"the required accuracy in the measurement of the model variables parameters must be satisfied."

Wave Model for Coastal Structures*

by

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Abstract

Wave models as a planning and design tool are used to predict the influence of environmental conditions on a proposed harbour layout. These models have to satisfy similarity criteria as described herein. Factors such as wave climate, scale selection, hydrographic surveys, instrumentation and documentation influencing the design of the wave models are discussed. The use of wave disturbance test and stability test in arriving at the optimum port layout and breakwater cross-section, respectively is also explained.

Introduction

For nearly half a decade now, major port projects are undertaken and still in progress to cope with the increasing international as well as domestic trade volume and to provide better port facilities to the fishing industry. To mention a few, some 91 national and municipal port constructions are funded by the Philippine Port Authority (PPA). In 1981, 34 projects were completed, the biggest of which was the Port of Davao. Philippine Port Authority has also started the construction of four IBRD-assisted ports (Cebu, Iloilo, Zamboanga and Cagayan de Oro) which are to meet the foreign traffic and domestic containerization. On the other hand, the Philippine Fish Marketing Authority (PFMA) has a total of 42 municipal fishing ports completed in 1981 and some 158 more are expected to be built in 1984. There are also five commercial fishing ports (Iloilo, Zamboanga, Lucena City, Camaligan and Sual) which are anticipated to serve the fishing industry's needs – like the Navotas Fishing Port and Fish Market.

Feasibility studies similar to the abovementioned projects are being conducted. Once found to be technically and economically viable, this type of infrastructure would involve huge costs which may run into millions of pesos. Hence, wave model studies should be considered as a planning and/or design tool in arriving at the optimum port layout considering environmental conditions and operational requirements. Hydraulic models allow the required safety and stability to be achieved and at the same time obtaining an economical and structurally optimal solution. Thus, it avoids erroneous decisions and saves unnecessary costs.

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This paper describes the similarity in conditions between the model and the prototype wave motion. Factors such as wave climate, selection of scale, instrumentation and documentation are considered in the design of wave model. In this case the wave model has a fixed bed, thus coastal problems on morphological processes are not dealt and are outside the scope of this paper though they can be conducted on the same wave model with movable bed. Wave disturbance test and stability test are also discussed.

Similarity Consideration for Wave Motion

A. Wave Propagation

The basic equation for similarity criteria for wave model is the general equation for celerity C,

$$C = \sqrt{\frac{gL}{2\pi} + \frac{2\sigma\pi}{\rho L} \quad \tanh \frac{2\pi d}{L}} \qquad (2.1)$$

where L is the wavelength, d is the depth of water and σ is the surface tension (for air/water σ = 74 mN/m). In the prototype, the influence of the surface tension can be neglected. This then is also the case in the wave model. This requires

$$\frac{gL}{2\pi} >>> \frac{2\rho\sigma}{\rho L}$$

Hence, the celerity equation is simplified to the Stokes gravity wave equation.

$$C = \sqrt{\frac{gL}{2\pi} \quad \tanh \frac{2\pi d}{L}} \qquad (2.2)$$

It is now possible to classify three cases:

a) Relatively deep water

For this case d >L/2 leading to tank 2nd/L nearly equal to unity.

$$C = \sqrt{\frac{gL}{2\pi}}$$

$$n_C = \sqrt{n_L} \qquad (2.3)$$

where n is scale of a parameter which is defined by the ratio between the prototype value and the model value of this parameter, e.g.,

$$n_C = \frac{C_p}{C_{\overline{m}}}$$

b) Relatively shallow water

Here $d < L/20$ which gives $\tanh \frac{2\pi d}{L}$ equal to $\frac{2\pi d}{L}$

This results in

$$C = \sqrt{gd}$$

$$n_C = \sqrt{n_d} \qquad (2.4)$$

c) Intermediate range

For $0.05 < d/L < 0.5$, equation (2.2) must be used in the similarity criteria. There will be no scale effect if $\tanh \frac{2\pi d_p}{L_p} = \tanh \frac{2\pi d_m}{L_m}$

Thus, $n_C = \sqrt{n_L} = \sqrt{n_d}$

The wavelength L and the wave celerity C are linked by the equation $L = CT$ where T is the wave period.

Thus, $n_L = n_C \; n_T$

For the general case, it can be concluded from $n_C = \sqrt{n_d}$ and $n_L = n_C \; n_T$ that $n_T = \sqrt{n_d} = \sqrt{n_L} = n_C$.

Distortion can be permitted depending on the type of wave deformation.

B. Wave Deformation

Various types of wave deformation do exist. First, refraction will be discussed. At the instant the wave front in the shallow water meets a bottom contour at an angle, the direction of travel is changed. This process of refraction (strictly speaking: depth refraction) is due to the fact that water waves propagate more slowly in shallower than in deeper water, and therefore the wave front tends to become more aligned with the contours. This implies that as long as the celerity is reproduced correctly, there will be no scale effects. Thus a sufficient condition is n_T is equal to $\sqrt{n_d}$.

Changes of celerity can also be caused by currents, resulting in current refraction. A correct reproduction can be obtained if the current is reproduced according to Froude condition. Obviously, for both types of refraction, no conditions have been set for n_H and n_L. The wave height in the model can be selected freely as long as the waves become not too steep. Thus, refraction can be reproduced in distorted model.

Waves are also observed in regions which are sheltered by breakwaters or the like. These disturbances are caused by the bending of incident waves around obstacles into 'shadow zones'. This is called diffraction. The wave height at any point along the obstacles must be reproduced correctly and thus this requires the wavelength scale n_L must be equal to horizontal scale n_l of the model. This, in turn, means that for studies of wave diffraction an undistorted model with $n_L = n_l$ is necessary.

Design of wave models

The design of a wave model requires the consideration of many aspects which are interrelated. These factors are the hydrographic conditions, wave climate, selection of model scale and the instrumentation including the documentation. Scale relations have to be deduced and a compromise has to be arrived between conflicting scale conditions based on the objective of the model study. The required accuracy in the measurement of the model variables/parameters must be satisfied. The laboratory facilities which include the wave basin, the instrumentation and the control system play an important role in the design of the model.

The early stage of the model study requires the collection of information on hydrographic condition at the site of the proposed port facility. The extent of survey works generally depends on the type of project whether it is an extension of an existing harbour, a new harbour in well defined area or a new project in an area with little or no reliable information. Existing harbours usually have hydrographic surveys for planning purposes, for control of maintenance of dredged area and for support of traffic.

For new projects, hydrographic data collection and field investigation programs are to be initiated. Investigations have to gather waves, currents, wind, water levels and sediment for at least a year to describe the seasonal variation.

A statistical analysis of the wave climate in the site to be studied has to be conducted. This design input to the model requires the determination of the seasonal probability including extreme condition and spectral distribution of wave heights, wave periods and direction of propagation in relation to wind condition. In addition, swell waves as well as long-period waves are given due consideration. In the absence of wave records, wind wave hindcasting methods such as SMB method (Sverdrup, Munk, Bretschneider), PNJ method (Pierson, Newman, James) or mathematical hindcasting models are utilized to predict the wave climate at the site.

The choice of the model scale is related to the size of the area to be investigated. The model scale has to satisfy the sea condition within the limits of the model and has to achieve a good measurement accuracy. The size of the model further depends on the similarity requirement as well as on economic consideration of model construction and operation. The scale of the wave model and its associated size is sometimes restricted by the dimension of the wave basin and existing wave generators.

In general, wave models should be undistorted if the wave parameters are to be dynamically similar according to Froude criterion and frictional effects are negligible. Distortion will be allowed based on objective of the model. Wave models which cover large areas require some geometric distortion to have a larger water depth.

The boundaries of the model must be oriented such that undesirable reflection is minimized especially if it does not occur in the prototype. Wave absorber must be provided to prevent the disturbances of the climate. The usual wave absorbers are sloping rough beach, bales of steel wool, expanded metals, plastic fibre, shingles and others.

The usual scales for wave action are : a) stability studies – 1:5 to 1:30 with 0.3 m wave height, b) reflection from slopes and isolated structure, determination of wave transmission of floating structure – 1:30 to 1:60 with wave period greater than 0.7s, c) basin studies of refraction, diffraction and reflection – 1:60 to 1:150 with wave height of 2 to 5 cm and wave period no less than 0.5 to 0.7s.

Knowing the wave climate at the site as earlier discussed, waves in the model are produced either mechanically or electronically. The wave forms are either regular sine waves or natural wave trains which are superposition of sine waves. The stochastic properties of the wave climate are simplified and are identified by the characteristic parameters such as significant wave height and its associated wave period. This permits the investigation of wave model with regular wave which are produced mechanically. These wave generators are usually flap or piston type and are driven by motors with gear reduction for variable wave period.

With the advances in hydraulics and experimental techniques, it is now possible to generate irregular waves. This allows the simulation of the prototype wave trains by producing the required energy spectrum in the model. The generation of wave trains is produced through servo controlled piston which is attached to a paddle.

Wave heights are detected by wave gauges which may be of the resistance or capacitance type. The wave heights are either directly recorded on strip charts which are manually analyzed or transmitted to appropriate data loggers which are further fed to a computer for analysis.

Photographs and video tapes are powerful tools in the measurement of wave-induced phenomena. They allow the documentation of wave direction and superposition through diffraction and reflection and determination of destructive characteristics of a breakwater.

Wave disturbance test

The wave disturbance test describes condition of the wharves for the different test conditions selected to represent the wave climate at the site. By wave climate, it means the statistical description of the waves taking into account wave propagation directions as well. The test results for each run may describe typical vessel movements, mooring and fender forces and wave heights at selected positions of the harbour.

This type of test can be best illustrated using the harbour layout as shown in Figure 1. The model requires the hydrographic survey of the harbour and its adjoining area to define the model limits. The wave climate is represented by various significant wave heights and wave period which are determined statistically. From the hydrographic survey and wave climate, a preliminary scale can be selected and checked against the size of the wave basin and wave generators. Wave generators are flexible enough to take care of the different possible wave direc-

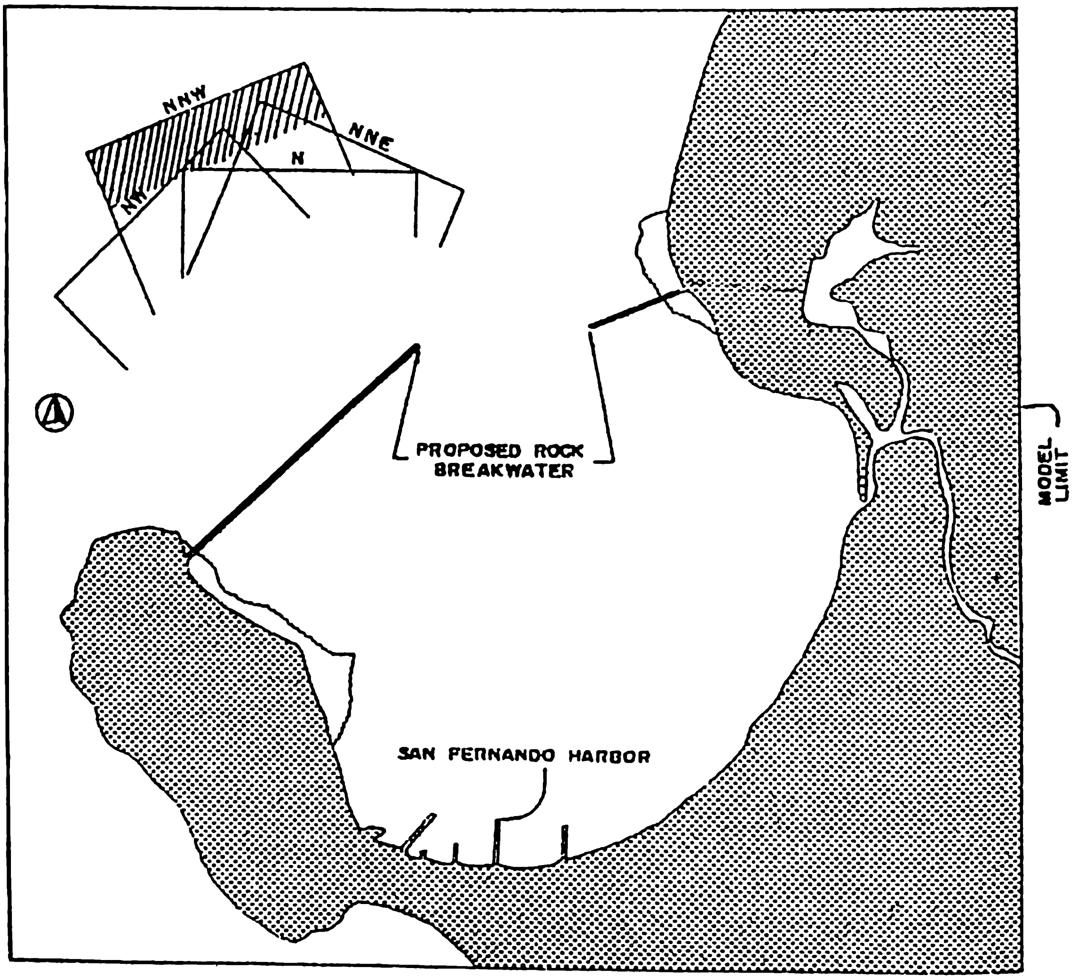

Figure 1. Proposed Breakwater Layout for San Fernando Harbour

tions. Wave absorbers are placed along the boundaries of the model in order to reduce the undesirable wave reflection. Wave gauges are to be installed at entrance, wharves and selected location inside the port. If ship movements are investigated, strain gauges are utilized in the measurement of forces along mooring line and on fenders.

From the initial results of the model, wave heights along the wharves are determined whether they are within acceptable limit. Improvements can be obtained by changing the port layout (i.e., length of breakwater, width of entrance and arrangement of approach channel), by changing the quay structure (i.e., orientation of berth/pier, and arrangement of absorbing or reflecting quay structure) and by improving the mooring system (i.e., rearrangement of bollard and fender position). Investigation of the resonance property of the harbour is also needed.

With these tests, the port designer can carry out cost/benefit analysis of the various alternative in terms of operational or safety conditions.

Stability Test of Breakwater

In deep water, breakwater usually adopts very steep slopes to minimize the volume of construction material. Large artificial concrete armour units on a steep slope are subjected to rapid break-down in case the main armour layer is seriously damaged. In deep water, the maximum incident waves are not limited by wave breaking, hence, the probability of a serious damage is further increased.

It is evident that there is a need for safer breakwater structures. Hence, model tests are powerful tools in the study of structural stability under different risks of damage, and in the study of breakwater construction stages.

In this kind of model test, the Froude model law applies. This states that the ratio of gravitation to inertia forces in the model shall be equal to the corresponding ratio in the prototype. The ratio can be expressed by the Froude number –N

$$N = \frac{\text{inertial force}}{\text{gravitational force}} = \frac{\gamma_s L^2 V^2}{g(\gamma_s - \gamma_w)d^3} \qquad (5.1)$$

where γ_w = specific weight of water, γ_s = specific weight of armour unit, g = acceleration, L = characteristic length, V = characteristic velocity.

Equation (5.1) reduces to

$$N = \frac{H}{\sqrt[3]{\frac{W}{\gamma_s}}\,(S-1)}$$

if the following relationships are utilized

$$L = \sqrt[3]{\frac{W}{\gamma_s}}\ , \quad V = \sqrt{gH} \quad \text{and} \quad S = \frac{\gamma_s}{\gamma_w}$$

where W = mean weight of armour weight, H = significant wave height. The Froude number in the model may be obtained by measuring H, W, γ_s and γ_w in the model. Using the Froude number in the model equal to the prototype Froude number, the corresponding prototype armour unit weight can be expressed as

$$W_{prot} = \frac{H^3{}_{prot}\ \gamma_{s\ (prot)}}{N^3\ (S_{prot} - 1)^3}$$

Comparing with the Hudson formula

$$W = \frac{\gamma_s H^3}{K_D (S-1)^3 a}$$

where K_D = stability parameter and a = slope of breakwater face the relationship $K_D = N^3/a$ can be deduced.

The extent of damage produced by the incident waves which is measured by counting the number of blocks moved is supplemented by photographs or videotapes documentation before, during and after the test. The damage to the breakwater is defined as the percentage of blocks or stones moved more than their own dimension. For the front armour unit, this damage percentage is given relative to the area between H above and H below the water line. The degree of damages is graded as follows:

Grade 1	No movements of the blocks.
Grade 2	Some blocks do rock, but do not move from mean position.
Grade 3	A few blocks are moved but the armour layer remains stable.
Grade 4	Blocks are moved continuously until the armour layer is destroyed.
Grade 5	The armour layer is destroyed in a short time.

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