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3-Dimensional Hydraulic Physical Model Evaluation for the Los Angeles/Long Beach Harbor Operation and Maintenance Study

Final Report

Prepared for

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Emerald Ocean Engineering

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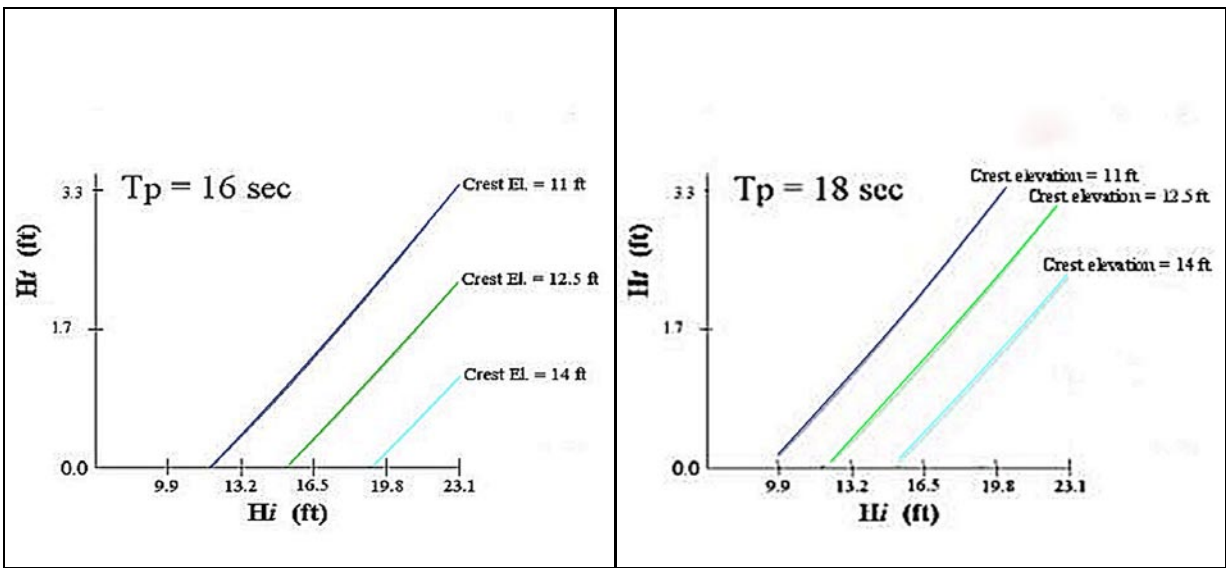
INTRODUCTION

The San Pedro breakwater, the westernmost component of the three breakwaters that protect the Los Angeles/Long Beach Harbor (LA/LB) complex (Figure 1), was constructed between 1895 and 1915. A survey of the entire three-breakwater system was recently performed using airborne mapping methods, bathymetric mapping sonar, side scan sonar, and visual observations (USACE 1996). The survey revealed that the crest of the San Pedro Breakwater ranges 1 to 3.5 ft below the +14 ft MLLW design elevation. The causes are not known at this time, nor is it known whether settlement will be progressive. However, the protection level afforded to the harbor is reduced, relative to the design elevation. Of particular concern is the potential for impacts on Port operations from increased low frequency wave energy levels at various terminals inside the harbor.

Figure 1. Aerial View of Los Angeles/Long Beach Harbor Complex

Wind waves have periods from about 1 to about 22 seconds, though some extremely long swell may have periods approaching 30 seconds. The wind wave climate outside of LA/LB is characterized by Rosatti, McKinney, and Puckette, 1998, based upon seven years of measurements at Platform Edith, located 9 miles offshore of the harbor. The average wave height in the most energetic month, January, was 3.7 ft. The highest wave measured was 18.5 f with a period of 16 sec, and waves around 10 ft were observed several times a year.

The basic function of a breakwater is to reduce the amount of wave energy entering the harbor. Wave energy propagates into the harbor through harbor entrances, and through and over the breakwater. Crest elevation is the controlling factor in the amount of energy overtopping the structure. There are no field measurements to correlate the amount, or even incidence, of overtopping at San Pedro breakwater with specific incident wave conditions, but overtopping has been observed routinely on the existing structure. Predictions of overtopping using the Coastal and River Engineering Support System by IHE Delft are shown in Figure 2. The transmitted wave height is calculated as a function of incident wave height and crest elevation, for an incident wave with a period of 16 sec (a) and 18 sec (b). For the 18.5- ft observed wave the predicted transmitted wave height is about 1 ft for the existing crest elevation, and near zero for the design crest elevation. If the incident period increases to 18 sec, which is not unusual in southern California, the difference between design and existing crest elevation is approximately a doubling of the transmitted wave height.



(a) **(b)**

Figure 2. Overtopping Wave Height for a 16-sec (a) and 18-sec (b) Incident Wave

Low frequency waves (also called long waves or infragravity waves) have periods that fall between the longest wind waves and the shortest tidal components, or from about 30 sec to 500 sec. Long waves can be found in two varieties: bound or free. Bound long waves are manifestations of groupiness in wind waves and the associated variation in set up in the water level. Bound long waves are forced to travels at the group velocity of the wind waves. Free long waves propagate through the water independently of shorter waves, and travel at the wave celerity associated with their period and the water depth. It is generally accepted that bound waves are “liberated” when their carrier wind waves break or reflect from a breakwater, and can then propagate as free long waves, but the exact mechanism of how this happens is still a topic of research. Other mechanisms for generating long waves in the ocean, such as oscillating atmospheric pressures, have been proposed. In any case, long waves in the open ocean have small amplitudes (on the order of one or two cm). However, once long waves are present inside of harbors, their amplitude can be amplified if their periods are close to the various resonant modes of the harbor or of individual basins in the harbor.

The harmonic “sloshing” back and forth of water in a harbor or basin is called seiche. Even when amplified, the amplitude of seiche motions is usually only a few cm, - less than a typical wind chop due to a light breeze - so seiche is seldom visible to the casual observer However, seiche can have very long periods and can contain a significant amount of energy. The period of the seiche is proportional to the size of the basin; in LA/LB, the periods of importance range from approximately one minute to as long as 30 minutes. Seiche is a significant concern in LA/LB harbors because of its impact on ship motions and ultimately, port operations (McGehee, 1991).

A free-floating ship is free to both translate along and rotate around three orthogonal axes. These motions are called surge, heave and sway, and pitch, roll, and yaw. Buoyancy acts as a restoring force on pitch, roll, and heave, so these are always oscillatory, or periodic, with natural frequencies governed by the vessel hydrodynamics. Mooring ship at a berth restricts these motions, but cannot completely eliminate them. In addition, the elastic nature of the mooring loads makes surge, sway, and yaw oscillatory as well. When the period of seiche in a basin is near the natural frequency of oscillation for a vessel in one or more of these six degrees of freedom (typically from one to several minutes), resonant oscillations build up in that motion. Once resonant oscillations commence, amplitudes of the vessel motion can build up to several m, large enough to damage vessels or berths, hamper loading and unloading, and even break mooring lines.

Low frequency wave energy in the harbor has been strongly correlated with wind wave energy offshore (Seabergh, 1999), so it is reasonable to question if increased overtopping by wind waves will increase low frequency wave energy in the harbor. This study was designed to address two specific questions:

1. Does the present condition of the breakwater result in significantly more low frequency wave energy in the harbor, compared to a structure at the design crest elevation?

2. What are potential future impacts on low frequency energy in the harbor if crest loss continues?

The amplitudes of the low frequency waves outside of the harbor are negligible relative to the breakwater dimensions, so it is obvious that the crest elevation will have no effect on direct transmission of free low frequency wave energy until the crest approaches the still water level. The first issue of the study became how to predict the indirect influence, if any, of overtopping wind waves on low frequency wave energy levels in the harbor, and the sensitivity of that influence to crest elevation. A numerical solution was considered, but had to be rejected. Two numerical models that have been used to investigate resonance in LA/LB are CGWAVE and

BOUSS2D. CGWAVE is a steady state solution to the mold slope equation, and while it includes non-linear wave propagation, it cannot duplicate the wave-wave interaction between wind waves and low frequency waves (Demirbilek and Panchang, 1998). BOUSS2D is a time-dependent, two space dimensional solution of the Boussinesque equation, and does simulate spectral energy transfer (Demirbilek, in prep). However, neither model can simulate wave overtopping.

Overtopping is typically simulated with large-scale, 2-d physical models (Carver, Dubose, and Wright. ♣93; Hudson. ♣61; Jackson.♣67; Keuligan, ♣73) to minimize the scale effects associated with surface tension and air entrainment. But simply measuring the overtopping on a typical section of breakwater in a flume would not answer how the overtopping wind wave energy is transformed into low frequency seiche energy. An overtopping wave impinging on the back side of the harbor surface is somewhat analogous to an impulse load, in that a broad range of frequencies are produced. The way the energy in those frequencies is propagated, attenuated, ort amplified depends upon the shape of the basins the harbor. In other words, a 3-dimensional (3-d) model is required to simulate the complex pattern of low frequency waves that will result in the harbor.

A 3-d physical hydraulic model of LA/LB (Figure 3) has been in use at the US Army Engineer Research and Development Center (ERDC) since 1973 to investigate many effects of harbor modifications on tidal circulation and harbor resonance (Seabergh, 1993). It was decided that this model was the only cost and time effective tool available to address the objectives. However, this required developing a testing program that could adapt the model to a purpose it was not designed for.

Figure 3. LA/LB Model at ERDC; View Looking Northeast with San Pedro Breakwater in the Foreground

METHODOLOGY

Model Description

The Los Angeles and Long Beach Harbors model, originally constructed in 1973, was molded in concrete grout at a vertical scale of 1:100 and a horizontal scale of 1:400 that reproduces San Pedro Bay and the Pacific Ocean seaward of the harbor out to the -91.5-m (-300-ft) MLLW contour. The model shoreline extended from 3.2 km (2 miles) northwest of Point Fermin to Huntington Beach. The total area reproduced in the model covered about 474 sq m (44,000 sq ft), representing 655 sq km (253 square miles) in the prototype. See Figure 4.

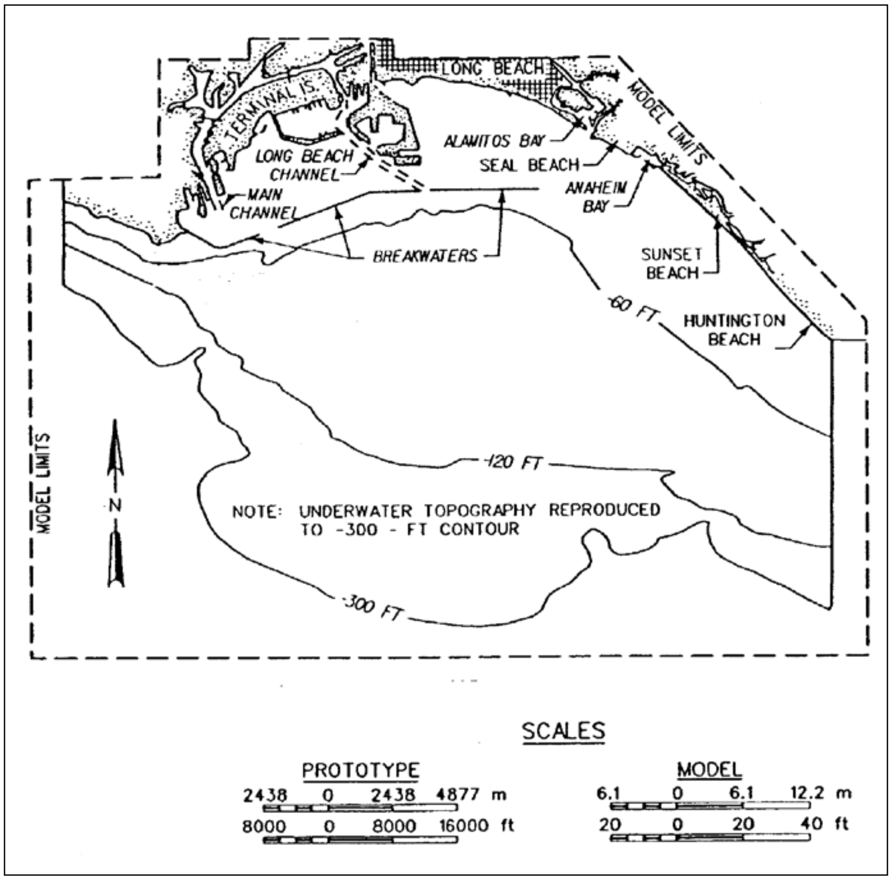


Figure 4. Layout of LA/LB Model

The model breakwater was originally constructed with an impermeable crest at an elevation of +14 ft MLLW (prototype), made from concrete cap segments, placed on top of a permeable rubble base. The size of the particles in the base section was selected to duplicate the (scaled) porosity of the prototype, based upon larger scale flume tests. Surveys conducted at the beginning of the study placed the present model crest elevation at +13 to +14 ft MLLW, so some minor settlement had occurred over the years.

The first test series was run with the existing crest elevation of +13.5 ft. A second test series was run with the crest manually adjusted downward to the current elevation of +12.5ft; that is, pushed down 0.01 ft at the model scale. This method of adjusting crest elevation would not be suitable to test a wide range of crest elevations. Grinding down and/or recasting the concrete segments were considered but dismissed as too time consuming and expensive. Mr. Bob carver at ERDC devised a clever and efficient solution. The concrete segments were removed and replaced with segments made from high-density, water resistant clay. The clay crest segments were easy to shape for any desired crest elevation and could be placed rapidly by hand.

Wave Generator

The electro hydraulic wave generator is composed of 13 segments, each independently controlled with a computer-generated command signal and equipped with a 4.57-m paddle. The segments can be positioned to approximate a curved wave front 23,744 m long (prototype). Random waves with a given energy spectrum can be simulated by the generator approaching from the south. All segments must move in phase with each other, but the gain in each segment can be varied. This allows a modest amount of directional variability, but large changes in wave direction require repositioning the segments, a major effort that was not an option for this study.

Data Acquisition

Wave data acquisition, wave generator control signals and feedback, and wave gage calibration were performed using an Automated Data Acquisition and Control System (ADACS). Wave data are collected at selected locations throughout the model. ADACS can handle 30 gages for each experimental run. The sensor used is a water-surface piercing, parallel-rod resistance type wave gage where the resistance between the two rods is measured and is directly proportional to submergence. This system can detect changes in water elevation to 0.03048 cm (0.001 ft), or within 0.5 per cent of the range of changes in most of the tests. Model wave data were collected at two sites between the wave paddle (Gages 21 and 24) and the harbor, and at 28 locations near the breakwater, the entrances, and throughout the harbor (Figure 5).

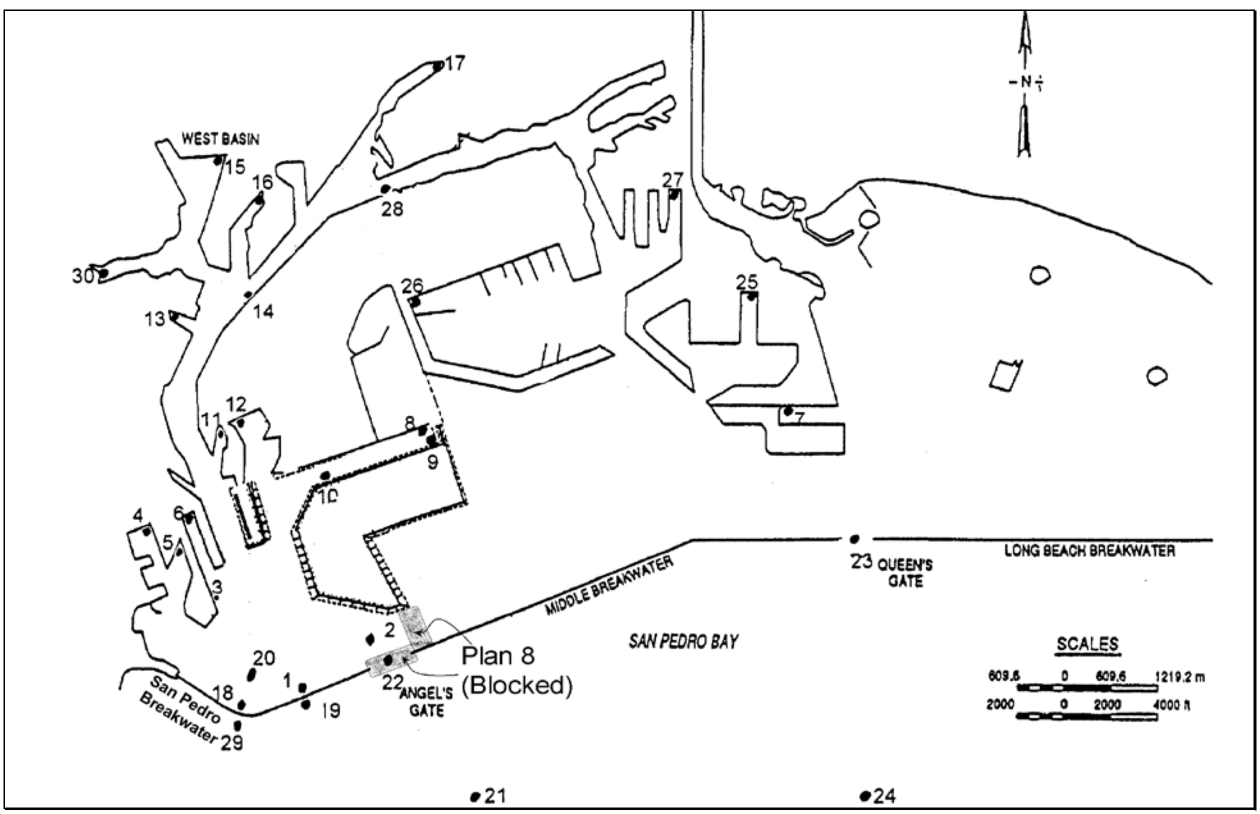


Figure 5. Location of Model Wave Gages

Study Constraints

In all previous studies of harbor resonance in the LA/LB model, low frequency waves were generated directly by the wave paddle and propagated into the harbor as free long waves. Prototype field data has shown there is some correlation (though not a simple one) between offshore wind wave energy and harbor resonant energy (Rosatti, McKinney, and Puckette, ■98). The ideal plan would be to generate model-scale wind waves large enough to overtop the breakwater in the model, and measure the resulting low frequency wave energy in the harbor for various crest elevations. The distortion of the physical model (its vertical scale is ¼ its horizontal scale) complicates this approach.

Seabergh, ♣93 describes how similitude is obtained in a distorted model. For diffraction and resonance, wave height can be scaled to the vertical sale, and wave length scaled to the horizontal scale respectively. Refraction is controlled by both vertical (depth) and horizontal (wavelength) scales, so similitude cannot be obtained for refraction and diffraction simultaneously. However, by assuming the shallow water approximation for celerity, the effects of the distortion on refraction can be neglected. Using this assumption, the time scale can be shown to be 1:40 for low frequency waves, with an error of under 1 per cent for waves with periods over 85 sec (prototype). The error in this assumption increases with increasing depth or decreasing wavelength, and would be quite large for the wind wave portion of the spectrum.

Physical limitations of the wave generator made this potential distortion error moot. Stroke and command signal limitations made the generator incapable of generating high frequency wave spectra with sufficient height to overtop the structure. Preliminary tests determined that the lower limit of wave periods for waves high enough to overtop the existing structure (O 10 ft prototype scale wave height) was 62.8 sec at prototype scale. Thus, the scaling impasse was replaced by another - the overtopping waves that could be generated in the model would not occur in nature (barring tsunamis). Such high energy-long period overtopping waves are extremely unlikely to occur naturally. Also, the way overtopping free long waves propagate through the harbor may be fundamentally different from the way long waves freed by overtopping wind waves do. The decision to proceed with the tests within these constraints was based on the following considerations and assumptions:

1. The incident waves will introduce wave energy into the harbor that varies with breakwater crest elevation.

2. Initial tests confirmed that these incident waves, just like wind waves in the prototype, produced oscillations in harbor basins at resonant frequencies well below the incident wave frequencies

3. Measured harbor energy will be normalized by incident energy. Trends in amplification of incident energy with crest elevation and incident wave energy at each site will be similar as for wind waves. By normalizing the amplifications again by the amplification at the existing crest elevation, the relative sensitivity of the amplification at any site to future changes in crest elevation can be obtained. Conversion of incident or harbor energy to prototype scale is neither valid nor required.

4. These incident overtopping waves, which transmit much more energy than overtopping wind waves, will serve as an upper limit for the prototype situation. If the effect of crest elevation is relatively small at a site for this study, then it will not likely be a problem for wind waves in the prototype. However, if significant problems are expected, additional and more refined testing would be indicated.

Testing Plans

Incident Waves

Incident waves were generated with a JONSWAP spectrum having a peak model period of 1.6 sec and a gamma of 3.3. Figure 6 is the undimensioned energy spectrum of the command signals for the 10 through 50 per cent gain levels. Five intensities of the spectra were used which produced wave heights at gage 21, in 200 ft of water directly in front of the generator, of approximately 0.02, 0.04, 0.06, 0.08, and 0.10 ft (model scale). The selected spectral intensities corresponded to electronic gains, i.e., wave generator settings of 10, 20, 30, 40, 50, and 60 percent of full gain. This produces conditions which range from relatively calm to major overtopping of the San Pedro Breakwater.

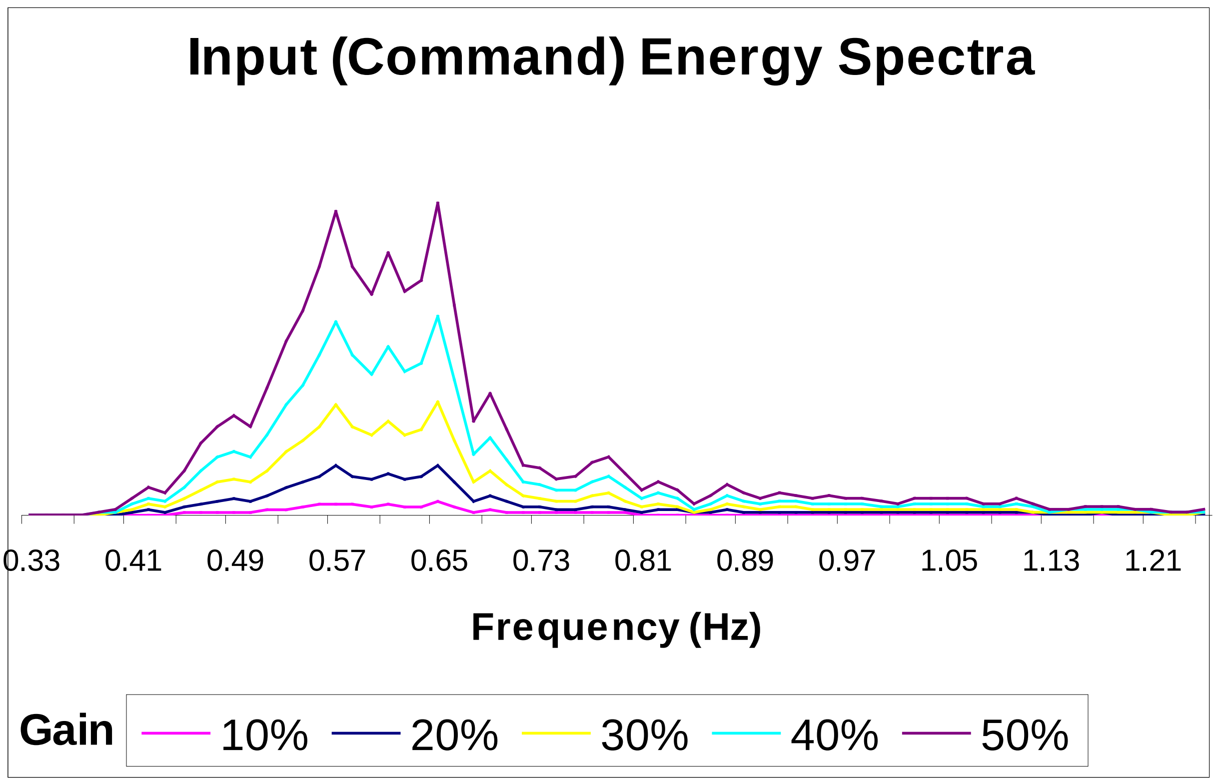


Figure 6. Input Spectra for Gain Levels 10 - 50 %

Breakwater Test Plans

A total of 9 plans were tested and a minimum of two repeat tests were conducted for each plan at all five wave generator gain levels. Including preliminary runs and extra repeat tests for certain conditions, 199 tests were conducted. Characteristics of these plans are listed in Table 1 and illustrated in Figure 7. The remaining analyses, as well as all of the plots in the Appendices, will be based upon the average values of the primary, secondary (first repeat) and tertiary (second repeat) data sets[1]. Intercomparisons of the three tests for each condition and other issues affecting uncertainty are discussed in Appendix C.

Table 1. Summary of Breakwater Plans

Plan	0	1	2	3	4	5	6	7	8
Crest (ft) MLLW	+13.5*	+12.5*	0.0	+7.5	+10.0	+12.5	+14.0	+24.0	+24.0**
Crest Material	concrete	concrete	clay	Clay	clay	Clay	clay	clay	clay

* Original construction
** Entrances blocked

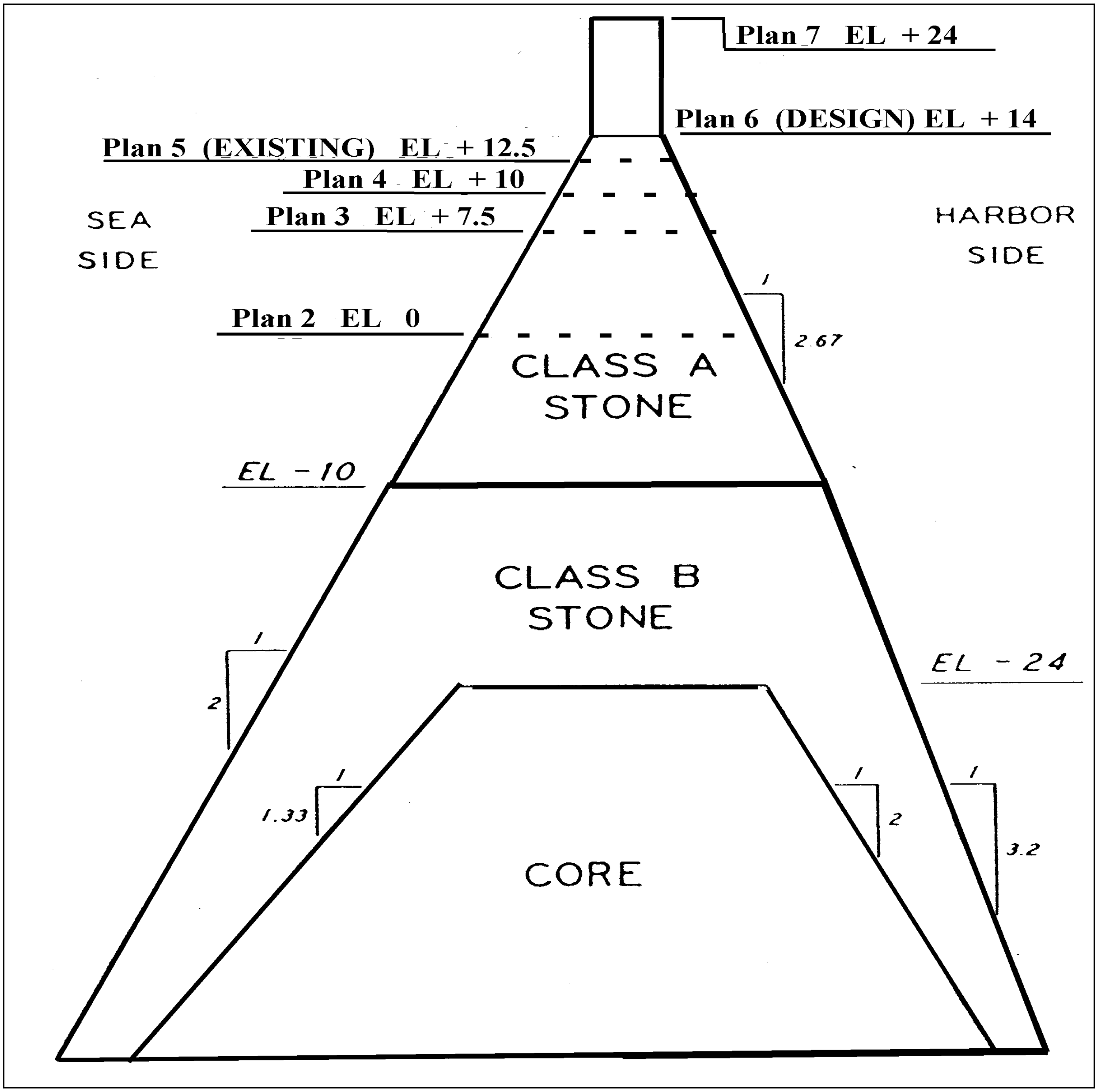


Figure 7. Sketch of Cross sections of Breakwater Plans

1 Two gages, numbers 7 and 21, were found to exhibit unacceptable calibration drift during the secondary runs for one of the plans tested (Plan 8). These data sets were edited during the analysis, and only the primary and tertiary runs were utilized to calculate the averages for these two gages for that plan. No other measurements were edited.

Plans 0 and 1 were considered base experiments that served to evaluate the overall performance of the system to the incident waves, to test the repeatability of the results for any plan, and to observe the sensitivity of the system to small changes in crest elevation. Plan 2 represented a crest elevation of 0.0 ft MLLW and was achieved by removing the existing concrete crest segments from the model. It provides the upper limit of sensitivity to crest elevation by allowing overtopping at all gain levels. Plans 3 through 6 simulate crest elevations from +7.5 ft MLLW - representing an extreme level of crest loss that is unlikely to occur without remedial action - to +14 ft MLLW, the design crest elevation. Plan 7 provided the lower limit of system sensitivity by raising the breakwater crest to +25 ft MLLW, eliminating overtopping at all gains. Plan 7 represents the maximum effectiveness that could be attained with a higher design crest. The section of the breakwater from +14 ft to +25 ft was assumed to be of constant width, as shown in Figure 7. Plan 8 was identical to Plan 7, but it also eliminated wave transmission through the entrances by blocking off the opening at Angels Gate and the connection between the Middle Breakwater and Pier 400 with concrete blocks (see Figure 5). Since the only energy that entered the harbor came through the breakwater itself, it provides a measure of the porosity of the breakwater. Data from Plans 2 through 8 are used in the next section to examine the effects of crest elevation on the harbor energy.

RESULTS

Total Energy

The total energy measured at a site is included in the energy-based significant wave height, H_{m0}. Plots of H_{m0} as a function of crest elevation and gain are found in Appendix A for all 30 wave gages. Gages located behind the breakwater in the outer harbor away from basins – Gages 1, 2, 18 and 20 – best demonstrate the expected trend with crest elevation and gain. Gage number 1, (Figure 8) is typical of this group: the measured energy increases with increasing gain (i.e., incident wave height) and decreases as crest height increases from +0 ft (Plan 2) to + 24 ft with the entrances blocked (Plan 8, labeled 24B). Cessation of major overtopping at any gain is evidenced by the flattening of the downward slope, at which point additional crest elevation has little additional effect.

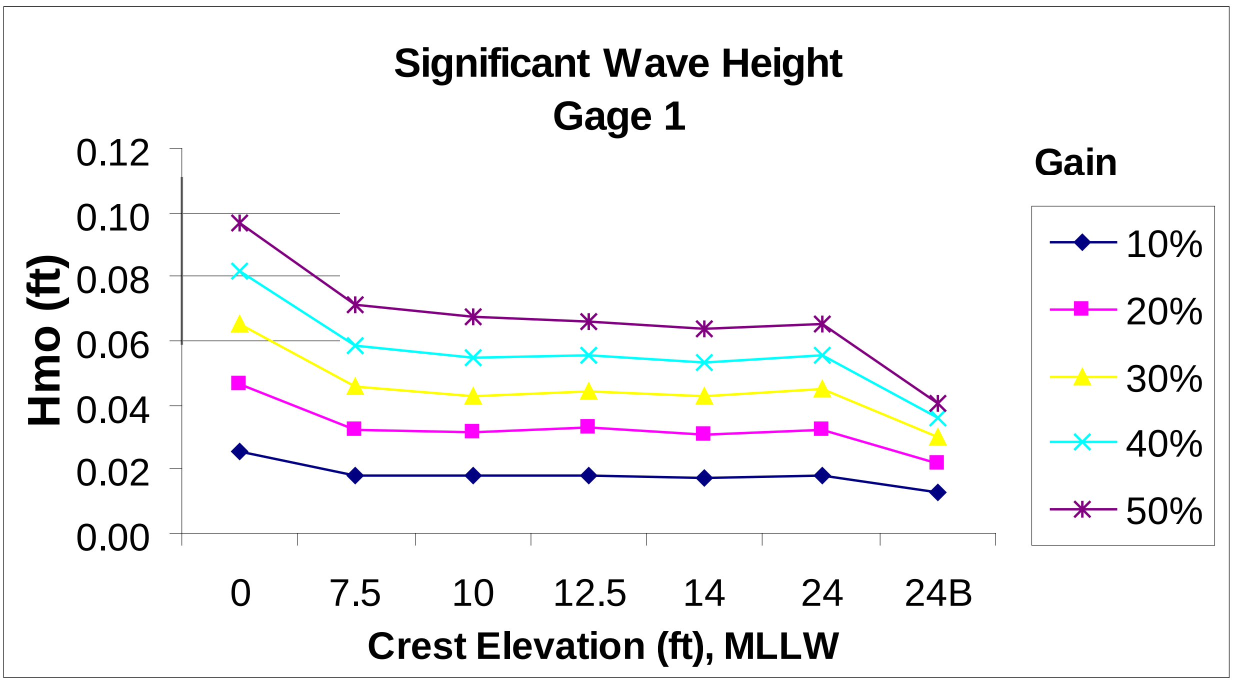


Figure 8. Measured Hm0 at Gage 1 * (B = entrances blocked)

Since the numerical values of H_{m0} amplification is not directly applicable to the prototype scale, a non-dimensional parameter is used to indicate performance. *Hamp,* defined as the ratio of H_{m0} at that gage to the measured incident H_{m0} at Gage 21, was calculated at each gage for each run. *Hamp* allows relative, nondimensional comparison of the severity of the wave motion at the various sites. Figure 9 shows *Hamp* at Gage 1.

Note that the stacking order of the curves for each gain in Figure 9 is reversed from Figure 8; *Hamp* for the 10 per cent gain is higher than *Hamp* at 50 per cent gain. That is because losses associated with breaking and friction losses increase at higher wave heights, whereas lower waves propagate with relatively less turbulence and losses. As expected, there is significant energy reduction as the crest elevation increases from 0 to +7.5 ft (Plan 3) for all gain levels, and moderate improvement as the crest increases to the existing elevation of +12.5 ft (Plan 5) at the higher gains associated with overtopping. Surprisingly, there is little additional benefit in increasing the crest beyond this elevation except for at the highest gain level, and only slightly more benefit in closing off the entrances altogether (Plan 8). This illustrates that significant amounts of incident energy are transmitted through the porous structure.

Note that *Hamp* > 1 for some cases. Though numerically identical, *Hamp* is not referred to as the transmission coefficient, *Kt*, because the energy measured at gages near harbor structures include a significant amount of reflected energy in addition to the incident, transmitted energy. For gages near a reflective wall, a partial standing wave will be established with a height of up to twice the incident wave. Thus the actual transmission coefficient for waves coming through the structure is not equal to *Hamp* when the crest is at 24B (~50 to 80), but transmission through the structure is significant.

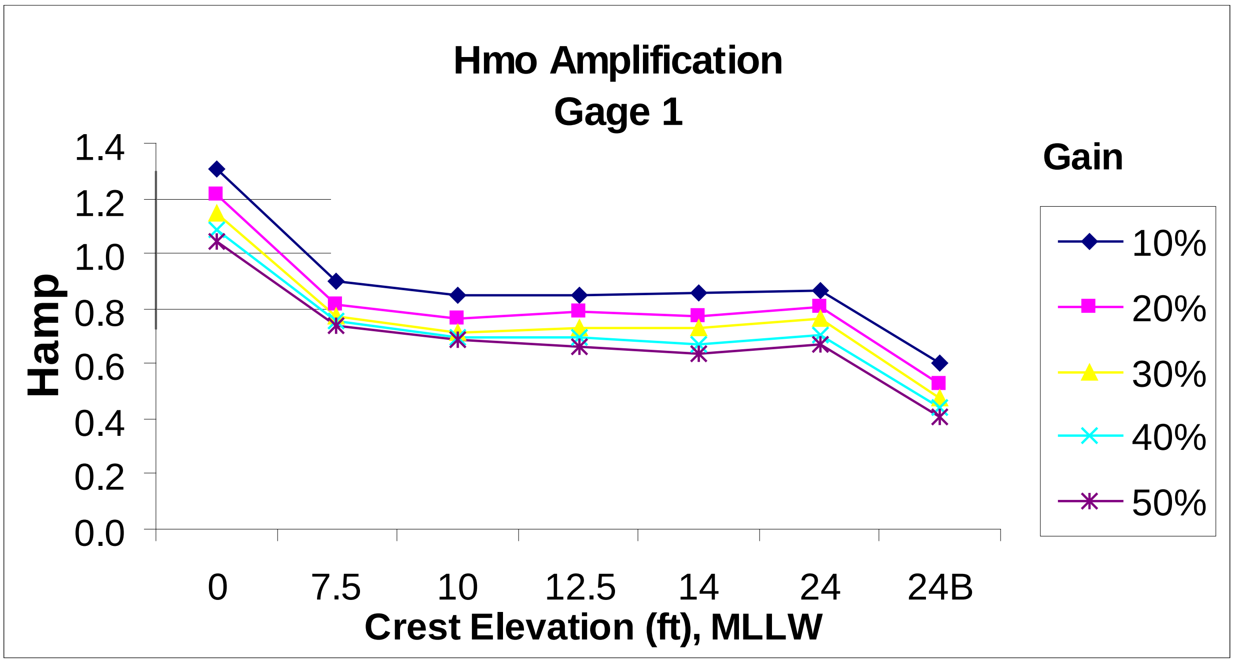


Figure 9. H_{m0} Amplification (*Hamp*) at Gage 1

The parameter *Hamp* permits relative comparison of the energy between gage sites. In order to illustrate the relative effect of the crest elevation at any one site, it would be useful to compare the energy at higher and lower crest elevations to the existing condition. The best way to illustrate this is to normalize the amplification again. The parameter *Hnrml* is obtained by dividing the amplification at each gain level by the amplification measured for the existing +7.5 ft condition (Plan 5). This allows a comparison of the sensitivity of changes in the crest elevation relative to the existing condition, regardless of the incident energy level. A value of *Hnrml* less than 1 means the total energy at that site is decreased relative to the existing conditions. A value of *Hnrml* greater than 1 means the total energy at that site increased relative to the existing conditions. Figure10 shows *Hnrml* for Gage 1. See Appendix A for plots of the average (of the three sets of tests) values of H_{m0}, *Hamp*, and *Hnrml* for all gages.

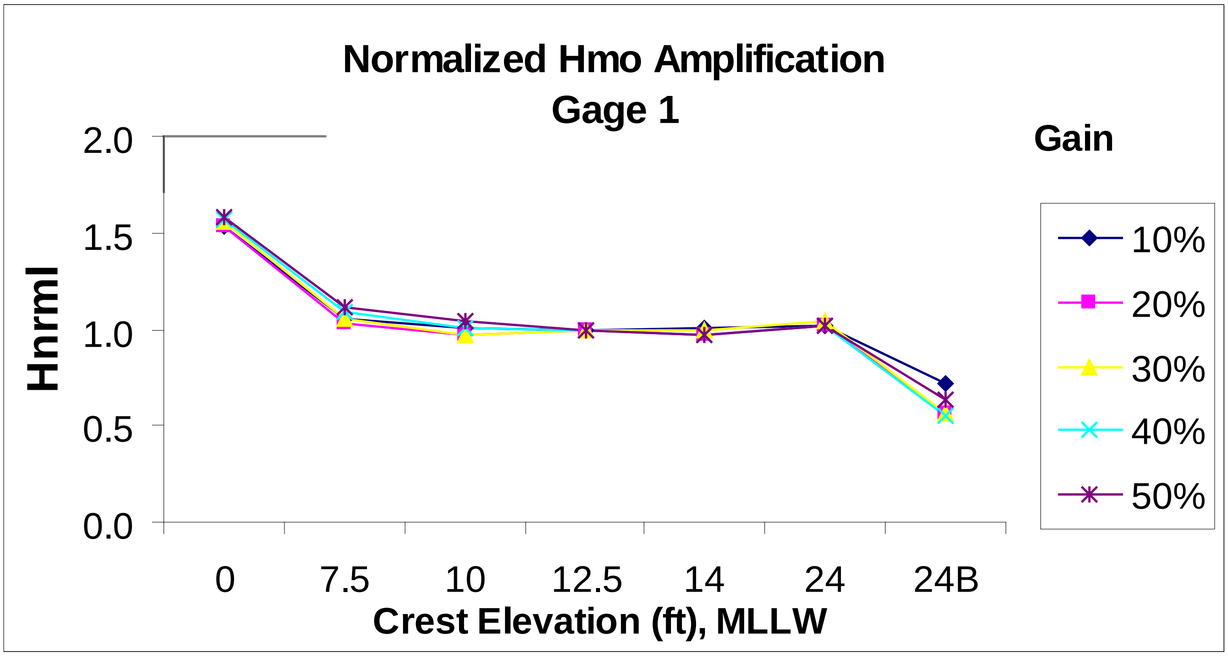
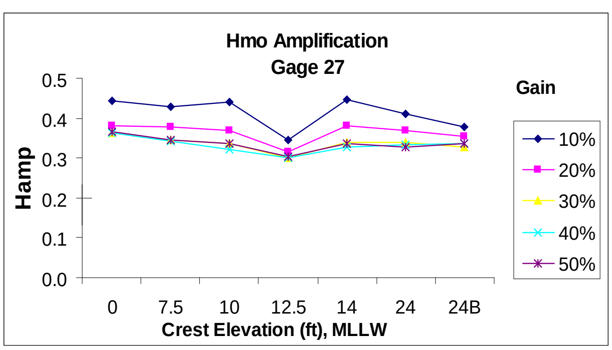
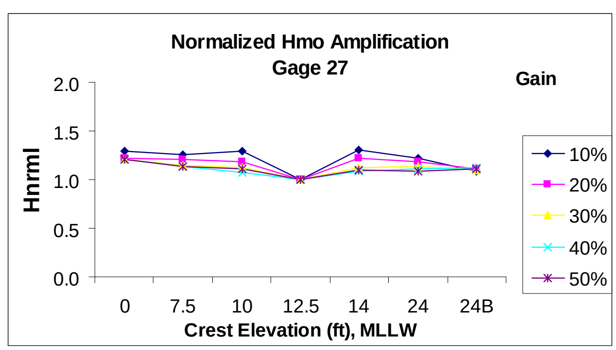


Figure 10. Normalized H_{m0} Amplification (*Hnrml*) at Gage 1

The remainder of the analyses will focus on the interior harbor gages (3-17, 25-28 and 30) since their response address the objectives of the study. These show a trend similar to Gage 1, but with one interesting difference: an increase in energy at the +14 and +24 ft crest elevations relative to the +12.5 ft elevation. Some even continue to increase after the entrances are blocked (see Appendix A). Gage 27 exemplifies this trend in the extreme (Figures 11). However, 15 of the 20 interior harbor gages exhibit this trend to some extent.

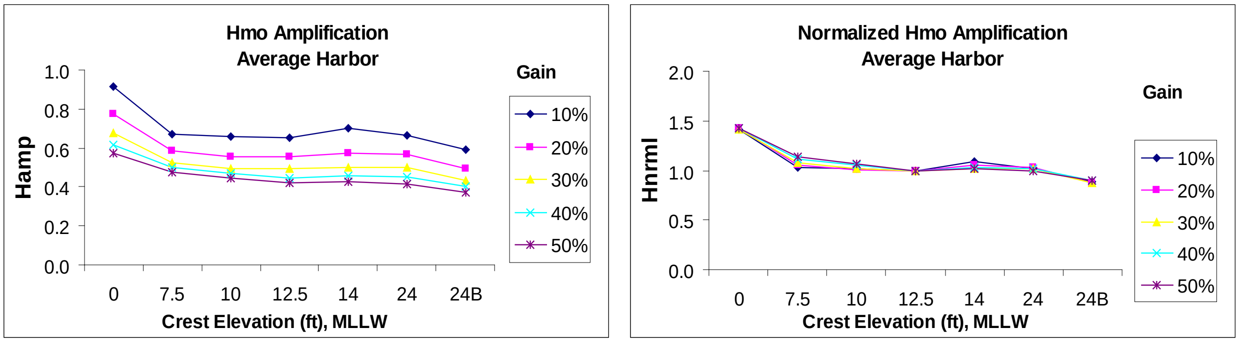
While the values change depending upon location, almost all gages show the same general shapes seen in Figures 8 - 10. $H_{m0,}$ *Hamp* and *Hnrml* curves are nearly parallel for each of the five gain levels. Thus, site-averaged *Hamp* and *Hnrml* are useful parameters to characterize the harbor's overall sensitivity to changes in the crest elevation. Figure 12 shows the average *Hamp* and *Hnrml* of all the interior harbor gages. The trend noted above is much less obvious, but there are definite minima at Plan 5 for all gain levels.





(a) **(b)**

Figure 11. Measured *Hamp* (a) and *Hnrml* (b) at Gage 27



(a) **(b)**

Figure 12. Average *Hamp* (a) and *Hnrml* (b) for Interior Harbor Gages

Low Frequency Energy

The measured spectrum at any gage in the harbor includes energy at frequencies above and below the peak of the incident energy. Figure 13 shows the relative (un-dimensioned) energy spectra for the input command signal at a gain level of 50%, the measured incident energy at Gage 21, and the resulting spectra at gages 5 and 30 when the crest elevation was at +12.5 ft. Gage 5 is directly behind the breakwater and experiences amplification of some of the higher frequency harmonics, up to 1.25 Hz. Gage 30 is at the very back of the west basin, and is completely protected from the higher frequency components, but resonates strongly at 0.57 Hz.

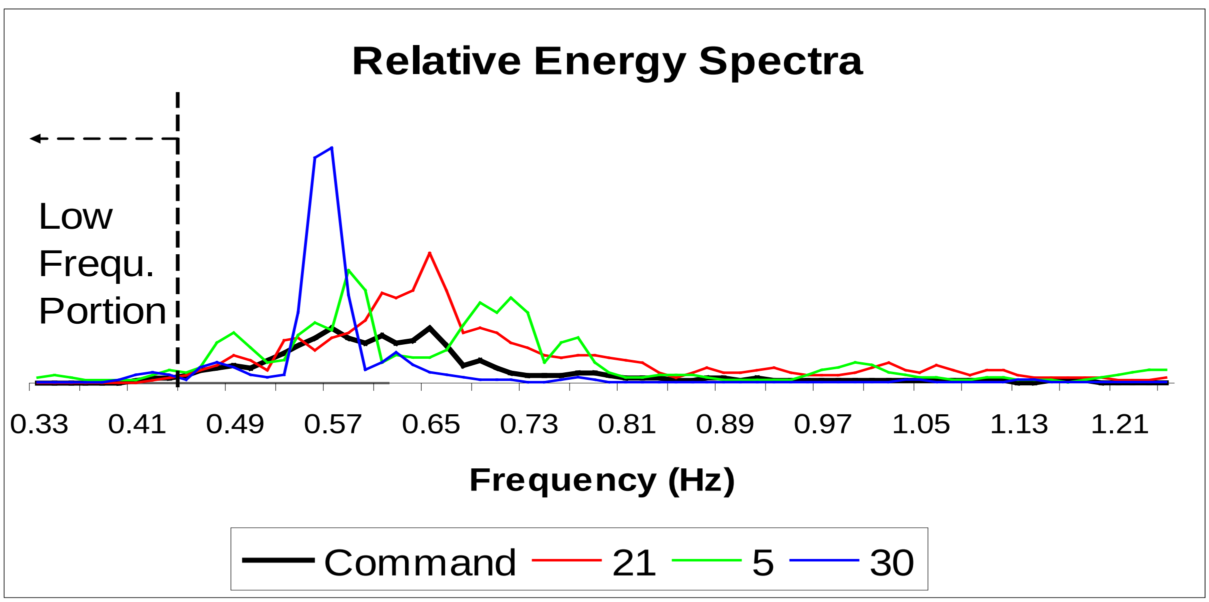


Figure 13. Energy Spectra for Input (Command) Signal, Measured Incident (Gage 21) and Gages 5 and 30 for Crest elevation of +12.5 and Gain level 50%

This section of the study examines the response induced in the harbor basins at the low frequency portion of the spectrum below the (unrealistically) high-energy peak. The low frequency cutoff is defined as all energy at or below 0.47 Hz (lower than 85-sec period, prototype), the point where the incident energy is reduced to 10 per cent of the peak energy. Figure 14 is an expanded view of that portion of the spectrum. The amplification of the incident low frequency energy, though less dramatic than at higher frequencies, is obvious.

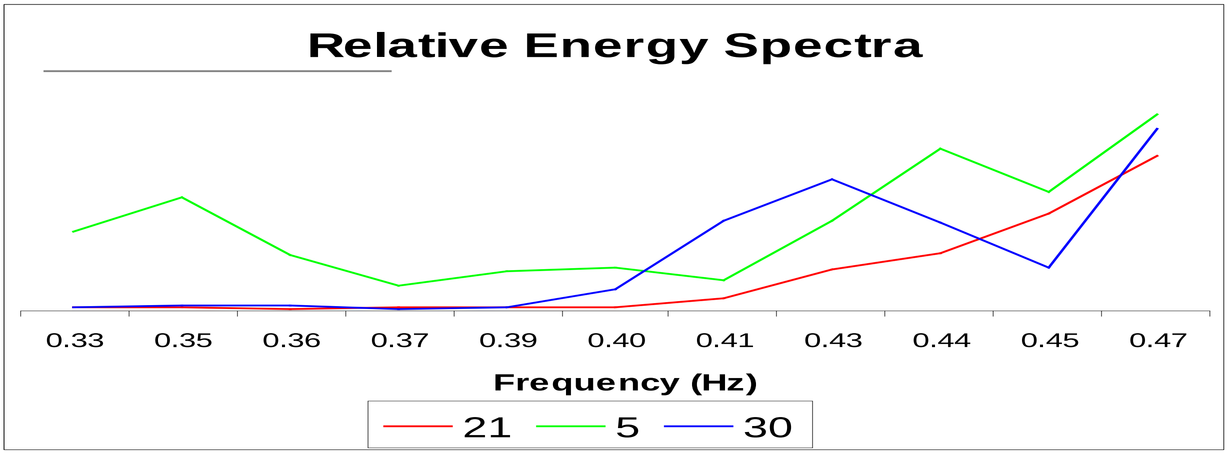
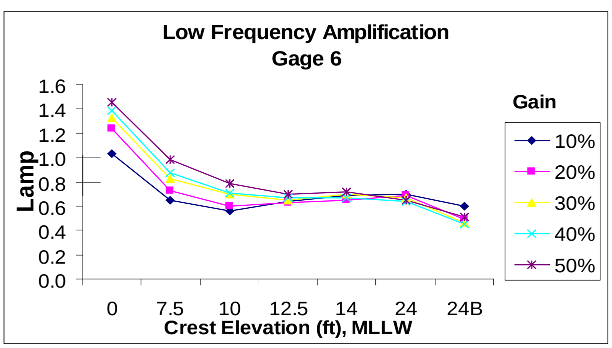
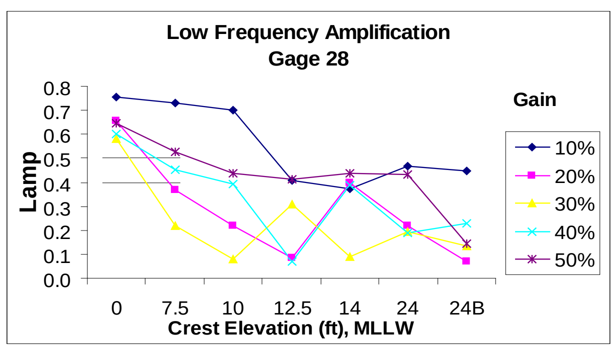


Figure 14. Low Frequency Portion of the Energy Spectrum for Incident (Gage 21) and Gages 5 and 30

Low frequency amplification (*Lamp*) is defined as the square root of the ratio of the sum of measured low frequency energy at a site to the sum of the measured low frequency energy at gage 21, and *Lnrml* is *Lamp* normalized by Plan 5 *Lamp*. Appendix B contains plots of *Lamp* and *Lnrml* for all gages. Just as for the total energy equivalents, *Lamp* is a measure of the severity of the low frequency energy at a location, and *Lnrml* indicates the sensitivity at that site to changes in crest elevation. Low frequency energy at most of the gages follows the same general trends seen in the total energy; Gage 6, for example (Figure 15(a)). Others, such as Gage 28 (Figure 15(b)) are not as well behaved. These anomalies can result when very little low frequency energy was measured, and result from dividing two small numbers close to the error limits of the system. In some cases no low frequency energy, as defined above, was measured. This could also indicate a non-linear response to crest elevation and/or incident energy at these locations.





(a) **(b)**

Figure 15. Low Frequency Amplification for Gage 6 (a) and Gage 28 (b)

Averaging *Lamp* and *Lnrml* for all gain levels reduces the effect of the anomalies and allows easy relative comparison between gages. Figure 16 shows the gain-averaged *Lamp*, or <u>*Lamp*</u> and Figure 17 the gain–averaged *Lnrml* (<u>*Lnrml*</u>) for Plans 3 – 7 (crest elevations from +7.5 ft through +24 ft) for the interior harbor gages. Plans 2 and 8 are omitted for simplicity, as they are unlikely to ever occur in nature. Note the evidence of an increase in <u>*Lnrml*</u> as the crest increases from +12.5 ft to +24 ft for Gage 28 and to a lesser extent, Gage 17. However, this tendency is much less prevalent at low frequencies than when using the total energy.

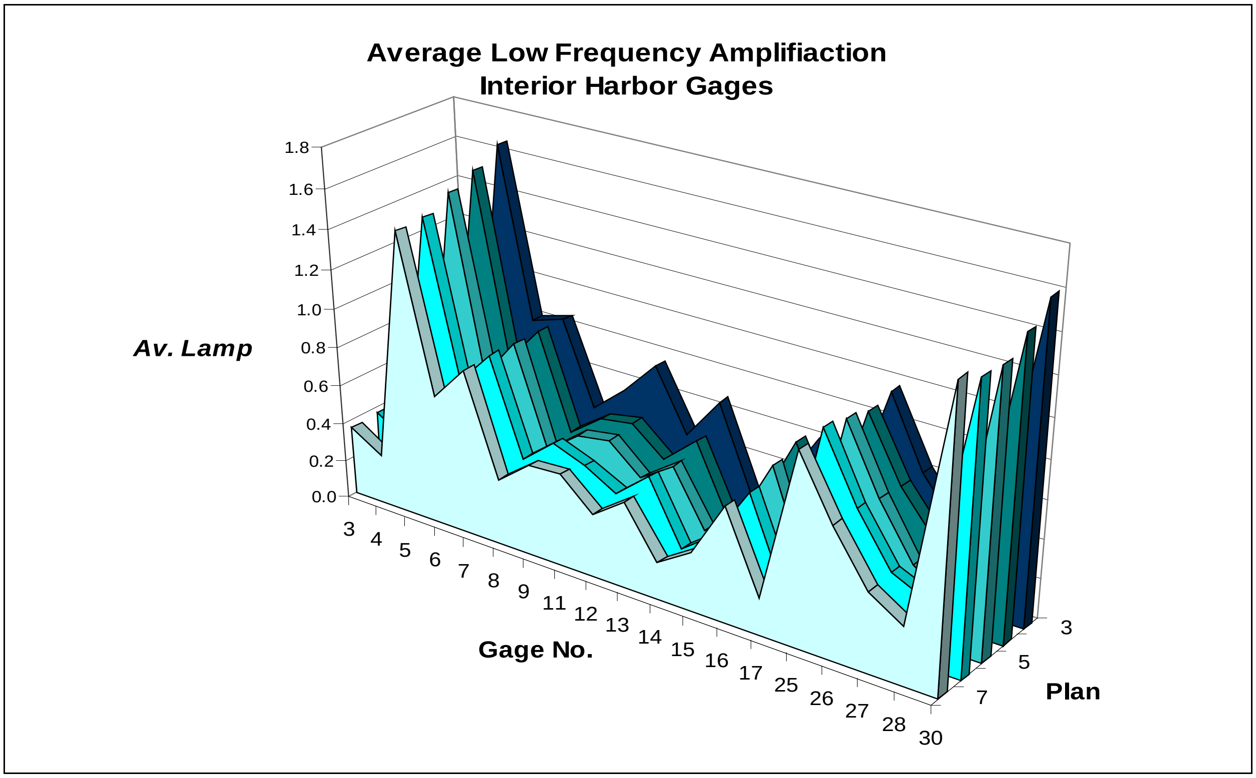


Figure 16. Average Low Frequency Amplification for Interior Harbor Gages

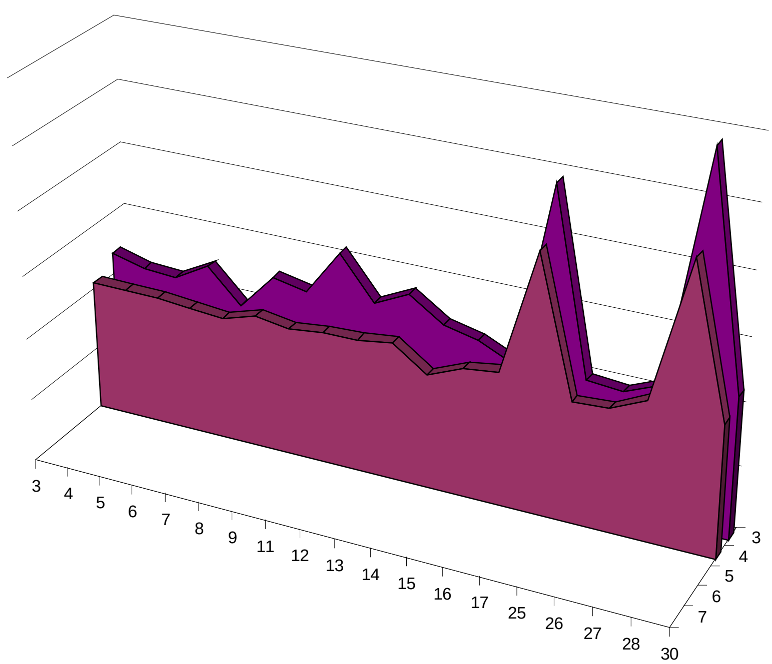


Figure 18 combines the essential information from the previous two plots: the ***Lamp*** for Plan5, the existing condition, together with ***Lnrml*** for crest elevations from +7.5 through +14 ft. (*Lnrml* for crest elevation +12.5 ft is 1.0, by definition, so it is omitted for clarity). That is, the black line shows the relative severity of low frequency waves at each site under existing conditions, the red lines show the relative change each site would experience if the crest loss continues, and the green line the change experienced if the crest is brought back to the design elevation. The gages are positioned along the X axis on order of decreasing existing (i.e., at +12.5 ft) amplification, instead of by gage number, to better illustrate the trends discussed below.

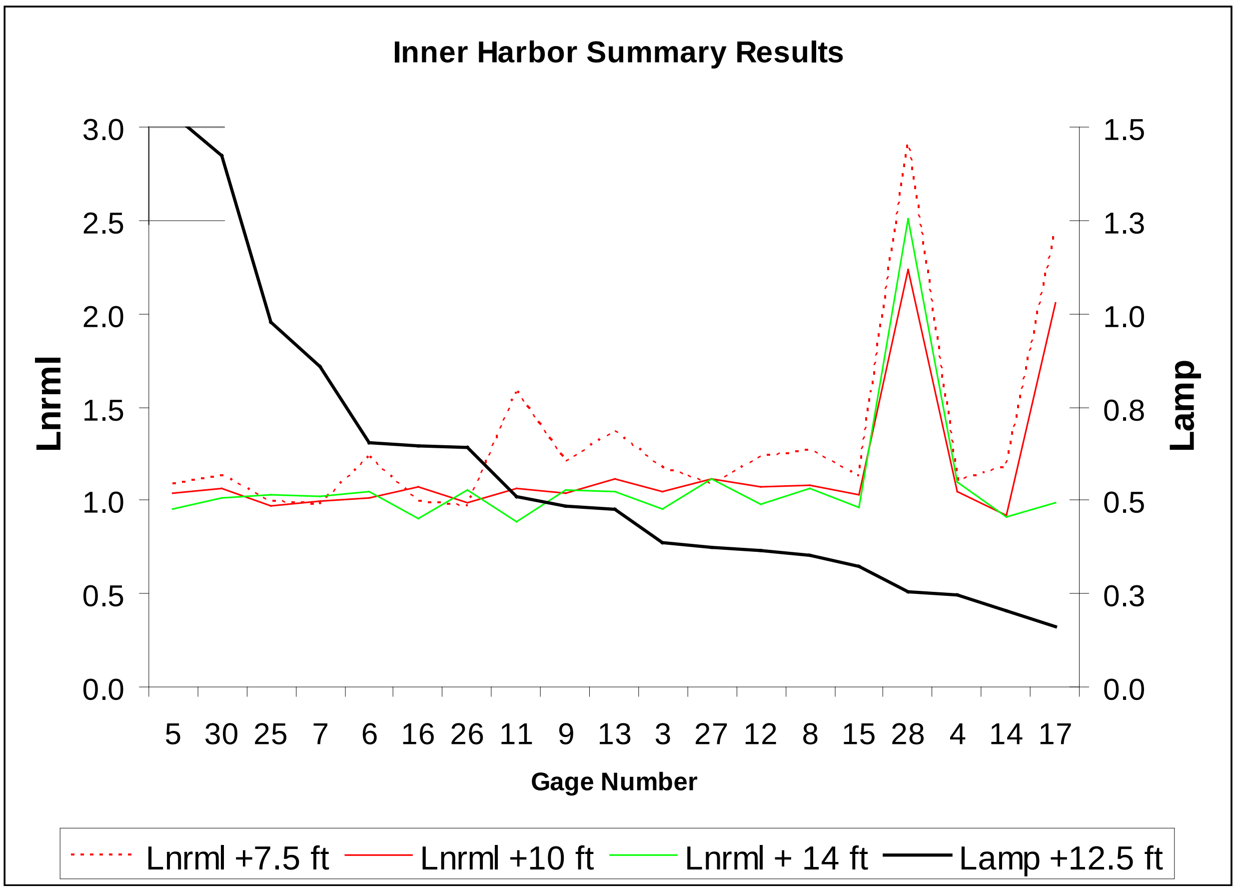


Figure 18. Average Low Frequency Amplification (crest = +12.5 ft) and Normalized Low Frequency Amplification (crest = +7.5, +10, and +14 ft)

DISCUSSION

Total Energy

This manifestation of the "harbor paradox" – an increase in harbor energy as crest elevation increases above some threshold - is not completely unexpected or illogical. The paradox was first described analytically by Miles and Munk (1961), as it applied to an optimal harbor entrance opening - reducing the entrance size below the optimum resulted in a net increase in harbor energy. The work was later revised by Miles 1970 to restrict the phenomenon to oscillations in the Hemholtz mode only. It would not seem that the observed wide-band increase in high and low frequency oscillations is a manifestation of the same effect.

More curious, the effect is strongest at 10 per cent and 20 per cent gain levels as the crest is raised from +12.5 ft to +24 ft (see Figure 12), despite the fact that those incident waves did not overtop the Plan 5 structure. Most curious is that the breakwater appears to have coincidentally "settled" into a low energy state for the harbor that is only slightly more energetic than a completely enclosed harbor. A significant amount of the energy enters through the structure. In order for this energy to be trapped inside the harbor, the breakwater would have to function as a sort of diode – transmitting energy inward more effectively than outward. The physical mechanism for such an occurrence is not obvious.

Another explanation is that the increase is amplification is due to a decrease in measured incident energy (the denominator in *Lamp*) rather than an increase in measured energy at an interior gage (the numerator). Oscillations of the model basin outside the breakwaters can result from reflections from the breakwater, the wave generator, and the sides of the model itself. Raising the crest elevation would increase this reflected energy. If Gage 21 is at a nodal position for that reflected wave, its measured energy would decrease as the crest increased, causing an apparent rise in amplification inside the harbor.

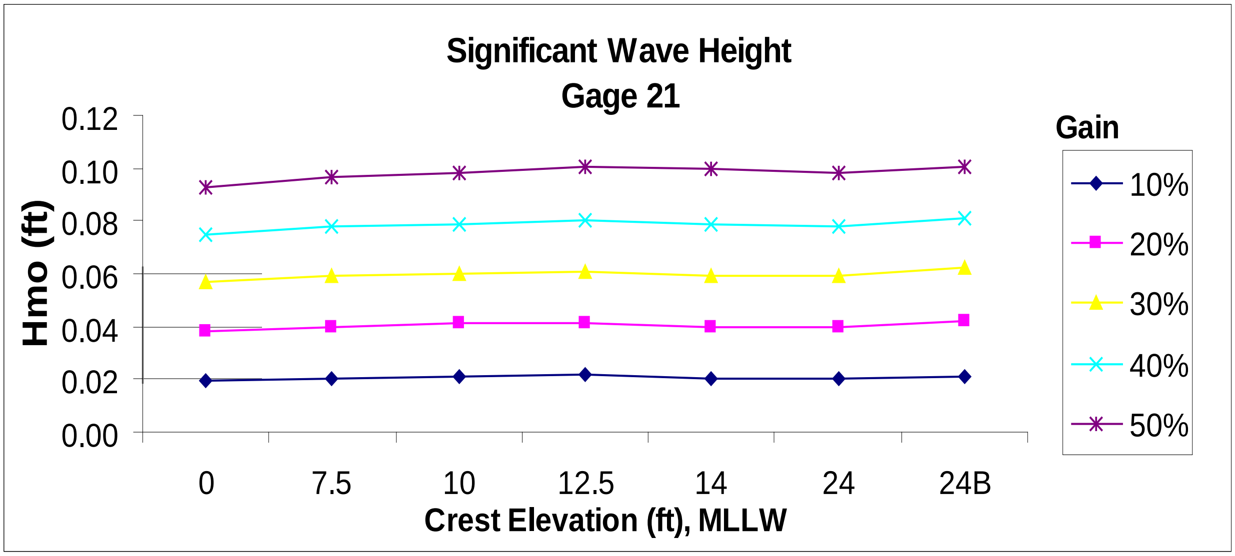


Figure 19. Measured Incident H_{m0} from Gage 21

Figure 19 plots H_{m0} against crest height for Gage 21. Since the command signal was supposed to be held constant for each gain level, the lines should be horizontal. There is a definite decrease in measured incident energy at the 0 ft elevation, but the decrease at +14 and +24 ft is slight and limited to the 40 per cent gain level. Some of the "paradox" may be explained by nodal effects, but part of it must be attributed to increases in breakwater crest height.

Low Frequency Energy

The harbor paradox is all but missing in the low frequency energy band; only Gages 28 exhibits it at when the crest is increased to the design elevation. Since this site has the fourth lowest low frequency energy level in the harbor, the effect could partly be the result of uncertainty in division using small numbers. Sites 5, 30, 25 and 7 are particularly responsive compared to other sites, while Sites 28, 4, 14, and 17 exhibit relatively low excitation. Sites 17 and 28 react strongly to additional crest loss, while site 28 reacts equally as strongly to crest gain. Most sites are relatively insensitive to positive or negative changes of the crest elevation on the order of a few ft. But the impacts of a small change at a site that is already energetic could be of more interest than large changes at a site with no existing operational problems. The following subjective criteria are utilized to identify sites of relative sensitivity. For sites at which ***Lamp*** under the existing crest elevation of + 12.5 ft is greater than or equal to one, an increase of 10 per cent or a decrease of 5 per cent is considered significant. If the existing ***Lamp*** is less than one but greater than or equal to 0.5, an increase of 50 per cent or a decrease of 10 per cent is considered significant. For sites with existing ***Lamp*** less than 0.5, an increase of 100 % or a decrease of 20 per cent is considered significant. By that criteria, sites 30, 28 and 17 would experience significant degradation if the crest is lowered to + 10 ft; sites 5 and 11 join that list if the crest loss continues to + 7.54 ft. Only sites 16 and 11 would receive significant improvement if the crest was raised to the design elevation of +14 ft. These six sites are shown in Figure 20.

Figure 20. Location of Sites Showing Significant Degradation with Crest Loss (yellow if it occurs at + 7.5 ft, red if at + 10 ft) and Improvement with Crest Repair (green)

CONCLUSIONS

1. The LALB model is able to generate waves that overtop the San Pedro Breakwater at its current crest elevation.

2. The overtopping waves produce low frequency oscillations in the various harbor basins. The energy in the basins increases linearly with incident energy and is sensitive to crest elevation.

3. The average total energy inside the harbor appears to display a variant of the “harbor paradox.” Total energy decreases as crest elevation is raised, reaches a minimum near a crest elevation of +12.5 ft MLLW, increases slightly for the design elevation of +14 ft, and decreases again when the crest is raised to + 24 ft. Average measured energy inside the harbor for the existing crest elevation is only 12 per cent higher than the configuration with no overtopping allowed and the harbor entrances blocked.

4. Sites with the highest low frequency amplification are relatively less sensitive to crest elevation. Sites with the most sensitivity have relatively less low frequency amplification.

5. Answer to Study Question 1: Most sites measured show negligible effects in low frequency energy due to a reduction in the crest elevation from +14 ft to +12.5 ft MLLW. Only sites 16 and 11 experience significant (about 10 per cent) benefits if the crest elevation is raised to +14 ft MLLW.

6. Answer to Study Question 2: Most sites measured are insensitive to further loss of crest elevation down to an elevation as low as +7.5 ft MLLW. Sites 17, 28 and 30 would experience significant increase in low frequency energy if the crest loss continued to an elevation of +10 ft MLLW. Sites 5 and 11 would experience significant increase in low frequency energy if the crest loss continued to an elevation of + 7.5 ft MLLW.

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