 3. The caissons will be placed by suspending them under a pontoon. An existing pontoon, named Golia, which is 60 m long and 20 m wide, was used for the immersion. The pontoon fits in the space where the gates will be resting in the caisson (see Figure 2), such that the caissons can be emerged during transport. Normally caissons (or tunnel elements) are immersed by single or double catamaran pontoons which have floaters at each side of the caisson. The present setup can seem less stable than this standard solution, so it had to be proven that it was stable enough, and the setup did not lead to too large line forces, under hydraulic loading by waves and currents.

The part of the placement operation that was modelled was as follows:

- The caisson is manoeuvred from the dock to the placement location. At this stage the caisson is afloat.
- The winches are set to maintain a constant load in the vertical lines, and the ballast tanks of the caisson are filled until the caisson is immersed.
- The caisson is filled such that the load on the lifting cables is equal to a pre-defined value, to be determined based on the tests.
- The caisson is lowered to the sea bed on steel support pins.

During all these stages the line loads and caisson movements should remain below limits under predefined flow and wave conditions. Three typical immersion stages (i.e. caisson elevations) were modelled, as depicted in Figure 6.

The typical (extreme) wave and current characteristics during which placement should be possible are:

- Significant wave height: $H_{m0}$ = 0.75 m,
- Peak wave period $T_p$ = 5.5 s,
- Bulk mean flow velocity U = ±1.25 m/s.

The significant wave height $H_{m0}$ is defined a four times the standard deviation of the water elevation. The peak wave period $T_p$ is the wave period corresponding to the peak of the wave energy density spectrum. The wave period was defined as the absolute wave period, i.e. as observed from an earth-fixed point, such that the intrinsic wave length for a given wave period changes with flow velocity. The bulk mean flow velocity U is defined as U = Q/A, where A is cross sectional area upstream of trench, and Q is total discharge.

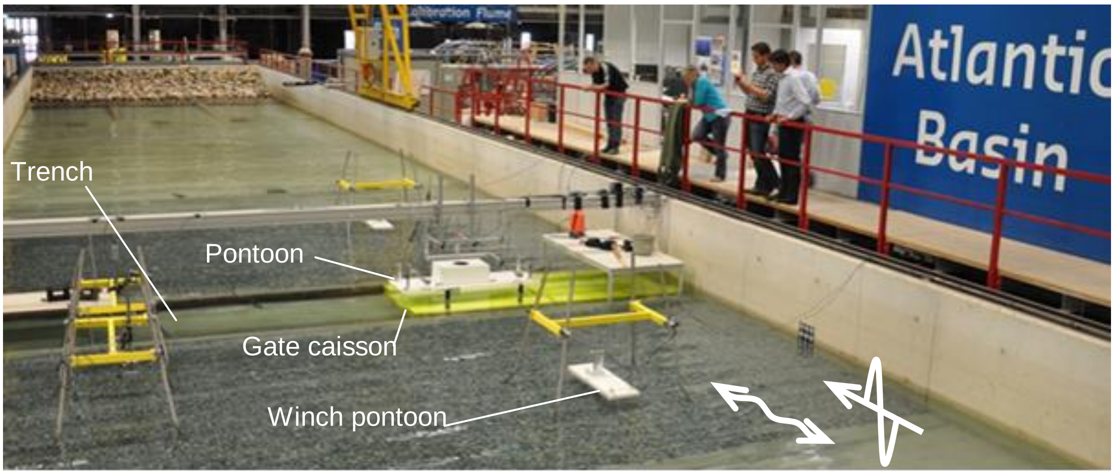


**Figure 4. Atlantic Basin with model set-up for caisson immersion.**

During immersion the caisson is held in place under wave and current loads by several types of cables: The setup of the cables is shown in Figure 5.

- 4 vertical lifting lines between pontoon and caisson, numbers 1-4 in Figure 5
- 4 horizontal contraction lines on caisson (flow direction), numbers 5-8 in Figure 5
- 2 horizontal longitudinal lines on caisson (transverse to flow direction), numbers 9-10 in Figure 5
- 4 horizontal mooring lines on pontoon (flow direction), numbers 11-14 in Figure 5

These fourteen steel cables have either a 40 or 60 mm diameter. The four lifting points between pontoon and caisson consist of multiple reeved cables. The extreme force on all these cables should be known.

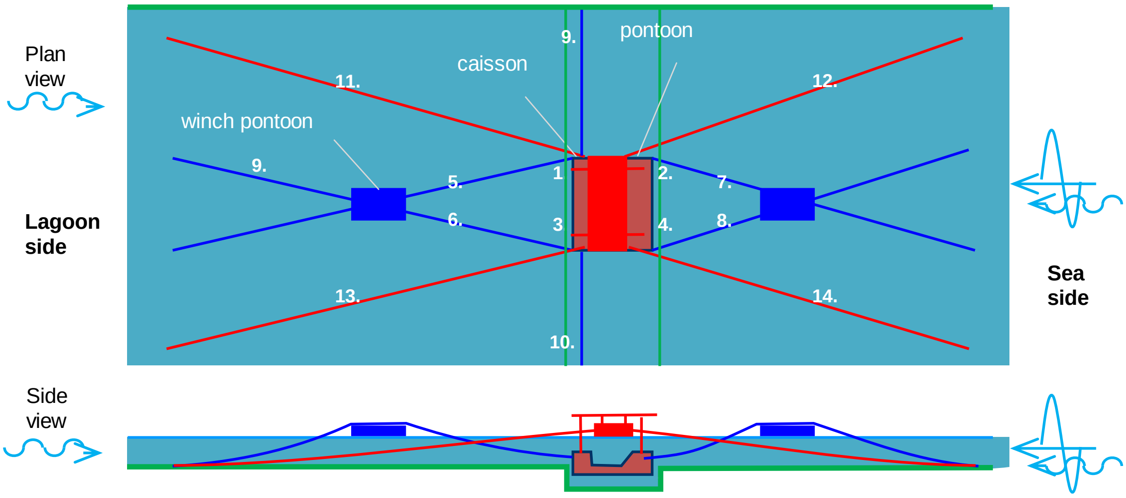


**Figure 5. Cable arrangement for caisson placement.**

## EXPERIMENTAL SETUP

The Atlantic Basin at Deltares was used for the project. This relatively new basin is especially suited for the proposed tests. Its design is partly based on the former Venice Basin, where –among other projects– the dynamic behaviour of the Venice Barrier was tested. It is a 9 m wide basin in which waves and (tidal) currents can be simulated simultaneously. A segmented wave generator is positioned at one of the short sides. The pumps have a maximum capacity of 3 $m^3/s$, and flow can be created in either direction, with flow depths up to 1.2 m. Flow is guided into and out of the basin from openings in the flume bed, spanning the width of the flume in front of the wavemaker and in front of the wave spending beach. The wavemaker is equipped with active reflection compensation, and can generate waves up to $H_{m0}$ = 0.25 m. In the test section in the middle of the flume an extra depth of 0.5 m is available which allowed modelling the deepened trench where the caissons are placed.

Froude scaling was used to scale the model. A geometric scale of scale 1:34.5 was applied. The caisson and pontoon models were constructed from water proof plywood. The second gate caisson to be placed was modelled. For this caisson position the flow velocities will be relatively high compared to those at the location of the first gate caissons near the bank, and any detrimental effect related to asymmetrical flow over the caisson will be included. A part of 300 m of the 360 m wide inlet was modelled. At this width a larger model scale was possible, and the far bank does not influence the flow at the caisson significantly yet at this width.

The required weight and weight distribution of the floating bodies were applied by trimming with steel weights. The correct mass and (roll and pitch) moments of inertia and centre of gravity were calculated from the weight (distributions) on the as-built drawings and reproduced in the caisson and pontoon model. The weights of the measurement instruments were also taken into account in this procedure.

The prototype weight of the caisson without ballast water (concrete plus outfittings) is over 20’000 tonnes. The model caisson was completely filled with water. Hence, a good initial weight distribution was obtained and limited extra ballasting was necessary.

The crossing lines that fixate the caisson in streamwise direction, the contractions, are supported by two winch pontoons, which were also modelled. These pontoons had the right draft and size, but not all moments of inertia were exactly reproduced, as they were also not known at full scale, and were expected to be of limited importance.

The load on each of the 14 cables was measured. To ensure the right weight (catenary) and flow resistance flexible steel cables with scaled diameter were used in the model. The multiple reeved cables of the four lifting points were modelled by one thick cable with representative diameter. As material stiffness does not follow Froude scaling, the stiffness of the ten horizontal lines on the pontoon and caisson was modelled by adding springs at the end of the cables with scaled elasticity. These springs were applied and integrated with the force transducers on small vertical towers, which could also be used to trim the cables. These are shown on the four edges of the immersion pontoon shown in Figure 6. The forces on the contraction lines (connected to the caisson) were measured at the (emerged) winch pontoons, on the side of the caisson.

**Figure 6. Model caisson (yellow) suspended under pontoon (white) at three stages of immersion.**

The immersion process takes several hours in reality. Because of this low speed, the tests could be executed with a fixed caisson elevation during a test run. Tuning and installing the setup was an elaborate operation which involved the following steps prior to testing:

- The theoretically calculated weight distribution is added to pontoon and caisson by steel weights.
- The loosely floating immersion pontoon model is balanced until draft and balance are correct.
- The caisson is placed on blocks at the right elevation.
- The pontoon is connected to the caisson and the required tension is given to the lifting cables.
- Now the blocks under the caisson are removed, and the weight distribution in the caisson is altered slightly until the pontoon (and caisson) is balanced.
- The vertical lifting lines are given an equal load by fine trimming.
- The horizontal lines are added to caisson and pontoon.
- Flow is started.
- The caisson location is determined by the (upstream) contractions and longitudinal lines. At slack water the required tension (roughly 100 kN) is put on the horizontal mooring lines and contractions.

**Measurements**

The forces on the lifting lines were measured by HBM Z6 force transducers, with 500 N (model scale) range. The forces on the horizontal lines were measured with one-component in-house developed (Bolder) dynamometers with a 50 N or 25 N (model scale) range.

Besides the line loads, the main measurements that were conducted were the pontoon motions (six degrees of freedom). The pontoon motions were measured using an earth-fixed, optical measurement system based on six laser distance sensors. These lasers measure the distance to a white rectangular box that is fixed to the pontoon with known dimensions and position. From these measurements the six degrees of motion are derived. During the tests the wave height (standard resistance type gauges), discharge (electromagnetic discharge measurement in return pipes), water depth, and flow velocity (electromagnetic velocity probe) were monitored to ensure constant conditions during a test run. The wave height was measured at sufficient distance from the caisson such that the reflections did not significantly influence the wave measurement (no nodes or antinodes present anymore). Under water video recordings were made to monitor the caisson movements. The overtopping onto the pontoon deck was monitored visually and recorded by video. Additionally, accelerometers in the corners of the caisson could be used to detect collisions of the caisson to the trench sides or the bed.

All electronic measurement signals (except the video recordings) were sampled at 17 Hz (100 Hz model scale), with an analogue low-pas filter applied around 8.5 Hz (50 Hz model scale).

**Table 1. Test programme.**

| Test no. | Ballast condition Caisson (t/point) | Top of caisson (m LMM) | U (m/s) | $H_{m0}$ (m) | $T_p$ (s) | Duration (hrs) | Aim |
|---|---|---|---|---|---|---|---|
| T001 | 200 | -10.50 m | 0 | 0.75 | 5.5 | 3 | end of ebb stage |
| T002 | 200 | -10.50 m | 0 | 0.50 | 5.5 | 3 | end of ebb stage |
| T003 | 200 | -10.50 m | 0 | 0.75 | 7.0 | 3 | end of ebb stage |
| T004 | 200 | -10.50 m | 0 | 0.50 | 7.0 | 3 | end of ebb stage |
| T005 | 200 | -10.50 m | +1.25 | 0.75 | 5.5 | 3 | flood |
| T006 | 200 | -10.50 m | +1.25 | 0.75 | 7.0 | 3 | flood |
| T007 | 200 | -10.50 m | +1.25 | 0.50 | 5.5 | 3 | flood |
| T008 | 200 | -10.50 m | +1.25 | 0.50 | 7.0 | 3 | flood |
| T009 | 200 | -10.50 m | +1.25 | 0.75 | 4.0 | 3 | flood |
| T010 | 200 | -10.50 m | 0.5 | 0.75 | 5.5 | 3 | alternative end of ebb stage |
| T011 | 200 | -10.50 m | -1.25 | 0.75 | 5.5 | 3 | maximum absolute ebb velocity |
| T012 | 200 | -10.50 m | -1.25 | 0.50 | 5.5 | 3 | maximum absolute ebb velocity |
| T013 | 200 | -1.50 m | 0 | 0.75 | 5.5 | 3 | end of ebb stage |
| T014 | 200 | -1.50 m | 0 | 0.50 | 5.5 | 3 | end of ebb stage |
| T015 | 200 | -1.50 m | 0 | 0.75 | 7.0 | 3 | end of ebb stage |
| T016 | 200 | -1.50 m | 0 | 0.50 | 7.0 | 3 | end of ebb stage |
| T017 | 200 | -1.50 m | +1.25 | 0.75 | 5.5 | 3 | flood |
| T018 | 200 | -1.50 m | +1.25 | 0.75 | 7.0 | 3 | flood |
| T019 | 200 | -1.50 m | +1.25 | 0.50 | 5.5 | 3 | flood |
| T020 | 200 | -1.50 m | +1.25 | 0.50 | 7.0 | 3 | flood |
| T021 | 200 | -1.50 m | +1.25 | 0.50 | 4.0 | 3 | flood |
| T022 | 200 | -1.50 m | +1.25 | 0.50 | 6.3 | 3 | flood |
| T023 | 200 | -1.50 m | +1.25 | 0.75 | 5.5 | 3 | effect pre-tension: no moorings |
| T024 | 200 | -1.50 m | +0.50 | 0.75 | 5.5 | 3 | alternative end of ebb stage |
| T025 | 200 | -1.50 m | -1.25 | 0.75 | 5.5 | 3 | end of ebb stage |
| T026 | 200 | -1.50 m | -1.25 | 0.50 | 5.5 | 3 | end of ebb stage |
| T027 | 50 | +0.55 m | 0 | 0.75 | 5.5 | 3 | emerged situation. ebb |
| T028 | 50 | +0.55 m | 0 | 0.75 | 7.0 | 3 | emerged situation. ebb |
| T029 | 50 | +0.55 m | +1.25 | 0.50 | 5.5 | 3 | emerged situation. flood |
| T030 | 50 | +0.55 m | +1.25 | 0.50 | 7.0 | 3 | emerged situation. flood |

**Test programme**

Prior to the final verification tests a two days of optimization test series were performed. During these tests a first check was performed on the setup. The pre-tension in the mooring lines was varied, and the amount of ballast weight in the caissons (i.e. lifting line loads) was checked. Moreover, the representative caisson elevations to be tested were evaluated. Additionally, calamities were investigated, for instance when the caisson would accidentally be tilted, increasing the cross-sectional area, and subsequently increasing the flow load. Finally, some mitigating measures for reducing the line forces (i.e. adding an additional pontoon to the main pontoon) were investigated. This led to the final setup to be tested.

Next, 30 different test runs were performed. These tests had a 3 hour (prototype) duration, and different hydraulic conditions and / or caisson elevation The test programme is given in Table 1. Additionally various free decay tests were conducted.

Three caisson elevations that seem crucial in the immersion process were tested. These elevations (of the top of the caisson) were SWL -10.5 m (caisson nearly completely in the trench), SWL -1.5 m (caisson obstructing majority of the flow), and SWL + 0.55 m (caisson emerged / floating). The elevation where the caisson is emerged, occurs for the longest duration, such that the most violent conditions (flow velocities) could be expected, and the ballast weight is lowest. During the stage when the caisson is just submerged the blockage of the channel is largest. And when the caisson is almost fully placed (just above the trench bottom), the caisson can hardly move due to the increased added mass and damping in consequence of the restricted inflow of water to and from the space under the caisson.

Combinations of wave heights of $H_{m0}$ = 0.5 and $H_{m0}$ = 0.75 m, wave periods of $T_p$ = 5.5 s and $T_p$ = 7 s were tested for flow velocities of U = 1.25 m/s (flood) U = 0 m/s (slack) and U = -1.25 m/s (ebb). These were mostly tested for the two submerged caisson elevations, and a limited set of conditions was tested for the emerged case. The caisson ballast was such that the lifting line load was 2000 kN per lifting point for the submerged cased, and 500 kN for the emerged case.

A single and constant water depth (SWL = Venice datum LMM, depth above rock bed = 11.35 m) was applied. All wave tests were conducted with a standard JONSWAP spectrum at the wavemaker.

## ANALYSIS OF RESULTS

Characteristic maximum values were determined for the pontoon motions and line forces. These forces are defined here as the forces that have a probability of 2.5% to be exceeded during a 3 hour period (i.e. the maximum force will be lower in 25 cases of 1000 realizations of 3 hour periods with these conditions). The peaks-over-threshold method was used to this end. A Generalized Pareto Distribution was fitted to the measured extreme values, and the 2.5% one-sided confidence value at an average return interval of 3 hours is determined using a bootstrapping method. See e.g. Van Os et al. (2012) for details on the applied POT method. This 2.5% exceedance value for the 3-hour maximum value is indicated by the top horizontal line of the vertical “error” bars (actually confidence bands) in the exceedance plots in Figures 7 and 11.

## MOVEMENTS

The natural frequencies of the main modes of movement were determined by giving the pontoon a free oscillation in a still basin (free decay test), and determining the significant peak with the highest frequency in the spectrum of the particular mode of movement. For the lowest caisson position, most modes of movement have rather large natural periods outside the range of interest (periods corresponding to the wave forcing, i.e. $T_p$ < 7 s), but for the higher caisson position, the natural periods become smaller, and come within the range of interest. For submerged conditions the roll motion (along the axis perpendicular with the channel) is determined by the large mass of the caisson, and the small water plane area of the pontoon, leading to very large natural periods of about 50 seconds. When the caisson becomes emerged, the roll period becomes much shorter (about 10 seconds), be it still outside the range of interest. The roll period of the pontoon alone (i.e. not fixed to the caisson) is about 5.3 s. The typical frequencies for roll and yaw can also be seen in the example spectrum of pontoon rotations in the right panel of Figure 7.

Yaw, sway, and surge motions are dominant, i.e. the motions of the pontoon in the horizontal plane, that are not influenced by the caisson. As expected, the wave period also turned out to have a large influence on the behaviour of the pontoon and caisson, see Figure 9.

During flood the same wave conditions (in terms of absolute wave period) were more detrimental for the motions and forces than during ebb. However, it turned out that during flood, the occurring wave heights are also smaller. This can be explained by the Doppler effect of the flow velocities in the tidal inlet on the wave height of the waves entering the inlet.

No collisions of the caisson with the bed, trench, or first caisson were observed by the underwater video or accelerometers. Also the pontoon was not seen to hit the caisson when the caisson was emerged, even in cases where the sway and yaw motion were relatively large.

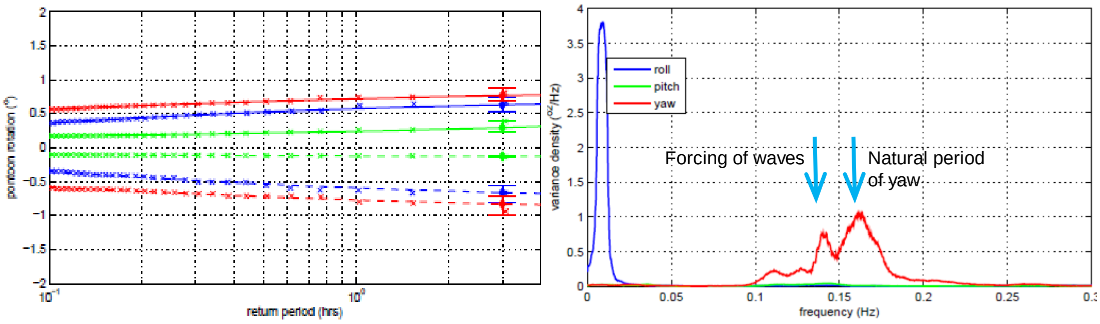


**Figure 7. Measured pontoon rotations. Left: exceedance curves, right: spectra. Test 8 ($H_{m0}$ = 0.50 m, $T_p$ = 7 s, U = +1.25 m/s, caisson elevation = SWL-10.5 m).**

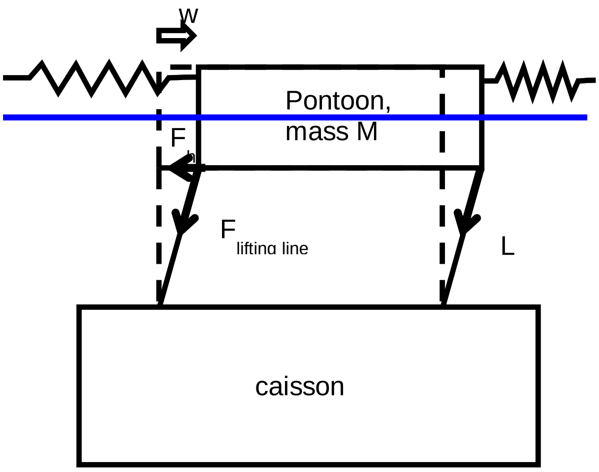


**Figure 8. Schematized mechanical model for estimation of natural frequency of sway motion.**

Loose floating bodies do not have a natural period for the sway motion, as there are no restoring forces. Due to the mooring cables and lifting lines the pontoon can have a vibrating motion in the sway direction. If the (wave) forcing has a similar frequency, resonance could occur, leading to large movements and forces. The natural (angular) frequency, $\omega_0 = 2\pi f_0$, can be estimated with the simple mechanical model in Figure 8, using the following formula:

$$\omega_0 = \sqrt{\frac{M}{k}} = \sqrt{\frac{M}{\frac{4F_{\text{liftingline}}}{L} + 4k_{\text{mooringline}}}}\,, \qquad (1)$$

where M is the mass of the pontoon (plus an added mass which assumed equal to $d^2W$, where d is the draft of the pontoon and W the width of 60 m), $F_{\text{liftingline}}$ the vertical force on each of the lifting lines, L the length of the lifting lines, and $k_{\text{mooringline}}$ the spring stiffness of each of the 4 mooring lines.

| Table 1. Period of free oscillation of sway motion (s). | | | |
|---|---|---|---|
| Caisson elevation | Mooring lines | Calculated $T_n$ | Measured $T_n$ |
| SWL-1.5 m | absent | 7.8 | 6 to 8 |
| SWL-1.5 m | present | 5.6 | 6.5 |
| SWL-10.5 m | absent | 11.8 | 8.6 |
| SWL-10.5 m | present | 6.7 | 6.3 |

The formula gives a reasonable first estimate of the natural period, which is also difficult to measure due to the relatively large damping in the system. When the calculated natural periods are compared to the periods measured in the decay tests, it seems that the right order of natural frequency can be estimated, see Table 1. Also the influence of the presence of mooring lines and length of the lifting lines seems to be predicted qualitatively. In the trends in Figure 9 it can be seen that for a test with wave conditions around the natural sway frequency ($f_0$ = 1 / 6.5 Hz) some resonance seems to occur, as it does not follow the upward trend with wave period. The sway motion for this wave period is comparable to that for the test with $T_p$ = 7 s.

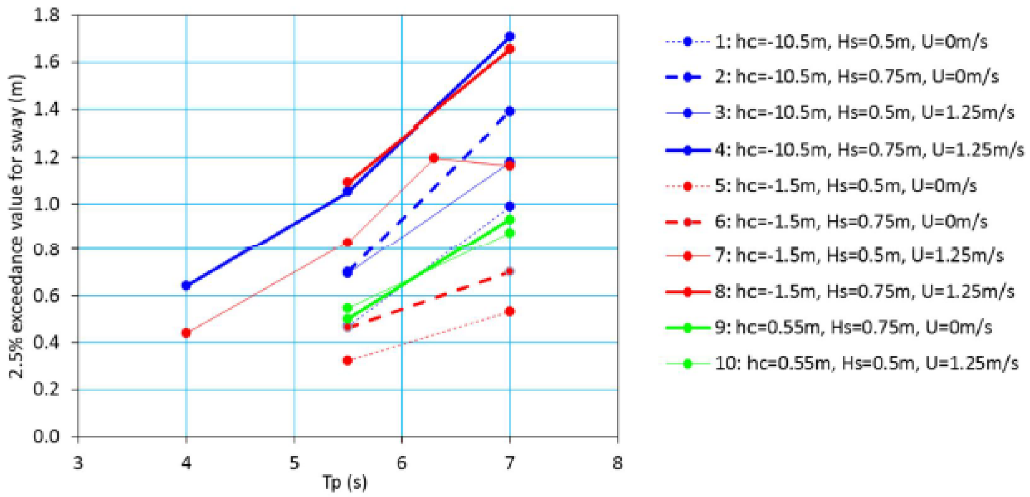


**Figure 9. Measured extreme 2.5% exceedance absolute sway motions.**

## LINE LOADS

In Figure 10 an example is given of the spectra and exceedance curves for all line forces for a single test, Test 12. It can be seen that the measured motions are also reflected in the spectra of the force measurements. This can be seen for instance, in the top left spectrum where the force spectrum of the lifting lines is depicted. The largest peak in the spectrum is related to the forcing of the waves (f = $1/T_p$ = 0.18 Hz). The second largest peak corresponds to the natural frequency of the sway motion (at this caisson elevation, and with moorings attached. There is some energy present in the lower frequencies, with several peaks. Here the peak with a period (f = 0.025 Hz) can be attributed to the roll motion of the caisson.

For the mooring line forces (bottom right spectrum), the largest forces can also occur at the frequencies corresponding to the sway motion.

### Lifting line loads

In Figure 11 representative 2.5% exceedance maximum values for the lifting line loads are presented. The maximum value of the four separate lines is presented. The caisson elevation has a large influence on these forces. It can be seen that the largest force fluctuations occur for the highest submerged caisson elevation (SWL-1.5 m). The loads increase in general with flow velocity, wave height, and wave period.

The maximum value for the lifting line force on which the initial design of the immersion setup was based was around 5000 kN per line. This is exceeded under conditions with large wave height ($H_{m0}$ = 0.75 m), during flood. Also slack cables (forces are zero) can occur under these conditions, for all caisson elevations. Slack cables can potentially yield large dynamic forces, and were not allowed.

A closer inspection of the occurring conditions at the site showed that due to the current effects on waves, the combination of large waves and flood current has a very low chance of occurring during the placement. Therefore the allowed wave conditions during flood were altered.

For the highest, floating, caisson elevation, the mean lifting line load that was used in the tests was 500 kN, instead of 2000 kN, such that a relatively small load fluctuation already caused slack cables (i.e. minimum force is zero). Based on the test results, the lifting line load could be increased during the floating stage.

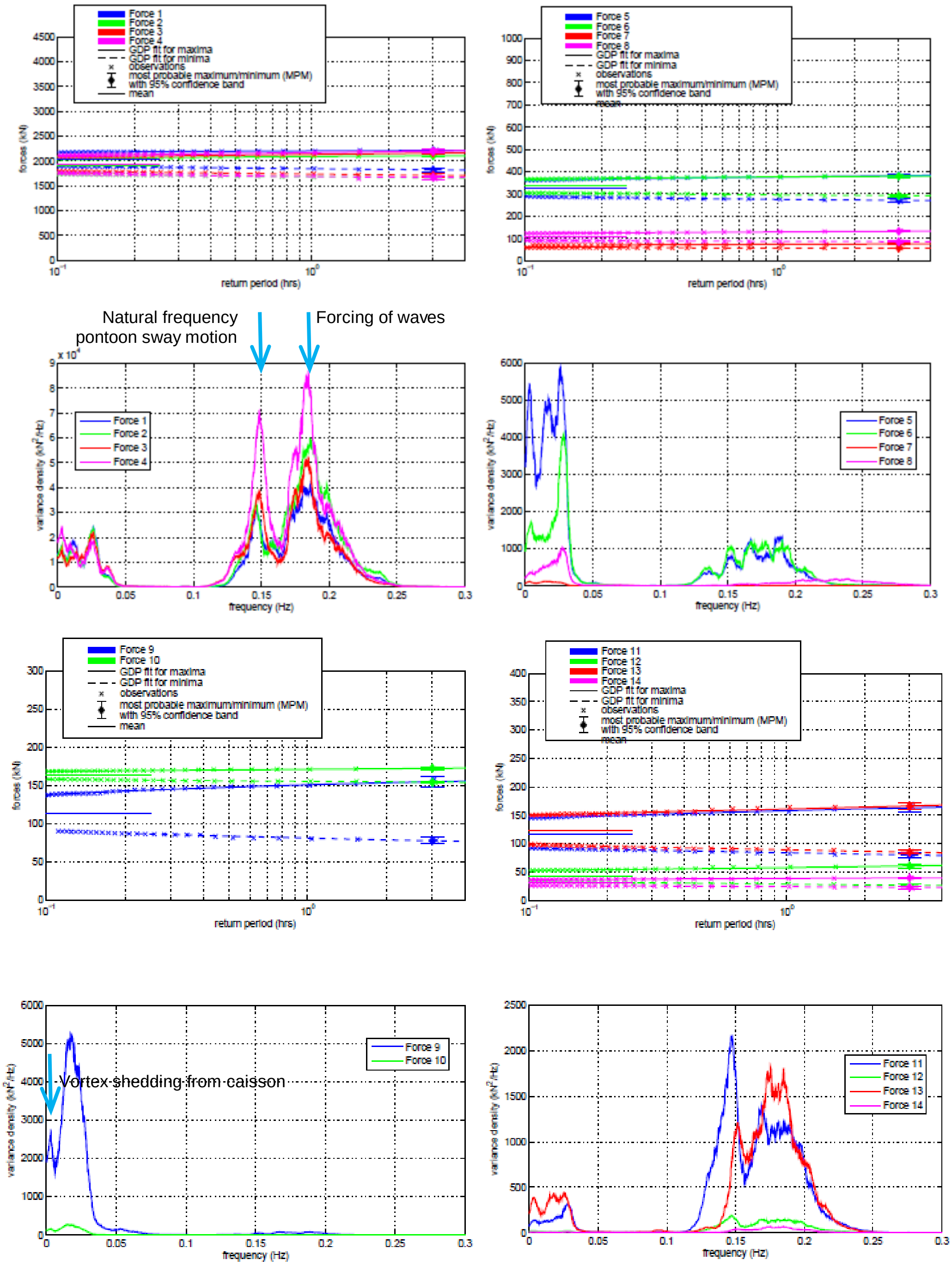


**Figure 10. Exceedance curves and spectra for line loads during Test 12 ($H_{m0}$ = 0.50 m, $T_p$ = 5.5 s, U = -1.25 m/s, caisson elevation = SWL-10.5 m). For lifting lines (top left), contraction lines (top right), longitudinals (bottom left), and mooring lines (bottom right).**

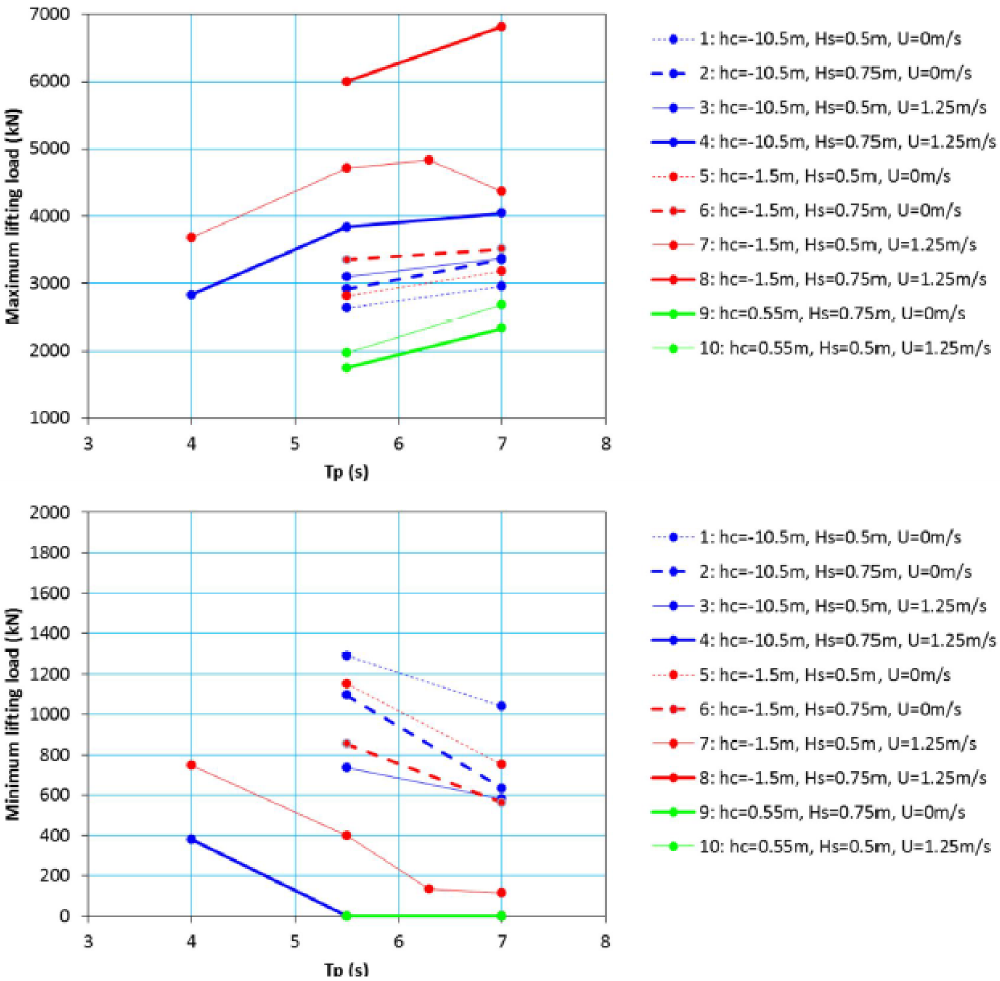


**Figure 11. Measured 2.5% extreme forces on the lifting lines as a function of wave period. Separate plots for maximum (top) and minimum (bottom) forces.**

## Contraction line loads

The contraction loads are mainly caused by the drag force that is exerted by the flow on the caisson. In Figure 12 the loads are therefore given as a function of bulk mean velocity U. A quadratic fit, as would be expected seems to apply. The trend lines do not go through zero, as there are also wave forces acting of the contractions. It seems that for the highest caisson elevations measured, the wave related forces are about 300-400 kN per line, and an extra force of roughly 450 $U^2$ (with [U] = m/s) is added by the drag forces due to the flow.

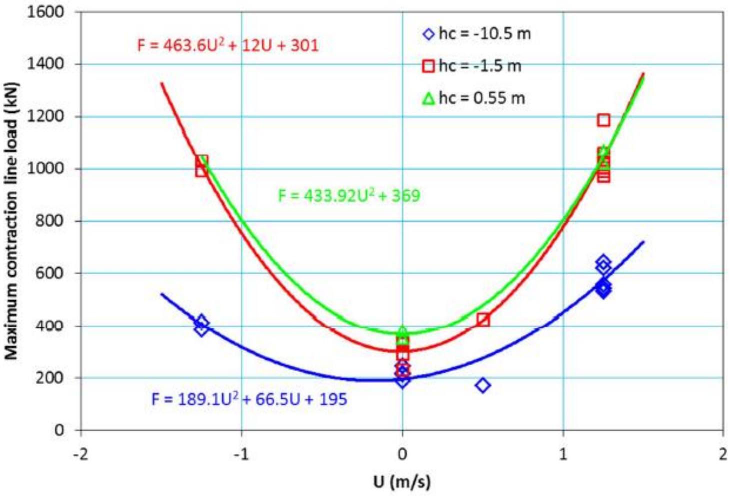


**Figure 12. Measured 2.5% maximum forces on the contraction lines as a function of flow velocity.**

## Mooring line loads

In Figure 14 the representative 2.5% maximum forces on the mooring lines are presented. The forces in the moorings depend mainly on the wave conditions. They increase with both $H_s$ (=$H_{m0}$) and $T_p$, see Figure 13. The extreme force that was measured occurs for a caisson elevation of SWL-1.5 m during flood and is nearly 600 kN. This is again the condition with large wave height during flood which has a low probability of occurrence.

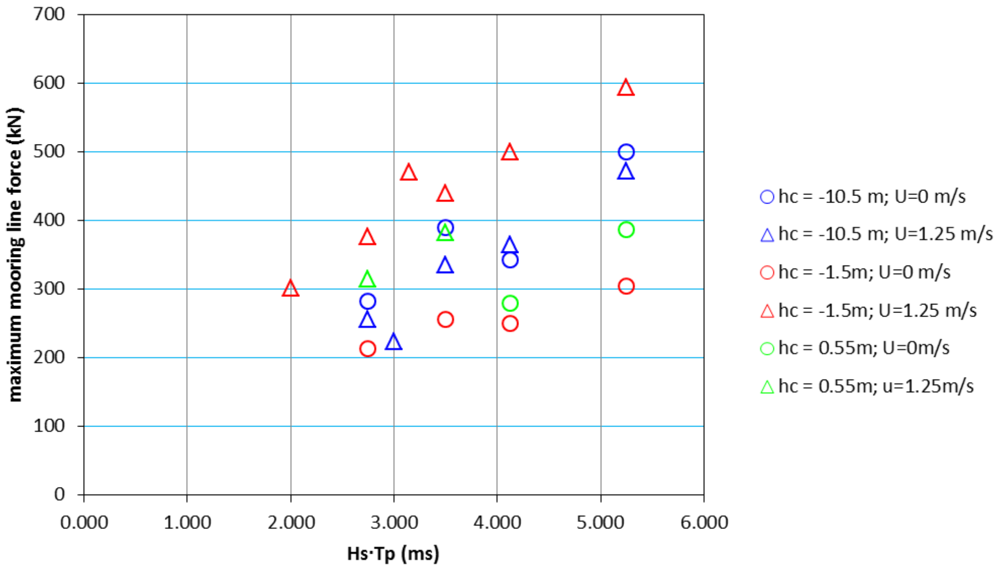


**Figure 13. Measured 2.5% maximum forces on the mooring lines as a function of wave parameter $H_sT_p$.**

## Longitudinal line loads

The largest forces on the longitudinals were measured at a caisson elevation of SWL -1.5 m. At this elevation the obstruction of the flow and waves is largest. No large force fluctuations at typical Strouhal numbers for Von Karman alternating vortex shedding from the sides of the caisson was measured. Typical Strouhal numbers of roughly St = $f_0$ L / U = 0.13 (L is length of caisson, perpendicular to the flow, $f_0$ the vortex shedding frequency) are reported for forces on for blunt bodies (Deltares, 1994). This yields a natural period of over 6 minutes. Some force fluctuation peaks around these frequencies were observed under high flow conditions, see e.g. Figure 10, but these has a limited influence.

**EXPERIENCE DURING PLACEMENT**

Actual caisson placement was started beginning of June, and on 27 August the placement of the last caisson was finished, see Figure 14. In general the wave conditions were low compared to the storm conditions that were tested. The following experiences were noted by the engineers at the site:

- During the floating situation of the caisson waves were encountered with maximum wave heights of about $H_s$ = 0.5 to 0.6 m, with a peak period of about $T_p$ = 3 to 4 s. These waves with small period did not have a large influence on the immersion operation, as predicted by the model tests.
- Measured maximum flow velocities during the operation (measured at 1 m depth) of ca. 1.2 m/s were encountered. Considerable forces were measured in the contractions (approx. 600-700 kN per line) but due to absence of waves no large peak forces were encountered. These forces are smaller than the extreme forces that are presented in Figure 12, which represent conditions with relatively large waves. It does correspond to the measured forces at these flow velocities minus the measured wave forces at zero velocity.
- The general behaviour of the forces was the same as in the model tests.
- The contraction system worked perfectly. The caisson could be positioned within a cm accuracy. The longitudinals had a large influence on the position of the caisson.
- The mooring system constantly had forces around 10 to 15 tonnes, without large fluctuations.
- The forces in the lifting lines were never larger than 2500 kN, due to limited wave action.

The immersion system that was used showed to be very stable. The model tests led to a good insight in the behaviour and operation of the immersion setup. It gave a good start in the detailed design process of the setup, and raised the confidence of the end client in the solution.

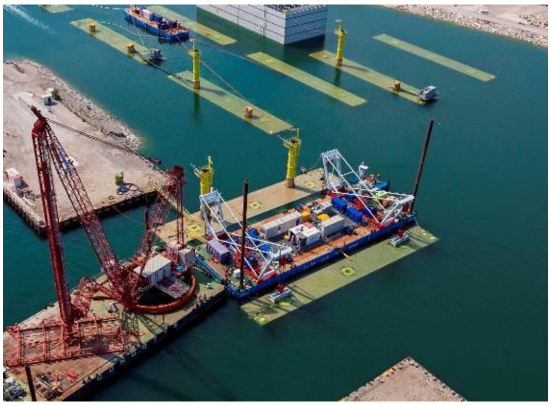


**Figure 14. Left: transport of caisson from building site, right: nearly placed caisson under wave action.**

**CONCLUSIONS**

The behaviour of the complicated immersion setup for the gate caissons in the Chioggia inlet was studied in a physical model. It was observed that the roll motion of the pontoon (and caisson) is very limited and has a low frequency. Yaw, sway, and surge motions are dominant, i.e. the motions of the pontoon in the horizontal plane, that are not influenced by the caisson. As expected, the wave period also turned out to have a large influence on the behaviour of the pontoon and caisson. During flood the same wave conditions (in terms of absolute wave period) were more detrimental for the motions and forces than during ebb. However, it turned out that during flood, the occurring wave heights are also smaller. This can be explained by the Doppler effect of the flow velocities on the wave height.

Based on the test results and analysis of the behaviour of the system, the required strength of various parts of the set-up was determined. The caissons have now been placed in the inlet. The methods applied can also be used for future immersion operations under waves and currents.

**REFERENCES**

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