NON-RESONANT WAVE AGITATION IN SMALL CRAFT HARBOURS

by

J.W. Kamphuis [1)] and D.A.Y. Smith [2)]

ABSTRACT

A model study of wave agitation in small craft harbours was performed using a square and a rectangular marina basin subjected to monochromatic waves. Wave agitation was measured in up to 273 points within the marina basin and overall wave energy levels were calculated from these measurements for 4 different wave periods, 6 different entrances and 5 different lengths of energy absorbing sections along the perimeter walls. These values were compared and found to correspond well with a rather simple theoretical expression.

INTRODUCTION

Ancient harbours were small craft harbours and their design was already very sophisticated (2,9)[3]. The development of harbour design from the early Minoans, Phoenicians and Romans, however, has not been a linear process. First, the same mistakes were often repeated throughout history (and indeed are repeated today). Secondly, with increase in the size of ships, design was mainly concerned with harbours for large vessels. Around 1900, a parting of the ways is evidenced and two distinct types of harbour designs are found — the large harbour for large vessels and the smaller craft harbour, mainly for fishing vessels. Not until the 1960's can the concept of "small craft harbour" or "marina" be found regularly in the literature and the design of these small craft harbours is very often simply a scaled down version of design for large commercial harbours.

Two examples of scaled down design may suffice.

It makes good sense when designing a harbour for large vessels, not to obstruct navigation unnecessarily and hence to design a relatively straight, open entrance, directed away from the predominant wave direction. Only "small waves", which do not unduly affect the stability of the large vessels, are permitted to enter the harbour. But this design criterion is anathema for small craft which are terribly disturbed by these so-called "small waves".

---

1. Professor of Civil Engineering, Queen's University, Kingston, Canada.

2. Engineer, Jamaica Bauxite, Kingston, Jamaica.

3. Numbers in brackets refer to the Reference section.

Applying the same entrance design criterion to both types of harbours is therefore ludicrous, especially in view of the fact that small craft are very easily maneuverable and can negotiate more complicated entrance configurations quite easily. An additional entrance design criterion for small craft harbours is that the entrance prevent penetration of waves generated by other small craft passing the entrance.

Vertical perimeter walls around a harbour also constitute sensible design for harbours with large vessels. The vessels can easily come alongside. Vertical sheetpile walls are inexpensive compared to the alternatives. Loading and unloading platforms can be constructed immediately adjacent to the vessels. The fact that wave energy is reflected by these walls, resulting in ever-present chop within the harbour and along the docks is of no concern to the large vessels. But in a small craft harbour reflected and re-reflected waves present an unacceptable level of motion. Hence vertical, reflecting perimeter walls constitute very poor design for small craft harbours.

It is possible to quote many examples of small craft harbours with open entrances and vertical, reflecting perimeters. Portsmouth Olympic Harbour, reconstructed for the 1976 Olympic games, is shown as one such example in Figure 1. The unacceptable energy levels in this marina basin prompted the Queen's University Coastal Engineering Laboratory to begin investigation of agitation in small craft harbours.

A literature search indicated very little work directly applicable to small craft harbour design — especially with respect to non-resonant agitation (as opposed to studies on resonance — so important for larger harbours containing large vessels). Hence a series of very basic research tests was initiated. So far, one earlier paper was published (5). The work discussed in this paper may be found in detail in the junior author's Ph.D. thesis (8). It consists of

a. Obtaining some basic data with respect to wave penetration, diffraction, reflection, etc.

b. Testing a simple theory to explain (overall average) energy levels in simple harbour configurations.

The program has been continued to investigate

c. Local wave energy levels in sections of the harbour

d. Energy absorber location design

e. Entrance design,

and will in the future also focus on

f. Arrangement of "furniture" (docks, piers, boats, etc.) within the harbour

g. Effects of irregular waves

h. Construction of a Finite Element Model based on the above experimental data.

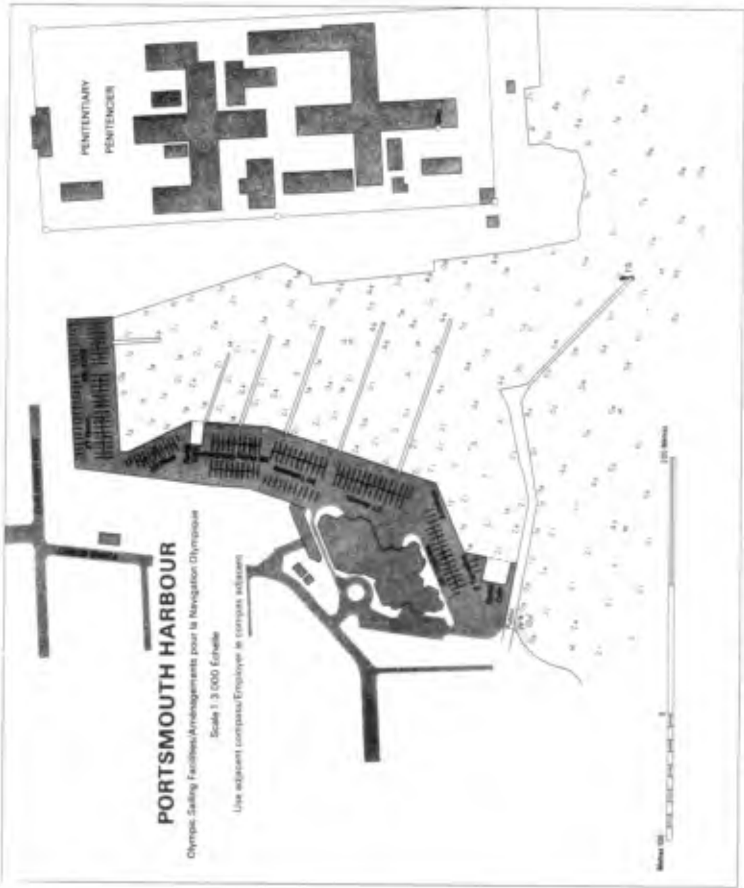


FIGURE 1: EXAMPLE OF SMALL CRAFT. HARBOUR DESIGN BY SCALING DOWN LARGE HARBOUR DESIGN CONCEPTS.

Some work on marina and harbour agitation has been published by others such as the Danish Hydraulics Institute and their System 21 (1), Daemrich and Kohlhase (6) and others. Their work consists of rather sophisticated mathematical and theoretical analysis, but is based on very limited data. The purpose of the work discussed in this paper is:

a. to provide an experimental data base on which to construct mathematical models,

b. to provide some simple relationships that can be used in preliminary engineering design.

The last point is very important since many small craft harbours are never really designed, but are evolved from committee meetings, etc. using available space and money as the basic design criterion, while hard technical study is only of secondary importance. A simple expression and indications of trends give the harassed engineer something in hand to plead his case.

THE EXPERIMENTS

The experimental facility is shown in Figure 2. Regular waves were generated in a 3-dimensional wave basin and two harbour models, a 6.1 m square and a 4.25 x 6.1 m rectangular one, were tested. Heavy wave filters were used and energy absorbing material was placed along the front face of the model to prevent coupling and secondary reflections between the model and the wave generator.

The testing procedure was as follows: after the generator was started, a period of approximately 20 minutes was found to be sufficient to damp long waves resulting from generator start-up. The square harbour was tested with fully reflecting vertical walls all around the perimeter for six different entrance widths (b = 0.61,1.07, 1.60, 2.13, 2.67 and 3.23 m). These tests were repeated using a horsehair, beach type absorber[1], first along the back wall, then along the back and one side, the back and both sides and all around the perimeter — each time testing for six entrance widths. Such complete series of tests were run for each of four wave periods (T = .985, 1.152, .858 and .69 seconds) and the whole program was completely repeated for the rectangular harbour. Wave measurements were taken by a bank of seven capacitance wave gauges, which moved to locations outside the harbour and to locations spaced at .15 m inside the harbour resulting in 189 to 273 individual wave height measurements within the harbour per test.

Because of the monochromatic nature of the incident wave, it was entirely possible to choose wave periods which caused very large agitations in the models without energy absorbing perimeters. A deliberate attempt was made to de-tune the model, i.e. to adjust the wave period slightly to cause agitation to be a minimum for the harbours without absorber. This method yields conservative results when

---

[1] The absorber exhibited reflection coefficients between 7 and 18%, depending on the incident wave period and would be comparable to prototype sloping rubble walls, launching ramps, etc.

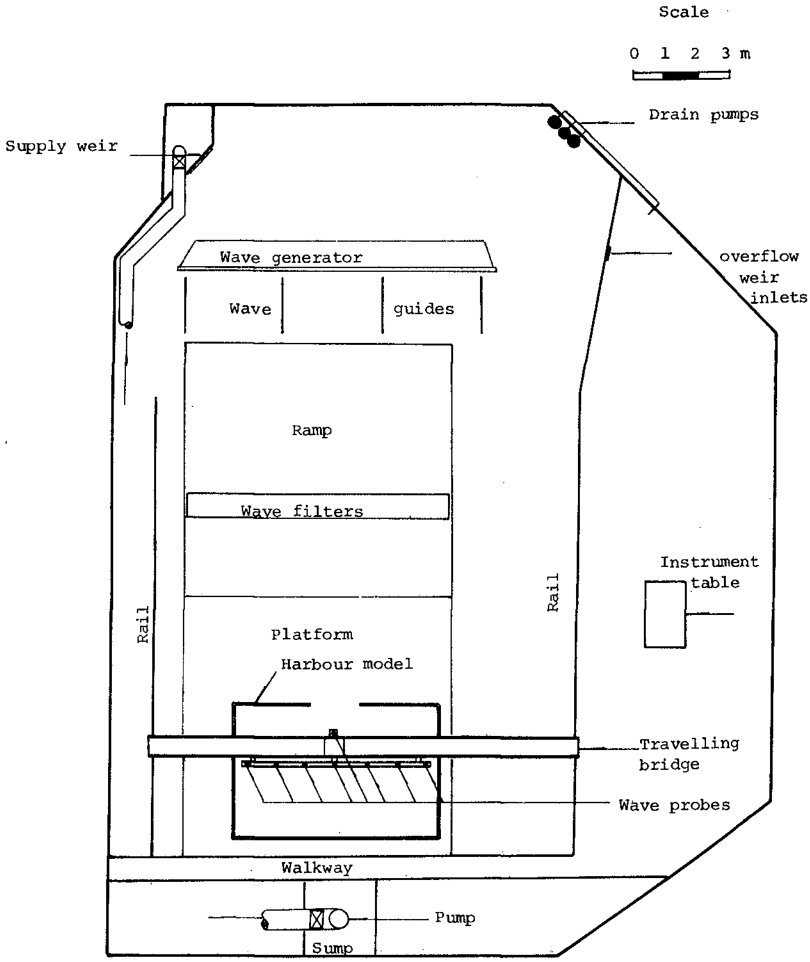


FIGURE 2: EXPERIMENTAL FACILITY.

discussing reduction in wave agitation by perimeter absorbers. Changes in wave period of 1/100 of a second showed remarkable impact on the wave action. This is frightening since the prototype waves contain all sorts of wave frequencies and could respond to any one of these frequencies rather violently.

EXPERIMENTAL RESULTS

The readings from the wave gauges were reduced in the first analysis to normalized wave height plots, of the variety shown in Fig. 3. Normalized wave height is defined as the ratio of local wave height (H) to the incident wave height (H_i). Figure 3(a) with the vertical, reflecting walls shows pronounced reflection patterns in spite of all efforts to de-tune the model. Comparison with Fig. 3(b) shows the influence of an absorbing perimeter. A decrease in overall energy level may be noted, but also a very marked decrease in local agitation, i.e. the internal reflection pattern is gone and the energy is more evenly distributed throughout the harbour. The latter is a particularly important consideration which is not studied in this paper but will be studied in future work. Also in Fig. 3(b), the measured wave agitation is compared with the output of a diffraction program, indicating that wave heights may essentially be determined from diffraction analysis if reflection from the perimeter is minimum. Figures 3(c) and 3(d) show the effect of increased entrance width.

It was also seen from the tests that the absorber was much more efficient when placed along the back wall than when placed along the sides and Fig. 4 shows some examples of overall energy level reduction, clearly indicating that absorber along the back wall only and absorber all around are almost equally effective at decreasing the overall energy level, while the former costs only 30% of the latter. This optimisation of absorber location is under further investigation and the topic of another paper.

THEORY

Assuming conservation of energy, it is possible to state:

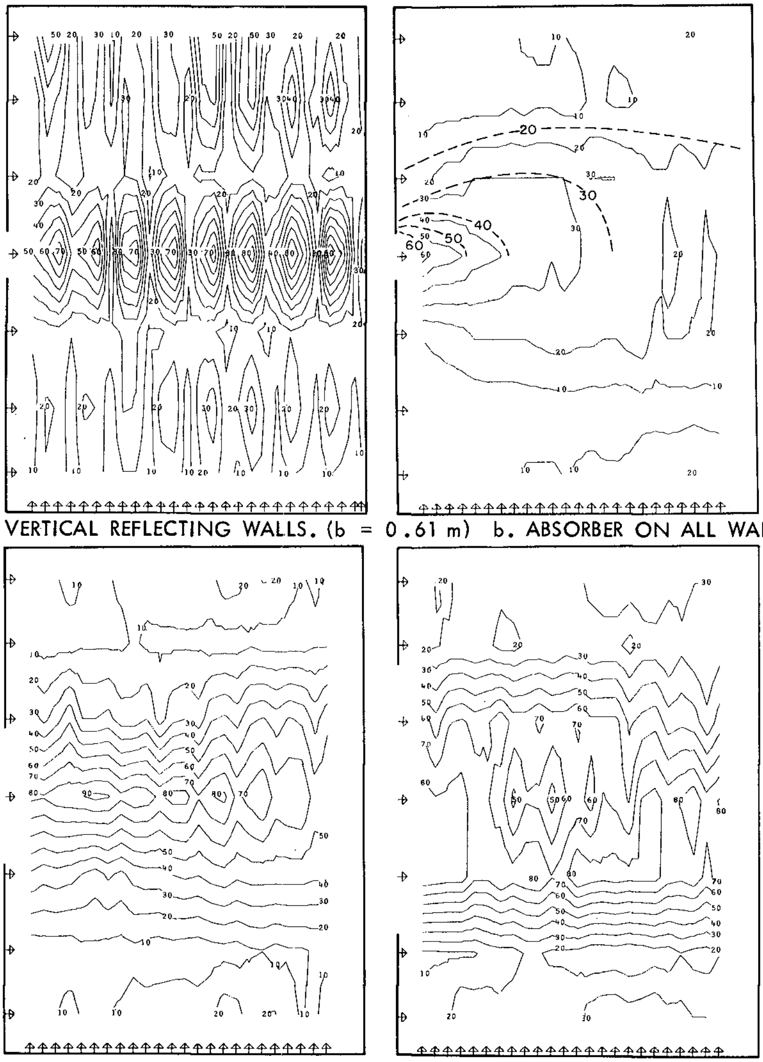
$$A \frac{dE(t)}{dt} = P_i - P_o - P_a - P_f - P_d \qquad (1)$$

where A is the harbour area,

$E(t)$ is the energy density in the harbour as a function of time,

P_i is the rate of energy input (Power in) through the harbour entrance,

P_o is the rate at which energy radiates out (Power out) through the harbour entrance,



a. VERTICAL REFLECTING WALLS. (b = 0.61 m) b. ABSORBER ON ALL WALLS.

c. b = 1.60 m d. b = 3.23 m

ABSORBER ALL AROUND.

FIGURE 3: NORMALIZED WAVE HEIGHT PLOTS.

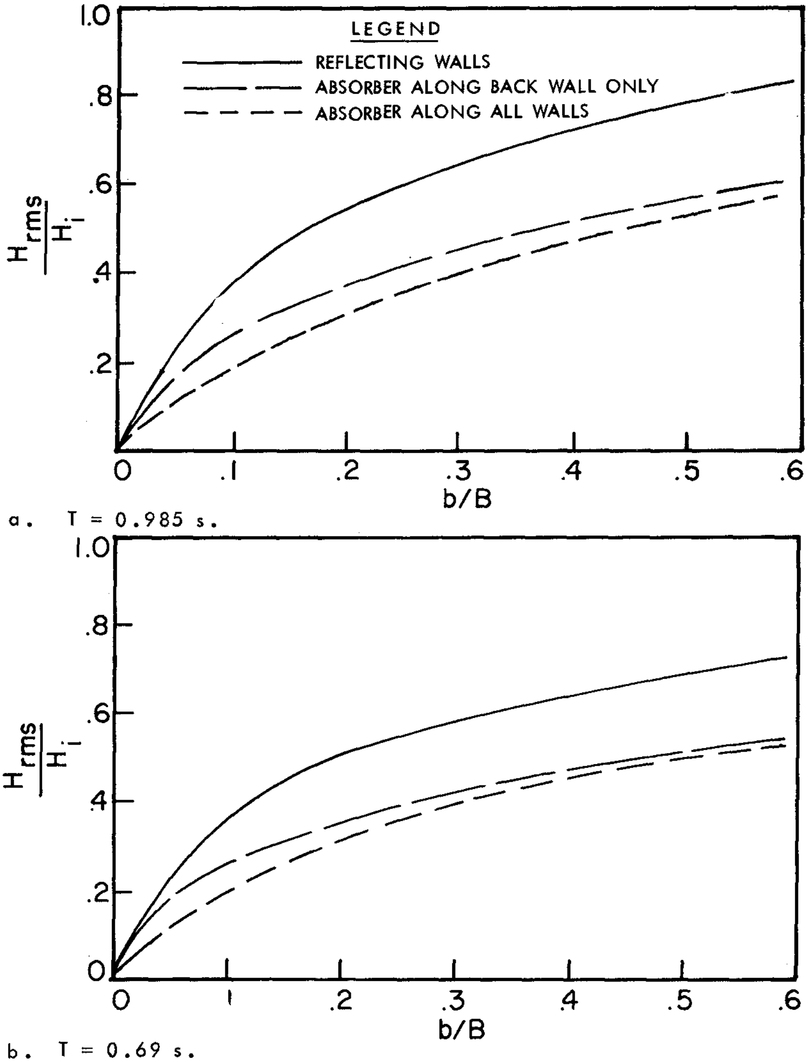


FIGURE 4: REDUCTION IN OVERALL ENERGY LEVEL BY ABSORBERS.

P_a is the rate at which energy is absorbed (Power absorbed) by the perimeter,

P_f is the rate of energy dissipation by bottom friction,

P_d is the rate of energy dissipation by internal friction.

There are additional terms such as energy dissipated by the docks, boats, etc. which will be included at a later stage of the work.

The term $E(t)$ in Eq. 1 describes the overall average energy density for the complete harbour in this particular study. In subsequent studies, the harbour will be divided to study energy buildup in particular sections individually. In either case, it is possible to define an RMS wave height for the harbour or particular section as:

$$E(t) = \frac{1}{8} \rho g \{ H_{rms} (t) \}^2 \tag{2}$$

for ease of comparison with the experimental results. Experimentally H_{rms} is simply the RMS value of all the wave heights measured by the probes within the harbour or within a particular section and this value of course corresponds to $t = \infty$.

The rate at which energy enters the harbour may be expressed as

$$P_i = bnC \frac{\rho g H_i^2}{8} \tag{3}$$

where b is the entrance width,

C is the phase velocity of the waves,

ρ is the density of the water,

g is the gravitational acceleration,

n is the ratio of group velocity to phase velocity

$$n = \frac{1}{2} \left\{ 1 + \frac{2kd}{\sinh 2kd} \right\}$$

where k is the wave number $(2\pi/L)$,

L is the wave length,

d is the depth of water.

In actual fact, Eq. 2 should use H_i', the incident wave height immediately inside the harbour entrance since the entrance causes energy losses. Work by Unluata and Mei (10) and Murakami and

Noguchi (7) states:

$$H_i' = H_i - K_e \frac{\hat{u}_e|\hat{u}_e|}{2g} \tag{4}$$

where K_e is an entrance loss coefficient

$\hat{u}_e$ is the maximum velocity in the entrance.

The value used for K_e was 1.5 and this will be verified in some later research. Equation 3 must therefore be rewritten as:

$$P_i' = bnC \frac{\rho g H_i'^2}{8} = bnCR^2 \frac{\rho g H_i^2}{8} = R^2 P_i \tag{5}$$

where $$R = \frac{H_i'}{H_i}$$

If complete and even diffusion of wave energy is assumed, it is possible to write:

$$P_a = (k_a^2 \frac{\varepsilon}{S}) P_i' \tag{6}$$

where k_a is the absorption coefficient for the perimeter absorbers,

ε is the length of absorber,

S is the length of harbour perimeter.

In actual fact diffraction takes place and Eq. 6 needs to be modified as:

$$P_a = \left\{ \sum_{j=1}^{J} k_{a_j}^2 \; k_{D_j}^2 \; \frac{\Delta S_j}{b} \right\} P_i' \tag{7}$$

Here the perimeter, S, has been divided into J incremental lengths ΔS_j,

k_{a_j} is the absorption coefficient for incremental perimeter length ΔS_j,

k_{D_j} is the diffraction coefficient for the waves reaching section ΔS_j.

Finally, the waves that are incident on the absorber have been modified by bottom friction and hence to be totally correct, Eq. 7 should be rewritten as:

$$P_a = \left\{ \sum_{j=1}^{J} k_{a_j}^2 \; k_{D_j}^2 \; \frac{\Delta S_j}{b} \right\} (P_i' - P_f) \tag{8}$$

where it is assumed that energy dissipation by friction occurs evenly throughout the harbour.

The weakest link in this rather simple analysis is the expression for radiation of energy outward through the entrance. It is assumed that the waves reflected from the face directly opposite the entrance radiate outward through the entrance completely. Any other reflected waves are assumed to re-reflect and remain in the harbour. Essentially a balance in error is assumed between ignoring dispersion of the waves involved in the outward radiation and ignoring the portion of wave energy escaping after secondary reflection. Thus

$$P_o = \left(\sum_{m=1}^{M} k_{r_m}^2 \, k_{D_m}^2 \, \frac{\Delta S_m}{b} \right) \left(P_i' - P_f \right) \tag{9}$$

where k_r is the reflection coefficient of perimeter length ΔS_m and the summation is only over a width of perimeter b, directly across the harbour entrance consisting of M incremental lengths of perimeter ΔS_m. Energy dissipation by friction for the return journey of the waves from the backwall to the entrance is also ignored in Eq. 9.

The rate of energy dissipation is based on work done earlier at Queen's and summarized in Ref. 4.

$$P_f = \frac{0.18 \, \rho \, \omega^2 \, H_{rms}^3}{8n \sinh^3 kd} \, f_w \tag{10}$$

where ω is the wave frequency $(2\pi/T)$,

T is the wave period,

f_w is the wave friction factor defined in Refs. 3 and 4.

The dissipation by internal friction, P_d, was found to be insignificant.

Introducing P_i' instead of P_i into Eq. 1 and integrating yields:

$$E = \frac{t}{A} \left(P_i' - P_o - P_a - P_f \right) \tag{11}$$

where the expression has been averaged over several wave periods. Substitution of Eqs. 2 to 10 now yields:

$$\frac{H_{rms}}{H_i} = \sqrt{\frac{t}{A} \left[bnCR^2 - \frac{0.18 \, \omega^2 H_{rms}^3}{ngH_i^2 \sinh^3 kd} \right] \left[1 - \sum_{j=1}^{J} k_{a_j}^2 \, k_{D_j}^2 \, \frac{\Delta S_j}{b} - \sum_{m=1}^{M} k_{r_m}^2 \, k_{D_m}^2 \, \frac{\Delta S_m}{b} \right]} \tag{12}$$

Note that to solve Eq. 12 requires both diffraction analysis and iteration.

Figure 5, based on calculations using the above equations, shows the influence of the individual terms in Eq. 11 as well as the development of the ratio H_{rms}/H_i. It may be seen that when the perimeter consists of reflecting walls, P_o is the important energy sink, as expected, while P_a is the dominant energy sink when absorbing perimeter walls are present. It may also be seen that the harbour takes a relatively short time to build up its wave energy to an asymptotic value. The dimensionless time scale used simply means time divided by the time it takes the wave to reach the back wall of the harbour (D is the depth of the harbour).

COMPARISON OF THEORY WITH EXPERIMENT

The relatively simple theoretical development of the previous section was compared with the experimental results and sample plots are shown in Figs. 6,7,8 and 9 (B is the width of the harbour). These figures indicate very good agreement except when the perimeter walls are reflecting. There are two possible reasons for this discrepancy:

a. Local values of H deviate very far from H_{rms} but on a rather regular reflection pattern (Fig. 3(a)). The seven wave probes shown in Fig. 2 can therefore consistently measure values of H which result in substantially high or low values of H_{rms} depending on the reflection pattern present in the harbour.

b. In the case of reflecting walls, the dominant energy sink in Eq. 11 is P_o, which is defined in the least reliable fashion.

CONCLUSIONS

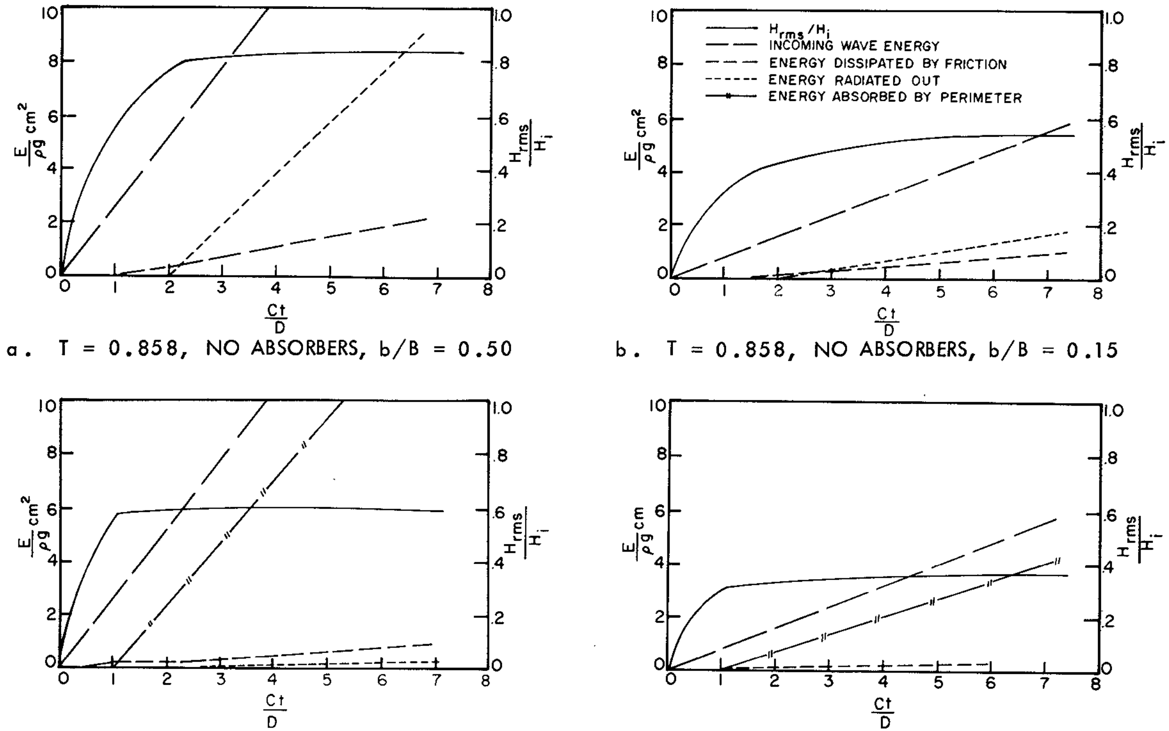
1. The average, overall energy level in a harbour may be adequately calculated using a relatively simple theoretical expression such as Eq. 1 or Eq. 11. For the simple square or rectangular harbour used in this paper, the expressions reduce to Eq. 12.

2. The fit of the theoretical expression improves with the absorption qualities of the perimeter.

3. It was further seen from the tests that:

   a. absorbing perimeter sections are valuable for reducing overall energy levels in a small craft harbour (Fig. 4).

   b. absorbing perimeter sections reduce local wave energy peaks or locally large wave heights drastically, spreading the energy more evenly throughout the harbour (Fig. 3(a) and (b)).



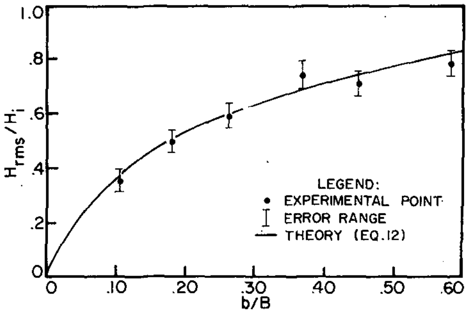
a. T = 0.858, NO ABSORBERS, b/B = 0.50

b. T = 0.858, NO ABSORBERS, b/B = 0.15

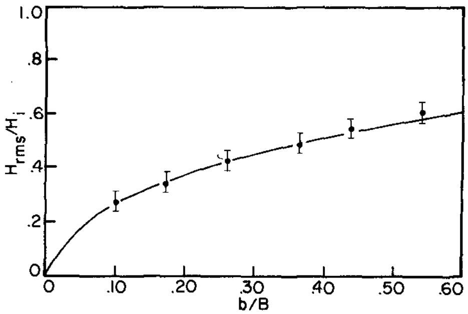
c. T = 0.858, ABSORBER ALONG BACK WALL, b/B = 0.50

d. T = 0.858, ABSORBER ALONG BACK WALL b/B = 0.15

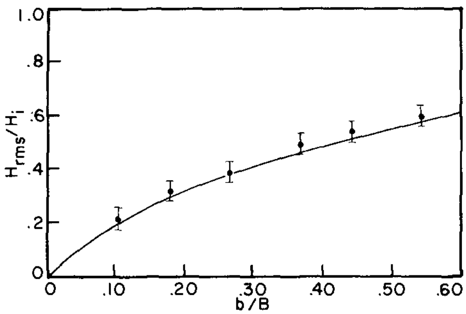
FIGURE 5: HISTORY OF INDIVIDUAL TERMS OF EQUATIONS 1 AND 12.



a. REFLECTING WALLS.



b. ABSORBER ON BACK WALL ONLY.



c. ABSORBER ON ALL WALLS.

FIGURE 6: NORMALIZED RMS WAVE HEIGHT COMPARISON WITH THEORY
T = 0.985 s RECTANGULAR HARBOUR.

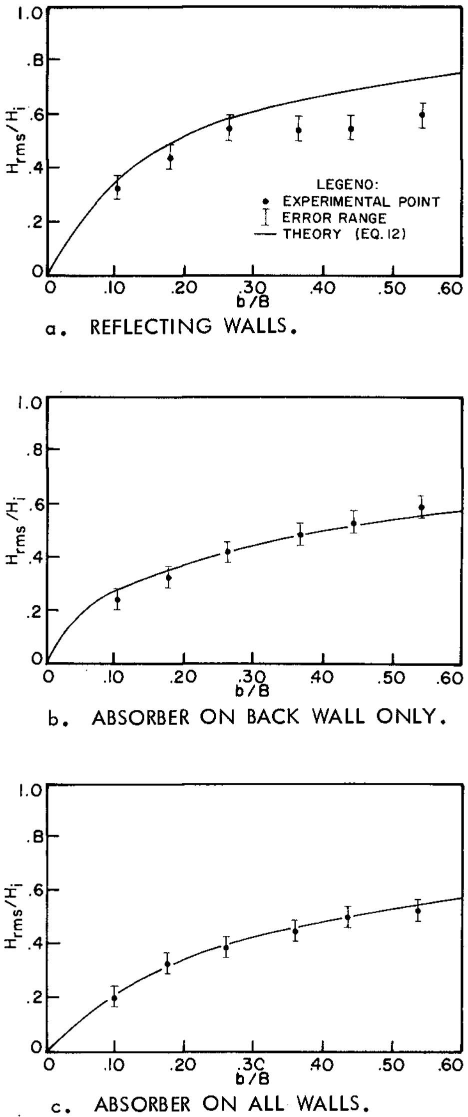
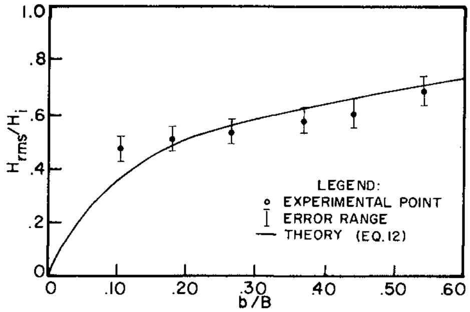
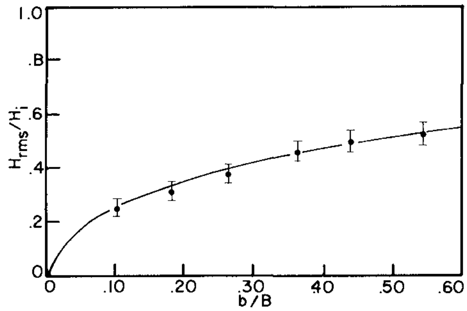


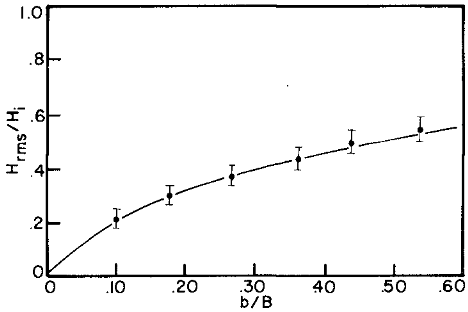
FIGURE 7: NORMALIZED RMS WAVE HEIGHT COMPARISON WITH THEORY T = 0.858 s RECTANGULAR HARBOUR.



a. REFLECTING WALLS.

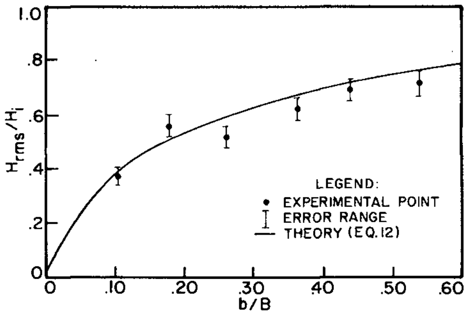


b. ABSORBER ON BACK WALL ONLY.

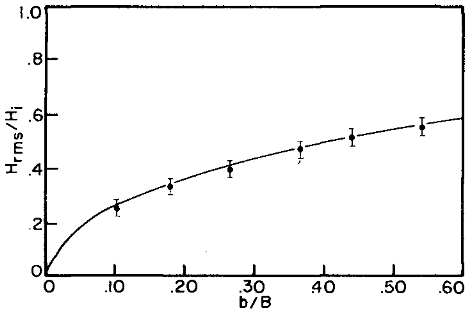


c. ABSORBER ON ALL WALLS.

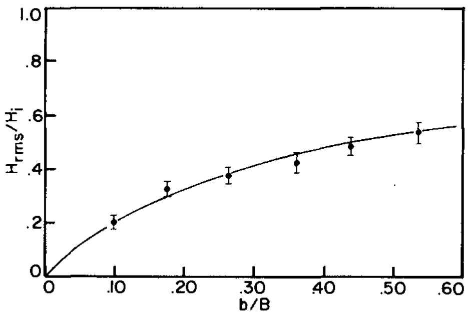
FIGURE 8: NORMALIZED RMS WAVE HEIGHT COMPARISON WITH THEORY
T = 0.69 s RECTANGULAR HARBOUR.



a. REFLECTING WALLS.



b. ABSORBER ON BACK WALL ONLY.



c. ABSORBER ON ALL WALLS.

FIGURE 9: NORMALIZED RMS WAVE HEIGHT COMPARISON WITH THEORY
T = 0.985 s SQUARE HARBOUR.

c. absorbing perimeter sections can be located judiciously in order to bring about maximum attenuation of wave action per unit length of absorber, (Fig. 4).

d. Energy levels in the harbour build up rapidly until the main energy sinks begin to function. In any case, response of a marina to outside agitation is rapid — of the order of the time taken for a wave to cross the marina and reflect back to the entrance, (Fig. 5).

Much more work needs to be done. This is only one building block which is useful in solving a rather pressing problem.

REFERENCES

1. Abbott, M.B., Petersen, H.M. and Skovgaard, O., (1978) "Computations of Short Waves in Shallow Water", *Proceedings, 16th Conference on Coastal Engineering*, Hamburg, pp 414-433.

2. Inman, D.L., (1974) "Ancient and Modern Harbours: a Repeating Phylogeny", *Proceedings 14th Conference on Coastal Engineering*, Copenhagen, pp 2049-2067.

3. Kamphuis, J.W., (1975) "Friction Factor Under Oscillatory Waves", *Waterways, Harbours and Coastal Engineering Journal*, A.S.C.E., Vol. 101, WW2, May 1975, pp 135-144.

4. Kamphuis, J.W., (1978) "Attenuation of Gravity Waves by Bottom Friction", *Coastal Engineering*, Vol 2, No 2, Oct 1978, pp 111-118.

5. Kamphuis, J.W., (1979) "Hydraulic Design of Small Craft Harbours", *Proceedings Canadian Society for Civil Engineering Conference on Coastal Engineering*, Kingston, April 1979, pp 133-152.

6. Kohlhase, S., Daemrich, K.F. and Berger, U., (1978) "A Numerical Approach for the Determination of the Wave Height Distribution in a Harbour", *Proceedings 16th Conference on Coastal Engineering*, Hamburg, pp 664-676.

7. Murakami, H., and Noguchi, E., (1977) "Effects of Entrance Loss on Wave Induced Oscillations in Rectangular Harbours", *Coastal Engineering in Japan*, Vol. 20, pp 27-42.

8. Smith, D.A.Y., (1980) On the Damping of Non-Resonant Wave Agitation in Small Craft Harbours. *Ph.D. Thesis*, Queen's University.

9. Townson, J.M., (1973) "History of Coastal Engineering", *Dock and Harbour Authority*, Vol 54, pp 16-19.

10. Unluata, U. and Mei, C.C., (1975) "Effects of Entrance Loss on Harbor Oscillations", *Waterways, Harbours and Coastal Engineering Journal*, A.S.C.E. Vol 101, WW2, pp 161-180.

ACKNOWLEDGEMENTS

The financial research support of the Natural Sciences and Engineering Research Council of Canada for this project is gratefully acknowledged. The junior author extends his appreciation for the MacLaughlin Fellowship he held throughout his studies.