- Experiments are conducted as a series of wave bursts with each burst of waves ending before re-reflected waves can again reach the structure.

- Active wave absorption is implemented at the wave board to detect and absorb unwanted reflected wave energy.

Ideally, coastal structures tested in wave basins should use fully directional irregular waves; however, often the testing is performed using oblique, long-crested waves. This compromise is not considered serious if the testing covers multiple approach angles. Floating or moored structures often respond to long-wave energy in the spectrum, so correct reproduction of the bound and free long waves is important.

## CONSTRUCTION AND OPERATION OF STRUCTURE MODELS

### Laboratory Facilities

Experience and appropriate modeling facilities are the two most critical components of successful physical modeling of coastal structures. Wave flumes are used for tests of rubble-mound structure trunk stability, runup and overtopping on impermeable and permeable slopes, forces on vertical walls, and loads on moored structures. Wave basin tests usually focus on rubble-mound head and trunk stability due to directional waves and how the structure planform impacts local hydrodynamics. Wave flumes must be reasonably large and constructed with precision so that uneven width or bottom elevation do not alter the translating waves. Glass side walls are standard along the sections where model testing takes place.

The most important piece of hardware is the wave generator. Most wave makers operate in "piston mode" with a vertical bulkhead that moves back and forth, or in "flap mode" with a planar bulkhead hinged at the bottom that moves back and forth in an arc. In days past, the back and forth motion of the wave board was sinusoidal, creating "regular waves." Now, most wave facilities feature programmable wave boards that simulate irregular waves conforming to specified spectral signatures. Capability to suppress spurious long waves and to absorb reflected wave energy is available with the more sophisticated wave machines.

Researchers have attempted to established a correspondence between laboratory results obtained using regular waves and results found using irregular waves. For rubble-mound armor stability, damage associated with regular wave height $H$ has been equated to irregular wave height parameters $H_{1/5}$ (Tanimoto, et al. 1982), $H_{1/10}$ (SPM 1984), $H_{1/20}$ (Jensen, et al. 1996), , and $H_{1/30}$ (Vidal, et al. 1995). Variations in laboratory techniques are thought to be the cause of the differing opinions (Jensen, et al. 1996). Different equivalences between regular and irregular waves have been proposed for other wave/structure phenomena such as wave runup, wave transmission, etc. All new laboratory studies should use irregular waves unless there is some compelling reason for using regular waves (e.g., theoretical analysis, validation of numerical model).

**Model Scale Selection**

Scale effects are lessened by larger models (smaller values of $N_L$), so engineers select model scales based on a combination of the facility's maximum water depth and wave generating capability. Table 1 lists typical length scales used by the major laboratories throughout the world.

**Table 1. Typical Model Length Scales for Coastal Structures**

| Structure Type | Scale Range | Typical Scale | Reference |
|---|---|---|---|
| | 1:5 – 1:70 | 1:40 – 1:50 | Hudson, et al. (1979) |
| Rubble-mound | 1:10 – 1:80 | 1:50 | Oumeraci (1984) |
| | – | 1:30 | Jensen and Klinting (1983) |
| Vertical-wall | 1:20 – 1:50 | – | Hudson, et al. (1979) |
| Floating | 1:6 – 1:27 | – | Hudson, et al. (1979) |

Several laboratories worldwide operate very large wave flumes that permit experiments at prototype or near-prototype scale.

**Model Construction Techniques**

The first step in model construction is to re-create the bathymetry in the vicinity of the structure out to the depth adjacent to the facility's wave generator. For economic reasons practically all models use a fixed-bed, and this does not adversely affect results for most coastal strucure models. However, toe stability studies may be a special case. A common method for constructing fixed-bed bathymetry consists of making bottom elevation templates that are affixed to the floor of the wave facility. The space between the templates is filled with compacted sand and capped with a concrete veneer about 50–70-cm thick.

At the Waterways Experiment Station rubble-mound structure model construction is done in a dewatered wave facility (Hudson and Davidson 1975). First, the core material (sieved, crushed basalt or limestone) is placed dry to the correct dimensions, then saturated with low-velocity spray and compacted with trowels to simulate compacting by waves. Underlayers are placed dry with a shovel and smoothed to the correct slope and dimensions by hand without compacting or rearranging of individual stones. The armor layer is placed by hand, and great care is taken to replicate the placement method (usually random) that typifies the prototype structure. The model builder must conscientiously avoid the natural temptation to "key in" the armor units. Nevertheless, model rubble-mound structures are typically tighter than constructed in prototype, and tend to be more stable than the prototype. Therefore, stable prototype armor units should be sized slightly larger than indicated by model tests.

Model stone armor units can be fabricated from basalt, limestone, or even granite, depending on which material best fits the scaling criterion for armor specific weight. Hand sorting and weighing stones assures correct gradation of stones in the armor layer. If the primary armor layer is to be constructed using artificial armor units, the units are molded by experienced personnel using special mixtures, such as brass filings in a plastic resin, to provide the correct armor unit weight.

Vertical-wall structure models used to determine pressures and impacts can be constructed out of any convenient, rigid material, such as wood, steel, plastic, etc. Pressure sensors can be mounted directly on the wall, flush with the external surface. An alternate model technique for determining loads on a vertical wall is to measure the total force and overturning moment of the structure using strain gauges mounted on the wall support points. Vertical-walled monolithic structures usually have sufficient mass to be stable against wave forces. However, if model stability tests are required, the structure's weight and mass distribution must be scaled according to the Froude criterion.

Models of floating coastal structures or vessels can be constructed of the same materials as the prototype, but this is not a requirement. Regardless of what material is used for model construction, the model must correctly: (1) reproduce the exterior geometry of the floating structure, (2) reproduce the total mass of the structure according to the weight scale, and (3) reproduce mass moments of inertia about the different axis.

**Model Operation**

Wave simulation in the model is achieved by scaling sea surface elevation time series realizations that represent design wave conditions, and then converting the time series to equivalent time series of wave board displacement that will produce the desired waves. Modern convention is to use irregular waves having a specified spectral shape. Hughes (1993) summarized techniques for synthesizing time series of irregular waves and converting into appropriate wave board displacement signals. A common practice is to *"calibrate"* the design waves by running each target wave condition in the wave facility without the structure in place and measuring the waves near where the toe of the structure will be during testing. The absence of the reflective coastal structure will provide a better estimate of incident waves at the structure. The calibration step is not essential, but it does allow adjustment of test wave parameters to provide even coverage over the range of test wave conditions. An alternative is to measure the wave condition with the structure in place and resolve the incident wave spectrum using one of the available techniques.

After the model has been constructed, it should be "shaken down" by running about 1,000 waves having the same peak wave period but a significant wave height about 50% to 60% of intended test conditions (Hudson and Davidson 1975, Tørum, et al. 1979). The goals of the model determine the specific test program. Jensen (1984) listed seven types of test procedures that might be considered in testing rubble-mound structures.

1. **Tests with Increasing Wave Heights.** This is the traditional testing method where structure stability testing starts out with mild wave conditions, and each subsequent test is conducted with incrementally increased wave heights. Testing is performed for a range of wave periods and water depths. Jensen

(1984) stated that each testing step should last the model equivalent of between 3 and 10 prototype hours (typical of storm duration), and Owen and Allsop (1983) suggested run lengths between 1000 and 5000 waves. Several researchers (Thompson and Shuttler 1975, van der Meer 1988, Mansard, et al. 1996) have stated that 5000 waves are needed to approach equilibrium damage levels.

2. **Tests of Design Condition.** This is a test conducted using a single design condition, usually to examine some singular aspect of the structure.

3. **Tests Reproducing Individual Storms.** If accurate estimates of an historical event are available, a structure's response to extreme events can be examined. A model can be verified by reproducing known prototype damage.

4. **Long Duration Tests.** The purpose of long-duration tests is to determine if initial damage to a structure continues until total destruction, or if the structure stabilizes in a partially damaged condition. These tests represent the impacts of long-duration storms. Recent experiments by Melby (1999) indicate that damage will continue to occur.

5. **Tests of Accumulated Storm Impacts.** These tests attempt to reproduce the accumulated impacts of a number of large storm events having different characteristics but all capable of causing damage. The storm parameters and duration are determined from historical records or from wave hindcasts. Melby (1999) conducted several experiments reproducing storm sequences, and he quantified damage progression as an empirical expression.

6. **Tests of Residual Stability.** These tests complete the testing program by examining what residual stability a damaged structure has. Some structures, such as those with steep slopes, may totally fail after initial damage with only a small increase in the incident wave condition.

7. **Tests of Structures Under Construction.** Coastal structures are particularly vulnerable to a wide range of wave conditions during construction. Tests of partially completed structures can provide information on potential extent of damage, or construction sequences to minimize potential damage.

Hudson, et al. (1979) noted the importance of repeat tests of rubble-mound stability. Repeat tests demonstrate the capability of the model to produce similar results under similar forcing conditions. However, various factors, particularly nonsimilarity in model armor layer placement, may result in repeat tests that have significantly different stability. In this case, there is no option but to conduct additional repeat tests to isolate the problem causing the nonsimilar results.

Owen and Briggs (1985) suggested that each design condition be tested five times and the post-test rubble slope profiles be compared. Hudson and Davidson (1975) recommended testing each structure three times with the armor layer replaced each time. The latter two tests could be limited to critical wave conditions determined during the first test.

## MEASUREMENTS AND ANALYSES

Usual data collection during rubble-mound structure stability testing includes recording wave data and recording changes to the rubble-mound profile. Wave gauges often are located in deeper water near the wave board and in shallow water immediately in front of the structure. Gauge arrays or point current meters might be used to extract the incident and reflected wave spectra using the methods summarized in Hughes (1993).

Sea surface elevations are generally obtained as analog records of voltage (or frequency) using either vertically-mounted resistance or capacitance, surface-piercing wave gauges. Voltages are converted to digital time series records having uniform spacing between data points. Care must be taken when selecting the sampling time interval for digitizing sea surface elevations. The minimum sampling rate for a laboratory wave period of 1 s is 10-Hz; however, most investigators prefer to collect at higher rates such as 20–30 Hz.

Wave gauges must be calibrated by raising and lowering the gauge known increments relative to still water to establish the (nearly) linear relationship between the sensor output and the elevation of the water level on the gauge. Ideally, the relationship is linear and a least-squares linear regression can be applied to obtain the necessary conversion equation. Sometimes it is prudent to use a higher-order curve-fit to increase the precision of the wave gauge calibration. During static calibration it is very important to not disturb the water because even the slightest water level fluctuation will influence the quality of the gauge calibration.

Analysis of measured wave data varies according to the needs of the testing program. Most laboratories have a standard suite of analyses that include both frequency domain (spectrum, cross-spectrum between adjacent gauges, reflection analysis between two or more gauges) and time-series (wave height and sea surface distributions, height-period joint distributions) analyses.

Damage to model rubble-mound structures can be quantified by several methods. Most fundamental is documenting the number of dislocated individual armor units through visual inspection. For more severe damage, profiles of the armor slope can be measured and plotted to obtain an eroded cross-sectional area. Rubble-mound structure profile changes were traditionally measured using a sounding rod fitted with a foot made of a circular plate having an area of one-half the average diameter of the armor stones. More recently the chore of measuring rubble-mound profiles has been automated, giving more accurate damage assessment at more frequent intervals and in electronic form. Davies, et al. (1994) and Melby (1999) described electromechanical devices that traverse the structure slope and resolve the profile. Profilers using traversing lasers have recently been implemented at the Coastal and Hydraulics Laboratory in Vicksburg.

Besides wave and structure profile data, auxiliary measurements might be needed with rubble-mound structures to document such phenomena as wave overtopping and transmission, flows and pressures within the structure, flow kinematics near the toe and slope of the structure, and stresses within individual armor units. Wave runup on smooth, impermeable structures is relatively easy to measure with electronic sensors embedded in the slope or with a wave gauge mounted along the slope. Runup on permeable rubble slopes is more difficult to measure accurately. Water from wave overtopping can be trapped in a catchment basin and weighed to give average overtopping rates.

Static and dynamic pressure measurements may be required in some coastal structure physical models. Static pressure (or total pressure under steady flow conditions) is easily measured using simple instruments, such as U-tube manometers, that give the pressure directly as vertical "head" of whatever fluid is used in the manometer. Measurement of dynamic pressures is accomplished using commercially available pressure transducers connected to appropriate signal conditioning units. Dynamic pressure gauges must provide a time history of pressure; and in the case of wave impacts on a structure, the instrument may need to sample at rates up to 1 MHz with little distortion in order to capture the shape of the pressure impulse.

Still photographs, movies, and video are essential for documenting coastal structure experiments. Photo-documentation can help explain instrument arrangements, special features of the experiment, relative scale and physical arrangement, and relative size of the waves to the structure. Photographs and video can be used as qualitative tools for capturing certain flow phenomena, such as wave runup and overtopping. And video can be used to demonstrate the effectiveness of design alternatives to the study sponsor, or to communicate experiment details with colleagues far away from the experiment site. Web cameras are now available which allow experiments in progress to be broadcast as video streams over the Internet.

## CONCLUSIONS

Design and optimization of coastal structures using small-scale physical models is an established and mature engineering technology. Successful modeling requires adherence to established similitude criteria and careful operation of the model facilities. As in most engineering endeavors, experience plays a crucial role in achieving accurate results, especially when interpreting model results in light of potential scale and laboratory effects. Maintaining quality laboratory facilities and retaining competent staff requires large commitments of time and resources. Consequently, there are only a limited number of laboratories in the world where coastal physical models are conducted.

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## APPENDIX – NOTATION

### Roman Symbols

| | | |
|---|---|---|
| $D$ | – | percent damage to cover layer (displaced/total armor units) |
| $E$ | – | modulus of elasticity |
| $F$ | – | function |
| $F$ | – | force |
| $F_E$ | – | elastic force |
| $g$ | – | gravitational acceleration |
| $h$ | – | water depth at structure toe |
| $H$ | – | wave height |
| $H_{1/n}$ | – | average of the highest $1/n$-th waves [e.g., $H_{1/10}$, $H_{1/20}$] |
| $\ell_a$ | – | characteristic linear dimension of armor unit |
| $L$ | – | characteristic length; wavelength |
| $m$ | – | subscript representing model |
| $ml$ | – | subscript representing "mooring line" |
| $N$ | – | prototype-to-model scale ratio of whatever quality is given as the subscript |
| $p$ | – | subscript representing prototype |
| $R_n$ | – | rubble-mound structure flow Reynolds number |
| $T$ | – | time |
| $T$ | – | wave period; time dimension; characteristic time |
| $V$ | | characteristic horizontal velocity |
| $V_w$ | – | water velocity in the vicinity of the cover layer |
| $W$ | – | weight; average weight of the armor stone; |
| $W_a$ | – | armor unit weight |
| $X$ | – | variable |

### Greek Symbols

| | | |
|---|---|---|
| $\alpha$ | – | seaside structure slope angle measured from the horizontal |
| $\beta$ | – | incident wave angle |
| $\gamma$ | – | specific weight |
| $\gamma_a$ | – | armor unit specific weight (= □$_a$ $g$) |
| $\gamma_w$ | – | water specific weight (= □$_w$ $g$) |
| $\Delta$ | – | shape of armor unit |
| $\mu$ | – | dynamic coefficient of viscosity |
| $N$ | – | kinematic coefficient of viscosity |
| $\xi_a$ | – | characteristic linear dimension of armor unit surface roughness |
| $\rho$ | – | mass density or fluid density |
| $\rho_a$ | – | mass density of armor units |
| $\rho_w$ | – | mass density of water |

# SELECTION OF A DESIGN WAVE HEIGHT FOR COASTAL ENGINEERING

Donald L. Ward[1], Edward F. Thompson[2], and Jun Zhang[3]

**Abstract:** A review is made of the most commonly used distribution functions for extremal wave analysis to estimate the sea state at extended return periods. Distribution functions included are the Fisher-Tippett Types I and II and the Weibull distribution. Methods of determining the distribution function providing the best fit to a given data set are included.

Sources of data, selection of storm events within the data set, and final selection of a design wave height are discussed.

## INTRODUCTION

Design of most coastal projects is predicated by selection of the wave environment the project is designed to withstand. The primary concern for design is usually the long-term variation of hydrodynamic processes, particularly extreme occurrences. The hydrodynamic conditions in a coastal area at any instant in time is referred to as a sea state. Although variations of processes within a sea state may be relevant to design, it is the variations over a long-term collection of sea states that is most commonly used for design. The sea state includes the entire wave and current environment, all of which play a significant role in affecting the longevity and survivability of a project, yet a single wave is frequently selected as representing the design sea state. This "design wave" may be depicted by its height, period, and the depth or offshore location at which it is defined. It is emphasized that the term "design wave" is a misnomer as the design condition is not a wave but a sea state.

The sea state for which a project is designed is generally a storm-induced sea state, and selection of the storm-generated design wave will be the focus of this paper. However, within the coastal environment the design wave may also be generated by a passing vessel (wake) or generated by an offshore geologic event such as an earthquake or volcanic eruption (tsunami). In addition, other wave-related factors beyond the scope of this paper may impact the design such as currents, winds, ice loading or impacts by ice floes, or impacts by vessels or logs. Where

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