OPERATIONAL ANALYSIS OF CRUISE SHIPS AGAINST LONG WAVES: THE EXPERIENCE AT VALPARAISO

by

Benjamín Hernández[1], Ricardo Figueroa[2] and Fernando González Chana[3]

ABSTRACT

The cruise industry has been undergoing considerable expansion in South America, particularly in Chile. To meet demand, Port of Valparaíso is planning to accommodate the cruise vessels at a dedicated terminal to promote the cruise industry and to provide passengers a world-class cruise experience. The existing passenger terminal is co-located with cargo terminals, and a dedicated cruise ship terminal is needed to reduce overlap between cargo and passenger operations. Valparaíso is a busy harbor, and several ongoing cargo terminal expansion projects are underway. A site has been selected for the dedicated cruise terminal that would provide separation from the cargo terminal, but place the moored cruise ships outside of the port's breakwater protection. In this paper, a methodology is presented for selecting the cruise terminal location, developing the swell wave climate at the site, and developing terminal solutions to minimize cruise ship movement and obtain a cost-effective solution.

To characterize the wave climate at the proposed terminal, a 36-year wave hindcast was used, based on re-analysis of Pacific Ocean winds. The spectral hindcast was propagated using a methodology that allows estimating the spectra at the nearshore project site considering the contribution of each component present in the spectra in deep water. This is important in bays like Valparaíso, since it considers the energy coming from all directions where it is possible for the waves to enter the bay. Wave simulations were developed using the Mike21 SW-FM (Spectral Waves-Flexible Mesh) numerical model, which is able to solve wave transformation processes such as refraction and shoaling, the energy balance of the inputs (induced by winds or conditions of distant swells), and attenuations (background friction and wave breaking).

The results of the wave modeling analysis showed that the terminal is exposed to long northwesterly swell waves, which are unfortunately present predominantly during Chile's summer cruise season. The peak wave period exceeds 16 seconds during these events. Consequently, a moored ship's response to the waves and the potential downtime due to ship motion behavior were modeled.

The aNyMOOR.TERMSIM model was used to determine the behavior of the ships under swell conditions. The model predicted the motions of the vessel as well as loads in mooring lines and fenders. The movements of the ship were studied through 6 degrees of freedom, which are defined with respect to the ship. Through orientation of the berth and optimization of mooring arrangements, the cruise ship could be moored safely at the location. However, excessive motion at the berth may affect passenger safety and comfort.

To evaluate the potential downtime due to motion, we reviewed the literature in regard to guidelines and recommendations for acceptable motion of cruise ships. References available includes PIANC (1995), Spanish ROM, and Nordforsk (1987). The recommended ranges varied greatly between the references. For the purposes of the evaluation, we adopted a median criterion for lateral movements and the Nordforsk guidelines for acceptable acceleration. In conducting the analysis, we identified a need for further investigation and developing guidelines and recommendations regarding the accommodation and the behavior of moored cruise vessels in locations where long period waves are present.

1 INTRODUCTION TO THE GLOBAL CRUISE INDUSTRY

Looking over the short-, medium- and long-terms, most lines and experts continue to feel the global cruise industry's best days are ahead. The broader industry fundamentals responsible for its dramatic rise over the past two decades are expected to remain in place: Introduction of new vessels and products, guest retention, an elevated level of guest satisfaction and value for money, adaptable business model, mobile assets, globalization of product offerings, and limited competition. These

[1] Moffatt & Nichol, Santiago, Chile, bhernandez@moffattnichol.com
[2] Moffatt & Nichol, Santiago, Chile, rfigueroa@moffattnichol.com
[3] Moffatt & Nichol, Santiago, Chile, fgchana@moffattnichol.com

fundamental trends will continue to propel the industry forward in terms of passenger and financial expansion.

Looking ahead, total cruise passenger levels are projected to increase worldwide over the next 15 years. The anticipated projection calls for cruise passenger levels to grow from 24.0 million in 2016 to between 36.0 and 44.0 million by 2030, with the medium projection scenario suggesting 38.0 million passengers by the end of this projection horizon. The leading cruise conglomerates—Carnival, RCCL, NCL, and MSC Cruises—are all poised to continue to expand, with Disney, Viking and other lines also looking to add supply and consumer momentum based on their unique brand positioning. Expansion of worldwide cruise and passenger activities will place continued demand for new and larger ports and destinations, as well as cruising regions.

These macro trends point to positive prospects for Valparaíso over the long term.

2 VALPARAISO’S CASE STUDY

Located along central Chile’s Pacific Coast, Valparaíso is a vital center of maritime commerce and leisure. The city and its port are also important to the cruise industry, playing a strategic role in the delivery of several itinerary offerings in South America. As a homeport—tethered to the airlift and hotels available from nearby Santiago—the city and port of Valparaíso provide the logistical gateway to cruises transiting the wilds of Patagonia, the Strait of Magellan, Cape Horn, and visiting Chilean and Argentinean ports along the way. As a transit port, Valparaíso opens its doors to a varied number attractions and excursions, from exploring the UNESCO designated Historic Seaport Quarter to Chilean wine country and other inland offerings. Figure 1 shows the strategic location of the Bay of Valparaíso.

Figure 1: Location of Bay of Valparaíso

Currently, homeporting and visiting cruise ships berth at the Port of Valparaíso’s cargo wharfs. While the current arrangement meets the basic operational needs of these vessels, it is less than ideal from a guest experience perspective. Reliance on extensive ground transportation and other logistical support from Valparaíso’s remote cruise terminal—Valparaíso Terminal de Pasajeros (VTP)—adds cost and time to the overall homeport and port-of-call operations. Container vessels are also given priority at the cargo wharfs, creating berthing conflicts for cruise vessels and potentially placing vessels at anchor and/or creating other logistical difficulties.

In addition to the limitations of the existing cruise ship operation, there is nowhere within the footprint of the existing port facility for the cruise industry to grow to deliver a guest experience commensurate with the attractiveness of the region, while supporting larger vessels and more frequent vessel calls.

To address these challenges, the Empresa Portuaria Valparaíso (EPV) initiated a study to evaluate the potential for the port to develop a dedicated cruise pier within the harbor.

3 NEW JETTY LOCATION

An alternatives analysis was developed for different locations in the Bay of Valparaíso, which were evaluated and compared using a multicriteria analysis. The selected alternative is a jetty located in front of the passenger terminal, with a single berthing position and an optional second berthing position in the opposite face of the structure.

The selection of the alternative considered the following aspects:

- Legal
- Environmental conditions
- Existing and projected infrastructure
- Logistic/operation of the new jetty with the existing passenger's terminal
- Capex and Opex

The selected option was the simplest and most cost effective; however, the seabed depth presented a design challenge. The solution included dredging works to allow ships to come in closer to the coast and to avoid high depths for pile driving. Figure 2 presents the proposed jetty location, whereas Figure 3 shows the proposed layout.

Figure 2: New Jetty Location

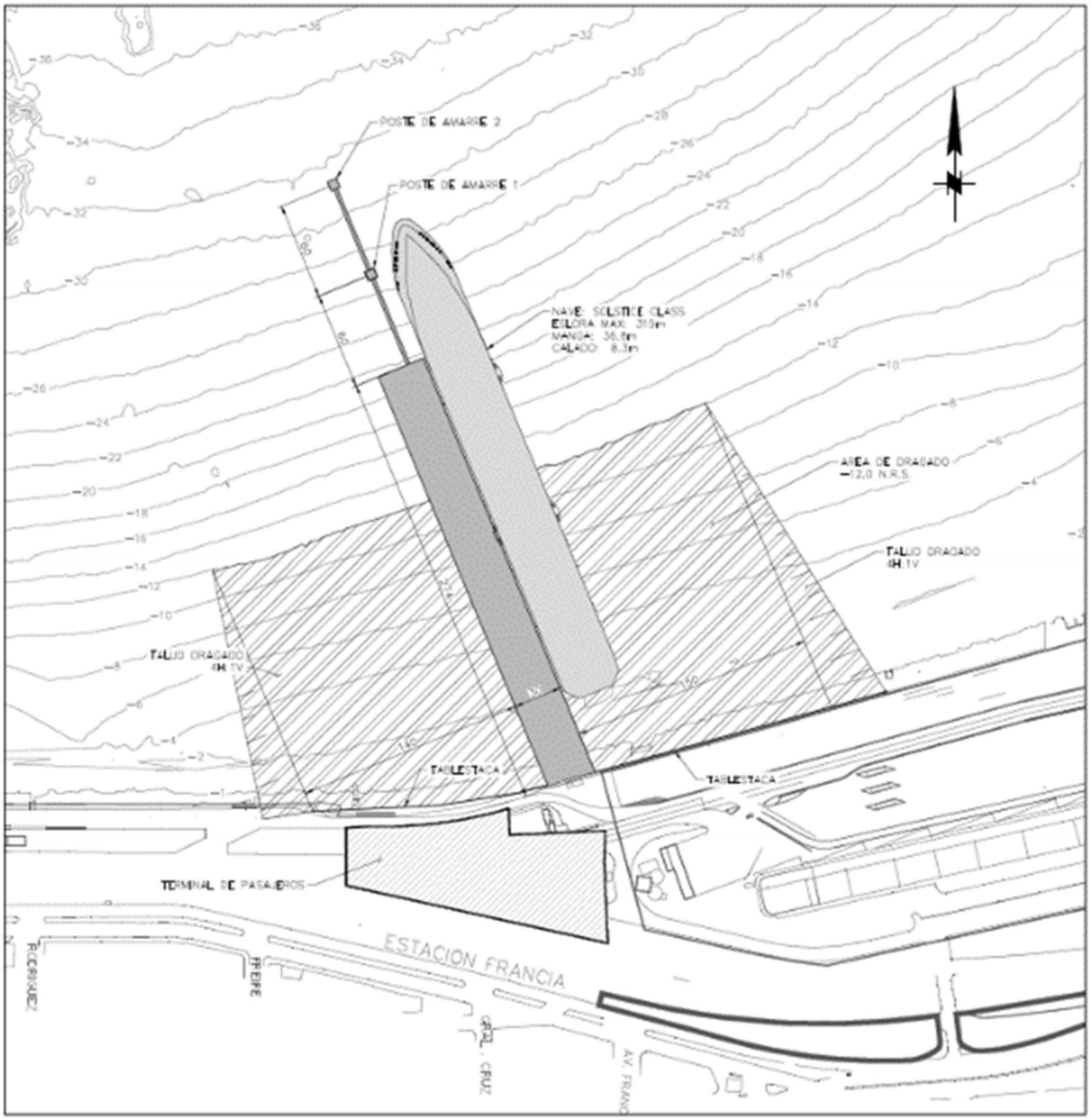

Figure 3: New Jetty Layout

4 RELEVANT ENVIRONMENTAL CONDITIONS

For purposes of the feasibility and concept study, mainly wave and wind conditions were studied to evaluate operational downtime, and water levels were analyzed to develop the concept design. However, additional phenomena, such as currents within the bay, should be considered during future design phases (basic and detailed design).

4.1 Waves and Winds at the Project Site

The Bay of Valparaíso historically has the main port terminal of Chile, because of the natural protection it offers against strong Pacific swells coming from the south, which are present on the Chilean coasts throughout the year. In addition, wave energy from the north increases agitation inside the bay. These waves are typically longer than the swells coming from the south. Also, the vulnerability of the bay to waves coming from the northwest quadrant, can be observed during extreme events, when the worst conditions are caused by local storms that approach the bay from the north-northwest.

A 36-year spectral hindcast was performed, propagating to the site within the bay. An appropriate methodology to transform waves in deep water to the coast consists of the simulation of unitary waves from deep waters that cover the spectra domain in frequency and direction. The results of these simulations provide enough information to determine the energy variations within the numerical domain and the directional distribution of the spectral components when propagating towards the coast. Then, these coefficients of agitation and redistribution of energy allow the transformation of the spectra from deep water to the locations near the coast at the project site.

For the Bay of Valparaiso, 130 combinations of periods from 4 to 22 seconds and directions from 180 to 360 degrees were defined, which correspond to the ranges of wave conditions in deep water. These cases were propagated with unitary wave heights, to directly obtain the transformation coefficients in each element of the numerical domain. The estimation of the spectra in the project site allows for the calculation of the bulk parameters commonly used for wave characterization, such as spectral wave height, peak period, and peak direction.

It should be noted that the estimation of the spectra in the project site, from the contribution of each spectrum bin in deep water, is important in bays like Valparaíso, since the estimate considers the energy coming from all directions that waves enter the bay. The morphology of Valparaíso presents a natural shelter provided by Punta de Angeles and Punta Curaumilla. Both headlands generate a significant transformation/decrease of the wave energy that comes from the south, which are commonly the most energetic systems within each sea state in deep water. However, swells from the northwest quadrant, which are not typically the most energetic offshore system in the spectrum, when propagated within the bay—although they do not undergo important transformation processes—can sometimes contribute to the increase of conditions of agitation inside the bay. A typical offshore spectrum in front of Valparaíso and a schematic transformation of each system into the Bay of Valparaíso are shown in Figure 4. As it can be seen, the transformation process play an important role in the final wave bulks parameters, which will ultimately be used for assessing the dynamic behavior of the vessels berthed at the project site. The wave analysis should be carefully examined and the study consider any wave system present in the wave spectrum.

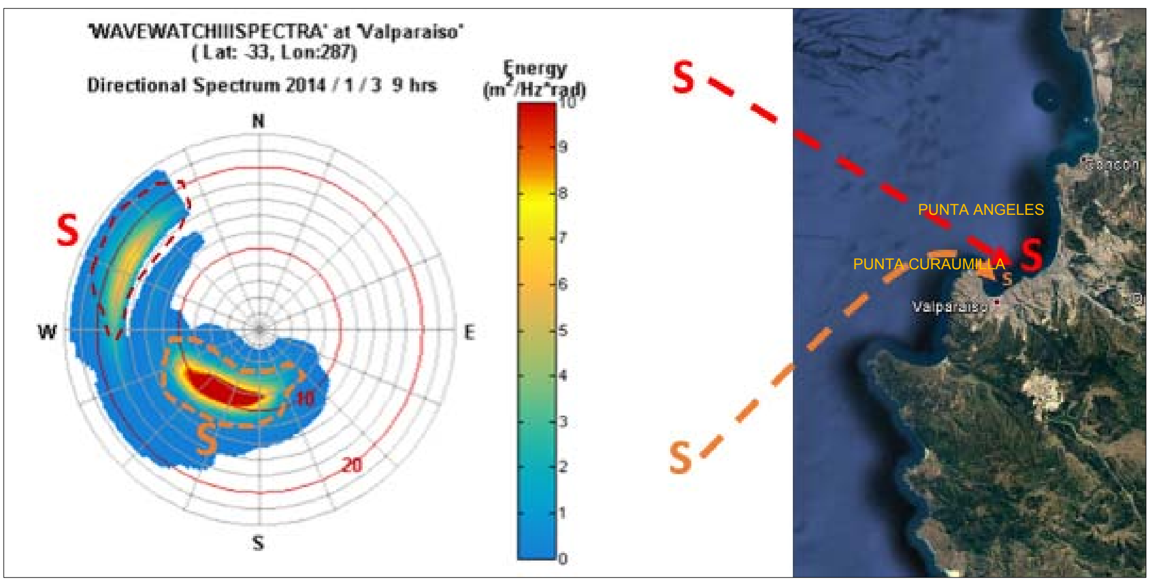

Figure 4: Offshore Representative Spectrum and Schematic Transformation of Each System into the Bay of Valparaíso

A Mike21 SW-FM (Spectral Waves-Flexible Mesh) numerical model was used to simulate the propagation of waves to the shore. Mike21 SW can solve the most relevant transformation processes, such as refraction and shoaling, the energy balance of the contributions induced by winds or swells conditions, and decreases from bottom friction, breaking, etc. In addition, Mike 21 SW-FM presents approximations to consider diffraction and reflection phenomena.

Validation of the wave analysis was carried out, comparing the propagated hindcast against wave field measurements located near the project site. Wave measurement campaigns on site involved approximately two months of measurements at the Yolanda 1 site and seven months at the Baron 2 site. Figure 5 shows the location of both measurement nodes and presents a comparison between the wave height and period measured at Yolanda 1 and Baron 2 (red dots), and the model results (line and black dots). Quantile-quantile graphs for each of the variables considered are also presented.

Regarding the comparisons in both nodes, it was observed that the results of the simulation manage to capture in form and magnitude the measured events for wave heights and peak periods. It should be noted that the time series located in Baron 2 includes the extreme event of August 2015, a storm that corresponds to the largest event presented in the 36 years of statistics.

Considering the correlation between the simulated and measured data in both locations, it was concluded that the models and methodology used in the present study can characterize waves in an appropriate way in this sector of the bay.

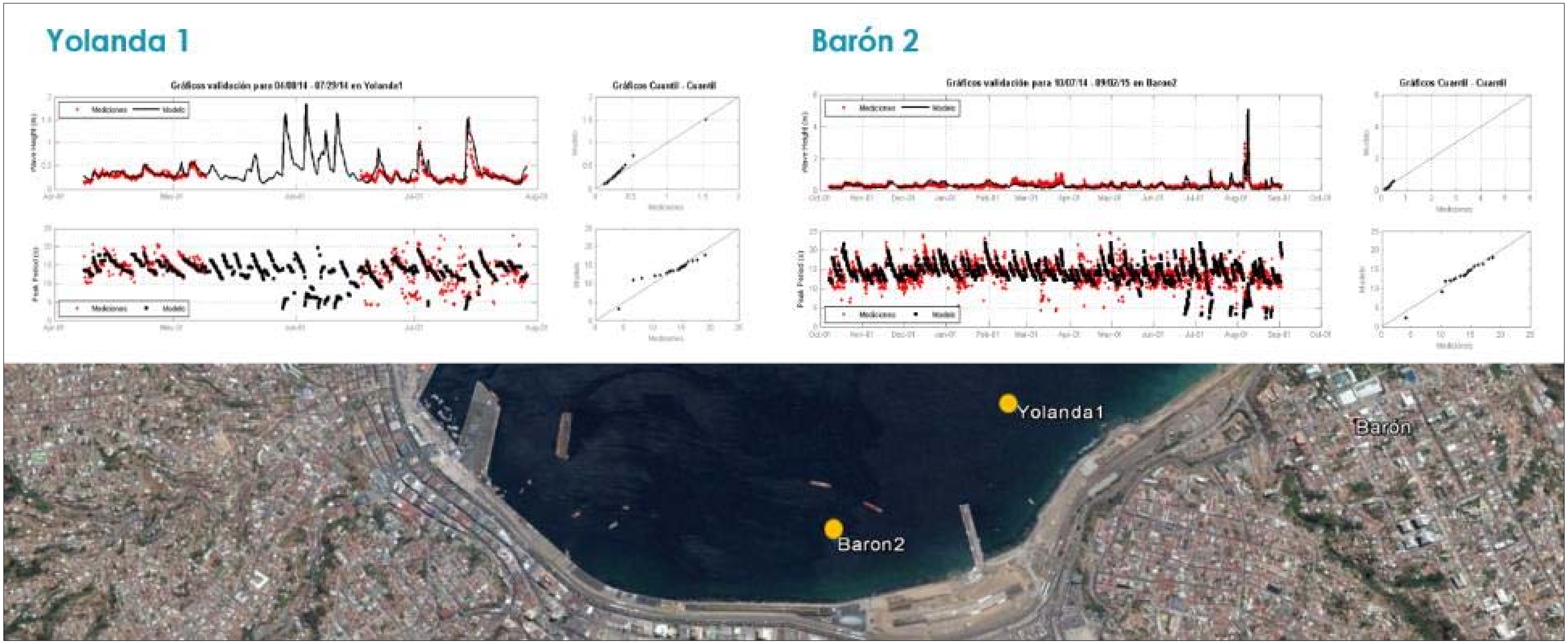

Figure 5: Wave Bulk Parameter Comparisons at Locations Yolanda 1 and Barón 2

For wind conditions, one year of statistics close to the project site was provided.

Both environmental factors, wind and waves, are shown in Figure 6. From these, the berth site of the proposed terminal was oriented considering that waves are driving the moored vessel behavior when berthed.

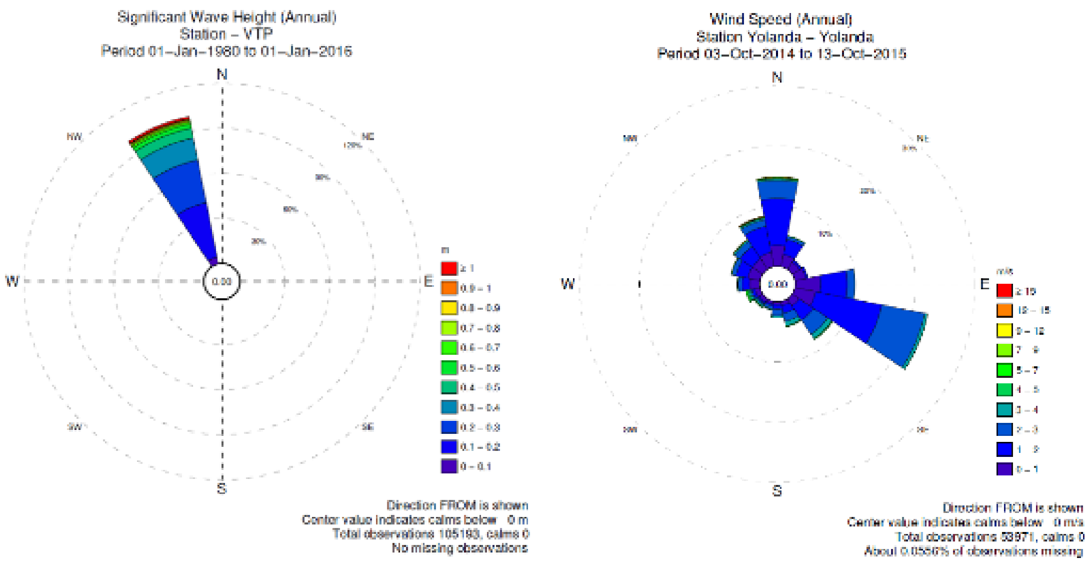

Figure 6: Waves and Winds at the Project Site

5 DETERMINATION OF THE EXPOSED SITE AVAILABILITY

Berth availability was a key element in the design because of the site exposure and the correlation between the cruise season and summer time when the energy from northwest quadrant tends to be more important than during the rest of the year. Short operational windows of 12 or 24 hours, and the rigidity of cruise schedules, implied that the likely availability of the berth site should be high enough to meet cruise line expectations.

Figure 7 shows the flowchart of the process adopted to estimate the availability and downtime due to environmental conditions. The environmental conditions (waves and winds) and vessel specifics were considered to establish the response of the berthed vessel due to the environmental influences. Vessel specifics included ropes, ship geometrics, terminal configuration, mooring arrangements, fenders, and bollards. Then, for a specific action, the vessel response output plus the given criteria can be compared to determine the following:

- Peak mooring line loads
- Peak fender loads
- Peak bollard loads
- Peak motions

If the results of one of the factors listed above is exceeded, then safe operating conditions may not be assumed. Thus, downtime must be considered under those particular conditions, with the corresponding decrease in berth availability.

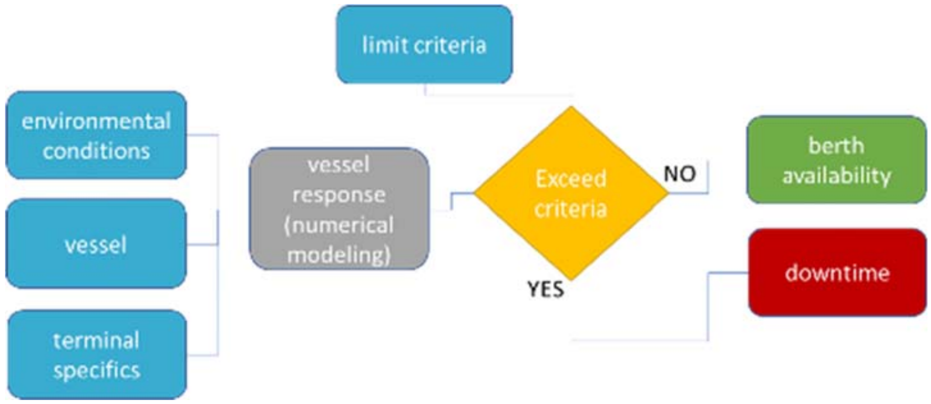

Figure 7: Availability/Downtime Estimation Flowchart

To determine the dynamic response of a ship berthed at the proposed project site, the model aNyMOOR.Termsim developed by Marin (Maritime Research Institute Netherlands) was used. The results of aNyMOOR provide a timeseries of ship movements, forces developed by the mooring lines, and reaction forces in the fenders and bollards at the proposed terminal.

The market study identified the characteristics of the cruise ships that could potentially call the new terminal. Vessels specifics are presented in the Table 1.

	Celebrity Cruises' Solstice-Class	**Holland America's Rotterdam Class**
Class:	Solstice-Class	Rotterdam-Class
Gross Tonnage:	122,000 GT	61,500 GT
LOA:	317 m	238 m
Beam:	36.8 m	32 m
Draft:	8.23 m	8.10 m
Capacity (Passengers):	2,850	1,400

Table 1: Design Vessel Characteristics

It is clear from the flow chart shown in Figure 7 that the berth availability is controlled by the thresholds selected as limiting criteria, and, consequently, choosing the appropriate set of values becomes crucial. The main challenge was selecting criteria that, while being conservative given the early stage of design, would not penalize the technical feasibility of the project.

5.1 Downtime Scenarios

To estimate the percentage of time during which the ship exceeds the movements and maximum forces allowed for its safe operation (downtime), the process shown in Figure 7 was applied, considering the following environmental conditions:

- Thirty-six years of wave hindcast, which consist of sea states every three hours from 1980 to 2015.
- One year of winds with records for every hour, corresponding to 2010.

Three scenarios were performed based on the available statistics, as follows:

(1) year 2010, using wave and wind statistic, both varying throughout the year;

(2) year 2010, waves varying along the year with most frequent wind conditions; and,

(3) 34 years of waves with most frequent wind condition.

These scenarios present multiple combination of wind statistics, since cruise ships are characterized by having a significant superstructure, and wind can have a significant impact on the vessel behavior when moored.

To estimate the response of the ship to the demands jointly generated by winds and waves together, 1,728 simulations were performed covering all possible combinations for each vessel. The ranges are presented in Table 2.

Parameter	Range	Number of cases
Wave height (m)	0.25, 0.50, 1.0, 1.5	4
Peak period (s)	7, 10, 13, 16, 19, 24	6
Peak direction (deg)	326,3 337.5, 348.8	3
Wind velocity (m/s)	1, 6, 11	3
Wind direction (deg)	22.5, 67.5, 112.5, 157.5, 202.5, 247.5, 292.5, 337.5	8
	Total Number of Simulations	**1728**

Table 2: Bulk Parameter Ranges for Waves and Wind

5.2 Limit Conditions for Safety Operation When Vessel is Moored

As mentioned, mooring limits are critical for estimating downtime. The following references were used to define the critical operating limits based on ship motions at berth and forces exerted on the mooring lines:OCIMF ¨Guidelines for safe working loads of mooring lines for line loads¨

- PIANC 1995¨Criteria for movements of moored ships in harbours¨
- Spanish Recomendación de obras marítimas ROM 2.0-11
- Nordforsk 1987 “Assessment of a ship performance in a seaway”

The maximum acceptable movements for safe operating conditions for ships at dock are presented in Table 3. It should be noted that reference material regarding the maximum movement of cruise ships is scarce. The ROM presents values for this type of vessel (Criteria A); however, there is no comment about the conditions under which these limits apply, and, comparatively, these movements are considerably more restrictive than for other types of ship/cargo. Therefore, a second criterion (Criteria B) for movement limits was established, which consists of the following:

- Criterion associated with passenger boarding/disembarking: A maximum motion at the vessel passenger door equal to 1 meter was employed to estimate an embarkation/debarkation threshold.
- Criteria associated with the comfort of passengers who remain on board while the vessel is docked: The maximum acceleration limits recommended by Nordforsk 1987 were used. These correspond to values under which people do not suffer from dizziness or experience loss of balance. The limits were applied to the maximum acceleration experienced on the upper deck of the cruise ship.

Reference	Lateral Acceleration (m/s²)	Vertical Acceleration (m/s²)	Surge (m)	Sway (m)	Heave (m)	Yaw (deg)	Pitch (deg)	Roll (deg)
Criteria A ROM 2011	-	-	0.8	0.8	0.5	0.2	0.2	0.2
Criteria B Nordforsk 1987 / From pilots and captains	0.2	0.3	1	1	1			2
PIANC 1995 Ferry	-	-	0.6	0.6	0.6	1	1	2
PIANC 1995 DWT>8000	-	-	0.3	0.3	0.3	1	1	1

Table 3: Criteria for Maximum Acceptable Ship Movement while Docked

With respect to the limits for the lines, maximum limits equal to 50% of the Minimum Breaking Load (MLB) of each line were adopted as a function of the corresponding vessel based on the OCIMF guideline.

5.3 Downtime Results Discussion

The results of the 1,728 simulations were used to estimate the vessel motions, forces on mooring lines, and maximum reactions to fenders. These variables were compared with the established limit criteria, identifying time periods when cruise ships would not operate safely due to one of the criteria being exceeded. The downtime estimation and its causes (excessive motions, mooring line tensions, or forces on fenders) were determined for the three scenarios defined in section 5.2.

With regards to operating limits, the analysis considered the limits established by the Spanish ROM, movements and the associated with the passenger doors, and accelerations. The analysis of the vessels response showed that events associated with long period swells produce that some parameters exceed the limits adopted for the ships operation, especially horizontal displacements (surge and heave) and the rotation around the ships longitudinal axis (roll). These waves principally occur during summer months, coinciding with the cruise ship season. In addition, the highest downtime and most adverse results were associated to the smallest design vessel.

A summary of the most relevant variables associated to the scenario that considered wave and wind during 2010 is presented in Figure 8, according to the following:

- (A) Wind speed and direction
- (B) Waves height and peak period
- (C) Peak to peak surge
- (D) Peak to peak roll for both design vessels

The subplots B and C in Figure 8 shows the thresholds for both criteria (A and B) for the motions that are driving the downtime estimation. There it can be seen that the threshold exceedance was associated with the high period, or events with wave heights greater than 0.5 m and peak periods above 15 seconds for both design vessels. In addition, winter waves also presented some events when these criteria were exceeded, which was associated with high sea waves and strong local winds.

By adopting the ROM criteria, the roll motion was found to be the critical parameter and drive the downtime estimation.

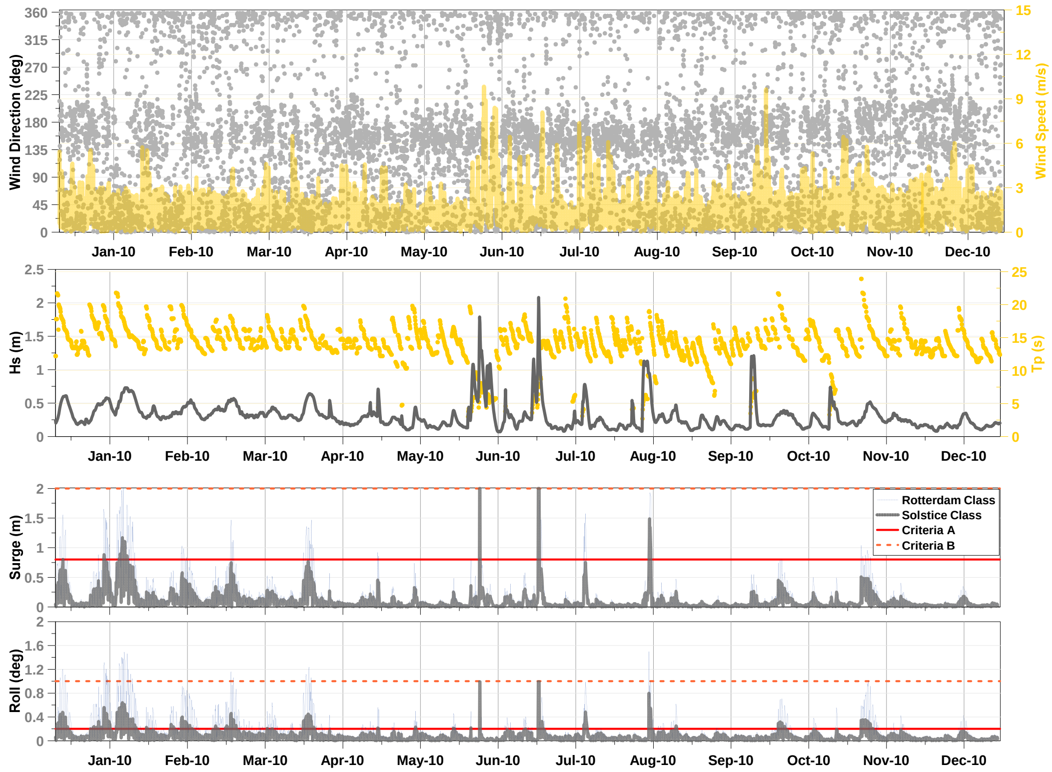

Figure 8: (A) Winds, (B) Waves, (C) Peak-Peak Surge, (D) Peak-Peak Roll. - for 2010 and operating thresholds under Criteria A and B

In contrast, the Nordforsk criteria developed for the operation of the ship at sea (seakeeping), where roll values of up to 2 degrees are allowed for cruises. The sensitivity between criteria is important for roll, where adopting a small threshold implies assuming a significant amount of downtime in contrast to the rest of the recommendations for similar ships. It must be kept in mind that the priority for this type of operation corresponds to avoiding mooring lines breakage due to ship movement.

For this particular case, differences on downtime estimations for both limit criteria analyzed, can reach 11% for the Solstice Class and 26% for the Rotterdam Class in Scenario 1 during the cruise season, while for the entire year the differences are 7% and 19% for the Solstice and Rotterdam Class respectively.

The results of Scenario 2 indicated that the wind and its variability are important, which makes sense when considering the characteristics of these ships with large superstructures. When variable wind speed was considered in the model, the downtime increased independently of the limit criteria adopted. Using an average constant wind value does not correspond to a conservative scenario for the estimation of downtime.

From the results of Scenario 3, it was evident that there are particularly severe years, which, in this particular case coincide with very intense El Niño/ENSO events, and some months experienced significantly higher downtimes than typically seen during regular years.

6 CONCLUSIONS OF THE VALPARAISO STUDY

The downtime analysis of the new jetty was conducted considering the following criteria:

- Allowable maximum vessel motion. The existing literature does not come to an agreement on reasonable thresholds for exposed cruise ship terminals, rather, a wide range of values can be adopted depending on the guideline/recommendation followed. The Spanish ROM establishes highly restrictive criteria for cruise ships without making any distinction on the type of terminal considered, specifically for rotational degrees of freedom, which 0.2 degrees (peak-to-peak) is recommended not to be exceeded. Given the ROM conservative recommendations, the Nordkforsk criteria was used instead to define the maximum allowable accelerations at the upper deck of the vessel while at berth and a maximum motion of one meter (peak-to-peak) at the passengers door.
- Tensions in mooring lines. A limit of 50% of the MBL was established for each line with a safety factor of two.
- Loads on fenders shall not exceed the rated reaction.
- Meteorological and oceanographic conditions. The analysis was conducted considering only one year of wind data from a publicly available source near the location of the new jetty. It was therefore recommended to develop a detailed wind study with site measurements that can reduce the uncertainty on the analysis and the impact over the downtime estimation.

Regarding the results, differences on downtime estimations for both limit criteria analyzed, can reach 11% for the Solstice Class and 26% for the Rotterdam Class in Scenario 1 during the cruise season While for the entire year the differences are 7% and 19% for the Solstice and Rotterdam Class respectively.

The existing literature for reasonable allowable downtime levels is scarce. Some authors proposed however a maximum annual average downtime of 2% for Nordic countries. On the other hand, Thoresen (2003) suggested two general recommendations without mentioning a specific type of cargo:

- Annual downtime (including stoppages caused by ship movements, maintenances, no availability of tugs, etc.) less or equal to 5%.
- Monthly downtime must not exceed 15%.

Thoresen highlights that these limits are specific to each project and must be evaluated case by case.

The Spanish ROM mentions that for liner service terminals (passengers, containers, ferries) 200 hours per year and 20 hours per month of downtime can be acceptable. These values can be increased twice when the utilization of the terminal is equal or less than 20%.

To decrease the probability that the cruise ship operation may be affected by site conditions, the following is recommended:

1. While the forecast systems allow for the advance warning of meteorological and oceanographic conditions, it is further recommended to develop a wind and wave forecast system in order to verify the operational windows for the cruise ship calls.
2. It is also recommended that the terminal implements a ship condition monitoring system, and establishes a protocol for recording vessel motions at the site, including extreme movements, breakage of mooring lines and damage on fenders.
3. To develop an action plan for those events the forecast and monitoring systems identify may affect the terminal operation
4. To implement state-of-the-art devices that reduce the ship movements at locations exposed to long swells. It is recommended to study the suitableness of these devices on the proposed site and the potential downtime reduction. Due to the characteristics of the exposed site, it is recommended that the terminal operators maintain a pre-tension system and change of the old mooring lines.

7 FINAL DISCUSSION

To evaluate the potential downtime due to motion, we reviewed the literature in regard to guidelines and recommendations for acceptable motion of cruise ships. References available includes PIANC (1995), Spanish ROM, and Nordforsk (1987).

In conducting the analysis, we identified a need for further investigation and developing guidelines and recommendations regarding the accommodation and the behavior of moored cruise vessels in locations where long period waves are present. Not only the recommended ranges varied greatly between the references, but the literature also suggested a wide range of decision parameters and variables.

It is therefore suggested further investigating, unifying criteria and developing new updated guidelines considering the specific requirements of the cruise ship industry, and defining, specifically, the following parameters:

- Maximum allowable vessel motion and rotation during berthing, unberthing and passenger disembarking
- Maximum wave height and period in relation to the design vessel dimensions
- Maximum wind speed in relation to the design vessel dimensions

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