RESPONSE OF MOORED VESSELS IN BUFFINGTON HARBOUR

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ABSTRACT

In a temporary facility built within Buffington Harbour, it was proposed to operate two floating vessels as casinos. An extensive program of physical and numerical model investigations was undertaken to design a harbour and mooring layout that would ensure effective operation with minimal downtime for casino operations. Through a sophisticated model testing program, the motions of the floating vessels were established for different sea states. These motions were then used as inputs to a ship simulator where client representatives participated in the full scale simulations in order to select the sea states that would cause discomfort to clients.

INTRODUCTION

Lehigh Portland Cement Company is the owner of Buffington Harbour facilities in East Chicago. Barden Developments and Trump Indiana proposed to operate two floating casino vessels in a recently constructed temporary harbour facility built within the existing Buffington Harbour. The facility is now complete and the two vessels are in place. Figure 1 shows an overall view of the harbour and the casino ships.

The two vessels are moored on either side of a floating barge/passenger loading dock, which services both vessels. The vessels leave the harbour and enter Lake Michigan whenever weather conditions permit, otherwise operations continue while moored. Being a temporary facility intended for several years' use only, it was important to keep costs down, while providing protection from waves to enable operation under most environmental conditions. This includes entry/exit to the harbour.

Baird & Associates was retained by Lehigh Portland Cement Company to develop preliminary and final designs for marine structures required to protect the vessels, and also to carry out tasks such as permitting, preparation of contract documentation,

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contractor negotiations and construction supervision. Analysis of environmental parameters (wave climate and water levels), physical and numerical model investigations of harbour wave agitation and response of the vessels, were parts of this study (Baird & Associates, 1996).

The Canadian Hydraulics Centre of the National Research Council of Canada was contracted by Baird & Associates to undertake physical model investigations to determine vessel motions and related mooring line loads for a variety of lake and harbour wave conditions. This information was required to establish downtime during which casino operations should be suspended due to excessive vessel motions.

PHYSICAL MODEL INVESTIGATIONS

Figure 2 shows a photograph of the two model casino vessels and the loading barge under study, while Figure 3 presents the layout of the harbour basin that was tested in the physical model. The model scale used for this study is 1:45.

This harbour layout, considered optimal, was established through a wave agitation study carried out earlier by Baird & Associates. Six different harbour concepts were studied under different combinations of wave heights and directions. This final harbour concept, with the proposed structures for casino operations, was tested as part of the ship mooring study, by measuring directly the response of the vessels induced by wave heights prevailing inside the test basin.

It should also be pointed out that physical model tests were carried out to assess the stability of the breakwater materials (armour, filter and core stone) on the north rubble mound structure. The potential impact of a storm during construction was also determined in a separate series of tests where the breakwater was constructed to varying degrees of completion and then subjected to a storm event. As a result of this work it was recommended that a 100 ft long revetment section, which extends along the west breakwall to the north of the north rubble-mound structure, be constructed (see Figure 3).

VESSEL CHARACTERISTICS

All three vessels, Trump Princess, Barden I and the barge were built at a 1:45 scale. Care was taken to reproduce as accurately as possible the salient characteristics of the vessels, including their hydrostatic conditions. Given below are some of the main characteristics of the vessels:
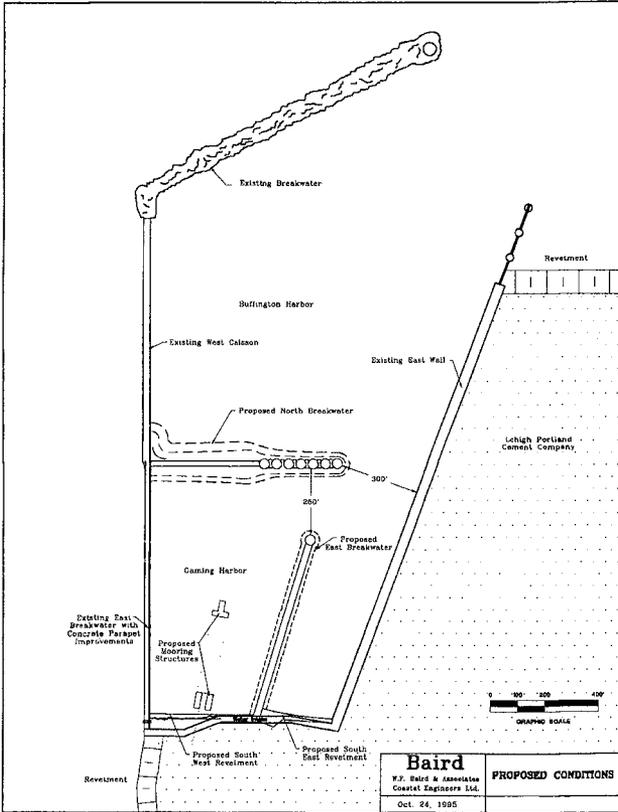
Characteristics	Trump Princess	Barden I	Barge
Length (LWL)(ft)	226	291	295
Beam (ft)	74	72	54
Draft (ft)	10.5	12	3.5
Displacement (tonne)	3570	2934	1584
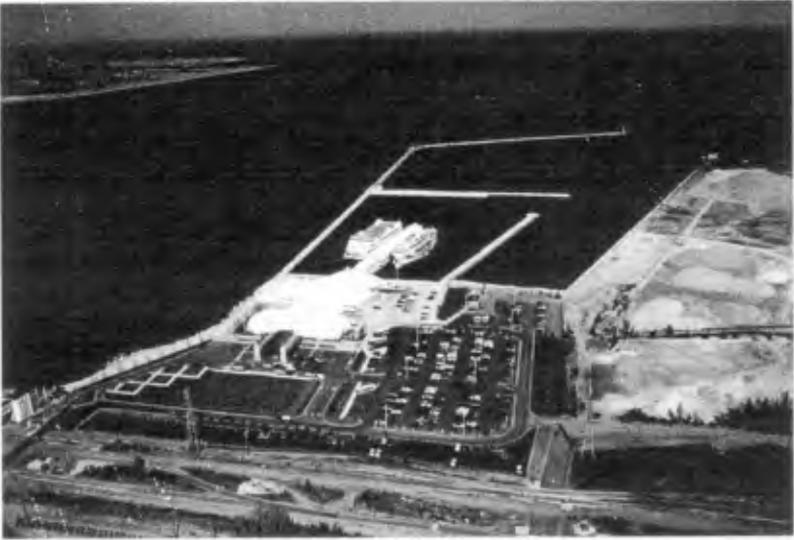
Figure 1: Overall View of Buffington Harbour and the Casino Facilities
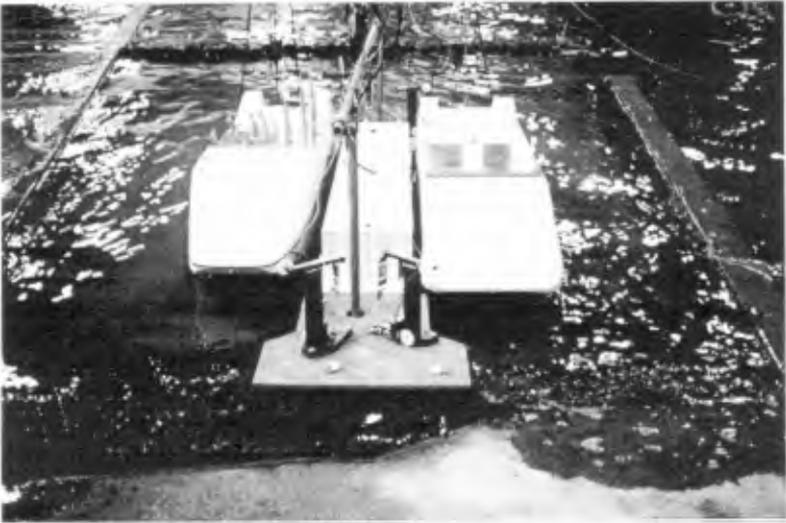
Figure 2: Photograph of Model Vessels in the Test Basin

Figure 3: Proposed Layouts of the Harbour and the Breakwater

WAVE CLIMATE

A wave machine located outside the model harbour generated the waves in the harbour. The drive signals to this wave generator, were already available from the initial phase of this study when the optimization of the harbour was investigated. To create these driving signals, irregular wave time series, having a record length of 20 minutes prototype, were synthesized from a spectrum using the random phase spectrum method.

An array of three gauges was deployed near the offshore region to monitor the water surface elevations and to resolve the incident and reflected wave fields from them. The range of wave heights (H_{m0}) and peak period (T_p) used during the testing program is shown in Table 1.

MEASURED VALUES

H_{m0}	T_p
(ft)	(s)
4.7	7.2
5.6	7.2
6.4	5.9
6.7	7.8
7.1	10.1
9.2	9.0
11.4	9.0

Table 1: Incident Wave Characteristics during the Ship Mooring Tests

The waves were run from two different directions: 41 degrees East of North and 56 degrees East of North. The water level was varied from 4.7 ft to 6.4 ft (with reference to low water datum) in order to reflect the range in design water levels expected for this temporary harbour. Some additional tests were also carried out using sea states $H_{m0} = 8$ and 10 ft, with $T_p = 8s$.

MOORING

Mooring Line Simulation

Figures 4 and 5 show the layout of the mooring lines, with the locations of the bollards on the barge, the end piers and both ships. From these locations, a line length was derived for each mooring, to which 4 to 6 feet was added in order to include the distance between the fairlead and the bollards onboard the ship.

All lines were made of 2 5/8 inch diameter double braid polyester assumed to have a constant unit stiffness EA $= 2.353 \times 10^3$ kips per foot of elongation per unit length, over the expected range of tensions. The bow and stern moorings were made of three lines in parallel, whereas the spring lines were only single lines. The net stiffness of each mooring was (n EA)/L, where n is the number of lines per mooring.

A thin steel cable attached to a set of springs simulated the elasticity of each mooring line. The springs were pre-calibrated to the desired load/elongation characteristics of the lines. Each line was also connected to a load cell to monitor the instantaneous loads. The hardware was designed in such a way that variable levels of pre-tension can easily be set in the mooring system (see Figure 6).

Static Verification of the Mooring Line Simulation

In order to verify that the mooring line simulation and the load cells gave the appropriate results, a simple static experiment was performed. A known force was applied horizontally at mid ship of the Trump Princess, pulling the ship away from the barge. At
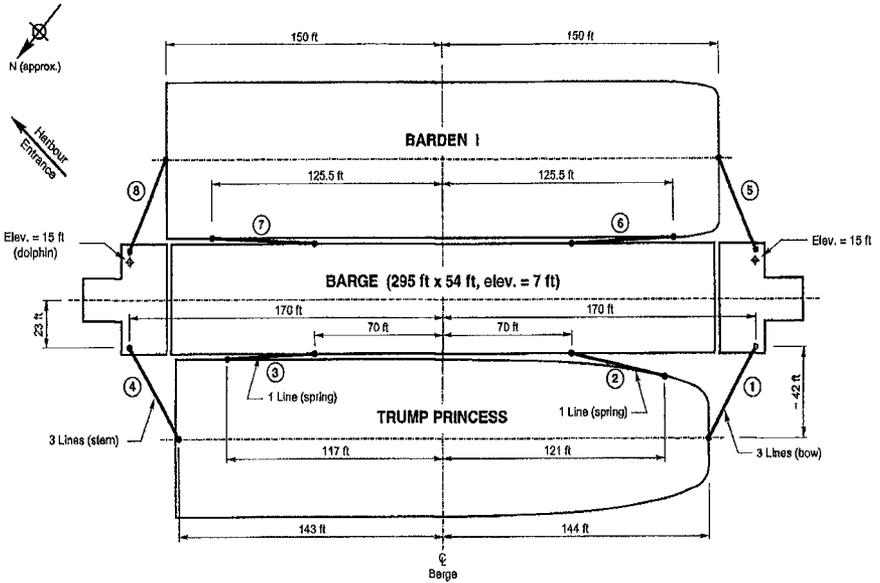
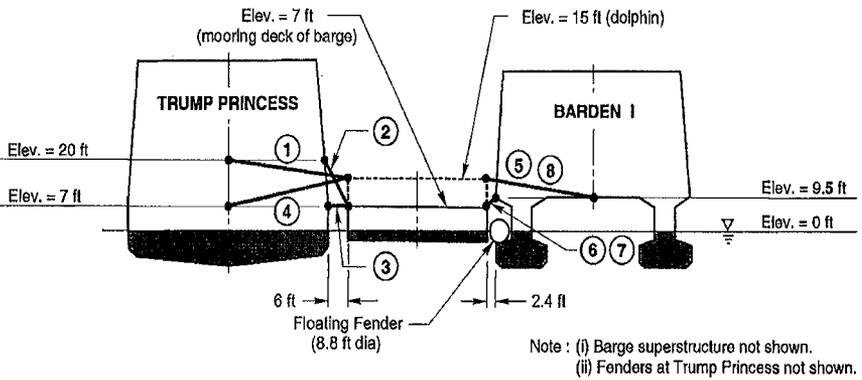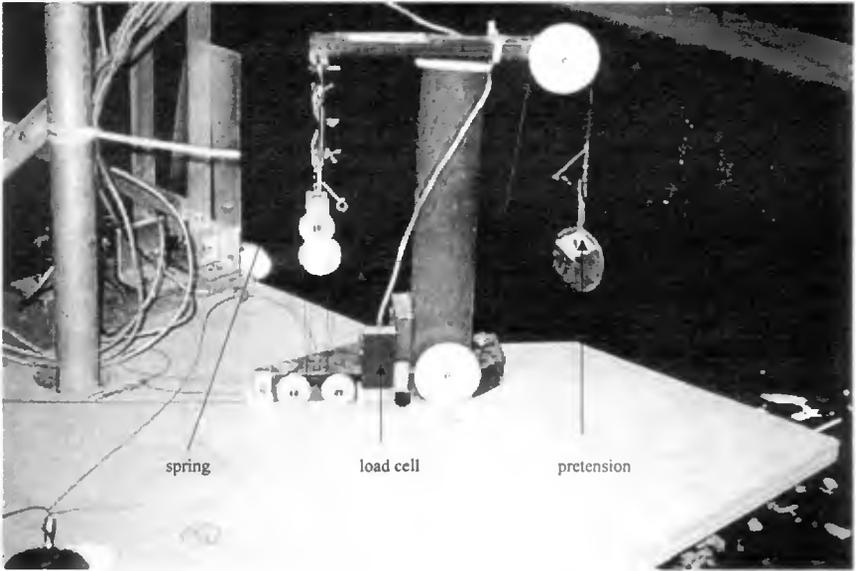**Figure 4: Buffington Harbour Moorings – Plan View**

Figure 5: Buffington Harbour Moorings – End View

Figure 6: Mooring Line Simulator

the same time the two spring lines were disconnected to ensure that only the two port
bow and stern lines were under tension. These line tensions were sampled and analyzed
by the same software used during the project. Table 2 shows the theoretical tensions
required to balance the system based on the geometry of the moorings, and the measured
values.

Weight	Bow Port Line Tensions (kips)			Stern Port Line Tensions (kips)		
(kg)	Theory	Measured	Diff (%)	Theory	Measured	Diff (%)
1.003	105.84	110.29	4.0	106.13	108.68	2.3
2.004	211.45	217.17	2.6	212.04	212.11	0.0

Table 4. Mooring Tensions During Static Tests

The difference between the theoretical and the measured values shows the effect of the
line friction when it goes around the fairleads. This test was a static test. It is expected
that during dynamic simulations, these differences would be smaller since a dynamic
friction coefficient is usually smaller than a static one.

Fenders
For the Trump Princess, three fenders were installed on the barge at the 7-ft elevation
(above Low Water Datum). They consisted of a piston and a linear spring inside a
cylinder bolted to the barge deck. The spring stiffness corresponded approximately to 130

kips/ft. The contact surface between the ship and the fender (the plastic head of the piston) was very small.

For the Barden 1, two fenders were installed to simulate Yokohama fenders as proposed by naval architects. They consisted of a circular pipe simulating round fenders 8.8 ft in diameter and 11.8 ft long, floating on the water surface and free to move, but within limits. These pipes could be considered as having no elasticity in compression.

INSTRUMENTATION

Two different types of instrumentation were used to measure the six degrees of freedom of motion on the vessels: Qualisys and accelerometers.

Qualisys
During the harbour tests, one of the ship models was instrumented with the Qualisys position system. This optical tracking system was used to measure the vessel position in six degrees of freedom. Its principle of operation is as follows: A light beam is sent from two fixed cameras which reflect from an array of eight reflective markers mounted on the vessel. The reflected light is captured by the cameras and processed by a computer/video system, which calculates the exact position of each reflected light beam every milli-second. Software is then used to convert the light positions into x, y, and z positions for the vessel. This results in a very accurate measurement of surge, heave and sway of the vessel within ±0.5 mm (±1 inch prototype) and roll, pitch and yaw angles within ±0.1 degrees. Note that the low frequency motions of the vessels can be measured accurately by this system.

The marker array is surveyed to locate the relative position of each marker and the array position relative to the vessel. To provide synchronization with the mooring forces data, a vertical heave accelerometer was installed on each vessel. It also provides a cross-check with the heave motion measured by the Qualisys system. To obtain the motions of the second ship, each test was repeated with the Qualisys system installed on the other ship. Care was taken to ensure that the repeated tests provided similar estimates of mooring line loads.

Accelerometers
The six degrees of freedom motions of the vessels can also be measured by an array of seven accelerometers. These units are precision linear servo accelerometers that are specifically designed for high accuracy applications at frequencies from 0 to 100 Hz. The QA-900 servo electronics generates a current that maintains a seismic element in a position-captured mode. The current required to keep the sensor mass stationary is thus proportional to the applied acceleration. These sensors have a measurement range of ±1 g, a resolution of 5 μg and a maximum linearity error of 30μg.

To obtain the displacements from the accelerations, an iterative analysis procedure was used to solve the full nonlinear differential equations that relate the various rigid body

displacement motions to the local accelerations measured at the seven discrete points. This iterative procedure employs a technique based on the Fast Fourier Transform (FFT).

The analysis method has been validated by comparing tests undertaken with a precision optical tracking system as described in Miles (1986). Within its valid frequency range, it can measure ship model motions with a typical accuracy of ± 1mm in surge, sway and heave and ±0.1 degree in roll, pitch and yaw. This instrumentation was used to measure the pitch and roll motions of the barge. Small plastic screws inside fixed aluminum brackets at the bow and stern restrained the barge. This provided freedom in heave, pitch and roll but prevented any significant surge, sway or yaw motion.

The barge was also equipped with a light vertical line running over a pulley to a small weight so that heave displacement at the midship point on the centerline could be measured directly. This was done by using a calibrated potentiometer that measured the angle of rotation of the pulley, which was linearly proportional to the heave displacement of the barge at the centre point.

TEST REPEATABILITY

Since the Qualisys system can measure the motions of only one vessel at a time, the tests were repeated in order to measure the motions of both the vessels (Trump Princess and Barden I) under each wave condition. Therefore it was essential that similar results were obtained when the tests were repeated. There were also two other issues: potential resonance build-up inside the harbour basin, and inadequacy of sampling rate. Additional sensitivity tests were therefore undertaken in order to address these two issues as well. These tests are described below.

Same Test
All tests were repeated at least once to be able to measure the motion of both ships with the same Qualisys system. In both instances, the mooring line tensions were measured, allowing a direct comparison. The cumulative distribution of the peak tensions calculated from these results indicated good repeatability. The small differences that were found could be attributed to the friction forces from the fenders against the ships and from the lines passing through the fairlead.

Wave Build-up in the Model
In order to ensure that there is no wave build-up in the model due to possible basin resonance, some tests were run for 40 minutes full scale instead of 20 minutes. The first 20 minutes and the next 20 minutes were analyzed separately. No differences in peak tension were found, implying that there is no wave build-up in the basin.
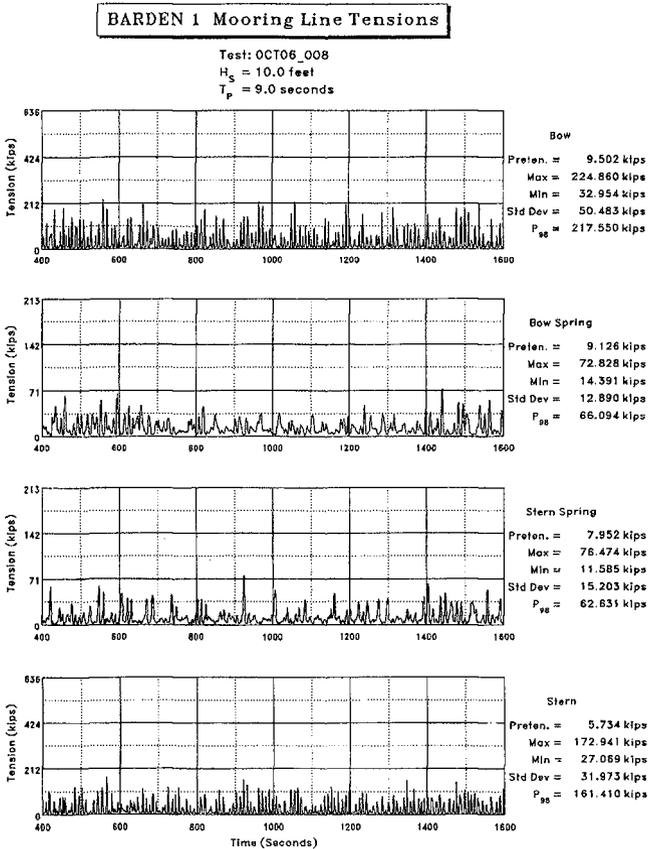
Effect of Data Sampling Rate
All channels were sampled by the data acquisition system at a rate of 20Hz. Additional tests were also undertaken at a higher sampling rate of 100 Hz to determine whether or not all peaks in the mooring tensions were measured properly or if there were other high

frequency phenomena. Once again the cumulative distribution of the peaks were examined. They were similar, implying that the 20 Hz sampling rate was sufficient.

TEST RESULTS

Mooring Line and Fender Loads

The mooring lines and fenders were modelled for all three vessels with each one requiring a unique setup to match the proposed prototype configuration. These tests included pretensioning the lines, modelling line elasticity, and fender stiffness. Mooring tensions were measured for each mooring line of both the Trump and Barden vessels (see an example of a graphical output of these measured tensions in Figure 7).

BARDEN 1 Mooring Line Tensions

Test: OCT06_008
H_S = 10.0 feet
T_P = 9.0 seconds

Bow
Preten. = 9.502 kips
Max = 224.860 kips
Min = 32.954 kips
Std Dev = 50.483 kips
P_{98} = 217.550 kips

Bow Spring
Preten. = 9.126 kips
Max = 72.828 kips
Min = 14.391 kips
Std Dev = 12.890 kips
P_{98} = 66.094 kips

Stern Spring
Preten. = 7.952 kips
Max = 76.474 kips
Min = 11.585 kips
Std Dev = 15.203 kips
P_{98} = 62.631 kips

Stern
Preten. = 5.734 kips
Max = 172.941 kips
Min = 27.069 kips
Std Dev = 31.973 kips
P_{98} = 161.410 kips

Time (Seconds)

Figure 7: Example Output of Barden I Mooring Line Tensions

From the time series of the mooring line tensions, the peaks (defined as the maximum occurring between two average values) were identified and statistically analyzed. These time series and also some basic statistics of the line tensions associated with each mooring line (pretension, maximum, minimum, standard deviation, and 98 percentile loading level) were summarized for each test conducted as shown in Figure 7. Note that the maximum scale in the Y-axis corresponds to the estimated breaking strength of the lines.

Motions
The six degrees of freedom motions of the two vessels derived from the Qualisys system corresponded to the motions at the centre of gravity of each vessel. By additional calculations, the motions and accelerations corresponding to the gaming room locations could easily be estimated. The summary results were then presented in terms of the significant amplitude for each degree of freedom. It is equal to twice the standard deviation of the motion, and is analogous to the concept of significant wave height (which is equal to four times the standard deviation). Figure 8 shows the increase in significant amplitudes of the various motions with the wave height, for Barden I.

The passengers will board the vessels from gangways located on the barge. To obtain the motions of the gangways, the relative motions between the vessels and the barge were also calculated.
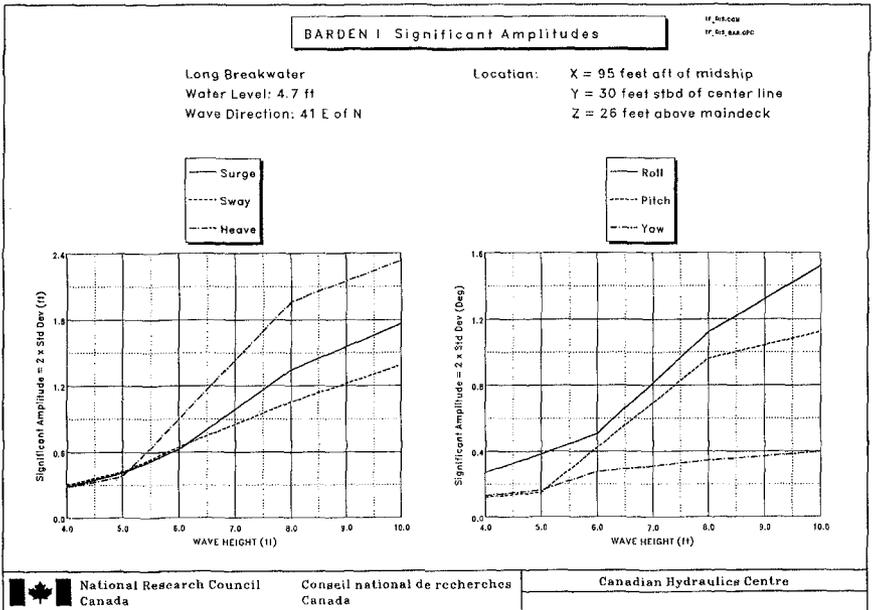
Figure 8: Six Degrees of Freedom Motions of Barden I

PASSENGER COMFORT

Determining the frequency of occurrence of ship motions, which exceed acceptable motions for client comfort, was a very important task in the design of the entire harbour facility. For this purpose, the motions and accelerations at various positions on both the gaming and loading barge vessels were computed in order to provide inputs to a full-scale ship simulator. The full scale simulator was utilized by representatives of both the Trump Princess and Barden as well as the naval architects, coastal engineers, and a human resources consultant, at the Marine Institute in St. John's, Newfoundland. During these tests, a series of gradually increasing motion and acceleration data sets were used to drive the simulator. The participants were inside the simulator room, but were not provided with external visuals (equivalent to casino without windows). The majority of the simulations were conducted for the most aft outside gaming position on the third level of the Trump vessel as this represents the most active part of the vessel during a storm condition. Other areas tested included more central gaming areas such as the first deck towards the centre of the vessel. These areas were tested to determine whether or not it would be feasible to continue gaming in some areas of the vessel should motions become excessive in the most active areas.

These tests, in combination with the motion and mooring line tension data sets and naval architects' input, resulted in a decision by the Trump and Barden representatives to limit gaming operations after wave exceed a significant wave height of 6 feet, and a peak wave period of 8 s or higher, offshore of Buffington harbour. Wave height levels of 6 feet (with peak periods less than 8s) or lower were considered acceptable for gaming at any position on the vessel. The surge motion was the most critical to passenger comfort.

FINAL RESULTS

The participation of the entire project team including naval architects, ship captains and representatives of Barden and Trump Princess during the test program facilitated the selection of the best possible design of the harbour facility. For example, the ship captains were able to maneuver the scaled ships through the model harbour entrance and the model harbour basin. They were able to observe vessel behaviour under a variety of wave conditions both while moored inside the basin and while offshore. Their comments were critical in choosing the optimal harbour layout. Similarly, the naval architects were able to observe the complex interactions that occur between the three floating vessels and to review the forces on each mooring line, which impacted the design of the mooring structures and the mooring arrangement. It also influenced the design of mooring points on the vessels themselves and the access points(gangways).

As a result of the mooring tension tests, the ship simulator tests, and design team meetings to discuss the related issues, three specific operating and related mooring conditions resulted. They are defined as follows:

Condition 1: Open Lake Cruising

Condition 1 mooring covers routine operations when the boat will be departing the harbour at regularly scheduled two-hour intervals, and then returning to the dock to exchange passengers. During this operation, one bowline, one stern line and one each forward and aft spring line will be deployed to moor the boats. This mooring arrangement will be adequate to permit safe loading and unloading of passengers, and will allow rapid deployment and release of mooring lines. The maximum permissible conditions of the wave and wind environment is expected to be limited by vessel maneuverability inside the gaming basin. At present this limiting environment is undefined and will be determined with experience. Environmental loading on the vessel is expected to be low.

Condition 2: Operating Alongside the Dock

When waves on the lake will produce vessel motions that are uncomfortable or unsafe to passengers, or winds are too high to permit safe maneuvering in or out of the harbour, gaming operations may be permitted with the vessels moored alongside the dock. In this case a heavy duty mooring system will be deployed which will secure the vessel to the dock, and will help limit vessel motions in surge and sway.

Condition 3: Survival

When wave conditions inside the harbour result in vessel motions that exceed limits determined for passenger comfort or safety, gaming operations will be shut down, and the passengers and unnecessary personnel will disembark. Additional storm mooring lines will be deployed to the breakwater dolphins, if they have not been rigged. The stern anchor line should also be connected. The gangways will then be pulled back from the vessels and the vessels will be moved off to the storm mooring position, approximately 40 feet off the dock. These conditions are expected to occur for 70 hours per year, on average. Five different storm-mooring configurations were tested in the physical model in order to find an optimal one.

CONCLUSIONS

The physical model provided results that were crucial for effective operation of the harbour with minimal downtime, and for determining an optimal design of the mooring layout and harbour structures.

By combining the frequency of occurrence of storms and the clients determination of acceptable level of motion, it was possible to make timely cost benefit decisions relating to harbour design and permissible wave agitation levels, while meeting the clients operational requirements and schedule objectives.

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