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Physical Models of Coastal Structures As Designed and Used by the US Army Corps of Engineers

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ABSTRACT

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This paper presents an overview of physical models as applied to design of coastal structures at the Coastal Engineering Research Center (CERC), of the US Army Corps of Engineers. A review of similitude laws is followed by the philosophy of two- and three-dimensional stability modeling of rubble-mound coastal structures. A brief summary of the San Juan National Historic Site breakwater and revetment stability study, conducted at CERC for the Jacksonville District of the US Army Corps of Engineers, is presented as an example of a typical physical model stability study.

ADDITIONAL INDEX WORDS: *Coastal structures, models, breakwaters, model laws.*

INTRODUCTION

From the time humans took their first steps they have been striving to better understand and control their surroundings. Humans' natural curiosities have led them to devise ways to reach beyond their limited physical capabilities. A simple lever and fulcrum allows an individual to move objects several times his weight. Given sufficient time one person equipped with only a hand axe could topple the world's largest tree. The list could go on and on, but the point is that humans have developed the ability to fashion tools to build what is hoped to be a better world. These tools can be divided into two basic types. First are those designed to build tangible objects, like a hammer and saw can be used to build a house. Secondly are those which aid in building the intangible object commonly referred to as human knowledge.

Once the physics of a physical phenomenon are well understood, a system of equations governing the process can be developed. By varying parameters in the system of equations, a knowledge of cause and effect for a given process is developed. The system of equations is solved using an analytical or numerical model. The key to the development of the analytical or numerical modeling tool is a strong understanding of the physics of the process. This is a luxury that does not exist in many instances due to the complexity of the process. When processes are complex, physical models play a major role. A physical model is a scaled down version of an object that exists either in reality or in someone's inventive imagination. A properly scaled model will recreate the physics of the process at a manageable (both physically and economically) size. The model then can be modified to improve the object's operation or measure the object's response to varying environmental conditions. Physical models are very common tools of inventors. Inventors have an idea of an object or process but do not know how portions of it will function or whether or not it is a feasible concept. A properly scaled physical model allows them to modify, test, and further improve their idea. In the same manner, engineers and scientists use physical models to gain improved understanding of existing physical structures and processes which are currently felt to be too complex to address with analytical or numerical models. Physical models are the focus of this paper. More explicitly, this paper is geared to a non-engineering audience that is interested in seeing a basic overview and some

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examples of how physical models of coastal structures are designed and used within the US Army Corps of Engineers.

BACKGROUND

Rubble-mound breakwaters and jetties (Figure 1) are constructed in an effort to control the wave environment in harbors and maintain navigation channels, respectively. Miles of these structures exist on the coastlines (oceans, lakes, and reservoirs) of the United States. The majority of them were built and are maintained by the US Army Corps of Engineers using guidance and information (SPM, 1984) gained from physical models.

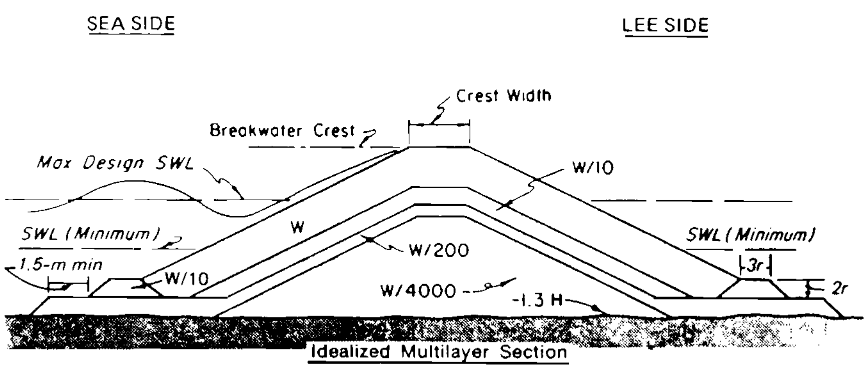
The positioning, length, height and alignment of a structure required to achieve a specified wave environment in a designated area is addressed in a three-dimensional (3-D) physical model similar to the one shown in Figure 2. The model also can address tidal and wave induced circulations, sediment movement, harbor oscillations, and much more. In many cases, once a 3-D model has been used to develop the length, height and alignment of the structure, a two-dimensional or three-dimensional model reproducing the structure at a larger scale (*i.e.*, less reduction in size) is used to aid in structural design. The two-dimensional model is commonly used to address structures being designed for wave attack that is approaching at an angle of 90 degrees (perpendicular) to the structure's crest. A three-dimensional model is used for design when the predominate angle of wave approach is oblique to the structure crest (*e.g.*, at breakwater ends, or heads). These latter larger scale structural models are commonly referred to as stability models and are the subject of the remainder of this paper.

MODEL SIMILITUDE

As summarized from HUDSON (1975) and STEVENS (1942), dynamic similarity between a model and its prototype involves satisfying both geometric and kinematic similarity and Newton's laws of motion. If the model and prototype are comprised of components having the same shape and spatial relationships then the two systems are geometrically similar and the relationship

$$L_m = L_r L_p \tag{1}$$

links linear dimensions between the two systems. The subscripts m and p refer to model and prototype, respectively, and L_r is length scale. For example, a L_r value of 0.1 means that every 1 foot increment in the model represents a 10 foot increment in the prototype. Kinematic similitude means that there is a defined relationship between particle motion in the model



Rock Size	Layer	Rock Size Gradation (%)
W	Primary Cover Layer[1]	125 to 75
W/10	Toe Berm and First Underlayer[2]	130 to 70
W/200	Second Underlayer	150 to 50
W/4000	Core and Bedding Layer	170 to 30

H = Wave Height
W = Weight of Individual Armor Unit
r = Average Layer Thickness

Figure 1. Typical cross section of three layered rubble-mound structure.

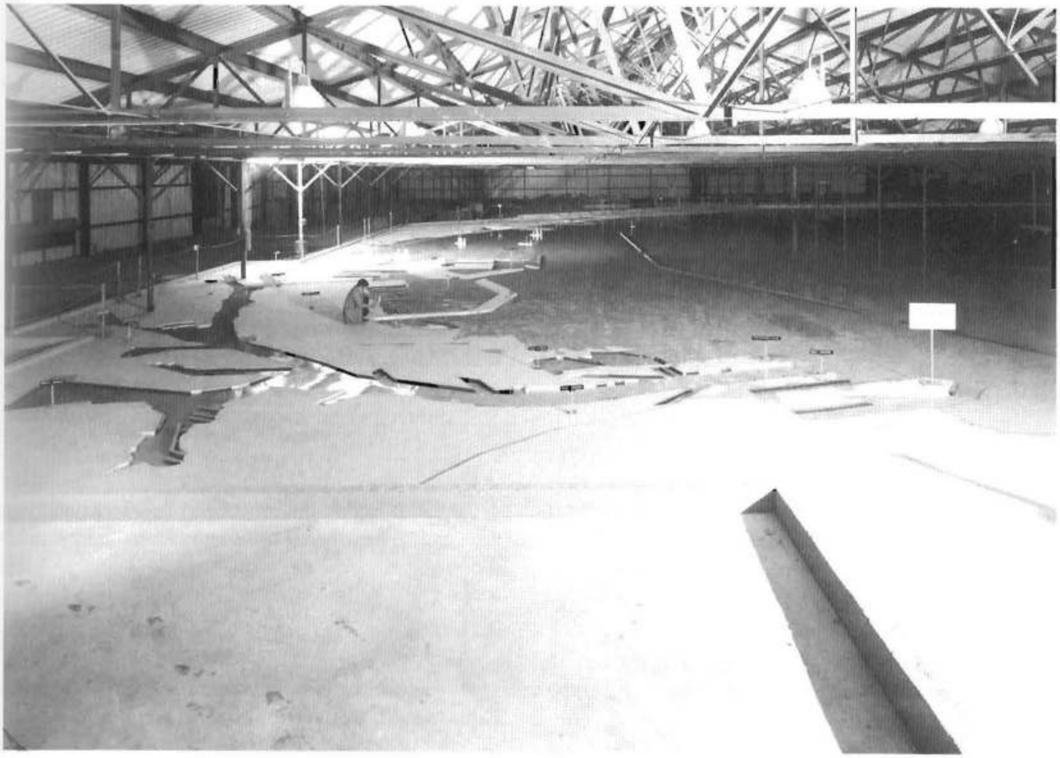


Figure 2. Example of three-dimensional wave action model (Los Angeles-Long Beach Model (Outlaw, *et al.*, 1975).

and the prototype. Two particles, one in the model and the other in the prototype are said to be homologous if they correspond to one another. Kinematic similitude is obtained if geometric similitude exists and if homologous particles are at homologous points at homologous times. Time interval relationships between the two kinematically similar systems are constant and defined as follows,

$$T_m = T_r T_p \qquad (2)$$

where T_r is the time scale.

Dynamic similarity occurs when there is similarity of masses and forces. Dynamic similarity requires that both kinematic and geometric similarity exist, and that the ratios of masses of various homologous particles or objects involved in motion occurrences are equal and ratios of homologous forces which affect motion occurrences of homologous objects are equal. Thus the relationships

$$M_m = M_r M_p \qquad (3)$$

and

$$F_m = F_r F_p \qquad (4)$$

are defined where M_r and F_r are the mass and force scales, respectively. Coastal fluid mechanics problems deal with systems whose elements are influenced by forces consisting of kinetic reaction due to inertia of an element's mass F_i, gravity F_g, viscous shear F_v, surface tension F_s, elastic compression F_e, and pressure resulting from or related to motion F_{pr}. Newton's second law of motion states that the vector sum of all active forces equals the element's mass reaction to those forces,

$$F_i = F_g + F_v + F_s + F_e + F_{pr} \qquad (5)$$

For overall similitude, the ratio of inertial forces, model to prototype, must equal the ratio of active forces,

$$\frac{(F_i)_m}{(F_i)_p} = \frac{(F_g + F_v + F_s + F_e + F_{pr})_m}{(F_g + F_v + F_s + F_e + F_{pr})_p} \quad (6)$$

Dynamic similitude requires that

$$\frac{(F_i)_m}{(F_i)_p} = \frac{(F_g)_m}{(F_g)_p} = \frac{(F_v)_m}{(F_v)_p} = \frac{(F_s)_m}{(F_s)_p} = \frac{(F_e)_m}{(F_e)_p} = \frac{(F_{pr})_m}{(F_{pr})_p} \quad (7)$$

Of these six equal force ratios, all but the pressure ratio $(F_{pr})_r$ are regarded as independent quantities. Only independent variables are considered in establishing similitude relationships. Also, all fluid weights and masses are proportional when influenced by the same gravitational field, but no known fluid exists with the necessary viscous, surface tension and elastic modulus properties necessary to totally satisfy Equation 7. However, it can be assumed that water is incompressible in the range of pressures occurring on rubble-mound structures and surface tension does not play a significant role for the range of wave amplitudes encountered on stability models. Therefore, the pressure, elasticity, and surface tension terms can be dropped without significantly influencing model accuracy and Equation 7 is reduced to the following form for stability models,

$$\frac{(F_i)_m}{(F_i)_p} = \frac{(F_g)_m}{(F_g)_p} = \frac{(F_v)_m}{(F_v)_p} \quad (7a)$$

Inertial reactions are always present in flow phenomena, thus inertial forces must be considered and to obtain dynamic similarity,

$$\frac{(F_i)_m}{(F_i)_p} = \frac{(F_g)_m}{(F_g)_p} \quad (7b)$$

and

$$\frac{(F_i)_m}{(F_i)_p} = \frac{(F_v)_m}{(F_v)_p} \quad (7c)$$

Inertial, gravitational, and viscous forces can be written in terms of their physical quantities (length L, velocity V, velocity gradient V/L, mass M, gravitational acceleration g, density ρ, and dynamic viscosity μ ,) as follows:

$$F_i = \text{mass} \times \text{acceleration} = (\rho L^3)(V^2/L) = \rho L^2V^2 \quad (8)$$

$$F_g = \text{mass} \times \text{gravitational acceleration} = \rho L^3 g \quad (9)$$

and

$$F_v = \text{viscosity} \times \text{velocity gradient} \times \text{area} = \mu VL \quad (10)$$

Equation 7b takes the form

$$\frac{(\rho L^2V^2)_m}{(\rho L^2V^2)_p} = \frac{(\rho L^3 g)_m}{(\rho L^3 g)_p} \quad (11)$$

which when rearranged and reduced takes the form

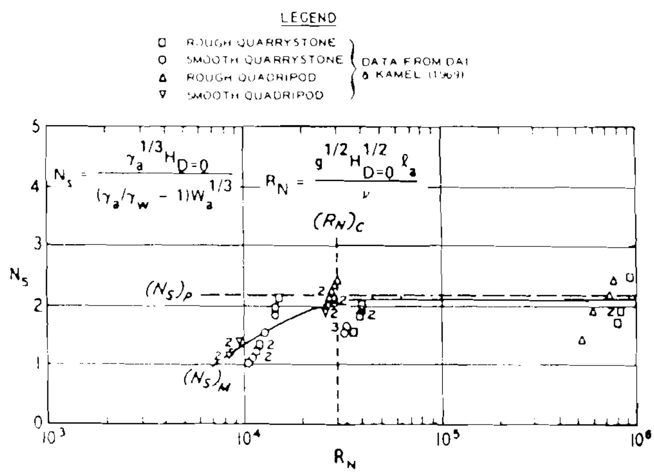


Figure 3. Scale effects on rubble-mound stability models.

$$\frac{V_m^2}{g_m L_m} = \frac{V_p^2}{g_p L_p} \quad (12)$$

and with the subscript r indicating model-to-prototype ratios,

$$\frac{V_r}{(g_r L_r)^{1/2}} = 1 \quad (13)$$

Equations 12 and 13 indicate that the ratio of gravitational to inertial forces should be equal in the model and the prototype. This is known as Froude model law and the dimensionless quantity $V/(gL)^{1/2}$ is called the Froude number When gravitational forces predominate, model design is based on Froude model law. In a similar manner, Equation 7c can be rewritten

$$\frac{(\rho L^2 V^2)_m}{(\rho L^2 V^2)_p} = \frac{(\mu VL)_m}{(\mu VL)_p} \quad (14)$$

which when rearranged and reduced takes the form

$$\frac{L_m V_m}{\nu_m} = \frac{L_p V_p}{\nu_p} \quad (15)$$

(where $\nu = \mu/\rho$, kinematic viscosity) and

$$\frac{L_r V_r}{\nu_r} = 1 \quad (16)$$

The ratio of viscous to inertial forces in the model should be equal to that of the prototype, as indicated in Equation 16. This is referred to as Reynolds model law and the dimensionless quantity LV/ν is called the Reynolds number Rn. When viscous forces predominate, Reynolds model law should control model design.

For complete dynamic similarity in rubble-mound stability models, the models need to be geometrically similar to their prototype counterparts and both model Froude and Reynolds numbers must be equal to those of the prototype. For the latter to be true the following equation must be satisfied.

$$\nu_r = L_r^{3/2} \quad (17)$$

which is derived by equating Equations 13 and 16 and solving for kinematic viscosity. This states that the viscosity of the fluid used in the model is dependent upon the linear scale of the model and vice versa. This is a virtually impossible condition to satisfy and is not economically feasible in the few cases where a liquid with the correct viscosity does exist. For this reason water is used as the fluid medium in all rubble-mound stability models. Thus perfect dynamic similarity is not achieved and this error is commonly referred to as a scale effect.

The magnitude of this scale effect can be viewed as how close the ratio of gravitational to viscous shear forces in the prototype matches the same ratio in the model. For a large number of hydraulic phenomena, including wave attack on rubble-mound structures, gravity forces predominate in the prototype processes and through proper linear scale selection can be made to predominate in the model. Thus, stability models are made geometrically similar and designed based on Froude model laws. The viscous scale effects are made negligible by sufficient sizing of the model. Forces on the rubble-mound armor units in a model designed this way are a function of Reynolds number

$$F_r = f(L_r V_r / \nu_r) \quad (18)$$

where L is a characteristic length and V is a characteristic velocity. The stability of a given armor unit is a function of the model's linear scale, wave dimensions and fluid viscosity. Water is both the prototype and the model fluid so the viscosity ratio is approximately unity. The characteristic length of the armor unit, defined by

$$l_a = k(W_a/\gamma_a)^{1/3} \quad (19)$$

where

- k = shape coefficient of armor unit (experimentally determined)
- W_a = weight of individual armor unit
- γ_a = specific weight of armor unit,

is used as the characteristic length in Equation 18. The velocity is defined by wave velocity, $V = f(gH)^{1/2}$ where H is the wave height. Thus, the following form of the Reynolds number is used in stability models

$$Rn = \frac{g^{1/2} H^{1/2} l_a}{\nu} \quad (20)$$

A series of tests were conducted at the US Army Corps of Engineers Waterways Experiment Station in 1968 (DAI and KAMEL, 1969) to determine the relationship between armor unit stability and Reynolds number so that a control could be developed to ensure that scale effects were either almost eliminated or

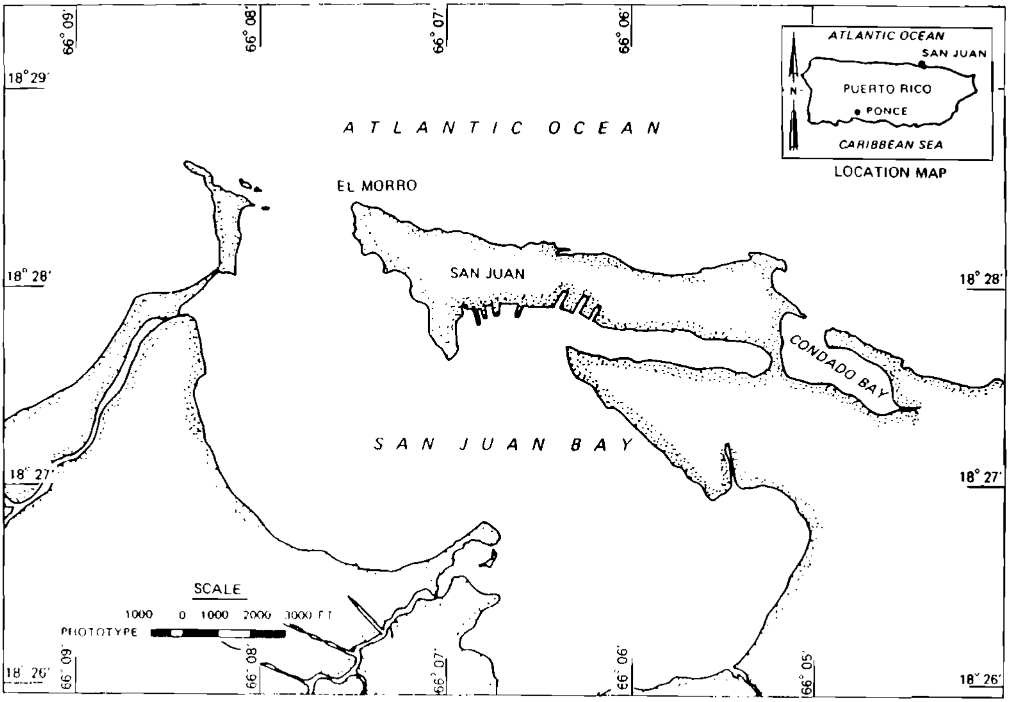


Figure 4. El Morro Castle location and vicinity maps.

adjusted for in model data analysis. An armor unit stability number N_s, defined as the ratio of drag forces on an armor unit to its submerged weight

$$N_s = \frac{\gamma_a^{1/3} H_{D-0}}{(\gamma_a/\gamma_w - 1) W_a^{1/3}} \tag{21}$$

where H_{D-0} is the wave height beyond which unacceptable armor unit displacement would occur and γ_W is specific weight of water in which armor is situated, was experimentally determined and plotted against Reynolds number, Figure 3. This plot shows that model tests conducted to check armor unit stability will have negligible stability scale effects as long as the model Reynolds number is equal to or greater than 3×10^4. For models with Reynolds numbers below this value the calculated stability number will be too low and it should be multiplied by a factor equaling the ratio $(N_s)_p/(N_s)_m$ as determined from Figure 3. A ratio greater than one means that the model will exhibit more damage than would be expected to occur in the prototype. In most cases, rubble-mound stability models can be scaled to ensure minimal viscous scale effects are present.

Through use of the linear scale, Froude model law, laws of mechanics and geometrical relationships, the model to prototype scaling relations can be derived. The velocity ratio is obtained directly from Froude model law which requires

$$\frac{V_m}{(g_m L_m)^{1/2}} = \frac{V_p}{(g_p L_p)^{1/2}} \tag{22}$$

and since $g_m = g_p$ it can be shown that

$$V_r = (L_r)^{1/2} \tag{23}$$

and length = velocity × time, therefore

$$T_r = \frac{L_r}{V_r} = (L_r)^{1/2} \tag{24}$$

Since force = mass × acceleration, the force ratio can be defined as follows

$$F_r = M_r \frac{dV_r}{dT_r} = L_r^3 \frac{(\gamma_w)_r V_r}{g_r T_r} \tag{25}$$

Figure 5. Aerial photograph of El Morro Castle.

With $g_r = 1$ and $V_r = (L_r)^{1/2} = T_r$ Equation 25 reduces to

$$F_r = L_r^3 (\gamma_w)_r \tag{26}$$

Knowing that weight = volume × specific weight it follows that the weight ratios for water and rubble-mound construction materials are defined by

$$(W_w)_r = L_r^3 (\gamma_w)_r \tag{27}$$

and

$$(W_a)_r = L_r^3 (\gamma_a)_r \tag{28}$$

respectively. For similarity to hold true,

$$F_r = (W_w)_r = (W_a)_r \tag{29}$$

This requires that

$$L_r^3 (\gamma_w)_r = L_r^3 (\gamma_a)_r \tag{30}$$

which reduces to

$$(\gamma_w)_r = (\gamma_a)_r \tag{31}$$

Equation 31 can also be written

$$\frac{(\gamma_w)_m}{(\gamma_w)_p} = \frac{(\gamma_a)_m}{(\gamma_a)_p} \tag{32}$$

which states that for perfect weight (force) similitude to be obtained, the ratio of the specific weight of the model water to prototype water must be the same as the ratio of the specific weights of the model and prototype construction materials. This requires that proper adjustments be made in the model construction material specific weights when dealing with a prototype salt water environment ($(\gamma_w)_p = 64.0$ pcf). Most all stability models are tested in a fresh water environment ($(\gamma_w)_m = 62.4$ pcf) which from Equations 31 and 32 requires that $(\gamma_a)_r = 62.4/64.0 = 0.975$.

Area and volume ratios are

$$A_r = L_r^2 \tag{33}$$

Figure 6. Typical eroded condition of slopes surrounding El Morro castle.

and

$$\overline{V}_r = L_r^3 \qquad (34)$$

respectively, while pressure is defined as force per unit area and thus the force ratio is defined as

$$P_r = \frac{F_r}{L_r^2} = \frac{L_r^3\,(\gamma_w)_r}{L_r^2} = L_r(\gamma_w)_r \qquad (35)$$

To summarize the similitude scaling relations, assume that a stability model of a rubble-mound structure to be placed in a salt water environment was to be constructed at a geometrically undistorted linear scale of 1:25 (model: prototype). The following defines scales to be used in this hypothetical model:

Characteristics	*Model-Prototype Scale Relations*
Length	L_r = 1:25
Area	$A_r = L_r^2$ = 1:625
Volume	$V_r = L_r^3$ = 1:15,625
Time	$T_r = L_r^{1/2}$ = 1:5
Force (Weight)	$F_r = W_r = L_r^3\,(\gamma_w)_r$ = 15,234.375
Pressure	$P_r = L_r(\gamma_w)_r$ = 24.275

CONSTRUCTION AND TESTING

The preceding discussions dealt with the methods and accuracies of modeling rubble-mound coastal structures as defined by laws of fluid mechanics. There are other factors besides these that control the validity of this type of modeling. It is essential that the model reproduce as closely as possible normal construction procedures used in the prototype and that prototype test conditions be selected using the best data available. It is very critical that accurate predictions or measurements of design wave and water level conditions be made available for reproduction in the model. If the design conditions are not accurate, it does not matter how well the model similitude laws have been followed. One of the most accepted design equations for rubble-mound coastal structures was developed at the Waterways Experiment Station and is referred to as the Hudson equation (HUDSON, 1958)

$$W_a = \frac{\gamma_a H^3}{K_D(\gamma_a/\gamma_w - 1)^3 \cot\alpha} \qquad (36)$$

where

- W_a = weight of individual armor stone
- H = design wave height
- γ_a = specific weight of armor stone
- γ_w = specific weight of water in which structure is situated
- α = angle the armor stone slope makes with the horizontal
- K_D = experimentally determined coefficient unique to armor unit shape and placement, structure geometry, design wave conditions, *etc.*

With weight being proportional to the wave height cubed, it readily can be seen that a small error in selection of design wave height would have a major impact on required armor unit weight. Many other approaches to defining armor stability have been developed and presented over the years, IRRIBARREN (1938 and 1950), BRUUN and GUNBAK (1976), LOSADA and GIMENEZ-CURTO (1979), HEDAR (1986), VAN DER MEER (1988) and CARVER and WRIGHT (in publication) for example, but for the present time, the Hudson equation remains the standard within the US Army Corps of Engineers.

The design water level is critical in that it can be the limiting factor for wave heights reaching the structure. It also is needed to set structure crown elevations that will produce the desired wave climate in the lee of the structure. Over prediction of design water level could result in an economically infeasible design due to large volume of material required to achieve the required crown elevation and the oversized armor stone required for stability in the more severe wave climate that could reach the structure due to deeper depth. On the other hand, prediction of a design water level that is too low could result in an inadequately designed structure both in regard to armor stone stability and excessive wave energy overtopping the structure due to low crown elevation associated with lower design water level.

Another factor which has a major affect on the structure design is the slope of the ocean or lake bottom over which the waves approach the structure. This is especially true for structures that are designed for depth-limited breaking waves. A depth-limited design wave is the maximum wave height for a given water depth,

Figure 7. Three-dimensional wave action model of existing conditions at El Morro Castle.

wave period, and foreslope that can reach the structure before the crest of the wave begins to curl over and initiate wave breaking. For a given period and water depth, depth limited breaking wave height increases as the foreslope steepens. Also, for a fixed water depth and foreslope, the depth-limited breaking wave height becomes larger as wave period increases. Thus, wave period is another design condition that is critical to stability and overall structure performance.

WHAT CAN A STABILITY MODEL ADDRESS?

In order to perform a stability model study, whether the study involves a specific prototype site or an idealized structure that is being used to conduct applied research necessary to improve guidance for rubble-mound structure design and/or performance, the following items must be defined:

(1) Proposed structure design (size, geometry, and construction materials).
(2) Structure performance criteria (allowable damage if any, maximum runup, wave transmission, *etc.* during exposure to design wave and water level conditions).
(3) Prototype wave and water level conditions to be used for design (incident wave direction(s), period(s), and depth(s) and storm surge levels).
(4) Bathymetric details of the area under and surrounding the proposed structure (depths and contours on which a decision can be made as to what type of representative bottom slope(s) should be simulated seaward of the structure).

The next step is to decide whether the study requires a two- or three-dimensional model and what linear scale should be used to preclude stability scale effects and still fit within the available test facilities and budget. During this

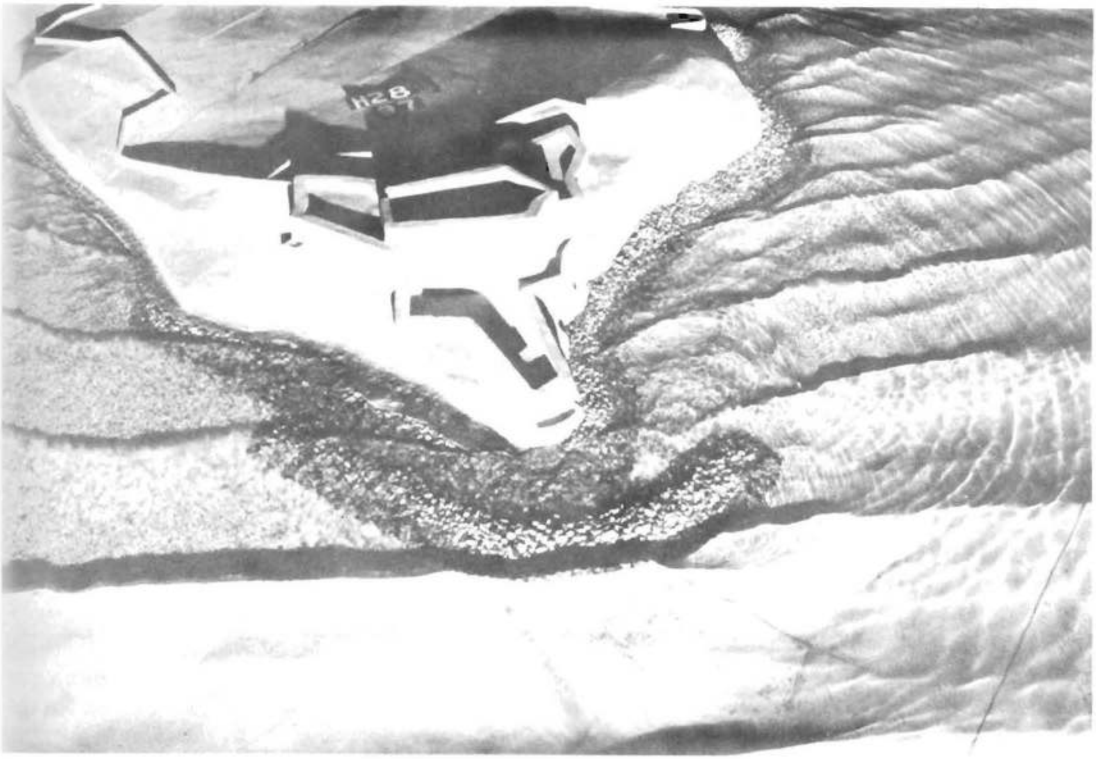


Figure 8. Three-dimensional wave action model of El Morro Castle with recommended offshore breakwater and revetments installed.

phase, the model designer must consider carefully the purpose of the model study. A stability model is most commonly used to address the following:

(1) Stability of armor layers protecting slopes, toes and/or crowns of rubble-mound structures when exposed to various combinations of waves and water levels. Various sizes and types of armor can be evaluated and compared in order to develop general design guidance for armor sizing or the sizes required for a specific site.
(2) Optimization of structure type, size, and geometry needed to meet desired performance specifications and budget restrictions.
(3) Wave runup, rundown, overtopping, reflection, absorption, and transmission characteristics, surface, internal and foundation static and dynamic pressures relative to various structure features (crown wall or ribs, walkways, roads, unique construction or armoring, *etc.*); and types and geometries when the structure is exposed to a range of wave and water level conditions. (Model structures designed to address wave transmission through the structures should be checked for proper scaling of underlayers and core material using guidance developed by KEULEGAN (1973).
(4) Methods of repairing damage on or improving performance of existing structures.
(5) Effects, if any, proposed structure modifications will have on an existing structure's stability and performance.

All of these items can be addressed on a quantitative basis. Due to limitations in the current state-of-the-art, other phenomena can only be evaluated on a qualitative basis. These include wave and current induced scour around structures and prediction of rubble-mound damage

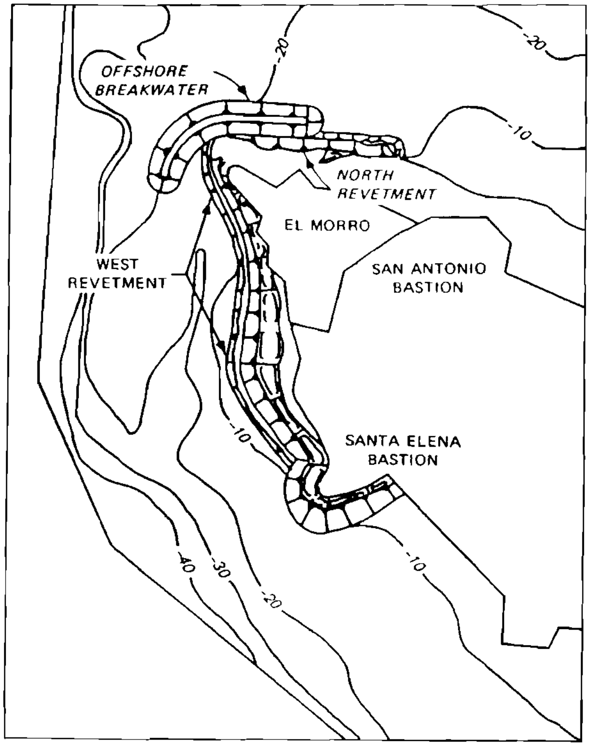


Figure 9. Proposed protective structures: offshore breakwater, north revetment, and west revetment.

levels that extend into the underlayers and core.

When all predominant design wave conditions approach with crests parallel to the structure crown and stability and other properties of the structure trunk are to be addressed, a two-dimensional model in most cases will be adequate to check the adequacy and/or optimize a proposed design. A three-dimensional model is required to address angular wave attack, design of structure heads or structures with complex geometries that vary along the structure lengths, and/or complex bathymetries surrounding structures.

CASE STUDY

Now that some of the basic background as to purpose and design procedures for rubble-mound stability models have been presented, a quick look at a site specific model study should draw this material together. In October 1974 Congress authorized the Secretary of the Interior in cooperation with the Secretary of the Army to conduct studies to determine the cause and extent of damage to the historic structures of the San Juan National Historic Site. The historic site is located at the old city of San Juan on the north coast of the Island of Puerto Rico (Figure 4). The area is part of the fortification complex built by the Spanish for defense of the city and as a base to support Spanish influence in the Americas. Construction was initiated in the 16th century and most of the structures present today were completed by the end of the 17th century. To ensure the preservation of fortifications, the San Juan National Historic Site was established by the Secretary of the Interior on 14 February 1949. The site includes the fortifications of La Princesa, San Cristobal, Castillo de San Felipe del Morro (El Morro castle (Figure 5), and numerous connecting walls and bastions (USAED, Jacksonville, 1974).

Years of direct wave attack on the cliffs surrounding the fortifications had resulted in extensive scour and undermining. Large cav-

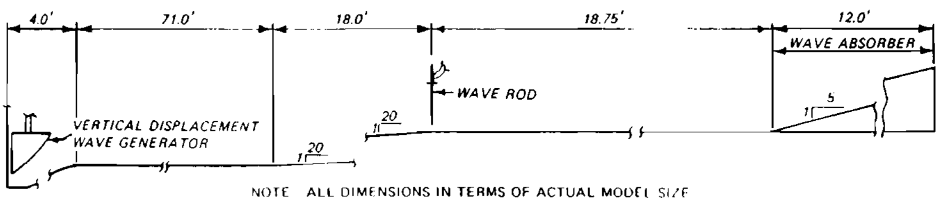


Figure 10. Flume geometry and wave rod location for calibration of the 2-D test flume for stability tests on the north slope.

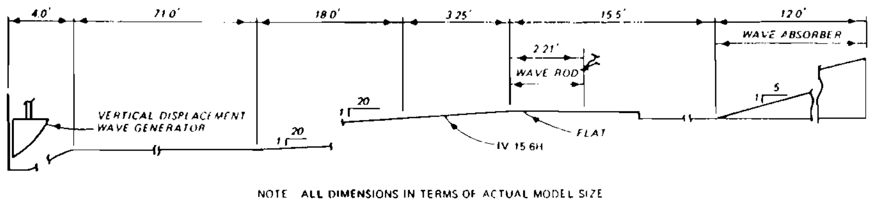


Figure 11. Flume geometry and wave rod location for calibration of the 2-D test flume for stability tests on the west slope.

erns and overhanging rock ledges had been carved out of the cliffs and were threatening the structural integrity of the rock foundations and walls of the historic fortifications. Figure 6 shows a typical example of the eroded foundations surrounding El Morro Castle.

At the request of the National Park Service, U. S. Department of the Interior, the Jacksonville District of the U. S. Army Corps of Engineers developed preliminary designs for an offshore breakwater and stone revetments to protect the deteriorating foundation and walls of the castle from future storm waves. The Jacksonville District funded the U.S. Army Corps of Engineers, Waterways Experiment Station to conduct model studies to check the adequacy and optimize the design of these proposed structures. During the period December 1977 through July 1979 three-dimensional wave action model tests (BOTTIN, 1979) (Figure 7) were conducted at an undistorted linear scale of 1:75 (model:prototype) to determine revetment locations and breakwater positioning and alignment. Results of the wave action model study recommended an offshore breakwater and stone revetment on the northern, or open-ocean, side of El Morro Castle and a stone revetment on the western, or bay, side of El Morro Castle (Figures 8 and 9).

Following the wave action model study, both two-dimensional and three-dimensional breakwater and revetment stability tests (MARKLE, 1981) were conducted during the period September 1979 through September 1980. The purposes of the stability studies were as follows:

Two-Dimensional Model Tests

Develop stable, economical and aesthetically pleasing designs for the trunk of the offshore breakwater, the north revetment, and the west revetment to protect the fortifications from storm conditions that would generate depth-limited breaking waves at design water levels of 0.0 and +1.9 ft mean sea level.

With the offshore breakwater and north revetment in place, determine the runup produced on the north slope by a range of wave heights with wave periods from 7 to 17 sec at the design water levels.

With the unprotected west revetment in place, determine the runup produced on the west slope for a range of wave heights with wave periods from 7 to 17 sec at the high design water level.

Both with and without the offshore breakwater and north revetment in place, expose the proposed construction trestle to a range of wave periods and wave heights at the design water levels to observe the actions of the waves on the trestle and its support pilings.

Three-Dimensional Model Tests

Check the stability of the head and adjacent trunk of the offshore breakwater for breaking wave wave conditions which could occur at the design water levels for waves approaching from north, N30W, and N72W.

If the armor-stone weight, found to be stable on the trunk of the breakwater during the two-dimensional tests, proved to be unstable on the breakwater head and adjacent trunk, optimize design of the breakwater head and trunk.

The two-dimensional and three-dimensional stability tests were conducted at geometrically undistorted linear scales (model to prototype) of 1:38.5 and 1:50.5, respectively. All two-dimensional tests were conducted in a 5-ft-wide, 4-ft-deep, and 124-ft-long concrete flume equipped with a vertical displacement wave generator capable of producing monochromatic waves of various period and heights. Figures 10 and 11 show cross-sectional views of the test flume as it was prepared for calibration prior to testing the north and west slope structures, respectively. A wave rod was placed in the flume at the location where the toe of the breakwater or revetment would be placed and the flume was calibrated for the design wave and water level conditions prior to installation of the test structures.

At the completion of calibration, the flume cross section was modified as shown in Figure 12 and tests were initiated on the offshore breakwater and north revetment. Seven different design alternatives were tested for the offshore breakwater and protected north revetment including both stone and dolos designs for the breakwater. Of the plans tested the design shown in Figures 13 and 14 was the optimum design for exposure to the 23 ft design breaking waves. A test of the proposed design for the unprotected north slope revetment (Figure 15) proved the 12-ton stone to be stable for depth limited breaking wave conditions.

An option for prototype construction of the offshore breakwater was to construct a railroad testle from shore and along the centerline of the proposed structure. Construction material and equipment could be transported and placed starting from the outer end of the breakwater and the trestle could be removed as construction moved shoreward. One concern was that the wave conditions could threaten the trestle. The trestle was exposed to a range of incident wave conditions both with and without a portion of the breakwater in place and it was found that incident wave heights greater than 10 ft created potentially hazardous conditions (Figure 16).

The flume cross section was modified as shown in Figure 17 to represent bathymetric and topographic conditions on the west slope and four unprotected west revetment armor stone designs were tested. A 2 ton armor stone proved to be marginally acceptable for the 10 ft design breaking wave while a 3.5 ton armor stone was completely stable for the same wave condition.

Three-dimensional stability tests were conducted in a wave basin 35.5-ft-wide, 3.5-ft-deep and 110-ft-long (Figure 18). The facility was equipped with a horizontal-displacement wave generator capable of producing monochromatic waves of various periods and heights. Following calibration of the test facility the west head and

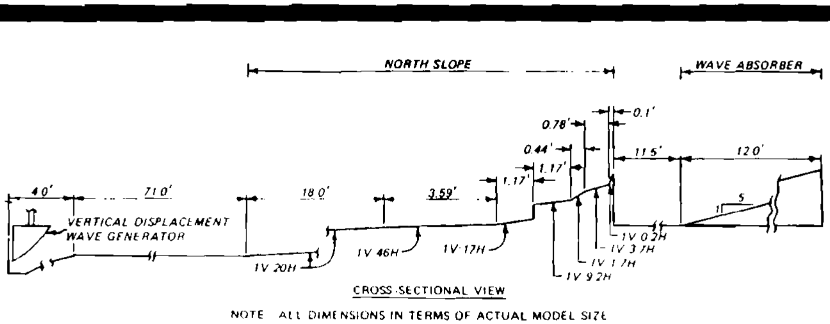


Figure 12. Flume geometry for the 2-D north slope tests.

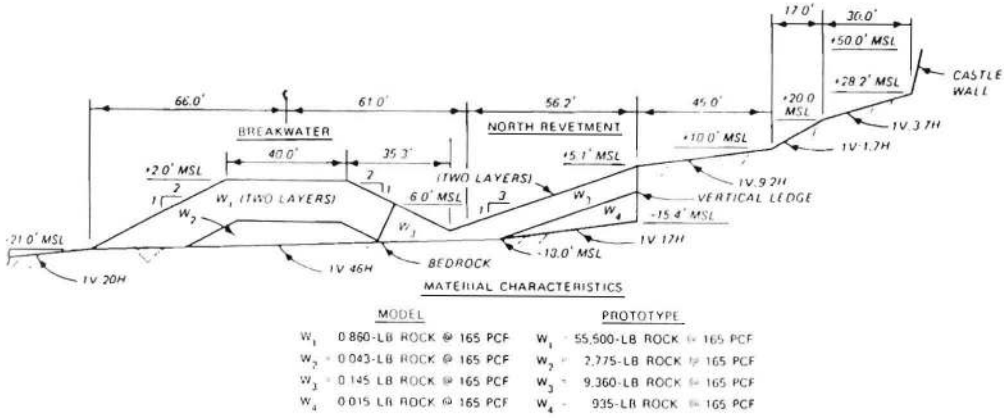


Figure 13. Details of offshore breakwater and protected north revetment as recommended by 2-D stability model study.

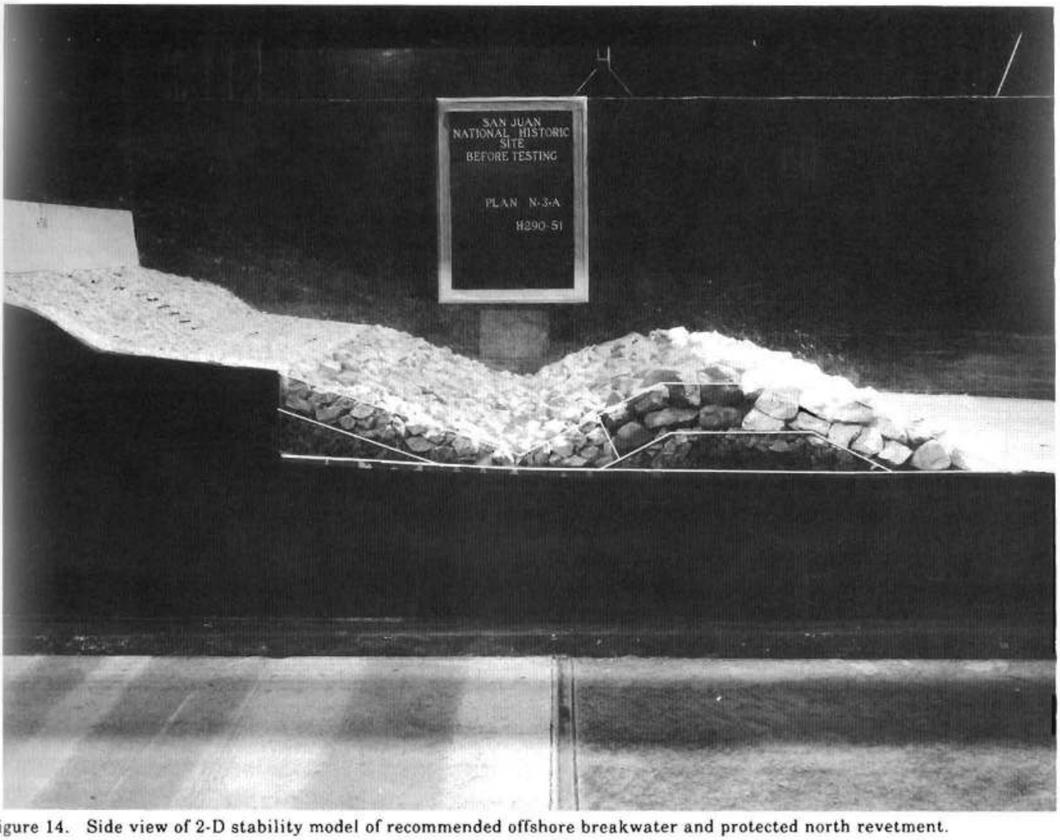


Figure 14. Side view of 2-D stability model of recommended offshore breakwater and protected north revetment.

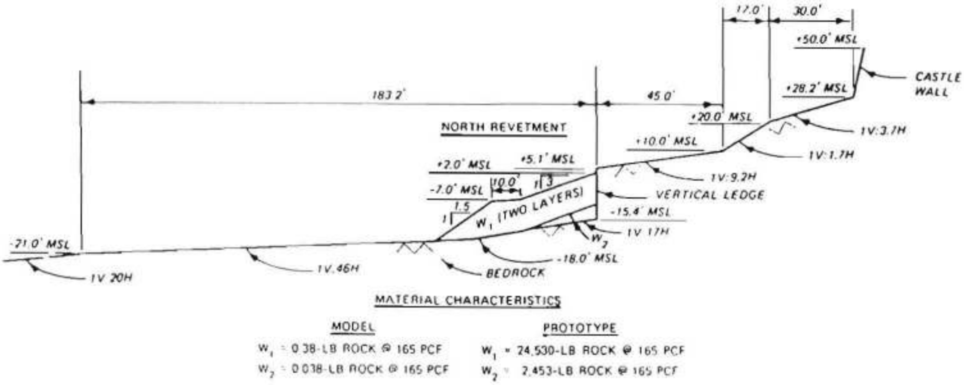


Figure 15. Details of unprotected north revetment as recommended by 2-D stability model study.

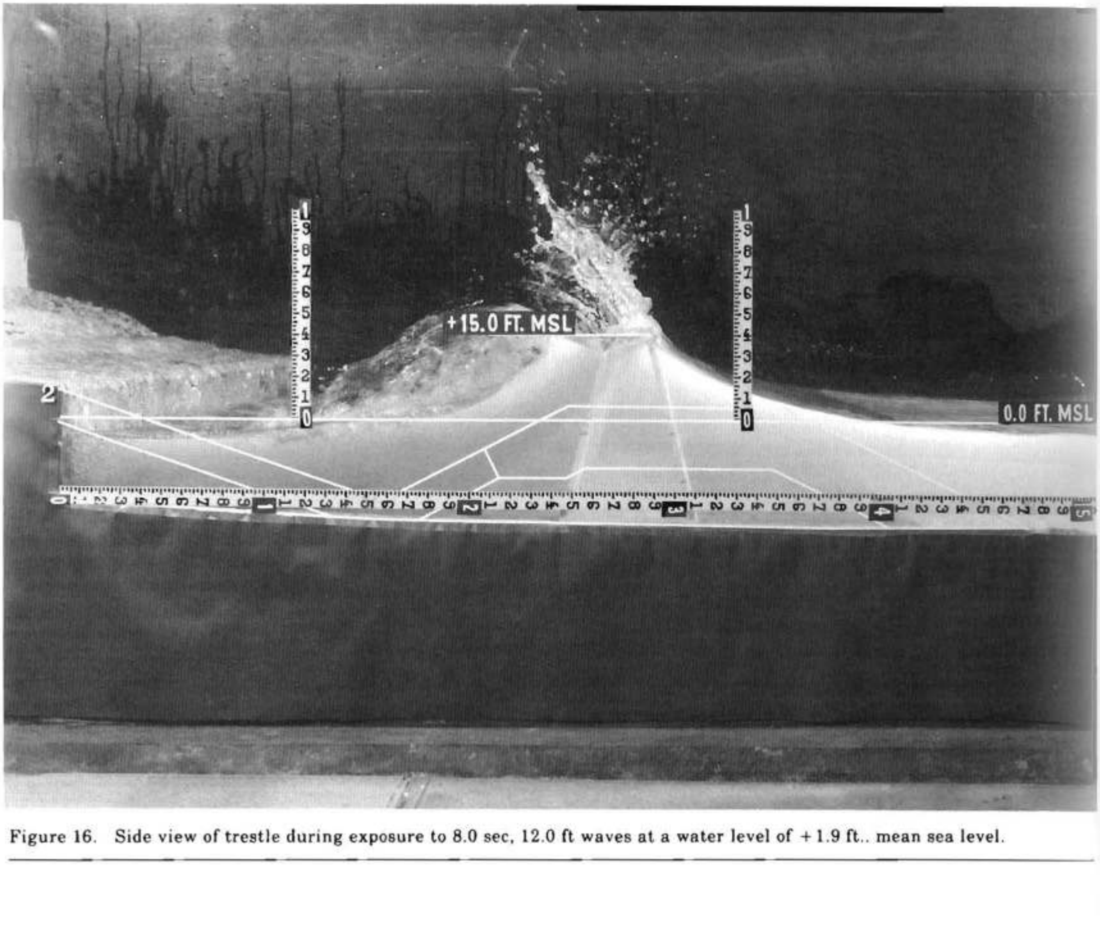


Figure 16. Side view of trestle during exposure to 8.0 sec, 12.0 ft waves at a water level of + 1.9 ft., mean sea level.

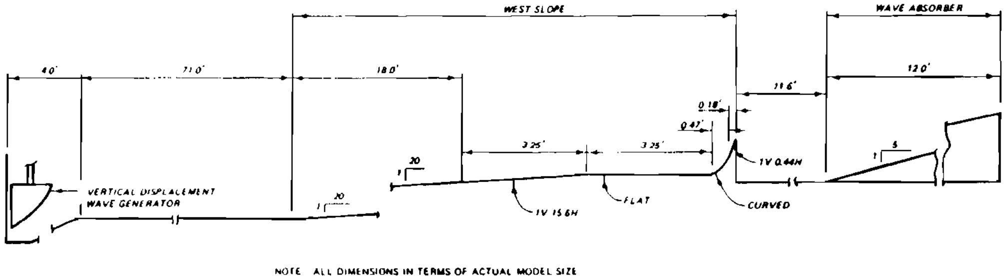


Figure 17. Flume geometry for the 2-D west slope tests.

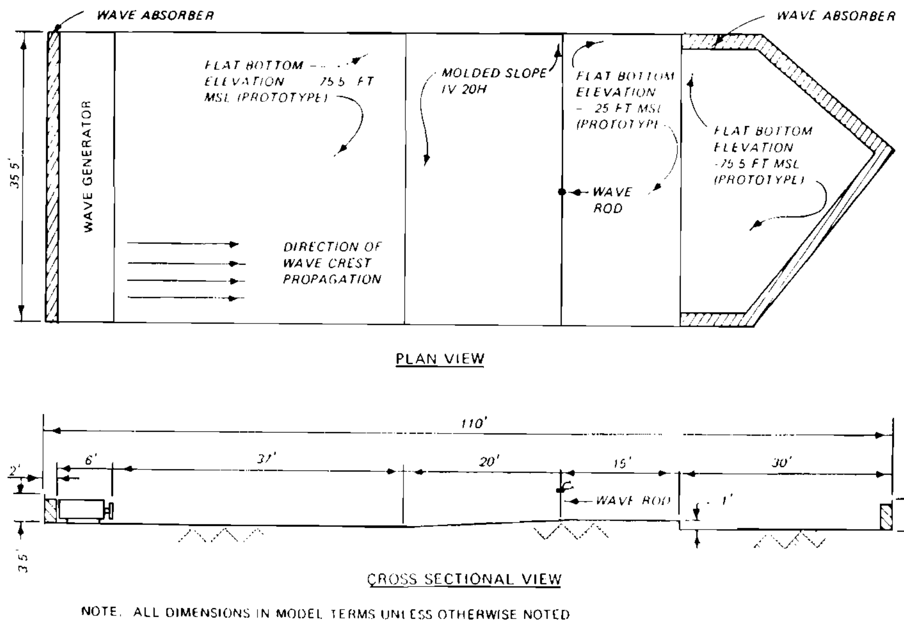


Figure 18. Wave basin geometry and wave rod location for 3-D stability model tests.

314 ft of the adjacent breakwater trunk were constructed in the test facility at the top of the 1V on 20H slope (Figure 19). The approximately 27.5 ton armor stone design (Figure 20) proved to be an adequate design for 28 ft depth-limited breaking waves incident from the north and N30W and approximately 21 ft waves arriving from N72W (Figure 21). The 21 ft waves were the maximum that could approach from this semi-protected direction.

Many of the design details and tests results of this rather lengthy and complex stability study have not been presented, but it is obvious that model test results provided designs that could be built with confidence that they were both stable and the most economical designs that could be used to protect the deteriorating foundations surrounding the fortifications at San Juan when exposed to depth-limited breaking wave conditions typical to that area. The results also provided insight into probable safe operating conditions when constructing from the trestle and the extent to which wave runup might be expected to occur once construction was completed.

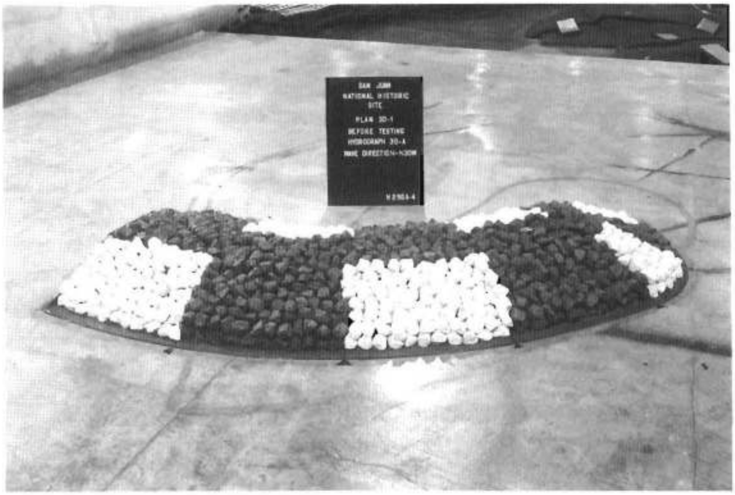


Figure 19. Sea-side view of offshore breakwater constructed in 3-D test facility.

SUMMARY

By following the basic laws of similitude, a very useful tool is created in the laboratory that can be used to provide safer and more economical designs for rubble-mound coastal structures. These designs can be developed through the guidance developed through the use of general research models or by explicit results derived from a site specific model study. The dollars spent on a model study will be returned many times over through the development of structure designs which do not fail during exposure to design storm conditions and which require less maintenance.

ACKNOWLEDGMENTS

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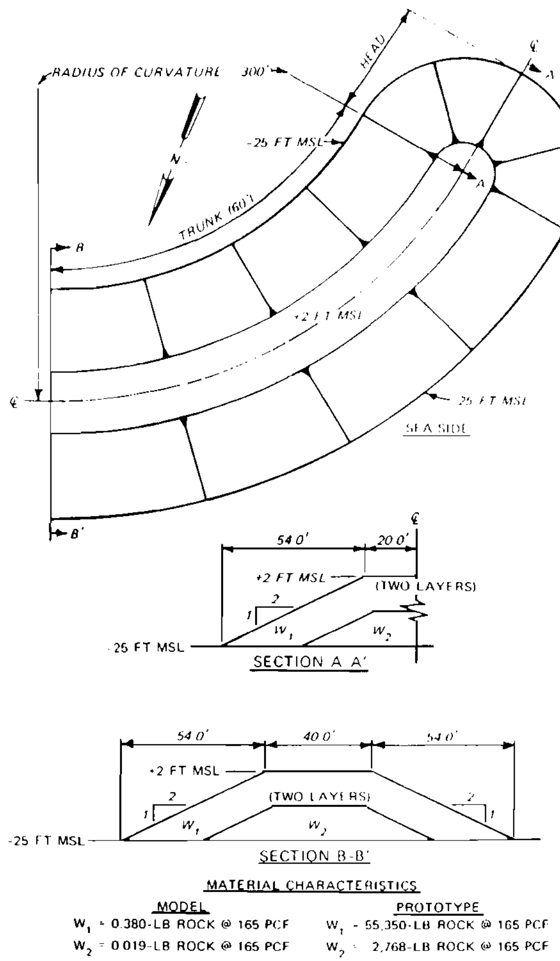

Figure 20. Details of the offshore breakwater as recommended by the 3-D stability model study.

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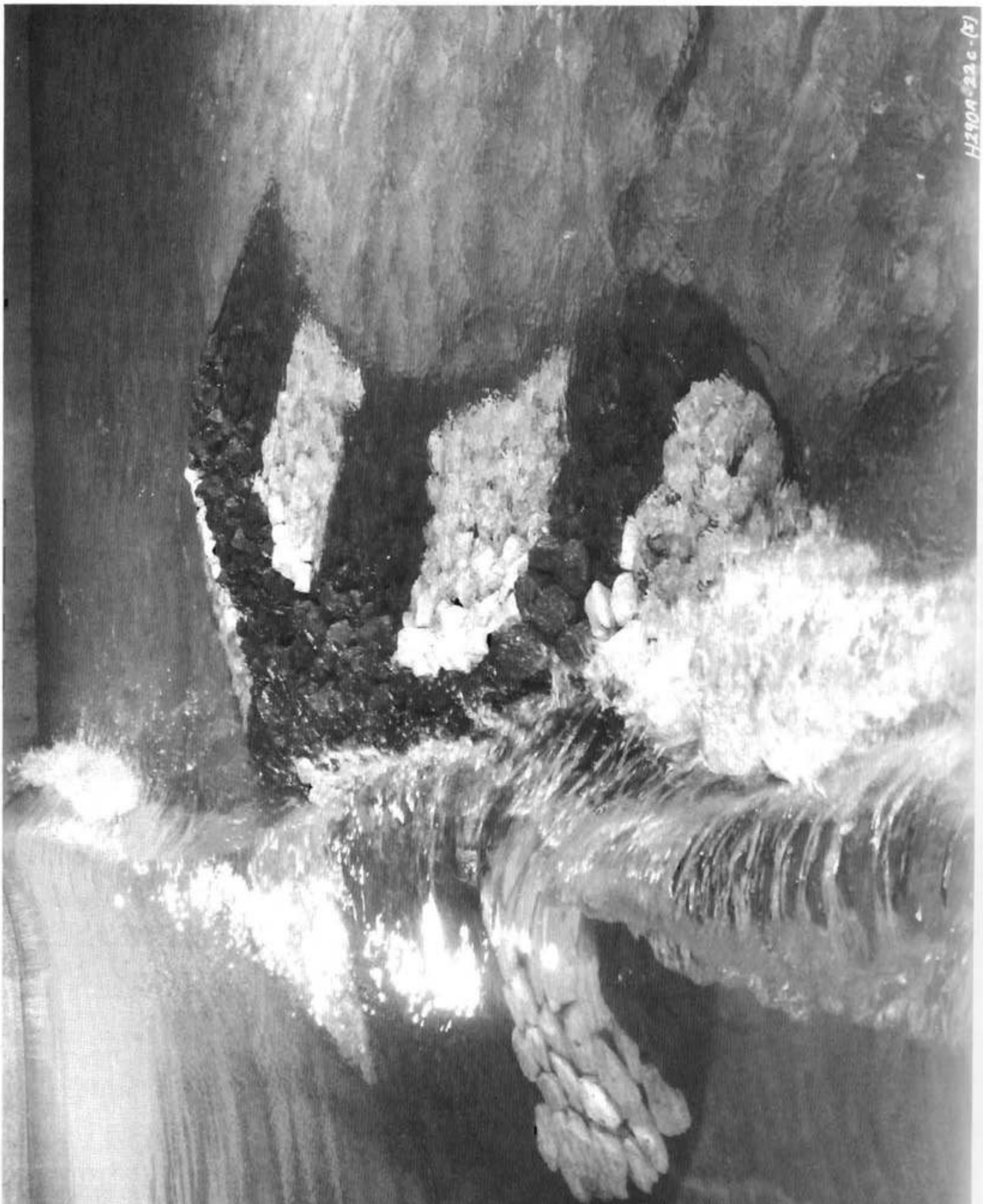

Figure 21. End view of offshore breakwater during wave attack in the 3-D stability model.