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# SCALE EFFECT TESTS FOR RUBBLE-MOUND BREAKWATERS

Hydraulic Model Investigation

by

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## FOREWORD

Authority for the U. S. Army Engineer Waterways Experiment Station to conduct Engineering Study 847, "Scale Effect Tests for Rubble-Mound Breakwaters," was contained in a letter from the Office, Chief of Engineers (OCE), dated 24 August 1955; however, the investigation was not begun until July 1957 because the testing facilities were being used to conduct model studies.

The investigation involved both large-scale and small-scale tests. The large-scale tests were conducted during the period July 1957 to June 1965 in the Research Division of the U. S. Army Coastal Engineering Research Center (CERC), Washington, D. C., under the direction of Mr. J. M. Caldwell, Chief Technical Advisor, and Mr. T. Saville, Jr., Chief of the Research Division. During the period April 1962 to January 1964, the large-scale tests were discontinued so that the testing facilities could be used for conducting higher priority studies. In addition to ES 847 funds, a portion of the large-scale tests was funded by CERC. The small-scale tests were conducted during the period January 1965 to July 1966 in the Wave Dynamics Branch, Hydraulics Division, of the Waterways Experiment Station under the direction of Mr. E. P. Fortson, Jr., Chief of the Hydraulics Division, and Mr. R. Y. Hudson, Chief of the Wave Dynamics Branch. The tests were performed by Mr. Y. B. Dai, project engineer, assisted by Mr. E. H. Brasfield, engineering technician, under the supervision of Mr. Hudson and Dr. A. M. Kamel, Special Assistant for Research to the Chief, Hydraulics Division. This report was prepared by Mr. Dai and Dr. Kamel, and was submitted for review to OCE and CERC in April 1968.

Liaison with the Office, Chief of Engineers, was maintained throughout the course of the investigation by means of progress reports and



conferences. Mr. C. E. Lee, Assistant Chief, Hydraulic Design Branch, Engineering Division, Civil Works, Office, Chief of Engineers, visited the Coastal Engineering Research Center and the Waterways Experiment Station at various times in connection with the study.

Successive Directors of the Waterways Experiment Station during the conduct of this study and the preparation of this report were COL A. P. Rollins, Jr., CE, COL E. H. Lang, CE, COL A. G. Sutton, Jr., CE, COL J. R. Oswalt, Jr., CE, and COL L. A. Brown, CE. Technical Directors were Mr. J. B. Tiffany and Mr. F. R. Brown.

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## NOTATION

$C_d$	Drag coefficient
$C_m$	Virtual mass coefficient
$\frac{dv}{dt}$	Acceleration of flow field
$D$	Water depth at toe of breakwater section, or damage
$F_d$	Drag force
$F_I$	Inertia force
$h_a$	Difference between crown elevation of test section and still-water level
$h_b$	Distance below still-water level to which primary cover layer extends
$H$	Wave height
$H_{D=0}$	Maximum wave height for which no damage occurred to a test section
$K_A$	Area coefficient of unit of cover layer
$K_V$	Volume coefficient of unit of cover layer
$\ell$	Characteristic linear dimension
$L$	Wavelength calculated for a water depth $D$
$\frac{L_a}{L_b}$	Linear scale ratio of models
$N_R$	Reynolds number
$(N_R)_c$	Critical value of Reynolds number
$N_s$	Stability number
$P$	Porosity of cover layer (percent voids)
$R$	Distance from still-water level measured positively downward along the slope of the breakwater (see plate A2)
$R_d$	Wave rundown on slope of breakwater section, measured vertically
$R_u$	Wave runup on slope of breakwater section, measured vertically
swl	Still-water level



$S_r$	Specific gravity of cover-layer unit relative to the water in which the breakwater was built, $S_r = \gamma_r / \gamma_w$
$t$	Time
$T$	Wave period
$v$	Velocity of flow field
$V$	Velocity of water particle parallel to side slope of breakwater
$V_R$	Value of $V$ at a distance $R$ equal to half the characteristic diameter of cover-layer unit
$W$	Width or half-width of breakwater crown
$W_r$	Weight of cover-layer unit
$x, y, z$	Axes
$\gamma$	Specific weight
$\delta$	Characteristic diameter of unit of primary cover layer
$\lambda$	Scale of model
$\nu$	Kinematic viscosity of water
$\pi$	Constant = 3.1416
$\rho$	Density
$\omega$	Velocity parameter

### Subscripts

$a, b$	Models having two different scales, or model and prototype
$r$	Unit of cover layer
$s$	Model-to-model ratio or model-to-prototype ratio
$w$	Water



## CONVERSION FACTORS, BRITISH TO METRIC UNITS OF MEASUREMENT

British units of measurement used in this report can be converted to metric units as follows:

<u>Multiply</u>	<u>By</u>	<u>To Obtain</u>
inches	2.54	centimeters
feet	0.3048	meters
feet per second	0.3048	meters per second
pounds	0.4535924	kilograms
pounds per cubic foot	16.0185	kilograms per cubic meter
tons	907.185	kilograms
Fahrenheit degrees	5/9	Celsius or Kelvin degrees*

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\* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula:  $C = (5/9)(F - 32)$ . To obtain Kelvin (K) readings, use:  $K = (5/9)(F - 32) + 273.15$ .



## SUMMARY

Laboratory investigations conducted by and for the Waterways Experiment Station under ES 815, "Stability of Rubble-Mound Breakwaters," determined the relative importance of the different variables with respect to the stability of rubble-mound breakwaters and formulated design criteria for those structures. In ES 815, test-wave dimensions, water depth, and the armor-unit sizes used corresponded to a model with a linear scale of about 1:50 for a prototype structure with rock armor units of about 20 tons. In order to determine the effects of model scale on the results obtained in the ES 815 and similar studies, the ES 847 tests were conducted duplicating the ES 815 testing techniques using model scales of 7.5:1, 1:1, and 0.5:1 relative to the linear dimensions of the ES 815 scale tests. The breakwater test sections used had primary cover layers composed of smooth or rough quarrrystones or quadripod armor units. The ES 847 investigation included: (a) tests for the selection of the maximum no-damage wave heights for the condition of no overtopping, (b) damage tests to determine the amount of damage to test sections when they were attacked by waves with heights about 1.6 times their maximum no-damage wave heights, and (c) determinations of wave runup and rundown on the breakwater slopes tested.

Test results indicated that, for the type of breakwater sections and armor units tested, no significant scale effect in the selected no-damage wave heights was present for models with scales of 7.5:1 and 1:1; however, a significant scale effect was found to occur for the tests of the 0.5:1-scale model. This scale effect is believed to have been due to the smallness of the 0.5:1 model, which caused the viscous forces to be significant and thus result in inaccuracy in model results. Results of damage and wave runup and rundown tests for the three models did not follow any trend that would indicate the existence or nonexistence of scale effect. It was concluded that no scale factor would be required when applying the results of ES 815 and similar tests to the design of full-scale breakwaters when the Reynolds number, as defined in this report, is equal to or greater than about  $3 \times 10^4$ .



Hydraulic Model Investigation

PART I: INTRODUCTION

Background

1. Scale effect may be defined as any hydraulic inaccuracy in model performance caused by the reduced size of the model. Such effects may be present to some degree in any model smaller than its prototype. The forces that may affect a flow field are those of pressure, inertia, gravity, viscosity, elasticity, and surface tension. To obtain dynamic similarity between two flow fields when all of these forces act, all corresponding force ratios must be the same in model and prototype. Fortunately, in most engineering problems some of the forces may not be involved, may be of negligible magnitude, or may oppose other forces in such a way that the effects of both are reduced. In each problem of similitude a good understanding of the fluid phenomena is necessary to determine how the problem may be satisfactorily simplified by elimination of the irrelevant, negligible, or compensating forces. Models involving wave action are designed and operated in accordance with Froude's model law in which the ratio between inertia and gravity forces is the same in both model and prototype. In these models the effect of viscous forces is assumed to be negligible. However, when the linear scale is too small, viscous forces may become significant and cause inaccuracies in model performance. Therefore, selection of scale for a wave action model usually requires a compromise between economy and the degree of accuracy required. The model should be small enough to be economical, yet large enough to render viscous effects negligible.

2. Attempts to determine by theoretical analysis the stability characteristics of rubble-mound breakwaters under attack by storm waves have not been successful. Instead, formulas ranging from completely empirical to semitheoretical have been developed on the basis of extensive



field observations and laboratory research. The formula most widely used by engineers in the United States is a semitheoretical one developed at the Waterways Experiment Station<sup>1</sup> as a result of a comprehensive laboratory investigation conducted under Engineering Study (ES) 815, "Stability of Rubble-Mound Breakwaters." The results of the ES 815 program have been very useful in determining the relative importance of the different variables with respect to the stability of rubble-mound breakwaters and in the formulation of design criteria for these structures.

### The Problem

3. In the ES 815 testing program, a compromise between the capabilities of the available testing facilities, economy, and accuracy resulted in using wave dimensions, water depths, and rock sizes that corresponded to a model with a linear scale of about 1:50. Although this scale may be considered adequate for most of the variables involved in the stability of rubble-mound breakwaters, it was feared that it might not be large enough to render the effect of viscous forces negligible. In order to determine the effects of model scale on the results obtained from the ES 815 laboratory investigation, it was decided to perform the ES 847 tests, which duplicated as nearly as possible the ES 815 testing techniques. In these tests linear scales of 7.5:1, 1:1, and 0.5:1, relative to the linear dimensions of the ES 815 scale tests, were used. After the effects of model scale had been determined, they were to be used in applying the ES 815 and other test results to the design of full-scale rubble-mound breakwaters to ensure their safe and economical design.

### Purpose and Scope of Studies

4. The purpose of the ES 847 study was to determine the effects of model scale on the results obtained from the ES 815 laboratory investigation. The results of tests conducted using model scales of 7.5:1, 1:1, and 0.5:1, relative to the ES 815 model scale tests, will be used to determine the scale factor required for applying the results of ES 815 and



other tests to the design of full-scale rubble-mound breakwaters. The following factors, which may cause scale effect, were controlled as much as possible in the three models: (a) wave form as affected by the distance of the test section from the wave generator, (b) surface roughness of armor units, and (c) difference in nesting of individual units in the cover layer due to differences in placing techniques.

5. Large-scale (7.5:1) and small-scale (1:1 and 0.5:1) tests of breakwater sections using smooth and rough quarrrystone and quadripod cover layers were conducted. The investigation included:

- a. Selection of the maximum no-damage wave heights for the condition of no overtopping. In these tests the maximum non-breaking wave heights that caused no damage to the cover layers were determined. Breakwater sections used had crown elevations sufficient to prevent overtopping by the test waves.
- b. Damage tests to determine the amount of damage to test sections attacked by waves larger than their no-damage wave heights.
- c. Measurements of wave runup and rundown on the slopes of the breakwater sections.



6. When rubble breakwaters are exposed to storm waves, the primary hydrodynamic forces acting on armor units in the cover layer are those of inertia and drag, which can be expressed as:

$$\text{Inertia force, } F_I = C_m K_V \ell^3 \rho_w \frac{dv}{dt} \quad (1)$$

$$\text{Drag force, } F_d = \frac{1}{2} C_d K_A \ell^2 \rho_w v |v| \quad (2)$$

For two models, a and b, the ratio between their inertia forces is

$$\frac{(F_I)_a}{(F_I)_b} = \frac{(C_m)_a}{(C_m)_b} \frac{(K_V \ell^3 \rho_w \frac{dv}{dt})_a}{(K_V \ell^3 \rho_w \frac{dv}{dt})_b} \quad (3)$$

and the ratio between their drag forces is

$$\frac{(F_d)_a}{(F_d)_b} = \frac{(C_d)_a}{(C_d)_b} \frac{(\frac{1}{2} K_A \ell^2 \rho_w v |v|)_a}{(\frac{1}{2} K_A \ell^2 \rho_w v |v|)_b} \quad (4)$$

Equations 3 and 4 can be rewritten as

$$(F_I)_s = \frac{(C_m)_a}{(C_m)_b} \frac{(K_V)_a}{(K_V)_b} \ell_s^3 \rho_s \left( \frac{dv}{dt} \right)_s \quad (5)$$

$$(F_d)_s = \frac{(C_d)_a}{(C_d)_b} \frac{(K_A)_a}{(K_A)_b} \ell_s^2 \rho_s v_s^2 \quad (6)$$

where subscript s indicates model-to-prototype ratio or model-to-model ratio.



7. From Froude's law it follows that

$$t_s = \sqrt{\frac{\rho_s \ell_s}{\gamma_s}} \quad (7)$$

$$v_s = \sqrt{\frac{\gamma_s \ell_s}{\rho_s}} \quad (8)$$

When the same liquid (i.e. water) is used in both models, it follows that  $\gamma_s = 1$  and  $\rho_s = 1$  and equations 7 and 8 reduce to

$$t_s = \sqrt{\ell_s} \quad (9)$$

and

$$v_s = \sqrt{\ell_s} \quad (10)$$

Substituting equations 9 and 10 into equations 5 and 6, respectively, yields

$$(F_I)_s = \frac{(C_m)_a}{(C_m)_b} \frac{(K_V)_a}{(K_V)_b} \ell_s^3 \quad (11)$$

$$(F_d)_s = \frac{(C_d)_a}{(C_d)_b} \frac{(K_A)_a}{(K_A)_b} \ell_s^3 \quad (12)$$

From the geometrical similarity of the models, it can be assumed that  $(K_V)_a = (K_V)_b$  and  $(K_A)_a = (K_A)_b$  and equations 11 and 12 reduce to

$$(F_I)_s = \frac{(C_m)_a}{(C_m)_b} \ell_s^3 \quad (13)$$

and

$$(F_d)_s = \frac{(C_d)_a}{(C_d)_b} \ell_s^3 \quad (14)$$



According to Lamb,<sup>2</sup> viscosity has a slight effect on the value of  $C_m$ . However, experiments by Keulegan<sup>3</sup> and by O'Brien<sup>4</sup> showed that  $C_m$  is a function of the geometric shape of the object and of the flow field around it but is not a function of Reynolds number. Therefore, it is reasonable to assume that, under the same test conditions, the  $C_m$  value for models of different scales remains constant and equation 13 can be written as

$$(F_I)_s = \ell_s^3 \quad (15)$$

thus indicating that the virtual mass coefficient  $C_m$  does not induce scale effect.

8. The drag coefficient  $C_d$  is a function of the Reynolds number ( $N_R$ ), i.e. a function of the ratio between the viscous and the inertia forces. For low values of  $N_R$ , the viscous forces are predominant and the value of  $C_d$  decreases and continues to decrease for increasing values of  $N_R$  until a critical value  $(N_R)_c$  is reached at which the viscous forces are no longer the predominant ones and the value of  $C_d$  no longer varies with  $N_R$ . This is true when the flow around an object is either steady or oscillatory as shown in plate 1. In a model designed based on Froude's similarity law, in order to neglect the effect of viscous forces, the value of  $C_d$  should be approximately the same for both model and prototype, i.e.,

a. For prototype values of  $N_R < (N_R)_c$  the linear scale of the model should be approximately the same as that of the prototype.

b. For prototype values of  $N_R \geq (N_R)_c$  the scale of the model should be large enough so that the model value of

$$N_R \geq (N_R)_c.$$

The above discussion indicates that the drag coefficient  $C_d$  is a factor by which scale effect could be induced in rubble-mound breakwater models designed based on Froude's similarity law.



### PART III: DESCRIPTION OF TESTS

#### Test Apparatus

9. The large-scale tests (7.5:1) were conducted at the U. S. Army Coastal Engineering Research Center (CERC), Washington, D. C., in a wave flume 15 ft\* wide, 20 ft deep, and 635 ft long, equipped with a bulkhead wave generator (fig. a of plate 2). The speed of the generator was controlled by a set of gears and a constant-speed motor. Wave heights were measured at the center line of the breakwater section without the test section installed, by an electric wave gage and by visual reading on a staff gage installed on the side of the flume. The difference in readings between the electric and staff gages did not exceed  $\pm 0.1$  ft. Since the last waves of some of the generated wave trains were about 30 to 40 percent larger than the significant height of the wave train, a wave skimmer (a drop-type structure) was provided to intercept enough of the energy of the last wave to reduce its height to a value less than the heights of the preceding waves. The wave periods at which the skimmer was used were 3.75 and 5.60 sec. The small-scale tests (1:1 and 0.5:1) were conducted at the Waterways Experiment Station (WES) in a wave flume 5 ft wide, 4 ft deep, and 119 ft long, equipped with a plunger-type wave generator (figs. b and c of plate 2). Wave heights were measured with a parallel-wire-type gage and recorded on an oscillograph. A filter-type wave skimmer was used to reduce the heights of the last waves in the wave trains whenever it was found necessary.

#### Types of Tests Conducted

10. Three series of tests were conducted on breakwater sections built of smooth or rough quarrrystone or quadripod armor units. In the first test series, no-damage wave heights, i.e. the maximum wave heights that caused no damage to the cover layers of the breakwater sections, were

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\* A table of factors for converting British units of measurement to metric units is presented on page ix.



determined using sections with crown elevations sufficient to prevent overtopping by the test waves. In the second series, damage tests were conducted to determine the amount of damage to breakwater sections similar to those used in the first series of tests, except that their crown elevations were made equal to the no-damage wave height. In these tests the breakwater sections were exposed to waves 1.6 times the no-damage wave height selected from the first test series. In the third series of tests, wave runup and rundown tests were conducted in which the heights of runup and rundown, measured vertically above and below still-water level, respectively, on the slope of each test section, were determined for the test waves used in the first two series of tests. All tests in this investigation were for nonbreaking waves, i.e. the water depth at the structure toe in each case was sufficient to prevent the breaking of waves due to lack of depth.

### Breakwater Sections Tested

#### Elements of test sections

11. The following types of breakwater sections were tested in this investigation. For all tests the armor units, which consisted of either smooth or rough quarrrystones or quadripods, were placed in a random manner, without attempting to interlock the units with one another.

- a. Quarrrystone cover-layer sections for no-damage wave tests (fig. a of plate 3). The crown elevation was high enough to prevent overtopping, and the primary cover layer was extended to a sufficient distance below still-water level to prevent damage to the secondary cover layer placed below the primary layer. The section had sea-side and harbor-side slopes of 1:1.5 from the crown down to the elevation to which the primary cover layer extended; below this, the sea-side slope was 1:1.5 and the harbor-side slope was 1:1.25.
- b. Quarrrystone cover-layer sections for damage tests (fig. b of plate 3). The test sections were essentially the same



as in a above except that the crown elevation above still-water level and the distance below still-water level to which the primary cover layer was extended were made equal to the previously selected no-damage wave heights for each test section of the 1:1 and 0.5:1 model scales. For the 7.5:1 test sections the crown elevations were greater than the no-damage wave height.

- c. Quadripod cover-layer sections for no-damage wave tests (fig. c of plate 3). The crown elevation was high enough to prevent overtopping. Two layers of quadripod units were used in the primary cover layer; they were placed only on the sea-side face and crown of the section. The section had a slope of 1:1.5 on both sea side and harbor side of the structure.
- d. Quadripod cover-layer sections for damage tests (fig. d of plate 3). The test sections were essentially the same as in c above except that the crown elevation above still-water level and the distance below still-water level to which the primary cover layer extended were made equal to the previously selected no-damage wave heights for each test section of the 1:1 and 0.5:1 model scales. However, the crown elevation for the quadripods in the large-scale tests (7.5:1) was not selected in this manner. The concrete cap for the CERC tests was placed at an elevation equal to the average value of the no-damage wave heights. Also, the sections had a crown width twice that of the sections in c; half the width was composed of quadripods and the other half was a concrete cap to support the crown quadripods.

#### Materials used

12. For the small-scale tests, two types of armor stones were used for the primary cover layer--rough and smooth quarrrystones. For the large-scale tests, only rough quarrrystones were tested. The rough quarrrystones (photographs 1a, b, and c), a mixture of granite and gneiss, had a



specific weight of 168.5 lb/cu ft. The smooth quarrrystones (photographs 1d and e) were limestone with a specific weight of 175 lb/cu ft and a surface texture somewhat smoother than that of granite and gneiss (the absolute values of the surface roughness were not scaled exactly).

13. Stones of the primary cover layer were selected and sized by hand so that their shapes and weights were approximately the same. The individual stones were weighed on a spring scale, and a 110-rock sample was selected for determining the shape characteristics. The shape of stones was determined by measuring the dimensions along three perpendicular axes x, y, and z. The shape was expressed in terms of the ratios  $x/z$  and  $y/z$ . Stones in the secondary cover layer had the same surface texture as those used in the primary cover layer and had nearly the same weight and shape; however, no attempt was made to control their weight as was done for stones of the primary cover layer. Stones of the secondary cover layer for the 7.5:1-scale model were selected by hand, whereas for the 1:1- and 0.5:1-scale models they were sized using sieves. Gradation curves for the rough and smooth quarrrystones used in this investigation are shown in plate 4.

14. The core material used in the test sections of the 7.5:1-scale model, sand with a medium grain size of 0.22 mm, was placed in 6-in. layers and tamped with a 12-in. circular plate at the end of a 5-ft handle. In order to prevent migration or leaching of the sand core through the voids between the relatively large armor stones, two intermediate underlayers (filters) between the armor stones and the sand core were provided. The second underlayer, next to the core material, consisted of a 6-in.-thick blanket of well-graded sand sized so that the particles were finer than a No. 4 U. S. Standard Sieve and coarser than a No. 40 U. S. Standard Sieve. The first underlayer consisted of a 12-in.-thick blanket of well-graded gravel sized so that 100 percent of the particles were smaller than 3 in. and larger than 1/2 in. The core material used in the 1:1- and 0.5:1-scale models was a mixture of sand and crushed basalt with a mean particle diameter of 1/8 in. Unlike the 7.5:1-scale model, only one underlayer was used in the test sections of the smaller scale models. This underlayer was composed of two layers of stones with weights approximately



one-tenth that of the armor stones used in the cover layer.

15. Two types of quadripods were used as cover layers for the 1:1 and 0.5:1 breakwater sections tested--rough and smooth quadripods (photograph 2). The rough quadripods were cast from concrete, the smooth quadripods from leadite. Leadite is the trade name of a caulking compound which has a specific weight approximately the same as that of concrete but is finer in grain size; thus the leadite quadripods were smoother than those molded from concrete. Only concrete quadripods were used in the 7.5:1-scale tests. (Again, as in the case of the quarystone armor units, paragraph 12, the absolute values of surface roughness were not scaled exactly.)

#### Method of constructing test sections

16. The model breakwaters were cross-sectioned with a sounding rod equipped with a ball and socket foot to facilitate adjustment to the irregular surface. The foot of the sounding rod was circular with a diameter equal to about one-half the average diameter of the armor units. A method of placing the materials in constructing the scale models of the breakwaters was selected which reproduced, as nearly as possible, the construction of full-scale structures. The test sections were constructed in the test flume on a sand base. Material from the base to the crown of the core material section (secondary cover layer and core material) was placed with the flume dewatered. The core material was compacted to simulate natural consolidation resulting from wave action during construction of full-scale structures. The primary cover layer was then placed on the breakwater section, after which the flume was flooded to the proper still-water level. For construction of the 7.5:1-scale model (photograph 3), the units of the primary cover layer were placed by loading them on a wooden skip, positioning the skip over the breakwater section with a crane, and then rolling the units off the skip and placing them on the breakwater in a random fashion. For construction of the cover layer of the 1:1- and 0.5:1-scale models, the units from the top of the core material to still-water level were placed by dumping them from a bucket or shovel at the water surface, whereas the units above still-water level were randomly placed by hand. Photographs 4 and 5 show cross sections and end views,



respectively, of the 0.5:1-scale test sections.

17. The weights of the armor units required in the small-scale models were determined from the weight and specific weight of the large-scale rock and the following transference equation. This equation was derived from the stability number ( $N_s$ ) for model rubble breakwaters. The stability number is a dimensionless term derived by Hudson<sup>1</sup> based on the assumption that the primary forces acting on armor units of rubble-mound breakwaters during wave attack are the drag force and the submerged weight of individual armor units. The dimensionless term is expressed as

$$N_s = \frac{H \gamma_r^{1/3}}{W_r^{1/3} (S_r - 1)} \quad (16)$$

By equating the stability numbers between two models, or model and prototype, the following relation is obtained:

$$\frac{(W_r)_a}{(W_r)_b} = \left( \frac{L_a}{L_b} \right)^3 \frac{(\gamma_r)_a}{(\gamma_r)_b} \left[ \frac{(S_r)_b - 1}{(S_r)_a - 1} \right]^3 \quad (17)$$

The following tabulation shows the measured and calculated weights and other characteristics of the cover-layer units tested in this investigation.

Cover-Layer Unit	Model Scale	$W_r$ lb	$\gamma_r$ lb/cu ft	$S_r$	P %	Ratio of Coordinates	
						x/z	y/z
Rough quarrrystone	7.5:1	161.5	168.5	2.70	41.6	1.69	1.36
	1:1	0.38	168.5	2.70	44.3	1.84	1.43
	0.5:1	0.048	168.5	2.70	49.6	2.63	1.76
Smooth quarrrystone	1:1	0.30	175.0	2.82	40.0	1.60	1.30
	0.5:1	0.046	175.0	2.79	46.0	2.60	1.87
Rough quadripod	7.5:1	76.0	150.0	2.40	50.0	--	--
	1:1	0.19	139.2	2.23	50.0	--	--
Smooth quadripod	1:1	0.18	139.8	2.24	50.0	--	--
	0.5:1	0.030	140.0	2.24	50.0	--	--

#### Test Conditions and Procedures

18. Tests were conducted using constant water depths (D) of 15, 2,



and 1 ft in models constructed with scales of 7.5:1, 1:1, and 0.5:1, respectively. Except for the first few tests, wave periods (T) were selected in such a manner that the relative depths (D/L) obtained in the three models were the same. The relative depths used were 0.434, 0.230, 0.135, 0.091, and 0.062. Fresh water with a specific weight of 62.4 lb/cu ft was used. The characteristics of waves tested in this investigation are tabulated below:

<u>Model Scale</u>	<u>T</u> <u>sec</u>	<u>L , ft</u>	<u>D</u> <u>ft</u>	<u>D/L</u>
7.5:1	2.61	34.50	15.0	0.434
	3.75	64.70	15.0	0.230
	5.60	111.00	15.0	0.135
	7.87	165.00	15.0	0.091
	11.33	242.00	15.0	0.062
1:1	0.95	4.58	2.0	0.434
	1.37	8.62	2.0	0.230
	2.04	14.70	2.0	0.135
	2.84	22.00	2.0	0.091
	4.14	32.00	2.0	0.062
0.5:1	0.67	2.28	1.0	0.434
	0.97	4.31	1.0	0.230
	1.45	7.43	1.0	0.135
	2.03	11.00	1.0	0.091
	2.93	16.40	1.0	0.062

19. Tests were performed duplicating the same procedures used in the ES 815 tests. Factors which may cause scale effect and which were controlled as much as possible in the three models are:

- a. Wave form as affected by the distance of the test section from the wave generator.
- b. Surface roughness of cover-layer units.
- c. Placing techniques.

The wave form (item a) was controlled by keeping constant in the three models the ratio of the distance of the model breakwater from the wave generator to the wavelength. The surface roughness of cover-layer units (item b) could not be scaled exactly, but this factor was controlled as much as possible by the selection of armor-unit material and shape of the units. Materials used were either limestone or a mixture of granite and gneiss for quarystone units, and either concrete or leadite for quadripods.



Quadripods molded from the same material have similar surface roughnesses and the shape is the same for each scale. The shape of quarrystone units was controlled by individually sizing and selecting the stones of the primary cover layers used in the three models. Differences in nesting of individual units due to differences in placing techniques (item c) were avoided as much as possible by utilizing the same technique in placing the units of the cover layers in the three models.

20. For each breakwater section, no-damage wave heights for the no-damage and no-overtopping criteria were determined by subjecting the test section to waves of increasing heights, until a wave height was found that was slightly less than that which would cause 1 percent damage to the test section. Thus, for the no-damage criterion 1 percent of damage to the cover layer was allowed. The cover layer of the test section was sounded transversely and longitudinally before and after testing. The average cross section was obtained from the average values of evenly spaced cross sections across the flume. The damage in percent was computed from the ratio of the volume of material eroded from the cover layer to the volume of material in the original primary cover layer before wave attack. Damage tests for the small-scale models were conducted by subjecting the test sections to wave heights 1.6 times that of the corresponding no-damage wave height. For the large-scale tests this ratio varied from about 1.4 to 1.7. The value of 1.6 is the ratio of the wave height that is not exceeded more than 1 percent of the time in a wave train to the significant wave height in the same wave train. The significant wave height is usually used as the design wave for practical design of rubble breakwaters. Thus, the wave heights selected for damage tests were 1.6 times the height of the significant waves. The amount of damage was determined in the same manner as that used in the no-damage wave height tests.

21. The duration of wave attack against the test section for the no-damage wave height and damage tests depended upon the scale of the models. The cumulative testing time for the models of 7.5:1, 1:1, and 0.5:1 scale was 82.2, 30.0, and 21.2 minutes, respectively. The duration of each test interval was usually short enough to prevent waves reflected from the wave-machine plunger or bulkhead from reaching the test section.



After each test interval, the wave machine was not again turned on until a still-water condition had been established in the testing flume. The run-and-stop procedure was not followed for the 2.61-sec wave period in the large-scale tests. The reflected waves for this short-period wave were small, and wave reflection did not become a problem until after a considerable period of operation. Thus, for these tests the wave generator was allowed to continue for periods of 5 to 10 minutes.

22. After the completion of each test series, and before starting a new one, all the units of the primary cover layer were removed and then replaced to the designed grade. This procedure was adopted to prevent any possible cumulative stabilization of the structure from waves of a previous test series.



## PART IV: RESULTS OF TESTS

### Presentation of Results

23. Results of the no-damage wave height and damage tests for rough quarrrystone, smooth quarrrystone, rough quadripods, and smooth quadripods are presented in tables 1 through 4, respectively. The values for  $T$ ,  $D$ ,  $h_a$ ,  $H$ ,  $H_{D=0}$ , and the percentage damage in these tables were determined experimentally, whereas  $L$  and  $N_s$  were computed. The damage is defined as the ratio of the volume of material eroded from the primary cover layer to the volume of material in the original primary cover layer before wave attack. Results of wave runup and rundown tests for rough quarrrystone, smooth quarrrystone, rough quadripods, and smooth quadripods are presented in tables 5 through 8, respectively. Values for  $T$ ,  $H$ ,  $R_u$ , and  $R_d$  were measured experimentally;  $L$  was computed.

### Analysis of Test Results

#### No-damage wave height tests

24. To study the effect of the model scale on the no-damage wave height, the test data on the no-damage waves given in tables 1 through 4 were rearranged as presented in table 9 and plotted in plate 5 as the relation between the model scale ( $\lambda$ ) and the relative no-damage wave height ( $H_{D=0}/\lambda$ ). It can be seen from plate 5 that:

- a.  $H_{D=0}/\lambda$  for tests with rough quarrrystone and rough quadripods is essentially the same for the 7.5:1- and the 1:1-scale models.
- b.  $H_{D=0}/\lambda$  for tests with rough quarrrystone, smooth quarrystone, and smooth quadripods for the 0.5:1-scale model is less than those for the 7.5:1- and 1:1-scale models.
- c.  $H_{D=0}/\lambda$  for the 0.5:1-scale model is on the average from 15 percent (for quarrrystone units) to 50 percent (for quadripod units) lower than those for the 7.5:1- and 1:1-scale models.



- d. For a given model scale, the no-damage wave heights are larger for rough cover-layer units than for smooth ones.
- e. For quarrrystone units, the test results for the 0.5:1-scale model are more scattered than those for the 7.5:1- and 1:1-scale models.

25. The findings mentioned in items a, b, and c above indicate that for the types of breakwater sections and cover-layer units tested, no significant scale effect with respect to the no-damage wave heights is obtained from testing of models with linear scales of 7.5:1 and 1:1; however, a significant scale effect is present in the no-damage wave heights obtained from testing of a 0.5:1-scale model.

26. The higher values of no-damage wave heights obtained for tests with rough cover-layer units, compared with values obtained for tests with smooth units (item d of paragraph 24), may be attributed to the differences between their coefficients of friction. Friction, which is directly proportional to the surface roughness, helps the units stay tightly together, thus increasing their stability. Since the force of friction is directly proportional to the product of the coefficient of friction and the weight of the unit, it is reasonable to assume that surface roughness will cause no scale effect in models of different scales provided that the surface roughness of the units is kept the same (same coefficient of friction) in the different scale models.

27. For quarrrystone units, the larger scatter in test results obtained from the 0.5:1 model as compared with the scatter for the 1:1 and 7.5:1 models (item e of paragraph 24) may be attributed to the high irregularity of the shape of the cover-layer stone used for the 0.5:1-scale model (photograph 1) and the differences in porosity of the stones in these three scale models. Although the primary cover-layer stones for all three models were selected individually, the smallness of the primary cover-layer stones used for the 0.5:1-scale model made it more difficult to control their shape than the shape of the stones used for the two larger models. This can be shown from the following tabulation of the deviations of the ratios  $x/z$  and  $y/z$  for stones used in the 0.5:1 and 7.5:1 models from the ratios for stones used in the 1:1-scale model.



Primary Cover-Layer Units	Model Scale	x/z	y/z	Deviation from 1:1-Scale Model, %	
				x/z	y/z
Rough quarrrystone	0.5:1	2.63	1.76	30	19
	1:1	1.84	1.43	0	0
	7.5:1	1.69	1.36	8	5
Smooth quarrrystone	0.5:1	2.60	1.87	39	31
	1:1	1.60	1.30	0	0

28. The significant scale effect present in no-damage wave heights obtained from testing of a 0.5:1-scale model is believed to be due to the relatively high values of  $C_d$  for the 0.5:1-scale model compared with  $C_d$  values for the 7.5:1 and 1:1 models. As stated in paragraph 8,  $C_d$  is a function of  $N_R$ . For low values of  $N_R$ , the viscous forces are predominant and the value of  $C_d$  decreases and continues to decrease with increasing values of  $N_R$  until a critical value  $(N_R)_c$  is reached for which the viscous forces are no longer the predominant ones and the value of  $C_d$  is no longer dependent on the value of  $N_R$ . The higher the coefficient of drag, the less stable the cover units will be and consequently the lower the value of the no-damage wave height. The relation between Reynolds number and the relative no-damage wave height ( $H_{D=0}/\lambda$ ) for the experimental data is given in table 10 and plate 6. For the definition of  $N_R$  and the method used in its computation, see Appendix A at the end of this report. It can be seen from plate 6 that, for  $N_R < \text{about } 3 \times 10^4$ ,  $H_{D=0}/\lambda$  increases with increasing values of  $N_R$ . However, when  $N_R \geq \text{about } 3 \times 10^4$ ,  $H_{D=0}/\lambda$  is no longer a function of  $N_R$ . This suggests that for the primary cover-layer units tested  $(N_R)_c$  is about  $3 \times 10^4$ . This value of  $(N_R)_c$  is in good agreement with the results obtained by O'Brien<sup>4</sup> for a sphere in an oscillatory flow (plate 1) where  $(N_R)_c \approx 2.5 \times 10^4$ . Therefore, for the units and breakwater sections tested, it is believed that the viscous forces will be negligible, and consequently no significant scale effect will be present in selection of the no-damage wave height if the linear scale of the model results in  $N_R$  values  $\geq 3 \times 10^4$ .

#### Damage tests

29. Damage tests were conducted to provide information concerning the scale effect for rubble-mound breakwaters attacked by waves about



1.6 times as high as the previously selected no-damage waves for the no-overtopping criteria. Since the crown heights of the test sections for the damage tests were made equal to the previously selected no-damage wave heights, considerable overtopping occurred and significant damage on both sea side and harbor side was caused by the overtopping waves. The results of the damage tests are presented in tables 1 through 4 and plotted in plate 7. It can be seen from plate 7 that the test results are widely scattered and do not follow any trend that would indicate the existence or nonexistence of scale effect for the damage tests. This is believed to be due to the variability and complexity of the overtopping waves which were the primary causes of the damage that occurred to the test sections. The overtopping waves in these tests varied from waves that broke seaward of the structure to waves that broke on the structure. With such wide variability in wave conditions a consistent trend in test results is hard to obtain. Hence scale effect for the damage criterion cannot be determined from the results of tests made in this investigation.

#### Wave runup and rundown tests

30. To study the effect of model scale on wave runup and rundown, the test data presented in tables 5 through 8 were plotted as the relation between wave steepness and ratio of wave runup or rundown to wave height (plates 8 and 9). The scatter in the test data shown in plates 8 and 9 may be due to the difficulty in defining the extent of runup and rundown on a pervious sloping surface. It can be seen that the test results do not follow any trend that would indicate the existence or nonexistence of scale effect for wave runup and rundown for the breakwater sections tested and for the cover-layer units used. Plates 8 and 9 show that under the same test conditions wave runup is greater than wave rundown and that both are functions of wave steepness.



## PART V: CONCLUSIONS

31. For the types of rubble-mound breakwater sections and cover-layer units tested, no significant scale effect in no-damage wave heights was obtained from testing of models with linear scales of 7.5:1 and 1:1 (relative to the linear dimensions used in the ES 815 tests); however, a significant scale effect was present in no-damage wave heights obtained from testing of the 0.5:1-scale model (plate 5).

32. Higher values of no-damage wave heights were obtained for tests with rough cover-layer units as compared with values obtained for tests with smooth units (plate 5). This was attributed to the difference between the coefficients of friction of rough and smooth units. Friction, which is directly proportional to surface roughness, helps the units stay together, thus increasing their stability. Since the force of friction is directly proportional to the product of the coefficient of friction and the weight of the unit, it is concluded that surface roughness will cause no significant scale effect in no-damage wave heights obtained from models of different scales as long as the test sections of these models are built of units having the same surface roughness.

33. The significant scale effect present in no-damage wave heights obtained from testing of a 0.5:1-scale model is believed to be due to the relatively high value of  $C_d$  for the 0.5:1-scale model compared with  $C_d$  values for the 7.5:1- and 1:1-scale models. The higher the coefficient of drag, the less stable the cover-layer units will be. The coefficient of drag is a function of Reynolds number; for low values of  $N_R$ , the viscous forces are predominant and the value of  $C_d$  decreases with increasing values of  $N_R$  until a critical value  $(N_R)_c$  is reached, after which the viscous forces are no longer the predominant ones and the value of  $C_d$  is no longer dependent on the value of  $N_R$ . For the breakwater sections and primary cover-layer units tested, a value of  $(N_R)_c \approx 3 \times 10^4$  was obtained (plate 6). Consequently, no significant scale effect will be present in no-damage wave heights obtained from models having a linear scale which corresponds to a  $N_R$  value of about  $3 \times 10^4$  or greater.

34. Results of damage tests were widely scattered (plate 7) and did



not follow any trend that would indicate the existence or nonexistence of scale effect. This was attributed to the wide range of variability of the overtopping waves which were the primary cause of damage to the test sections. The overtopping waves varied from waves breaking on the test section to waves breaking seaward of the test section. With such wide variability in wave conditions a consistent trend in test results was hard to obtain; hence scale effect for damage criterion remains unknown.

35. Results of tests of wave runup and wave rundown (plates 8 and 9) did not follow any trend that would indicate the existence or nonexistence of scale effect. The test results showed that wave runup was greater than wave rundown and that both were functions of wave steepness.



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Table 1  
Results of  $H_{D=0}$  and Damage Tests, Rough Quarrrystone

$H_{D=0}$ Tests							Damage Tests							
T	L		$h_a$	$H_{D=0}$			$h_a$	H	$H/H_{D=0}$		Damage, %			
sec	ft	D/L	ft	ft	$H_{D=0}/L$	$N_s$	ft	ft		H/L	Sea Side	Harbor Side	Total	$N_s$
Scale, 7.5:1; Cover Layer $W_r = 161.5$ lb and $\gamma_r = 168.5$ lb/cu ft ; D = 15.0 ft														
2.61	34.50	0.434	4.50	2.95	0.085	1.76	--	--	--	--	--	--	--	--
3.75	64.70	0.230	4.50	3.25	0.050	1.94	4.41	5.44	1.67	0.083	26.2	4.9	31.1	3.24
5.60	111.00	0.135	4.50	--	--	--	4.18	5.28	--	0.048	15.1	6.8	21.9	3.15
7.87	165.00	0.091	4.50	3.30	0.020	1.97	4.15	5.11	1.55	0.031	4.0	3.5	7.5	3.05
11.33	242.00	0.062	4.50	4.20	0.017	2.50	4.24	5.77	1.37*	0.024	7.3	15.1	22.4	3.44
Scale, 1:1; Cover Layer $W_r = 0.38$ lb and $\gamma_r = 168.5$ lb/cu ft ; D = 2.0 ft														
0.95	4.58	0.434	0.59	0.43	0.094	1.93	--	--	--	--	--	--	--	--
1.37	8.62	0.230	0.59	0.41	0.048	1.84	0.41	0.66	1.60	0.077	12.7	3.0	15.7	2.96
2.04	14.70	0.135	0.59	0.44	0.032	1.98	0.44	0.71	1.60	0.048	10.0	4.4	14.4	3.18
2.87	22.00	0.091	0.59	0.41	0.019	1.84	0.41	0.66	1.60	0.030	8.0	2.1	10.1	2.96
4.14	32.00	0.062	0.59	0.35	0.011	1.57	0.35	0.38*	1.10	0.012	2.0	--	2.0	1.70
Scale, 0.5:1; Cover Layer $W_r = 0.048$ lb and $\gamma_r = 168.5$ lb/cu ft ; D = 1.0 ft														
0.67	2.28	0.434	0.30	0.15	0.066	1.33	0.14	0.24	1.60	0.105	3.4	0.2	3.6	2.15
0.97	4.31	0.230	0.30	0.14	0.033	1.25	0.14	0.22	1.57	0.051	9.2	1.0	10.2	1.97
1.45	7.43	0.135	0.30	0.14	0.019	1.25	0.14	0.22	1.57	0.030	6.2	5.6	11.8	1.97
2.03	11.00	0.091	0.30	0.24	0.022	2.15	0.24	0.38	1.58	0.035	7.8	8.3	16.1	3.40
2.93	16.40	0.062	0.30	0.22	0.013	1.97	0.22	0.35	1.60	0.021	5.7	10.6	16.3	3.13

\* Maximum nonbreaking wave.



Table 2  
Results of  $H_{D=0}$  and Damage Tests, Smooth Quarrrystone

$H_{D=0}$ Tests							Damage Tests							
T sec	L ft	D/L	$h_a$ ft	$H_{D=0}$ ft	$H_{D=0}/L$	$N_s$	$h_a$ ft	H ft	$H/H_{D=0}$	H/L	Damage, %			$N_s$
Scale, 1:1; Cover Layer							$W_r = 0.30$ lb and $\gamma_r = 176.0$ lb/cu ft ; D = 2.0 ft							
0.93	4.45	0.450	0.45	0.36	0.081	1.66	--	--	--	--	--	--	--	--
1.31	8.00	0.250	0.45	0.36	0.045	1.66	0.36	0.56	1.56	0.070	--	--	26.8	2.58
1.88	13.30	0.150	0.45	0.34	0.025	1.57	--	--	--	--	--	--	--	--
2.65	20.00	0.100	0.45	0.36	0.018	1.66	0.36	0.56	1.56	0.028	--	--	21.7	2.58
Scale, 0.5:1; Cover Layer							$W_r = 0.046$ lb and $\gamma_r = 174.0$ lb/cu ft ; D = 1.0 ft							
0.67	2.28	0.434	0.30	0.12	0.053	1.12	0.12	0.19	1.58	0.083	1.7	0.5	2.2	1.77
0.97	4.31	0.230	0.30	0.13	0.030	1.21	0.13	0.21	1.61	0.049	6.2	0.2	6.4	1.95
1.45	7.43	0.135	0.30	0.12	0.016	1.12	0.12	0.19	1.58	0.026	5.3	4.8	10.1	1.77
2.03	11.00	0.091	0.30	0.22	0.020	2.05	0.22	0.35	1.59	0.032	6.5	5.9	12.4	3.26
2.93	16.40	0.062	0.30	0.18	0.011	1.68	0.18	0.29	1.61	0.018	3.2	6.2	9.4	2.69



Table 3

Results of  $H_{D=0}$  and Damage Tests, Rough Quadripods

$H_{D=0}$ Tests							Damage Tests							
T sec	L ft	$H_{D=0}$ D/L	$h_a$ ft	$H_{D=0}$ ft	$H_{D=0}/L$	$N_s$	$h_a$ ft	H ft	$H/H_{D=0}$	H/L	Damage, %			$N_s$
											Sea Side	Harbor Side	Total	
Scale, 7.5:1; Two Layers of Quadripods $W_r = 76.0$ lb and $\gamma_r = 150.0$ lb/cu ft ; D = 15.0 ft														
2.61	34.50	0.434	3.60	1.70	0.049	1.51	2.60	2.95	1.73	0.086	--	--	10.1	2.64
3.75	64.70	0.230	3.50	2.30	0.035	2.05	2.60	4.00	1.73	0.062	--	--	28.1	3.58
5.60	111.00	0.135	--	--	--	--	--	--	--	--	--	--	--	--
7.87	165.00	0.091	3.80	2.90	0.018	2.58	2.60	4.10	1.41	0.025	--	--	12.1	3.68
11.33	242.00	0.062	3.80	2.60	0.011	2.26	2.60	4.20	1.68	0.017	--	--	6.0	3.78
Scale, 1:1; Two Layers of Quadripods $W_r = 0.19$ lb and $\gamma_r = 139.2$ lb/cu ft ; D = 2.0 ft														
0.99	4.96	0.404	0.50	0.32	0.065	2.39	--	--	--	--	--	--	--	--
1.31	8.00	0.250	0.50	0.31	0.039	2.31	0.31	0.50	1.61	0.058	--	--	100.0	3.70
2.04	14.70	0.135	0.50	0.29	0.020	2.15	0.29	0.46	1.59	0.031	--	--	26.5	3.56
2.65	20.00	0.099	0.50	0.33	0.016	2.46	0.33	0.48*	1.45	0.024	--	--	5.2	3.64
1.14	32.30	0.062	0.50	0.31	0.010	2.30	0.31	0.38*	1.23	0.012	--	--	8.0	3.44

\* Maximum nonbreaking waves.



Table 4  
Results of  $H_{D=0}$  and Damage Tests, Smooth Quadripods

$H_{D=0}$ Tests							Damage Tests							
T sec	L ft	$D/L$	$h_a$ ft	$H_{D=0}$ ft	$H_{D=0}/L$	$N_s$	$h_a$ ft	H ft	$H/H_{D=0}$	$H/L$	Damage, %			$N_s$
											Sea Side	Harbor Side	Total	
Scale, 1:1; Two Layers of Quadripods $W_r = 0.18$ lb and $\gamma_r = 139.8$ lb/cu ft ; D = 2.0 ft														
0.95	4.58	0.434	0.51	0.26	0.057	1.93	--	--	--	--	--	--	--	--
1.37	8.62	0.230	0.51	0.27	0.031	2.00	0.28	0.43	1.59	0.050	--	--	53.0	3.18
2.04	14.70	0.135	0.51	0.29	0.020	2.15	0.28	0.46	1.58	0.031	--	--	16.7	3.40
2.86	22.00	0.091	0.51	0.28	0.013	2.08	0.28	0.45	1.61	0.020	--	--	8.0	3.33
4.14	32.00	0.062	0.51	0.30	0.009	2.23	0.28	0.38*	1.27	0.012	--	--	5.4	2.82
Scale, 0.5:1; Two Layers of Quadripods $W_r = 0.03$ lb and $\gamma_r = 140.0$ lb/cu ft ; D = 1.0 ft														
0.67	2.28	0.434	0.26	0.08	0.035	1.08	0.09	0.13	1.63	0.057	--	--	21.2	1.76
0.97	4.31	0.230	0.26	0.09	0.021	1.22	0.09	0.14	1.56	0.033	--	--	15.5	1.89
1.45	7.43	0.135	0.26	0.08	0.011	1.08	0.09	0.13	1.63	0.018	--	--	25.0	1.76
2.03	11.00	0.091	0.26	0.10	0.009	1.35	0.09	0.16	1.60	0.015	--	--	13.0	2.16
2.93	16.40	0.062	0.26	0.10	0.006	1.35	0.09	0.16	1.60	0.010	--	--	25.0	2.16

\* Maximum nonbreaking wave.



Table 5  
Results of Tests of Wave Runup and Rundown, Rough Quarystone

T sec	L ft	H ft	D/L	H/L	R <sub>u</sub> ft	R <sub>d</sub> ft	$\frac{R_u}{H}$	$\frac{R_d}{H}$
Scale, 7.5:1, h <sub>a</sub> = 4.4 to 6.0 ft , D = 15.0 ft , W <sub>r</sub> = 161.5 lb , γ <sub>r</sub> = 168.5 lb/cu ft								
2.61	34.50	2.86	0.435	0.083	3.98	--	1.39	--
		3.06		0.089	3.90	--	1.28	--
		3.17		0.092	4.07	--	1.28	--
3.75	64.70	2.51	0.230	0.039	2.80	--	1.12	--
		2.72		0.042	3.11	--	1.14	--
		3.05		0.047	3.83	--	1.26	--
		3.05		0.047	4.27	--	1.40	--
		3.42		0.053	4.04	--	1.18	--
		3.42		0.053	4.49	--	1.31	--
		5.44		0.084	--	2.36	--	0.43
5.60	111.00	5.28	0.135	0.048	--	3.58	--	0.66
		5.28		0.048	--	3.94	--	0.75
7.87	165.00	3.03	0.091	0.018	3.74	--	1.24	--
		3.13		0.019	4.02	--	1.39	--
		3.38		0.021	4.53	--	1.34	--
		3.44		0.021	4.40	--	1.28	--
11.33	242.00	4.03	0.062	0.017	5.63	--	1.40	--
		4.29		0.018	5.77	--	1.35	--
		5.77		0.024	--	3.12	--	0.54
		5.77		0.024	--	3.67	--	0.64
Scale 1:1, h <sub>a</sub> = 0.41 to 0.59 ft , D = 2.0 ft , W <sub>r</sub> = 0.38 lb , γ <sub>r</sub> = 168.5 lb/cu ft								
0.95	4.58	0.39	0.440	0.085	0.29	0.16	0.74	0.41
		0.43		0.094	0.41	0.20	0.95	0.47
		0.44		0.096	0.37	0.15	0.84	0.34
1.37	8.62	0.40	0.232	0.046	0.46	0.21	1.15	0.53
		0.43		0.050	0.48	0.19	1.12	0.44
		0.66		0.077	*	0.22	--	0.33
2.04	14.70	0.30	0.136	0.020	0.46	0.33	1.53	1.10
		0.40		0.027	0.52	0.39	1.30	0.97
		0.44		0.030	0.56	0.44	1.27	1.00
		0.52		0.035	*	0.50	--	0.96
2.87	22.00	0.40	0.091	0.018	0.48	0.41	1.20	1.03
		0.44		0.020	0.60	0.44	1.33	0.98
		0.45		0.021	*	0.45	--	1.00
4.14	32.00	0.32	0.063	0.010	0.52	0.23	1.63	0.72
		0.38		0.019	0.53	0.39	1.40	0.79
Scale 0.5:1, h <sub>a</sub> = 0.14 to 0.30 ft , D = 1.0 ft , W <sub>r</sub> = 0.048 lb , γ <sub>r</sub> = 168.5 lb/cu ft								
0.67	2.28	0.13	0.438	0.057	0.15	0.08	1.15	0.62
		0.17		0.075	0.18	0.08	1.06	0.47
		0.20		0.088	0.19	0.09	0.95	0.45
		0.21		0.092	0.17	0.08	0.81	0.38
0.97	4.31	0.14	0.232	0.033	0.16	0.10	1.14	0.71
		0.15		0.035	0.19	0.11	1.27	0.73
		0.19		0.044	0.19	0.13	1.00	0.68
		0.22		0.051	0.22	0.15	1.00	0.68
1.45	7.43	0.14	0.135	0.019	0.18	0.12	1.29	0.86
		0.15		0.020	0.21	0.13	1.40	0.87
		0.19		0.026	0.26	0.25	1.37	1.32
		0.22		0.030	0.20	0.17	0.91	0.77
2.03	11.00	0.20	0.091	0.018	0.27	0.19	1.35	0.95
		0.25		0.023	0.35	0.23	1.40	0.92
		0.29		0.026	0.37	0.25	1.28	0.86
		0.39		0.035	0.36	0.17	0.92	0.44
2.93	16.40	0.19	0.061	0.012	0.30	0.13	1.58	0.68
		0.21		0.013	0.31	0.14	1.48	0.67
		0.23		0.014	0.33	0.15	1.44	0.65
		0.27		0.016	0.35	0.18	1.30	0.67
		0.35		0.021	0.38	0.20	1.09	0.57

\* Overtopping.



Table 6

## Results of Tests of Wave Runup and Rundown, Smooth Quarrrystone

<u>T</u> <u>sec</u>	<u>L</u> <u>ft</u>	<u>H</u> <u>ft</u>	<u>D/L</u>	<u>H/L</u>	<u>R<sub>u</sub></u> <u>ft</u>	<u>R<sub>d</sub></u> <u>ft</u>	<u><math>\frac{R_u}{H}</math></u>	<u><math>\frac{R_d}{H}</math></u>
Scale 1:1, $h_a = 0.45$ ft , $D = 2.0$ ft , $W_r = 0.30$ lb , $\gamma_r = 176.0$ lb/cu ft								
0.93	4.45	0.17	0.45	0.038	0.11	--	0.65	--
		0.30		0.067	0.19	--	0.63	--
		0.39		0.088	0.23	--	0.59	--
		0.49		0.111	0.29	--	0.59	--
1.31	8.00	0.23	0.25	0.029	0.16	--	0.70	--
		0.32		0.040	0.28	--	0.88	--
		0.36		0.045	0.25	--	0.69	--
		0.39		0.049	0.34	--	0.87	--
		0.57		0.071	0.43	--	0.75	--
		0.66		0.083	0.46	--	0.70	--
1.88	13.30	0.12	0.15	0.009	0.12	--	1.00	--
		0.33		0.025	0.30	--	0.91	--
		0.36		0.027	0.34	--	0.94	--
		0.55		0.041	0.55	--	1.00	--
		0.66		0.050	0.66	--	1.00	--
2.65	20.00	0.10	0.10	0.005	0.09	--	0.90	--
		0.29		0.015	0.27	--	0.93	--
		0.33		0.017	0.31	--	0.94	--
		0.35		0.018	0.34	--	0.97	--
		0.37		0.019	0.36	--	0.97	--
		0.50		0.025	0.50	--	1.00	--
Scale 0.5:1, $h_a = 0.12$ to $0.30$ ft, $D = 1.0$ ft,								
$W_r = 0.046$ lb , $\gamma_r = 174.0$ lb/cu ft								
0.67	2.28	0.10	0.438	0.044	0.10	0.05	1.00	0.50
		0.13		0.057	0.13	0.06	1.00	0.46
		0.17		0.075	0.16	0.07	0.94	0.41
		0.21		0.092	0.19	0.08	0.90	0.38
0.97	4.31	0.12	0.232	0.028	0.15	0.10	1.25	0.83
		0.14		0.033	0.18	0.11	1.29	0.79
		0.16		0.037	0.20	0.12	1.25	0.75
		0.21		0.049	0.21	0.13	1.00	0.62
1.45	7.43	0.12	0.135	0.016	0.17	0.13	1.42	1.08
		0.15		0.020	0.20	0.16	1.33	1.07
		0.19		0.026	0.21	0.19	1.10	1.00
2.03	11.00	0.17	0.091	0.016	0.24	0.20	1.41	1.18
		0.20		0.018	0.27	0.21	1.35	1.05
		0.22		0.020	0.29	0.22	1.32	1.00
		0.24		0.022	0.32	0.24	1.33	1.00
		0.29		0.026	0.35	0.28	1.21	0.97
		0.35		0.032	0.36	0.28	1.03	0.80
2.93	16.40	0.17	0.061	0.010	0.28	0.12	1.65	0.71
		0.19		0.012	0.30	0.13	1.58	0.68
		0.21		0.013	0.33	0.13	1.57	0.62
		0.25		0.015	0.36	0.14	1.44	0.56
		0.29		0.018	*	0.18	--	0.62

\* Overtopping.



Table 7

Results of Tests of Wave Runup and Rundown, Rough Quadripods

<u>T</u> <u>sec</u>	<u>L</u> <u>ft</u>	<u>H</u> <u>ft</u>	<u>D/L</u>	<u>H/L</u>	<u>R<sub>u</sub></u> <u>ft</u>	<u>R<sub>d</sub></u> <u>ft</u>	<u>R<sub>u</sub></u> <u>H</u>	<u>R<sub>d</sub></u> <u>H</u>
Scale 7.5:1, $h_a = 2.6$ ft, $D = 15.0$ ft, $W_r = 76$ lb, $\gamma_r = 150$ lb/cu ft								
2.61	34.50	1.55	0.434	0.045	1.00	0.80	0.65	0.52
		1.75		0.051	1.00	0.80	0.57	0.46
		1.95		0.057	1.20	1.10	0.62	0.56
		2.35		0.068	1.70	1.20	0.72	0.51
		2.95		0.086	1.80	1.50	0.61	0.51
3.75	64.70	2.20	0.230	0.034	1.90	1.60	0.86	0.73
		2.30		0.036	2.20	1.50	0.95	0.65
		2.80		0.043	3.60	--	1.29	--
		3.15		0.049	*	--	--	--
		4.00		0.062	*	2.38	--	0.60
7.87	165.00	2.95	0.091	0.018	3.80	--	1.29	--
		3.10		0.019	4.10	--	1.32	--
		3.20		0.019	*	--	--	--
		4.10		0.025	*	--	--	--
11.33	242.00	2.50	0.062	0.010	3.10	1.60	1.24	0.64
		2.75		0.011	2.80	--	1.38	--
		4.20		0.017	*	2.44	--	0.58

Scale 1:1,  $h_a = 0.50$  ft,  $D = 2.0$  ft,  $W_r = 0.19$  lb, $\gamma_r = 139.2$  lb/cu ft

1.31	8.00	0.32	0.250	0.040	0.30	--	0.94	--
		0.34		0.043	0.34	--	1.00	--
		0.36		0.045	0.36	--	1.00	--
2.04	14.70	0.26	0.136	0.018	0.33	0.24	1.27	0.92
		0.29		0.020	0.34	0.23	1.17	0.79
		0.31		0.021	0.41	0.27	1.32	0.87
		0.33		0.022	0.38	0.27	1.15	0.82
		0.47		0.032	*	0.44	--	0.94
2.65	20.00	0.33	0.100	0.017	0.37	--	1.12	--
		0.35		0.018	0.38	--	1.09	--
		0.37		0.019	0.39	--	1.05	--
		0.40		0.020	0.45	--	1.13	--
		0.45		0.022	*	0.47	--	--
4.14	32.30	0.20	0.062	0.009	0.46	0.26	1.53	0.87
		0.32		0.010	0.49	0.22	1.53	0.69
		0.35		0.011	0.53	0.30	1.52	0.86

\* Overtopping.



Table 8

## Results of Tests of Wave Runup and Rundown, Smooth Quadripods

T sec	L ft	H ft	D/L	H/L	R <sub>u</sub> ft	R <sub>d</sub> ft	$\frac{R_u}{H}$	$\frac{R_d}{H}$
Scale 1:1, $h_a = 0.51$ ft , D = 2.0 ft , $W_r = 0.18$ lb , $\gamma_r = 139.8$ lb/cu ft								
0.95	4.58	0.24	0.438	0.052	0.17	0.13	0.71	0.54
		0.28		0.061	0.21	0.15	0.75	0.54
		0.32		0.070	0.26	0.12	0.81	0.38
1.37	8.62	0.27	0.232	0.031	0.32	0.18	1.19	0.67
		0.30		0.035	0.30	0.20	1.00	0.67
		0.32		0.037	0.31	0.22	0.97	0.69
		0.43		0.050	*	0.37	--	0.86
2.04	14.70	0.26	0.135	0.018	0.33	0.28	1.27	1.08
		0.29		0.020	0.35	0.28	1.21	0.97
		0.32		0.022	0.38	0.29	1.19	0.91
		0.35		0.024	0.43	0.28	1.23	0.80
		0.46		0.031	*	0.42	--	0.91
2.87	22.00	0.28	0.091	0.013	0.37	0.22	1.32	0.79
		0.30		0.014	0.39	0.30	1.30	1.00
		0.33		0.015	0.42	0.35	1.27	1.06
		0.36		0.016	*	0.40	--	1.11
		0.45		0.020	*	0.43	--	0.96
4.14	32.30	0.28	0.062	0.009	0.44	0.27	1.67	0.97
		0.32		0.010	0.49	0.29	1.53	0.91
		0.33		0.010	0.46	0.28	1.40	0.85
		0.35		0.011	0.51	0.29	1.46	0.83

Scale 0.5:1,  $h_a = 0.26$  ft , D = 1.0 ft ,  $W_r = 0.03$  lb ,  $\gamma_r = 140.0$  lb/cu ft

0.67	2.28	0.07	0.439	0.031	0.07	0.05	1.00	0.72
		0.10		0.044	0.11	0.05	1.10	0.50
		0.13		0.057	0.11	0.06	0.85	0.46
0.97	4.31	0.08	0.232	0.019	0.04	0.05	0.50	0.63
		0.09		0.021	0.08	0.06	0.89	0.67
		0.12		0.028	0.12	0.07	1.00	0.58
		0.14		0.032	*	0.11	--	0.79
1.45	7.43	0.08	0.135	0.011	0.09	0.09	1.10	1.10
		0.09		0.012	0.08	0.11	0.89	1.20
		0.12		0.016	0.13	0.13	1.18	1.18
		0.15		0.020	0.16	0.13	1.07	0.87
2.03	11.00	0.08	0.091	0.007	0.11	0.10	1.38	1.25
		0.09		0.008	0.12	0.09	1.34	1.00
		0.10		0.009	0.11	0.12	1.10	1.20
		0.16		0.015	*	0.19	--	1.19
2.97	16.40	0.09	0.061	0.005	0.13	0.09	1.45	1.00
		0.11		0.007	0.14	0.08	1.27	0.73
		0.12		0.008	0.14	0.10	1.17	0.84
		0.16		0.010	*	0.12	--	0.75

\* Overtopping.



Table 9

Relation Between  $H_{D=0}$  and  $H_{D=0}/\lambda$

Primary Cover-Layer Units	D/L	$H_{D=0}$ , ft			$\frac{H_{D=0}}{\lambda}$		
		$\lambda = 7.5$	$\lambda = 1.0$	$\lambda = 0.5$	$\lambda = 7.5$	$\lambda = 1.0$	$\lambda = 0.5$
Rough quarrrystone	0.434	2.95	0.43	0.15	0.39	0.43	0.30
	0.230	3.25	0.41	0.14	0.43	0.41	0.28
	0.135	--	0.44	0.14	--	0.44	0.28
	0.091	3.30	0.41	0.24	0.44	0.41	0.48
	0.062	4.20	0.35	0.22	0.56	0.35	0.44
Smooth quarrrystone	0.434	--	0.36	0.12	--	0.36	0.24
	0.230	--	0.36	0.13	--	0.36	0.26
	0.135	--	0.34	0.12	--	0.34	0.24
	0.091	--	0.36	0.22	--	0.36	0.44
	0.062	--	--	0.18	--	--	0.36
Rough quadripods	0.434	1.70	0.32	--	0.23	0.32	--
	0.230	2.30	0.31	--	0.31	0.31	--
	0.135	--	0.29	--	--	0.29	--
	0.091	2.90	0.33	--	0.39	0.33	--
	0.062	2.60	0.31	--	0.35	0.31	--
Smooth quadripods	0.434	--	0.26	0.08	--	0.26	0.16
	0.230	--	0.27	0.09	--	0.27	0.18
	0.135	--	0.29	0.08	--	0.29	0.16
	0.091	--	0.28	0.10	--	0.28	0.20
	0.062	--	0.30	0.10	--	0.30	0.20



Table 10

Relation Between Reynolds Number and the Relative No-Damage Wave Height

Scale	Primary Cover-Layer Units	$\delta^*$ , ft	T sec	$H_{D=0}$ ft	$H_{D=0}/\lambda$	$V_R^{**}$ ft/sec	$N_R$
7.5:1	Rough quarrrystone	0.98	2.61	2.95	0.39	7.50	$6.07 \times 10^5$
			3.75	3.25	0.43	8.49	$6.98 \times 10^5$
			5.60	--	--	--	--
			7.87	3.30	0.44	9.04	$7.29 \times 10^5$
			11.33	4.20	0.56	9.48	$7.70 \times 10^5$
1:1	Rough quarrrystone	0.13	0.95	0.43	0.43	2.61	$2.88 \times 10^4$
			1.37	0.41	0.41	2.70	$2.90 \times 10^4$
			2.04	0.44	0.44	2.95	$3.22 \times 10^4$
			2.87	0.41	0.41	2.90	$3.12 \times 10^4$
			4.14	0.35	0.35	3.00	$3.22 \times 10^4$
0.5:1	Rough quarrrystone	0.066	0.67	0.15	0.30	1.58	$8.70 \times 10^3$
			0.97	0.14	0.28	1.60	$8.75 \times 10^3$
			1.45	0.14	0.28	1.70	$9.26 \times 10^3$
			2.03	0.24	0.48	2.81	$1.53 \times 10^4$
			2.93	0.22	0.44	2.59	$1.42 \times 10^4$
1:1	Smooth quarrrystone	0.12	0.93	0.36	0.36	2.00	$1.98 \times 10^4$
			1.31	0.36	0.36	2.04	$1.99 \times 10^4$
			1.88	0.34	0.34	2.31	$2.31 \times 10^4$
			2.65	0.36	0.36	2.40	$2.40 \times 10^4$
0.5:1	Smooth quarrrystone	0.065	0.67	0.12	0.24	1.40	$7.50 \times 10^3$
			0.97	0.13	0.26	1.60	$8.60 \times 10^3$
			1.45	0.12	0.24	1.60	$8.60 \times 10^3$
			2.03	0.22	0.44	2.21	$1.18 \times 10^4$
			2.93	0.18	0.36	2.29	$1.24 \times 10^4$
7.5:1	Rough quadripods	0.84	2.61	1.70	0.23	4.32	$2.98 \times 10^5$
			3.75	2.30	0.35	7.50	$5.20 \times 10^5$
			5.60	--	--	--	--
			7.87	2.90	0.39	9.72	$6.73 \times 10^5$
			11.33	2.60	0.34	9.10	$6.32 \times 10^5$
1:1	Rough quadripods	0.11	0.99	0.32	0.32	--	--
			1.31	0.31	0.31	2.22	$2.00 \times 10^4$
			2.04	0.29	0.29	2.29	$2.09 \times 10^4$
			2.65	0.33	0.33	2.50	$2.27 \times 10^4$
			4.14	0.31	0.31	2.80	$2.54 \times 10^4$
1:1	Smooth quadripods	0.11	0.95	0.26	0.26	1.81	$1.64 \times 10^4$
			1.37	0.27	0.27	2.30	$2.09 \times 10^4$
			2.04	0.29	0.29	2.41	$2.18 \times 10^4$
			2.87	0.28	0.28	2.40	$2.18 \times 10^4$
			4.14	0.30	0.30	2.80	$2.54 \times 10^4$
0.5:1	Smooth quadripods	0.056	0.67	0.08	0.16	1.10	$5.12 \times 10^3$
			0.97	0.09	0.18	1.20	$5.54 \times 10^3$
			1.45	0.08	0.16	1.20	$5.54 \times 10^3$
			2.03	0.10	0.20	1.30	$6.03 \times 10^3$
			2.93	0.10	0.20	1.80	$8.35 \times 10^3$

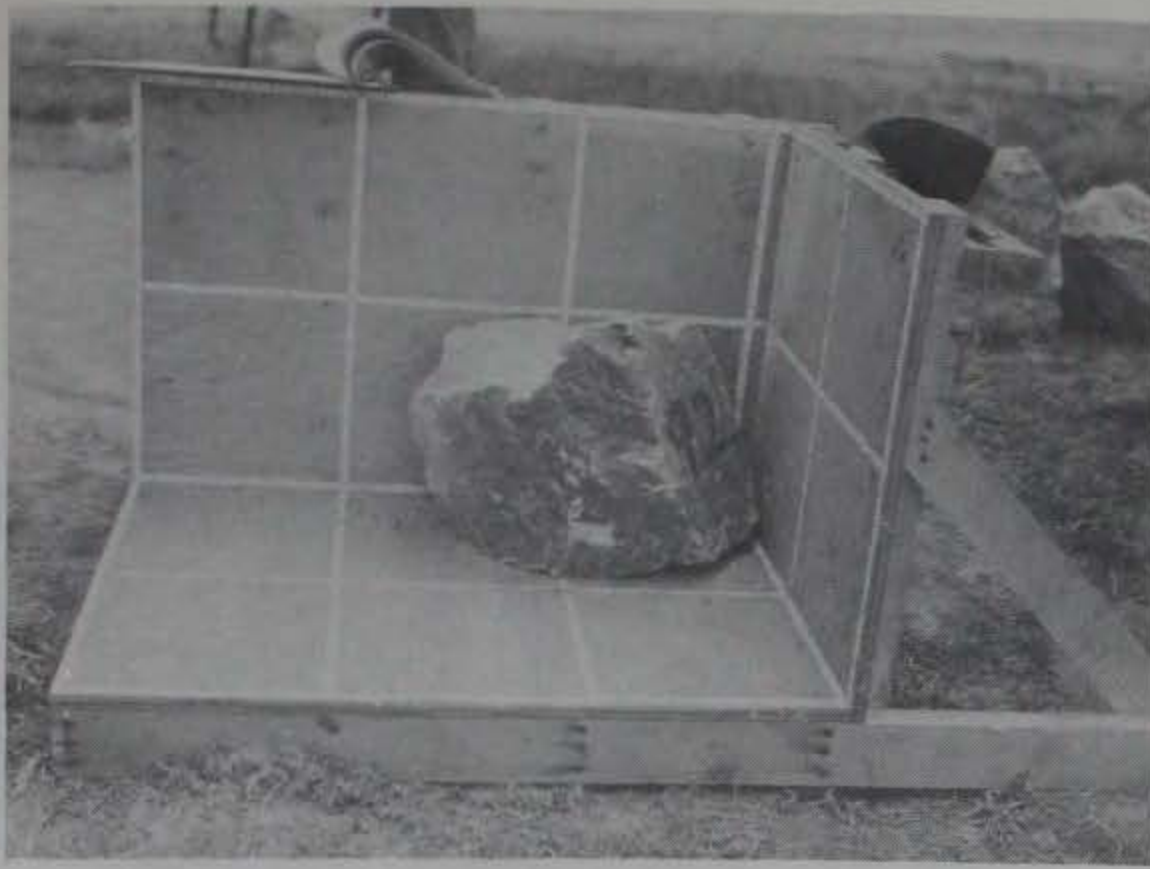
\* Characteristic diameter of armor unit defined as:

a. Average of x, y, and z for quarrrystone units.

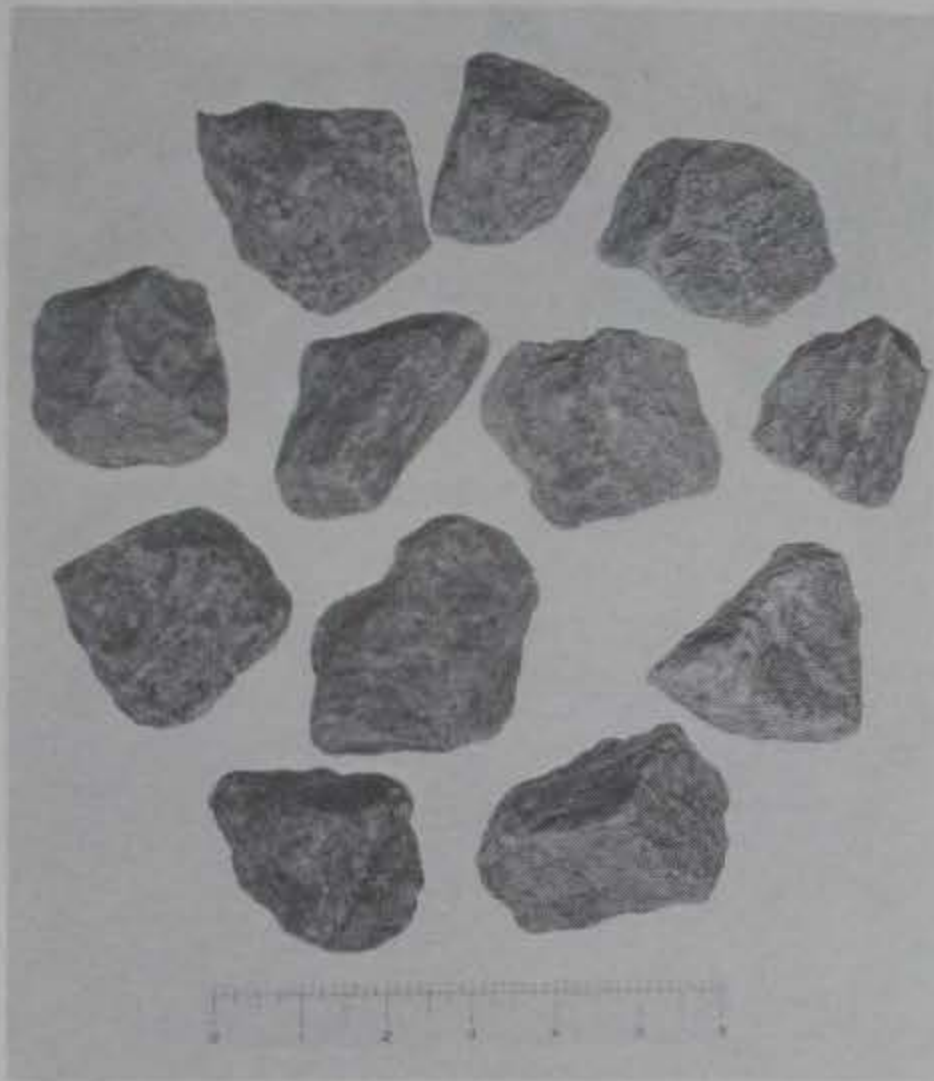
b. Dimension G for quadripod units (see photograph 2).

\*\* From table A1 of Appendix A.

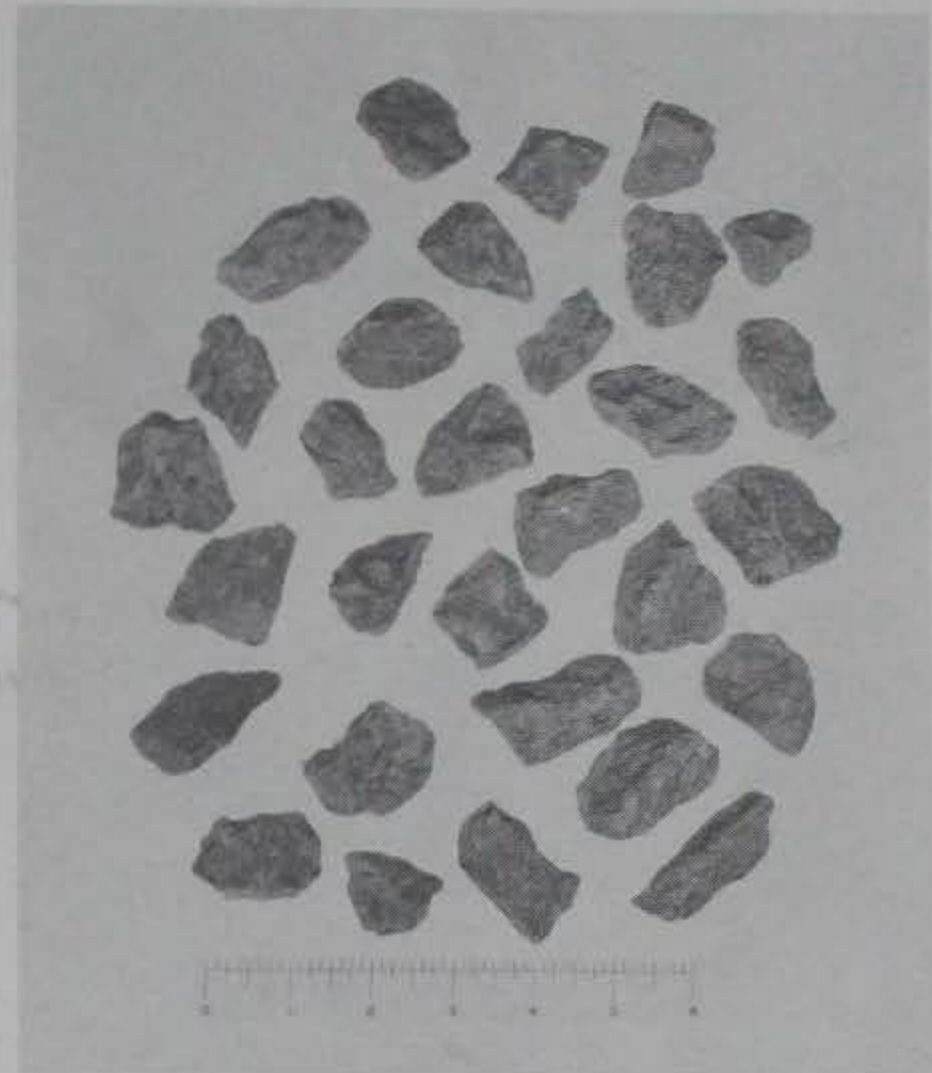




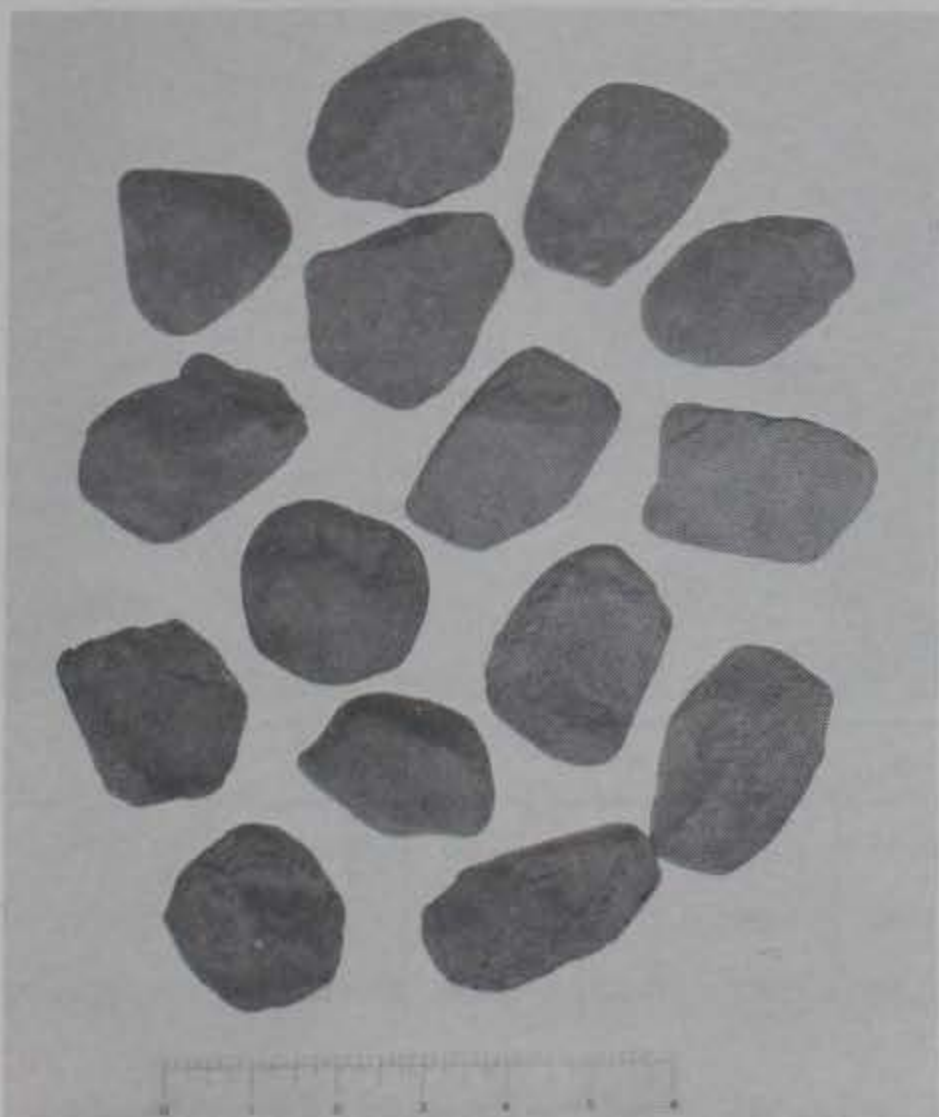
a. Rough quarrystone, 7.5:1 scale



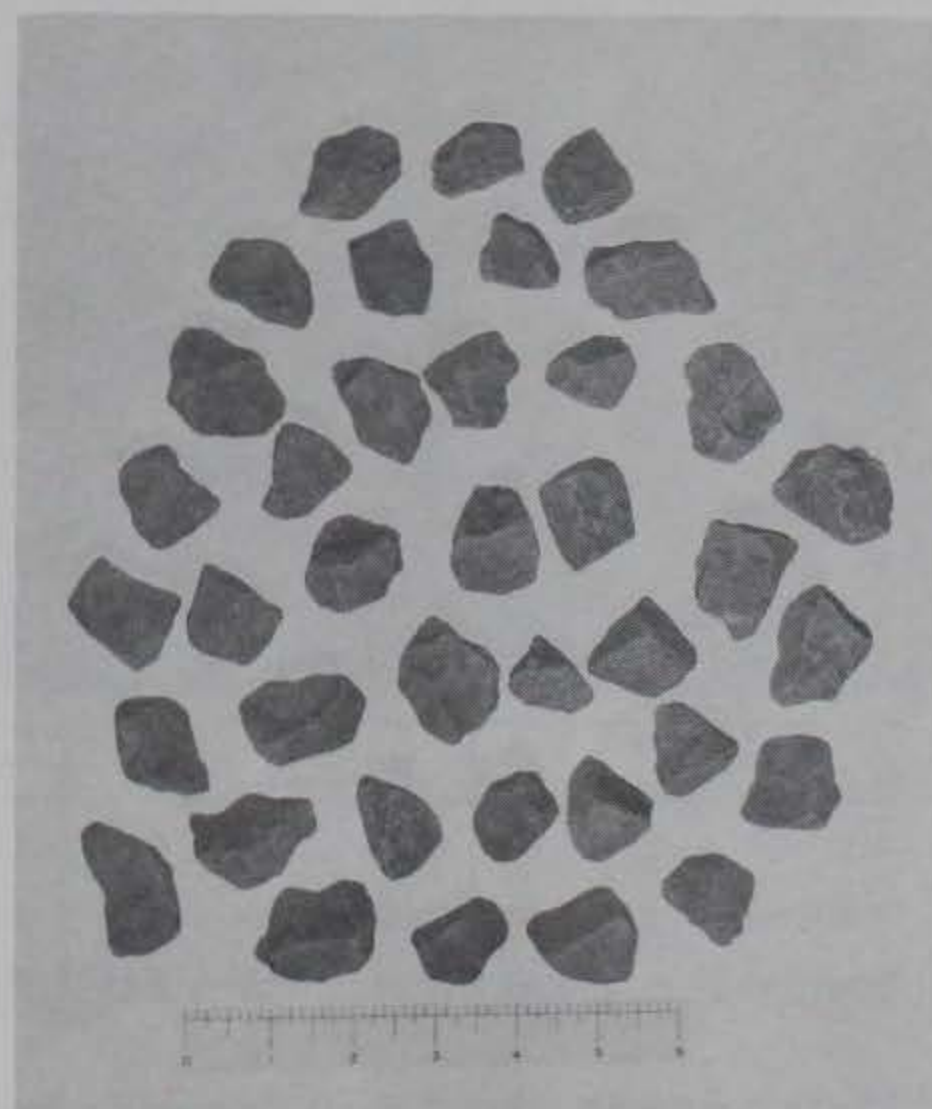
b. Rough quarrystone, 1:1 scale



c. Rough quarrystone, 0.5:1 scale



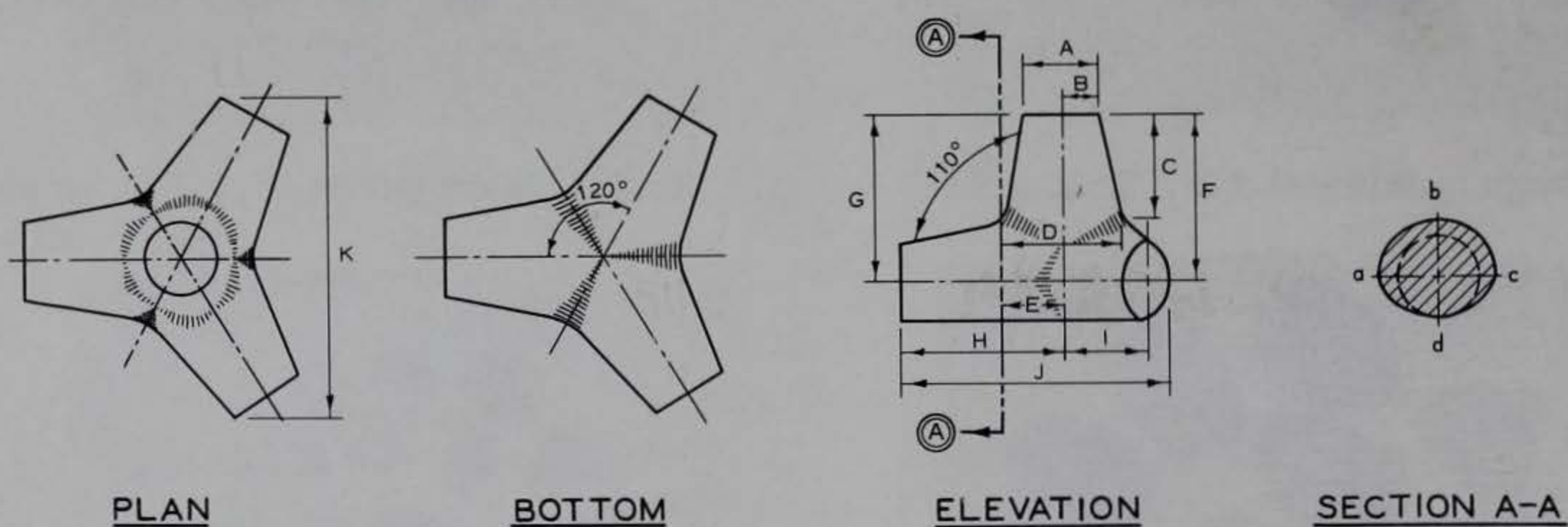
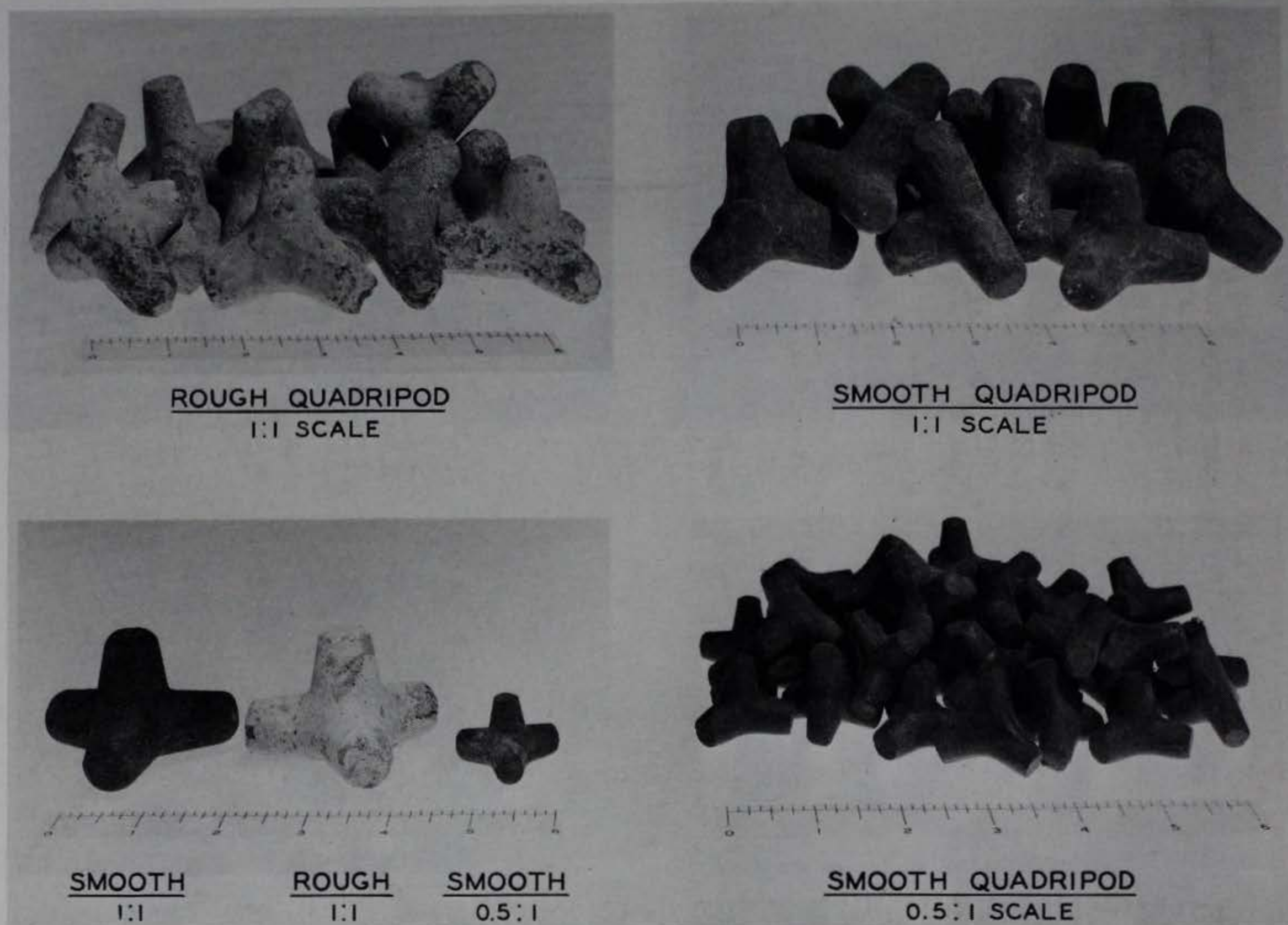
d. Smooth quarrystone, 1:1 scale



e. Smooth quarrystone, 0.5:1 scale

Photograph 1. Rough and smooth quarrystone used in study





DIAMETER OF SEMICIRCLE  $abc$  = DIMENSION D  
 MAJOR AXIS OF SEMIELLIPSE  $adc$  = DIMENSION D  
 MINOR AXIS OF SEMIELLIPSE  $adc$  = DIMENSION A

DIMENSIONS OF QUADRIPOD MODELS, INCHES

SYMBOL SCALE	A	B	C	D	E	F	G	H	I	J	K
7.5:1.0-SCALE	4.42	2.25	6.22	6.67	3.37	9.37	10.01	9.37	4.72	16.20	18.60
1.0:1.0-SCALE	0.59	0.30	0.83	0.89	0.45	1.25	1.32	1.25	0.63	2.16	2.48
0.5:1.0-SCALE	0.30	0.15	0.42	0.45	0.23	0.63	0.66	0.63	0.32	1.08	1.28

Photograph 2. Rough and smooth quadripod units used in study

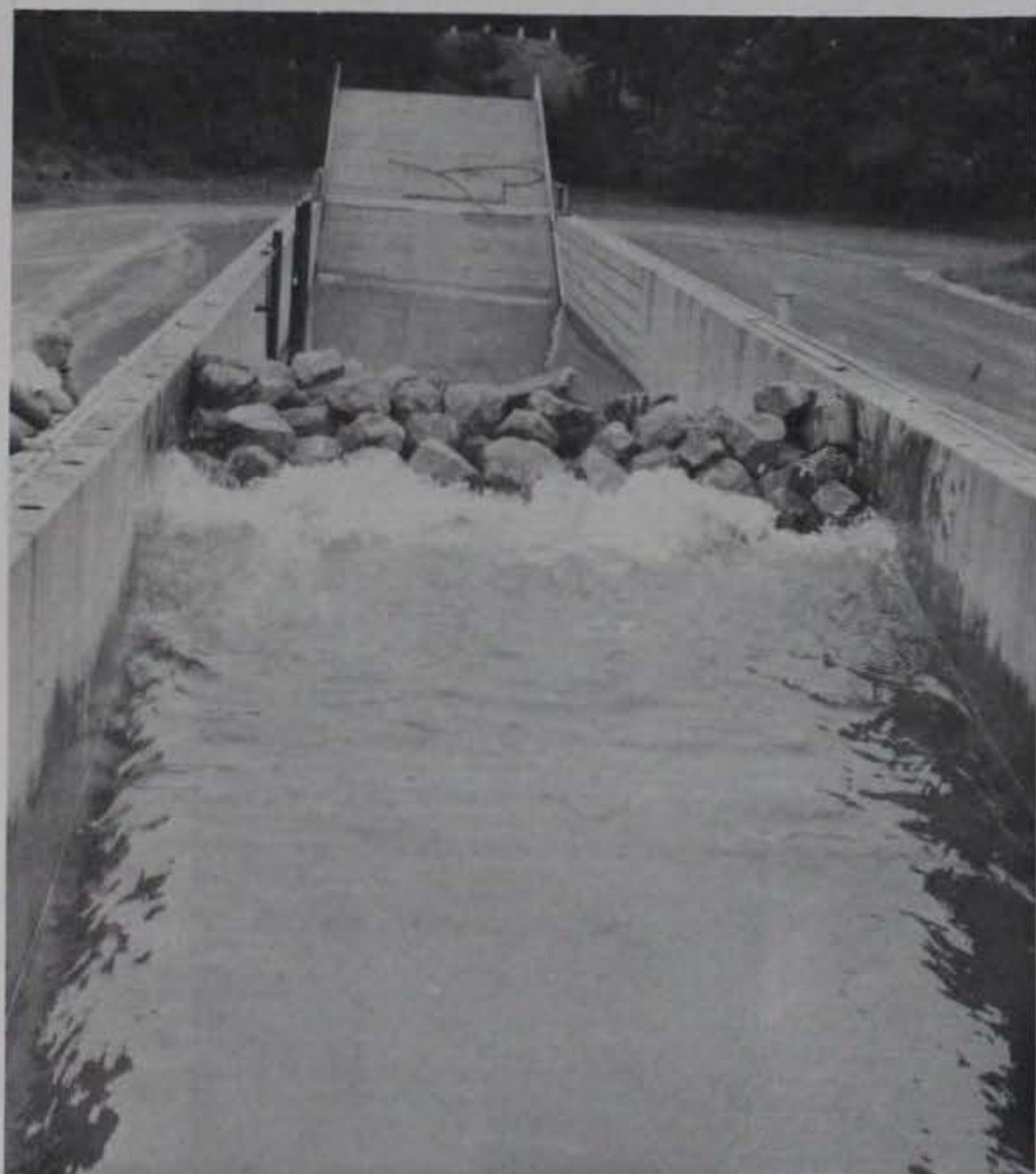




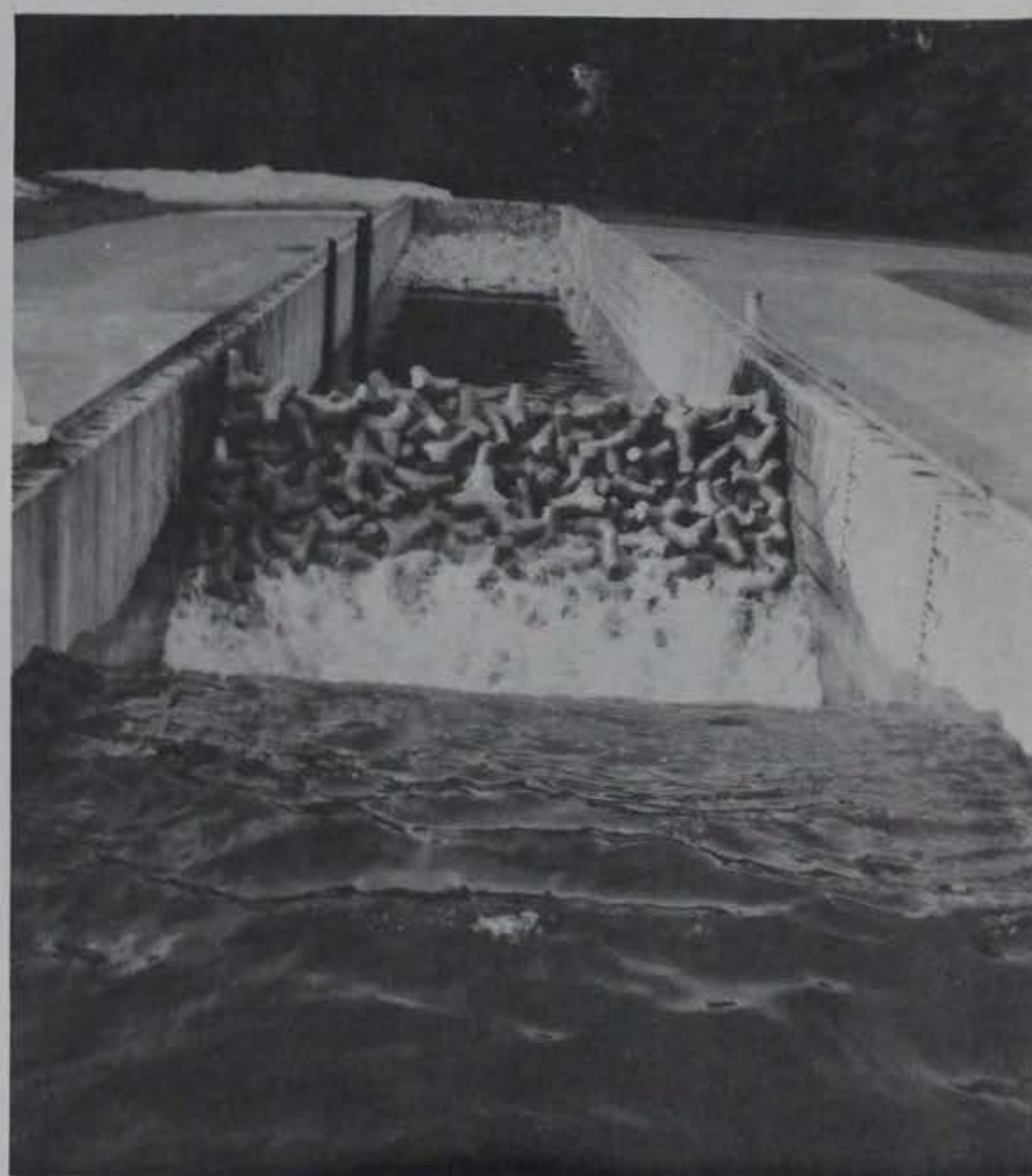
a. Construction of quarry-stone cover layer



b. Construction of quadripod cover layer



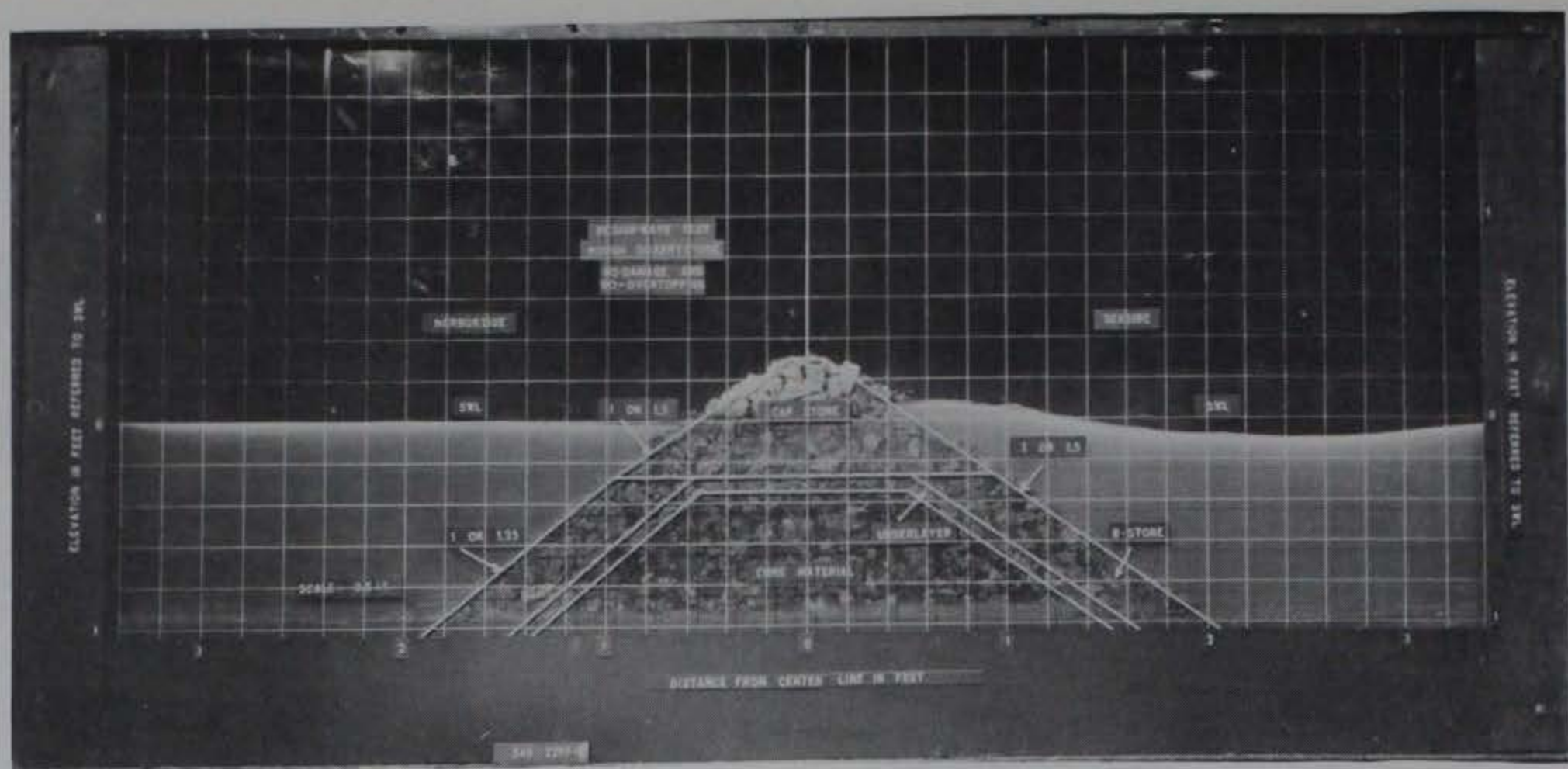
c. Testing of quarrystone cover layer



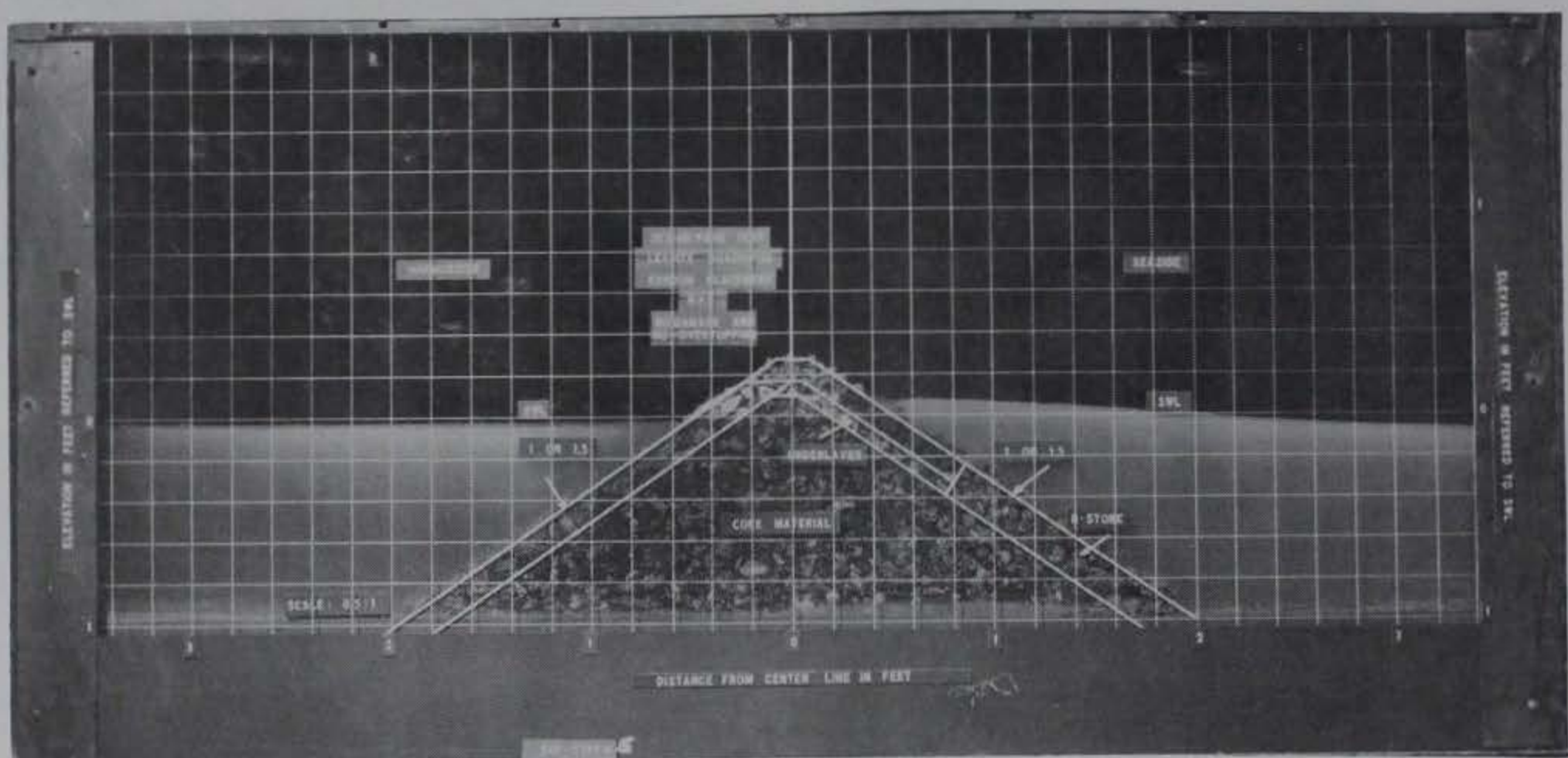
d. Testing of quadripod cover layer

Photograph 3. Construction and testing of 7.5:1-scale models

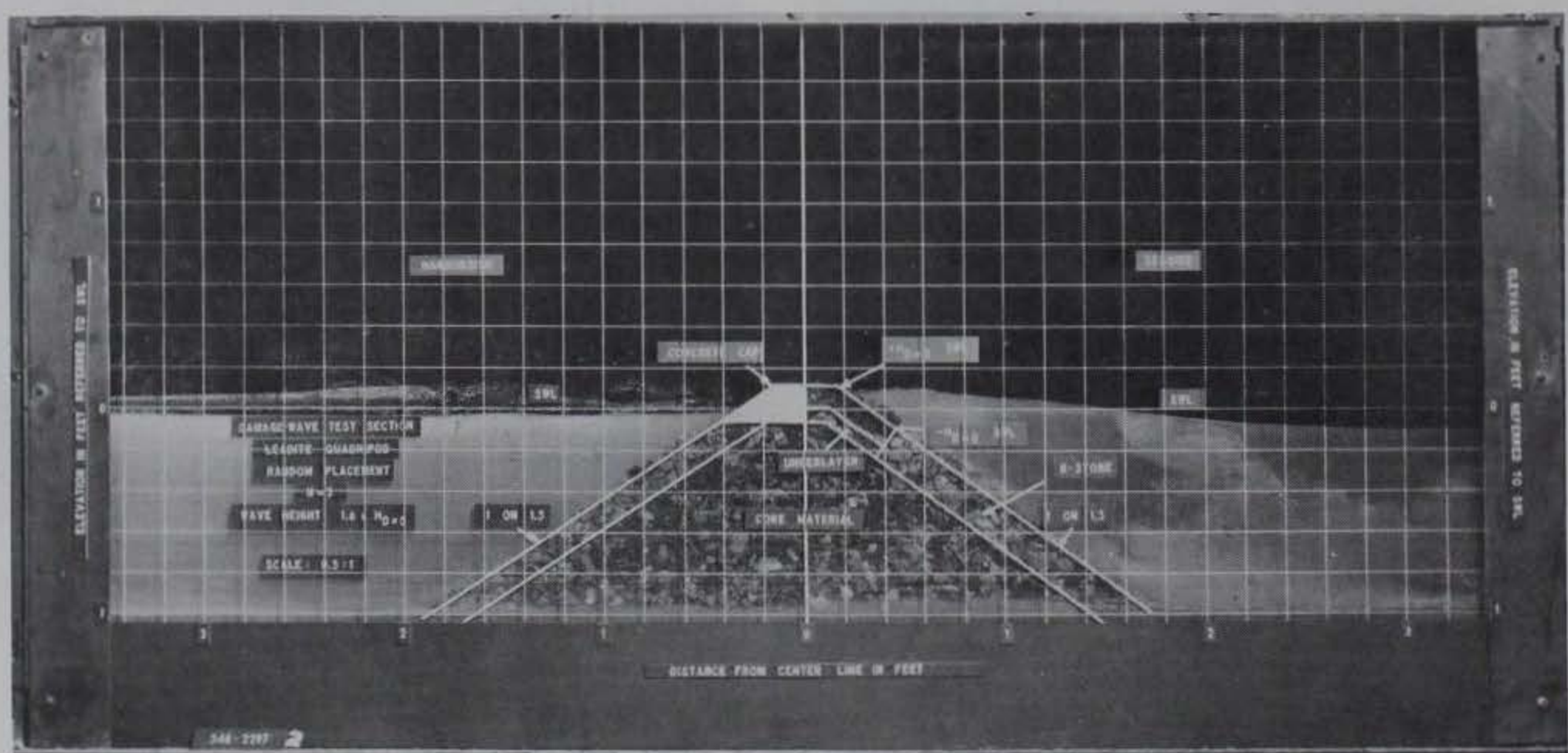




a. No-damage wave test, rough quarrystone cover layer



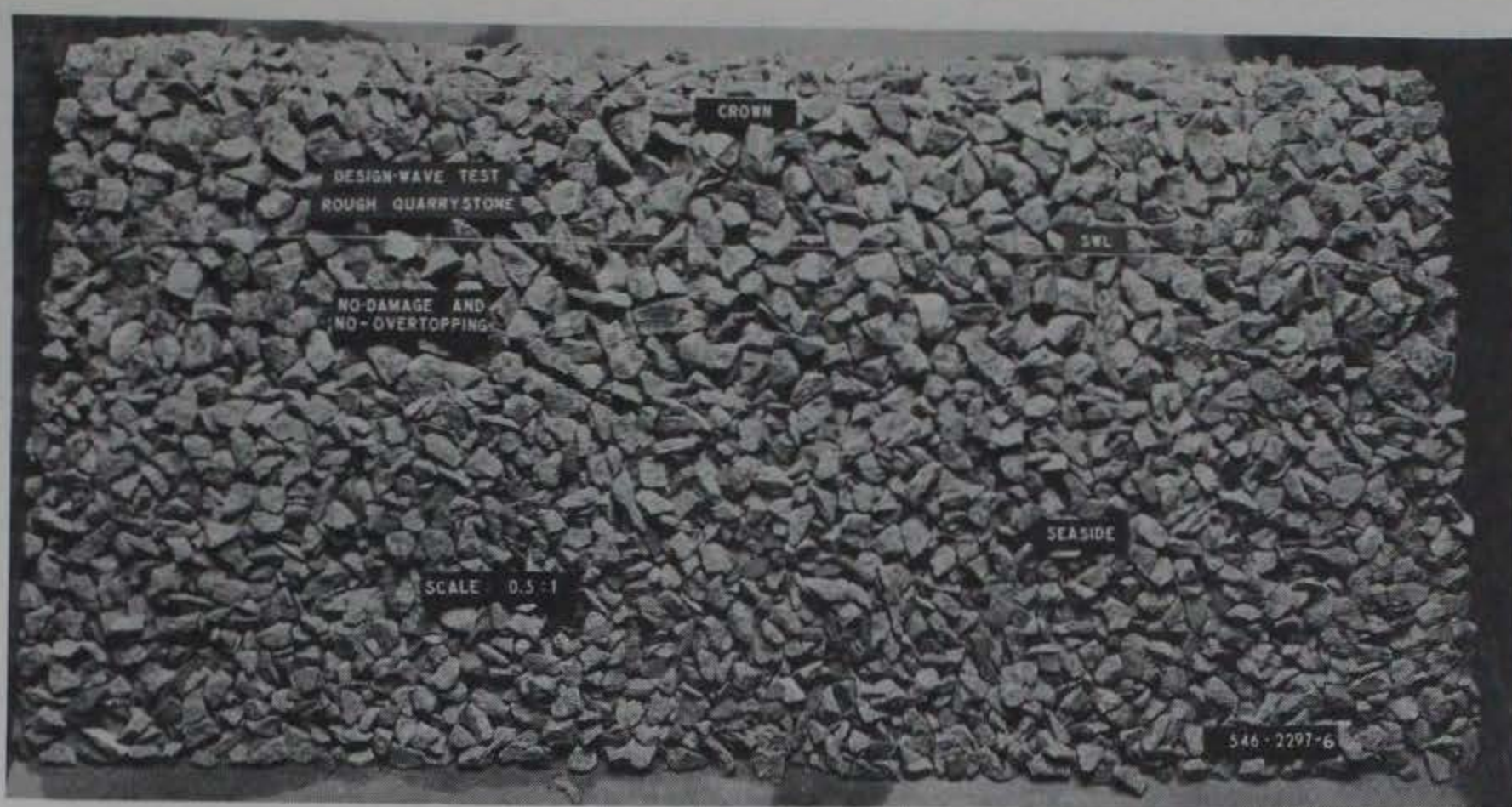
b. No-damage wave test, smooth quadripod cover layer



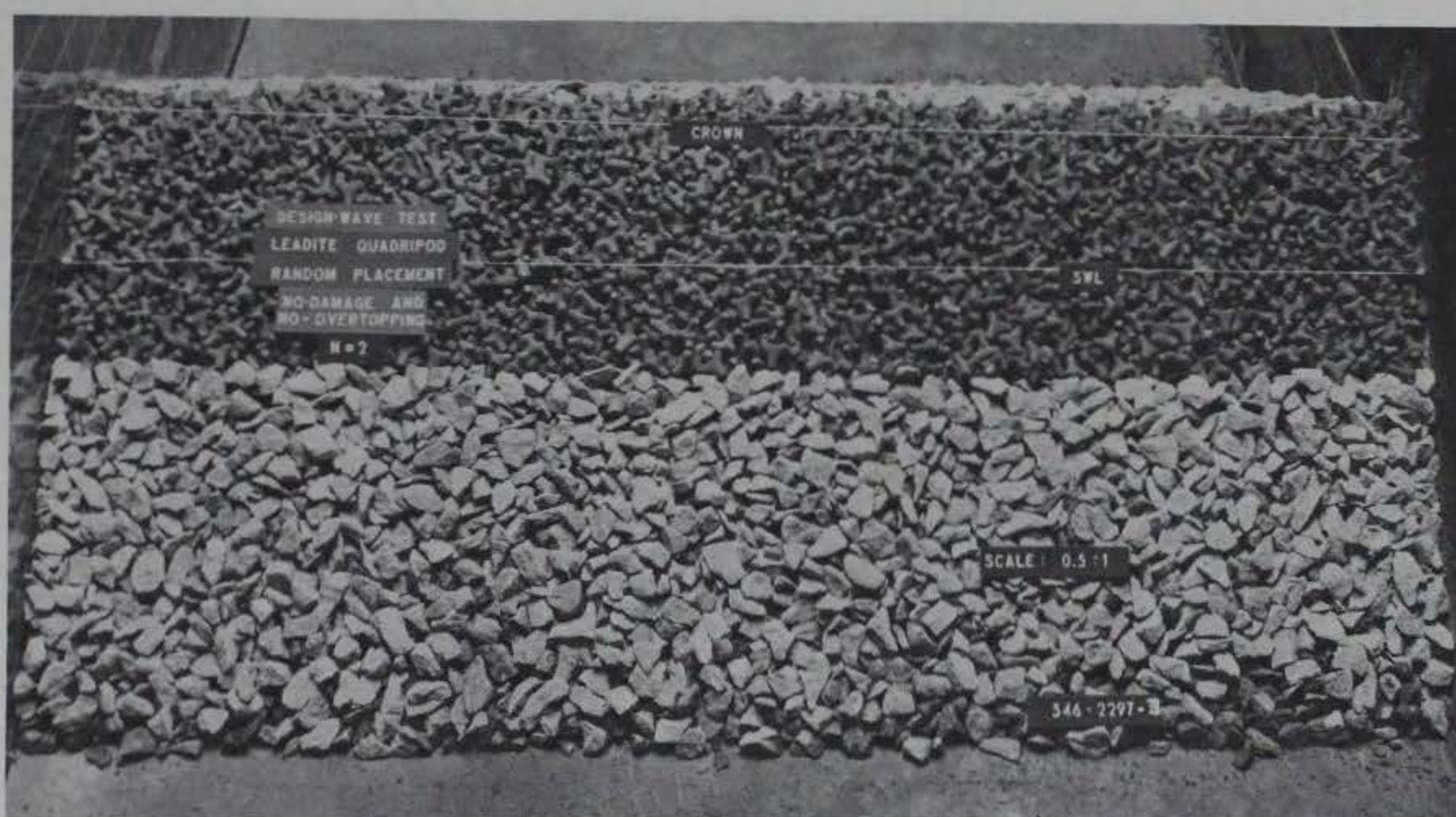
c. Damage test, smooth quadripod cover layer

Photograph 4. Cross sections of the 0.5:1-scale test sections

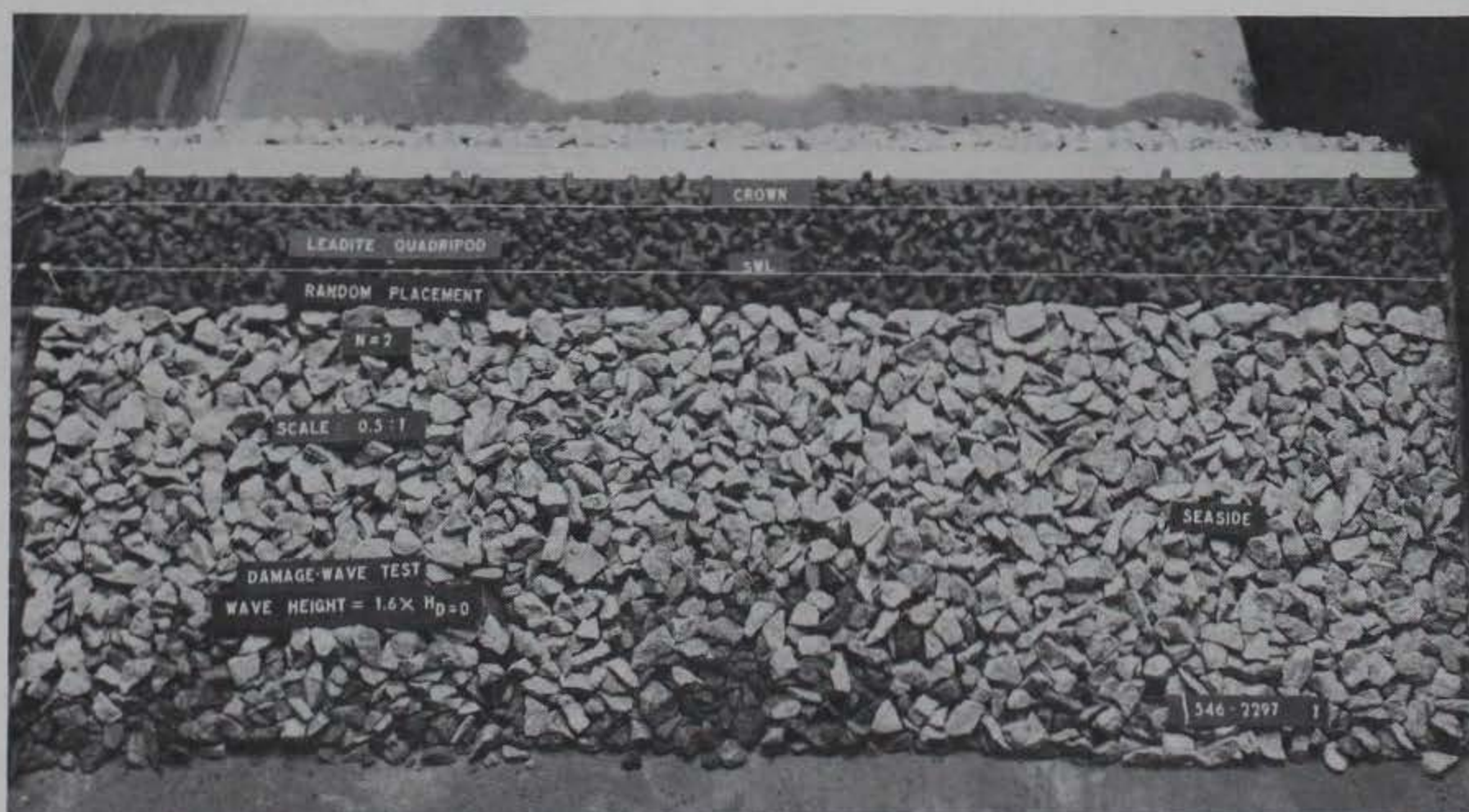




a. No-damage wave test, rough quarrystone cover layer



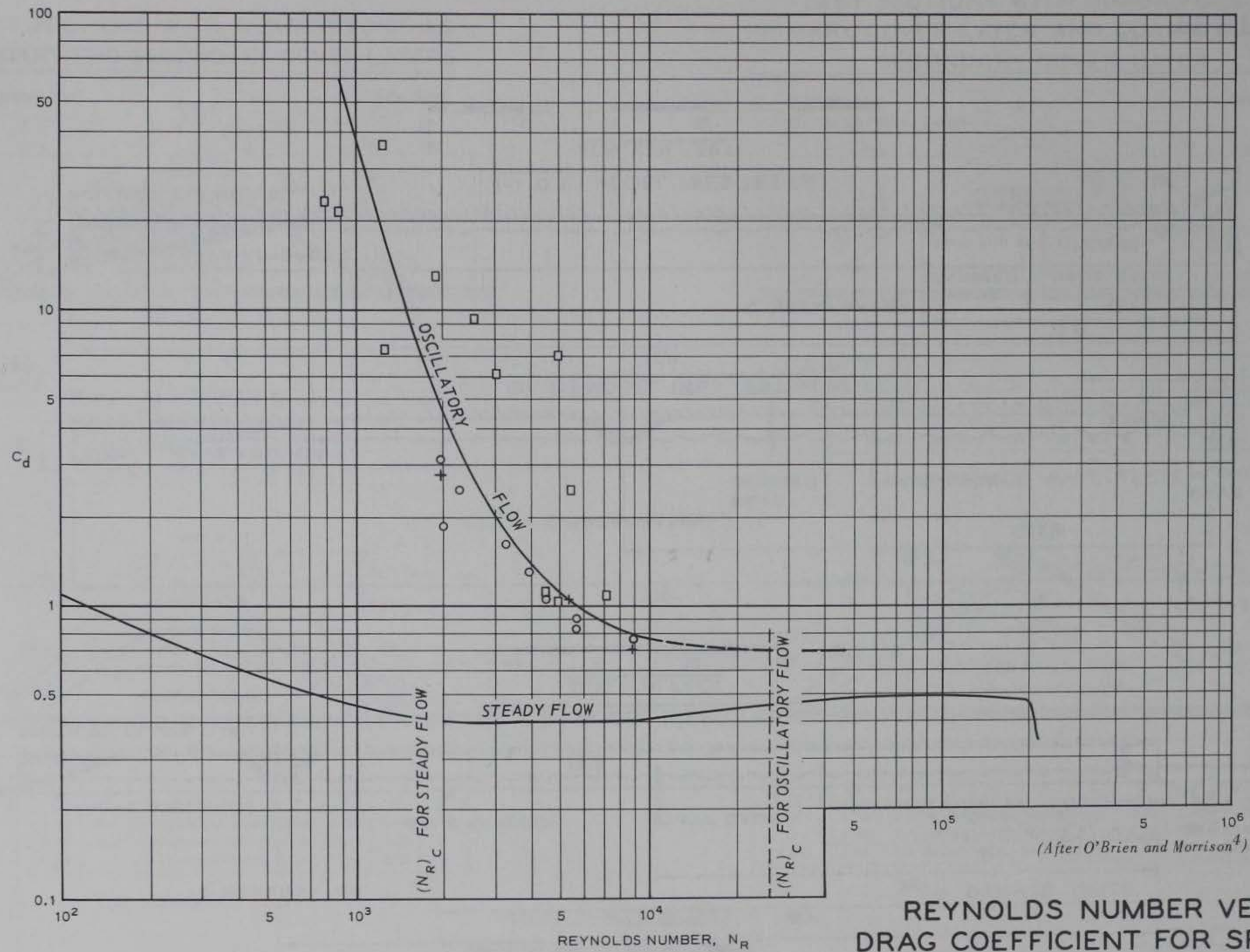
b. No-damage wave test, smooth quadripod cover layer



c. Damage test, smooth quadripod cover layer

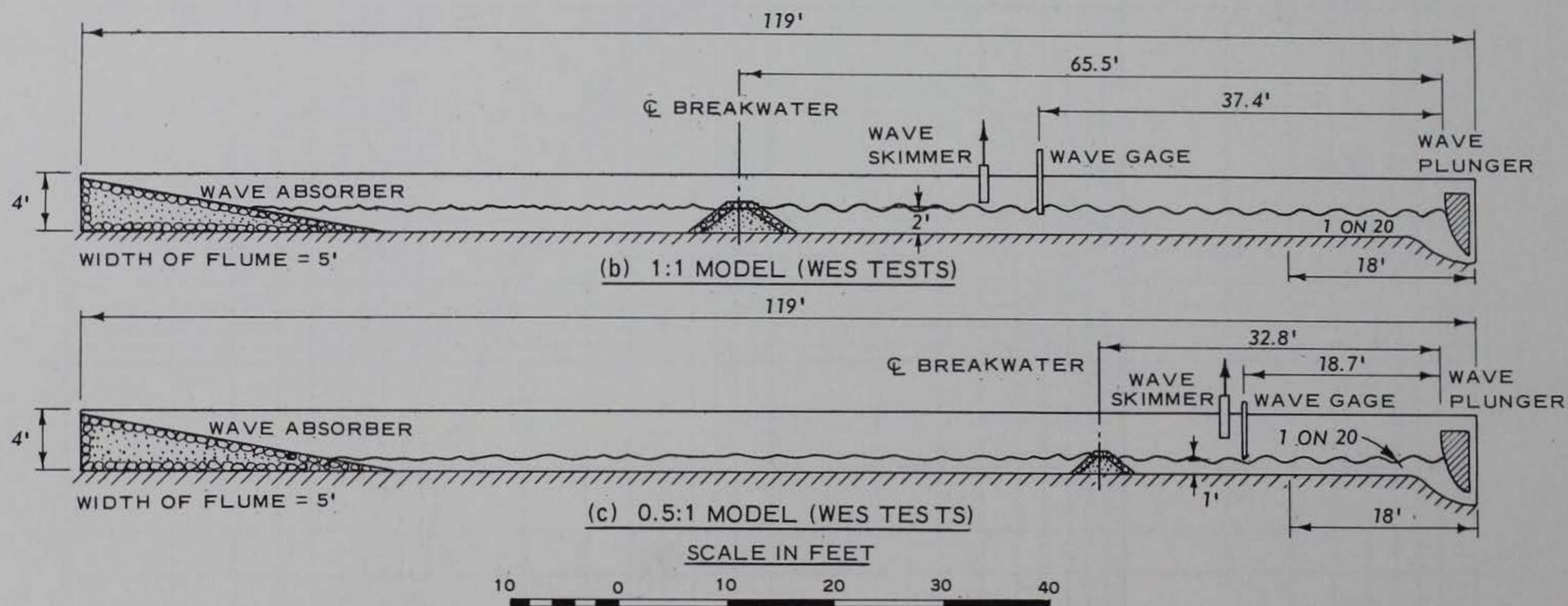
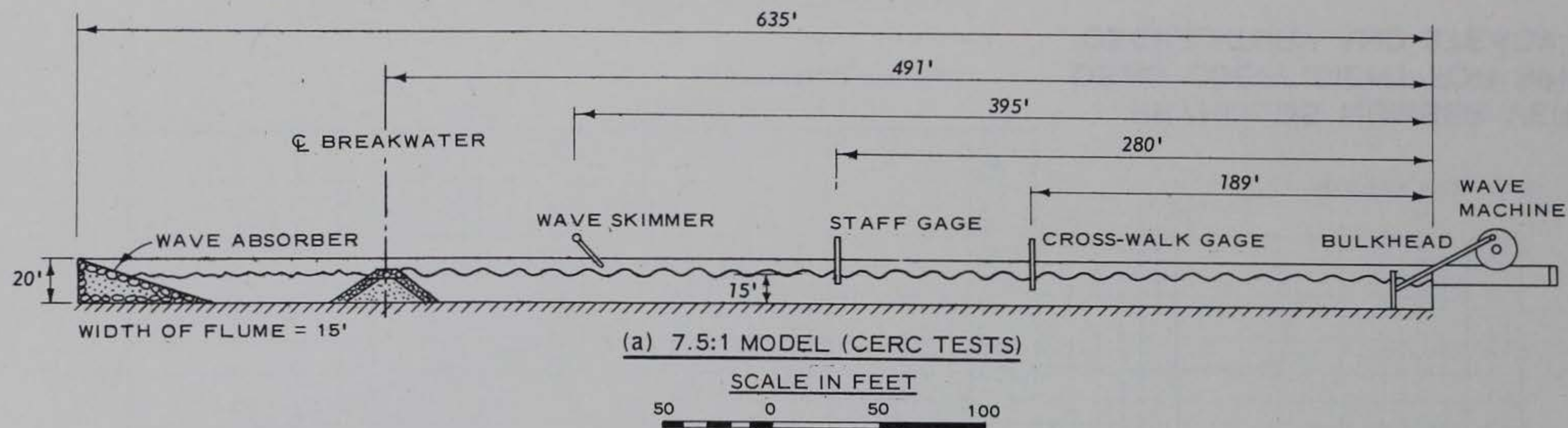
Photograph 5. End views of the 0.5:1-scale test sections





REYNOLDS NUMBER VERSUS  
DRAG COEFFICIENT FOR SPHERE IN  
OSCILLATORY AND STEADY FLOWS

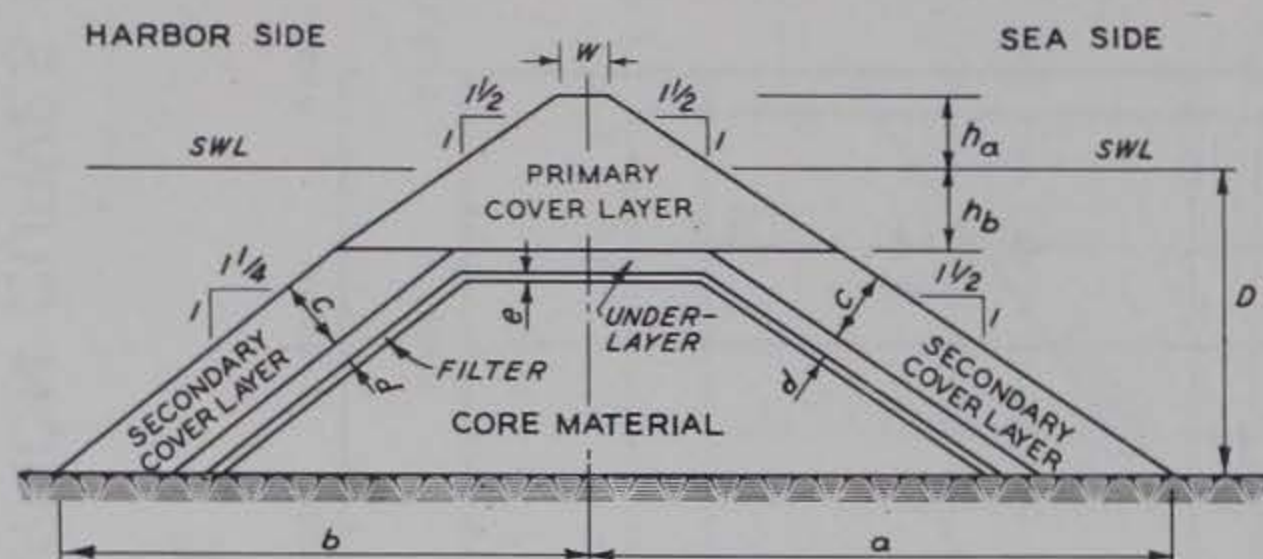




TEST SETUP



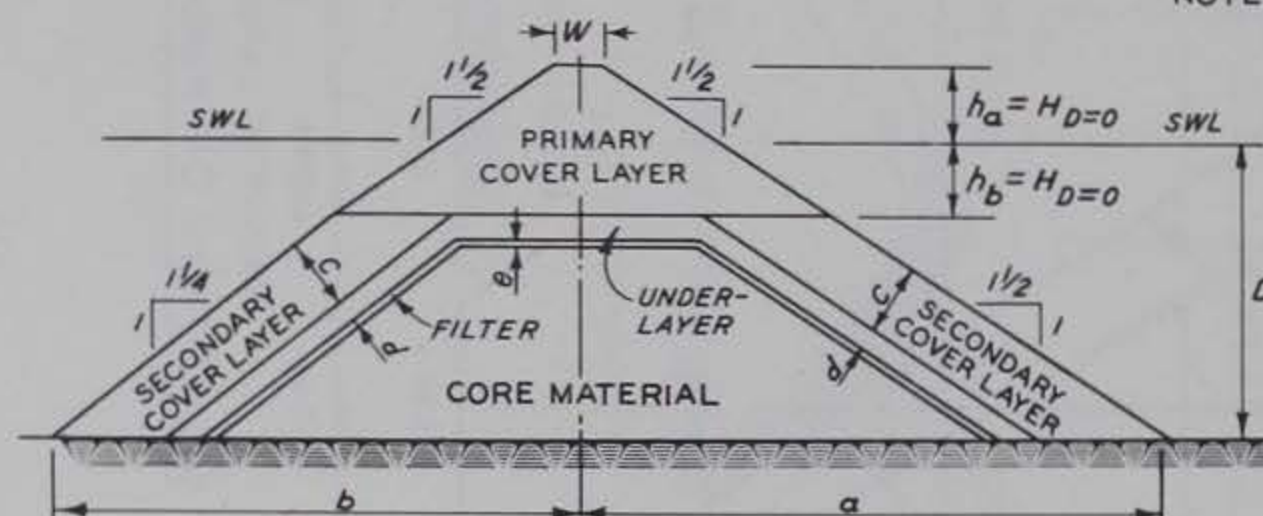
## TEST SECTIONS WITH QUARRYSTONE AS PRIMARY AND SECONDARY COVER LAYERS



MODEL SCALE	W	D	$h_a$	$h_b$	a	b	c	d	e
7.5:1	2.70	15.0	4.50	4.20	30.55	27.85	3.50	1.00	0.50
1:1	0.36	2.0	0.60	0.56	4.07	3.70	0.47	0.20	0
0.5:1	0.18	1.0	0.30	0.28	2.04	1.85	0.24	0.10	0

a. NO-DAMAGE WAVE TESTS

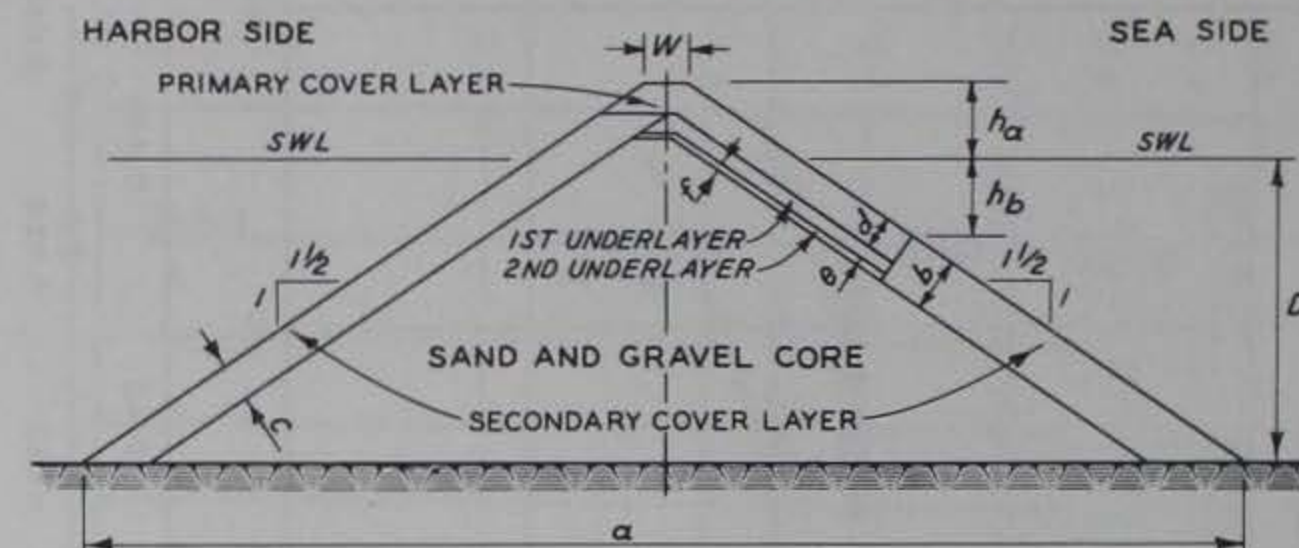
NOTE: ALL DIMENSIONS ARE IN FEET



MODEL SCALE	W	D	$h_a$	$h_b$	a	b	c	d	e
7.5:1	2.70	15.0	VARIES	VARIES	VARIES	VARIES	3.50	1.00	0.50
1:1	0.36	2.0	VARIES	VARIES	VARIES	VARIES	0.47	0.20	0
0.5:1	0.18	1.0	VARIES	VARIES	VARIES	VARIES	0.24	0.10	0

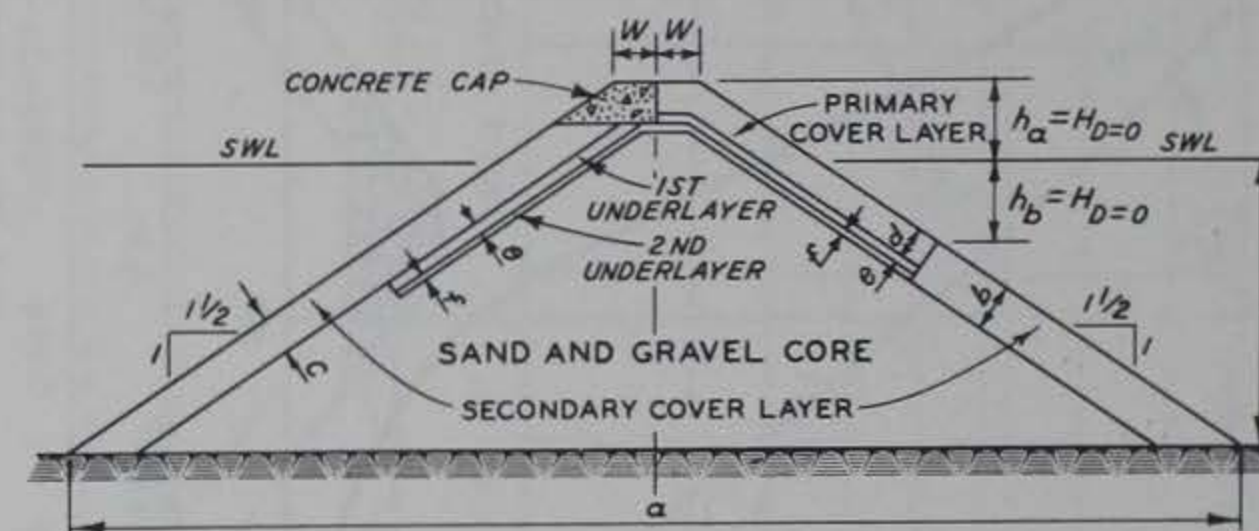
b. DAMAGE TESTS

## TEST SECTIONS WITH QUADRIPODS AS PRIMARY COVER LAYER AND QUARRYSTONE AS SECONDARY COVER LAYER



MODEL SCALE	W	D	$h_a$	$h_b$	a	b	c	d	e	f
7.5:1	2.30	15.0	3.80	3.80	58.70	2.60	1.90	1.60	0.70	0.30
1:1	0.31	2.0	0.51	0.51	7.84	0.35	0.25	0.21	0.13	0
0.5:1	0.16	1.0	0.26	0.26	3.92	0.18	0.13	0.11	0.06	0

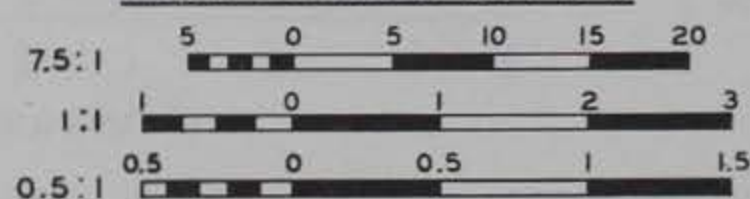
c. NO-DAMAGE WAVE TESTS



MODEL SCALE	W	D	$h_a$	$h_b$	a	b	c	d	e	f
7.5:1	2.30	15.0	VARIES	VARIES	VARIES	2.60	1.90	1.60	0.70	0.30
1:1	0.36	2.0	VARIES	VARIES	VARIES	0.35	0.25	0.21	0.13	0
0.5:1	0.18	1.0	VARIES	VARIES	VARIES	0.18	0.13	0.11	0.06	0

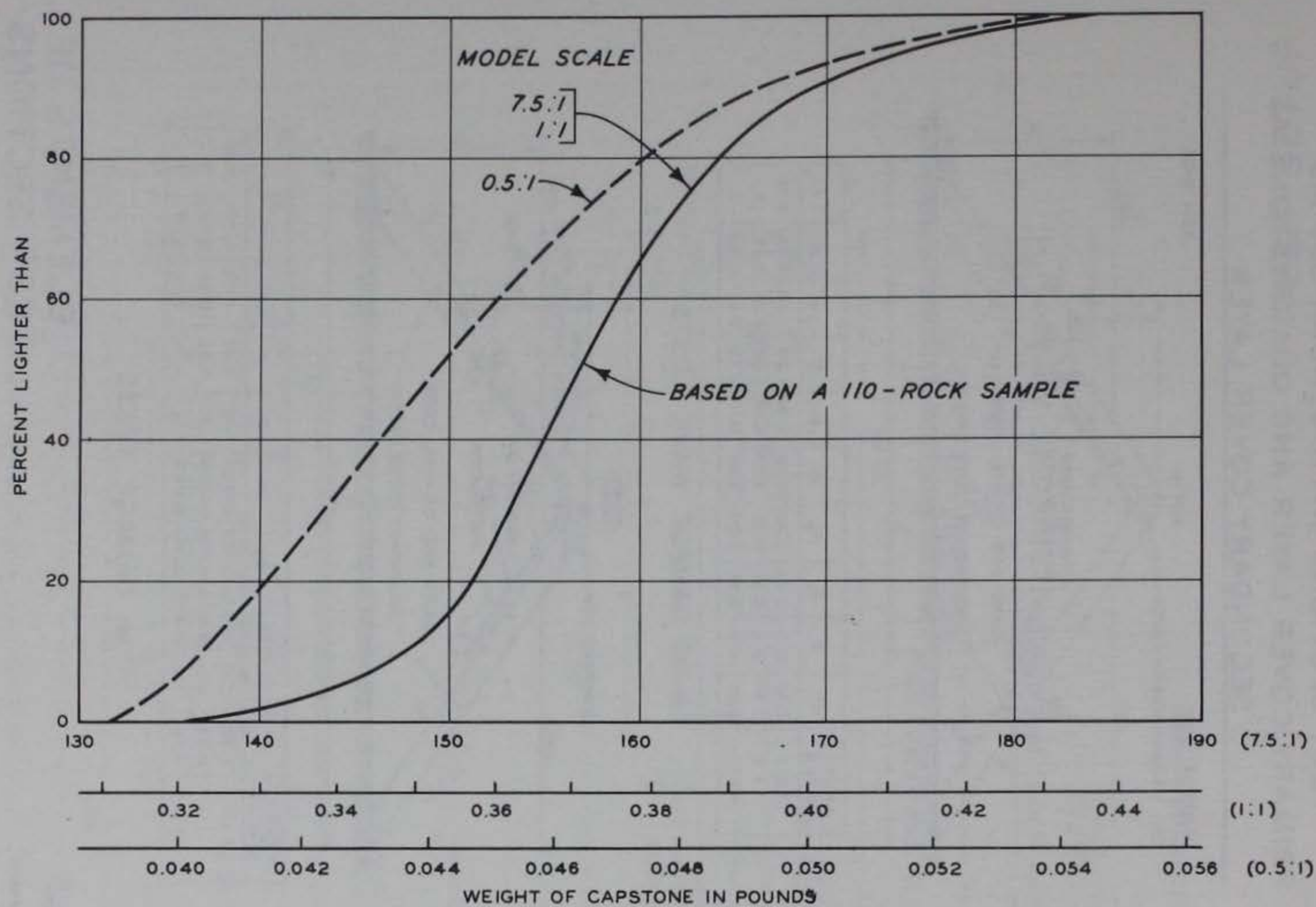
d. DAMAGE TESTS

### MODEL SCALES IN FEET

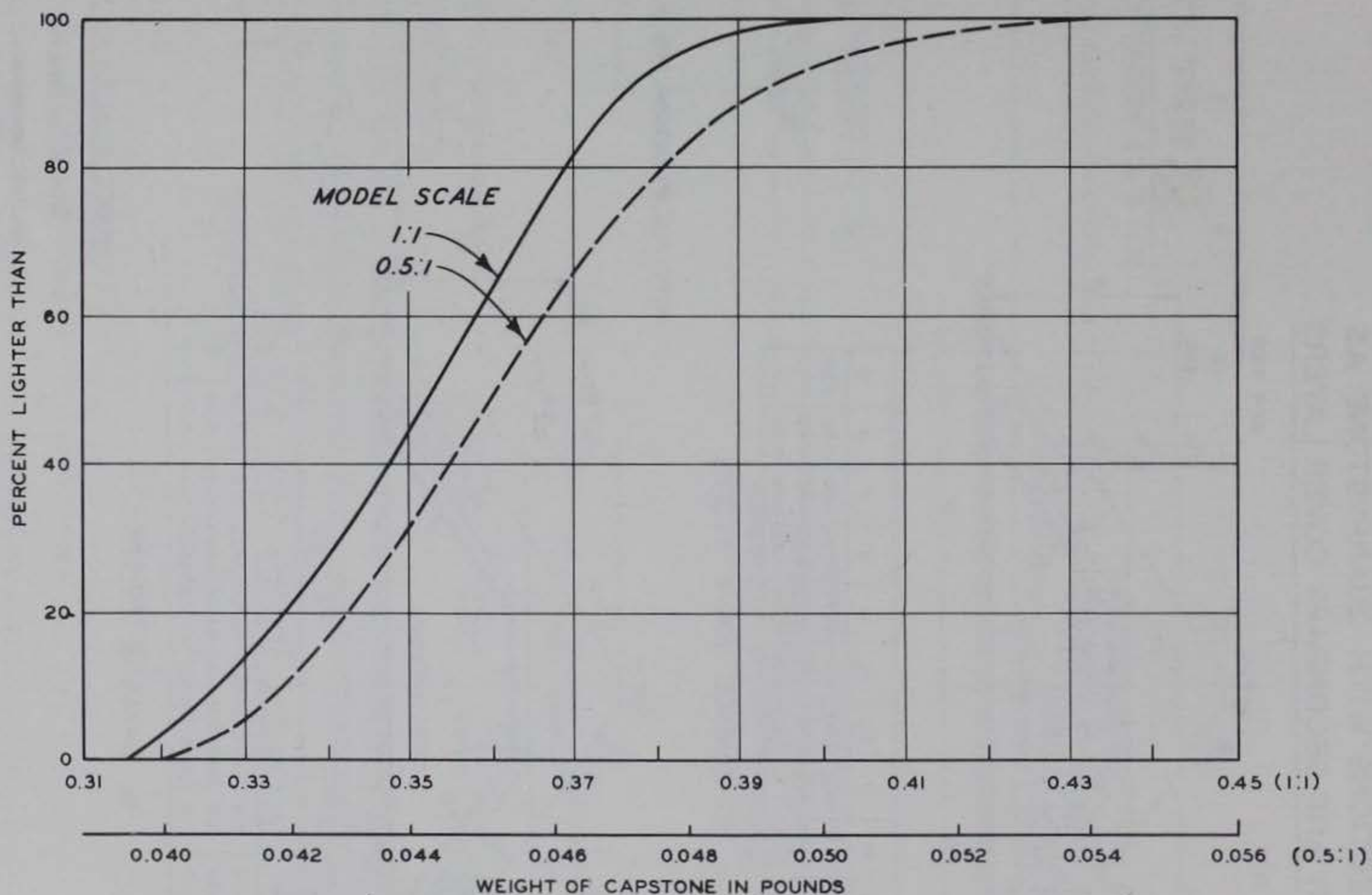


### ELEMENTS OF TEST SECTIONS





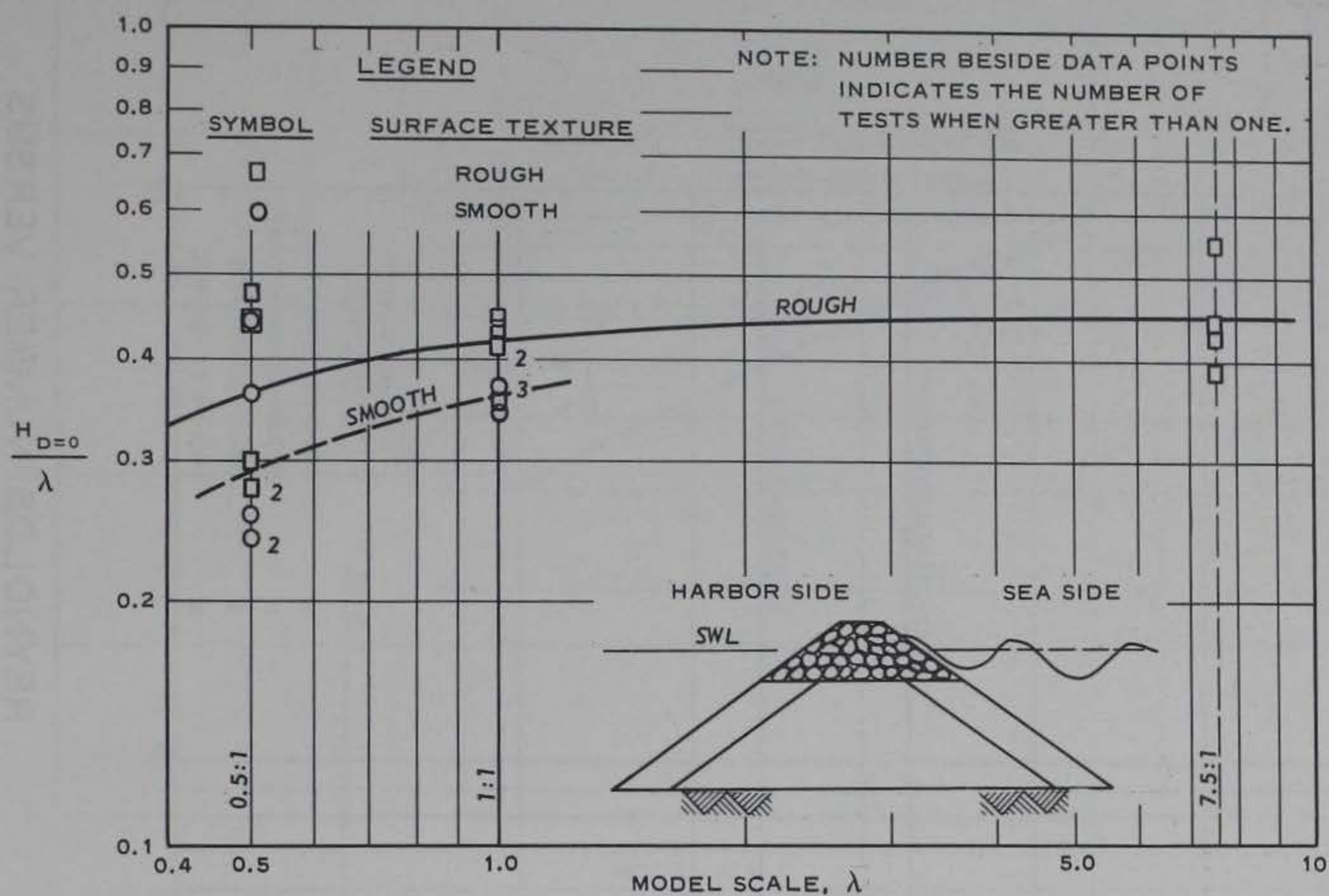
GRADATION OF ROUGH QUARRYSTONE



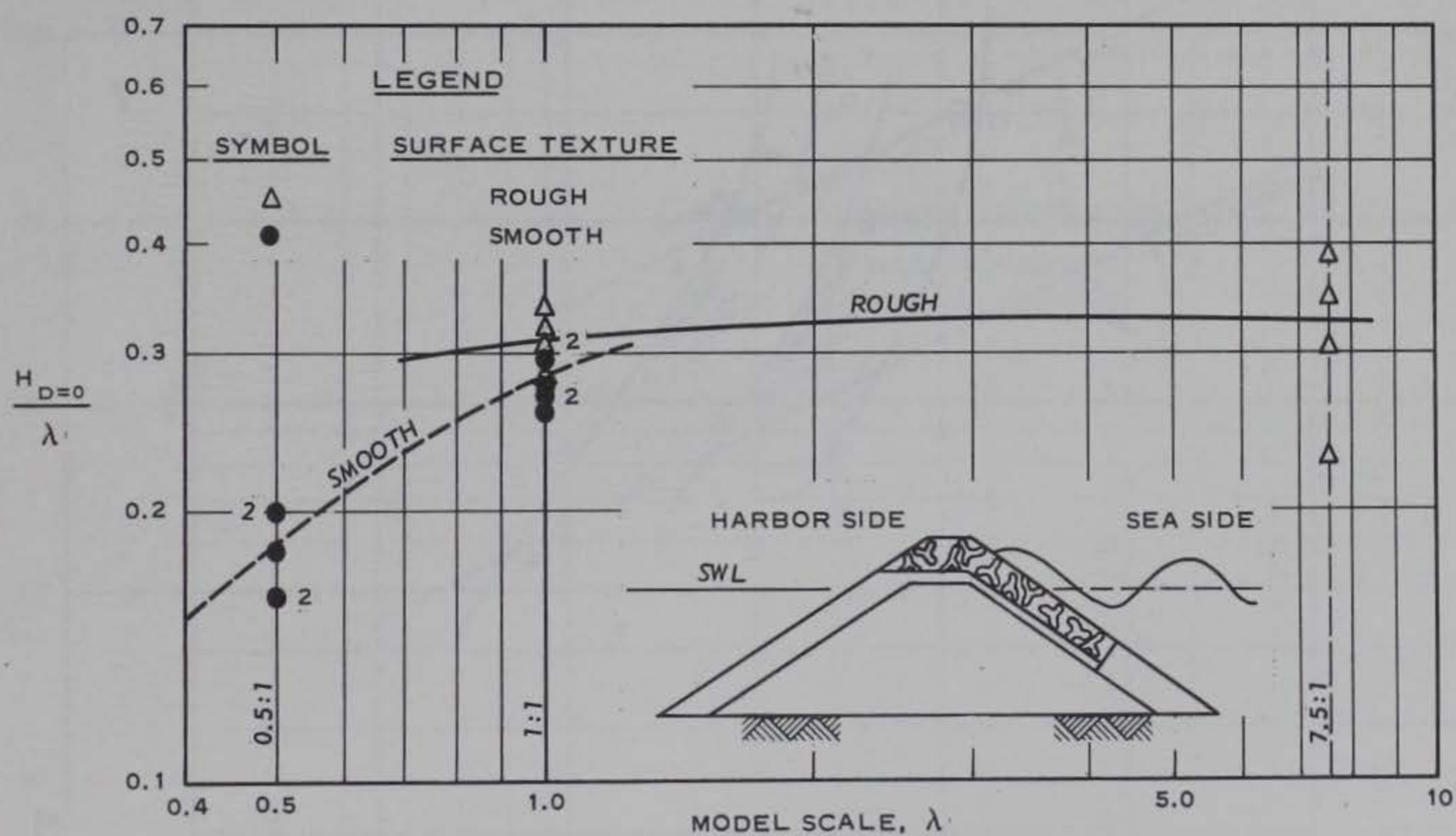
GRADATION OF SMOOTH QUARRYSTONE

GRADATION CURVES FOR  
STONES USED IN  
PRIMARY COVER LAYER





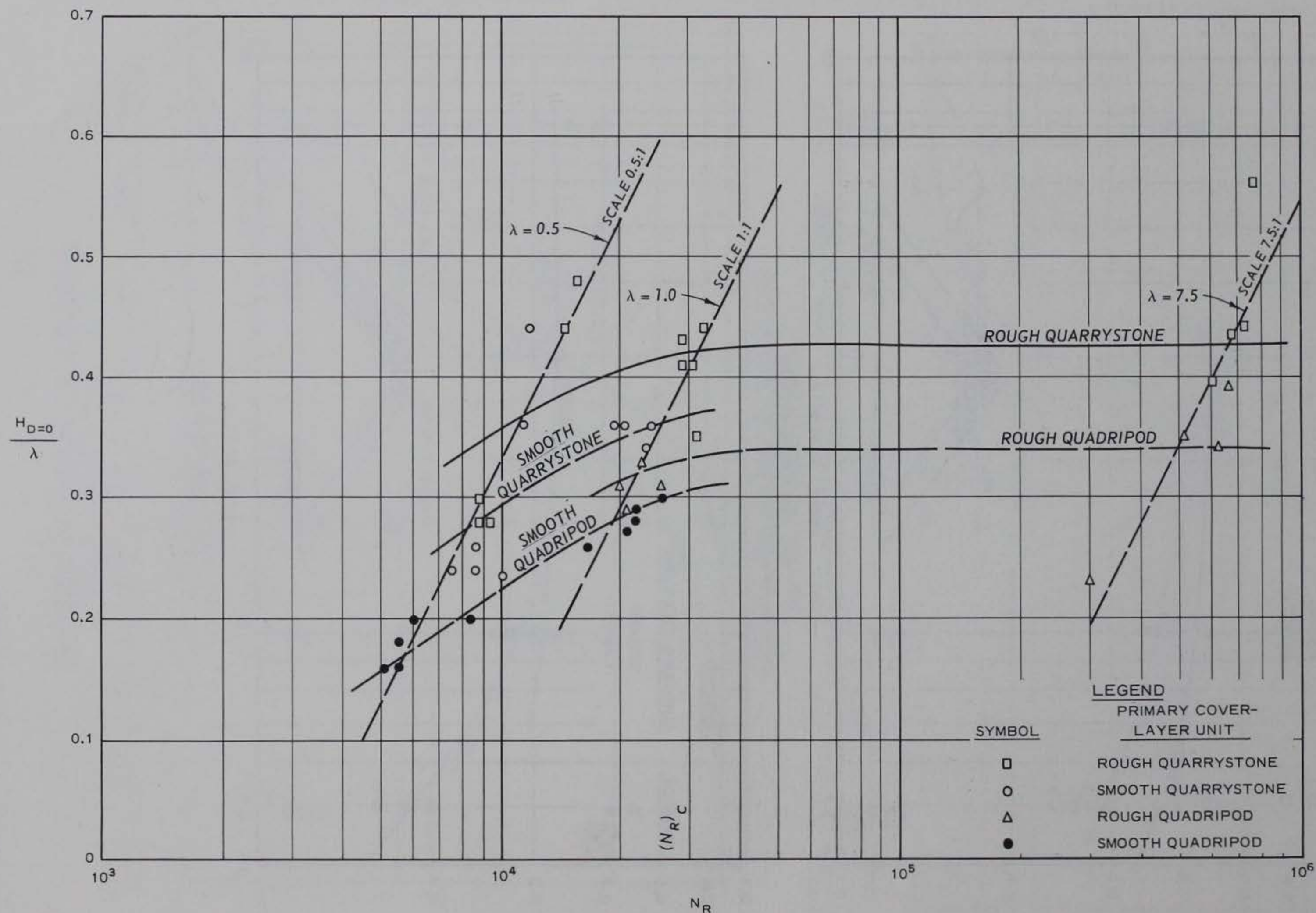
(a) QUARRYSTONE



(b) QUADRIPODS

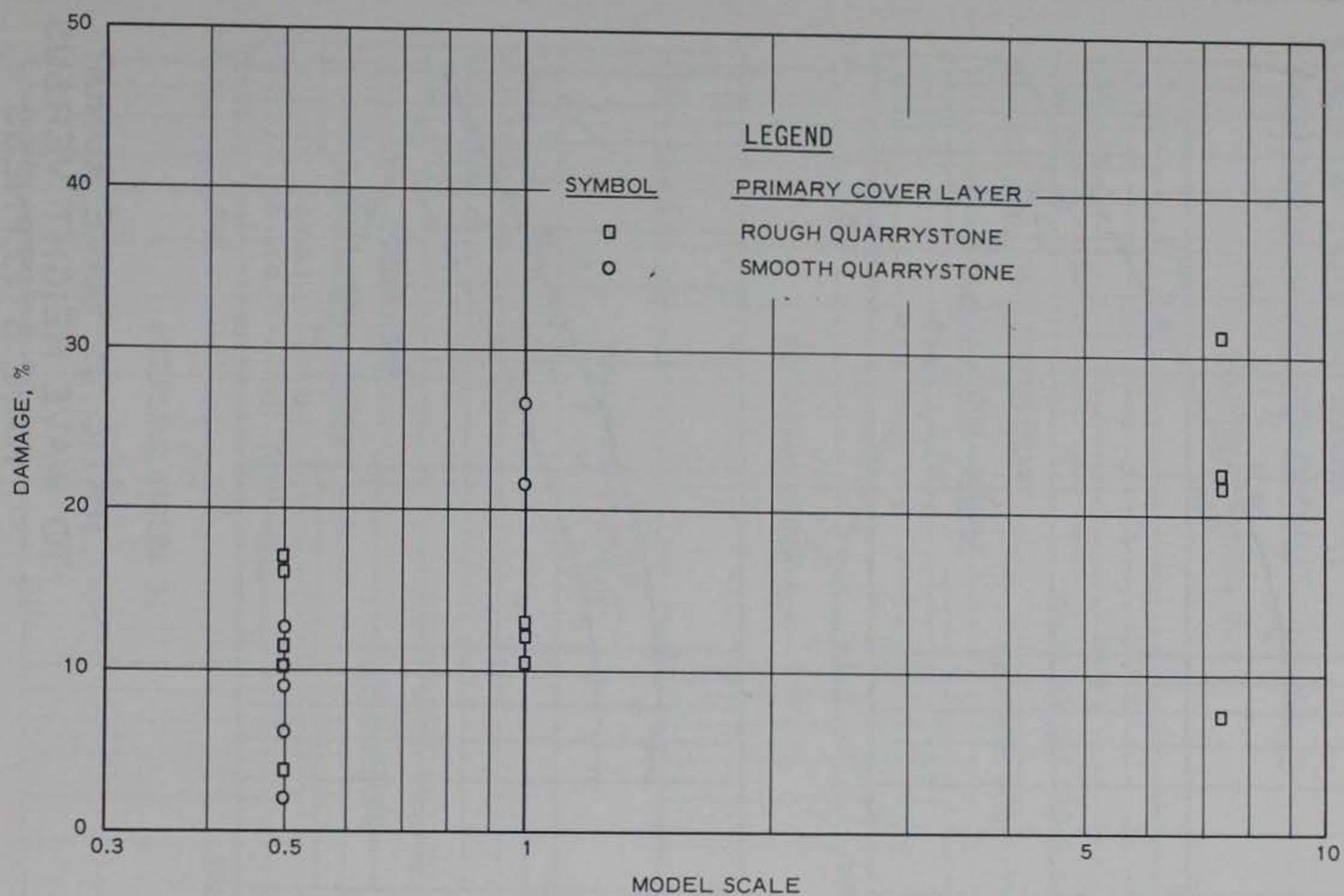
MODEL SCALE VERSUS  
RELATIVE NO-DAMAGE WAVE HEIGHT



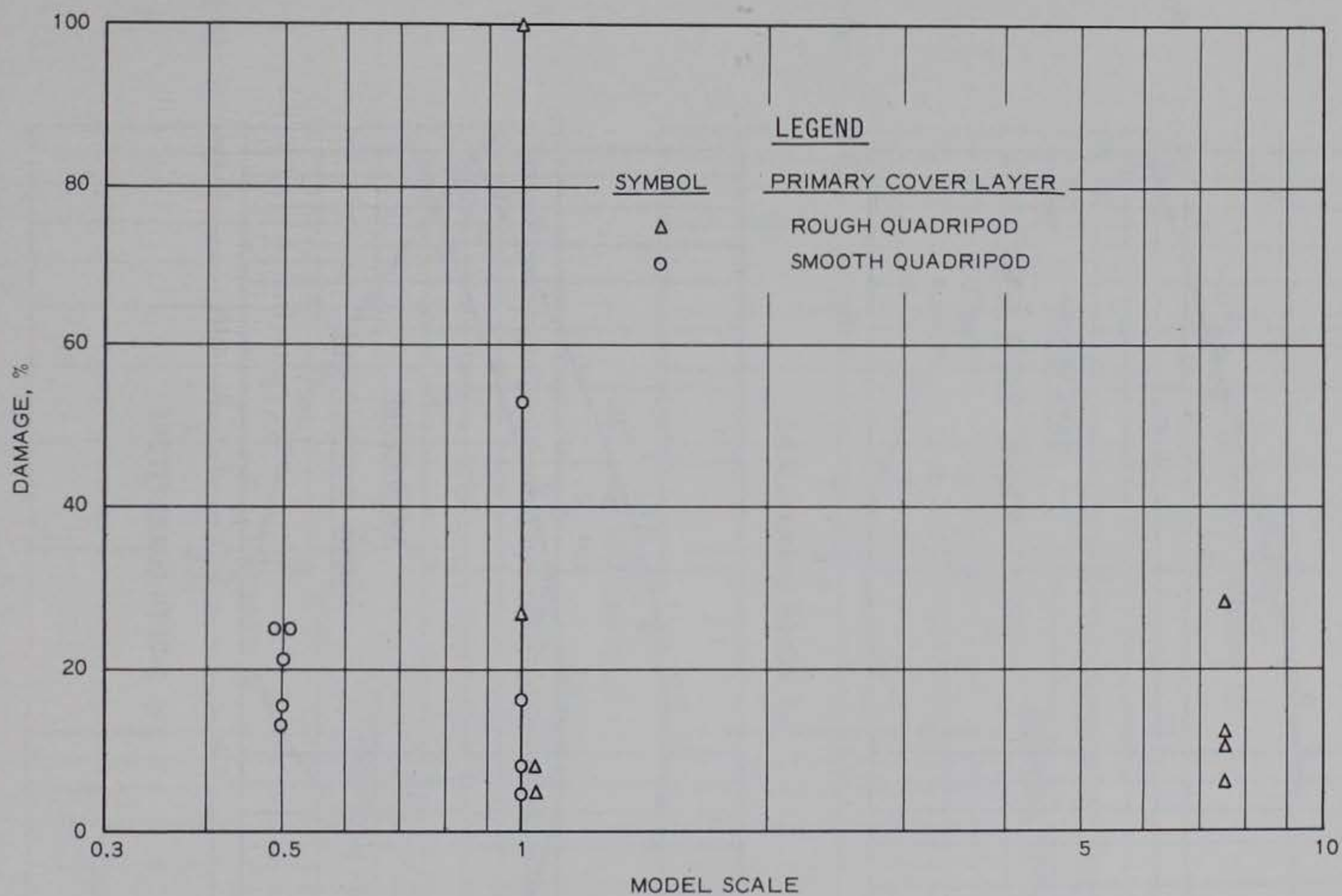


REYNOLDS NUMBER VERSUS  
RELATIVE NO-DAMAGE WAVE HEIGHT





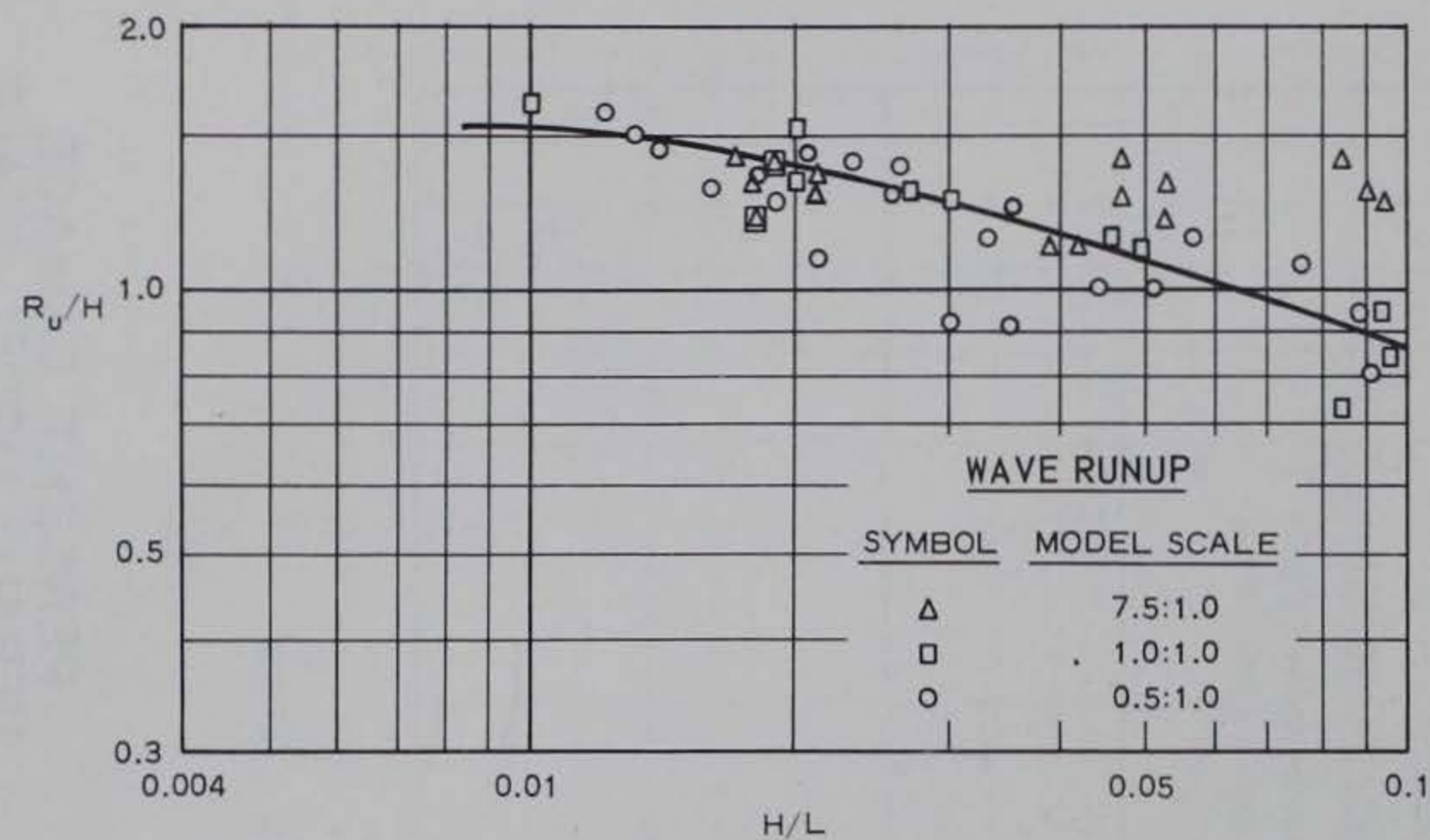
a. QUARRYSTONE COVER LAYER



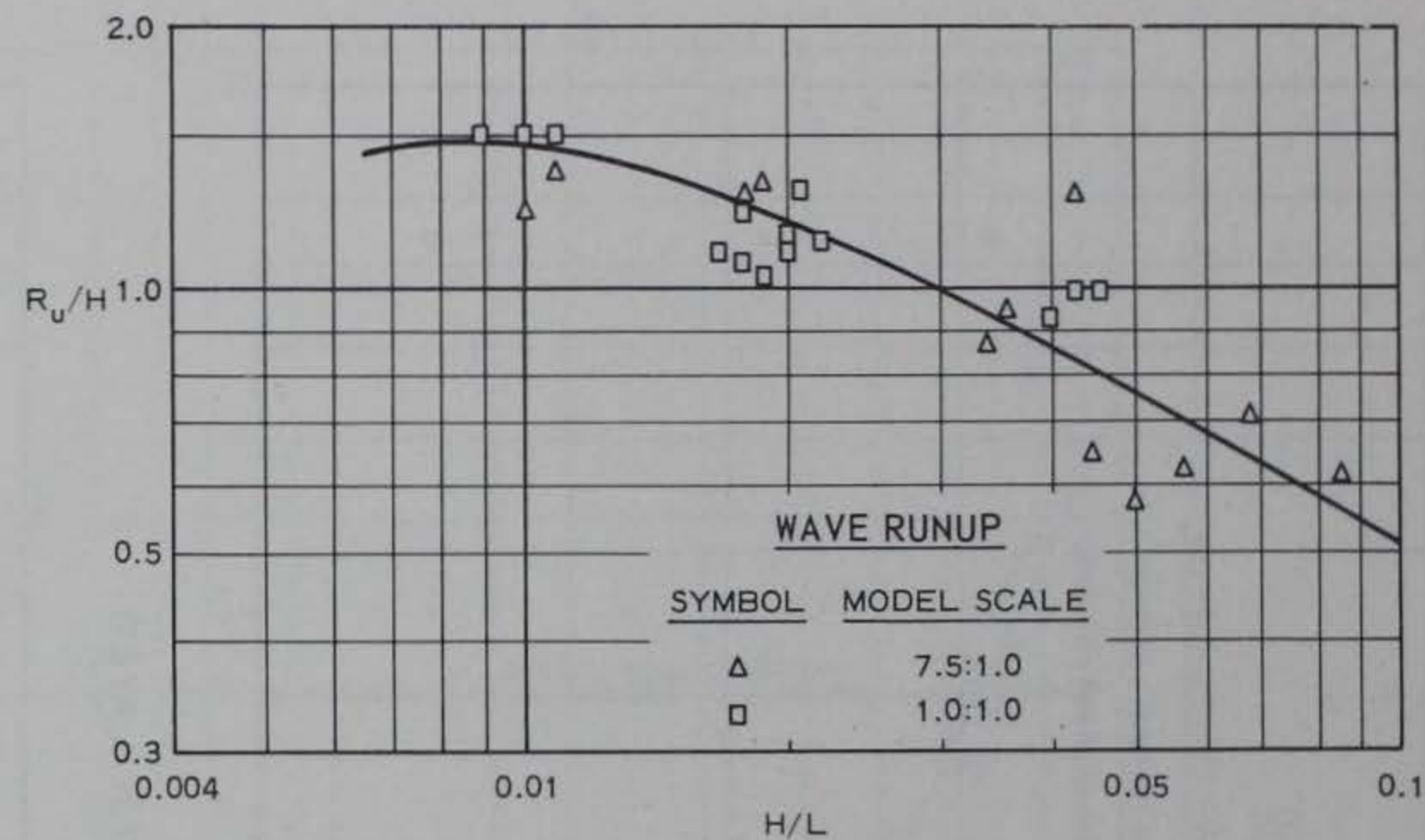
b. QUADRIPOD COVER LAYER

PERCENT DAMAGE  
VERSUS MODEL SCALE

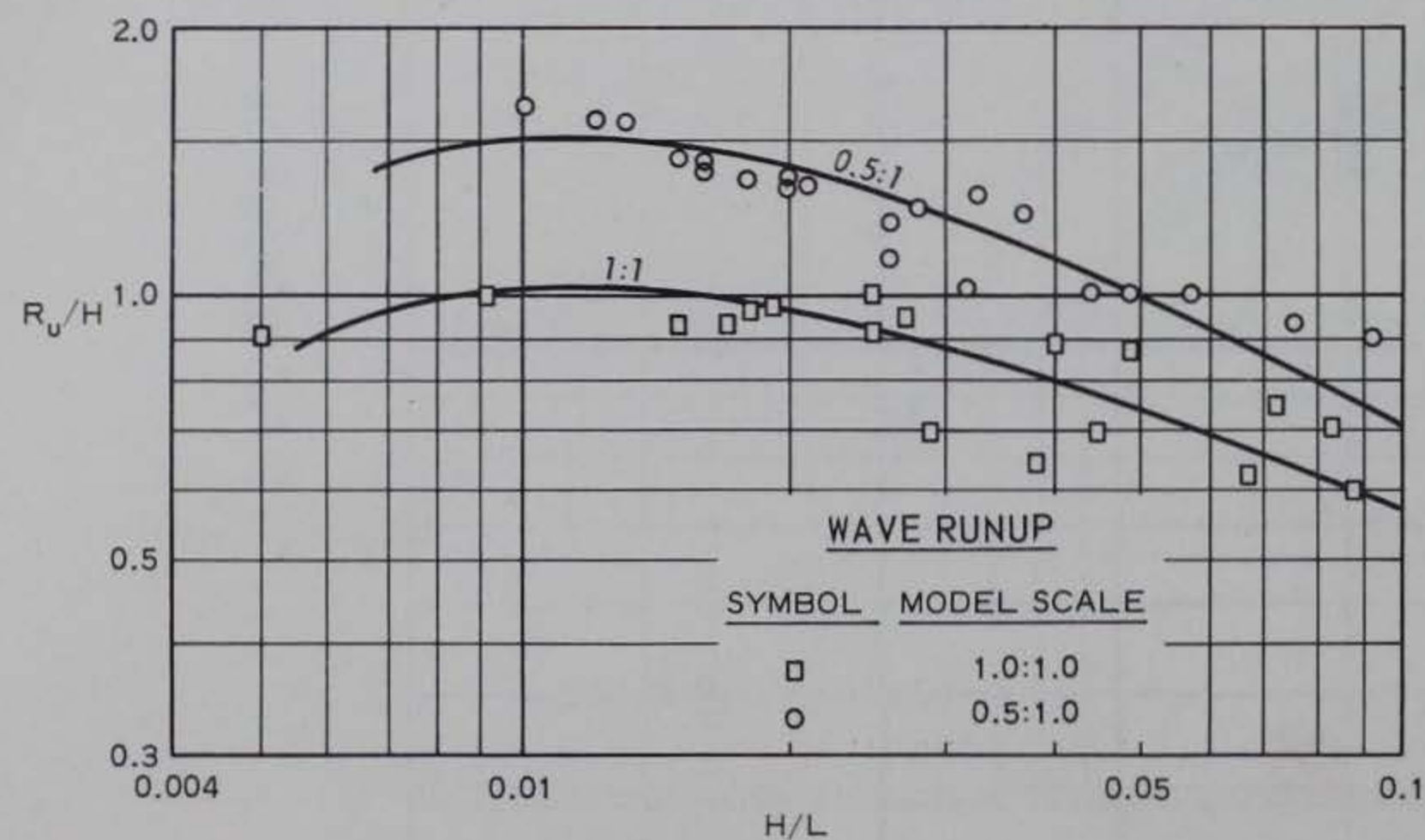




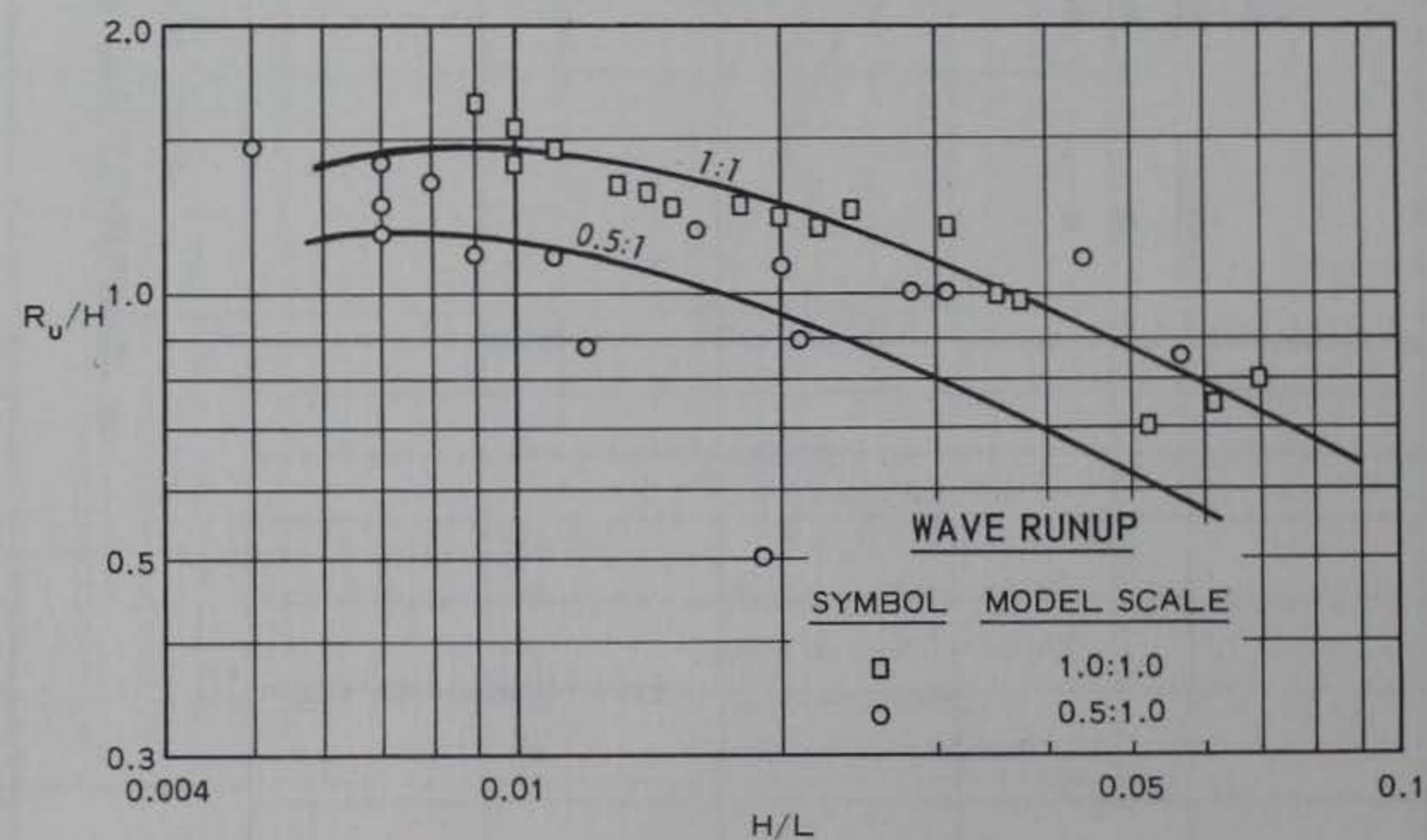
(a) ROUGH QUARRYSTONE



(c) ROUGH QUADRIPOD



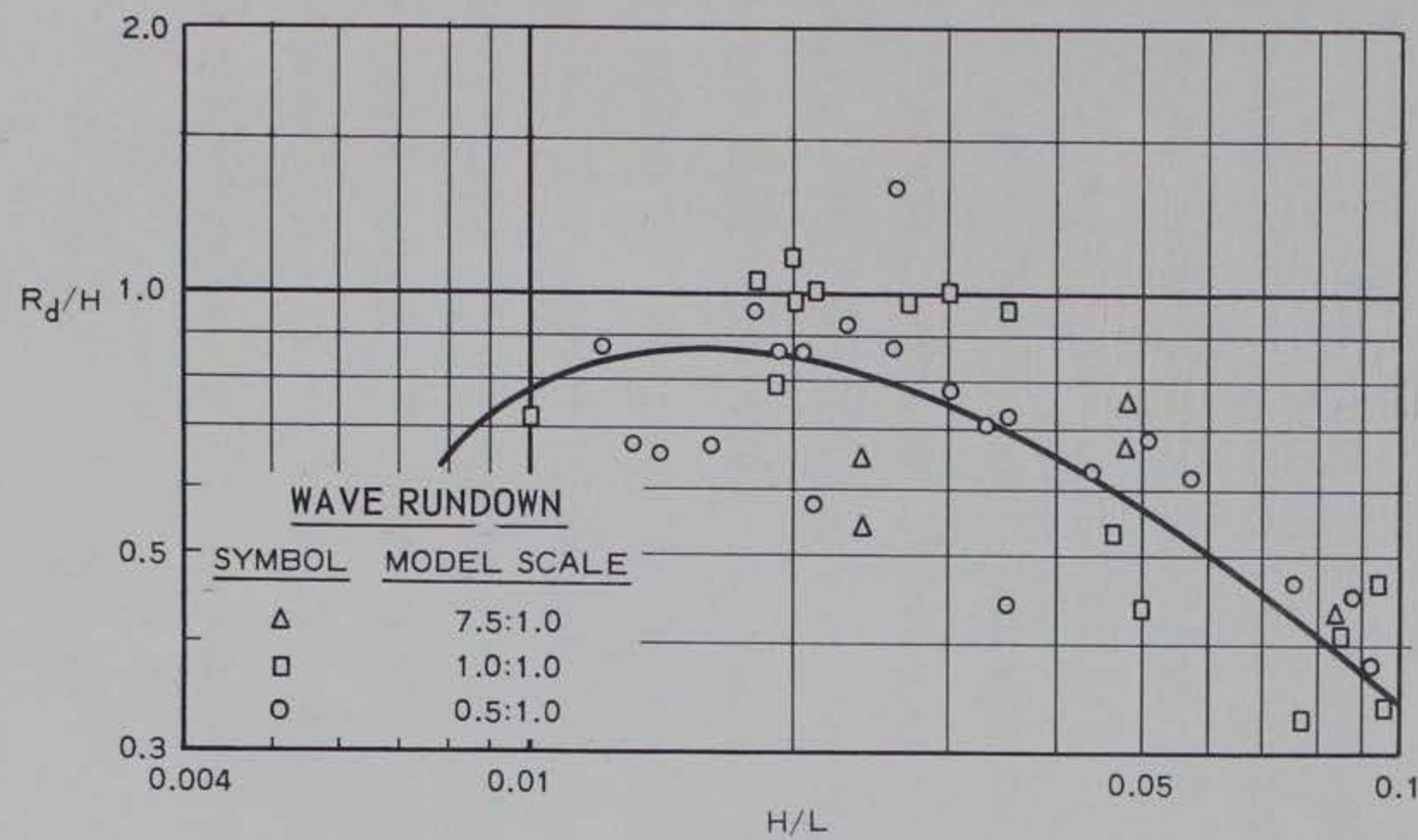
(b) SMOOTH QUARRYSTONE



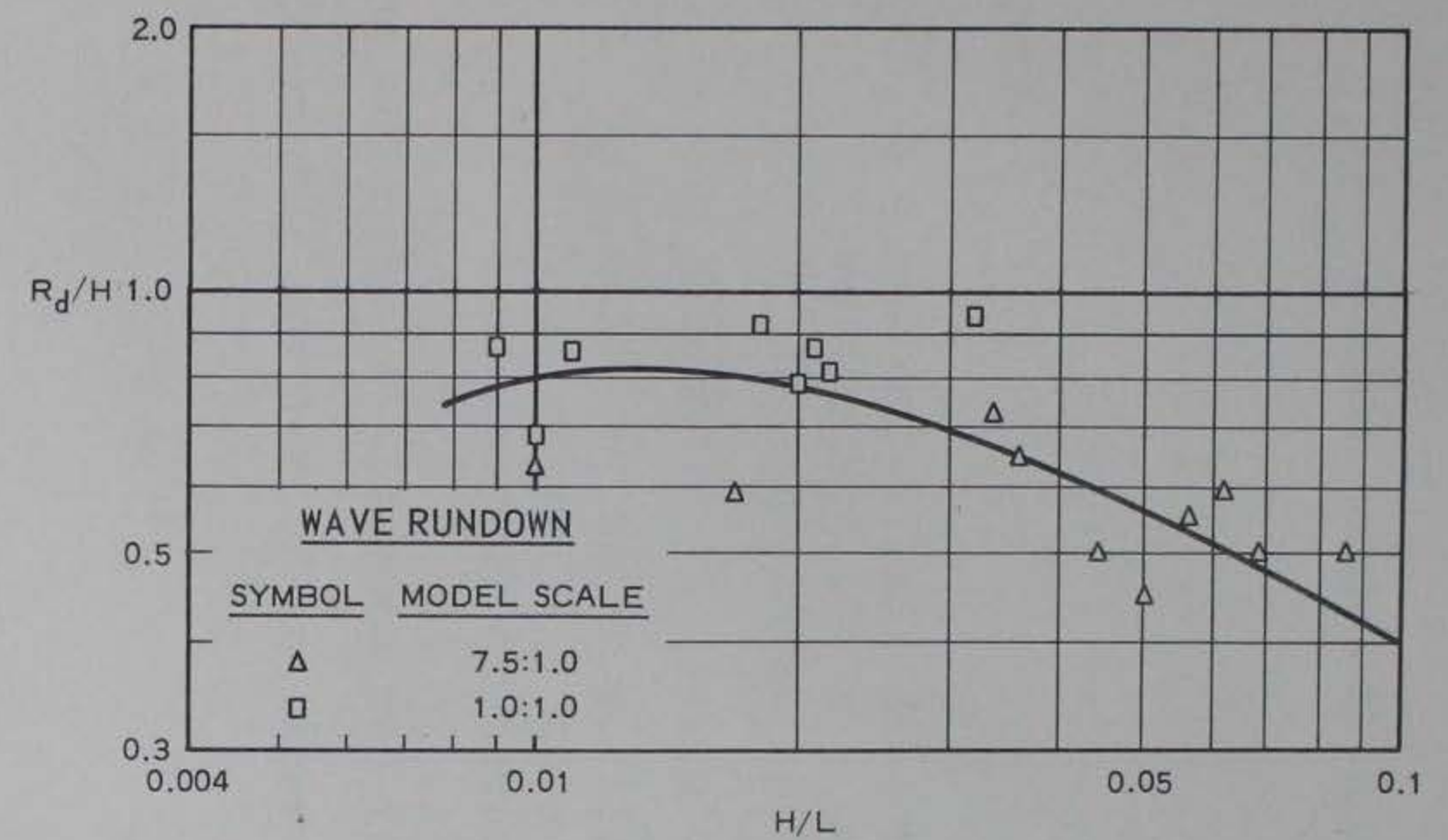
(d) SMOOTH QUADRIPOD

**RATIO OF WAVE RUNUP  
TO WAVE HEIGHT VERSUS  
WAVE STEEPNESS**

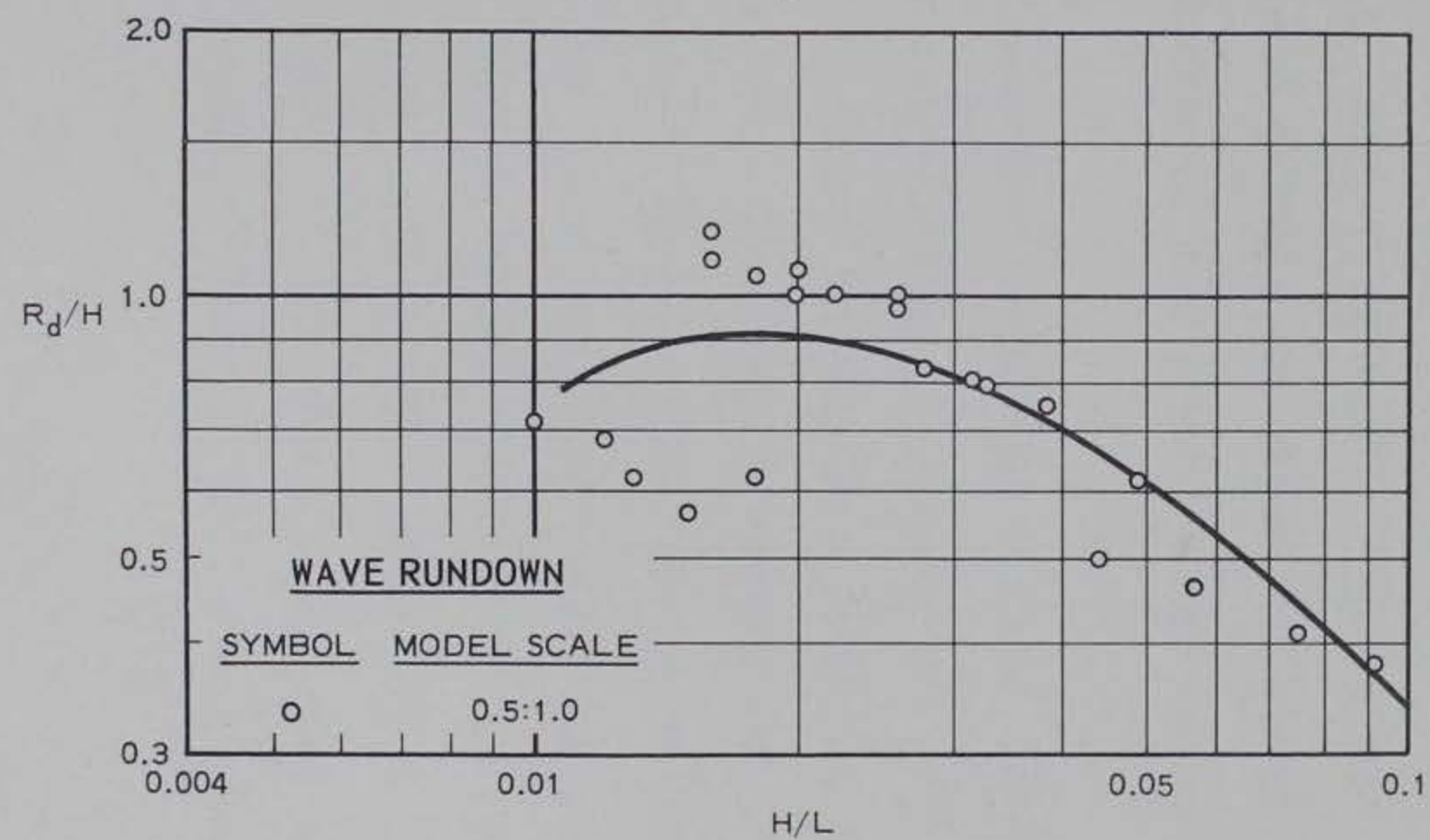




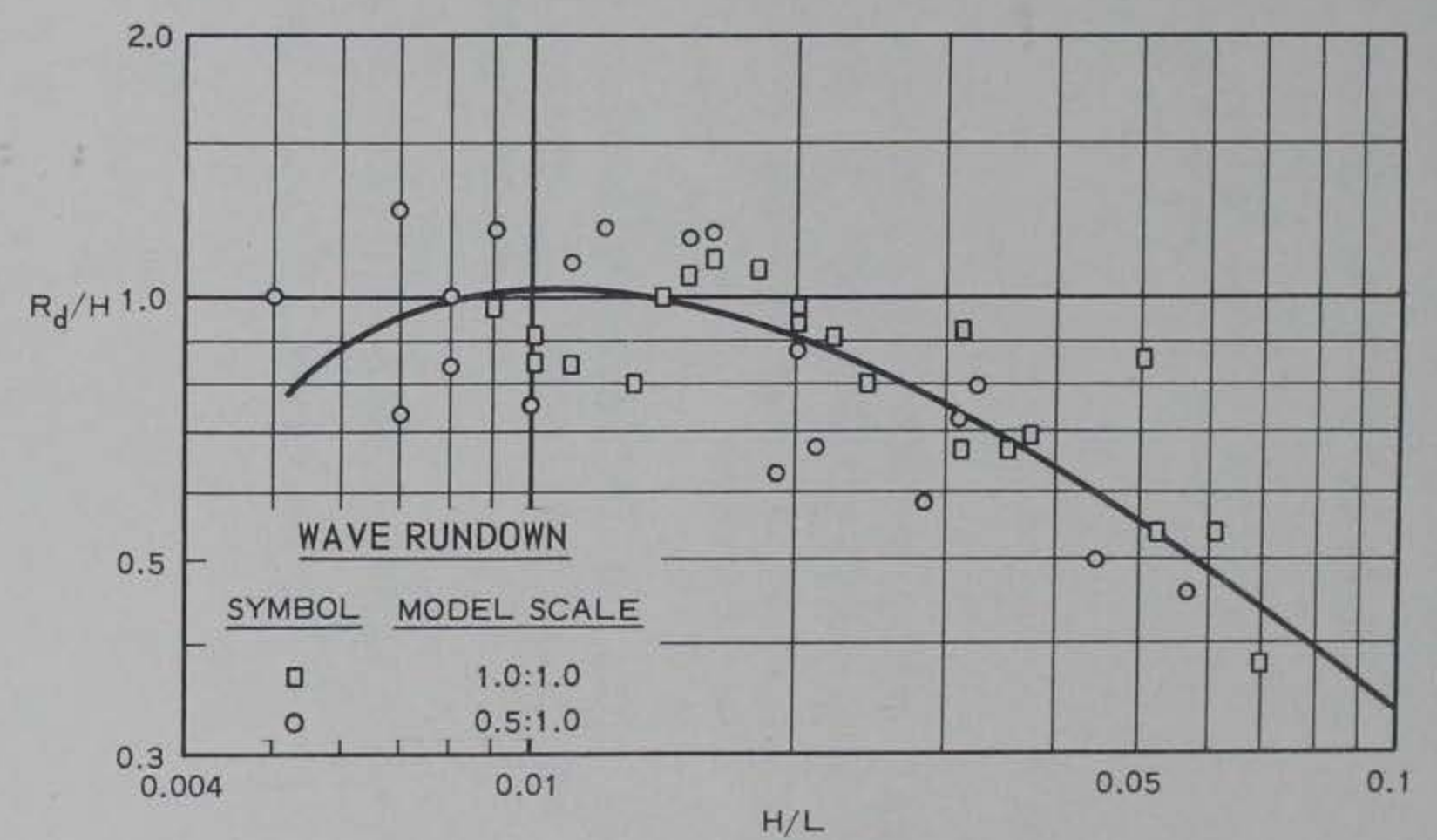
(a) ROUGH QUARRYSTONE



(c) ROUGH QUADRIPOD



(b) SMOOTH QUARRYSTONE



(d) SMOOTH QUADRIPOD

RATIO OF WAVE RUNDOWN  
TO WAVE HEIGHT VERSUS  
WAVE STEEPNESS



## APPENDIX A: METHOD OF COMPUTING REYNOLDS NUMBER

1. In this report Reynolds number is expressed as

$$N_R = \frac{V_R \delta}{\nu} \quad (A1)$$

where

$\delta$  = characteristic diameter of unit of primary cover layer, defined as average of  $x$ ,  $y$ , and  $z$  for quarystone and as dimension  $G$  for quadripod units (see photograph 2)

$\nu$  = kinematic viscosity of water at 60 F

$V_R$  = value of water particle velocity parallel to side slope of breakwater  $V$ , at a distance  $R$  equal to half the characteristic diameter of cover-layer unit

The velocity  $V$  is obtained from a study on the velocity field on the underwater portion of an impervious sloping breakwater<sup>5,6</sup> as

$$V = \frac{\omega H}{T} \cos \frac{2\pi}{T} t \quad (A2)$$

where  $\omega$  is a velocity parameter which is a function of  $R/L$  as shown in plate A1. Knowing the value of  $\omega$  for different  $R/L$  values,  $V$  can be obtained for a given wave height and period as shown in plate A2. It can be seen from plate A2 that  $V$  increases for decreasing values of  $R/L$  and  $V \rightarrow \infty$  as  $R/L \rightarrow 0$ .

2. Since most damage to breakwater sections occurs in the vicinity of the still-water level (swl), a representative value of  $V$  for calculating  $N_R$  would be the average velocity to which a unit of the primary cover layer located at swl is exposed. For small values of  $R/L$ , equation A2 is invalid and will result in large differences in the value of  $V$  for small changes in  $R/L$  as shown in plate A2. To overcome this difficulty an asymptote was drawn to the lower values of  $V$  and was used in predicting  $V$  for small values of  $R/L$ . The point of interception between the asymptote and the ordinate (point P in plate A2) was calculated from the maximum runup on the breakwater slope. In establishing the



relation between  $V$  and  $R/L$ , the wave height  $H$  in equation A2 was taken as the no-damage wave height ( $H_{D=0}$ ). Table A1 gives particle velocities  $V_R$  for each form of the primary cover-layer units used in the three models tested in this study. These  $V_R$  values were used for computing the  $N_R$  values given in table 10 of the main text of this report.

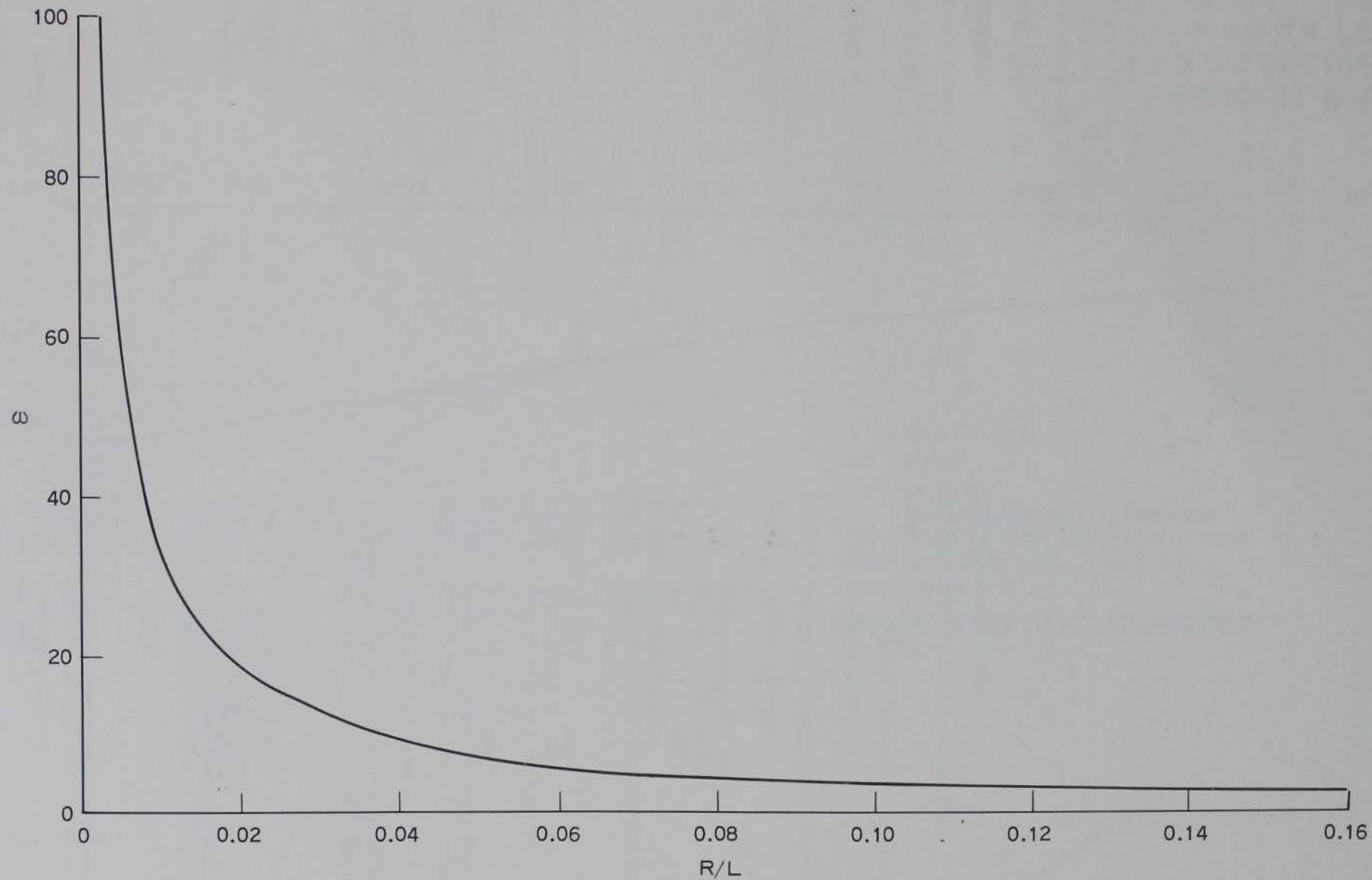


Table A1

## Water Particle Velocity Parallel to Slope of a Rubble-Mound Breakwater

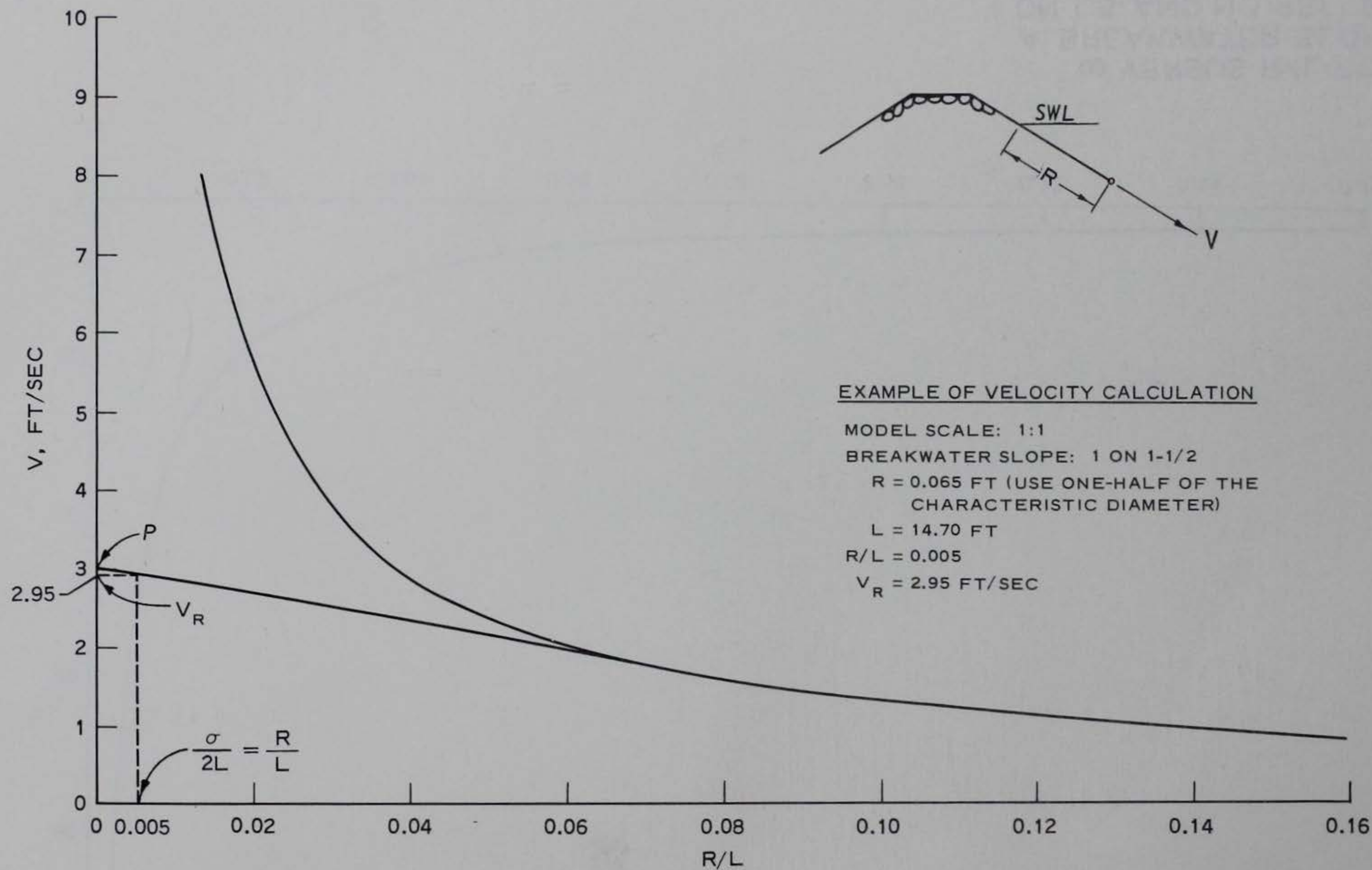
Scale	Primary Cover-Layer Unit	T sec	$H_{D=0}$ ft	$V_R$ ft/sec
7.5:1	Rough quarrystone	2.71	2.95	7.50
		3.75	3.25	8.49
		5.60	--	--
		7.87	3.30	9.04
		11.33	4.20	9.48
1:1	Rough quarrystone	0.95	0.43	2.61
		1.37	0.41	2.70
		2.04	0.44	2.95
		2.87	0.41	2.90
		4.14	0.35	3.00
0.5:1	Rough quarrystone	0.67	0.15	1.58
		0.97	0.14	1.60
		1.45	0.14	1.70
		2.03	0.24	2.81
		2.93	0.22	2.59
1:1	Smooth quarrystone	0.93	0.36	2.00
		1.31	0.36	2.04
		1.88	0.34	2.31
		2.65	0.36	2.40
0.5:1	Smooth quarrystone	0.67	0.12	1.40
		0.97	0.13	1.60
		1.45	0.12	1.60
		2.03	0.22	2.21
		2.93	0.18	2.29
7.5:1	Rough quadripods	2.61	1.70	4.32
		3.75	2.30	7.50
		5.60	--	--
		7.87	2.90	9.72
		11.33	2.60	9.10
1:1	Rough quadripods	0.99	0.32	--
		1.31	0.31	2.22
		2.04	0.29	2.29
		2.65	0.33	2.50
		4.14	0.31	2.30
1:1	Smooth quadripods	0.95	0.26	1.81
		1.37	0.27	2.30
		2.04	0.29	2.41
		2.87	0.28	2.40
		4.14	0.30	2.80





$\omega$  VERSUS  $R/L$  FOR  
A BREAKWATER SLOPE OF  
1 ON 1.5 AND NO REFLECTION





V VERSUS R/L FOR  
 $T = 2.04$  SECONDS AND  
 $H = 0.44$  FEET



DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

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4. DESCRIPTIVE NOTES (Type of report and inclusive dates)			
Final report			
5. AUTHOR(S) (First name, middle initial, last name)			
Yin Ben Dai Adel M. Kamel			
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13. ABSTRACT Laboratory investigations conducted by and for the Waterways Experiment Station under ES 815, "Stability of Rubble-Mound Breakwaters," determined the relative importance of the different variables with respect to the stability of rubble-mound breakwaters and formulated design criteria for those structures. In ES 815, test-wave dimensions, water depth, and the armor-unit sizes used corresponded to a model with a linear scale of about 1:50 for a prototype structure with rock armor units of about 20 tons. In order to determine the effects of model scale on the results obtained in the ES 815 and similar studies, the ES 847 tests were conducted duplicating the ES 815 testing techniques using model scales of 7.5:1, 1:1, and 0.5:1 relative to the linear dimensions of the ES 815 scale tests. The breakwater test sections used had primary cover layers composed of smooth or rough quarrrystones or quadripod armor units. The ES 847 investigation included: (a) tests for the selection of the maximum no-damage wave heights for the condition of no overtopping, (b) damage tests to determine the amount of damage to test sections when they were attacked by waves with heights about 1.6 times their maximum no-damage wave heights, and (c) determinations of wave runup and rundown on the breakwater slopes tested. Test results indicated that, for the type of breakwater sections and armor units tested, no significant scale effect in the selected no-damage wave heights was present for models with scales of 7.5:1 and 1:1; however, a significant scale effect was found to occur for the tests of the 0.5:1-scale model. This scale effect is believed to have been due to the smallness of the 0.5:1 model, which caused the viscous forces to be significant and thus result in inaccuracy in model results. Results of damage and wave runup and rundown tests for the three models did not follow any trend that would indicate the existence or nonexistence of scale effect. It was concluded that no scale factor would be required when applying the results of ES 815 and similar tests to the design of full-scale breakwaters when the Reynolds number, as defined in this report, is equal to or greater than about $3 \times 10^4$ .			



14.	KEY WORDS	LINK A		LINK B		LINK C	
		ROLE	WT	ROLE	WT	ROLE	WT
	Breakwaters Hydraulic models Rubble-mound breakwaters						