CHAPTER 148

LARGE SCALE MODEL TESTS
of
PLACED STONE BREAKWATERS

by
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Abstract

Large scale model studies reveal that Reynolds scaling can affect the apparent stability and wave modifying properties of layered breakwater structures. Results of a study for a breakwater configuration designed to protect offshore power and port facilities in water depths to 60 feet are presented and discussed. The armor layer of this structure is formed from quarried rock of irregular rectangular parallelepiped shape, individually placed perpendicular to 1:2 seaward slope and crest. The resulting armor layer is relatively smooth, densely packed and very stable. Model studies of similar configurations were studied at 1:10, 1:20 and 1:100 scale ratios. Stability, runup, rundown and reflection were measured for a variety of water depths, wave heights and periods. Analysis of the large scale test results establish that the placed stone armor is approximately as stable as dolos armor units. Runup, rundown and reflection respond similar to rough, impermeable slopes. Comparison of large and small scale results demonstrate that relative increases in drag forces at lower Reynolds numbers decrease stability and runup in small scale models.

Introduction

The challenge of offshore power production and deep draft port facilities has stimulated interest in large protective breakwater structures. Some elegant wave attenuation schemes have been proposed and a variety of artificial armor unit shapes are being investigated. There are, however, many offshore locations where natural rock structures are the most economical alternative for protective breakwaters. One method of stone or rock construction which has received little attention is the placed stone construction technique. This method has been used with considerable success for two decades along the Pacific Northwest coast of the continental United States and yet the advantages of this type of breakwater construction have not been carefully studied.

A ·unique feature of this specific construction technique is that rock is quarried for an approximately rectangular parallelepiped shape with one major axis. Then the rock is individually placed on the breakwater surface with the long axis perpendicular to the slope. A single layer of armor units placed in this manner provides a densely packed, relatively smooth surface with stability approaching that of dolos armor units.

This construction technique was studied superficially in 1961 (Jackson, 1963). Although the tests indicated that placed stone was more stable than random stone, an increase in the stability coefficient was not recommended because of the limited number of tests. However, the outstanding maintenance record of jetties along

the coasts of Oregon and Washington indicate that these structures have been conservatively designed. In order to compensate for the lack of sound design information, this study was undertaken to investigate the overall hydraulic behavior of placed stone armor breakwaters. Included in the study are runup, rundown, reflection and stability.

The specific design being considered is a 100 foot high structure which is proposed for use in relatively deep water (50 ± 10 feet) to protect offshore nuclear power plants and superports. A cross section of the structure is presented in Fig. 1. The crest of the structure is 35 feet wide. It slopes at 2:1 on the seaward face to MLLW where it breaks to a slope of 1.5:1. The back face falls away quickly at 1.25:1 and encounters a concrete caisson at MHHW. The caisson provides a working platform for constructing the breakwater and maximizes mooring area on the leeward side of the structure. The placed stone armor material is represented by the A+, A and B designation in the figure. All other materials are barge dumped or randomly placed. The largest armor, A+ (25-35 tons) extends from ten feet below MLLW to ten feet above MHHW. This is considered to be the region which experiences the largest wave impact loads.

The study was conducted at a large scale to minimize scale effects. It is known that drag forces are an important mechanism for retarding runup, dissipating energy and loading armor units so that, in general, Reynolds similarity cannot be neglected in breakwater modeling. Since drag coefficients increase at low Reynolds Number, one would expect small models to produce relatively high drag

PROTOTYPE BREAKWATER SECTION

DIMENSIONS IN FEET

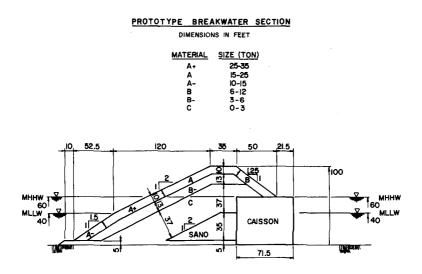| MATERIAL	SIZE (TON)
A+	25-35
A	15-25
A-	10-15
B	6-12
B-	3-6
C	0-3

Fig. 1. Prototype Breakwater Cross Section

forces and therefore less runup, less reflection and less stable conditions. Therefore, extrapolating small model results to prototype scale could yield an uneconomical, overdesigned armor unit and an underdesigned crest elevation.

In order to quantify the scale effect, this study was conducted at three scale ratios: 1:10, 1:20 and 1:100. Froude similarity was used to dimension each model, and model results expressed in dimensionless form were compared. The hypothesized scale effects were found to occur and to be significant in the small model.

The structure was found to behave like a rough, impermeable slope in terms of runup and rundown. The placed stone armor units were found to be extremely stable, with stability coefficients approaching that of dolos.

Test Conditions and Procedures

A test program of monochromatic wave excitation was conducted at the Oregon State University Wave Research Facility. The wave channel is 342 feet long, 12 feet wide, 15 feet deep and has a 290 foot test section. The wave board is of the flap type variety which is hinged at the bottom in a section which has a total depth of 18 feet. The board is controlled by a 150 HP, 3500 psi pump with an attached hydraulic servomechanism activated by an electronic function signal generator. The installation is unique in that it has water on only one side of the wave board. This scheme reduces the power requirements of the wave generator by one-half and eliminates the need for a dissipative media behind the wave board. The facility has the capability of producing solitary waves, periodic waves and random waves for modeling ocean wave spectra. Breaking waves up to five feet high can be generated and the useful frequency range is from 0.2 to 2.0 hertz.

Three model scales were tested, 1:10, 1:20 and 1:100. Each scale was exposed to prototype waves periods of 9, 13.5 and 16 seconds. Wave heights were increased from prototype heights of approximately 15 feet to breaking wave heights which exceeded 45 feet for the two longer wave periods. Each wave condition was continued until 500 waves had been produced or significant damage had occurred.

Two bottom slope conditions were modeled during the test. The model itself was supported on concrete slabs approximately five feet above the bottom of the test channel. A "flat" bottom was created by extending the false bottom horizontally to an equivalent prototype distance of 1000 feet from the toe of the structure. A "sloped" bottom was created by shoaling the bottom at a 1:12 slope from 40 feet (prototype) in front of the structure to a greater depth 520 feet seaward. The bottom proceeded horizontally from that point. Tests of all three scales were conducted using the flat bottom configuration first, followed by the sloping bottom. The flat bottom limited wave heights due to breaking of finite amplitude partial standing waves in the vicinity of the breakwater. The sloping bottom permitted sustained large amplitude waves during stability tests.

In addition to varying bottom slope, wave height and period, three different still water depth conditions were investigated: 40, 50 and 60 feet. Each test run proceeded by establishing the slope, depth and wave period and incrementally increasing the wave height relative to the previous run at the same period. The waves were allowed to interact with the structure until a quasi-steady state wave environment was established. Then, each of the following parameters were measured: incident and reflected wave height and period, runup, rundown and damage.

Incident and reflected wave heights were resolved using the wave envelope method. The partial standing wave envelope was profiled using an acoustic wave gauge mounted on a moving carriage. Incident and reflected wave heights were solved from the sum and difference of antinode and node amplitudes. Runup and rundown were quantified relative to elevation gradelines on the channel walls adjacent to the model. Average values across the width of the model were recorded. Damage was recorded as it occurred by stopping the test and noting the number of stones and surface area affected. Progressive damage was evaluated by continuing the tests without repairing the damaged area until catastrophic failure was imminent or 500 waves had passed.

Interpretation of Results

Runup
     Runup is the vertical distance above still water attained by a wave rising on some prescribed surface. Its magnitude is a function of both the wave and surface properties. Runup is an essential design parameter for ocean and coastal structures if overtopping is to be minimized or avoided.

It is common to express runup relative to the offshore wave height which produced this condition. This measure of relative runup allows a design engineer to proceed directly from offshore wave forecasting to runup calculations at the structure if refraction does not alter the wave form. Local wave conditions probably dominate the runup process, however, it may be very difficult to calculate local modifications caused by wave interaction with a complex structure. Attempts to predict runup analytically have generally not been successful except for conditions of simple, mild, impermeable slopes (Le Mehaute, et. al., 1968). In the absence of dependable runup predictions, experimentally determined values of runup have been an essential recourse.

Runup data collected in the context of this study have been assembled to facilitate comparison with other studies. Accordingly, relative runup (runup divided by deepwater wave height, R_u/H_o) is presented graphically as a function of a deepwater wave steepness parameter (H_o/T^2). According to linear wave theory deepwater wave steepness is:

$$\text{steepness} = \text{wave height/wave length}$$
$$= H_o/L_o = 2\Pi\, H_o/gT^2$$

where   g = gravitational acceleration
and   T = wave period.

The constant, $2\Pi/g$, had been dropped from this expression for numerical expediency. The resulting steepness parameter is dimensional, with units of ft/sec^2.

The data are presented in Figures 2 through 5. Flat and sloped bottom re-
sults are combined at the 1:10 and 1:20 scales (Figs. 2 and 3) and separated
at the 1:100 scales (Figs. 4 and 5). Note that depth and period identities
have been retained for clarity by utilizing a uniform symbol notation as indi-
cated in the legend on each figure.

Mean trends interpreted from these figures indicate that relative runup
increase with:
1) increasing wave steepness
2) increasing wave period
3) increasing bottom slope
4i) increasing depth on flat bottoms
4ii) decreasing depth on sloping bottoms.
This behavior is a significant contrast to that depicted in popular design re-
sources, such as the Shore Protection Manual (U.S. Army, 1973), wherein period
and depth dependence are often difficult to resolve. Curves represented by the
dashed lines in Figs. 2-5 serve to illustrate this apparent dichotomy. Both
curves were taken from the Shore Protection Manual; curve B represents runup on
a graded riprap, 1:2 impermeable slope while curve C represents runup on a rubble,
1:2 permeable slope. The curves are presented as a synthesis of data for com-
binations of wave periods, heights and water depths. One would interpret from
these curves that relative runup decreases for increasing values of $H_0/T^2 > 0.1$.
In contrast, consider the 9 second period data in Figure 4. Here it is clearly
shown that relative runup increases with wave steepness for a given constant
value of wave period and water depth. The same behavior can be observed in the
1:10 scale results in Fig. 2. The reason for this behavior is a strong dependence
on wave period. In all of the figures, the short wave periods occur below and
to the right while the long wave periods occur above and to the left. For a
given wave steepness, the shorter period waves are not as high and propogate
at a slower speed than longer waves. Therefore, less power is available for
conversion to runup, and less runup occurs. Viewed as an entire collection of
data, the mean trends follow the dashed lines because for a given range of
design wave heights, the steeper waves are dominated by short periods while the
less steep waves are dominated by long periods.

The reference lines, B and C, in each of Figs. 2-5 reveal additional inform-
ation about general runup characteristics on this structure. In Fig. 2 it is
apparent that the large scale data tends to group around line B indicating that
the densely packed, placed stone surface responds to runup similar to an im-
permeable riprap slope. Line C, representing a permeable rubble slope, yields
less runup because surging flow on this surface can penetrate the interstices
of the relatively porous rubble. The response at the 1:20 scale in Fig. 3 is
similar to the 1:10 scale. However, at the 1:100 scale, (Figs. 4 and 5) es-
sentially all data points fall below reference line B, indicating less overall
runup at smaller scales. This concurs with the anticipated scale effect, i.e.,
flow at low Reynolds number in the small model produces higher drag forces rel-
ative to the inertia of the surging fluid, thereby retarding runup to a greater
degree then at large scale and at prototype conditions. Because the 1:20 and 1:10
scale data is so similar, it would appear that the Reynolds number at these two
scales is high enough to yield a nearly constant surface drag coefficient. Since
this drag coefficient should also be suitable for all larger Reynolds numbers, it
is to be concluded that the 1:20 and 1:10 scale results are also representative
of prototype conditions. The 1:100 scale results, however, tend to underestimate
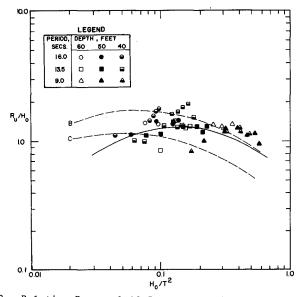prototype runup by approximately 20%.

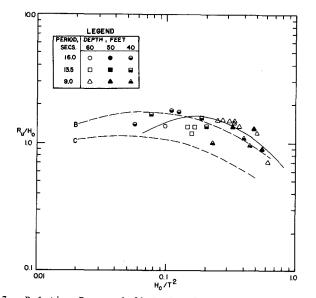Fig. 2. Relative Runup, 1:10 Scale, Sloped and Flat Bottom

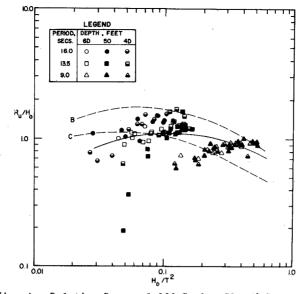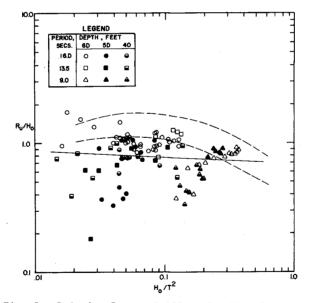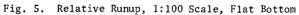Fig. 3. Relative Runup, 1:20 Scale, Sloped and Flat Bottom

Fig. 4. Relative Runup, 1:100 Scale, Sloped Bottom

Fig. 5. Relative Runup, 1:100 Scale, Flat Bottom

Comparing Figs. 4 and 5 indicates that flattening the bottom slope in front of the breakwater tends to reduce runup. This behavior is to be anticipated and has been demonstrated in other studies as well. The flat bottom imposes a depth restriction on the finite amplitude partial standing waves seaward of the structure. The waves break within one wave length on the flat bottom reach if the superimposed incident and reflected wave heights exceed approximately one still water depth. This breaking limitation does not develope on the sloping bottom until the incident wave height alone exceeds the depth at some point along the slope. Thus, the flat slope combined with reflection from the breakwater surface protect the structure from very high incident waves.

Wave period and water depth dependence may be separated graphically by non-dimensionalizing runup in terms of water depth rather than deepwater wave height. This is accomplished in Figs. 6 and 7 where the data for the 1:10 scale model and the 1:100 scale model are presented. Least square exponential fit lines are drawn through the data at indicated constant values of d/T^2. Note that d/T^2 is proportional to the water depth divided by deepwater wave length. The effect of wave period is evident in both figures with long period data on the left and short period data on the right. For a given value of wave steepness and depth, the short period waves always produce less absolute runup. The effect of water depth also separates well on these graphs. It is readily apparent within each group of constant period data that water depth increases from left to right. Therefore, for a given wave period and steepness, shallower water produces more runup relative to the depth. This simply demonstrates that the shoaling effect is more pronounced in shallow water.

Rundown

Rundown is the vertical distance between the still water level and the minimum elevation attained by a wave on a specified surface. Rundown is an important design parameter because it identifies the minimum elevation exposed to large wave impact loads and large local velocities. The region between maximum runup and rundown requires the greatest care in the selection and placement of breakwater armor material. Placement of armor to some depth less than maximum rundown may initiate failures at the toe of the structure which later propogate up the slope.

Rundown data for the 1:10 and 1:100 scale models are presented in Figs. 8 and 9, respectively. The dashed line in each figure is reproduced from the Shore Protection Manual and represents relative rundown on an impermeable, graded riprap, 1:2 slope. Interpretation of the data on these curves reveals that relative rundown increases with:
1) increasing depth
2) increasing period
3) decreasing steepness
4) decreasing model size.
Although not presented in this discussion, the flat bottom tends to increase rundown relative to the sloping bottom at the 1:100 scale.

Comparison of runup and rundown dependence on depth and steepness suggests a useful analogy to wave profile distortions resulting from finite amplitude effects. Waves of finite height tend to develope higher crests and shallower troughs as wave steepness increases and as the ratio of water depth to wave length decreases. Similarly, runup increases with increasing steepness and decreasing depth while rundown decreases under the same conditions. Thus, the ratio of rundown/runup re-
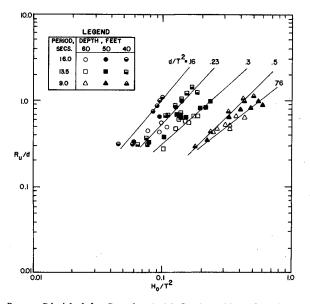
Fig. 6.   Runup Divided by Depth, 1:10 Scale, Sloped and Flat Bottom
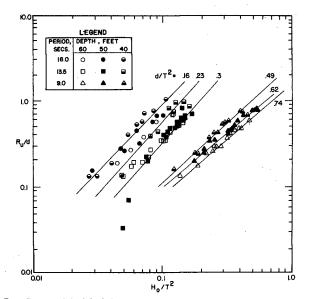

Fig. 7.   Runup Divided by Depth, 1:100 Scale, Sloped Bottom
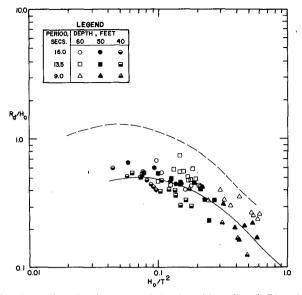
Fig. 8.   Relative Rundown, 1:10 Scale, Sloped and Flat Bottom
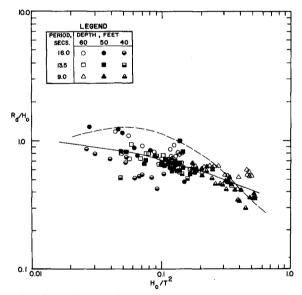

Fig. 9.   Relative Rundown, 1:100 Scale, Sloped Bottom

sponds as the ratio of trough amplitude/crest amplitude to similar changes in
depth and steepness.

The scale effect also produces opposite changes in runup and rundown. Small
scale models tend to reduce relative runup due to increased friction. Comparing
Figs. 8 and 9, however, indicates that rundown increases in the small model. This
response can be explained in terms of the cyclic behavior of runup and rundown.
Each event repeats once each wave period so that if a greater portion of a period
is required for runup, then less time will be available for rundown before the
next runup cycle begins. In large models, relative runup is increased and a
greater fraction of the wave period is required for maximum runup to be attained.
A reduced fraction of the wave period remains for rundown, hence, maximum run-
down is reduced in large models. Conversely, small models take less time for
reduced runup so more time is available to yield increased rundown. The scale
effect is accentuated in rundown, as evidenced by the least squares, best fit,
solid line through the data at both scales. The 1:100 rundown results are approx-
imately 40% larger than the 1:10 rundown results.

Reflection
    The reflection coefficient is defined as the ratio of the reflected wave
height to the incident wave height. Reflection is important because the result-
ing partial standing wave condition can impose a limit on marine traffic activity
in the vicinity of the structure and influence adjacent sediment shoaling patterns.

Reflection coefficient (C_r) data for the 1:10 and 1:100 scale models are
presented in Figs. 10 and 11, respectively. The solid line through the data re-
presents a least squares, best fit average for the entire collection. An ex-
amination of these figures discloses that reflection increases with:
    1) decreasing depth
    2) increasing period
    3) decreasing steepness
    4) increasing model size.
Although not presented in this discussion, the reflection coefficient behavior
is not significantly different for flat bottom configuration when compared to
similar conditions on a sloping bottom.

The response to period and steepness is consistent with energy dissipation
considerations along the breakwater surface. Surface drag is a nonconservative
force which increases with the square of local velocities. Wave particle vel-
ocities increase with increased wave steepness and reduced period. These changes
induce higher drag forces, more energy dissipation and therefore consume energy
available for generating the reflected wave. Conversely, a reduction in wave
steepness or increase in period causes a reduction in local velocities and energy
dissipation, thereby increasing reflection as observed in Figs. 10 and 11. The
observed scale effect also follows this trend. Low Reynolds number flow in the
small model causes proportionately higher drag and reduces reflection by up to 10%.

Stability
    Stability is a measure of the ability of breakwater armor to resist damage
from wave attack. Ultimately, the integrity of the entire structure is dependent
upon design considerations which adequately account for stability requirements.
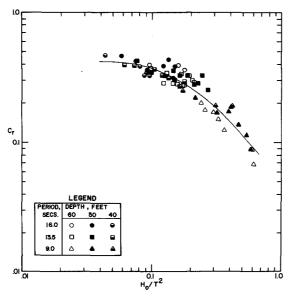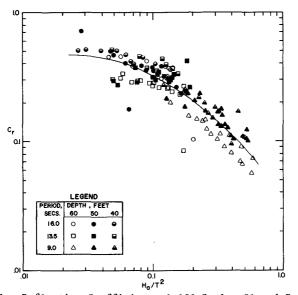Several definitions for stability are currently in use, some more elegant than
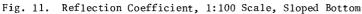
Fig. 10.   Reflection Coefficient, 1:10 Scale, Sloped and Flat Bottom

Fig. 11.   Reflection Coefficient, 1:100 Scale, Sloped Bottom

others. The one definition which is subject to the least confusion quantifies
stability as that wave height which causes an "acceptable" level of damage to a
particular structure under specified conditions of water depth and wave period.
"Acceptable" damage is most always less than 5% of the seaward armor surface area,
usually less than 1%. This limiting wave height has been found to be weakly de-
pendent on water depth and wave period. Attempts to develope a dimensionless
stability coefficient for comparison of alternative armor units have led to a
variety of expressions which are proportional to the zero damage wave height
divided by the cube root of the armor unit volume. Hudson's formula (Hudson, 1953),
was developed to quantify stability of units which rely only on their submerged
weight for stability. Although it was not intended for use in describing units
which have interlocking strength, Hudson's stability coefficient is still the most
widely used standard for armor unit comparison.

No damage is often an uneconomical and unnecessary design requirement. Paul
and Baird (1971) have attempted to identify alternative failure modes for more
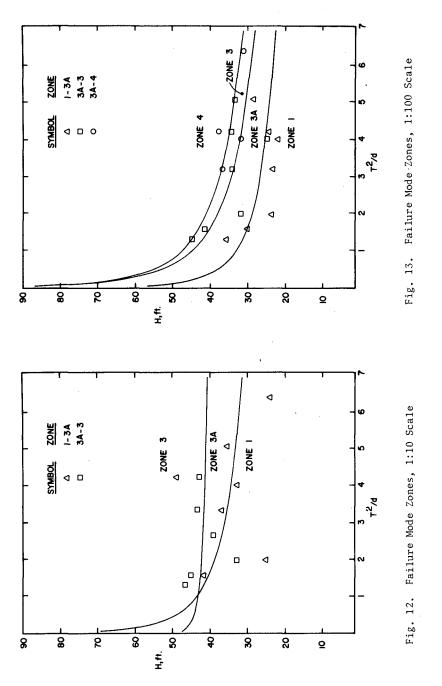flexible design requirements. These modes or failure zones are:
    Zone 1: No movement of armor units
    Zone 2: Local movement but no displacement
    Zone 3: Few units displaced
    Zone 3a: Damage stops before 10 units are displaced per 100 lineal feet
             of breakwater
    Zone 4: Continuous damage will ultimately destroy armor layer
    Zone 5: Immediate, complete failure of the armor layer.
This failure mode analysis was used to identify levels of failure in the placed
stone study. Results for the 1:10 and 1:100 scale models are presented in Figs.
12 and 13, respectively. Damage to A and A+ armor materials are summed in
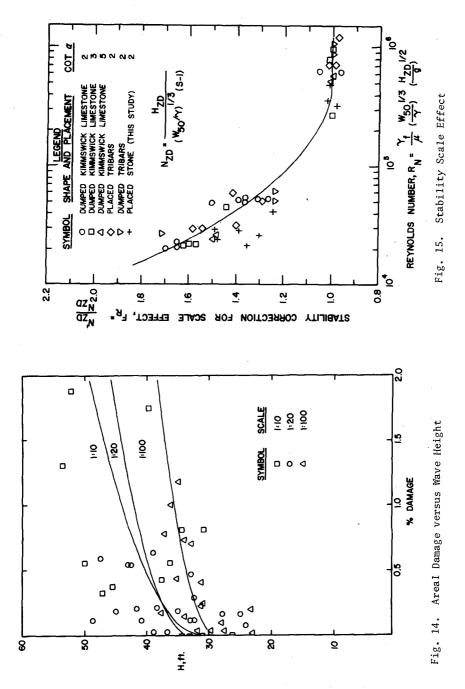these figures.

The failure mode analysis indicates a slight dependence on relative depth.
This results from long waves at shallow depths (high T^2/d) attacking the A- layer
below MLLW. Smaller wave heights can damage this layer in shallow water. Higher
waves are required to cause the same damage in water of greater relative depth
(low T^2/d). At both scales, increasing wave heights cause increasing levels of
damage. However, proportionately higher prototype waves are required to cause
the same level of damage in the large model. Zone 4 could not be achieved at
the 1:10 scale because equivalent prototype wave heights in excess of 55 feet
could not be generated.

Levels of damage can also be quantified in terms of the percent of the armor
surface area experiencing displaced units after exposure to 500 design waves.
This data is presented in Fig. 14, for all three scales and all combinations of
wave period and water depth. Least squares, best fit lines have been extended
through the data at each scale. Again, larger waves cause more damage. The
scale effect is readily apparent in this figure. The 1:100 scale model indicates
that comparable damage will be caused by a wave height which is less than 80% of
that indicated by the 1:10 scale results. Zero damage wave heights (H_{ZD}) ex-
trapolated from Fig. 14, provide the following estimates for Hudson's stability
coefficient (K_D) at each scale:

Scale	H_{ZD}	K_D
1:10	35'	29
1:20	35'	29
1:100	28'	23

Fig. 13. Failure Mode Zones, 1:100 Scale

Fig. 12. Failure Mode Zones, 1:10 Scale

Fig. 15. Stability Scale Effect

Fig. 14. Areal Damage versus Wave Height

Stability scale effects have been investigated by Thomsen, et.al. (1972), for several armor unit shapes. The results are summarized in Fig. 15. In this study, a zero damage stability coefficient, N_{ZD}, and Reynolds number, R_N, have been defined as presented on the figure, wherein:

H_{ZD} = zero damage wave height (Zone 3-a or less)
W_{50} = average armor unit weight
γ = material specific weight
S = material specific gravity
γ_f = fluid specific weight
μ = fluid dynamic viscosity.

The scale effect is defined as the ratio of the large scale stability coefficient, N'_{ZD}, divided by a smaller scale stability coefficient, N_{ZD}. Data from the placed stone study are superimposed on the results of Thomsen, et.al., as indicated in the legend. Thomsen concluded that Reynolds numbers in excess of $3 \cdot 10^5$ must be achieved to avoid scale effects. Also, the no damage wave height will be overestimated by approximately 60% if the scale is reduced by another factor of five. The results from the present study support this conclusion. The 1:20 scale model occurs at the limiting Reynolds number and shows no significant scale effect. The 1:100 scale model is one-fifth of the limiting Renolds number size, and a 40% reduction in stability is indicated, as shown in Fig. 15. Thus, small models underestimate prototype stability due to the magnification of drag forces at low Reynolds number.

Summary

The results of this study provide research and design information about the total hydraulic behavior of placed stone armor breakwaters. The armor surface responds to runup similar to an impermeable, graded riprap slope. Rundown, however, is reduced. Reflection coefficients are relatively low, compared to a smooth, impermeable reflecting surface. The structure is extremely stable, similar to that of dolos armor. Comparison of large and small model results indicate that scale effects distort small model results by decreasing runup, reflection and stability while increasing rundown.

Acknowledgements

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