SUGAR POINT – A NEW CRUISE SHIP TERMINAL FOR BARBADOS

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In late 2010, Barbados Port Inc. (BPI) selected the Sugar Point team, a joint venture of SMI Infrastructure Solutions and Royal Caribbean Cruise Lines (RCCL), to undertake a Front End Engineering Design (FEED) study for a new cruise ship terminal adjacent to the existing Port of Bridgetown. The proposed new facility has been designed to accommodate the largest cruise ships in the world (RCCL's *Oasis* class), will alleviate congestion in the existing port (which presently serves both cargo and cruise operations) and will significantly improve the arrival experience of cruise passengers. This paper provides an overview of the FEED study, focusing on the technical investigations undertaken to assess the safe navigation, berthing and mooring of large cruise ships, and to define extreme wave loads on the piers. A companion paper (Knox et al., 2014) provides more detailed information on the physical modeling undertaken to support the FEED study.

Keywords: cruise ships, ports, navigation, moored ship response, downtime, physical modeling

PROJECT OVERVIEW

Project Background and Objectives

The Port of Bridgetown (refer to Figure 1) currently serves both cruise and cargo operations, with cargo operations severely constrained during the cruise season (November through April). In late 2010, Barbados Port Inc. (BPI) issued a Request for Proposals (RfP) to finance, design and build a new cruise ship pier (two berths) adjacent to the existing port. The primary objectives of the project envisioned by BPI in the RfP were as follows:

- Ease congestion in the existing port;
- Separate cruise and cargo operations.

Figure 1. Existing Port of Bridgetown (photo courtesy of Foster & Ince)

The Sugar Point team, a joint venture of SMI Infrastructure Solutions Inc. and Royal Caribbean Cruise Lines, submitted a bid for the base project, as well as an alternative bid for an expanded and visionary project concept ("Sugar Point") that included three piers (six berths), the cruise terminal and a multi-use development on newly reclaimed land. The Sugar Point team presented this alternative bid as a visionary concept that would revitalize Bridgetown's waterfront and achieve the following additional objectives:

- Create a world class cruise facility/destination and a significant public amenity for Barbadians;
- Encourage home porting.

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In early 2012, BPI awarded a contract to the Sugar Point team to undertake a Front End Engineering Design (FEED) Study for the expanded project concept. This paper provides an overview of the project concept and a summary of key investigations that were undertaken as part of the FEED study to address significant technical challenges.

Project Description

The project site is located on the southwest coast of Barbados, between the Port of Bridgetown and the Bridgetown Fishing harbour, as shown in Figure 2. The nearshore bathymetry is relatively complex, and includes a number of shoals and channels, with maximum water depths in the order of 30 m. Although the site is located on the lee (sheltered) side of the island, it is an open coast site, with exposure to a range in wave conditions, including southerly seas (year round), westerly swells (winter months) and extreme hurricane conditions (infrequent, but possible).

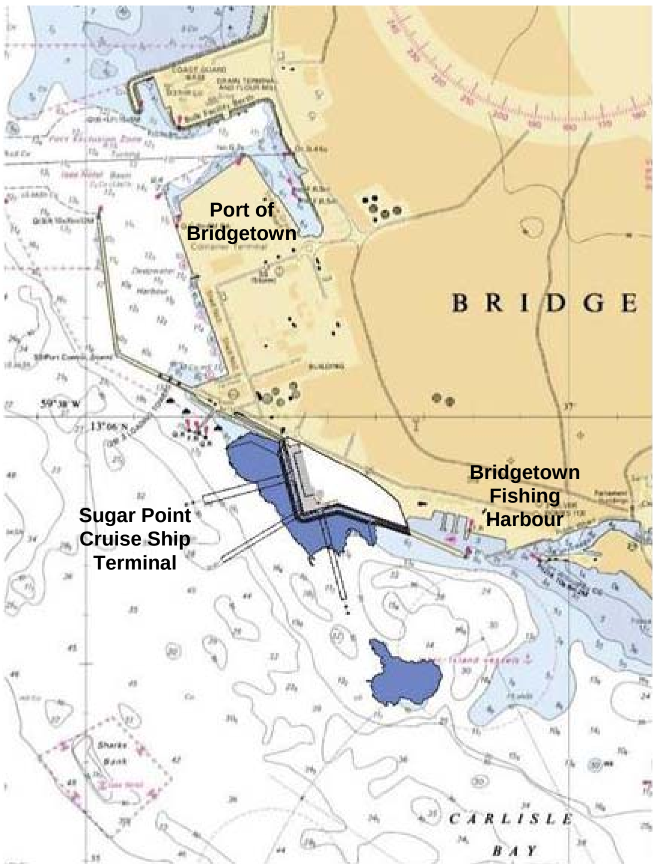


Figure 2. Sugar Point Project Location

The proposed project layout is shown in Figure 3 and represents the outcome of a comprehensive FEED study that considered the project objectives, site conditions, environmental impacts, functional performance and cost. Key elements of the project include the following:

- Three 350 m long pile-supported piers providing berths for six large cruise ships;
- Approximately 415,000 m^3 of dredging;
- Approximately 15 acres of land reclamation;
- Approximately 725 m of armour stone revetment;
- Cruise terminal building and associated infrastructure;
- Multi-use landside development.

The project will be implemented in phases, with the first phase to include two piers, dredging, land reclamation and associated shoreline protection works, and the cruise terminal. Construction of Phase I is expected to start in 2015, with the facility expected to be operational for the 2016-17 cruise season.

Figure 3. Sugar Point Project Layout (image courtesy of LandDesign)

Key Engineering Considerations, Site Challenges and Design Issues

The primary engineering considerations in the development of the project layout included safe navigation, berthing and mooring for the range in vessels that will use the facility, the size of the land reclamation area required to accommodate the proposed landside development, cut/fill balance, environmental impacts and cost. Specific site challenges and design issues included the following:

- Complex bathymetry, with depths up to 40 m;
- Variable subsurface conditions (calcareous sediments with varying degrees of cementation);
- Open coast site exposed to complex wave climate (seas, swells and hurricanes);
- Range in design vessels (LOA up to 362 m, DWT up to 225,000 t);

→ Risk of operational downtime (due to excessive vessel motions);
→ Definition of extreme wave uplift loads;
→ Geotechnical and structural design to resist extreme wave uplift loads.

The following section presents an overview of the FEED study undertaken for this project, focusing on specific technical investigations undertaken during to address the key design issues noted above.

FRONT END ENGINEERING DESIGN STUDY

Study Overview

The overall objective of the FEED study was to develop a recommended project layout and Basis of Design suitable for costing and construction by the nominated design-build contractor, Weeks Marine Inc. The FEED study included the following key activities:

- Definition of existing site conditions (bathymetry, benthic habitat, subsurface conditions, structures and utilities);
- Definition of operational and extreme metocean conditions (winds, waves, water levels and currents);
- Assessment of coastal processes;

- Assessment of conceptual alternatives for project layout, structure types and phasing;
- Environmental impact assessment (EIA) and approvals;
- Navigation simulations;
- Physical and numerical modelling of wave-structure interaction and moored ship response;
- Coordination with landside planning and design team;
- Basis of Design (report, plans and specifications) for marine and civil works.

The following sections provide additional detail on navigation simulations and numerical and physical modelling undertaken to support the development of the recommended project layout and Basis of Design, focussing on the key issues of safe navigation, moored ship response and downtime, extreme wave loads and structural design.

Navigation Simulations

Navigation simulations for the Sugar Point project were undertaken using a 360^o full mission bridge simulator at the STAR Center in Fort Lauderdale, Florida (refer to Figure 4). The primary objectives of these simulations were to confirm the project layout, in particular the pier spacing and navigation aids, and to define limits for safe berthing.

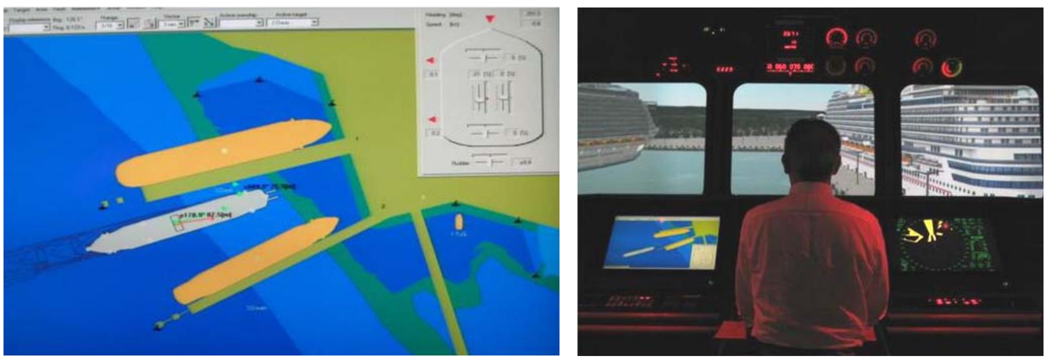


Figure 4. Sugar Point Navigation Simulations at the STAR Center

A total of seven days of simulations were completed using the largest vessels operated by three major cruise lines, including Royal Caribbean's *Oasis* and *Freedom*, Carnival's *Dream* and Norwegian's *Epic.* Simulations were undertaken for both arrival and departures manoeuvres at all three piers, under a range in environmental conditions (wind, currents, waves and visibility).

The simulations included participation by Captains from Royal Caribbean, Carnival and Norwegian, as well as pilots from BPI. In general, the simulations demonstrated that the proposed project layout allows for the safe arrival and departure of large cruise ships, with no navigation concerns raised by the Captains. The one exception was the *Oasis*; specifically, Royal Caribbean indicated that they would not use an inner berth (between Piers 1 and 2) if there is another vessel at the opposite berth, as the clearance between these two berths is insufficient given the much larger beam of the *Oasis*. Given the fact that *Oasis* class vessels are not expected to call frequently at Bridgetown, as well as the fact that Pier 2 will not be constructed as part of the first phase of project development, BPI accepted this operational constraint.

The navigation simulations also demonstrated that the proposed layout for aids to navigation (AtoNs) was acceptable. Finally, the navigation simulations provided guidance on operational limits for safe berthing, in particular limiting wind speed speeds for Piers 1 and 2 (generally aligned with the prevailing trade winds) and Pier 3 (generally broadside to the prevailing trade winds).

Moored Ship Response and Downtime

As noted earlier, the Sugar Point project will be developed on an open coast location that is exposed to a complex wave climate, including seas, swells and hurricanes. From an operational perspective, the exposure of the site represents a risk with respect to facility downtime caused by excessive wave-induced motions of moored vessels. In addition to lost revenue and negative perception within the industry associated with missed calls, excessive ship motions may result in broken mooring lines, which is a significant safety concern.

In order to address this critical issue, Baird undertook extensive modeling and analyses of moored ship response and downtime, including the following key tasks:

1. Development of metocean database for the project site;
2. Definition of allowable motions for cruise ships;
3. Physical and numerical modelling of moored ship response;
4. Development of downtime estimates.

Metocean Database - As noted earlier, the wave climate at the site is complex and includes locally generated seas associated with the prevailing easterly trade winds, longer period swells associated with winter storms in the North Atlantic, and hurricane waves. The seas refract/diffract around Needhams Point and approach the site from the SSE-S, while the swells propagate around the west side of Barbados and approach the site from the NW-W (refer to Figure 5). Hurricane waves may approach the site from the SE through W.

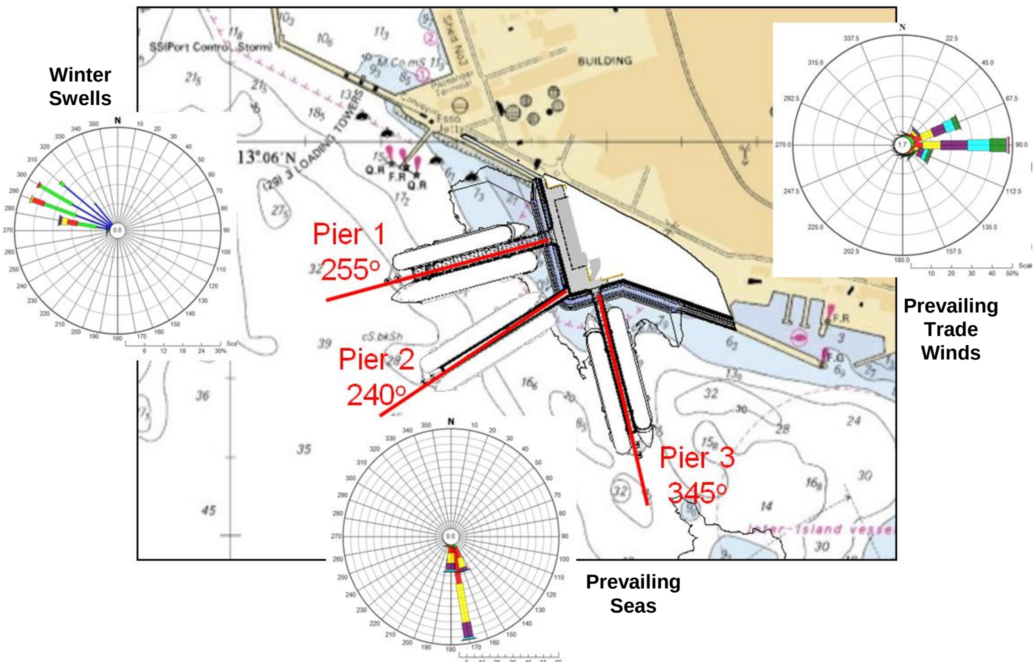


Figure 5. Prevailing Metocean Conditions at Project Site

A comprehensive metocean database was developed for the project site, including winds, waves, currents and water levels. The database incorporates site-specific measurements of waves, currents and water levels collected over a period of two years, and the development of a ten year wind-wave hindcast database to define the day to day (operational) conditions at the site. The wind-wave modelling included a WaveWatchIII hindcast for the entire Atlantic Ocean and Caribbean Sea, with a nested SWAN model grid used to simulate the complex spectral transformation of the waves as they propagate across shallow water into the project site. The numerical model results were validated against measured data, including several NOAA deepwater wave buoys, satellite altimeter and scatterometer data, and local AWAC measurements. The resulting database provides an estimate of the prevailing seas and swells on an hourly basis over a continuous ten year period, and was used as input to the downtime analysis.

Allowable Motions for Cruise Ships - The definition of allowable motions was a critical input to the downtime analysis. A literature review was undertaken to assess this issue; while most of the published information related to cargo vessels (Nordforsk 1987; PIANC, 1995), some information specific to cruise ships was also identified (CHC, 1997; ROM, 2011). In addition, this issue was discussed with Captains from several cruise lines during the navigation simulations at the STAR Center. Review of the available information led to the selection of maximum allowable motions (horizontal and vertical) at the passenger door for use in the downtime analysis. In addition, allowable mooring line loads were defined based on criteria presented in OCIMF (1997).

<u>*Physical and Numerical Modelling of Moored Ship Response*</u> - A hybrid modelling approach, including both physical and numerical models, was used to assess moored ship response for the Sugar Point project, with the overall modelling approach developed to leverage the strengths, and address the weaknesses, of each approach. In particular, the hybrid approach takes advantage of the increased accuracy of physical modelling and the increased efficiency of numerical modelling.

First, an extensive physical model investigation was undertaken at National Research Council of Canada's Ocean, Coastal and River Engineering (OCRE) hydraulics laboratory to provide information to support design development for the project. Construction of the 1:50 scale model included accurate simulation of the nearshore bathymetry and proposed project, including dredging, land reclamation and Piers 1 and 3. The testing program included two separate sets of tests, the first to assess moored ship response (i.e. wave induced vessel motions, mooring line loads and fender reactions) under a range in operating conditions, and the second to assess wave-structure interactions under a range in extreme hurricane conditions.

The moored ship response (MSR) tests included tests with two Royal Caribbean vessels, an *Oasis* class vessel (225,000 DWT, the largest cruise ship currently sailing), and a *Vision* class vessel (75,000 DWT, typical of vessels which presently call at Bridgetown). Figures 6 and 7 present photographs of the model wave basin during the MSR tests. Approximately 125 MSR tests were completed under a range in wave conditions, with varying wave heights, periods and directions selected to simulate typical and severe sea and swell conditions at the site; wind and current loads on the vessels were also simulated. Measurements of vessel motions, mooring line loads and fender reactions were made using sophisticated arrays of instrumentation. The physical model results were subsequently used to calibrate/validate the numerical modelling approach, as summarized below (a companion paper by Knox et al. 2014 provides more detailed information on the physical modelling undertaken for this project).

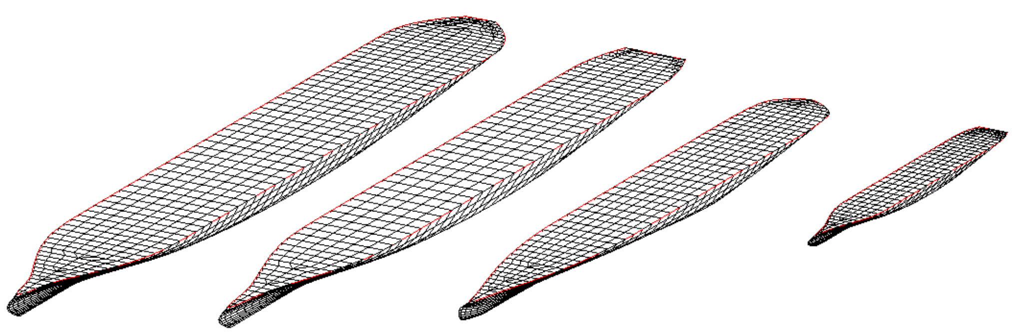
Figure 6. Overview of Physical Model during Moored Ship Response Tests

Figure 7. Closeup of Oasis at Berth 1N during Moored Ship Response Tests

Numerical modelling of MSR was undertaken using Baird's in-house Wavescat and Quaysim models. Wavescat is a frequency domain hydrodynamic panel model and was used to simulate wave-ship interaction effects, including the diffraction of waves around the ship's hull, the associated wave forces and the hydrodynamic coefficients due to motions of the ship. The resulting wave forces and hydrodynamic coefficients are then input to Quaysim (a time domain model) to determine the resulting ship motions and mooring loads, including consideration of the non-linear load-deflection characteristics of the selected mooring lines and fenders. The Quaysim model outputs time series of ship motions in six degrees of freedom (at a specific location of interest, in this case the passenger door) and forces in the mooring lines and fenders. Statistical analysis are then undertaken to determine the expected hourly maximum values, with these values compared to allowable criteria to determine if downtime occurs under the specified metocean conditions.

Initially, the numerical models were set up, calibrated and validated against the physical model test results. Subsequently, the numerical models were used to assess moored ship response for a wider range in wind and wave conditions, and also for different vessels and different berths.

The model simulations were undertaken for four different vessels, including Royal Caribbean's *Oasis*, *Freedom* and *Vision* classes, and a smaller vessel. As noted earlier, the *Oasis* class represents the largest cruise ships presently in operation. The *Freedom* class is representative of the largest cruise ships which presently call at Bridgetown, while the *Vision* class represents typical vessels (i.e. average size) which presently call at Bridgetown. The smaller vessel is representative of luxury cruise ships that call at Bridgetown. Figure 8 presents the model hull meshes for the four different vessels.



Oasis (LOA = 362 m) Freedom (LOA = 339 m) Vision (LOA = 279 m) Luxury (LOA = 142 m)

Figure 8. Numerical Model Hull Meshes

Downtime Analyses - The expanded MSR database available from the numerical model simulations was utilized, along with the operational wave climate and estimated threshold conditions for acceptable operations, in order to develop downtime estimates for the facility. The overall approach used to estimate downtime was qualitatively validated based on actual experience from a similar (exposed) facility in Saint Maarten.

For example, Figure 9 presents results of the analysis for the winter of 2011-12, including the estimated occurrence of downtime for the four different vessels at Piers 1 and 3 (upper panel) associated with the prevailing Westerly swells and Southerly seas (lower panel).

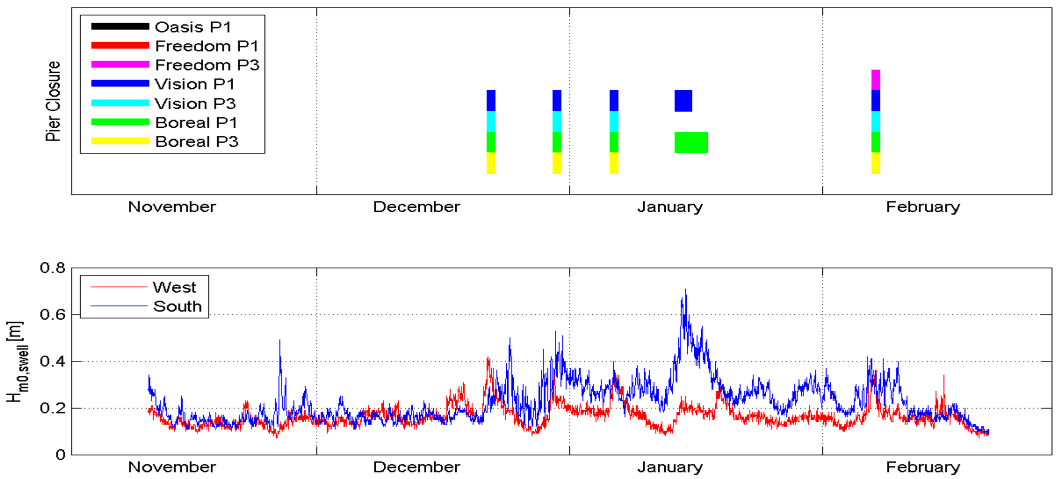


Figure 9. Estimated Downtime Events due to Westerly Swells and Easterly Seas

As expected, the results of the analyses confirm that the longer period westerly swells will be the controlling factor with respect to operational downtime for the proposed facility. Figure 10 presents time series data for the westerly swells hindcast through the cruise seasons of 2006-07, 2007-08 and 2010-11. These three years are representative of average, mild and severe seasons respectively. The red zones in these figures represent periods when downtime was estimated for the *Vision* at Pier 3. As noted above, the *Vision* represents typical vessels that presently call at Bridgetown; larger vessels would generally experience less downtime, while smaller vessels would generally experience more downtime. In addition, the results in Figure 10 are for Pier 3; the MSR model results generally indicate lower downtime for Piers 1 and 2.

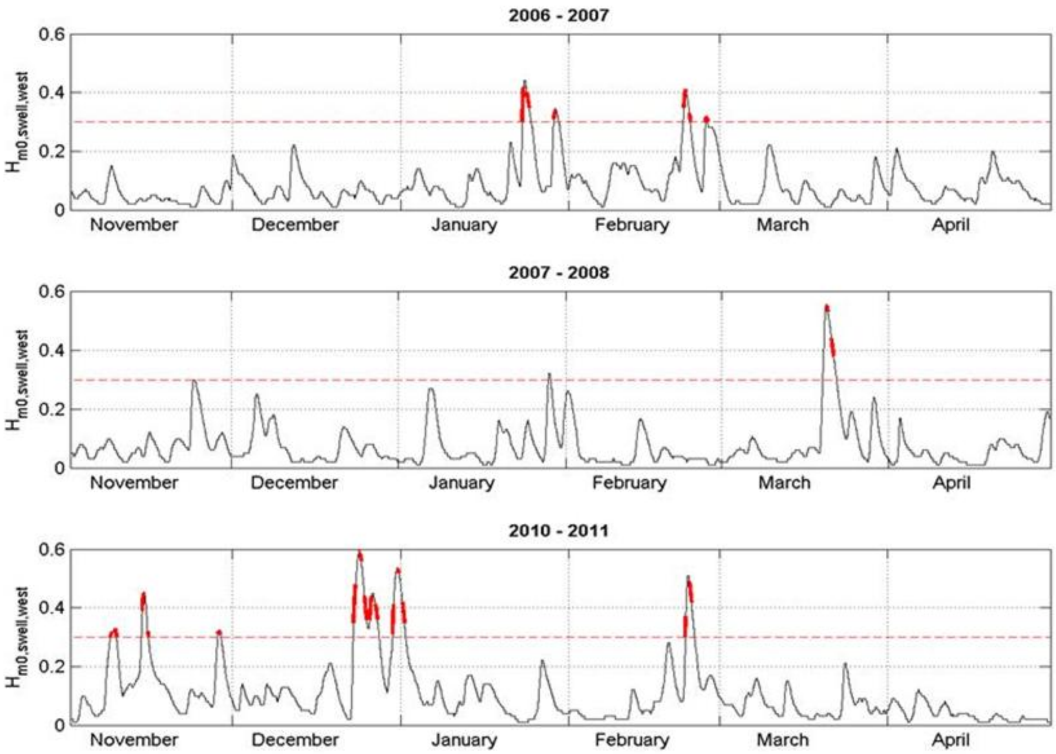


Figure 10. Estimated Downtime (red) of Vision at Pier 3 due to Westerly Swells Average Season (top), Mild Season (middle) and Severe Season (bottom)

It is important to note that the information presented above is based on estimates of both waves (i.e. hindcast data) and moored ship response (i.e. numerical model simulations). The occurrence of downtime will be dependent on the actual wind, wave and current conditions prevailing at the time, the anticipated (forecast) metocean conditions and the vessel itself, with the decision to berth or depart ultimately resting with the Captain of each vessel.

The overall conclusion of the MSR and downtime analysis is that downtime due to metocean conditions (i.e. wind, waves and currents) is expected to be within acceptable levels for a cruise berthing facility in the Caribbean. Further, given the continuing trend towards larger vessels, downtime will tend to be lower in the future. Finally, Barbados has the benefit of an alternative, sheltered, berthing location in the adjacent port that can be utilized during extreme conditions.

Extreme Wave Loads and Structural Design

As noted earlier, the project site may be exposed to extreme hurricane conditions (waves and surges), and the marine and coastal structures must be designed to resist these events. Key design issues for the proposed project included wave uplift loads on the pier decks, and wave overtopping and flooding of the land reclamation area. These issues were investigated using the 1:50 scale physical model described earlier, including the use of various instrumentation systems and visual observations to assess and quantify the following wave-structure interactions:

- Horizontal and vertical wave loads on the pier decks;
- Wave overtopping onto the land reclamation area;
- Stability of scour and shoreline protection structures.

Approximately 280 wave-structure interaction tests were undertaken, including severe sea and swell events, and hurricane waves and surges up to the 200 year event (Hs = 7.3 m, Tp = 11 to 14 s, SW to W direction). Wave loads on the pier decks were measured using sophisticated instrumentation systems, including global forces on deck spans using load cells, and local pressures on individual structure elements using pressure sensors. Tests were completed for a conventional solid deck concept, and also for an innovative open deck concept, the objective of which was to reduce the overall uplift loads on the pier structure, thereby reducing the substructure (pile) design requirements and costs. Figures 11 to 13 present photographs of the instrumentation systems and tests in progress.

Figure 11. Force-Pressure-Force (FPF) Instrumentation Array on Solid Deck Pier

Figure 12. Hurricane Wave Interaction with Solid Deck Pier

Figure 13. Hurricane Wave Interaction with Open Deck Pier

Measurements of wave overtopping were made using catchment basins, complemented by a visual assessment of the severity of the overtopping with respect to public safety (i.e. safe, marginal or unsafe). The wave overtopping tests were undertaken with several different configurations of shoreline protection structures, including vertical wall, sloping revetment and hybrid wall revetment concepts. In addition, the effect of various wave walls and flood barriers was also tested. Stability of the scour protection and revetment structures was monitored visually, with sequential photographs of specific test sections collected to monitor damage progression, if any. Figure 14 presents a photograph of the construction of a model revetment. Figure 15 presents photographs of wave overtopping of a vertical wall during severe storm events. Finally, Figure 16 presents a compilation of wave overtopping data from the physical model tests.

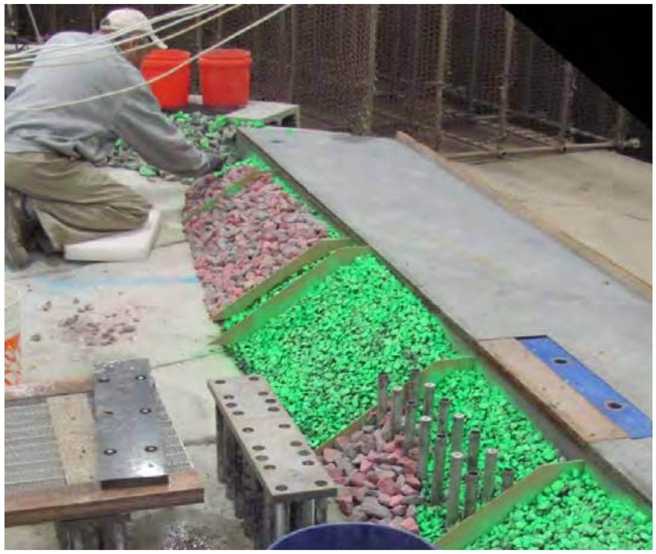


Figure 14. Construction of Armour Stone Revetment

Figure 15. Wave Overtopping during Severe Storm Event

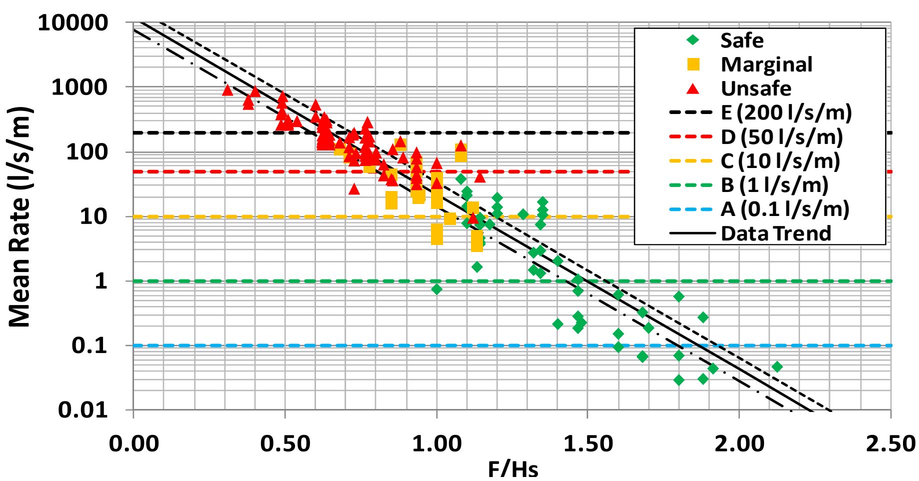


Figure 16. Mean Wave Overtopping Rate versus Relative Freeboard – Compilation of Test Results

As noted earlier, a companion paper by Knox et al. 2014 provides additional information on the physical modelling undertaken for this project. The physical model results were used to develop design wave loads for inclusion in the Basis of Design, to develop an effective flood protection system to limit the risk of site flooding due to wave overtopping, and to support preliminary design development of the shore protection structures. This information was subsequently used by the nominated design-build contractor to advance the design sufficient to develop a price proposal for the project.

PROJECT SUMMARY AND STATUS

The Front End Engineering Design (FEED) study and Basis of Design (BoD) were completed in September 2013. The FEED study included a comprehensive program of physical and numerical modelling to investigate critical design issues, including moored ship response and downtime, and extreme wave loads on the marine structures. These studies were critical to the development of the project layout and BoD, and also to the regulatory approval process.

The project received a recommendation for approval from the Chief Town Planner (Town and Country Planning Development Office) in December 2013, with the Prime Minister's Office granting "planning permission" for the project in May 2014. Pending successful completion of negotiations related to project financing, construction of Phase I is expected to start in 2015, with the facility expected to be operational for the 2016-17 cruise season.

ACKNOWLEDGMENTS

The following organizations are acknowledged for their significant contributions to the successful planning and design of the Sugar Point project:

- Owner – Barbados Port Inc.;
- Developer – SMI Infrastructure Solutions Inc. and Royal Caribbean Cruise Lines;
- Design-Build Contractor – Weeks Marine Inc.;
- Benthic Habitat and Marine Ecology - Carib Marine Contracting & Research Inc.;
- Subsurface Investigations – Capital Signal Company Ltd.;
- Navigation Simulations – STAR Center;
- Physical Modelling – National Research Council of Canada;
- Landside Masterplan – LandDesign;
- Site Servicing – ACI.

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