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ROLE OF PHYSICAL MODELING IN DEVELOPING A NEW CRUISE SHIP TERMINAL AT AN EXPOSED SITE

by

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ABSTRACT

This paper describes the role of physical modelling in the design and development of a new cruise ship terminal at an exposed site on the coast of Barbados, outside the Port of Bridgetown. Large scale 3D hydraulic model studies were conducted to focus on two of the key technical challenges surrounding the project: the risk of downtime due to excessive ship motions forced by the prevailing winds, seas and swells; and the extreme wave loads and overtopping associated with waves generated by large storms. The physical modelling was separated into two phases. The first phase investigated the moored ship response of two different model cruise ship vessels under a range of operational wind and wave conditions. The results of this phase helped determine the range of conditions where the motions of the ships and the associated loads on the portside elements were within acceptable limits, and showed that the expected downtime for the design vessels was satisfactory. The second phase of the study focused on wave-structure interactions, and in particular the impact of extreme waves on the proposed structures, including wave-induced loads on the pier decks, and the wave overtopping and flooding of the landside development. Several innovative measures were developed and tested to accommodate / mitigate the loads on the pier decks as well as reduce the wave overtopping. These physical model studies played a key role in the front end engineering design of the new port, and their results were crucial in assessing various alternatives, optimizing preliminary designs, and validating the layout, costing and construction of the new facility.

1 INTRODUCTION

A joint venture of SMI Infrastructure Solutions and Royal Caribbean Cruise Lines (RCCL) proposed a new cruise ship terminal for an exposed site on the shore of Carlisle Bay, just outside the existing port of Bridgetown, Barbados. The coastal engineering firm Baird & Associates (Baird) were subsequently retained by SMI/RCCL to undertake a Front End Engineering Design study on their behalf. The project, called the Sugar Point Cruise Ship Terminal, encompasses up to three new cruise ship piers/jetties, dredging and land reclamation works, with associated upland improvements that will both attract people to the site as well as support the cruise terminal operations. The proposed terminal, which is being designed to accommodate the largest cruise ships in the world, would alleviate congestion in the existing port (which currently serves both commercial and cruise operations) and would significantly enhance the experience of cruise passengers. The site is exposed to persistent seas generated by the prevailing trade winds, as well as intermittent low-amplitude swells generated by winter storms in the North Atlantic Ocean, and is occasionally exposed to large waves generated by passing hurricanes and tropical storms. The recommended project layout includes three 350m long pile-supported piers with berths for six large cruise ships, 415,000m^3 of dredging, 15 acres of land reclamation and multi-use landside development (see Figure 1). The project will be implemented as a design-bid contract (FIDIC Yellow Book), with construction of Phase I to begin in 2014 and to be operational for the 2016-17 cruise season. The Phase I marine works are estimated at approximately \$120M USD, including dredging, land reclamation, Piers I and III, as well as relocation of a sewer outfall that is within the project footprint.

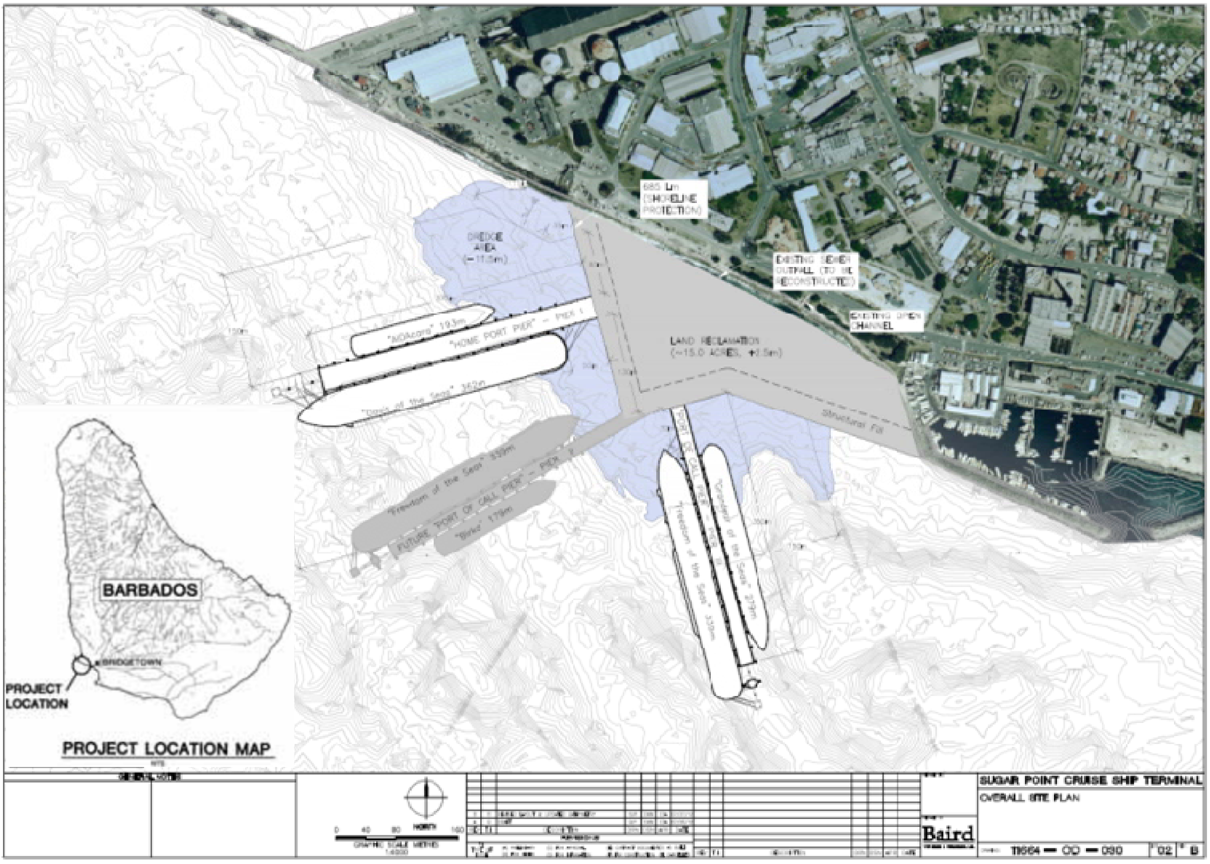


Figure 1: Location and layout plan of the Sugar Point Cruise Ship terminal.

As part of the design process, Baird commissioned the National Research Council of Canada's Ocean, Coastal and River Engineering portfolio (formerly the Canadian Hydraulics Centre) to conduct three-dimensional physical model studies of the proposed cruise ship terminal. The main goals of the studies were to help define the range of wave, wind and water level conditions that would allow for the safe and comfortable berthing operations and mooring of the various cruise ships, and also to help design the port structures to withstand the wave induced loads, pressures, run-up and overtopping flows produced by large storms.

2 PHYSICAL MODELING

A 1:50 scale three-dimensional physical model of the new terminal, complete with the surrounding bathymetry, the existing shoreline, the new land reclamation area, the new dredging and two of the new piers was constructed in a 36m by 30m wave basin at the National Research Council in Ottawa. The model bathymetry was formed in concrete and was based on a combination of high-resolution soundings from the project site and the proposed dredging plan. The bathymetry was faithfully replicated from the -30m contour up to the land's edge. The layout of the model in the testing basin is shown in Figure 2 and Figure 3.

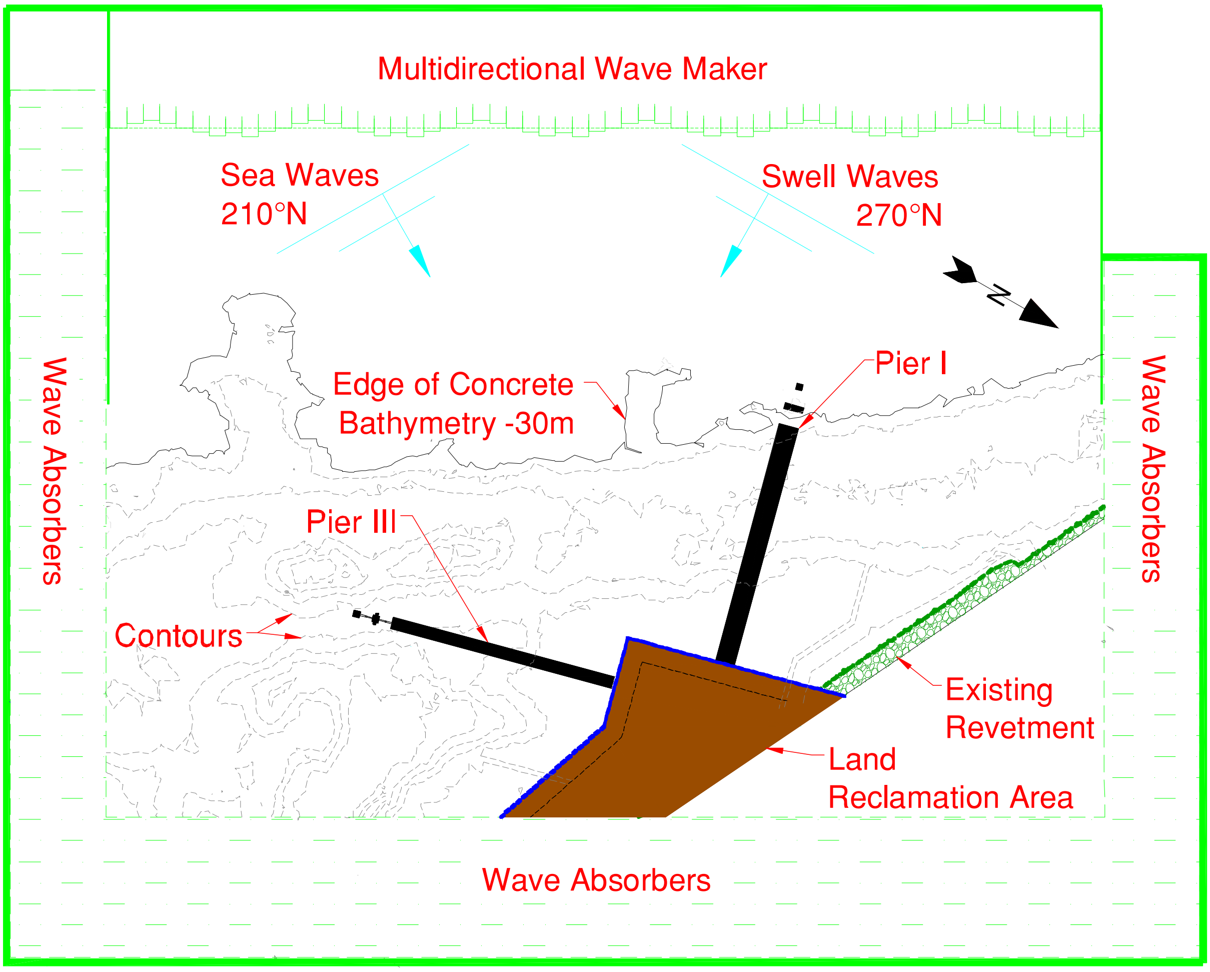


Figure 2: Physical model layout.

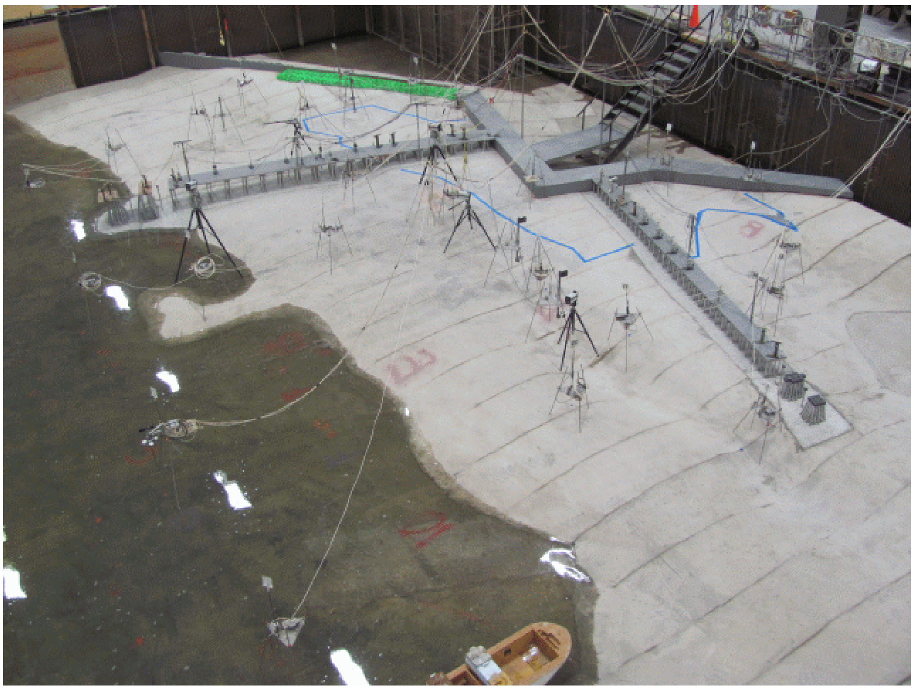
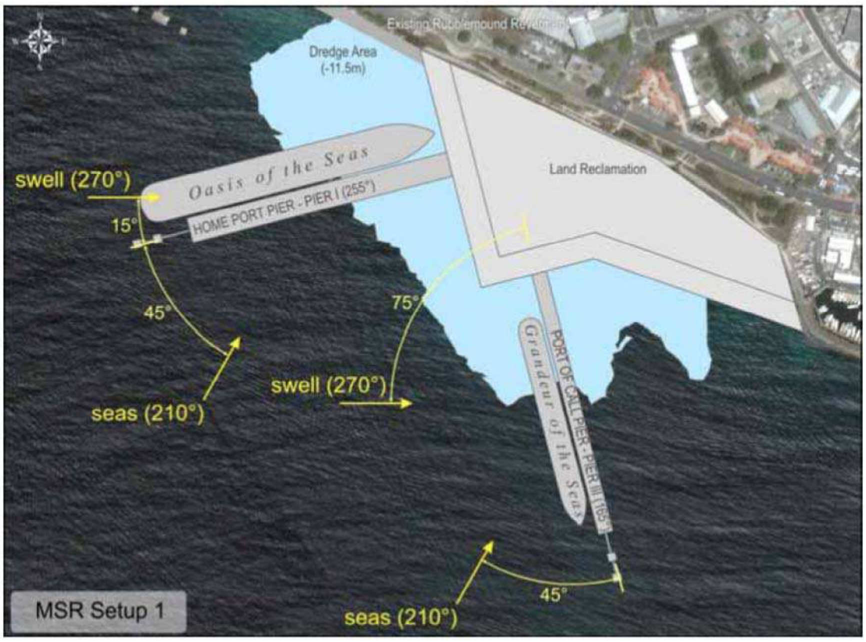


Figure 3: Physical model after bathymetry and port construction.

The operational, storm, and extreme wave climates near the project area were studied and used to develop a set of sea and swell waves representing operational conditions, and another set representing extreme conditions (storm waves). In general, the wave conditions selected for modelling span the 0.1%, 1% and 10% exceedance probability range. At the project planning phase, the physical model design was optimized to provide a balance between using a large model scale (yielding more reliable data) and using a scale small enough to model the entire project site. Among the considerations influencing the model design was the ability of the wave generator to produce short-crested seas over a ~60° range of mean directions. In reality, swells are expected to approach the site from 270°N to 315°N, while operational seas are expected to approach from 160°N to 180°N. Hurricane waves may approach the site from a range of directions between 200°N and 270°N. Unfortunately, the full directional range of seas and swells at the site could not be generated in one physical model arrangement. Since the primary focus of the physical model was the extreme loads associated with hurricanes, and the longer period (westerly) swells were anticipated to be more important to moored ship response than the shorter period (southerly) seas, the wave machine orientation was set to 240°N so that waves approaching from 210°N to 270°N could be modelled. A schematic and table illustrating the set of wave conditions developed for use in the physical model is shown in Figure 4.



H_{m0}	T_p	Wave Direction
(m)	(s)	(°N)
Operational Waves		
Seas		
0.65	9	210
0.8	9	210
1.15	6	210
Swells		
0.2	12	270
0.4	13	270
0.7	14	270
1	14	270
Combined Sea/Swell		
0.8 & 0.4	9 & 13	210 & 270
Storm Waves		
4.5	8	210/240/270
4.5	10	210/240/270
5.5	10	210/240/270
6.5	10	210/240/270
6.5	12	210/240/270
7.5	12	210/240/270

Figure 4: Wave conditions for the Sugar Point physical model study.

2.1 Model Setup and Procedures

2.2 Phase 1 – Modelling and Assessment of Moored Ship Behaviour

The physical modelling study was conducted in two phases. The first phase focused on the operational considerations of the port, including the behaviour of moored cruise ships under operational sea and swell conditions. Two different ships were modelled in this study as representative vessels that would frequent the port. The target ships were selected from RCCL's fleet, and were the 279m long Grandeur of the Seas as well as their flagship vessel, the 360m long Oasis of the Seas. Models of both ships were designed and fabricated at NRC, and were ballasted to replicate the mass properties and the dynamic characteristics of the prototype vessels. The Grandeur was ballasted to replicate a displacement of 36,000 tonnes and draft of 7.8m, while the Oasis was ballasted to 105,500 tonnes and 9.2m draft.

The port structures in the physical model were designed and constructed to closely replicate the preliminary prototype designs. All model structures were laid out with precision on the model bathymetry, and surveyed into place. A portion of the existing rubblemound revetment and vertical wall along the shoreline north of the new port site was replicated in the model, although the armour stone was slightly oversized to withstand the larger hurricane waves in the second phase of the model testing. Although the upland design details were largely undefined when this study was undertaken, the main features of the land reclamation area were reproduced in the model. A simple boxed crib structure was built to represent the vertical sea wall at the edge of reclamation. The top elevation of the land reclamation area was originally set to +2.5m CD, although it was later raised to higher elevations and fitted with various design elements to mitigate wave overtopping.

The structure design details simulated in the model are presented in this paragraph; the physical model results were subsequently used to support detailed design development. Pier I, intended to be the home port pier, is 370m long, 30m wide, has a top deck elevation of +2.9m CD, and is supported by double pile bents capped with a 6.5m wide by 1m thick pile cap. The double pile bents have two rows of seven 1.2m diameter steel piles, and are spaced at 20m intervals along the pier. Two smaller mooring dolphins supported on battered piles are located beyond the outer end of the pier. The pier and dolphin structures were fabricated in the model using aluminum tubing piles, and a combination of PVC and timber for the pile caps and pier decking. The decking was rigidly connected to the pile caps and piles, and a cement mortar was used to replicate the seabed below the pier. Pier III was designed and modelled in a similar fashion, with the main differences being that the pier deck was 350m long by 18m wide, and that the substructure comprised single rows of five 1.2m diameter piles spaced at 10m intervals. Two mooring dolphins supported on battered piles were also modelled beyond the outer end of Pier III.

The mooring line and fender simulators used in the model to replicate the behaviour of the prototype mooring lines and fenders were installed on each model pier to match initial mooring layout designs. Photographs of the two model piers during preparations for the operational testing are shown in Figure 5. The mooring simulators were each configured to simulate the non-linear load-elongation behaviour of one or more prototype mooring lines. Mooring line tensions are recorded using shear beam load cells, and pre-tensions are applied using counter weights. The fender simulators were configured to simulate the non-linear load-deflection response of one or more prototype fenders, including the fender buckling at high loads. Shear beam load cells were used to measure the loading on each model fender.

Figure 5: Photographs of Pier I (left) and Pier III (right) in the physical model during preparations for the moored ship response phase.

The reactions at each fender and the tension loads in all mooring lines were measured continuously during the study and compared with safe working limits. Tests were conducted with both vessels moored at their berths simultaneously, the Oasis at Pier I and the Grandeur at Pier III. Additional tests were performed with the Grandeur moored at Pier I and the Oasis removed from the physical model.

The 6-axis motions of the vessels were measured using two high-precision motion tracking systems manufactured by Qualysis Inc. The Qualysis cameras use infra-red light reflections from reflective markers fixed to the model ships to determine the position and orientation of the vessels in real time with very high precision. The ship motions were compared against thresholds for passenger comfort and safety.

The effect of a steady wind blowing the vessels, either directly on or directly off their berths, was simulated in the model as a steady horizontal force. For each ship, the wind force was applied through a horizontal string that was attached at the center of windage. The steady force was generated by running the string through a pair of low friction pulleys and suspending a weight from the other end of the string.

A segmented directional wave machine was used to generate short-crested waves matching the operational sea and swell wave conditions in Figure 4. Seas and swells approaching from different directions were simulated together in some cases. Twenty-four capacitance wave probes were positioned throughout the model to measure the wave agitation levels in locations of interest. A summary of the test conditions and model setup for the different moored ship test series is shown in Table 1, while Figure 6 shows the Oasis of the Seas moored at Pier I.

Test Series	Wave Directions	Pier I - North		Pier III - West	
	(°N)	Vessel	Wind	Vessel	Wind
Cal	210, 240, 270	N/A	N/A	N/A	N/A
A	210, 270	Oasis	Off Berth	Grandeur	Off Berth
B	210, 270	Oasis	None	Grandeur	None
C	210, 270	Oasis	On Berth	Grandeur	On Berth
D	210, 270	Oasis	Off Berth	Grandeur	None
E	210, 270	Oasis	None	Grandeur	None
F	210, 270	Grandeur	None	None	None

Table 1. Summary of test conditions for the moored ship response phase of the study.

Figure 6: Oasis of the Seas moored at Pier I.

2.3 Phase 2 – Modelling and Assessment of Structure Performance

After the first phase of the study was completed, the setup of the model was changed so that the wave-structure interactions at the port under more intense storms could be investigated (without the vessels in the port). The main change to the model was removing the pier decks, mooring simulators and fender simulators and related instrumentation systems that had been used in the phase 1 study. These were replaced with pier decks that provided a more detailed simulation of the conceptual designs and which included instrumentation to measure wave uplift pressures and forces. Also, revised designs for the land reclamation area, including scour protection at the foot of the vertical wall around the perimeter of the reclamation area, as well as various rock and concrete armour unit revetments, were simulated and studied in the structure performance assessment phase of the study.

One of the primary concerns facing the design team was designing for, and if possible, mitigating the uplift forces and pressures on the pier decks and their support elements. This concern was exacerbated by the unfavourable subsurface conditions beneath the piers; specifically, the presence of calcareous sediments limits the tensile (uplift) capacity of conventional driven piles. As such, the wave uplift loads were the controlling factor with respect to pier design. The deck of both model piers was initially constructed to represent solid concrete decking; however, in order to mitigate the wave uplift forces, Pier I was also modelled with the central portion of the deck comprised of an open grating. The overall ratio of solid to open decking in this case was approximately 50%.

Selected portions of both model pier decks were designed so they could be fitted with instrumentation to measure either the wave forces acting on a complete deck panel (including the pile cap), or the local wave pressures on specific deck elements. Specially designed deck panels fitted with pressure and force sensors were installed in these locations. As shown in Figure 7, the locations where the instrumented deck panels could be installed were concentrated at the nearshore end, the offshore end, and in the middle of each pier. In each location, the model was designed so that a single pressure panel could be installed between a pair of force panels (see Figure 8). The set of three instrumented deck panels were sometimes moved to new locations as a set between different test series. Dummy deck panels without instrumentation were inserted whenever the instrumented panels were removed. Information on the wave induced pressures and loads acting on the inner, outer and central portions of both pier decks was obtained in this way.

The pressure panels were rigidly connected to the pile caps and each fitted with several pressure sensors facing both down and up. The force panels were free floating elements (they did not touch the piles or pile caps) and were each suspended from a 6-axis load cell located above the centre of the force panel. Each load cell was mounted to a rigid beam supported on adjacent pile caps by threaded rods.

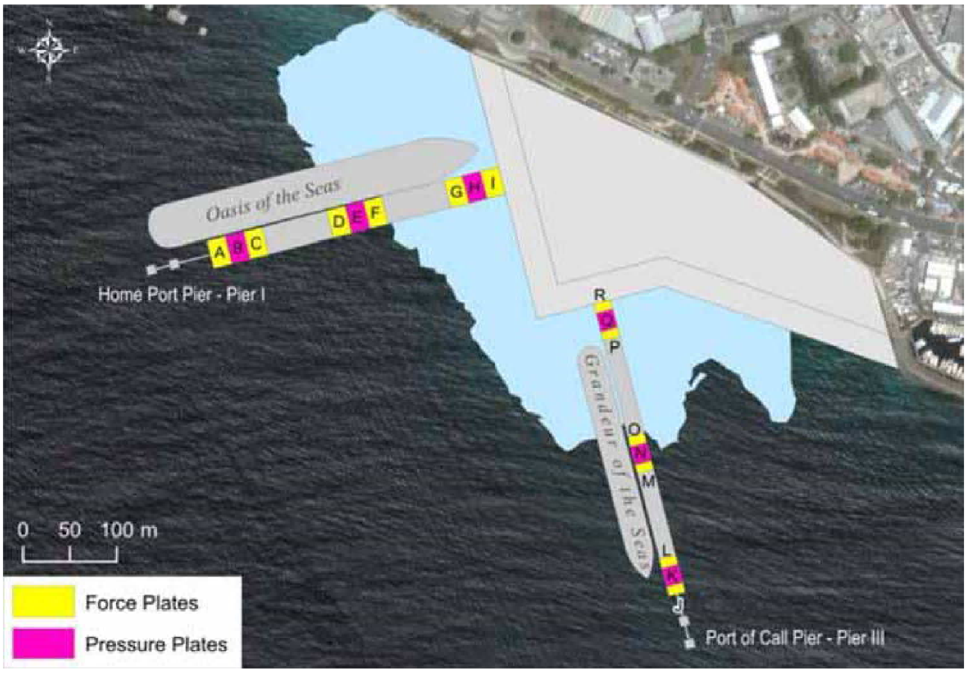


Figure 7: Location of force panels and pressure panels in the physical model.

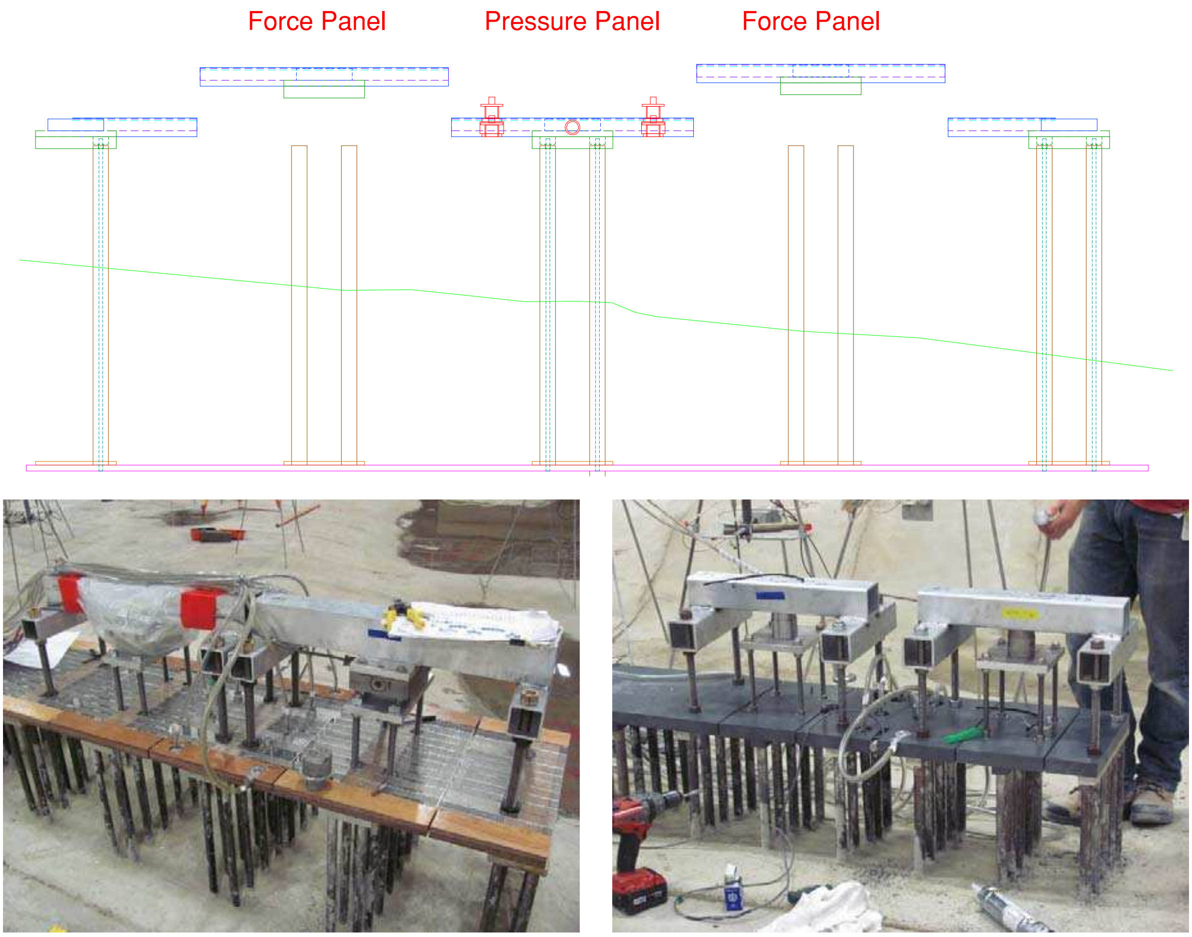


Figure 8: Conceptual design of the force and pressure panels (top) and installation of the panels in the physical model (bottom).

The seaward perimeter of the land reclamation area was modelled as a simple box caisson like structure with vertical walls and a 30m wide (flat) land elevation at +2.5m CD to simulate the proposed 'hardscape promenade' around the perimeter of the land reclamation area. During the Phase 2 tests, wave overtopping rates onto the promenade area were measured at two locations (see Figure 9). The wave overtopping measurement system consisted of a collection tray set at a certain elevation, conveying the overtopping flows into a reservoir fitted with a water level sensor. After the initial tests, the elevation of the promenade area was raised to +3.15 CD. In addition, several modifications were made during the testing program to reduce wave overtopping onto/beyond the promenade, including: raising the elevation of the collection tray (to ascertain the overtopping flows at various elevations); adding a flood wall set back 20m or 30m inland from the seaward edge of the promenade (to various elevations); and installing a 0.5m high sea wall along the seaward edge of the promenade. The sea wall was constructed in 10m sections with 1m gaps to allow water to drain back to the sea. The effects of a building a 3:1 sloping berm in front of the flood wall (to simulate a landscaped berm) were also investigated.

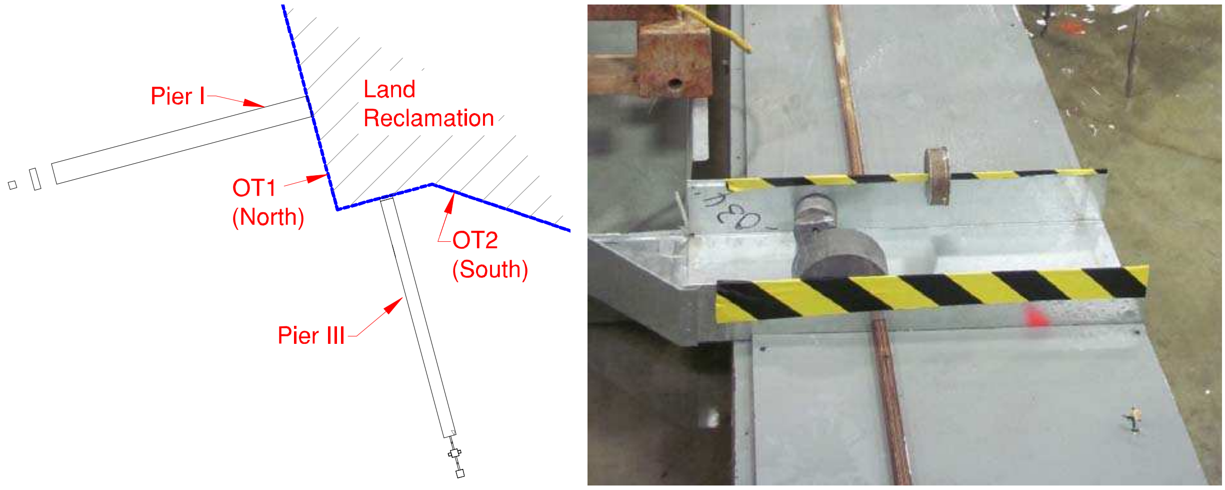


Figure 9: Wave overtopping at the land reclamation area – measurement locations (left) and photograph of the catchment tray.

The seaward perimeter of the land reclamation area was fronted with several types of protective structures. Initially, the vertical wall was protected with different designs of low profile scour protection mats using armour stones varying in size from 0.5 tonnes to 4 tonnes. The stability and performance of three different revetments fronting the land reclamation area was also investigated. The revetment's ability to reduce wave overtopping and the uplift forces on the adjacent pier decks was studied, as well as the performance of the revetment armour layers to withstand wave attack. Initially, a rock revetment with 5-10t armour stone was investigated at two different crest elevations: +2m and +3m CD. The second type of revetment used Core-Loc® units that represented ~5.2m^3 units at full scale. The third revetment design assessed in the model was a "hybrid" design featuring a vertical wall fronted by a low-crested rock berm with armour stone sloping down at 1:3 from -5m CD to the dredge elevation of -11 m CD. This hybrid design featured a triangular plan form configuration at the landward end of the piers that was intended to reflect wave energy away from the piers and potentially lower the wave induced loads on the pier deck. Several different sizes of armour stone were investigated for the hybrid design. The three different model revetments are shown in Figure 10.

The loading and response of the port structures in extreme conditions was assessed using short-crested realizations of the storm wave conditions summarized in Figure 4. The water level was varied from +0m CD (LAT) to +1.7m CD (estimated range in extreme water levels) to understand its effect on the wave loads and overtopping flows. Twenty-two capacitance wave probes were positioned around the basin to measure the wave conditions in key locations.

a) b) c)

Figure 10: Several different revetment designs were modelled and assessed: a) rock armour, b) Core-Loc® armour, c) hybrid low crested rock armour structure with triangular wall at the root of the pier.

2.4 Data Analysis

Due to space limitations, only the analysis and results of the moored ship response phase of the study will be discussed in this paper.

NRC's GEDAP software was used for all analysis procedures. GEDAP is a general-purpose software system for the synthesis, analysis and management of laboratory data that also includes modules for real-time experiment control and data acquisition functions. Standard GEDAP time-domain, frequency-domain and statistical analysis algorithms were applied to analyse in considerable detail the wave conditions measured in the model, as well as the motions of the model vessel and the loads on the mooring lines and fenders. The GEDAP analysis routines included graphical presentations of the model data, and also allowed for the tabular organization of many key model outputs. Sample output graphs showing the two dimensional motions of one of the vessels, and the loads in the mooring lines and fenders, are shown in Figure 11, Figure 12, and Figure 13 respectively.

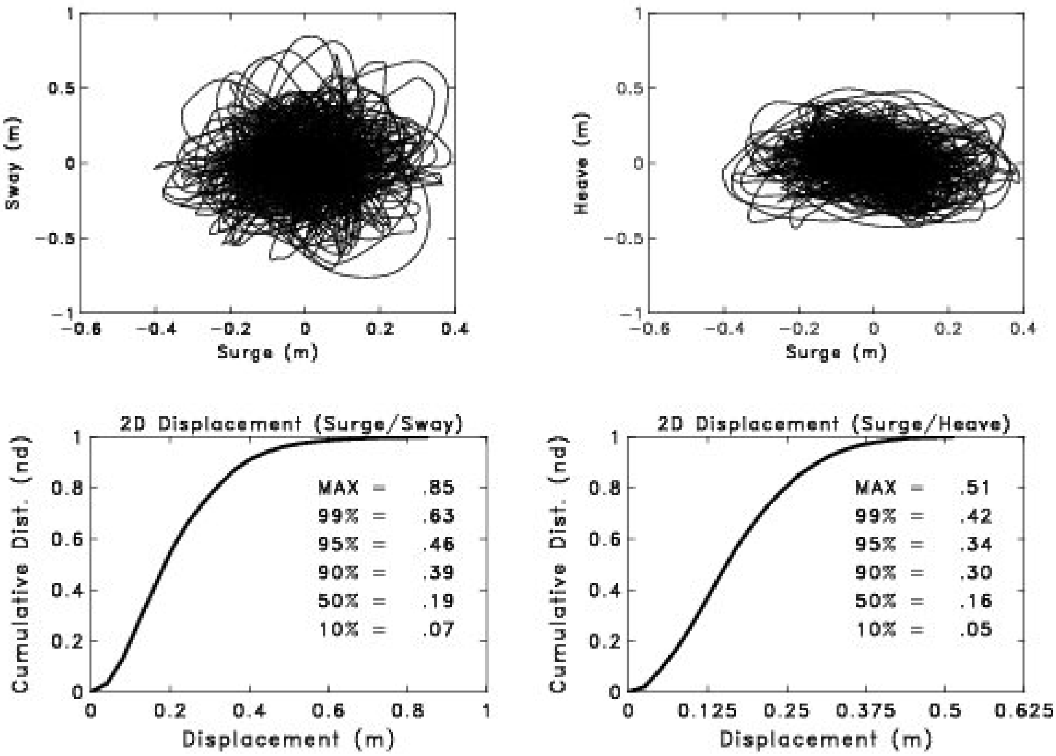


Figure 11: Sample outputs from the GEDAP motion analysis. Top: 2D planar motion track lines, bottom: 2D motion exceedance curves.

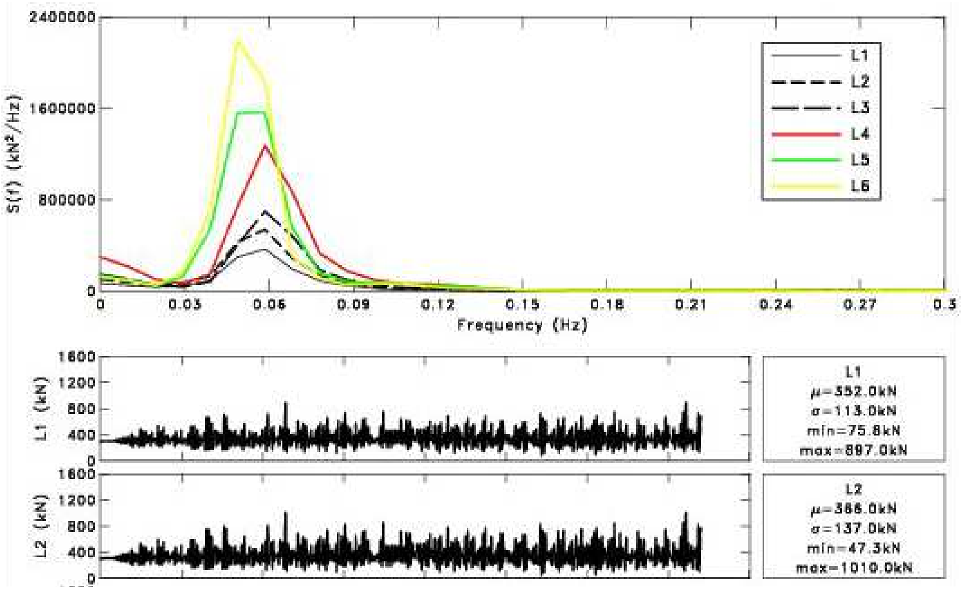


Figure 12: Sample outputs from the GEDAP mooring line load analysis. Top: spectral analysis of the mooring line loads, bottom: time series of two line loads. (Note that each model mooring line represents two prototype lines.)

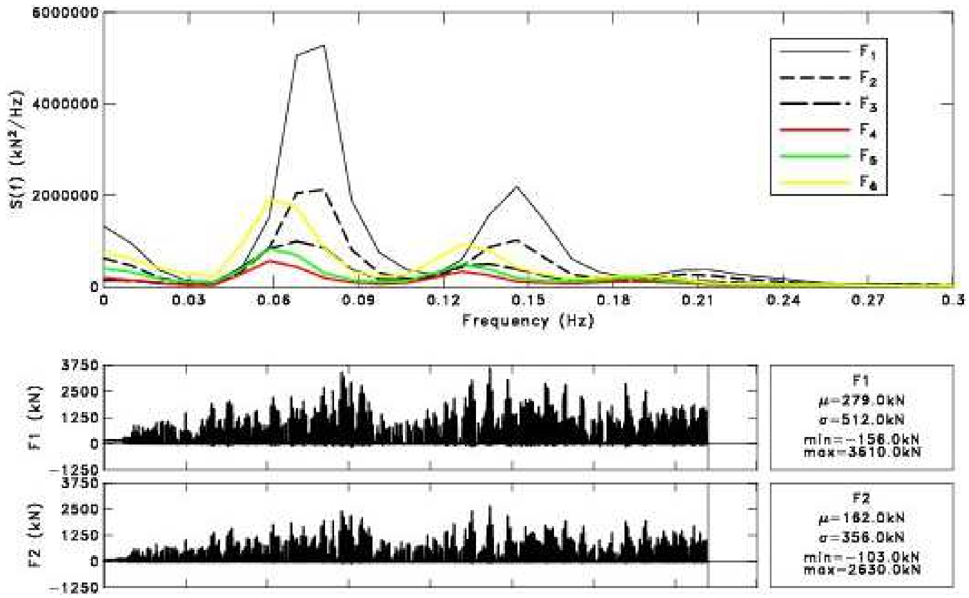


Figure 13: Sample outputs from the GEDAP fender load analysis. Top: spectral analysis of the loads, bottom: time series of the fender loads. Note that each model fender represented 1.5 prototype fenders.

3 RESULTS AND DISCUSSION

Due to space limitations, only results from first phase of the study, in which the behaviour of moored cruise ships was modelled and assessed, are presented and discussed below. The second phase of the study, which focused on the performance of the port structures in extreme waves, will be discussed in a second paper to be presented later this year at ICCE 2014.

A total of 125 different moored ship response tests were conducted. The sensitivity of the motions and mooring/fendering loads of each vessel to different combinations of waves (height, period, direction), wind conditions (off-berth, on-berth, no wind), and vessel locations (Oasis at Pier I, and

Grandeur at Piers I and III) were investigated. The outputs from the physical model were used to develop estimates of berth downtime due to excessive vessel motions or mooring/fendering loads for the proposed new cruise terminal. These estimates confirmed that cruise ships can be safely moored at the new piers in virtually all operational conditions. However, the unprotected berths should not be occupied in storm conditions

3.1 Thresholds for mooring line loads, fender loads and ship motions

While a ship is moored, exceeding the motion, velocity, or acceleration thresholds can lead to uncomfortable or unsafe loading operations, while large motions can result in broken mooring lines or damaged portside fenders. Thresholds and criteria for the moored ship motions, as well as the mooring and fender loads, were developed using various sources. Based on a review of published literature, including PIANC (1995), Nordforsk (1987) and ROM (2011), as well as discussion with Captains from various cruise lines, the vessel motion criteria adopted for the Sugar Point project were as follows: 1.0m maximum peak-to-peak horizontal motion (i.e. surge and sway) at the passenger door; 1.0m maximum peak-to-peak vertical motion (i.e. heave) at the passenger door. Mooring line thresholds were based on the guidance provided by PIANC (1995) and OCIMF (1997), with the threshold adopted for the project limits line loads set to 55% of the guaranteed minimum breaking load. The fender load criteria was set by the manufacturer's rating, whereby the maximum allowable load was set to 95% of the buckling load. A "downtime" condition was assumed whenever any one of these motion or force thresholds was exceeded. The ship motion, mooring line and fender load data were monitored and analysed continuously during testing to assess trends in the results. This analysis not only allowed the researchers to identify test conditions when the allowable criteria were exceeded, but also allowed them to modify the testing program to maximize the value of the model outputs to the project.

3.2 Behaviour of the Oasis of the Seas while moored at Pier I

The behaviour of the 360m long Oasis of the Seas vessel moored at Pier I was assessed in a broad range of wind and wave conditions. The motion data was compared against the motion limits proposed by ROM (2011) for surge, sway and heave, and the PIANC (1995) criteria for roll, pitch and yaw. In general, the swell waves caused higher motions than the sea waves. The surge, sway, heave, pitch and yaw motions of the Oasis were well below the thresholds adopted for this project. Only the roll motions induced by the larger swell waves even approached the threshold criteria, yet the maximum roll limit was not exceeded (see Figure 14). The shorter period, and more southerly, sea waves generally caused higher maximum mooring line loads than the swell waves, with the forward breasting lines often experiencing the largest loads. In general, higher fender loads were experienced towards the rear of the vessel, and longer period waves tended to increase the fender loads. The wind load on the Oasis at pier I had a small effect on the maximum mooring line loads. However, the fender loads were appreciably higher with the wind blowing the Oasis onto the berth, particularly for sea wave conditions. The vessel motions were marginally reduced with the wind blowing the Oasis onto the berth.

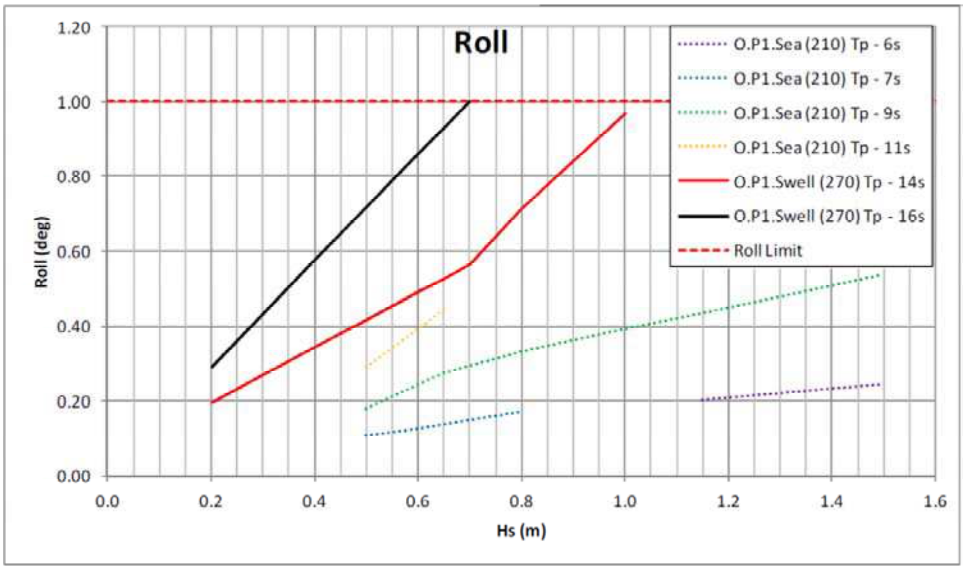


Figure 14: Influence of wave height and wave period on roll motions of the Oasis of the Seas at Pier I.

3.3 Behaviour of the Grandeur of the Seas while moored at Pier I

Following the tests with the Oasis, the smaller Grandeur of the Seas was moored at Pier I, and its behaviour was monitored under a range of wave conditions. No wind loads were applied to the Grandeur. The influences of wave height, period and direction on the motions of the Grandeur moored at Pier I were similar to the trends of the larger Oasis. Again, the swell waves excited larger motions than did the seas; however, for all wave conditions that were tested, the maximum surge, sway, heave, pitch and yaw motions remained below the motion thresholds adopted for this project. However, the roll motions induced by some of the swell wave conditions exceeded the threshold criteria. Comparing the motions, line loads, and fender loads for the Grandeur moored at Pier I with like conditions when this vessel is moored at Pier III (see below) show that Pier I is the more tranquil location. The motions and loads were consistently lower for the Grandeur at Pier I. However, mooring and fender load limits still exceeded the threshold limits, particularly for the larger and longer swells.

3.4 Behaviour of the Grandeur of the Seas while moored at Pier III

The behaviour and performance of the Grandeur of the Seas moored at Pier III was assessed in a wide range of wave and wind conditions. Again, the motion criteria of ROM (2011) were adopted for surge, sway and heave, and the criteria of PIANC (1995) were used for roll, pitch and yaw. Since the Grandeur was oriented more broadside to the incoming waves while berthed at Pier III (refer to Figure 4), the vessel experienced relatively more motion here compared to when it was berthed at Pier I. Also, the period of some of the longer swell waves approached the natural roll period of the vessel, which tended to excite this type of motion, often causing the vessel to approach or exceed the threshold criteria. The longer period swell waves also caused higher maximum mooring line loads and fender loads than the sea waves (see Figure 15) The effects of wind blowing the Grandeur towards Pier III tended to reduce maximum mooring line loads and increase maximum fender loads, but had little effect on the motions of the vessel. With the wind direction reversed, blowing the vessel off the berth, the fender loads were decreased and the mooring line loads were similar to the case with no wind acting on the vessel. When comparing the vessel motions with wind blowing the Grandeur off the berth to those with no wind, the motions were generally higher with the off-berth wind for the sea wave conditions, but lower for the swell waves.

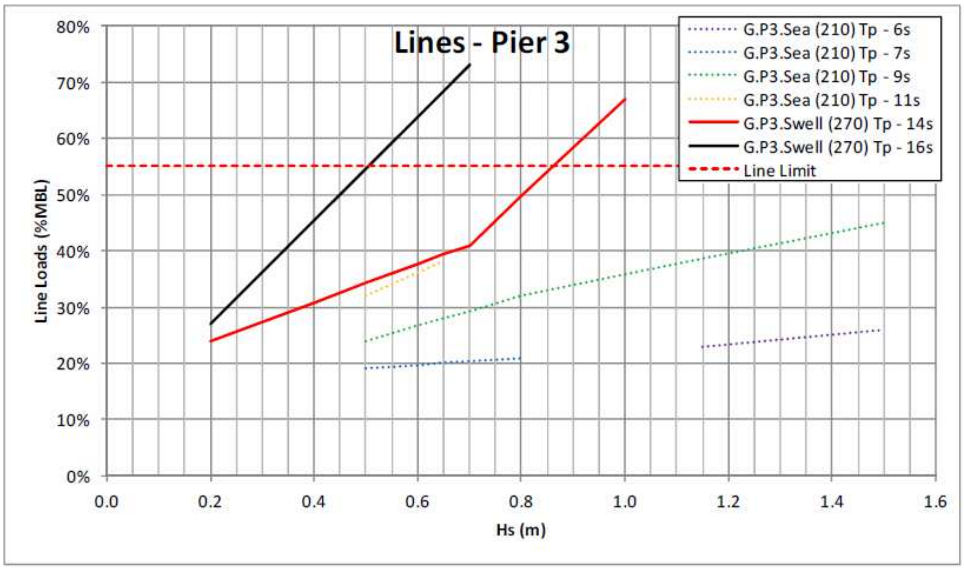


Figure 15: Influence of wave height and wave period maximum mooring line loads for the Grandeur of the Seas at Pier III.

3.5 Numerical modelling of moored ship response

The 1:50 scale physical model proved to be an excellent method for simulating and predicting moored ship behaviour and mooring loads at the new cruise terminal in a range of realistic operational conditions. However, not all operational conditions, nor all ship types and mooring configurations, could be assessed in the physical model. Hence, a numerical model (QUAYSIM) was also developed and used to estimate moored ship response under a broader range of conditions than was considered in the physical model study. The numerical model was first calibrated/validated against the results of the physical model, thereby allowing the results of the numerical model to be used with confidence.

The outputs from the physical model study were used in conjunction with results from the numerical modelling, together with a comprehensive analysis of the metocean conditions at the site, to develop estimates of berth availability or downtime for the new cruise terminal. The numerical model was used to identify distinct events in a given year that had the potential to cause downtime, and provide examples of recent years that could be considered mild, typical or severe in terms of potential downtime (see Figure 16). These estimates confirmed that cruise ships can be safely moored at the new piers in nearly all operational conditions. However, the unprotected berths should not be occupied in storm conditions.

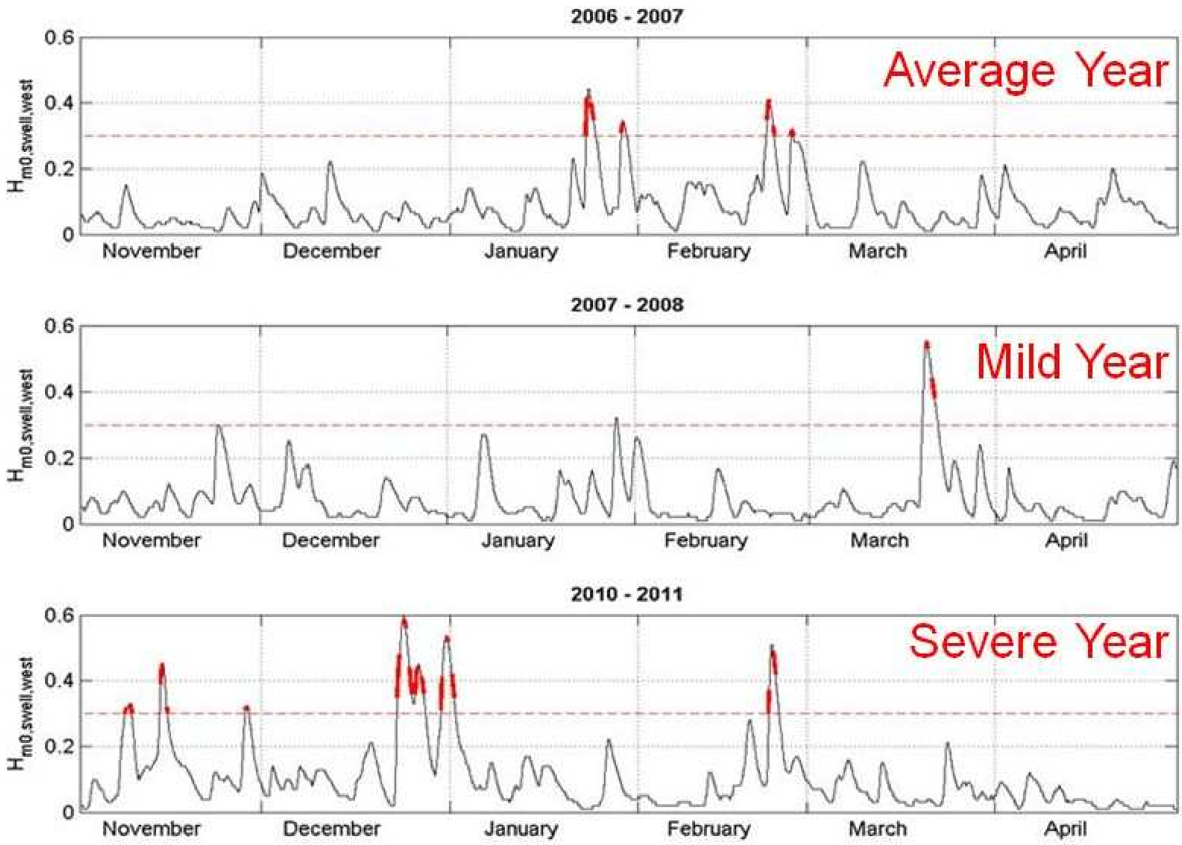


Figure 16: Example plot of downtime analysis.

4 SUMMARY AND CONCLUSIONS

A large new cruise ship terminal is proposed on the open coastline outside the Port of Bridgetown in Barbados. The new facility will (ultimately) include three large pile-supported ship piers with berths for six large cruise ships, dredging, approximately 15 acres of land reclamation, and associated landside development. Two key challenges for the project were: the risk that the prevailing seas and swells would cause excessive moored ship motions and downtime; and designing the new port structures to resist and mitigate the large wave forces and overtopping flows due to large waves generated by passing storms and hurricanes.

Large scale physical hydraulic modelling is an excellent approach for investigating and developing solutions to these types of complex hydrodynamic problems. In a well designed physical model, the complex wave conditions near a project site, and the propagation and transformation of the waves over complex nearshore bathymetries and around port structures, can be simulated with good accuracy. The behaviour and response of moored ships to winds and waves can be faithfully replicated in a physical model. A physical model can also be used to reliably simulate the interaction of extreme waves with port structures and measure the loading on, and response of, these structures with precision. Critical issues such as the wave uplift pressures and forces on pier decks, the stability of various rubble-mound structures, and the performance of overtopping mitigation measures, can be studied and design solutions can be developed and tested. Moreover, as demonstrated in this study, physical modelling is a valuable tool for assessing the performance of alternative layouts and designs, and for optimizing designs to suit site-specific local conditions. Physical modelling represents the state of the art in understanding moored ship response and wave interactions with complex marine structures, and is recognized as the standard of care for large coastal engineering projects.

The results of the moored ship response phase of the study were used to define a range of wind and wave conditions where ship motions, mooring line loads and fender forces were within acceptable limits. Also, the moored ship response data were used to calibrate and validate a numerical model that was then used to develop downtime estimates for the proposed facility under a wider range of conditions. The second phase of the study, which focused on the performance of the port structures in storm conditions, generated a large body of knowledge and data that allowed the design team to advance and improve the port structure designs in several important ways. First, the design of the land reclamation was revised to incorporate several measures to reduced wave overtopping and improve flood protection. Second, a rubble-mound revetment protecting the toe of the land reclamation was tested, optimized and validated. Third, the study was used to establish design loads for two alterative pier deck designs, one with a solid deck slab and the other with large grated openings. These results were used by the design team to develop detailed structural designs for the new pier structures. The physical model studies played a key role in advancing the design of the new port, and their results were crucial in assessing various alternatives, optimizing preliminary designs, and validating the layout, costing and construction of the new facility.

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