A MODEL STUDY OF WAVE RUN-UP
ON SMOOTH AND ROUGH SLOPES

A Thesis

Presented to

the Faculty of Graduate Studies and Research

University of Manitoba

In Partial Fulfilment

of the Requirements for the Degree

Master of Science in Civil Engineering

by

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Session 1962-1963.

ACKNOWLEDGEMENTS

The author is deeply indebted to all those who have contributed or assisted in making this thesis possible.

A special thanks is due to Professor E. Kuiper, and Prof. W. F. Riddell, whose technical advice and encouragement throughout the investigation was appreciated.

The Winnipeg Supply and Fuel Company, who supplied test material free of charge, and the Prairie Road Builders Association whose financial help made this study possible are sincerely thanked.

The names of those whose help, guidance, and co-operation made this study a success are given below:

Prof. W. D. Alexander, Mechanical Engineering Department,

Mr. O. Tonn, Mechanical Engineering Technician,

Mr. R. Muir, Civil Engineering Workshop,

Mr. D. Gillies, Civil Engineering Technician,

Mr. F. Stevenson, Student.

ABSTRACT

This investigation was undertaken to determine design charts for wave run-up on dykes or earth dams when the wave height is in the same dimensional range as the median diameter of the riprap material. The tests performed to develop these charts involved testing several combinations of slope and riprap material over a wide range of waves.

Several conclusions can be made from this investigation;

(1) The results of some of the tests conducted in the present study give very similar results as previous tests performed by R. P. Savage,[1] thus verifying the model data and test procedures.

(2) Wave run-up on riprap where the median diameter is in the same dimensional range as the impinging wave height is less than run-up on material of a smaller diameter, all the dimensionless parameters being the same.

(3) The design charts presented for smooth and rough slopes on pages 61 to 65 and 71 to 76 are supported by sufficient evidence that the designer should have confidence in the results so long as the dimensionless parameters involved are within the range of the dimensionless parameters that are given in the graphs.

(4) The reversed smooth slopes give considerably less run-up than ordinary smooth slopes.

1. Savage, R. P., "Wave Run-up on Smooth and Roughened Slopes", Journal of the Waterways and Harbours Division, Proc. Paper 1640, Page 10.

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CHAPTER I

INTRODUCTION

Freeboard[1] is defined as the difference in elevation between the top of the dam and the maximum reservoir level that would be attained during the spillway design flood level. The portion of the dam above the maximum reservoir level is provided to protect the dry side of the structure from damage. This damage may refer to the structure itself, but in most cases the greatest portion of the damage involves private property and human life. Often a failing structure offers no warning, and within minutes total communities can be destroyed causing millions of dollars of damage, not to mention the human suffering involved.

The beginning of a sequence of events causing a failure of a dam in which freeboard is involved usually is due to three main reasons. These reasons are that inadequate freeboard was provided for the design conditions due to lack of knowledge of the components of freeboard at the time of the design; or, that the design flood was exceeded by nature; or, that the design wind velocity and resulting waves exceeded expected magnitudes. Any combination of the above three conditions to a lesser degree may be equally as disastrous.

The consequent events in the failure is that the wave run-up is increased in elevation due to the increasing water levels and wave heights until overtopping of the structure occurs. The water then gains velocity as it flows down the dry side of the dam causing

1. Technical Terms can be found in Appendix A, page 83.

erosion at the toe of the structure and loss of soil strength due to saturation of the soil until a major slide and failure of the structure occurs. The slide usually lowers the structure in height so that free flow begins over the dam failures thus increasing erosion, which in turn increases the flow. This vicious cycle continues until a portion of the structure is completely breached. Once this condition exists the situation is out of hand and the consequences must be suffered.

During the past five years in the Province of Manitoba alone, approximately a million dollars annually has been spent on riprap to protect dykes and dams from failure. This figure does not include money spent on increasing the height and mass of the structure required to contain the waves and increased water level due to the action of the wind.

In the years prior to 1950 very little research had been undertaken in North America with regard to freeboard. Design of freeboard was by a rather haphazard method until the Zuider Zee Commission in Holland presented a formula based on observations and theory to calculate the effect of wind causing increased water levels known as wind set-up. Literature as late as 1950 recommended that the wave run-up on a structure can be taken as 1.5 times the design wave height above the still water level.

Tests for the amount of wave run-up on a structure made recently in the United States include tests on smooth slopes, tests on small diameter material as roughened slopes with an impervious core and tests on relatively large diameter material as a rubble mound breakwater. The need for tests on relatively large diameter material on impervious layers has been suggested in American literature.

However, the tests undertaken at the University of Manitoba are believed to be the first to simulate the above conditions; that is, to test riprap on sloping shore structures when the median diameter of the material approaches the impinging wave heights.

As mentioned above, United States engineers have done considerable recent research in the field of freeboard, but a survey of the literature indicates that the present study is the first general researdh done on this subject in Canada. Although this study is predominately a study on wave run-up, there is another investigation underway at the University of Manitoba on wind set-up. The results of these tests by Mr. R. W. Newbury will be available during the early part of 1964.

The calculation of a reasonable amount of freeboard for a given structure location depends upon many factors. A discussion of these variables has been given in Chapter II. Chapter II also contains a review of the dependency of wind set-up on the variables involved, with Chapter III being abstracts from the literature on the subject of wave run-up. The remaining chapters deal exclusively with wave run-up and the tests performed on shore structures. Chapter IV deals with the wave generating mechanism and the test procedures. The results of the tests are given in Chapter V, with a discussion of results and conclusions given in Chapter VI.

CHAPTER II

VARIABLES RELATED TO FREEBOARD

Freeboard, as defined previously, is the difference in elevation between the top of the dam and the maximum reservoir level that would be attained during the spillway design flood level. The components of freboard shown in Figure 1 must be of such a magnitude that the combined action of wind set-up and wave run-up does not exceed the top of the dam.

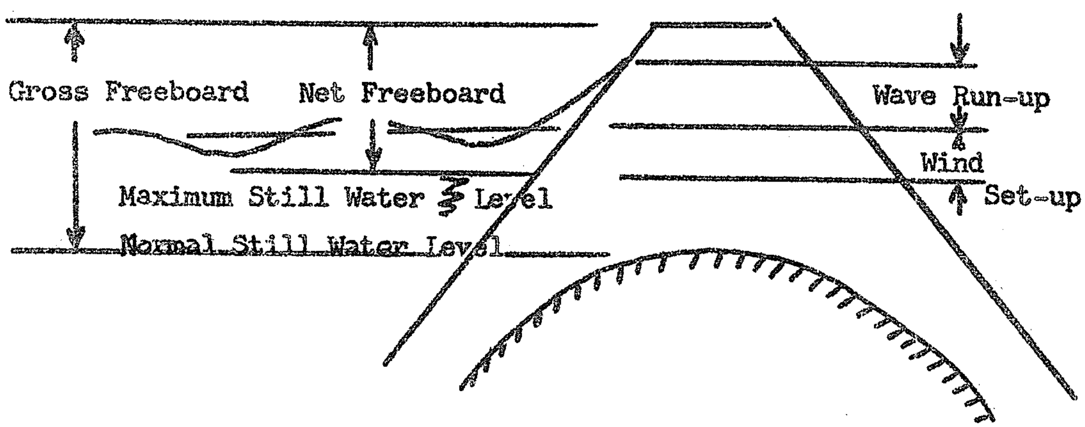


Figure 1

Engineers sometimes refer to freeboard as "gross freeboard" or "net freeboard". Gross freeboard refers to the difference in elevation between the spillway crest of a dam and the top of the dam. Net freeboard refers to the difference in elevation between the maximum elevation of the spillway design flood and the top of the dam. The word freeboard in this study will refer to net freeboard unless otherwise specified.

The remainder of this chapter deals with the variables related to freeboard. Freeboard can be composed of as many as four independent variables; namely, wave run-up, wind set-up, tides and seiches. Freeboard for inland reservoirs usually is composed of only wave run-up and wind set-up since tides and seiches are relatively minute for such bodies of water. A small margin of safety is usually provided by an additional height of dam beyond the estimated required freeboard.

Wind set-up depends on variables such as wind velocity, wind direction, fetch length, depth of reservoir, and shape of reservoir. Wave run-up depends on the wave height, wave period, slope of the shore structure, roughness on the slope, and direction of the incoming waves. The wave height and wave period are variables which depend on the wind velocity, fetch length, fetch width and depth of reservoir. The purpose of this thesis is to study wave run-up, and therefore, any variables related to this subject are discussed to some length in the following pages of this chapter.

A method of procedure to calculate wind set-up is given after the discussion of variables, with a small discussion on subject of wind set-up. Tides and seiches are discussed just to the extent of their respective causes.

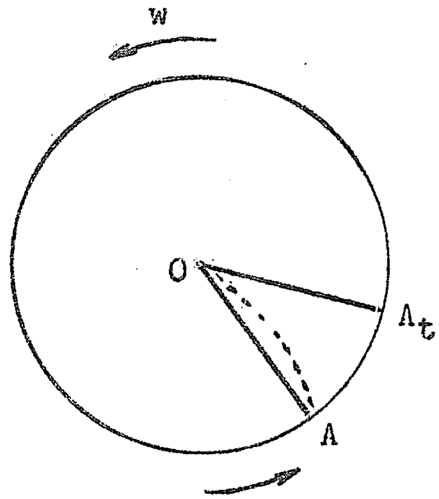
WIND AND WIND VELOCITY

Wind has been referred to as air on a mission - to re-establish the equilibrium of the atmosphere.[1] The force inducing motion is caused by a horizontal pressure gradient that acts on a unit cube of air. The pressure difference acting on opposite sides of the cube of air is always understood to be directed from high to low pressure.

Air flowing nearly horizontally is known as wind. A stream of air flowing in any other direction is known as air current. Winds are mainly caused by horizontal differences in pressure, and therefore the motion induced could be expected to move directly from a high pressure to a low pressure region. However, observations show that the direction of the wind is along isobars, with a slight drift towards the low pressure area. The relationship between wind direction and pressure centre is expressed by Buy Ballot's law: If an observer stands with his back to the wind, the lower pressure is on his left in the Northern Hemisphere and on his right in the Southern Hemisphere.[2]

The forces that cause the deflection of horizontal movement of air which makes the low pressure area appear to the left in the Northern Hemisphere are an apparent deflecting force, the cyclostatrophic force and friction. The effect of the apparent deflecting force can be realized by considering a circular plane, rotating about its centre, O, with the angular velocity of the earth's rotation.

1. Lonstreth, T. M., Understanding the Weather, 1st edition.
2. Linsley, Kohler, and Paulus, Applied Hydrology, fifth edition, 1949.



Apparent Deflecting Force
<u>Figure 2</u>

If a particle is projected through the air from O to A, A being a point on the circumference of the circular plane, an observer in space would see the particle move from O to A in a straight line. However, in the time, t, required for the particle to travel the distance OA, A moves from A to A_t. An observer standing at O and originally facing A is facing A_t at the end of time t so from his standpoint the parth of the particle appears to have missed A_t, the final position of A, but has hit the original point A. Therefore, to an observer in the Northern Hemisphere, the particle seems to be deflected to the right.

The frictional resistance to wind always acts in the opposite direction to the motion of the wind. The net effect of friction is to cause an outward drift of wind in the direction of the pressure gradient. The frictional force diminishes with height and usually becomes negligible about 2,000 feet above the ground. The variations in the velocity of wind over land and water is due to the difference in frictional resistance provided by each surface. The velocity of the wind increases over water to a considerable extent in some instances.

The cyclostrophic force is caused by the particles of air being subjected to the centrifugal force due to the rotation of the earth. This force tends to drive the air across the isobars, thus slightly changing the direction of the wind.

Wind velocity depends upon the forces acting at the time of consideration. Hence, different combinations of these forces can be in effect to give different winds. In the next few lines the simplest of all winds, the geostrophic wind, caused by two forces will be considered.

The geostrophic wind is a steady horizontal flow of air which results when the pressure gradient force, F_g and the deflecting force F_d, balance each other. The velocity of this wind is given by the expression

$$v_G = \frac{1}{2w\ P_a \sin \emptyset} \quad \frac{\delta P}{\delta l}$$

where w is the angular velocity of the earth's rotation,

P_a is the air density,

$\emptyset$ is the latitude,

$\frac{\delta p}{\delta l}$ is the horizontal pressure gradient,

and v_G is the velocity of the wind.

Formula such as that given above are given for the other combinations of forces. However, in practice it has become the custom of engineers to base all designs affected by wind on the basis of the frequency and magnitudes recorded in the past. This so-called "hind-casting" is solely dependent on past records and therefore, weather records become extremely important. Weather stations throughout the world have been collecting data for many years. However, engineers confronted with the problem of a design wind velocity often find that the project is hundreds of miles from the nearest weather station. Therefore, it becomes very important to establish a weather station wherever a project is anticipated. Short term weather stations are of little importance by themselves, but combined with surrounding stations indications or trends can be predicted from the short term stations.

The anemometer is used for the measurement of wind velocity. Cup anemometers are most commonly used for official meteorological observations. Wind speed varies as height and it has become common in the past few years to take velocity readings at the 25ft level.[3] Wind velocities at different levels are commonly corrected to the 25 ft. level. This is done by a statistical formula,

$$\frac{V_H}{V} = \frac{H}{h}^{1/n}$$

where V_H = velocity in miles per hour at a fictitious height, H feet above the ground.

V = velocity in miles per hour at the actual station anemometer, h feet above the ground.

n = constant for condition of study.

3. U.S. Army, Corps of Engineers, Concepts of Surface Wind Analysis and Record Velocities, Project CW 178, Tech. Bulletin No. 1, 1959.

The term "n" is not constant for all possible conditions; it varies somewhat with height, ground cover, terrain roughness and air mass temperature gradient. In general n varies as height for which $1/n$ is $\frac{1}{5}$ to $\frac{1}{3}$ for heights below 6 feet, and $\frac{1}{n}$ is $\frac{1}{7}$ for greater heights than 6 feet. On the average, $\frac{1}{n}$ equals $\frac{1}{7}$ for high winds, and appears to be conservative for selection of design winds.

Fetch.

An area of water over which the wind is blowing and generating waves is known as the fetch length or fetch area. In ocean areas, the determination of the fetch area is a complex problem, as well as the determination of the wind velocity. Therefore, this report will deal with inland reservoirs where the fetch is limited by the physical dimensions of the reservoir, and the wind velocity is obtainable by direct measurement.

Due to the fact that inland reservoirs are small in area, the weather disturbance can be considered to cover the whole area. This eliminates the decay distance known in ocean areas, and the fetch of inland reservoirs is usually taken as the distance from shore to shore measured in the direction of the wind. Since wind directions are determined from weather station reports, the wind direction being given on an 8 cardinal point system and variation in direction of wave travel due to refraction is common, it is necessary to use the 30° semi sector rule to limit the possible fetch. That is, waves may be assumed to vary in direction by as much as 30° with direction and still be undiminished in size.

Relatively small reservoirs produce a problem not common to ocean waters. It has been realized that the width of fetch limits the height to which waves may rise. A method of determining the effect of fetch width is given by Saville[2]. Figure 3 is reproduced from this report. The graph is entered with a ratio of width to length and a corresponding ratio of the effective fetch to fetch is obtained. Simple multiplication gives the resulting effective fetch.

Waves.[4]

(a) Deep Water Waves.

Waves generated in deep water are of the type known as oscillatory waves, in which the particles of water making up the wave oscillate in a circular orbit about some mean position, as shown in Figure 4.

An oscillatory wave is well defined if the wave length, L (see Appendix A, List of Common Symbols), the horizontal distance between two successive crests; the wave height, H, the vertical distance to a crest from the preceding trough; the wave period, T, the time for two successive crests to pass a given point, and the depth, d, over which the particle moves, are known.

The velocity or celerity, c, with which an oscillatory wave progresses is related to the period and length by

$$L = CT \tag{1}$$

4. Beach Erosion Board, Corps of Engineers, Shore Protection Planning and Design, Tech. Report No. 4, 1961.

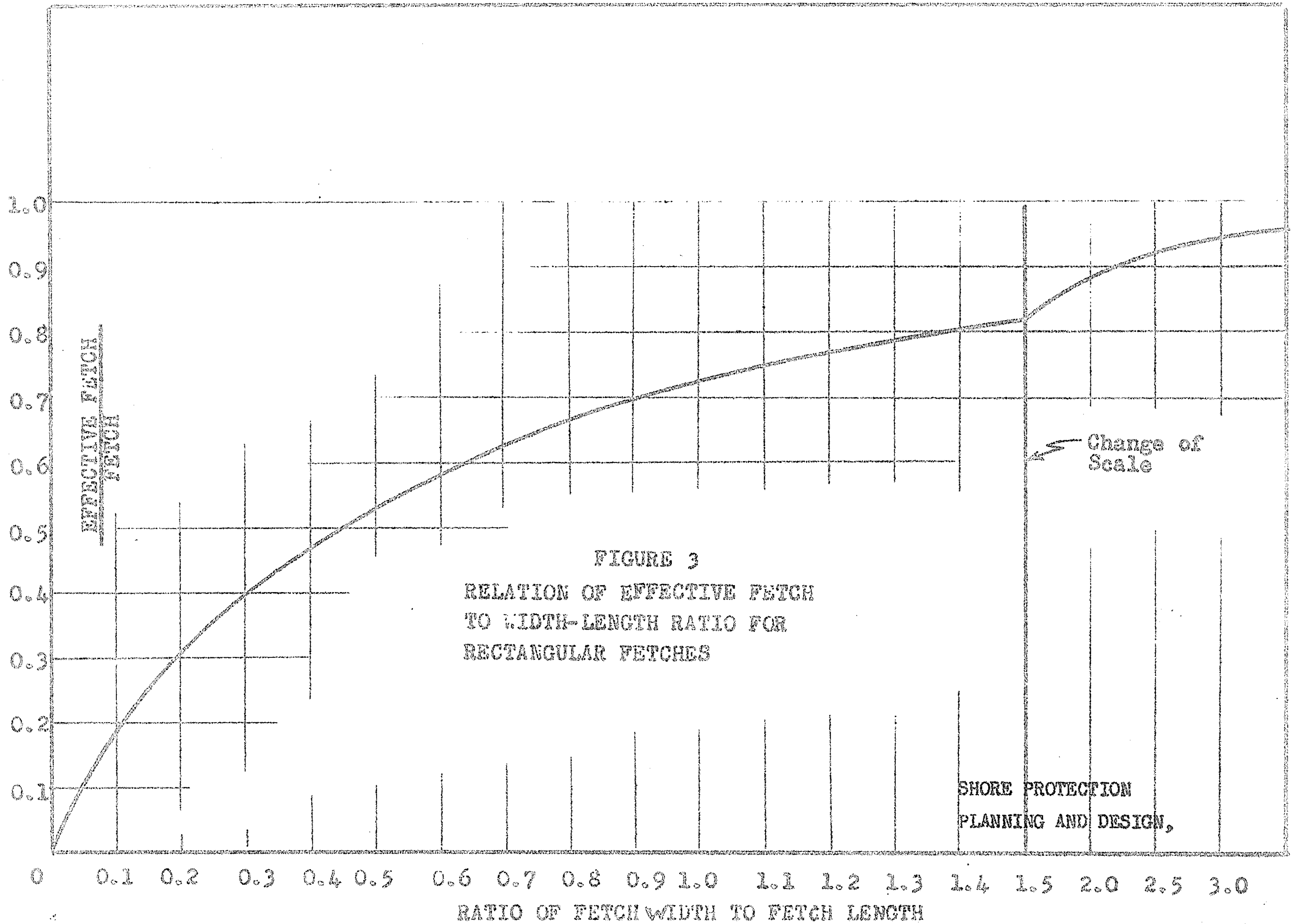
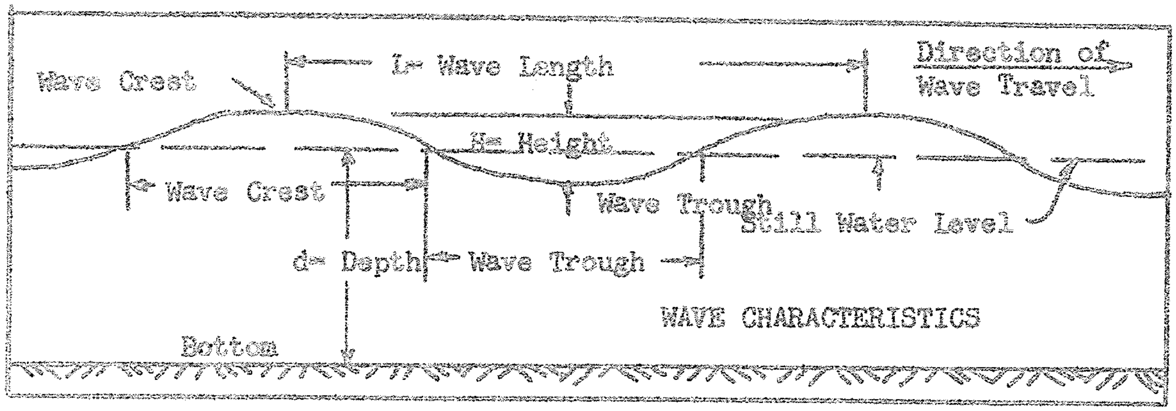
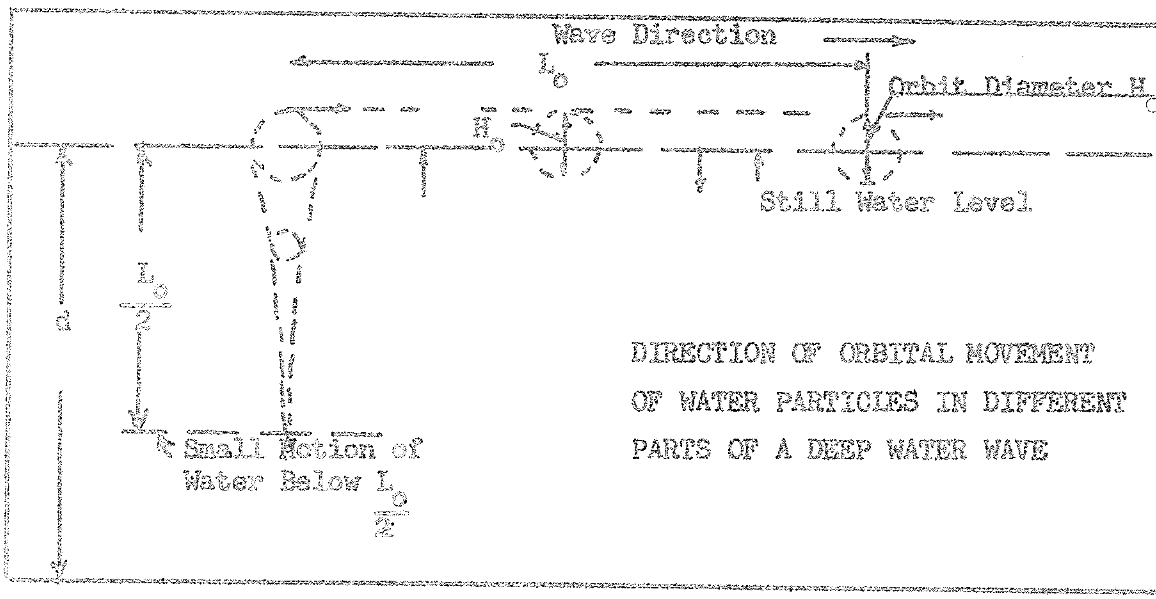


FIGURE 3
RELATION OF EFFECTIVE FETCH
TO WIDTH-LENGTH RATIO FOR
RECTANGULAR FETCHES





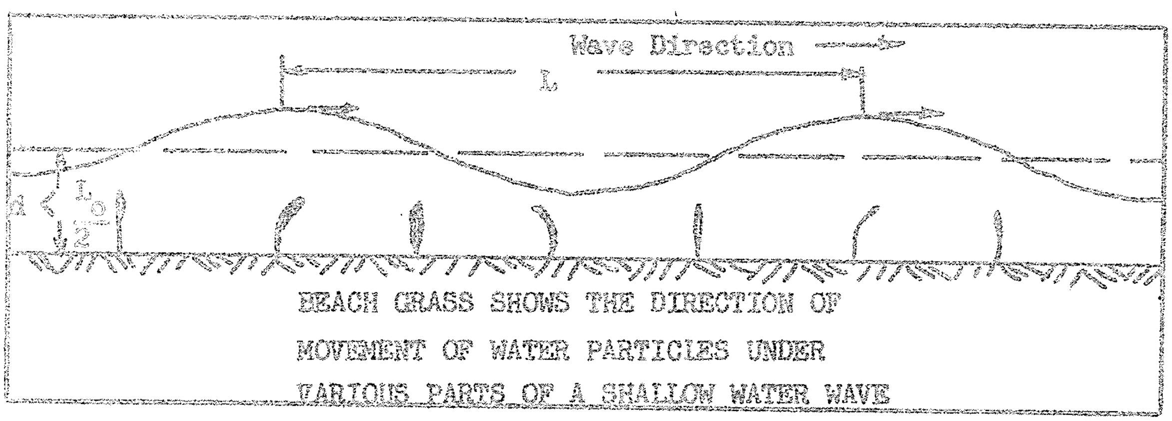


FIGURE 4 WAVE CHARACTERISTICS AND
DIRECTION OF WATER PARTICLE MOVEMENT

and to the depth and length by

$$C^2 = \frac{gL}{2\pi}\tanh\frac{2\pi d}{L} \tag{2}$$

where g is the acceleration of gravity and tanh is the hyperbolic function of the tangent.

As the water depth becomes large relative to the wave length, the hyperbolic tangent ($\tanh\frac{2\pi d}{L}$) approaches unity, the wave velocity becomes independent of depth, and

$$C^2 = \frac{gL}{2\pi} \tag{3}$$

This condition, where the depth is great enough so that the wave characteristic is independent of depth, is termed "deep water" and is generally noted by the subscript "o", as L_o and C_o. For deep water conditions, since $L_o = C_oT$, then

$$C_o = \frac{gT}{2\pi} \tag{4}$$

substituting numerical values for g and 2π, equation 4 becomes

$$C_o = 5.12T \tag{4a}$$

where T is in seconds and C_o is in feet per second and again since $L_o = C_oT$

$$L_o = 5.12T^2 \tag{4b}$$

Equation 4b is important in that latter chapters, T^2, will appear in dimensionless numbers as having the units of feet. This is due to the fact that the units of g are included in the term T^2.

Deep water actually occurs only at an infinite depth, but tanh $\frac{2\pi d}{L}$ approaches unity closely at much smaller ratios of depth to wave length. A ratio of "relative depth", that is depth to wave length, of 0.5 gives a value of tanh $\frac{2\pi d}{L}$ of 0.9963, and this relative depth by general usage has been accepted as "deep water".

Figure 5 shows the diagram that is presently used for predicting deep water wave heights and periods. This method of deep water wave forecasting is known as the Bretschneider revised, Sverdrup-Munk method. This diagram allows the determination of the significant wave height and significant wave period; which by definition are described as a statistical term denoting waves with the average height and period of one-third highest waves of a given wave group.

In using this diagram, the actual wind velocity U, the fetch length F, and that estimated duration t, of a wind must be known. The diagram is then entered with the known value of U on the right if the velocity is in statute miles per hour. The "U" line is then followed across to its intersection with the fetch line F, or the duration line t, whichever comes first from the left side of the graph.

As an example consider a wind of 50 miles per hour, duration of 8 hours, and a fetch length of 150 miles. Following the method given above it is found that the duration of the wind intersects the U = 50 miles per hour line first and therefore duration governs.

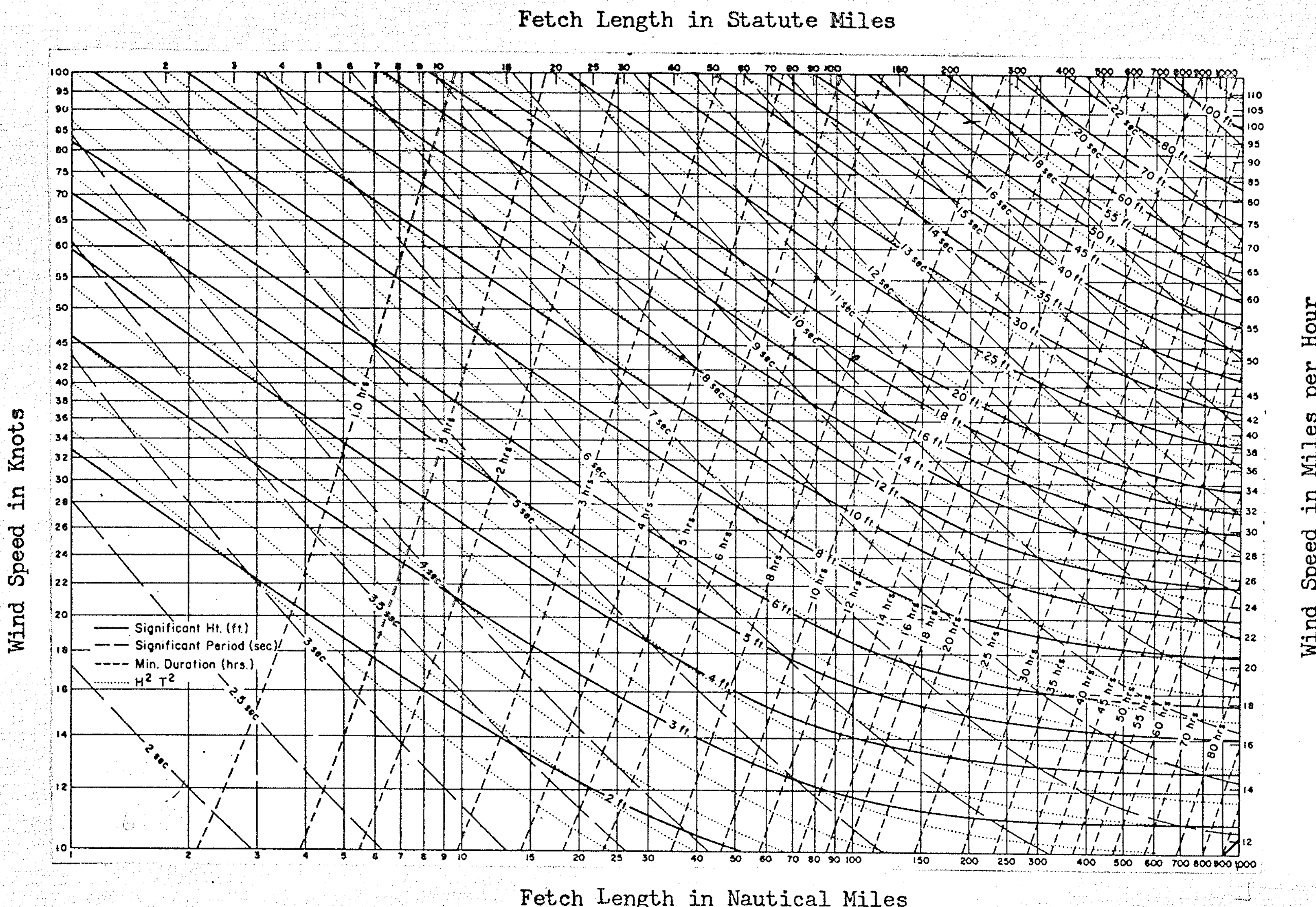


FIGURE 5 DEEP WATER WAVE FORECASTING CURVES AS A FUNCTION OF WIND SPEED, FETCH LENGTH, AND WIND DURATION

The significant wave height is found to be 18 feet and the significant period is 10 seconds. It can be noted from the diagram that for the same wind speed and fetch length as above, a wind duration of greater than 11 hours is required before the fetch length would govern the wave characteristics.

(b) Shallow Water Waves.

Shallow water is defined as water whose depth is less than 1/25th of the wave length. Waves generated in such areas are known as shallow water waves. Water having a depth between 1/2 and 1/25th of the wave length is known as "transitional".

The equations relating the wave characteristics given under the heading "Deep Water Waves" applies also to shallow water waves. However, the equation relating depth and length, equation (2)

$$C^2 = \frac{gL}{2} \tanh \frac{2\pi d}{L}$$

becomes very dependent on depth in shallow water. As the water depth becomes quite shallow the hyperbolic function $\tanh \frac{2\pi d}{L}$ approaches $\frac{2\pi d}{L}$ and the wave velocity becomes

$$C^2 = gd \qquad (5)$$

The formula given above will be recognized as the same expression giving the critical velocity of flow in a stream or channel. This means that a wave produced in a stream flowing at critical depth will not travel upstream nor downstream, but would remain "standing"; the wave produced being called a standing wave. A standing wave has no significance with regard to freeboard, but it is interesting to note this relationship.

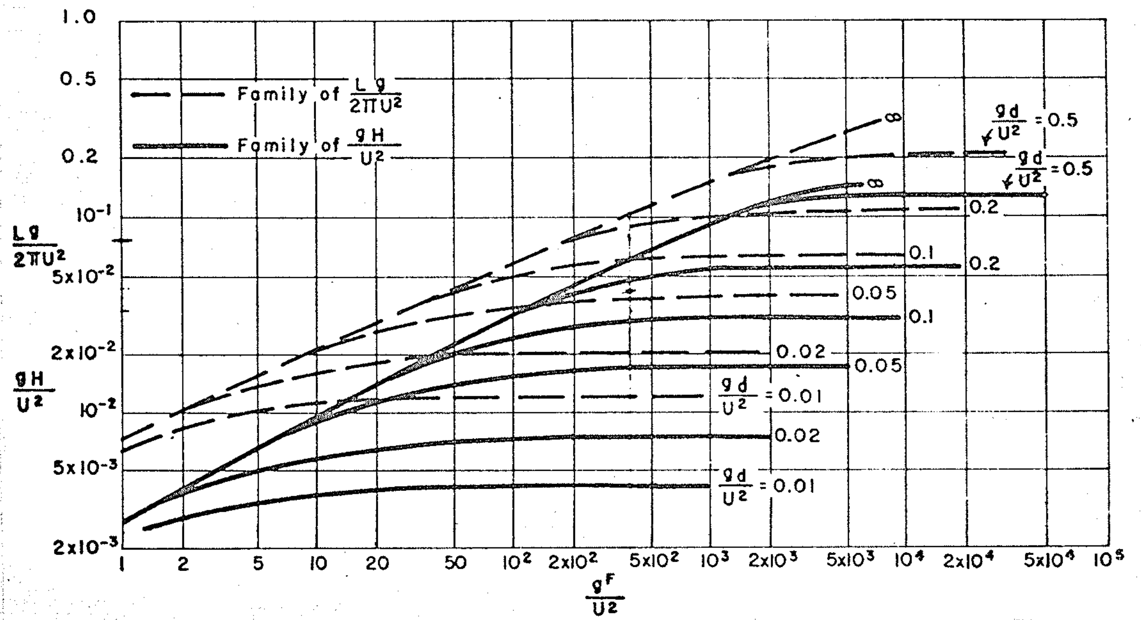
A method of forecasting shallow water waves is given by Thysse and Schijf.[5] The empirically determined relationships between forecasting parameters are presented in two sheaves of curves, both in Figure 6. To utilize the curves, the wind direction and the speed U, must be determined by any means available, usually wind records; and, the fetch length, F, in the wind direction measured. The relationships $\frac{gF}{U^2}$ and $\frac{gd}{U^2}$ are then calculated, where g is the acceleration due to gravity and d is the mean depth over the fetch, and the wind velocity U, in feet per second. Figure 6 is then entered with $\frac{gF}{U^2}$ as abscissa and followed to its intersection with the computed $\frac{gd}{U^2}$ curves, either plotted or interpolated. Values of $\frac{gH}{U^2}$ and $\frac{gL}{2\pi U^2}$ are read off as ordinates. Once these have been determined, simple multiplication enables determination of the fetch wave height, H, and the wave length L. The wave period may be determined from combining equations 1 and 2; that is

$$L = CT \tag{1}$$

$$C^2 = \frac{gL}{2\pi} \tanh \frac{2\pi d}{L} \tag{2}$$

Squaring equation (1) and substituting C^2 into equation (2) we find that

5. Thysse and Schijf, <u>Ocean Navigation Communication</u> IV, XVII International Navigation Congress Section II.



GROWTH OF WAVES IN A LIMITED DEPTH

FIGURE 6

$$T^2 = \frac{2\pi L}{g \tanh \frac{2\pi d}{L}} \qquad (6)$$

As an example consider the following conditions:

Fetch Length, F = 10 miles or 5.28×10^3 feet,

Wind Speed, U = 45 miles per hour - 66 feet per second,

Mean Depth in Fetch = 20 feet.

$$\frac{gd}{U^2} = 0.148 \qquad \frac{gF}{U^2} = 3.90 \times 10^2$$

Then from the curves in Figure 6, in which the solid curve is used to read the values of $\frac{gH}{U^2}$, and the dashed curve used to read values of $\frac{Lg}{2\pi U^2}$ it is found that:

$$\frac{gH}{U^2} = 3.5 \times 10^{-2} \quad \text{and} \quad \frac{Lg}{2\pi U^2} = 7 \times 10^{-2}$$

from which H = 4.7 feet and L = 59.6 feet. Equation (6) gives the wave period as 3.5 seconds.

Nomograph for Determining Size and Thickness of Riprap.[6]

The size of riprap to be placed on a slope is a variable if considering a new dyke or dam. It is not only important to know the riprap size, but also to know that the size of material selected is stable on a given slope.

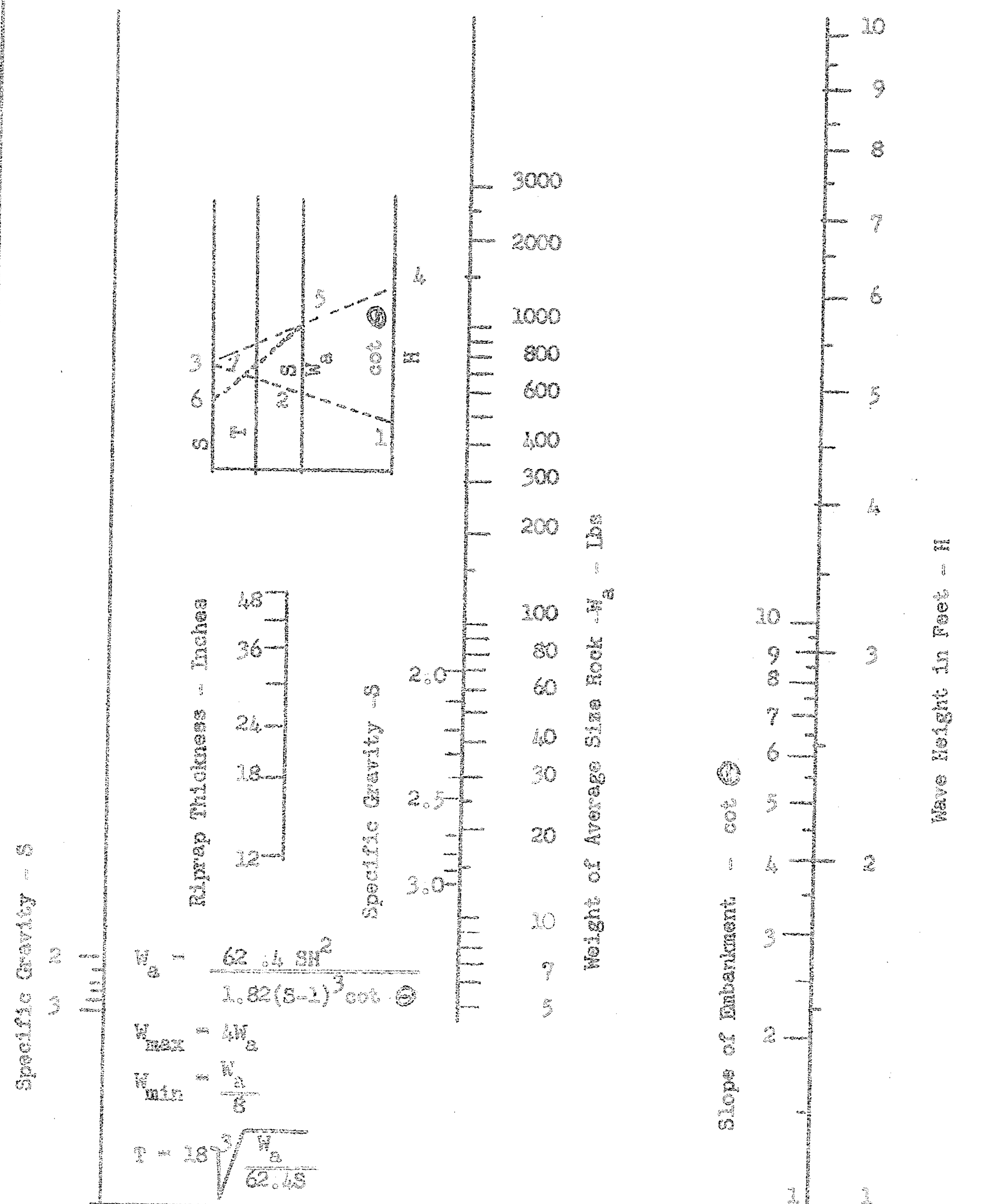
6. "Stone for Slope Protection Against Wave Action", by George E. Bertram, Crushed Stone Journal, March - June, 1962.

The nomograph on the following page, Figure 7, may be used to determine the size and thickness of riprap to be used for a given slope and wave height so that the riprap will be stable for design conditions.

Given the slope of the embankment, cotangent θ (1) and the specific gravity, S (2), locate point (3) on the left side. With the given design wave height (4), joint this to point (3), which locates point (5), the weight of the average size of rock. The maximum and minimum weight of rock may be computed from the equations appearing in the lower left corner of the nomograph. Reasonable tolerances of about 10 percent should be established for these limits in specifications.

The riprap thickness may be determined by drawing a line from point (5) to the specific gravity scale on the extreme left and where it crosses the thickness scale (7) the required thickness is read.

The method of obtaining the size and thickness of riprap material as given above has been derived from observations of riprap movement of a given size for waves of a given height. The resultant nomograph and formulae are of empirical nature and research on this subject could produce important data for the design size of riprap material.



$$W_a = \frac{62.4\,SH^2}{1.82(S-1)^3 \cot\theta}$$

$$W_{max} = 4W_a$$

$$W_{min} = \frac{W_a}{8}$$

$$T = 18\sqrt[3]{\frac{W_a}{62.4S}}$$

SLOPE PROTECTION NOMOGRAPH FOR GRADED RIPRAP FOR EARTH DAMS

FIGURE 7

Miscellaneous Variables.

The two most important variables; namely, wind and waves were discussed in the preceding pages. It is the purpose of the next few paragraphs to discuss a few more variables and their relation to freeboard.

Reservoir depth has been mentioned to the extent that it distinguishes between deep water waves and shallow water waves. Depth plays another important role in that it affects wind set-up to a great extent. In fact, depth is so critical at times in shallow water that the lake bottom becomes exposed, and special consideration of the problem is necessary.

The slope of a structure and the riprap size has no effect on wind set-up, but it does control wave run-up to a large extent. It has been proven that slope may vary relative wave run-up R/H_o' by a factor of 4.0 on smooth slopes,[6] and that for a given slope 1 on 3 that material size has varied wave run-up by a factor of 1.85.

It has been common in the past to take the effect of the angle between the axis of the structure and a line perpendicular to the crests of the incoming waves by reducing the wave run-up by the sine of the angle.

The shape of a reservoir has an important effect on wind set-up.[7] This is illustrated by considering a rectangular reservoir

6. Savage, Rudolph P. "Wave Run-up on Roughened and Permeable Slopes", Journal of Waterways and Harbours Division, Proc. Paper 1640.

7. Kuiper, Prof. E., "Flood Control", University of Manitoba, (unpublished) Page F17.

and a triangular reservoir of the same fetch length when the wind is blowing towards the apex of the triangle.

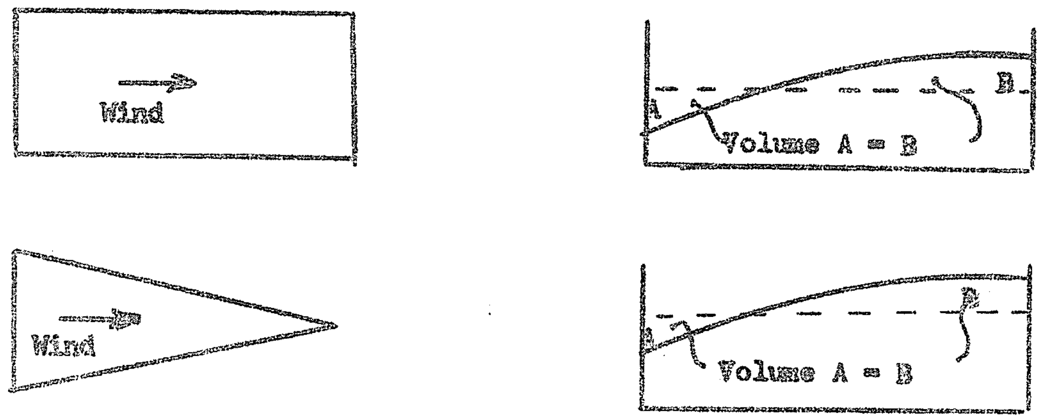


Figure 8

EFFECT OF SHAPE ON WAVE SET-UP

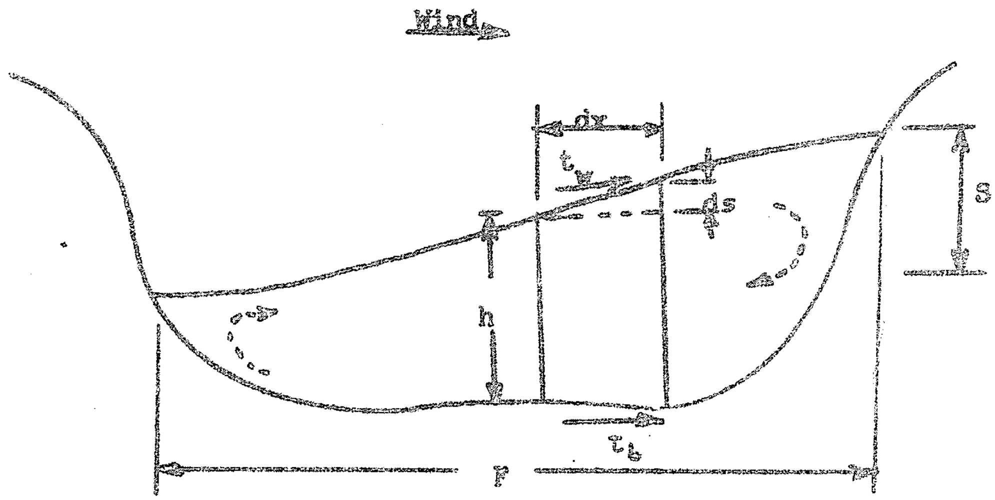
Since the slope of the water surface is only a function of the wind velocity and the depth, it is true that the shape of the water surface is the same in both cases. Also, the volume of water above and below still water level must be the same in both cases. Hence, the wind set-up must be greater in the triangular section by a factor of 1.3 in order that the shape of the water surface and the volumes of water in sections A and B remain constant in both cases.

Wind Set-up.

A wind passing over any water surface will induce a surface current in the general direction of the wind movement. The current of water is caused mainly by the tangential stresses between the wind and water at the water surface, and to a lesser degree by the difference in atmospheric pressure over the water surface, which at the same time is causing the wind. This surface current produces a piling up of water at the leeward side and a lowering of water level at the windward side with a return flow along the bottom. The difference in water level from leeward to windward side caused by wind-water tangential stress, and atmospheric pressure gradient is known as wind set-up.

Wind set-up has been measured in the field, and results show the importance of set-up in relation to freeboard. Observations on Lake Erie, having an average depth of 58 feet, showed that 12.2 feet of set-up occurred in the year 1909. In 1957, a similar set-up occurred where the difference in elevation from end to end was measured as 13.2 feet. Calculations and actual recorded water surface elevations along the lake have been compared, and results are shown in Figure 10, page 27.

The theory for the determination of wind set-up results from the forces acting on an element of water in the cross section of an inland reservoir shown below:



WIND SET-UP ON AN INLAND RESERVOIR

Figure 9

Considering the forces such as wind stresses to the right, bottom friction to the right, and excess hydrostatic head to the left acting on the element of water, the following equations result:

$$t_w . d_x + t_b . d_x = \frac{1}{2} p . g . (h + d_s)^2 - \frac{1}{2} p . g . h .^2$$

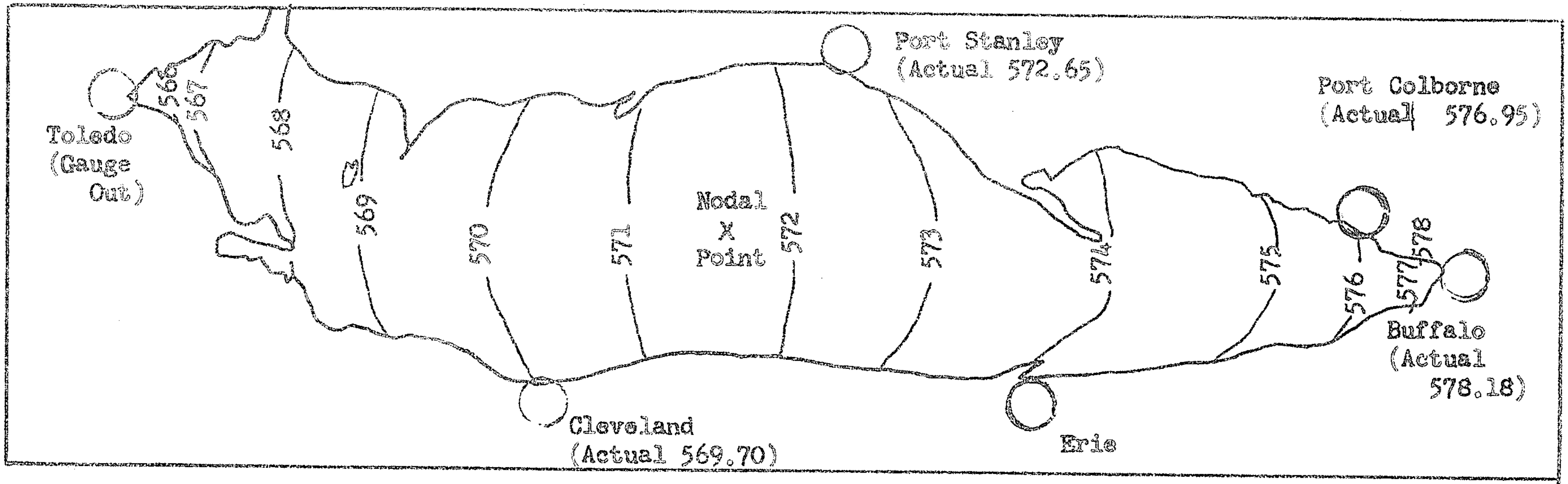
or $$(t_w + t_b)\, d_x = p.g.h.d.s.$$

and $$\frac{d_s}{d_x} = \frac{t_w + t_b}{p.g.h.} \qquad (13)$$

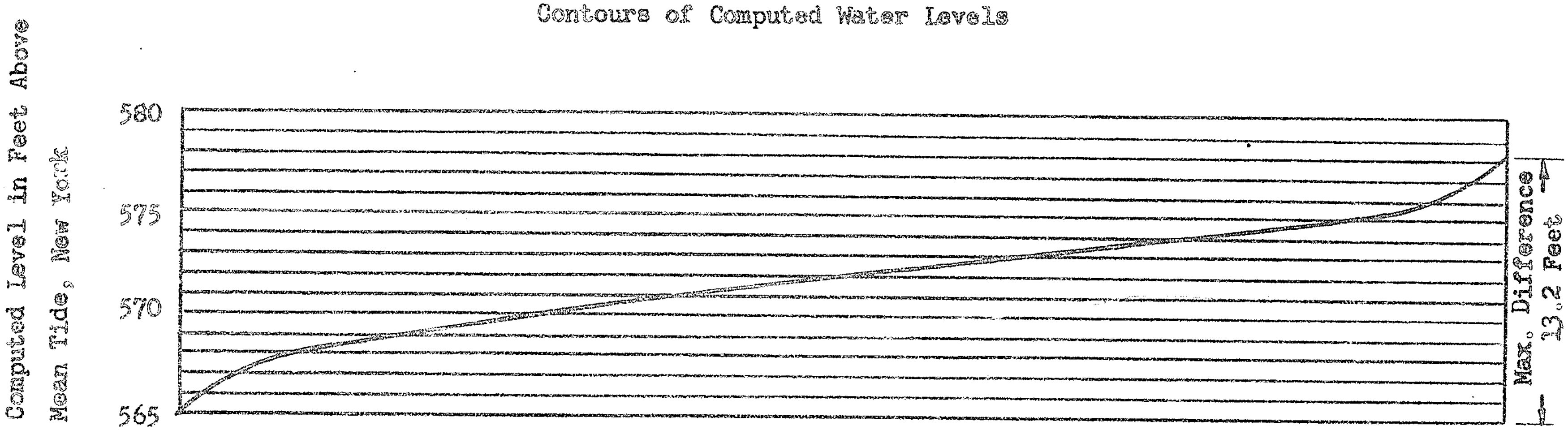
where $\frac{d_s}{d_x}$ is the slope of the water surface,

pg is the unit weight of water,

and h is the depth of water.



Contours of Computed Water Levels



Profiles of Computed Water Levels

FIGURE 10 WIND EFFECT ON LAKE ERIE

For simple cases in nature where the depth of water is constant, the reservoir is approximately rectangular in shape, and the wind velocity is constant, a formula for total wind set-up can be determined. It has been determined that the wind stress is proportional to the velocity of the wind squared, and that the bottom stress is only a fraction of the wind stress. Therefore, it can be written that

$$S = \frac{V^2 F}{CD} \tag{14}$$

where S is the set-up above stillwater level,

V is the velocity of the wind in miles per hour,

F is the fetch length in miles,

D is the average depth in feet,

C is a coefficient that has been determined to be 1600 on the Zuiderzee, Lake Erie, and Lake Ontario. It is common to find values of C equal to 800, but for such cases the wind set-up is defined as from leeward to windward sides.

It is interesting to note the difference in the water surface profiles of a body of water with a rectangular bottom profile and a bottom profile that is concave upward. The effect of depth on the shape of the water surface profile can be seen by comparing Figure 8 and 10. Since the only change in depth in Figure 8 is due to the wind set-up itself, very little change in the slope of the water surface is observed. However when the bottom profile is concave upward the depth becomes very small towards the shore and a considerable change in slope of the water surface takes place at both the windward and leeward sides as shown in Figure 10.

Situations in nature are common where the reservoir, or inland lake varies in depth and width, and where the wind velocity is not constant over the full length or fetch. In such cases, it is convenient to divide the reservoir into sections and to apply the wind set-up formula in terms of slope, starting at the nodal point. The nodal point is defined as that point on the still water surface that remains at the same elevation when the design wind is blowing. Methods of determining the nodal point, and of applying the slope equations to sections of a reservoir are given in "Shore Protection Planning and Design", Beach Erosion Board, Technical Report No. 4, 1961.

A suggested method of calculating wind set-up is given below:[8]

(1) Select the area to be investigated.

(2) Obtain all wind and water level data available from past storms.

(3) Investigate the physical factors which might affedt wind set-up elevations or computations.

(4) With the knowledge of available wind data and physical features, determine the most suitable approach to the investigation.

(5) Outline formulae and procedures for computation, and perform computations and compare with observations.

8. Corps of Engineers, U. S. Army, Shore Protection Planning and Design, Beach Erosion Board, Technical Report No. 4, 1961.

(6) Study the discrepencies between computations and observations, and attempt to reconsile these discrepencies. Make the necessary logical and justified changes in the procedures.

(7) Repeat the above procedures until satisfactory agreement is reached.

(8) Apply the design storm to the area using the calibrated method.

(9) Study the results and determine if the results are reasonable.

<u>Tides and Seiches.</u>

Tides are the periodical movements in the level of a water surface due to periodical effect of natural forces. These forces are the mass attraction of the water towards the moon and sun. Tides are of very significant height with regard to freeboard of sea and ocean shore structures. However, tides on inland lakes and reservoirs are of little importance and the effect is always neglected.

Seiches are standing waves of relatively long period which occur in lakes, canals, and reservoirs. The mechanics of such generation is not completely understood, although all available evidence proves rather conclusively that lake seiches are the result of sudden change, or a series of intermittent periodic changes in atmospheric pressure and corresponding changes in wind velocity. Seiches, along with inland tides, are of little significance when designing freeboard and their effect is usally neglected.

CHAPTER III

ABSTRACTS FROM THE LITERATURE ON WAVE UPRUSH

In the past ten years a large collection of information on freeboard has been made by the Beach Erosion Board, Corps of Engineers, Department of the Army, United States Government, which has been compiled into a book called "Shore Protection Planning and Design". This book is invaluable to anyone that is studying shore problems as well as freeboard.

The present author has attempted to review the literature to the extent that an estimation of wave run-up can be made from the presented material.

The following pages will be a review of the literature as given by the main contributors. There are many merits of presenting wave run-up data in terms of deep water wave theory. The first section of this chapter will deal with a method of converting wave run-up data in shallow water to equivalent wave run-up in deep water.

The remainder of this chapter will deal with the material of the authors dealing with the research completed on the subject of wave run-up.

Relationship Between Shallow Water and Deep Water Theory - Energy.[1]

The total energy per unit crest length in one oscillatory wave is given by

1. Corps of Engineers, U. S. Army, Shore Protection Planning and Design, Beach Erosion Board, Techncial Report No. 4, 1961.

$$E_T = \frac{1}{8} p g H^2 L \quad (1 - M \frac{H^2}{L^2}) \tag{7}$$

where $p = \frac{w}{g}$ and is the mass density of water, $p = 1.96$ sec.^{2}/ft.^{4} for fresh water and M is an energy coefficient defined as

$$M = \frac{\pi^2}{2 \tanh^2 (2\pi \frac{d}{L})} \tag{8}$$

It should be recognized that the total energy in the wave is not forward moving energy. Part of the energy represented by the oscillatory motion of the water in the wave form is referred to as the kinetic energy E_K; this kinetic energy in effect remains on location without advancing with the wave train. The remaining energy is represented by the fact that water has been moved out of the wave trough and appears above the mean level as the wave crest. The latter energy is referred to as potential energy, E_p, in the wave form; this energy, in effect, moves forward with the wave form and generally expends itself on the shore. The relationship holds that

$$E_t = E_K + E_p \tag{9}$$

The value of the potential energy, E_p, which is continually moving forward to the shore can be computed from the relationship,

$$E_p = n E_t \tag{10}$$

where $n = \frac{1}{2} \left[1 + \frac{4\pi d/L}{\sinh\left(\frac{4\pi d}{L}\right)} \right]$

In deep water, that is d/L equals 0.5, $\sinh \frac{2\pi d}{L}$ becomes very large and n becomes approximately $\frac{1}{2}$. Thus in deep water one-half the total energy of a wave appears as kinetic energy and one-half as potential energy.

In shallow water, $\frac{d}{L}$ becomes small and a very close approximation for total energy in a shallow wave derived from equation 8 is:

$$E_T = \frac{w H^2 L}{8} \qquad (11)$$

If it is assumed that when a wave is travelling toward shore that no energy flows laterally along a wave crest, then the transmitted energy remains constant between two lines drawn perpendicular to the wave crest. Lines drawn perpendicular to a wave crest are known as orthogonals. Considering deep water conditions, the transmitted energy between two orthognals is

$$E_o = \frac{1}{2} b_o E_t$$

where "o" refers to deep water conditions and b_o is the spacing between orthogonals.

Since a wave travels from deep water to shallow water the potential energy, or that energy represented by wave height, remains the same but the total energy decreases progressively as the kinetic energy of the wave in the shallow water may be expressed as:

$$E = n\ b\ E_t$$

where b is the spacing between orthogonals in shallow water

and n is the same as in equation 10.

If the potential energy in deep and shallow water is equated between the same two orthognals we find that

$$\frac{1}{2}\ b_o\ E_{to} = n\ b\ E_t$$

and

$$\frac{E_t}{E_{to}} = \frac{1}{2}\ \frac{1}{n}\ \frac{b_o}{b} \qquad (12)$$

and from Equation 10

$$\frac{H}{H_o} = E_t/E_{to}\ \frac{L_o}{L}$$

and equation 12 can be written as

$$\frac{H}{H_o} = \frac{1}{2}\ \frac{1}{n}\ \frac{L_o}{L}\quad b_o/b$$

The term $\frac{1}{2}\ \frac{1}{n}\ \frac{L_o}{L}$ is known as the shoaling coefficient, H/H_o.

The term b_o/b is known as the refraction coefficient. However, there is no spreading of orthogonals in the tests performed so that this coefficient is of little interest in the present study.

Wave Run-up.

Wave run-up is known as the vertical height to which water from a breaking wave will rise or run up on a given shore structure. This factor determines the top elevation to which the structure must be built to prevent wave overtopping and damage by erosion. The variables upon which wave run-up depends have been discussed in Chapter I. It is the purpose of this section to review design methods used to date for determining wave run-up.

Literature as late as 1950 states that wave run-up on smooth shore structures has been taken as 1.5 times the wave height.[2] Since that time much research has been done on this subject and results of the tests have shown rather conclusively that the determination of wave run-up is a complex problem involving several variables besides wave height. Results of tests indicate that run-up could be as high as four (4.0) times the wave height.[3]

Savage also tested the effect of roughness and permeability of riprap material on several slopes. These results are only valid for conditions where the depth of water at the toe of the structure is greater than three (3.0) times the deep water wave height. It has been shown by Saville[4] that varying the water depth at the toe of a structure has negligible effect on the relative run-up when the water depth at the toe of the structure is in the order of three (3)

2. Creager & Justin, "Hydro Electric Handbook", 2nd Edition, page 329.

3. Savage, Rudolph P, "Wave Run-up on Smooth and Roughened Slopes", Journal of the Waterways and Harbours Division, Proc. Paper 1640, Page 1640 - 10.

4. Saville, T. Jr., Journal of Waterways Division of the A.S.C.E., Vol. 82, April 1956.

times the deep water wave height or greater. Hudson[5] tested large diameter material, but for rubble mound breakwaters where no impervious layer or core was involved.

The next few pages will deal with the material given by the three mentioned authors on the subject of wave run-up.

Robert Y. Hudson, Wave Run-up, U.S. Army Engineer, Waterways Experimental Station, Vicksburg, Mississippi.

The tests conducted at this Experimental Station for the effect of wave run-up on rubblemound breakwaters were conducted from 1942 to 1950 inclusive. The primary function of a breakwater is to provide adequate protection from wave action in selected harbour areas. There is considerable experimental data in the literature concerning wave run-up on paved slopes, beach slopes and shore line structures, and a few theoretical methods of computing wave run-up on smooth slopes.

Although limited in scope, the small scale tests of wave run-up on sloping structures conducted by Granthem[6] provide some information on this subject. Granthem's tests were conducted in a manner that approximated the action of waves on a rubble-mound breakwater. Although derivation of a theoretical basis for interpretation and correlation of the test data was not attempted it was believed

5. Hudson, R. Y., "Laboratory Investigations of Rubble Mound Breakwaters", Proc. of Waterways and Harbors of A.S.C.E. Vol. 85, Paper No. 2171, 1959.

6. Granthem, K.N., A Model Study of Wave Run-up on Sloping Structures, University of California Technical Report Series 3, Issue 348, Berkeley, California, 1953.

that the important parameters suggested by Granthem's tests could be used to correlate data obtained in the tests by Hudson. Granthem concluded from the results of his tests that the primary variables affecting wave run-up are: the wave steepness (H/L),[7] the relative depth (d/L), the angle of the seaside slope (θ), and the porosity of the structure (P). Hydraulic roughness of the slope, r, thickness (t), and the obliquity of wave attack β, are also believed to affect wave run-up. Thus correlation of the run-up data for rubble mound breakwaters may be accomplished by the functional relationship

$$R/H = f(\theta, H/L, P, \frac{d}{L}, r, \beta, t)$$

Since in Hudson's tests the porosity was constant and the wave obliquity was 0 degrees the functional relationship reduces to

$$R/H = f(\theta, H/L, \frac{d}{L}, r, t)$$

The tests were performed in a flume 119 feet long, 5 feet wide and 4 feet deep. The breakwaters were hand placed in the flume and the waves mechanically generated to determine the wave run-up. The run-up was measured by visual observation. The average of five individual readings was recorded for each side wave used in the testing of each section. Each of the five individual readings represented the average run-up for a wave train consisting from 10 to 15 waves.

7. See Notation in Appendix A, page 84.

Results of the run-up observations are presented graphically in Figure 11. These data show that the wave run-up factor (R/H) is a function of the breakwater slope, wave steepness and, to some extent, the hydraulic roughness of the breakwater surface. The effects of relative depth are obscured by the wide range of scatter in the observed values of run-up, which is attributed to difficulties in defining and observing the extent of run-up on a rough, porous, sloping surface, and the complexity of the phenomenon of wave motion on rubble mound slopes. The range of scatter should be even larger for wave run-up measurements on full scale structures. Therefore, it is believed that the upper limits of the envelopes of data points, indicated by the solid lines in Figure 11 should be used in selecting design crown elevations when overtopping of a proposed rubble mound breakwater cannot be tolerated.

The test data show that breakwater slope and wave steepness are primary variable affecting wave run-up on porous rubble mound breakwaters of the type tested. Within the range of test conditions used to date, R/H decreases when either cot θ or d/L is increased.

The tests were not designed to study the effects of the hydraulic roughness of the breakwater surface on wave run-up. The results of the tests on the 1 on 2 slope are on only one size stone, which was approximately 0.10 pound size stone. The tests on the 1 on 4 slope used 0.10 and 0.30 pound size stone, but the results are not noticeably affected by the stone size.

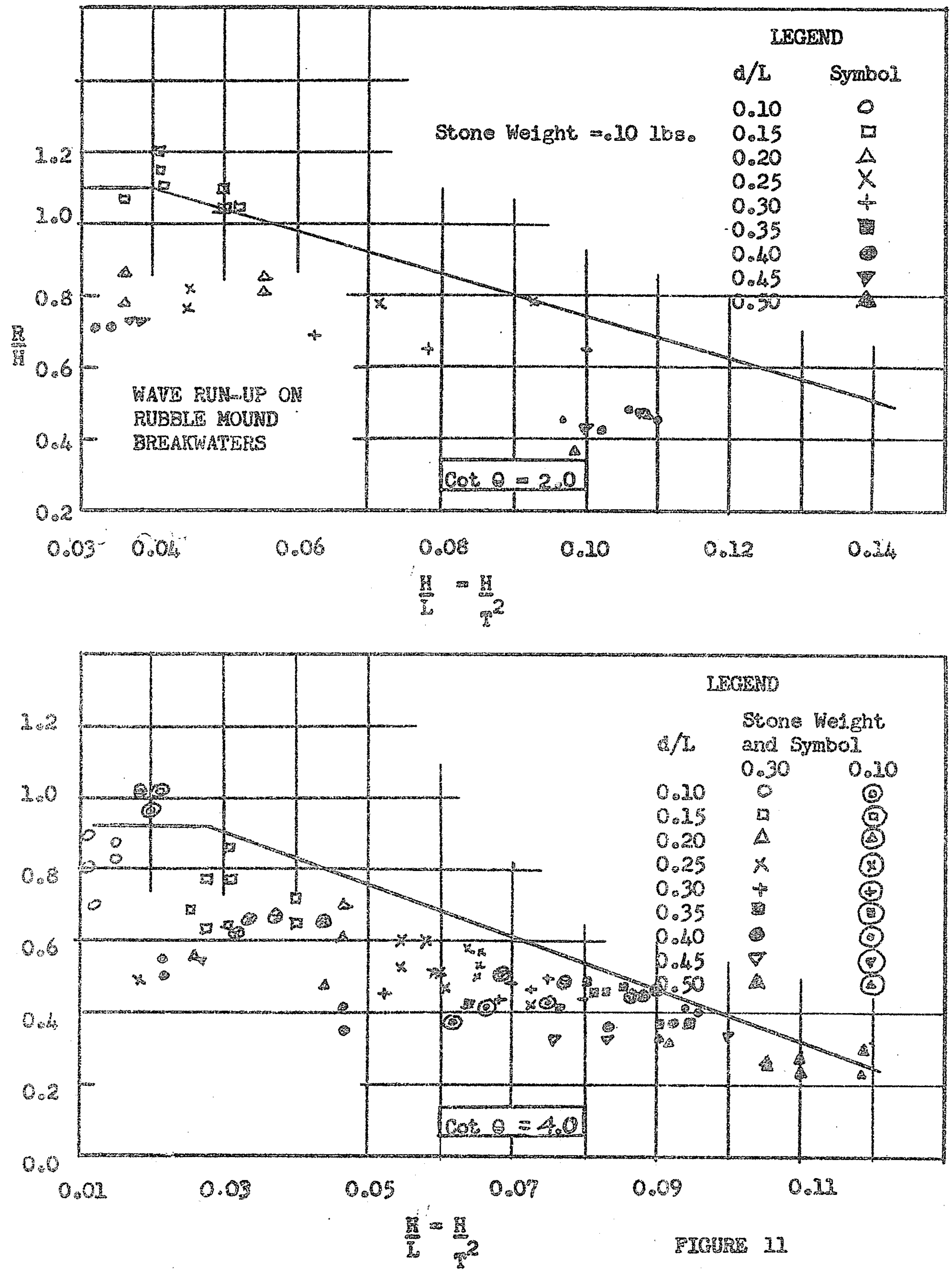


FIGURE 11

Hudson

The results of tests on a slope of 1 on 5 on which both sizesof stone were used did show that the size of stone does affect wave run-up.

Hudson concluded from the tests conducted that for the conditions tested, in which the H/d ratio was comparatively small, the stability of rubble mound breakwaters is not appreciably affected by variations in the d/L and H/L. The tests indicated that the breakwater slope (cot θ) and wave steepness H/L are the primary variables affecting wave run-up on rubble mound breakwaters where the H/d ratio is sufficiently large so that breaking waves do not occur on or seaward of the breakwater slope; and that, wave run-up decreases when values of either H/L or cot θ are increased.

<u>Saville, Thorndike, Jr., Wave Run-up on Shore Structures, Waterways and Harbors Division, A.S.C.E., 1956.</u>

A need for more adequate design data on the height of wave run-up on shore structures had long been evident, with many protective structures along the shores of rivers, lakes, reservoirs and the oceans having been designed to meet run-up requirements, that is freeboard, by essentially rule of thumb methods rather than on a sound factual basis. Such methods as multiplying the maximum expected wave height by an arbitrary factor of 1.5 to obtain a value of the wave run-up has been common in the past.

Recognizing the lack of basic data, the Beach Erosion Board, as a part of its general research program on factors basic to shore protection and the design of shore structures, initiated in 1952 a comprehensive test program of a generalized nature on wave run-up and its accompanying factor wave overtopping. The tests were carried out at the Beach Erosion Board in a steel wave flume 96 feet long, 1.5 feet wide, and 2 feet deep. Waves were generated by a pusher type wave generator in which the wave period could be regulated by varying the speed of the motor, and the wave height by varying the eccentricity of the plunger arm.

The purpose of the tests was to determine wave run-up on shore structures due to wave action, and to show the effect of wave steepness, H/L, the structure depth d, and the type of structure. Since the type of structure limits the results to a great extent, the present author will eliminate any data given by Saville that is not related to run-up on smooth and rough slopes.

The tests were conducted in the same manner as those tests performed by Hudson. The difference in the tests was that Saville varied the depth of water at the toe of the structure for every test slope, and hence with the four different depths of water there were four corresponding sets of data for each slope that was tested.

The data was presented in graphical form using the dimensionless parameter relative run-up R/H_o' as the ordinate and the dimensionless parameter proportional to the wave steepness H_o'/T^2 as the abscissa. The data was presented in terms of isolines of structure depth d/H_o'. From these graphs it was concluded that run-up on a structure depends on the wave steepness H_o'/T^2, and on the depth of water at the toe of the structure unless the depth is greater than 3 times the wave height in which case no effect on wave run-up was recorded.

The report given by Saville was concluded by stating that the curves presented should enable more adequate designs of necessary wall crest elevations, although additional work remains to be done to provide complete data for the full range of pertinent design problems.

Savage, Rudolph P., Wave Run-up on Roughened and Permeable Slopes.

The tests conducted by Savage were with the Research Division of Beach Erosion Board and were completed in 1958. The literature presented is the most recent published material on the subject of wave run-up.

These tests were performed to find the effect of roughened and permeable slopes on wave run-up on a relatively gentle slope of one on thirty to a vertical wall.

The tests were conducted in a wave tank 96 feet long, 2 feet deep, and $1\frac{1}{2}$ feet long. The waves were generated by a vertical bulkhead push-pull type generator driven through a varidrive unit by a $2\frac{1}{2}$ h.p. electric motor.

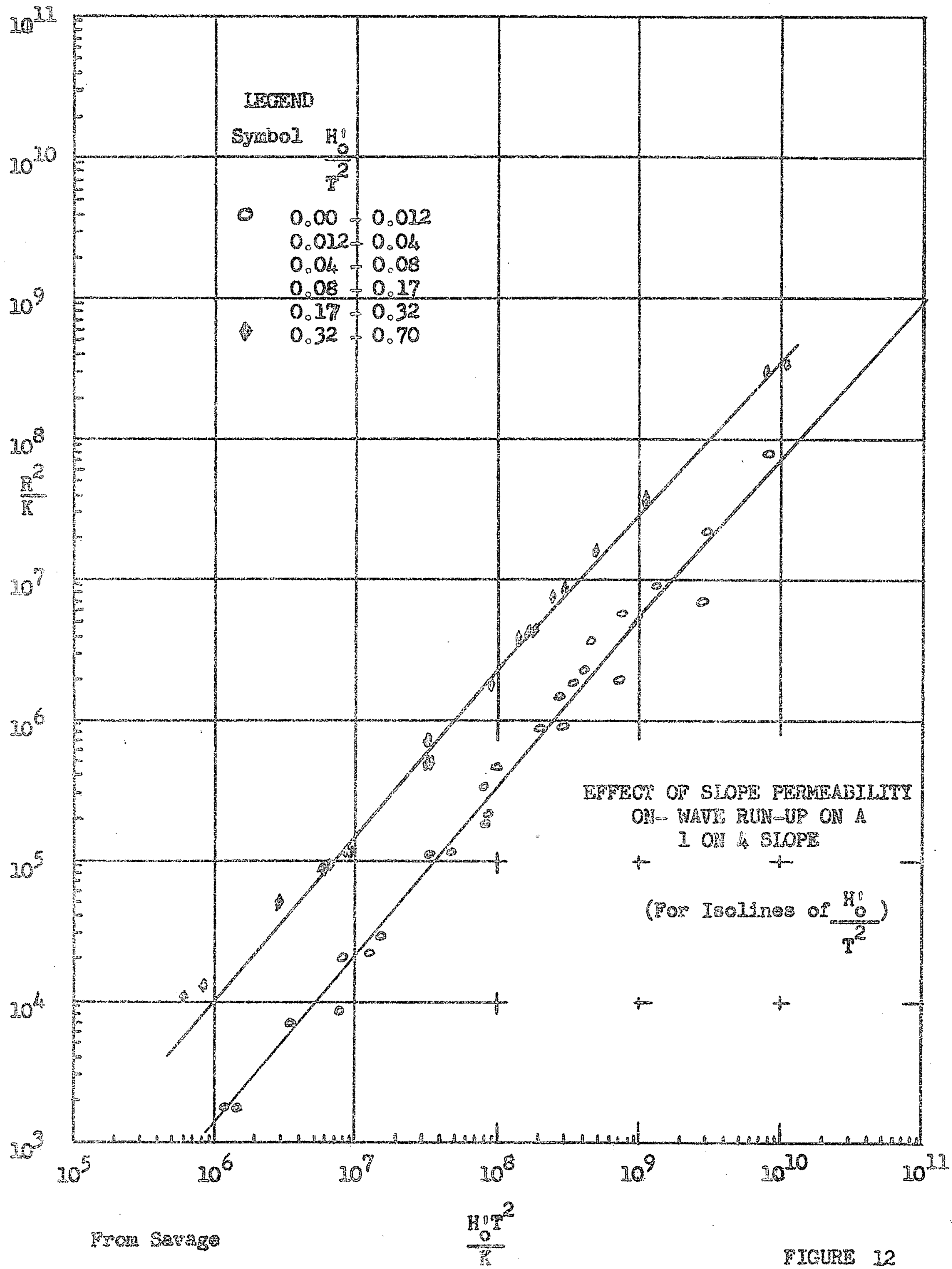
The effect of roughness was tested by covering the smooth slopes with a single layer of material glued to the slope; the effect of permeability K, was tested on slopes composed entirely of the material to be tested. The diameter of materials tested ranged from 0.20 mm to 10 mm, and the permeability ranged from 0.033×10^{-8} to 14.1×10^{-8} feet^2.

The wave characteristics were determined by calibrating the wave generator for the 1.25 foot water depth. The wave generator was calibrated by placing a wave absorber in the beachend of the wave tank and generating a wave of known and reproducible settings on the generator eccentric and varidrive. The wave height and wave period was measured, and the procedure repeated for each combination of wave heights and wave periods used in the tests. With the measured wave heights, wave periods and water depths the deep water wave characteristics were calculated using shallow water wave theory.

The different roughness materials were glued to the range of slopes tested, and the different materials used to build different slopes for the tests to determine the effect of permeability on wave run-up. The recorded and calculated data was then plotted in terms of dimensionless numbers on logarithmic paper. The smooth plywood slopes were tested by placing the slope in the wave tank and measuring the wave run-up for waves of given characteristics. The smooth slope data was plotted in the form shown in Figure 15 of the data of the present study. The relative run-up R/H_o' was plotted against the deep water wave steepness, H_o'/T^2 for each slope. From these curves a smooth composite graph similar to Figure 19 was drawn which shows the effect of slope on relative run-up.

The data from wave run-up tests on roughened slopes were shown in the same form as that in Figure 21 of the present study. These are dimensionless plots of R/d where R is the wave run-up and d is the median diameter of the material tested, versus $H_o'T^2/d^2$ functions as the reciprocal of a dimensionless roughness coefficient.

Figure 12 shows the form in which the effect of slope permeability on wave run-up was represented for various slopes. This figure is of only one slope, 1 on 4, but it shows the characteristics



From Savage

FIGURE 12

of the effect of permeability.

Savage concluded from the tests performed that the dimensionless plots of wave characteristics and wave run-up as shown throughout the results are very satisfactory and it is recommended that all data on wave run-up be plotted using these same parameters in order to allow comparison of results. Other general conclusions were that for a particular slope the wave run-up increases as the wave steepness decreases; the effect of roughened slopes on wave run-up increases as the parameter $H_o'T^2/d^2$ decreases; and that the effect of slope roughness on wave run-up increases as the wave steepness H_o'/T^2 decreases. Also, for a constant H_o'/T^2 and $H_o'T^2/d^2$, the effect of slope roughness on wave run-up decreases as the slope steepens.

The conclusions drawn from the tests on permeable slopes were that the wave run-up squared is related to the inverted permeability coefficient $\frac{H_o' T^2}{K}$ for isolines of H_o'/T^2; and that the effect of permeability appears greater than the effect of roughness but it must be remembered that the tests on permeability incorporate the effect of roughness in the results. In both the roughness and permeability tests, the effect of the slope roughness or permeability on wave run-up increases as $\frac{H_o'T^2}{d^2}$ or $\frac{H_o'T^2}{K}$ decreases and as the slope becomes flatter.

In the conclusions made by Savage it is stated;

"The results of run-up tests on smooth and roughened slopes should be applicable to prototype conditions when the dimensionless parameters involved are within the range of the dimensionless parameters given in the graphs, with the possible exception of conditions where the diameter of the roughness material equals or exceeds the impinging wave heights."

Therefore, it is the purpose of the present study to confirm the tests performed by Savage: and, furthermore, to provide design charts for wave run-up when the median diameter of the roughness material is in the same dimensional range as the impinging wave heights.

CHAPTER IV

THE MODEL, WAVE GENERATOR, AND TEST PROCEDURES.

Most models are built for one specific prototype. In such cases data observed from the model is immediately transformed into the corresponding data in terms of the prototype. This transformation of data is done in accordance to the laws of models, depending on what factors govern the particular phenomena. Each predominant force gives a corresponding set of model laws. It is possible that one model may have more than one predominant or governing force, whereby it is common to derive relationships to express the model data in terms of the prototype combining both forces. Forces governing hydraulics have had dimensionless numbers determined for each force. Some of the dimensionless numbers have particular names. For instance, the Froude number is used when gravity forces dominate; the Weber Number is used when surface tension dominates.

A dimensionless number is a number that is made up of quantities having the physical dimensions and combined in such a manner that the dimensions cancel and the resulting number is pure or "dimensionless." The concept of models is derived from dimensionless numbers. A dimensionless number, made up of magnitudes observed in one occurrence, will be exactly the same as the dimensionless number made up of homologous magnitudes in a similar occurrence. From this statement it follows that if a phenomena can be set up in the laboratory so that the occurrences resulting are the same as those happenings occuring in nature that dimensionless numbers can be derived to express both phenomena; that is, model and prototype.

The Model.

The model consisted of waves of known characteristics produced by a wave generator, as described below, breaking and running up on beaches of different slopes and surface material.

Waves[1] are produced by gravity forces and therefore they must be modelled in accordance to the Froude Law. In determining the size of waves to be tested it was necessary to limit the waves to such a size that no capillary waves were produced. The smallest wave tested was in the order of 100 times larger than a capillary wave and the effect of surface tension would be negligible. The largest wave produced was 0.580 feet in height, larger waves being limited by the height of the flume.

The beach was modelled by placing any given slope in the flume, and then this plywood slope was covered with a 4" layer of the material to be tested. The materials were of such a size that the waves tested could not produce any noticeable movement in the material. The wave run-up was the dimension to be measured in the laboratory, and it was not necessary to model the riprap material with respect to specific gravity or any other physical quantity since the stability of riprap material with respect to wave characteristics was not considered in this particular study.

1. The Committee of the Hydraulics Division on Hydraulics Research, Hydraulic Models, A.S.C.E., 1942.

Wave Generator.

The mechanism was designed to produce wave of various heights and periods, and was fitted to one end of an existing flume which had the dimensions of 44 feet long, 3 feet wide and 2'-4" high. The flume was of convenient size for wave run-up tests since the sides of the flume were glass at the end in which the slopes were placed, allowing observations to be taken very easily. A schematic diagram is given showing the generator in Figure 13 and Picture No. 1. The slope 1 on X shown in Figure 13 has been expressed as a function of cot θ as shown in Table 5, Appendix B.

The paddle inducing the energy and producing the waves was made of plywood and fitted to the cross sectional area of the flume allowing $\frac{1}{4}$ inch clearance at all sides. The paddle was driven by an arm of adjustable length. This arm, as shown in Figure 13, was connected to an eccentric arm which was solidly attached to a 1" diameter shaft, driven by bicycle accessories from another shaft of the same dimensions, but of twice the length. This second shaft had only one function; that is it allowed a speed ratio change of 9:1 simply by substituting pulleys with different numbers of teeth.

The input power was supplied by a 5/8" air drill, which has several advantages over other methods of producing waves with variable period. Due to the fact that variable speed alternating current motors are not manufactured and to the fact that direct current is dangerous around water, even though variable speed may be achieved, electric motors were considered not satisfactory.

The drill was supplied by a $\frac{1}{2}$" air line running from

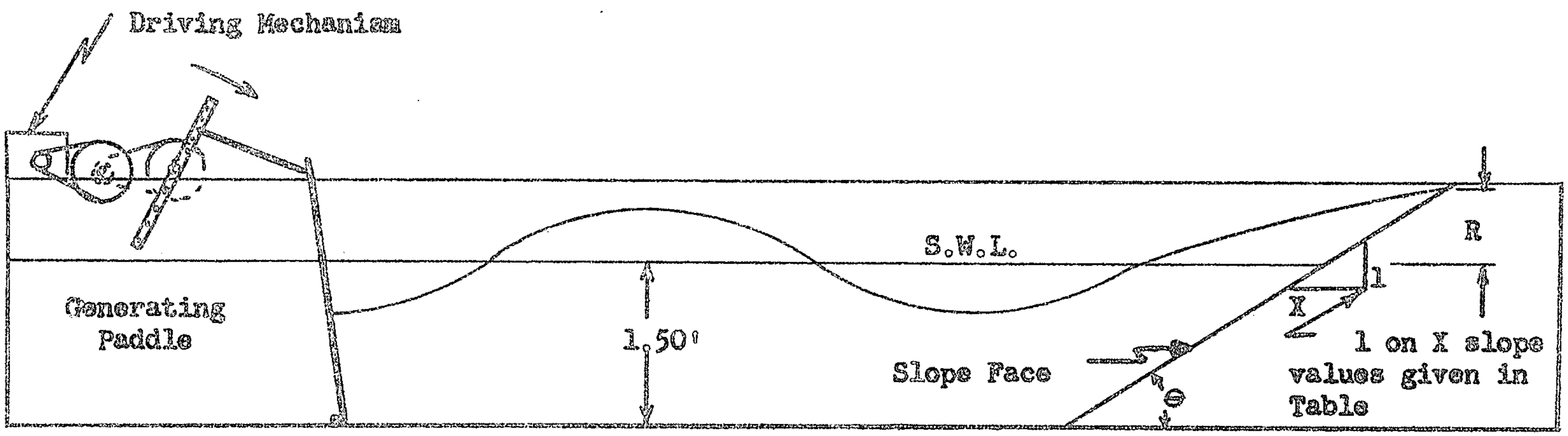


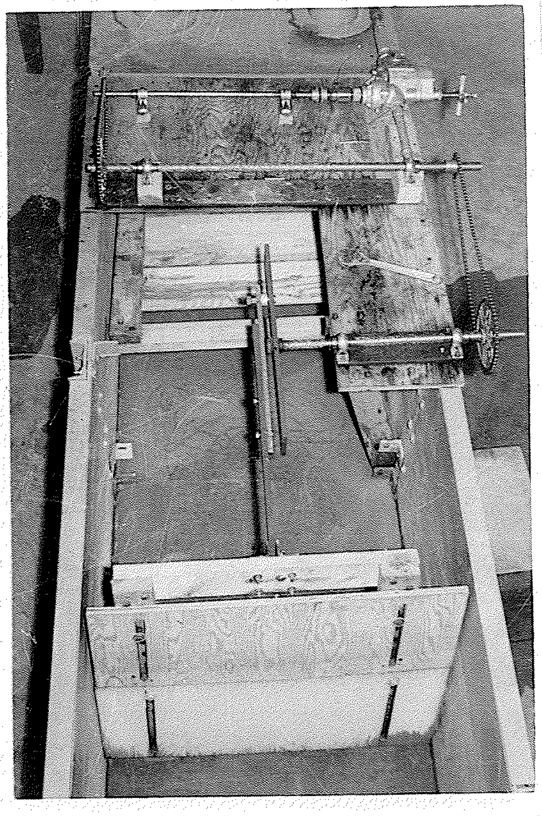
FIGURE 13 SCHEMATIC DIAGRAM OF MODEL SET-UP FOR WAVE RUN-UP TESTS

the Mechanical Engineering Department air compressor. This compressor maintains the tank pressure between 80 and 100 psi. (pounds per square inch) automatically. A reducer valve in the line allowed complete control of the pressure entering the air drill, simply by turning a dial. The losses in the line allowed a maximum pressure at the drill of 65 psi, but the maximum pressure during tests was regulated to 44 psi. The dial could be closed so that no pressure was obtained on the output side of the valve.

The variation in pressure from zero to 44 psi allowed a complete and continuous series of waves ranging in period from zero to 4.0 seconds. Calibration of the gauge allowed the 6 chosen wave periods to be set within at least $\pm$0.1 second accuracy.

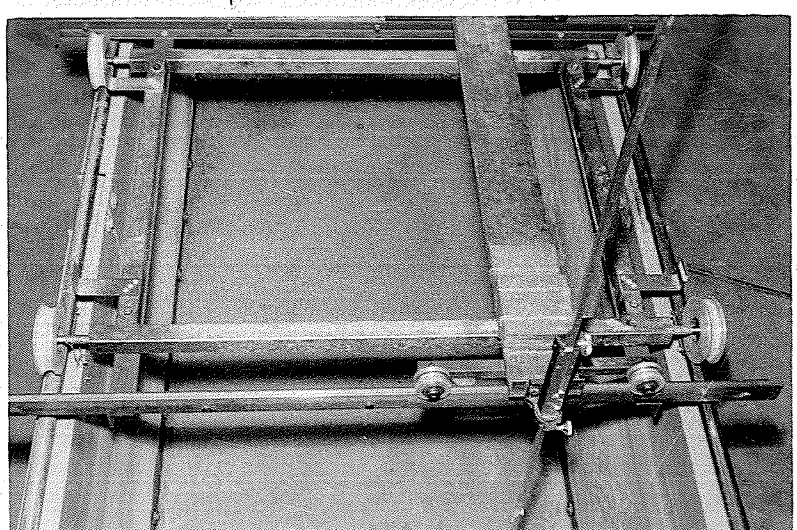
The wave height was changed by varying the eccentricity of the driving arm on the driving shaft. Waves ranging in height from 0.01 to 1 foot could be attained. However, in actual testing waves no smaller than 0.075 feet nor larger than 0.580 feet were tested. Heights of these waves were measured to the nearest $\pm$0.005 feet. Water depths were measured with a point gauge and vernier which could be read to the nearest $\pm$0.001 feet.

The wave heights and run-up were measured by the two-way point gauge shown in Picture 2. This gauge can move longitudinally or laterally on the flume. The wave heights were measured by marking the crest and trough of the wave on the glass panel of the flume with a wax pencil. The lateral movement of the point gauge allowed the measurement of the wave height. The wave run-up was measured directly since the still water level was constant for each test.



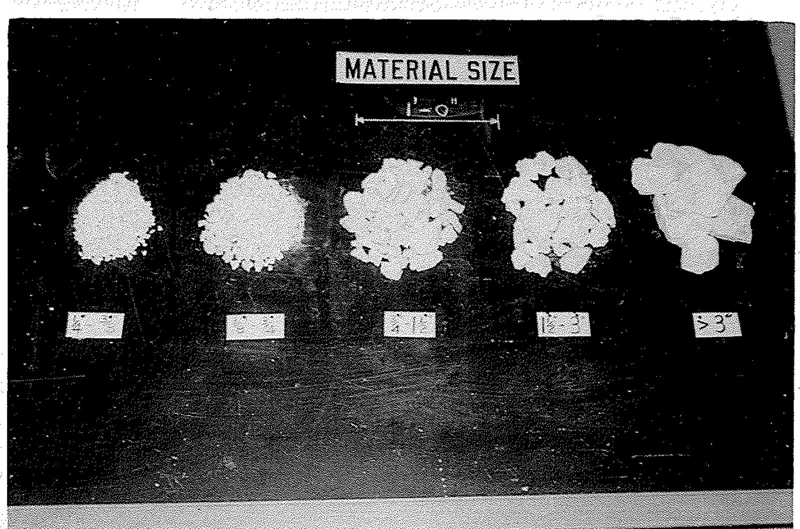
PICTURE 1

WAVE GENERATING APPARATUS



PICTURE 2

TWO-WAY POINT
GAUGE



PICTURE 3

RELATIVE SIZE
OF TESTED MATERIAL

The two-way point gauge moves longitudinally on two rails fixed securely to the top of the flume. The elevation of the rails was checked by filling the flume partly full and measuring down to the horizontal water surface. The rails were found to be parallel to the water surface.

Test Procedure.

The theory given in Chapter II and III gives indication that if wave run-up tests are performed in deep-water then the results can be used for any deep or shallow water condition in nature. In order to maintain deep water conditions; that is, relative depth, d/L, greater than 0.5 and to test waves of 4.0 second period, it can be seen from equation 4b in Chapter II, $L_o = 5.12\ T^2$, that a depth of 40.8 feet is required. This dimension of depth is impossible to obtain in most laboratories. Therefore, it has become the practice to test shallow water waves with a depth of water greater than three times the deep-water wave height or greater, since Saville[2] proved that if the above condition exists in shallow water that the wave run-up is affected negligibly. Since the wave run-up corresponds to deep water conditions, the equivalent deep water wave height can be obtained from the measured wave height by use of the shoaling coefficient.

The tests were arranged so that waves to a height of 0.50 feet could be tested. Therefore, a depth of water of 1.50 feet was required so that wave run-up would be unaffected by depth.

2. Saville, T., Jr., Wave Run-up on Shore Structures, Journal of Waterways Division of ASCE, V. 82, 1956.

The flume was filled to a depth of 1.50 feet and a wave absorber placed in the opposite end to the wave generator. The wave height was varied by changing the eccentricity of the driving arm, and the wave period was varied by changing the input pressure into the air drill. In this manner variations were made until a convenient wave period was obtained and a complete range of wave heights were obtained for each given wave period. After several trials and variations a complete test pattern was arranged. The wave absorber allowed several waves to be calibrated before the interference of waves became prominant. The wave absorber consisted of a frame around the inside perimeter of the flume. Horizontal vanes were connected by hinges to the frame and allowed to lap over one another. This frame was placed at approximately 4 feet from the end of the flume, allowing a wave to pass through the frame by opening the vanes, but the rebounding wave off the end of the flume automatically closed the vanes thus eliminating rebounding waves in the area of wave characteristic measurements. Before each slope was tested, the test pattern was run to check the variation of wave height with slope. It was found that the steep slopes did affect wave height. Therefore, it became necessary to measure the wave heights on different slopes, which explains the different wave heights shown in Table 3, Appendix C.

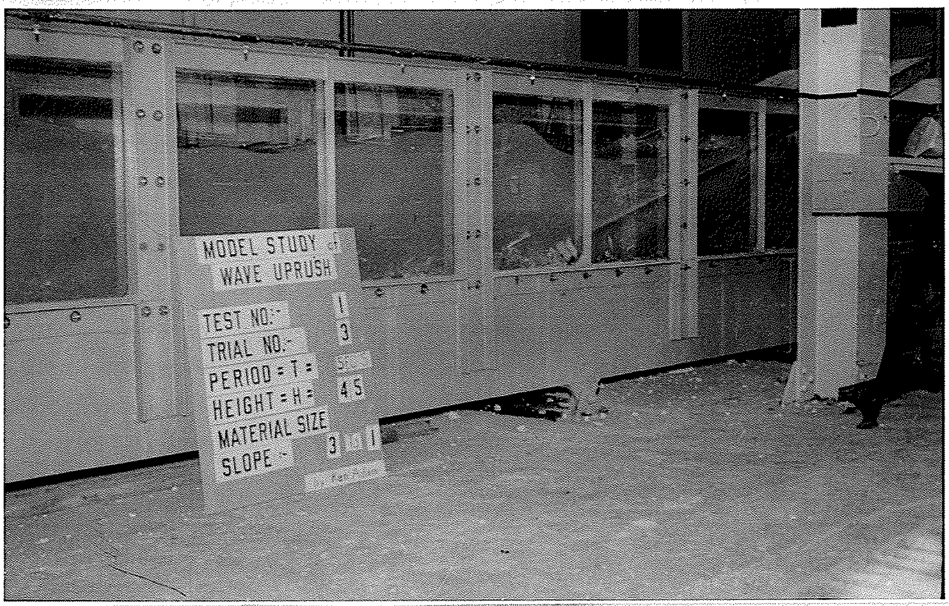
It was observed that the steep slopes maintained a constant wave height for any given slope if the third to sixth wave was measured after the wave generator was started. Hence, it became standard procedure to measure wave run-up caused by the 3rd, 4th, 5th, and 6th wave. The same wave conditions were run twice in each test, and the results of the wave run-up were averaged for each test.

The smooth slopes were tested by securing the plywood slope in the flume. The clearance needed to make the slope moveable was filled with polyethelyne stripping so that flow through the slope would not interfere with wave run-up. The test pattern was then run over each slope and the resultant wave run-up recorded. The smooth slopes tested are as given in Table 1, Appendix B.

The reversed smooth slopes are believed to be the first of this kind tested. They were tested for purely theoretical consideration, although practical application could arise where the data could be used especially in steel plate or reinforced concrete piers or retaining walls. The tests on the reversed smooth slopes were the same as on the smooth slopes.

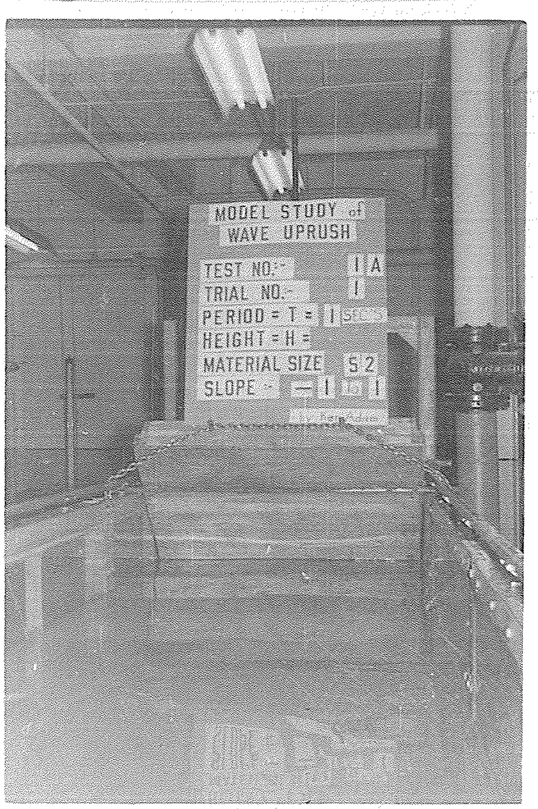
Pictures of a wave breaking on a smooth slope, a reversed slope prior to testing, and a wave breaking on a smooth slope can be seen in Pictures 4, 5, and 6 respectively. The number of reversed smooth slopes can be seen in Table 1, Appendix B.

The roughened slopes were tested by placing the five different material sizes shown in Picture 3 onto the different slopes given in Table 1 in 4" layers. The test pattern as given for the smooth slopes was used for roughened slopes as well. The materials were handled the least number of times to eliminate as much manual work as possible, and to prevent breakage of the material. Slight breakage of the material could not be avoided.



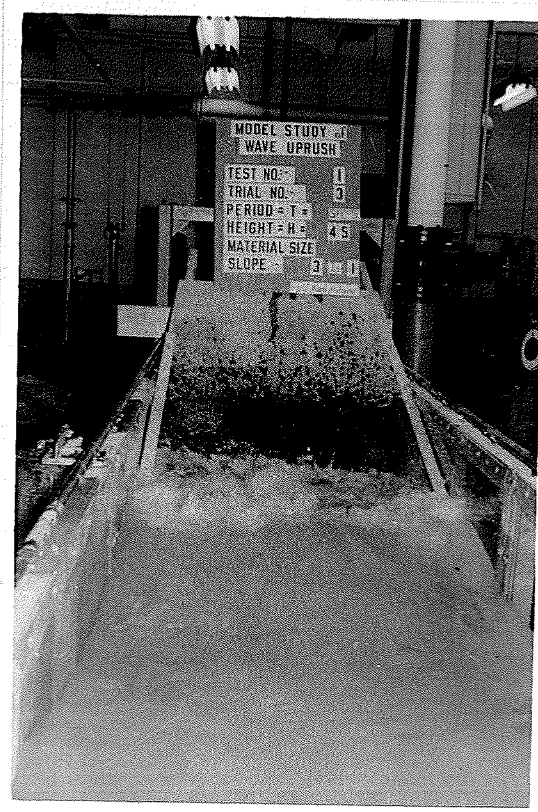
PICTURE 4

SIDE VIEW OF A WAVE BREAKING
ON A SMOOTH SLOPE



PICTURE 5

SMOOTH REVERSED SLOPE
PRIOR TO TESTING



PICTURE 6

WAVE BREAKING ON
A SMOOTH SLOPE

The material used for testing ranged in size from $\frac{1}{4}$" to 6". The limestone material was donated by the Winnipeg Supply and Fuel Company from its Stonewall, Manitoba quarry. This material was used not only for its availability, but also to simulate limestone which has been used as riprap on the Grand Rapids Power Project undertaken by Manitoba Hydro, and other limestone riprap which is gaining popularity for many small reservoir projects throughout the province.

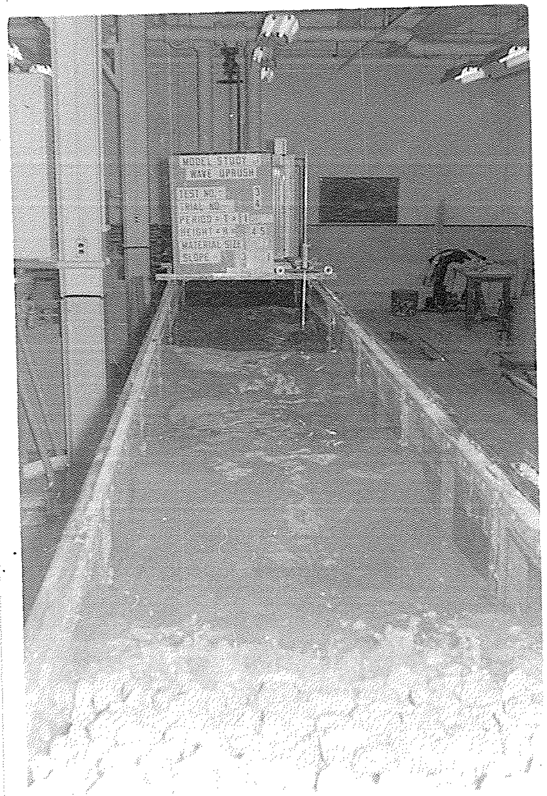
The range of size each material is given in Table 1, Appendix B. Each material was tested on every slope, but if the smaller diameters were found to be unstable on the steeper slopes that range of material was removed, and results noted. Readings of wave run-up and wave height were measured and recorded as in the previous tests.

The pictures on page 58 show waves breaking on roughened slopes in Pictures 7 and 8, and a roughened slope prior to testing in Picture 9.

The test apparatus worked favourably under all test conditions, and the test pattern gave results over the full range required in order to derive design charts.

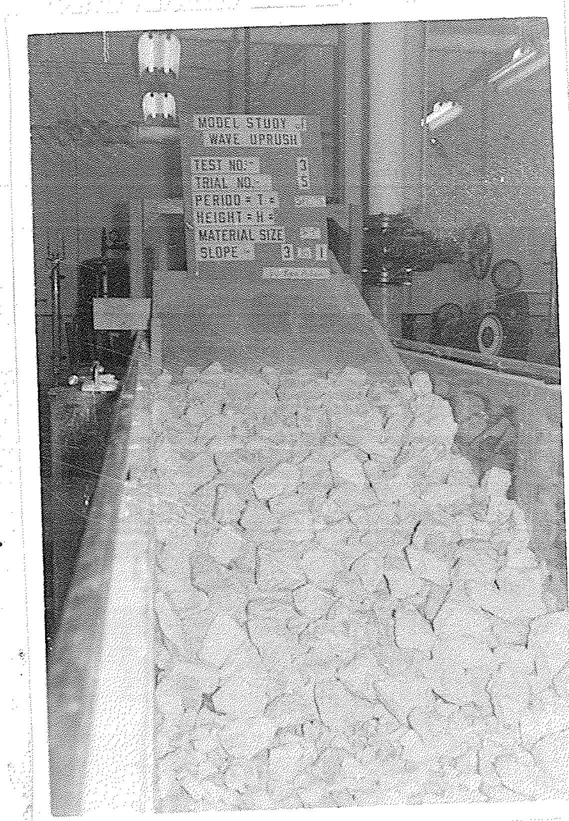
PICTURE 7

A HIGH WAVE BREAKING ON A ROUGHENED SLOPE



PICTURE 8

A WAVE BREAKING ON
A ROUGHENED SLOPE



PICTURE 9

A ROUGHENED SLOPE
PRIOR TO TESTING

CHAPTER V

RESULTS OF THE TESTS

It was standard practice throughout all tests to measure the wave run-up and the wave heights. Other variables that were known at the end of each test was the period for each wave, the equivalent deep water wave length, L_o, and the depth of water, d, over which the waves were travelling. The latter two variables allowed the calculation of d/L_o and the corresponding function of H/H_o', the shoaling coefficient[1] to be read from Figure 14. In this manner the equivalent deep water wave height, H_o', is derived.

Smooth Slopes.

Figures 15 to 18 inclusive shows the method of plotting the smooth slope data as given in Table 3, in Appendix C. This is a dimensionless plot of the relative run-up, R/H_o', versus a function of the deep water wave steepness, H_o'/T^2. Actually H_o'/T^2 equals 5.12 H_o'/L_o the deep water wave length. However, L_o equals $gT^2/2\pi$ equals 5.12 T^2. All the dimensionless parameters used in the present study have appeared previously in the literature and their usage to explain wave run-up data is generally accepted.

Although the scatter of points in Figures 15 to 18 remain the same throughout, it was observed that the wave run-up was more erratic on the relatively steep slopes. This can possibly be

1. See Glassary of Terms, Appendix A.

CHAPTER V

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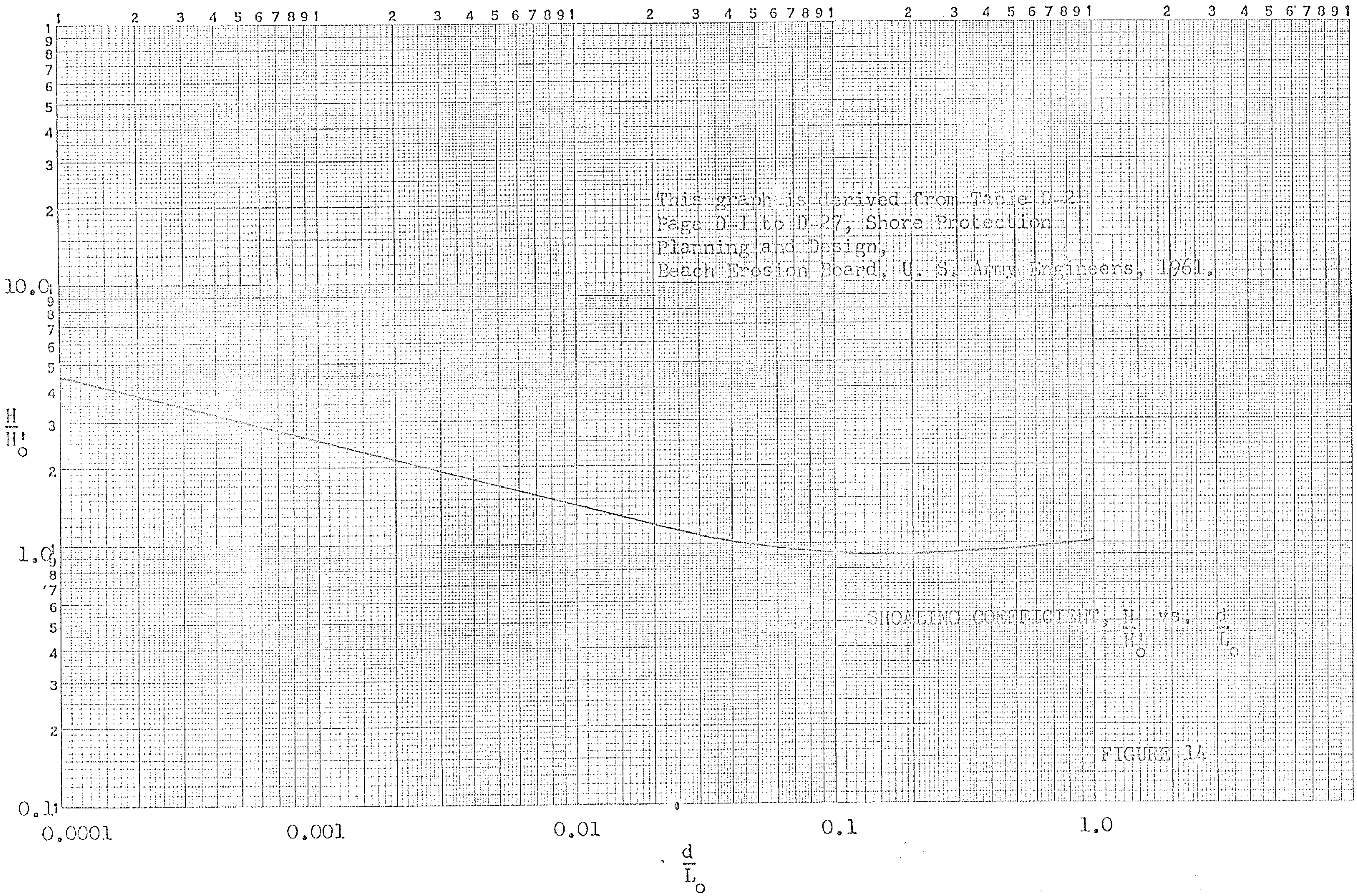
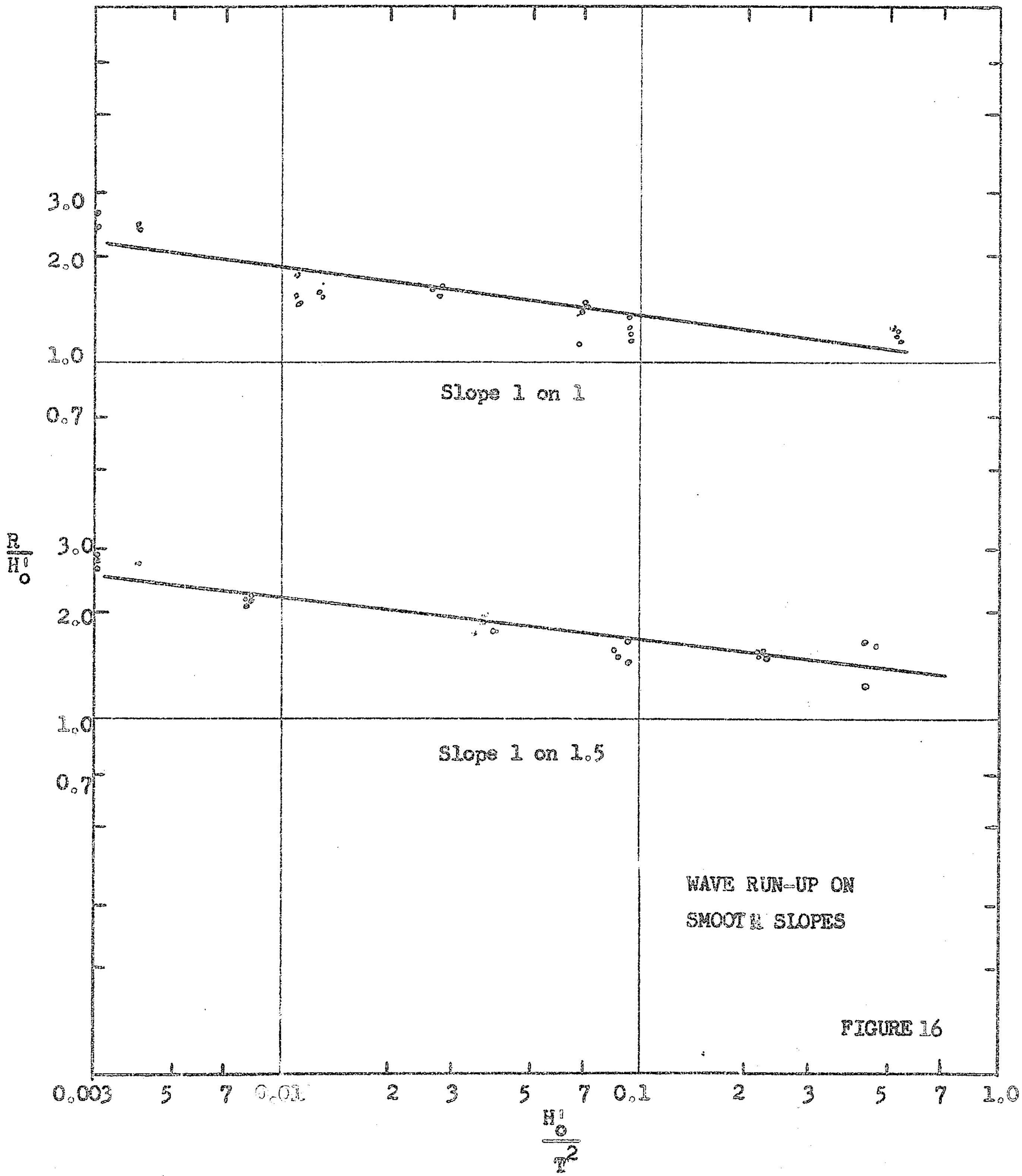
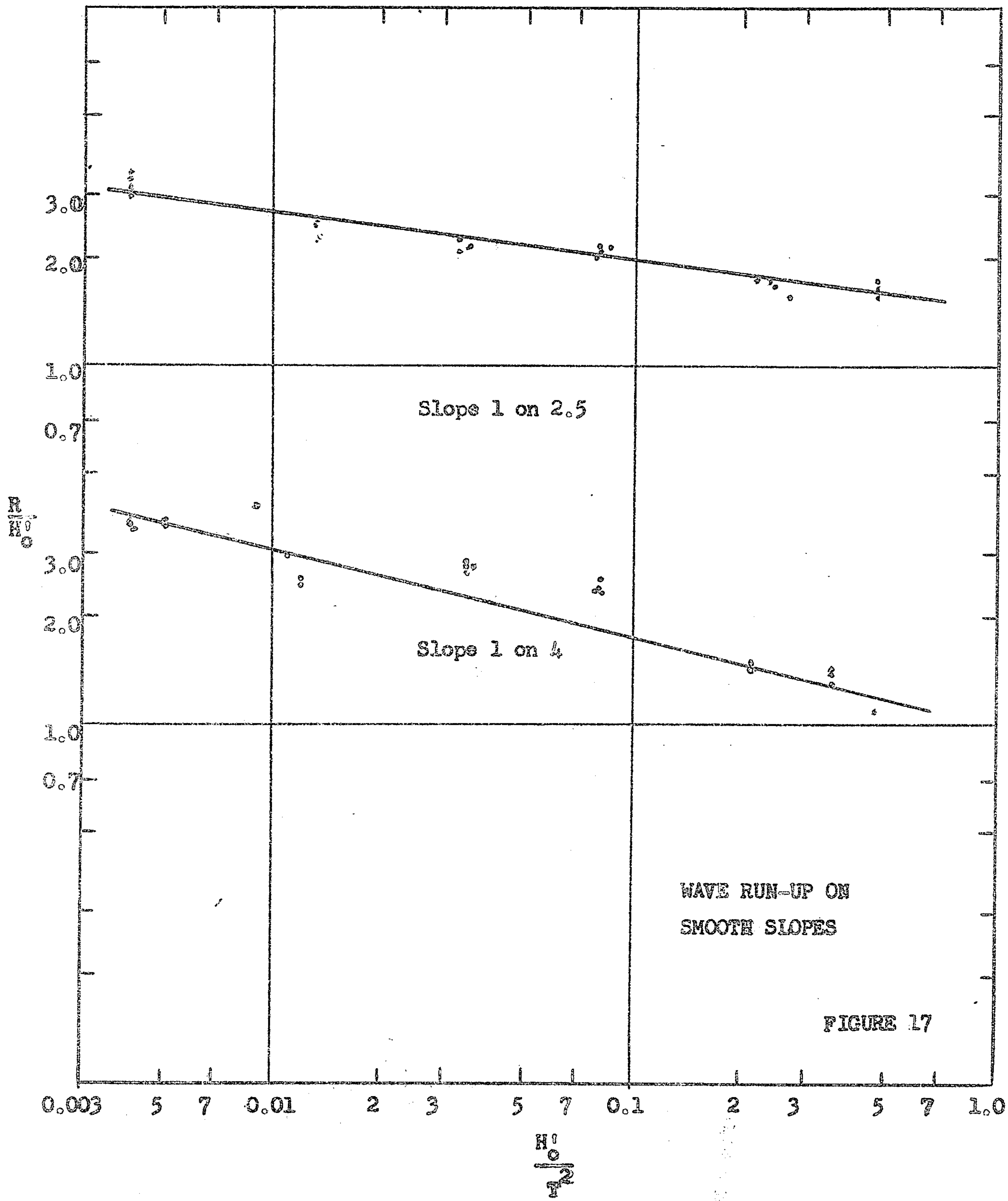
1. See Glossary of Terms, Appendix A.


This graph is derived from Table D-2
Page D-1 to D-27, Shore Protection
Planning and Design,
Beach Erosion Board, U. S. Army Engineers, 1961.
SHOALING COEFFICIENT, $\frac{H}{H'_o}$ vs. $\frac{d}{L_o}$
FIGURE 14
$\frac{H}{H'_o}$
$\frac{d}{L_o}$
0.1
1.0
10.0
0.0001
0.001
0.01
0.1
1.0



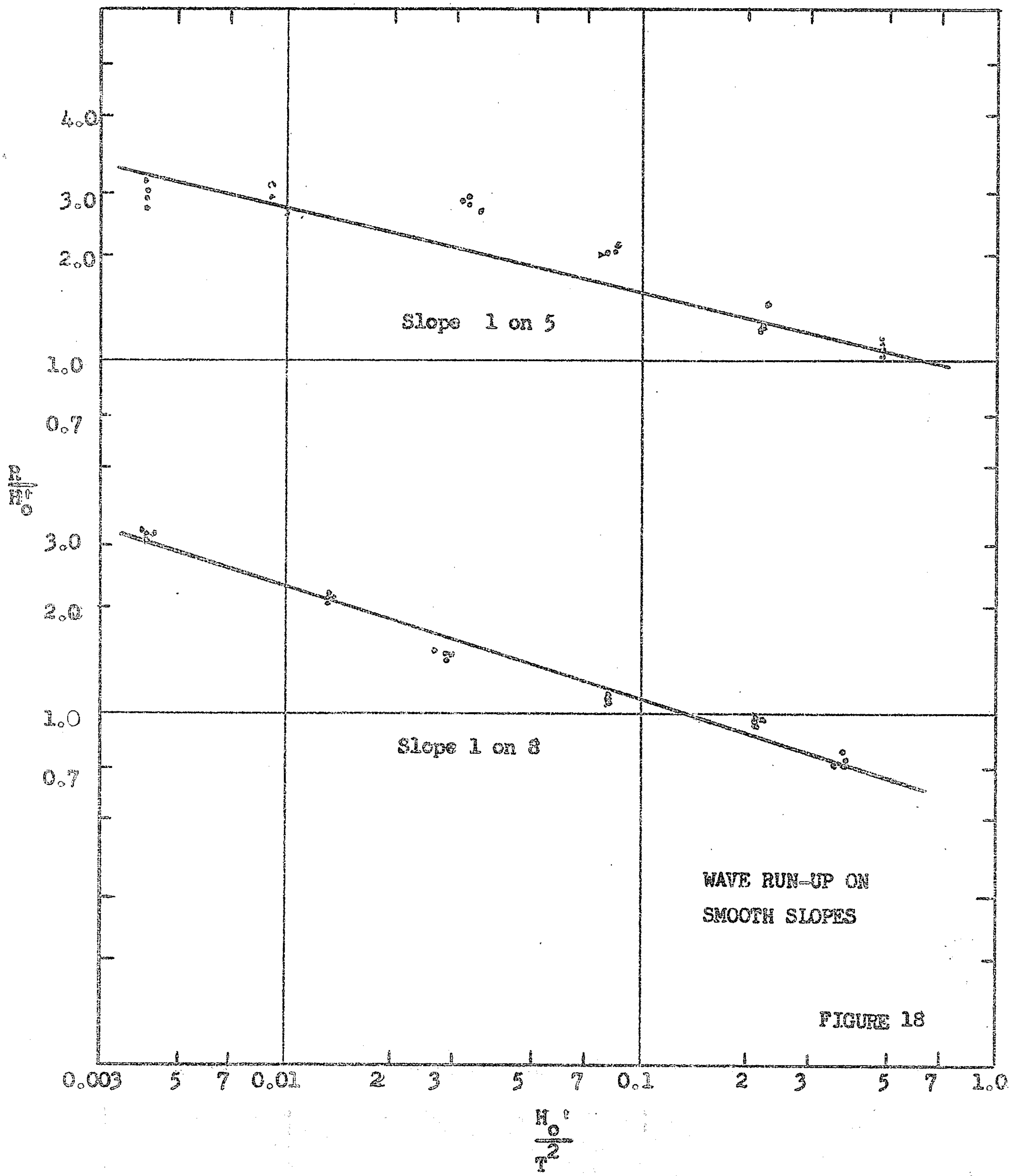
3.0
2.0
1.0
0.7
Slope 1 on 1
3.0
2.0
1.0
0.7
Slope 1 on 1.5
R/H'o
0.003
5
7
0.01
2
3
5
7
0.1
2
3
5
7
1.0
H'o/T²
WAVE RUN-UP ON
SMOOTH SLOPES

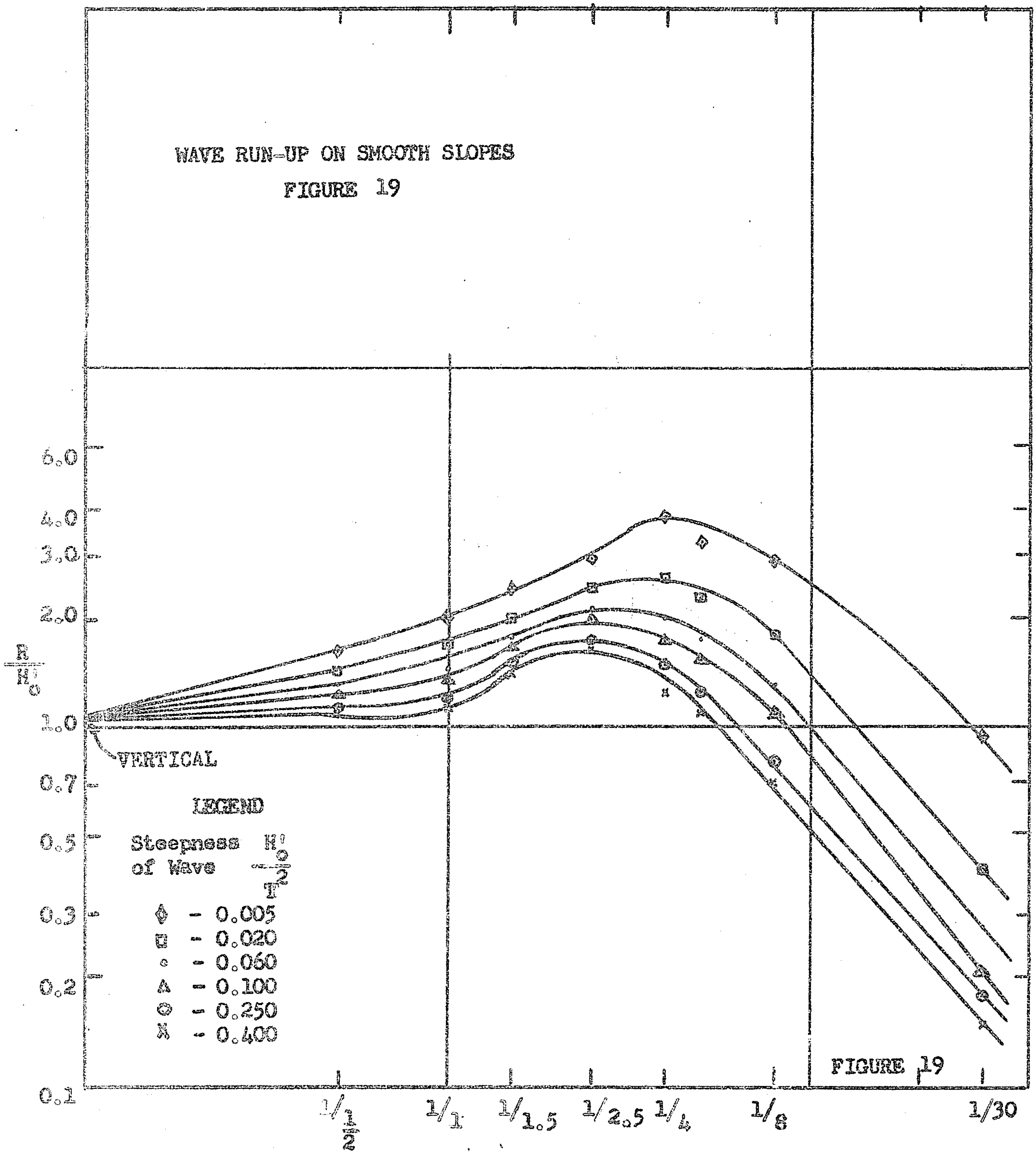
FIGURE 16



WAVE RUN-UP ON SMOOTH SLOPES

FIGURE 17


4.0
3.0
2.0
Slope 1 on 5
1.0
0.7
$\frac{R}{H_o'}$
3.0
2.0
1.0
Slope 1 on 8
0.7
WAVE RUN-UP ON
SMOOTH SLOPES
FIGURE 18
0.003 5 7 0.01 2 3 5 7 0.1 2 3 5 7 1.0
$\frac{H_o'}{T^2}$



WAVE RUN-UP ON SMOOTH SLOPES
FIGURE 19
6.0
4.0
3.0
2.0
R/H'o
1.0
VERTICAL
0.7
0.5
0.3
0.2
0.1
LEGEND
Steepness of Wave H'o/T²
◊ - 0.005
□ - 0.020
∘ - 0.060
Δ - 0.100
⊙ - 0.250
✕ - 0.400
FIGURE 19
1/½
1/1
1/1.5
1/2.5
1/4
1/8
1/30
SLOPE

explained by the fact that on mild slopes the wave breaks further away from where the actual run-up measurement is taken than on steep slopes. That is to say that for steep slopes the plunge point is very close to the run-up measuring point, and the splash from the plunging wave interferes with the run-up measurement. This would account for irregular measurements of wave run-up.

After the smooth slope data had been plotted in the form already mentioned, a smooth curve was drawn by eye through the points for each slope. From these curves a composite graph Figure 19 was drawn which shows the effect of slope on the relative run-up for isolines of H_o'/T^2.

Figure 19 can be interpreted by considering the two extreme slopes, the vertical slope as a steep slope and a 1 on 30 slope as a mild slope. The theory explains the fact that the relative run-up R/H_o' is 1.0 for a wave breaking on a vertical slope. This would be expected since the kinetic energy is equal to the potential energy, the potential energy being one-half the wave height above still water level. Therefore, when the kinetic energy is transferred into potential energy the water rises the full wave height above the still water level, the run-up being equal to the wave height or $R/H_o' = 1.0$.

The effect of a very mild slope may be considered by assuming that a wave travels from deep water onto a horizontal ledge placed at one-half the wave height below the still water level. As the wave passes over the ledge the wave will break, and both the kinetic and potential energy will dissipate and the wave run-up could be considerably less than the wave height thus giving small ratio for the R/H_o' values on mild slopes.

The intermediate slopes from 1 on 1 to 1 on 6 give relative run-up R/H_o' values as high as 4.0 and as low as 1.0 depending on the wave steepness and the slope. The wave steepness indicates not only the ratio of the wave height to wave length, but some insight is given into the wave period and its effect. Also, if the wave height is considered constant for two H_o'/T^2 values, the wave steepness gives an indication of the volume of water per unit width contained within a wave.

If a wave of low steepness breaks on an intermediate slope for a given wave height and velocity it will have considerably more momentum than a wave of the same height and velocity but of relatively high steepness value, and therefore would be expected to travel further up a smooth slope than a wave of high steepness. Since the wave height was considered the same in both cases, the R/H_o' value would be higher for the wave of low steepness as well as the wave run-up, R.

The wave period could be expected to vary wave run-up to a large degree simply by the timing of the backwash from the previous wave interfering with an approaching wave. Depending on the period alone, two waves could reinforce or interfere and thus vary wave run-up to a large extent. Although this argument is used considerably in wave run-up literature, it is almost impossible to explain the phenomena in quantitative form.

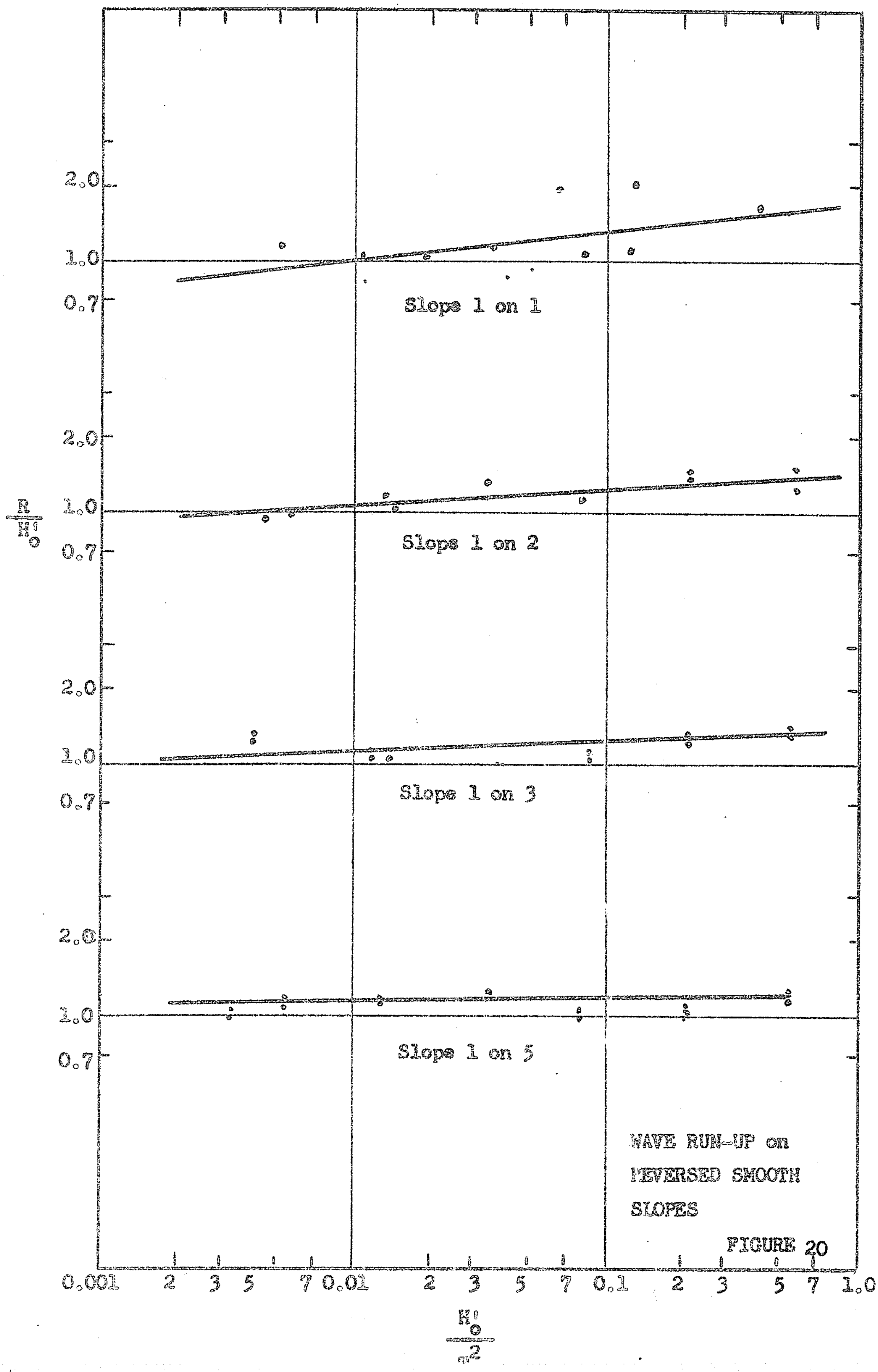
Reversed Smooth Slopes.

The data for the reversed smooth slopes was plotted in the same manner as for smooth slopes. The vertical smooth plate tested with smooth slopes, Figure 15, can be used for reference, as a reversed smooth slope. It can be noted that the slope of the line drawn by eye through the points for the reversed smooth slopes in the plot of relative run-up to wave steepness in Figure 20 is of a negative or reversed slope as compared to the smooth slope lines. This reverse in the slope of the lines in the graph could be expected since the tested slope was reversed. However, further discussion will be given in Chapter VI.

The results of the reversed slopes were not plotted in terms of slope and relative run-up with isoline of H_o'/T^2. This is due to the fact that the author feels that run-up on reversed slopes may depend to a large extent on the depth of water at the toe of the structure. However, field conditions with the same relative depth as that tested should have similar wave run-up. The effect of depth on wave run-up could not be tested with the available facilities.

Roughened Slopes.

The data for roughened slopes as given in Table V, Appendix C, is plotted in Figures 21 to 26. These graphs are dimensionless plots of R/d where R is the wave run-up and d is the median diameter of the roughness material, versus $H_o'T^2/d^2$ where H_o' is the deep water wave height and T is the wave period. The parameter R/d gives the wave run-up in terms of the median



WAVE RUN-UP on REVERSED SMOOTH SLOPES

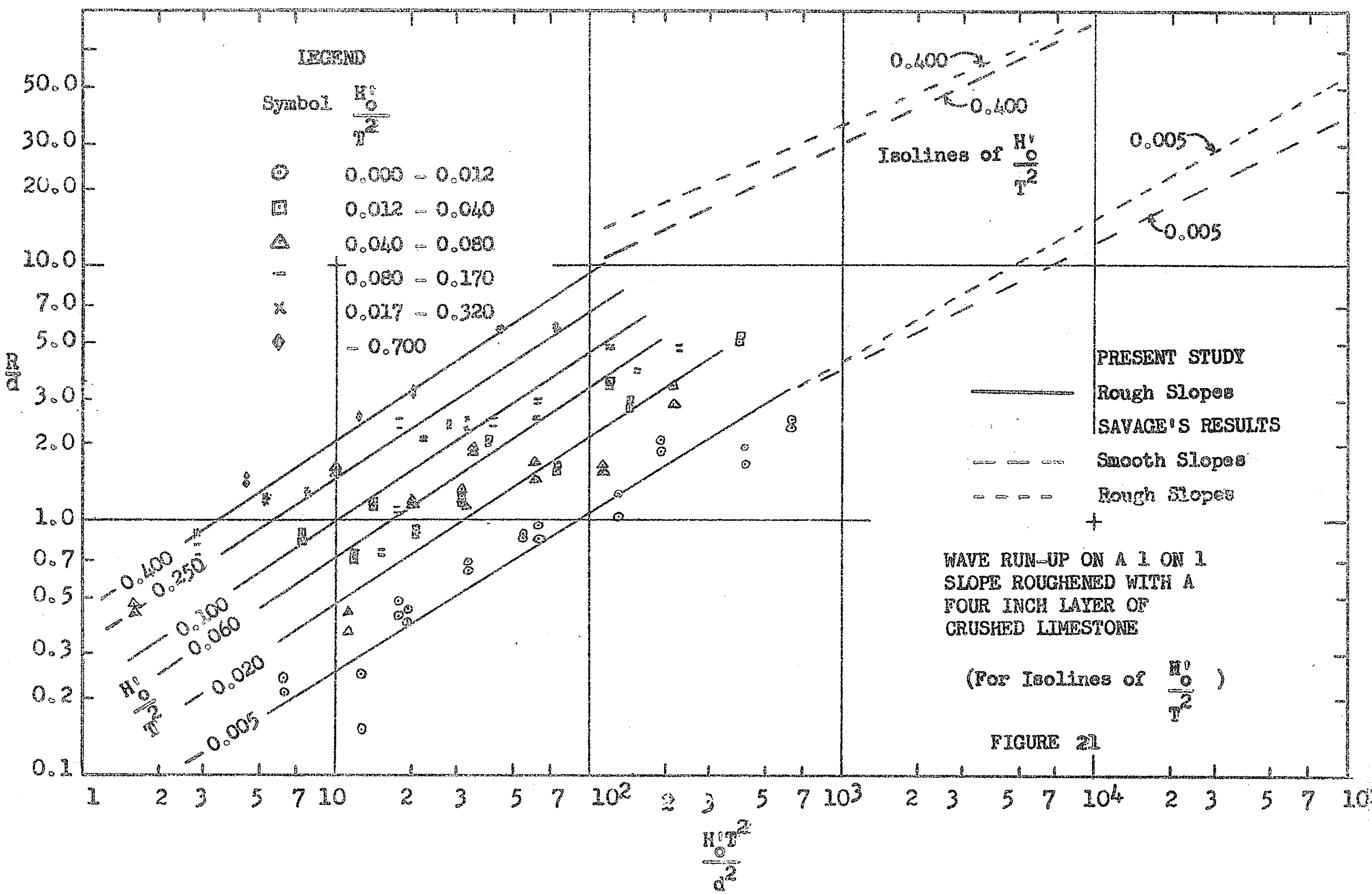
FIGURE 20

diameter of the roughness material and $\frac{H'T^2}{d^2}$ functions as the reciprocal of a dimensionless roughness coefficient.

The long dashed lines shown in Figures 21 to 26 were taken from the smooth slope data in Figure 19. Their position and slope were obtained by assuming that for some large value of $\frac{H_o'T^2}{d^2}$, the roughness of the slope would no longer have measurable effect on wave run-up. This assumption is supported by the fact that Savage[2] tested 0.2 mm sand and observed no significant reduction in wave run-up for the slopes tested. The 0.2 mm diameter or any smaller diameter could be used in combinations of H_o' and T to compute the roughness coefficient which would be essentially equivalent to smooth slope conditions. The values of H_o' and T used in these computations were chosen such that they represented the particular H_o'/T^2 values represented in the figures. The particular value of H_o'/T^2 with any given slope would give a corresponding value of R from Figure 19. This R and the assumed value of d then gives the R/d parameter for the roughness coefficient. Thus, each of the smooth slope lines was determined by obtaining two points by the above method, and projecting them into the range of the test results.

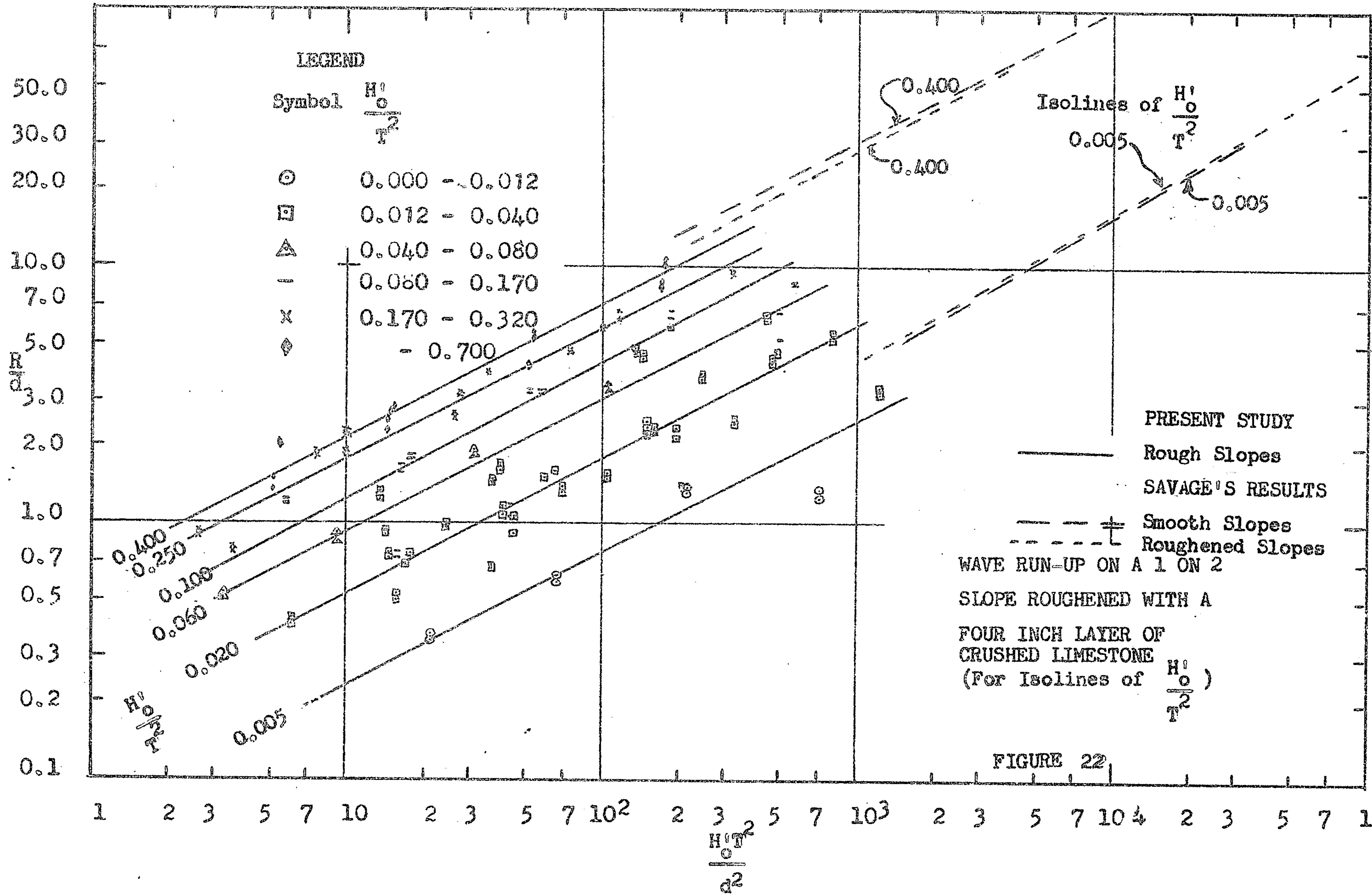
The short dashed lines represent Savage's results. Some of the lines drawn have been placed by interpolation, since Savage did not test all slopes included in the present study. The results of the tests compare favourably, and in all cases, the results give the same tendencies and pattern as the results given by Savage.

2. Savage, R. P., "Wave Run-up Smoothed and Roughend Slopes", Journal of the Waterways Division of the ASCE, v. 82, 1958.



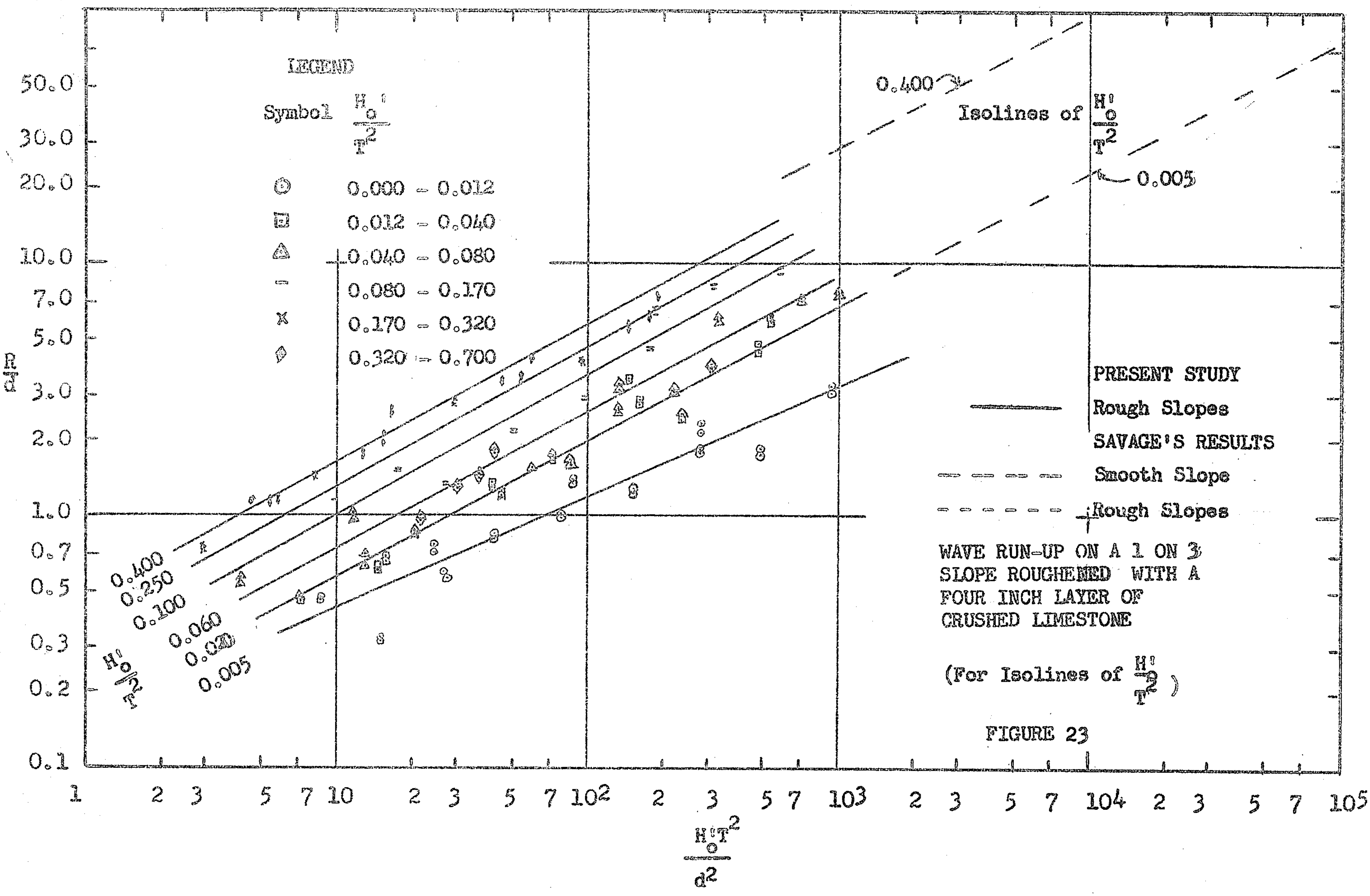
LEGEND
Symbol $\frac{H'_o}{T^2}$
0.000 - 0.012
0.012 - 0.040
0.040 - 0.080
0.080 - 0.170
0.017 - 0.320
- 0.700
0.400
0.400
0.005
0.005
Isolines of $\frac{H'_o}{T^2}$
0.400
0.250
0.100
0.060
0.020
0.005
$\frac{H'_o}{T^2}$
PRESENT STUDY
Rough Slopes
SAVAGE'S RESULTS
Smooth Slopes
Rough Slopes
WAVE RUN-UP ON A 1 ON 1 SLOPE ROUGHENED WITH A FOUR INCH LAYER OF CRUSHED LIMESTONE
(For Isolines of $\frac{H'_o}{T^2}$)
$\frac{R}{d}$
$\frac{H'_o T^2}{d^2}$

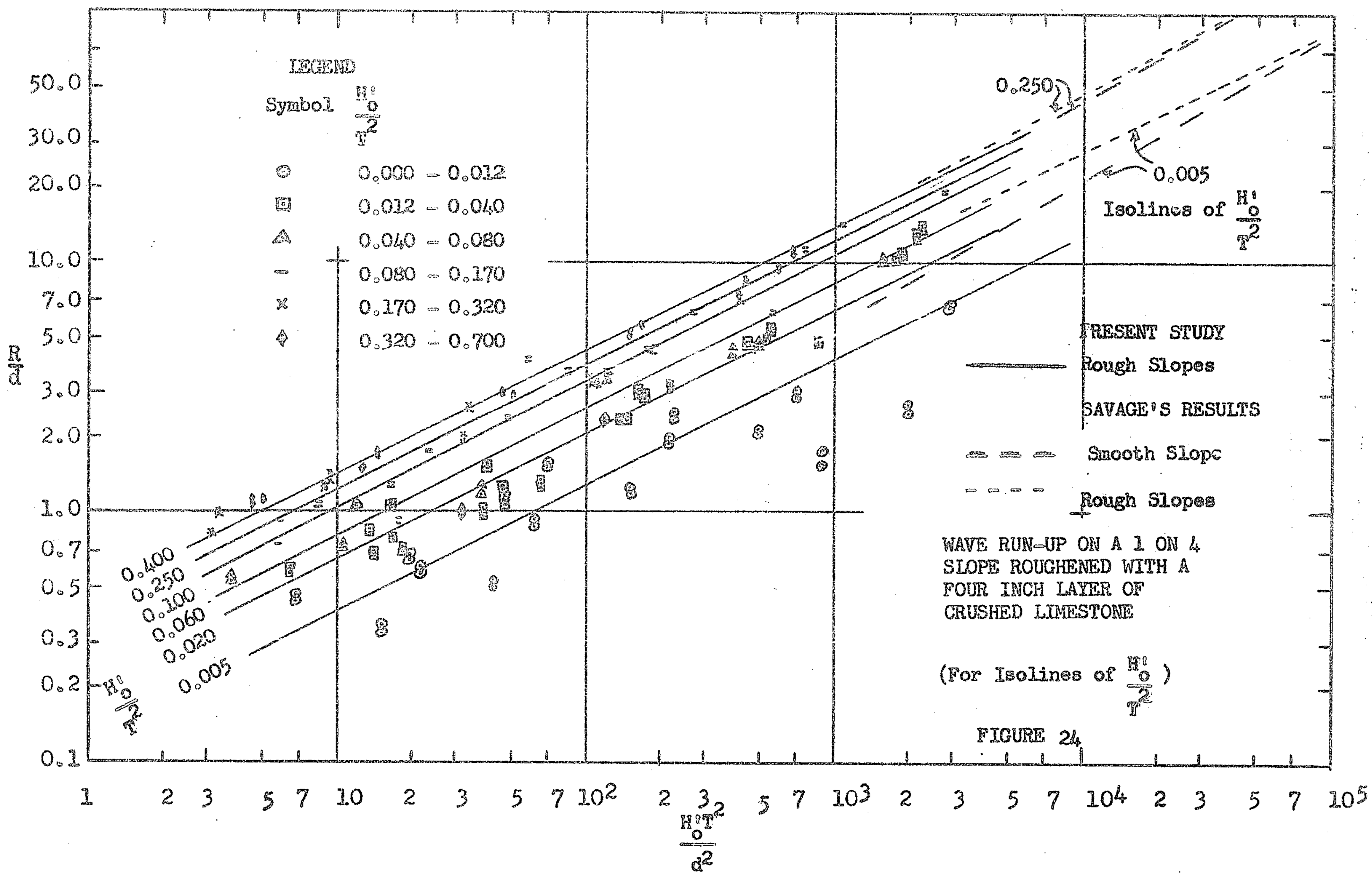
FIGURE 21



WAVE RUN-UP ON A 1 ON 2 SLOPE ROUGHENED WITH A FOUR INCH LAYER OF CRUSHED LIMESTONE (For Isolines of $\frac{H_o'}{T^2}$)

FIGURE 22


LEGEND
Symbol $\frac{H_o'}{T^2}$
0.000 - 0.012
0.012 - 0.040
0.040 - 0.080
0.080 - 0.170
0.170 - 0.320
0.320 - 0.700
0.400
Isolines of $\frac{H_o'}{T^2}$
0.005
PRESENT STUDY
Rough Slopes
SAVAGE'S RESULTS
Smooth Slope
Rough Slopes
WAVE RUN-UP ON A 1 ON 3 SLOPE ROUGHENED WITH A FOUR INCH LAYER OF CRUSHED LIMESTONE
(For Isolines of $\frac{H_o'}{T^2}$)
0.400
0.250
0.100
0.060
0.020
0.005
$\frac{H_o'}{T^2}$
$\frac{R}{d}$
$\frac{H_o' T^2}{d^2}$
50.0
30.0
20.0
10.0
7.0
5.0
3.0
2.0
1.0
0.7
0.5
0.3
0.2
0.1
1
2
3
5
7
10
2
3
5
7
10^2
2
3
5
7
10^3
2
3
5
7
10^4
2
3
5
7
10^5
FIGURE 23



WAVE RUN-UP ON A 1 ON 4 SLOPE ROUGHENED WITH A FOUR INCH LAYER OF CRUSHED LIMESTONE

(For Isolines of $\frac{H'_o}{T^2}$)

FIGURE 24

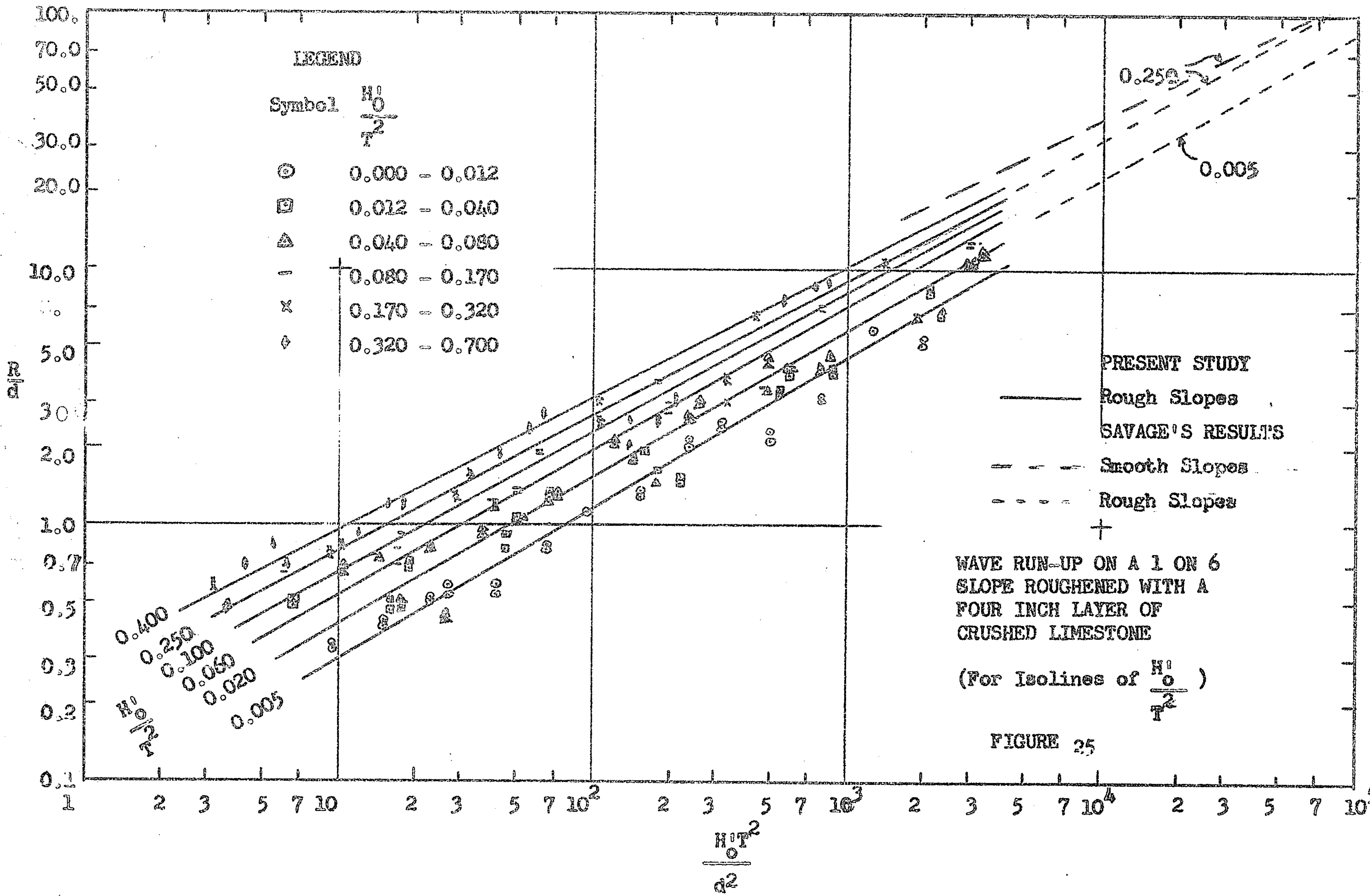
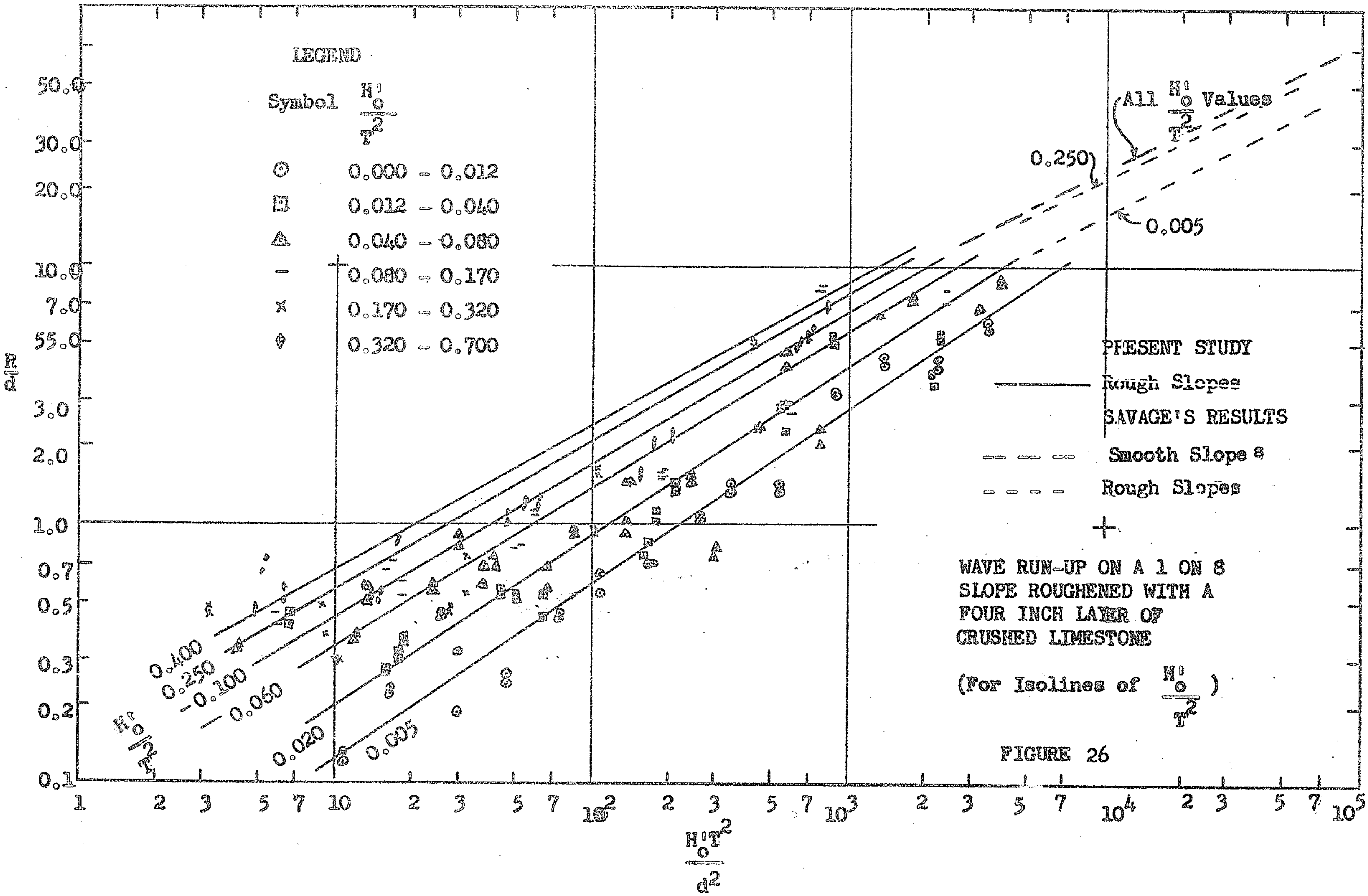

LEGEND
Symbol $\frac{H_o'}{T^2}$
0.000 – 0.012
0.012 – 0.040
0.040 – 0.080
0.080 – 0.170
0.170 – 0.320
0.320 – 0.700
PRESENT STUDY
Rough Slopes
SAVAGE'S RESULTS
Smooth Slopes
Rough Slopes
WAVE RUN-UP ON A 1 ON 6
SLOPE ROUGHENED WITH A
FOUR INCH LAYER OF
CRUSHED LIMESTONE
(For Isolines of $\frac{H_o'}{T^2}$)
0.250
0.005
0.400
0.250
0.100
0.060
0.020
0.005
$\frac{H_o'}{T^2}$
$\frac{R}{d}$
$\frac{H_o'T^2}{d^2}$
100.
70.0
50.0
30.0
20.0
10.0
5.0
2.0
1.0
0.7
0.5
0.3
0.2
0.1
1
2
3
5
7
10
10^2
10^3
10^4
10^5

FIGURE 25



WAVE RUN-UP ON A 1 ON 8 SLOPE ROUGHENED WITH A FOUR INCH LAYER OF CRUSHED LIMESTONE

(For Isolines of $\frac{H_o'}{T^2}$)

FIGURE 26

CHAPTER VI

DISCUSSION AND CONCLUSIONS

The tests conducted at the University of Manitoba on wave run-up have been presented in Chapter V in graphical form. It is the purpose of the present chapter to discuss specific points about the data, and to draw the conclusions that the tests support by the data and graphs presented previously.

Discussion.

The tests performed on smooth slopes were two-fold in purpose and result. These tests were used to verify the model, and furthermore, to verify the data presented by R. P. Savage on smooth slopes. Savage found that the maximum relative run-up, $R/H_o' = 4.10$ occured on a slope of 1 on 5 with relatively small values of wave steepness, $H_o'/T^2 = 0.005$. It was found from Savage's data that the maximum relative wave run-up for waves of relatively high steepness, $H_o'/T^2 = 0.400$, to occur on a slope of 1 on 2.5. The relative run-up, $R/H_o' = 1.5$ in this case.

It can be seen from Figure 19 that the maximum run-up in the present study was found to be 3.90 times the deep water wave height, and it occured on a slope of 1 on 4, for a wave steepness, $H_o'/T^2 = 0.005$. Figure 19 also indicates that the maximum run-up for a wave steepness of 0.400 occured on a slope of 1 on 2.5 and that the run-up was 1.5 times the wave height.

The very close agreement of the results given by Savage and the present study indicates that the apparatus and facilities used in the present investigation is very similar to that used by Savage. However, more important, the close agreement gives confidence that measuring techniques, test patterns and range of waves tested are adequate for the present test.

A wave on a vertical face converts its kinetic energy into potential energy and the resulting wave is known as a standing wave. The maximum height that the wave rises on the face of the structure is wave height, H, above the still water level. Therefore, the relative run-up, $R/H_o' = 1.0$. The tests performed by Savage indicate that the maximum relative run-up on a vertical slope is $R/H_o' = 1.5$, whereas the present study indicates the maximum relative run-up, $R/H_o' = 1.05$ which corresponds more closely to the theoretical value.

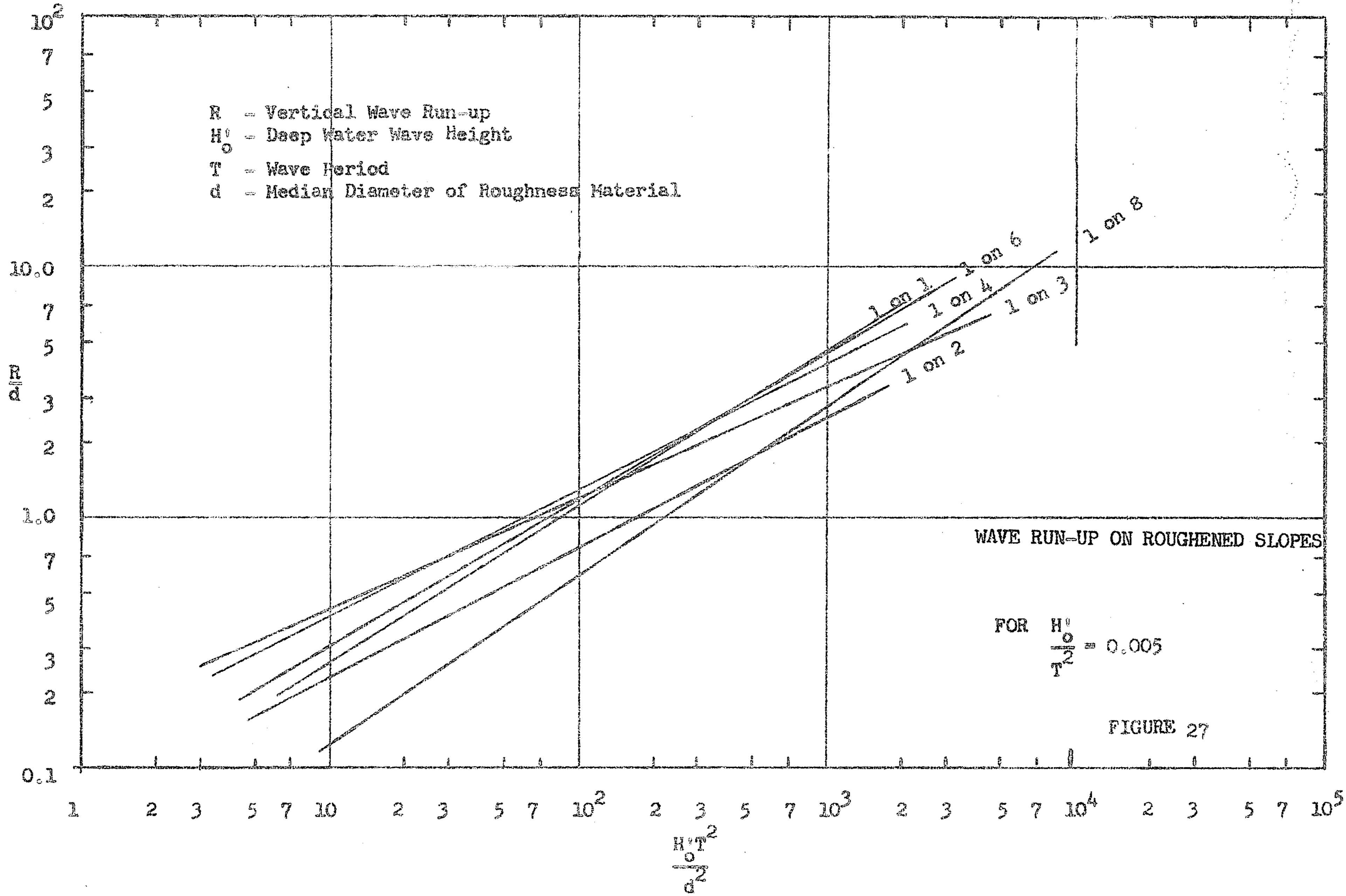
The tests on reversed smooth slopes have little practical interest, but the results indicate that the maximum wave run-up on a reversed smooth slope is 1.7 times the wave height, and occurs on a slope of 1 on 2. It is the opinion of the author that wave run-up on reversed smooth slopes may depend on wave depth to a larger degree than on ordinary smooth slopes. Since the effect of depth on reversed slope wave run-up was not tested, the data contained in Figure 20 should be used with caution if the problem of a design of a reversed slope should arise.

The roughened slopes tested, where the diameter of the riprap material was in the same dimensional range as the wave height, shows close agreement with the extension of Savage's results and the limits as given by the smooth slope data. In no case did the wave uprush on roughened slopes exceed the wave uprush for smooth slopes as would be expected. Also, in no case did the wave run-up on the roughened slopes exceed the run-up on small diameter material as indicated by Savage's results in Figures 21 to 26. In general, the results of the tests on roughened slopes gave results close to the results expected.

Figures 27 and 28 are plots of the dimensionless parameters R/d and $H_o'T^2/d^2$ for isolines of slope. Figure 27 indicates that waves of low steepness give maximum wave run-up on slopes of 1 on 4 or 1 on 6. Figure 28 indicates that waves of high steepness gives maximum wave run-up on the steeper slopes such as 1 on 1 or 1 on 2. In general, both diagrams give the same tendencies as smooth slopes.

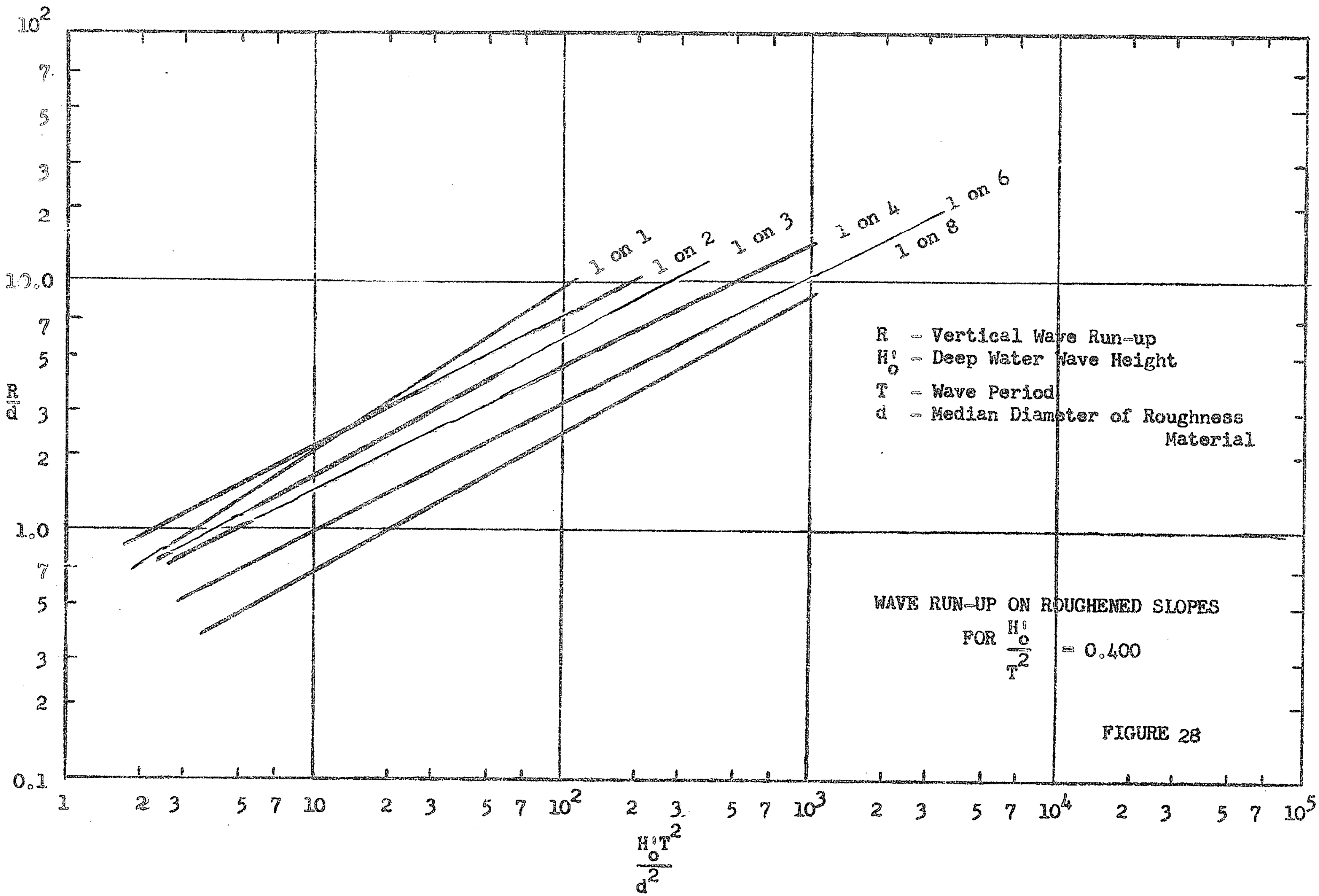
The roughened slope data presented in Figures 21 to 26 inclusive show that the effect of slope roughness on wave run-up increases as the wave steepness, H_o'/T^2 decreases; that for a constant H_o'/T^2 and $H_o'T^2/d^2$ the effect of slope roughness increases as the slope decreases; and that the effect of slope roughness on wave run-up increases as the parameter $H_o'T^2/d^2$ decreases.

It is suggested by the author that if the riprap diameter should exceed the wave height by a factor of 4.0, for example, that a portion of a wave may approach a particular stone and the resultant run-up could be closer to smooth slope design criteria than for very rough slopes. This is due to the fact that the one stone may consititute a smooth slope for a portion of the wave. Although this argument is logical, it has no practical interest since the



R - Vertical Wave Run-up
H'o - Deep Water Wave Height
T - Wave Period
d - Median Diameter of Roughness Material
1 on 1
1 on 6
1 on 8
1 on 4
1 on 3
1 on 2
R/d
H'oT²/d²
10²
10.0
1.0
0.1
1
10
10³
10⁴
10⁵
WAVE RUN-UP ON ROUGHENED SLOPES
FOR H'o/T² = 0.005

FIGURE 27



WAVE RUN-UP ON ROUGHENED SLOPES

FOR $\frac{H_o'}{T^2} = 0.400$

FIGURE 28

approaching wave in such a case would be a fraction of the design wave, and the resulting uprush even on a smooth slope would not reach the design wave height, and therefore would be contained easily within the reservoir by the existing freeboard.

Conclusions.

From the above discussion several conclusions can be made from the data presented:

(1) The results of some of the tests conducted in the present study give very similar results as previous tests performed by R. P. Savage, thus verifying the model data and test procedures.

(2) Wave run-up on riprap, where the median diameter is in the same dimensional range as the impinging wave height, is less than run-up on material of a smaller diameter, all the dimensionless parameters being the same.

(3) The design charts presented for smooth and rough slopes on pages 61 to 65 and 71 to 76 are supported by sufficient evidence that the designer should have confidence in the results so long as the dimensionless parameters are in the same range as those given in the graph.

(4) The reversed smooth slopes give considerably less run-up than ordinary smooth slopes.

APPENDIX A

Notation and Glossary of Terms

NOTATION

Symbol	Definition	Units in F, L, T System
A	Area	L^2
a	Acceleration	L/T^2
B_o	Height of wind set-up above mean lake level	L
b	Length of wave crest between orthogonals	L
$\bar{b}$	Subscript "b" refers to breaking wave conditions.	-
C	Wave velocity	L/T
C_o	Deep water wave velocity	L/T
D	Decay distance	L
D_d	Shoaling coefficient, H/H_o'	-
d	Depth of water, measured from the still water level.	L
d	Median diameter of the riprap material	L
E_p	Mean potential energy of one wave per unit length of crest	$\frac{LF}{L}$
E_k	Mean kinetic energy of one wave per unit length of crest	$\frac{LF}{L}$
F_m, F_{min}	Minimum fetch length.	L
g	Acceleration of gravity.	L/T^2
H	Wave height.	L
Hav.	Average of wave heights for a specified period of time.	L
H_o'	Deep water wave height.	L

Symbol	Definition	Units in F, L, T System
$\frac{H_o'}{L_o}$	Deep water wave steepness	-
$\frac{H_o'}{T^2}$	$5.12\ H_o'/L_o$	-
$\frac{H_o' T^2}{d^2}$	Inverted roughness coefficient.	-
L	Wave length.	L
L_o	Deep water wave length.	L
L_s	Shallow water wave length.	L
$\bar{o}$	Subscript "o" refers to deep water conditions.	-
R	Vertical height of wave run-up above SWL.	L
SWL	Still water level.	-
T	Wave period.	T
t	A time.	T
U	Velocity of surface wind.	L/T
V	A velocity	L/T
V_g	Geostrophic wind velocity.	L/T
w	Unit weight.	F/L^3
w	Angular velocity	L/T
P_w	Mass density, W/g	$\frac{FT^2}{L^4}$

GLOSSARY OF TERMS

Amplitude, wave - the wave height from trough to crest.

Backwash - the return of the water following the uprush of the waves.

Backwash - (1) see Backwash,

(2) water or waves thrown back by a breakwater or cliff.

Beach Berm - A nearly horizontal portion of the beach or backshore formed by the deposit of material by wave action.

Berm, Artificial - (1) formed for bank stabilization,

(2) formed to make a wave break prematurely.

Bottom - the ground or bed under any body of water.

Boulder - a rounded rock more than 12" in diameter; larger than a cobblestone.

Breaker - a wave breaking on the shore, over a reef, etc. Breakers may be roughly classified into three kinds although there is much overlapping:

(1) spilling breakers - break gradually over quite a distance.

(2) plunging breakers tend to work over and break with a crash.

(3) surging breakers peak up, but then instead of spilling or plunging they surge up the beach face.

Breakwater - a structure protecting a shore area, harbour or basin from waves.

Capillary wave - a wave whose velocity of propagation depends on the surface tension of the liquid in which the wave is travelling.

Crest Length, Wave - the length of a wave along its crest.

Crest of Wave - the highest part of a wave.

Decay of Waves - the change waves undergo after they leave a generating or fetch area and enter an area of calm.

Deep water - water of depth such that the waves are not affected by the bottom. It is customary to consider water deeper than one-half the surface wave length as deep water.

Depth - the vertical distance from the still water level to the bottom.

Dyke - a wall, mound or structure built around a low-lying area to prevent flooding.

Duration - the length of time the wind blows in essentially the same direction over the fetch area.

Duration, Minimum - the time necessary for steady state wave conditions to develop for a given wind velocity over a given fetch area.

Fetch - the continuous area of water over which the wind blows in essentially the same direction.

Fetch Length - the horizontal distance over which the wind blows.

Following wind - a wind blowing in the same direction that the waves are travelling.

Freeboard - the additional height of a structure above design high water level to prevent overflow.

Front of the Fetch - it is that end of the generating area toward which the wind blows.

Generating Area - see fetch area.

Generation of waves - the creation of waves by natural or mechanical means.

Gradient - with reference to wind it is the difference in pressure between isobars divided by the distance between isobars.

Gravity waves - a wave whose velocity of propagation is controlled primarily by gravity.

Height of wave - the vertical distance between a crest and the preceding trough.

Isobars - lines of equal barometric pressure.

Kinetic energy - in an oscillatory wave, a summation of the energy of motion of the particles within the wave. This energy does not advance with the wave form.

Knot - a unit of speed used in navigation. It is equal to one nautical mile, 6,080.20 ft. per hour.

Length - the horizontal distance between similar points on two successive waves measured perpendicularly to the crest.

Median Diameter - the diameter which marks the division of a given sample into two equal parts by weight.

Monolithic - a type of construction in which the structure's component parts are bound together to act as one.

Nautical Mile - the length of a minute of arc, of 1/21,600 of an average great circle of the earth.

Orbit - in water waves the path of a water particle affected by the wave motion.

Oscillation - a periodic motion to and fro, or up and down.

Oscillatory wave - a wave in which each individual particle oscillates about a point with little or no permanent change in position.

Overtopping - the amount of water passing over the top of a structure as a result of wave run-up or surge action.

Plunge Point - (1) for a plunging wave, the point at which the wave curls over and falls.

(2) the final breaking point of the wave just before they rush up on the beach.

Potential Energy of Waves - in a progressive oscillatory wave, the energy resulting from the elevation or depression of the water surface from the undisturbed level. This energy advances with the wave form.

Progressive Wave - a wave which is manifested by the progressive movement of the wave form.

Propagation of waves - the transmission of waves through water.

Prototype - in laboratory usage, the original structure, concept, or phenomenon used as a basis for constructing a scale model or copy.

Reflected Wave - the wave that is returned from shore when a wave impinges upon a very steep beach, barrier, or other reflecting surfaces.

Refraction of Waves - the process by which the direction of a wave moving in shallow water at an angle to the contours is changed. The part of the wave advancing in shallower water moves more slowly than that part still advancing in deeper water, causing the same crest to bend toward alignment with the under-water contours.

Ride-up - see run-up.

Riprap - a layer, facing or protective mound of stones randomly placed to prevent erosion, scour, or sloughing of a structure or embankment, also, the stone so used.

Rubble - loose angular water-worn stones along a beach.

Rubble mound structure - a mound of random-shaped and random-placed stones protected with a cover layer of selected stones or specially shaped concrete armour units.

Run-up - the rush of water up a structure on the breaking of a wave. Also uprush. The amount of run-up is the vertical height above still water level that the rush of water reaches.

Seiche - a periodic oscillation of a body of water whose period is determined by the resonant characteristics of the containing basin as controlled by its physical dimensions. The periods range from a few minutes to an hour or more.

Set-up, wind - (1) the vertical rise in the still water level on the leeward side of a body of water caused by wind stresses on the surface of the water.

(2) the difference in still water level between the windward and leeward sides of a body of water caused by wind stresses on the surface of the water.

Shallow Water - water of such a depth that surface waves are noticably affected by the bottom topography. It is customary to call water shallow when the depth is less than one-twenty-fifth of the wave length.

Shoaling Coefficient - the ratio of the height of a wave in water of any depth to its height in deep water with the effect of refraction eliminated.

Significant wave - a statistical term denoting waves with the average height and period of the one third highest waves of a given wave group.

Slope - the degree of inclination to the horizontal.

Still Water Level - the elevation of the water surface if all wave action were to cease.

Swash - see uprush, run-up.

Tide - the periodic rising and falling of the water that results from gravitational attraction of the moon and sun acting upon the rotating earth.

Transitional - in regard to progressive gravity waves, water whose depth is less than ½ but more than 1/25 the wave length.

Uprush - the rush of water up onto a beach following the breaking of a wave.

Velocity of Waves - the speed with which an individual wave advances.

Wave - a ridge, deformation, or undulation of the surface of a liquid.

Wave Forecasting - the theoretical determination of future wave characteristics, usually from observed or predicted meteorological phenomena.

Wave steepness - the ratio of a wave's height to its length, $\frac{H_o}{L_o}$

Wind Wave - a wave that has been formed and built up by wind.

Wind - the horizontal natural movement of air.

APPENDIX B

TABLE 1

SLOPES AND MATERIALS TESTED

Riprap Material Size (inches)	Slope 1/30*	1/8	1/6	1/5	1/4	1/3	1/2.5	1/2	1/1.5	1/1	1/2	Vertical
Reversed Smooth	-	-	--	x	-	x	-	x	-	x	-	x
Smooth	x	x	-	x	x	-	x	-	x	x	x	x
$\frac{1}{4}$" - 3/8"	-	x	x	x	x	x	-	x	-	x	-	-
$\frac{1}{2}$" - $\frac{3}{4}$"	-	x	x	-	x	x	-	x	-	x	-	-
$\frac{3}{4}$" - $1\frac{1}{2}$"	-	x	x	-	x	x	-	x	-	x	-	-
$1\frac{1}{2}$" - 3"	-	x	x	-	x	x	-	x	-	x	-	-
3" - 6"	-	x	x	-	x	x	-	x	-	x	-	-

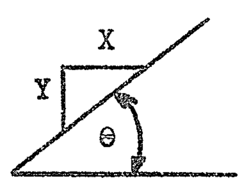
* Tested by Savage, but used in these results.

TABLE 2

SLOPES EXPRESSED AS

FUNCTIONS OF COT θ, $\frac{X}{Y}$

Slope	Cot θ	Angle
1 on 1	1	45° 00'
1 on 2	2	26° 34'
1 on 3	3	18° 26'
1 on 4	4	14° 02'
1 on 5	5	11° 19'
1 on 6	6	9° 28'
1 on 7	7	8° 08'
1 on 8	8	7° 08'
1 on 9	9	6° 30'
1 on 10	10	5° 43'
1 on 30	30	1° 54'



APPENDIX C

SMOOTH SLOPES - LABORATORY DATA

Period T Seconds	Slope							
	Vertical				1 on 0.5			
	H	H'_o	$\frac{H'_o}{T^2}$	$\frac{R}{H'_o}$	H	H'_o	$\frac{H'_o}{T^2}$	$\frac{R}{H'_o}$
4.0	.230	.18	.011	1.25	.090	.072	.004	1.31
4.0	.140	.11	.007	0.90	.090	.072	.004	1.56
4.0	.080	.06	.004	0.90	.100	.090	.005	1.88
4.0	.095	.08	.005	0.95	.095	.076	.005	1.59
3.0	.240	.22	.025	1.01	.095	.086	.010	1.31
3.0	.220	.20	.022	1.00	.110	.099	.012	1.36
3.0	.160	.14	.016	1.07	.110	.099	.012	1.46
3.0	.130	.12	.013	1.02	.105	.098	.011	1.40
2.5	.580	.56	.090	1.18	.180	.174	.028	1.35
2.5	.350	.34	.055	1.01	.130	.125	.020	1.75
2.5	.300	.29	.047	1.11	.115	.111	.018	1.57
2.5	.220	.21	.034	1.15	.140	.135	.022	1.55
2.0	.440	.46	.115	1.03	.310	.320	.080	1.18
2.0	.440	.46	.115	1.04	.300	.310	.077	1.25
2.0	.310	.32	.080	1.07	.300	.310	.077	1.36
2.0	.210	.22	.055	1.08	.310	.320	.080	1.27
1.5	.530	.58	.258	0.81	.430	.470	.209	1.08
1.5	.430	.47	.210	1.13	.430	.470	.209	1.16
1.5	.400	.44	.195	0.97	.430	.470	.209	1.23
1.5	.280	.30	.133	0.98	.430	.470	.209	1.17
1.0	.560	.59	.590	0.84	.500	.530	.530	1.00
1.0	.500	.53	.530	1.04	.500	.530	.530	1.16
1.0	.300	.32	.320	1.11	.500	.530	.530	1.00
1.0	.190	.20	.200	1.04	.500	.530	.530	1.06

TABLE 3

SMOOTH SLOPES - LABORATORY DATA

Period T Seconds	Slope							
	1 on 1				1 on 1.5			
	H	H'_o	$\frac{H'_o}{T^2}$	$\frac{R}{H'_o}$	H	H'_o	$\frac{H'_o}{T^2}$	$\frac{R}{H'_o}$
4.0	.060	.050	.003	2.60	.065	.052	.003	2.88
4.0	.075	.060	.004	2.42	.060	.048	.003	2.80
4.0	.065	.055	.003	2.40	.065	.052	.003	2.63
4.0	.080	.065	.004	2.48	.070	.056	.004	2.75
3.0	.110	.099	.011	1.45	.080	.072	.008	2.15
3.0	.125	.113	.013	1.67	.085	.076	.008	2.08
3.0	.105	.095	.011	1.76	.085	.076	.008	2.16
3.0	.125	.113	.013	1.55	.080	.072	.008	2.18
2.5	.155	.150	.024	1.67	.230	.222	.035	1.76
2.5	.170	.165	.027	1.53	.235	.227	.037	1.86
2.5	.180	.175	.028	1.64	.235	.227	.037	1.94
2.5	.165	.160	.026	1.60	.240	.232	.037	1.83
2.0	.310	.320	.080	1.47	.360	.372	.093	1.42
2.0	.300	.310	.077	1.11	.360	.372	.093	1.65
2.0	.310	.320	.080	1.47	.340	.352	.088	1.58
2.0	.310	.310	.077	1.37	.330	.342	.085	1.50
1.5	.190	.210	.093	1.32	.440	.480	.213	1.54
1.5	.190	.210	.093	1.20	.440	.480	.213	1.51
1.5	.190	.210	.093	1.18	.440	.480	.213	1.54
1.5	.190	.210	.093	1.24	.470	.512	.227	1.48
1.0	.500	.530	.530	1.15	.400	.423	.423	1.65
1.0	.490	.520	.520	1.10	.400	.423	.423	1.40
1.0	.485	.510	.510	1.25	.400	.423	.423	1.24
1.0	.490	.520	.520	1.20	.430	.455	.455	1.61

TABLE 3 (continued)

SMOOTH SLOPES - LABORATORY DATA

Period T Seconds	Slope							
	1 on 2.5				1 on 4			
	H	H'_o	$\frac{H'_o}{T^2}$	$\frac{R}{H'_o}$	H	H'_o	$\frac{H'_o}{T^2}$	$\frac{R}{H'_o}$
4.0	.065	.060	.004	3.30	.090	.070	.005	3.56
4.0	.070	.060	.004	3.15	.080	.060	.004	3.60
4.0	.060	.050	.003	3.55	.085	.070	.005	3.68
4.0	.065	.060	.004	3.44	.080	.060	.004	3.68
3.0	.125	.112	.013	2.46	.120	.107	.012	2.43
3.0	.130	.117	.013	2.60	.090	.081	.009	3.50
3.0	.125	.112	.013	2.21	.120	.107	.012	2.41
3.0	.130	.112	.013	2.55	.110	.099	.011	2.93
2.5	.210	.202	.032	2.08	.230	.222	.036	2.74
2.5	.200	.193	.031	2.30	.220	.212	.034	2.81
2.5	.220	.212	.034	2.12	.220	.212	.034	2.65
2.5	.210	.202	.032	2.24	.220	.212	.034	2.70
2.0	.310	.320	.080	2.08	.305	.315	.079	2.39
2.0	.330	.342	.085	2.13	.310	.320	.080	2.51
2.0	.300	.312	.078	2.00	.305	.315	.079	2.37
2.0	.330	.320	.080	2.10	.305	.315	.079	2.37
1.5	.550	.600	.267	1.57	.440	.480	.214	1.44
1.5	.490	.535	.238	1.71	.440	.480	.214	1.47
1.5	.440	.480	.214	1.75	.440	.480	.214	1.43
1.5	.500	.545	.243	1.69	.440	.480	.214	1.42
1.0	.440	.465	.465	1.73	.330	.350	.350	1.39
1.0	.440	.465	.465	1.65	.330	.350	.350	1.41
1.0	.440	.465	.465	1.56	.330	.350	.350	1.30
1.0	.440	.465	.465	1.62	.440	.465	.465	1.08

TABLE 3 (continued)

SMOOTH SLOPES - LABORATORY DATA

Period T Seconds	Slope 1 on 5				Slope 1 on 8			
	H	H'_o	$\frac{H'_o}{T^2}$	$\frac{R}{H'_o}$	H	H'_o	$\frac{H'_o}{T^2}$	$\frac{R}{H'_o}$
4.0	.080	.060	.004	2.75	.080	.060	.004	3.14
4.0	.070	.060	.004	3.07	.075	.060	.004	3.20
4.0	.070	.060	.004	3.21	.080	.060	.004	3.20
4.0	.070	.060	.004	2.95	.070	.060	.004	3.06
3.0	.095	.085	.009	2.96	.130	.117	.013	2.04
3.0	.095	.085	.009	3.21	.135	.121	.013	2.12
3.0	.110	.099	.011	2.55	.130	.117	.013	2.12
3.0	.100	.090	.010	2.60	.130	.117	.013	2.16
2.5	.205	.198	.032	2.92	.170	.164	.026	1.49
2.5	.225	.217	.035	2.70	.180	.174	.028	1.47
2.5	.200	.193	.031	2.88	.180	.174	.028	1.43
2.5	.210	.202	.032	2.80	.175	.179	.029	1.45
2.0	.330	.342	.085	2.16	.310	.320	.080	1.06
2.0	.310	.320	.080	2.04	.310	.320	.080	1.09
2.0	.305	.315	.079	2.02	.310	.320	.080	1.06
2.0	.320	.332	.083	2.08	.310	.320	.080	1.11
1.5	.450	.490	.218	1.21	.430	.470	.209	0.92
1.5	.455	.495	.220	1.27	.430	.470	.209	0.96
1.5	.450	.490	.218	1.25	.430	.470	.209	0.98
1.5	.470	.510	.227	1.49	.440	.480	.214	0.97
1.0	.450	.476	.476	1.16	.350	.370	.370	0.71
1.0	.450	.476	.476	1.13	.350	.370	.370	0.73
1.0	.450	.476	.476	1.04	.330	.350	.350	0.71
1.0	.450	.476	.476	1.09	.350	.370	.370	0.78

TABLE 3 (continued)

REVERSED SMOOTH SLOPES – LABORATORY DATA

Period T Seconds	Slope 1 on 1				Slope 1 on 2			
	H	H'_o	$\frac{H'_o}{T^2}$	$\frac{R}{H'_o}$	H	H'_o	$\frac{H'_o}{T^2}$	$\frac{R}{H'_o}$
4.0	.105	.084	.005	1.15	.080	.064	.004	0.94
4.0	.175	.140	.009	1.00	.090	.072	.005	0.98
3.0	.185	.168	.019	1.04	.130	.118	0.13	1.15
3.0	.105	.095	.011	0.83	.125	.122	.014	1.03
2.5	.260	.250	.040	0.88	.220	.212	.034	1.32
2.5	.320	.310	.050	0.94	.215	.207	.033	1.15
2.0	.135	.140	.035	1.13	.305	.315	.079	1.14
1.5	.210	.230	.103	2.02	.430	.470	.210	1.49
1.5	.130	.142	.063	1.95	.430	.470	.210	1.36
1.0	.500	.530	.530	1.58	.500	.530	.530	1.51
1.0	.380	.400	.400	1.65	.500	.530	.530	1.28

Period T Seconds	Slope 1 on 3				Slope 1 on 5			
	H	H'_o	$\frac{H'_o}{T^2}$	$\frac{R}{H'_o}$	H	H'_o	$\frac{H'_o}{T^2}$	$\frac{R}{H'_o}$
4.0	.070	.056	.004	1.34	.080	.064	.004	1.17
4.0	.080	.064	.004	1.25	.080	.064	.004	1.09
3.0	.120	.108	.012	1.16	.130	.118	.013	1.17
3.0	.140	.127	.014	1.06	.130	.118	.013	1.15
2.5	.235	.227	.036	1.01	.220	.212	.034	1.25
2.5	.245	.236	.038	1.00	.220	.212	.034	1.16
2.0	.320	.330	.082	1.09	.310	.320	.080	1.04
2.0	.315	.325	.081	1.14	.310	.320	.080	0.98
1.5	.430	.470	.210	1.33	.430	.470	.210	1.05
1.5	.430	.470	.210	1.23	.430	.470	.210	0.99
1.0	.500	.530	.530	1.42	.500	.530	.530	1.14
1.0	.500	.530	.530	1.32	.500	.530	.530	1.23

TABLE 4

ROUGHENED SLOPES - LABORATORY DATA

Slope 1 on 1

Size of Slope Material					¼" - 3/8"		½" - ¾"		¾" - 1½"	
T	H	H'_o	$\frac{H'_o}{T^2}$	Symbol	$\frac{R}{d}$	$\frac{H'_oT^2}{d^2}$	$\frac{R}{d}$	$\frac{H'_oT^2}{d^2}$	$\frac{R}{d}$	$\frac{H'_oT^2}{d^2}$
4.0	.090	.072	.004	○			1.64	420.0	1.28	130.0
4.0	.090	.072	.004	○			1.92	420.0	1.02	130.0
4.0	.135	.108	.007	○			2.31	631.0	1.87	194.0
4.0	.135	.108	.007	○			2.50	631.0	2.08	194.0
3.0	.130	.118	.013	□			5.00	387.0	3.40	120.0
3.0	.130	.118	.013	□			5.15	387.0	3.52	120.0
3.0	.070	.063	.007	○				207.0	0.85	63.8
3.0	.070	.063	.007	○				207.0	0.96	63.8
2.5	.210	.202	.032	□	N			461.0	2.77	143.0
2.5	.210	.202	.032	□				461.0	3.00	143.0
2.5	.110	.106	.017	□	O			241.0	2.57	74.9
2.5	.110	.106	.017	□				241.0	2.67	74.9
2.5	.320	.308	.048	△	T			702.0	2.88	218.0
2.5	.320	.308	.048	△				702.0	3.40	218.0
2.0	.480	.496	.124	–				724.0	4.70	223.0
2.0	.480	.496	.124	–				724.0	4.91	223.0
2.0	.330	.341	.085	–				498.0	3.85	153.0
2.0	.330	.341	.085	–		T		498.0	3.95	153.0
2.0	.240	.248	.062	△				362.0	1.55	112.0
2.0	.240	.248	.062	△		E		362.0	1.65	112.0
1.5	.130	.141	.062	△				116.0	1.93	35.9
1.5	.130	.141	.062	△		S		116.0	1.87	35.9
1.5	.230	.250	.111	–				205.0	2.88	63.7
1.5	.230	.250	.111	–		T		205.0	3.00	63.7
1.5	.430	.469	.208	x				385.0	4.80	120.0
1.5	.430	.469	.208	x		E		385.0	4.80	120.0
1.0	.24	.253	.253	x				92.3	2.35	28.6
1.0	.24	.253	.253	x		D		92.3	2.45	28.6
1.0	.37	.390	.390	◊				142.0	5.35	44.1
1.0	.37	.390	.390	◊				142.0	5.35	44.1
1.0										
1.0										
1.0	.61	.644	.644	◊				235.0	5.88	72.8
1.0	.61	.644	.644	◊				235.0	5.98	72.8

TABLE 5

ROUGHENED SLOPES - LABORATORY DATA

Slope 1 on 1

Size of Slope Material					$1\frac{1}{2}$" - 3"		3" - 6"	
T	H	H'_o	$\frac{H'_o}{T^2}$	Symbol	$\frac{R}{d}$	$\frac{H'_o T^2}{d^2}$	$\frac{R}{d}$	$\frac{H'_o T^2}{d^2}$
4.0	.090	.072	.004	○	0.69	36.4	0.25	12.8
4.0	.090	.072	.004	○	0.64	36.4	0.15	12.8
4.0	.135	.108	.007	○	0.85	54.5	0.45	19.3
4.0	.135	.108	.007	○	0.88	54.5	0.40	19.3
3.0	.130	.118	.013	□	1.17	33.6	0.75	11.8
3.0	.130	.118	.013	□	1.22	33.6	0.70	11.8
3.0	.070	.063	.007	○	0.42	17.9	0.21	6.3
3.0	.070	.063	.007	○	0.48	17.9	0.24	6.3
2.5	.210	.202	.032	□	2.07	39.8	1.15	14.1
2.5	.210	.202	.032	□	2.00	39.8	1.18	14.1
2.5	.110	.106	.017	□	0.91	20.9	0.90	7.4
2.5	.110	.106	.017	□	0.88	20.9	0.83	7.4
2.5	.320	.308	.048	△	1.44	60.7	1.20	20.6
2.5	.320	.308	.048	△	1.70	60.7	1.17	20.6
2.0	.480	.496	.124	—	2.55	62.5	2.13	22.2
2.0	.480	.496	.124	—	2.50	62.5	2.07	22.2
2.0	.330	.341	.085	—	2.35	42.9	0.73	15.3
2.0	.330	.341	.085	—	2.50	42.9	0.77	15.3
2.0	.240	.248	.062	△	1.17	31.2	0.37	11.1
2.0	.240	.248	.062	△	1.33	31.2	0.43	11.1
1.5	.130	.141	.062	△	1.55	10.0	0.43	1.6
1.5	.130	.141	.062	△	1.60	10.0	0.47	1.6
1.5	.230	.250	.111	—	1.07	17.8	6.73	2.8
1.5	.230	.250	.111	—	1.12	17.8	0.80	2.8
1.5	.430	.469	.208	×	2.30	33.3	1.25	5.3
1.5	.430	.469	.208	×	2.50	33.3	1.18	5.3
1.0	.240	.253	.253	×	1.28	7.9	0.88	2.8
1.0	.240	.253	.253	×	1.31	7.9	0.89	2.8
1.0	.370	.390	.390	◇	2.56	12.3	1.40	4.4
1.0	.370	.390	.390	◇	2.70	12.3	1.47	4.4
1.0								
1.0								
1.0	.610	.644	.644	◇	3.15	20.2	2.07	7.2
1.0	.610	.644	.644	◇	3.20	20.2	2.00	7.2

TABLE 5 (continued)

ROUGHENED SLOPES - LABORATORY DATA

Slope 1 on 2

Size of Slope Material					1/4" - 3/8"		1/2" - 3/4"		3/4" - 1 1/2"	
T	H	H'_o	$\frac{H'_o}{T^2}$	Symbol	$\frac{R}{d}$	$\frac{H'_oT^2}{d^2}$	$\frac{R}{d}$	$\frac{H'_oT^2}{d^2}$	$\frac{R}{d}$	$\frac{H'_oT^2}{d^2}$
4.0	.150	.120	.009	○			1.25	701.0	1.39	216.0
4.0	.150	.120	.008	○			1.35	701.0	1.33	216.0
4.0	.260	.208	.013	□			3.38	1214.0	2.46	374.0
4.0	.260	.208	.013	□			3.19	1214.0	2.56	374.0
3.0	.270	.244	.027	□			5.30	800.0	3.84	247.0
3.0	.270	.244	.027	□			5.10	800.0	3.64	247.0
3.0	.175	.158	.018	□			3.95	518.0	2.24	160.0
3.0	.175	.158	.018	□			3.95	518.0	2.35	160.0
2.5	.220	.212	.034	□			4.71	483.0	2.35	150.0
2.5	.220	.212	.034	□			4.62	483.0	2.46	150.0
2.5	.210	.202	.032	□			4.25	461.0	4.37	143.0
2.5	.210	.202	.032	□	N		4.42	461.0	4.58	143.0
2.5	.200	.193	.032	□			6.55	440.0	4.58	136.0
2.5	.200	.193	.032	□	O		6.35	440.0	4.80	136.0
2.0	.390	.403	.100	–			8.70	588.0	5.77	181.0
2.0	.390	.403	.100	–	T		8.50	588.0	5.87	181.0
2.0	.330	.341	.085	–			5.10	498.0	2.14	153.0
2.0	.330	.341	.085	–			6.30	498.0	2.24	153.0
2.0	.130	.135	.034	□			2.12	197.0	1.50	60.7
2.0	.140	.145	.036	□		T	2.32	211.0	1.60	65.2
1.5	.120	.130	.058	△			3.28	106.0	1.92	33.2
1.5	.120	.130	.058	△		E	3.47	106.0	1.81	33.2
1.5	.210	.229	.102	–			6.35	188.0	3.20	58.4
1.5	.210	.229	.102	–		S	6.75	188.0	3.31	58.4
1.5	.360	.392	.174	×			9.55	321.0	5.77	100.0
1.5	.360	.392	.174	×		T	9.80	321.0	5.87	100.0
1.0	.220	.232	.232	×			4.53	84.7	2.56	26.2
1.0	.220	.232	.232	×		E	4.63	84.7	2.67	26.2
1.0	.300	.317	.317	×			6.35	116.0	3.85	35.8
1.0	.300	.317	.317	×		D	6.75	116.0	3.94	35.8
1.0	.430	.454	.454	◊			8.30	166.0	4.10	51.3
1.0	.430	.454	.454	◊			8.70	166.0	4.15	51.3
1.0	.450	.475	.475	◊			10.20	173.0	5.33	53.7
1.0	.460	.485	.485	◊			10.60	177.0	5.55	54.8

TABLE 5 (continued)

ROUGHENED SLOPES - LABORATORY DATA

Slope 1 on 2

Size of Slope Material					$1\frac{1}{2}$" - 3"		3" - 6"	
T	H	H'_o	$\frac{H'_o}{T^2}$	Symbol	$\frac{R}{d}$	$\frac{H'_o T^2}{d^2}$	$\frac{R}{d}$	$\frac{H'_o T^2}{d^2}$
4.0	.150	.120	.008	○	0.59	60.6	0.37	21.4
4.0	.150	.120	.008	○	0.61	60.6	0.35	21.4
4.0	.260	.208	.013	□	1.54	105.0	0.67	37.2
4.0	.260	.208	.013	□	1.49	105.0	0.68	37.2
3.0	.270	.244	.027	□	1.39	69.5	1.00	24.4
3.0	.270	.244	.027	□	1.33	69.5	0.97	24.4
3.0	.175	.158	.018	□	0.91	45.0	0.53	15.8
3.0	.175	.158	.018	□	1.06	45.0	0.50	15.8
2.5	.220	.212	.034	□	1.17	41.8	0.73	14.8
2.5	.220	.212	.034	□	1.06	41.8	0.76	14.8
2.5	.210	.202	.032	□	1.70	39.8	0.90	14.1
2.5	.210	.202	.032	□	1.60	39.8	0.93	14.1
2.5	.200	.193	.032	□	1.43	38.0	1.23	13.5
2.5	.200	.193	.032	□	1.46	38.0	1.33	13.5
2.0	.390	.403	.100	–	3.35	50.8	1.77	18.0
2.0	.390	.403	.100	–	3.25	50.8	1.83	18.0
2.0	.330	.341	.085	–	1.17	43.0	0.77	15.3
2.0	.330	.341	.085	–	1.06	43.0	0.73	15.3
2.0	.130	.135	.034	□	0.69	17.0	0.43	6.1
2.0	.140	.145	.036	□	0.75	18.3	0.40	6.5
1.5	.120	.130	.058	△	0.91	9.2	0.50	3.3
1.5	.210	.130	.058	△	0.85	9.2	0.53	3.3
1.5	.210	.229	.102	–	1.68	16.3	1.17	5.8
1.5	.210	.229	.102	–	1.60	16.3	1.23	5.8
1.5	.360	.392	.174	×	3.14	27.8	1.83	10.0
1.5	.360	.392	.174	×	3.20	27.8	1.90	10.0
1.0	.220	.232	.232	×	1.81	7.3	0.87	2.6
1.0	.220	.232	.232	×	1.92	7.3	0.93	2.6
1.0	.300	.317	.317	×	2.18	10.0	0.77	3.6
1.0	.300	.317	.317	×	2.29	10.0	0.80	3.6
1.0	.430	.454	.454	◆	2.50	14.3	1.40	5.1
1.0	.430	.454	.454	◆	2.40	14.3	1.33	5.1
1.0	.450	.475	.475	◆	2.72	14.9	2.06	5.3
1.0	.460	.485	.485	◆	2.87	15.3	2.00	5.4

TABLE 5 (continued)

ROUGHENED SLOPES – LABORATORY DATA

Slope 1 on 3

Size of Slope Material					$\frac{1}{4}$" – 3/8"		$\frac{1}{2}$" – $\frac{3}{4}$"		$\frac{3}{4}$" – $1\frac{1}{2}$"	
T	H	H'_o	$\frac{H'_o}{T^2}$	Symbol	$\frac{R}{d}$	$\frac{H'_oT^2}{d^2}$	$\frac{R}{d}$	$\frac{H'_oT^2}{d^2}$	$\frac{R}{d}$	$\frac{H'_oT^2}{d^2}$
4.0	.105	.084	.005	○			1.73	491.0	1.29	151.0
4.0	.105	.084	.005	○			1.84	491.0	1.23	151.0
4.0	.195	.156	.010	○			3.08	911.0	1.77	280.0
4.0	.195	.156	.010	○			3.27	911.0	1.82	280.0
3.0	.160	.145	.016	□			4.42	476.0	3.42	146.0
3.0	.160	.145	.016	□			4.80	476.0	3.48	146.0
3.0	.095	.086	.009	○			2.12	282.0	1.34	87.1
3.0	.095	.086	.009	○			2.31	282.0	1.39	87.1
2.5	.235	.227	.036	□			5.95	518.0	2.78	160.0
2.5	.235	.227	.036	□			6.15	518.0	2.89	160.0
2.5	.450	.434	.069	△			7.50	990.0	3.96	307.0
2.5	.450	.434	.069	△			7.85	990.0	3.85	307.0
2.5	.320	.308	.049	△			7.11	702.0	3.21	218.0
2.5	.320	.308	.049	△			7.30	702.0	3.10	218.0
2.0	.380	.393	.099	—			9.60	574.0	4.65	177.0
2.0	.380	.393	.099	—			9.20	574.0	4.55	177.0
2.0	.280	.290	.072	△			5.95	423.0	2.57	131.0
2.0	.280	.290	.072	△			6.15	423.0	2.67	131.0
2.0	.155	.160	.040	△			2.50	237.0	1.71	72.0
2.0	.155	.160	.040	□			2.40	237.0	1.66	72.0
1.5	.150	.163	.072	△			3.37	133.0	1.77	41.6
1.5	.150	.163	.072	△			3.17	133.0	1.82	41.6
1.5	.205	.223	.099	—			6.35	183.0	2.56	56.9
1.5	.205	.223	.099	—			6.73	183.0	2.67	56.9
1.5	.350	.381	.169	—			8.00	312.0	2.89	97.2
1.5	.350	.381	.169	—			8.27	312.0	2.94	97.2
1.0	.245	.258	.258	×			4.04	94.2	2.89	29.2
1.0	.245	.258	.258	×			4.23	94.2	2.78	29.2
1.0	.380	.400	.400	◆			5.57	146.0	3.42	45.2
1.0	.380	.400	.400	◆			5.77	146.0	3.32	45.2
1.0	.460	.485	.485	◆			6.14	177.0	3.42	54.8
1.0	.460	.485	.485	◆			6.34	177.0	3.58	54.8
1.0	.490	.517	.517	◆			7.30	189.0	4.17	58.4
1.0	.490	.517	.517	◆			7.50	189.0	4.28	58.4

TABLE 5 (continued)

ROUGHENED SLOPES – LABORATORY DATA

Slope 1 on 3

Size of Slope Material					$1\frac{1}{2}"$ – 3"		3" – 6"	
T	H	H'_o	$\frac{H'_o}{T^2}$	Symbol	$\frac{R}{d}$	$\frac{H'_o T^2}{d^2}$	$\frac{R}{d}$	$\frac{H'_o T^2}{d^2}$
4.0	.105	.084	.005	○	0.85	42.4	0.33	15.0
4.0	.105	.084	.005	○	0.82	42.4	0.32	15.0
4.0	.195	.156	.010	○	0.98	78.7	0.60	27.9
4.0	.195	.156	.010	○	1.01	78.7	0.57	27.9
3.0	.160	.145	.016	□	1.30	41.3	0.63	14.5
3.0	.160	.145	.016	□	1.35	41.3	0.62	14.5
3.0	.095	.086	.009	○	0.72	24.5	0.48	8.6
3.0	.095	.086	.009	○	0.77	24.5	0.47	8.6
2.5	.235	.227	.036	□	1.25	44.7	0.66	15.8
2.5	.235	.227	.036	□	1.22	44.7	0.70	15.8
2.5	.450	.434	.069	△	1.59	85.4	1.33	30.3
2.5	.450	.434	.069	△	1.65	85.4	1.30	30.3
2.5	.320	.308	.049	△	1.52	60.7	0.96	21.6
2.5	.320	.308	.049	△	1.54	60.7	1.00	21.6
2.0	.380	.393	.099	—	2.20	49.5	1.50	17.6
2.0	.380	.393	.099	—	2.18	49.5	1.53	17.6
2.0	.280	.290	.072	△	1.46	36.5	0.70	13.0
2.0	.280	.290	.072	△	1.41	36.5	0.63	13.0
2.0	.155	.160	.040	△	0.85	20.2	0.46	7.2
2.0	.155	.160	.040	□	0.82	20.2	0.43	7.2
1.5	.150	.163	.072	△	1.01	11.6	0.53	4.1
1.5	.150	.163	.072	△	0.96	11.6	0.57	4.1
1.5	.205	.223	.099	—	1.25	15.8	0.83	5.7
1.5	.205	.223	.099	—	1.30	15.9	0.80	5.7
1.5	.350	.381	.169	—	1.33	27.0	1.15	9.7
1.5	.350	.381	.169	—	1.36	27.0	1.15	9.7
1.0	.245	.258	.258	x	1.41	8.1	8.76	2.9
1.0	.245	.258	.258	x	1.44	8.1	0.73	2.9
1.0	.380	.400	.400	◆	1.78	12.6	1.11	4.5
1.0	.380	.400	.400	◆	1.73	12.6	1.12	4.5
1.0	.460	.485	.485	◆	2.12	15.2	1.14	5.4
1.0	.460	.485	.485	◆	1.97	15.2	1.15	5.4
1.0	.490	.517	.517	◆	2.55	16.3	1.14	5.8
1.0	.490	.517	.517	◆	2.66	16.3	1.13	5.8

TABLE 5 (continued)

ROUGHENED SLOPES - LABORATORY DATA

Slope 1 on 4

Size of Slope Material					$\frac{1}{4}$" - 3/8"		$\frac{1}{2}$" - $\frac{3}{4}$"		$\frac{3}{4}$" - $1\frac{1}{2}$"	
T	H	H'_o	$\frac{H'_o}{T^2}$	Symbol	$\frac{R}{d}$	$\frac{H'_o T^2}{d^2}$	$\frac{R}{d}$	$\frac{H'_o T^2}{d^2}$	$\frac{R}{d}$	$\frac{H'_o T^2}{d^2}$
4.0	.105	.084	.005	○	2.63	1966	2.02	491	1.17	151.0
4.0	.105	.084	.005	○	2.50	1966	2.11	491	1.22	151.0
4.0	.150	.120	.007	○	6.70	2808	3.07	700	1.97	216.0
4.0	.150	.120	.007	○	6.90	2808	2.88	700	1.87	216.0
3.0	.155	.140	.015	□	11.15	1845	4.70	459	2.40	142.0
3.0	.155	.140	.015	□	10.75	1845	4.62	459	2.35	142.0
3.0	.075	.068	.008	○	1.73	896	2.31	223	1.50	68.8
3.0	.075	.068	.008	○	1.53	896	2.50	223	1.55	68.8
2.5	.200	.193	.031	□	10.35	1766	4.80	440	2.35	136.0
2.5	.200	.193	.031	□	10.18	1766	4.62	440	2.30	136.0
2.5	.250	.241	.039	□	14.20	2205	5.57	549	2.98	170.0
2.5	.250	.241	.039	□	13.85	2205	5.38	549	2.88	170.0
2.5	.240	.231	.037	□	12.85	2114	4.90	527	2.98	163.0
2.5	.240	.231	.037	□	13.25	2114	5.00	527	3.09	163.0
2.0	.375	.388	.097	—	19.20	2270	6.44	566	4.42	175.0
2.0	.375	.388	.097	—	19.95	2270	6.25	566	4.53	175.0
2.0	.255	.264	.068	△	10.00	1544	4.22	385	2.29	119.0
2.0	.255	.264	.068	△	10.35	1544	4.52	385	2.34	119.0
2.0	.140	.145	.036	□	4.60	848	3.07	212	1.23	65.2
2.0	.140	.145	.036	□	4.80	848	3.27	212	1.33	65.2
1.5	.135	.147	.065	△	4.60	485	3.36	120	1.28	37.5
1.5	.135	.147	.065	△	4.80	485	3.55	120	1.17	37.5
1.5	.210	.229	.101	—	11.15	756	4.41	188	4.00	58.3
1.5	.210	.229	.101	—	11.50	756	4.70	188	4.16	58.3
1.5	.300	.327	.145	—	14.40	1079	6.15	268	3.57	83.3
1.5	.300	.327	.145	—	14.20	1079	6.35	268	3.68	83.3
1.0	.265	.280	.280	X	7.10	410	3.46	102	1.92	31.8
1.0	.265	.280	.280	X	7.50	410	3.27	102	2.03	31.8
1.0	.280	.295	.295	X	8.83	432	3.27	108	2.66	33.4
1.0	.280	.295	.295	X	8.65	432	3.36	108	2.56	33.4
1.0	.380	.400	.400	◊	9.20	586	5.00	146	3.04	45.2
1.0	.380	.400	.400	◊	9.60	586	5.18	146	2.93	45.2
1.0	.425	.448	.448	◊	11.10	656	5.77	164	2.82	50.7
1.0	.425	.448	.448	◊	10.75	656	5.86	164	2.94	50.7

TABLE 5 (continued)

ROGHENED SLOPES - LABORATORY DATA

Slope 1 on 4

Size of Slope Material					$1\frac{1}{2}$" - 3"		3" - 6"	
T	H	H'_o	$\frac{H'_o}{T^2}$	Symbol	$\frac{R}{d}$	$\frac{H'_o T^2}{d^2}$	$\frac{R}{d}$	$\frac{H'_o T^2}{d^2}$
4.0	.105	.084	.005	○	0.50	42.4	0.33	15.0
4.0	.105	.084	.005	○	0.53	42.4	0.35	15.0
4.0	.150	.120	.007	○	0.93	60.6	0.60	21.5
4.0	.150	.210	.007	○	0.88	60.6	0.57	21.5
3.0	.155	.140	.015	□	1.52	39.9	0.67	14.0
3.0	.155	.140	.015	□	1.49	39.9	0.69	14.0
3.0	.075	.068	.008	○	0.64	19.4	0.47	6.8
3.0	.075	.068	.008	○	0.67	19.4	0.44	6.8
2.5	.200	.193	.031	□	0.96	38.0	0.82	13.5
2.5	.200	.193	.031	□	1.01	38.0	0.84	13.5
2.5	.250	.241	.039	□	1.06	47.5	0.77	16.8
2.5	.250	.241	.039	□	1.14	47.5	0.79	16.8
2.5	.240	.231	.037	□	1.20	45.5	1.04	16.1
2.5	.240	.231	.037	□	1.22	45.5	1.07	16.1
2.0	.375	.388	.097	—	2.34	48.9	0.90	17.3
2.0	.375	.388	.097	—	48.9	48.9	0.94	17.3
2.0	.255	.264	.068	△	0.96	33.3	1.03	11.8
2.0	.255	.264	.068	△	1.01	33.3	1.05	11.8
2.0	.140	.145	.036	□	0.72	18.3	0.57	6.5
2.0	.140	.145	.036	□	0.69	18.3	0.60	6.5
1.5	.135	.147	.065	△	0.75	10.4	0.55	3.7
1.5	.135	.147	.065	△	0.72	10.4	0.53	3.7
1.5	.210	.229	.101	—	1.28	16.2	0.92	5.8
1.5	.210	.229	.101	—	1.30	16.2	0.74	5.8
1.5	.300	.327	.145	—	1.73	23.2	1.09	8.3
1.5	.300	.327	.145	—	1.76	23.2	1.05	8.3
1.0	.265	.280	.280	×	1.22	8.8	0.82	3.1
1.0	.265	.280	.280	×	1125	8.8	0.84	3.1
1.0	.280	.295	.295	×	1.41	9.3	1.00	3.3
1.0	.290	.295	.295	×	1.33	9.3	0.97	3.3
1.0	.380	.400	.400	◊	1.44	12.6	1.09	4.5
1.0	.380	.400	.400	◊	1.46	12.6	1.12	4.5
1.0	.425	.448	.448	◊	1.73	14.1	1.14	5.0
1.0	.425	.448	.448	◊	1.70	14.1	1.12	5.0

TABLE 5 (continued)

ROUGHENED SLOPES - LABORATORY DATA

Slope 1 on 6

Size of Slope Material					1/4" - 3/8"		1/2" - 3/4"		3/4" - 1 1/2"	
T	H	H'_o	$\frac{H'_o}{T^2}$	Symbol	$\frac{R}{d}$	$\frac{H'_oT^2}{d^2}$	$\frac{R}{d}$	$\frac{H'_oT^2}{d^2}$	$\frac{R}{d}$	$\frac{H'_oT^2}{d^2}$
4.0	.105	.084	.005	○	5.00	1965	2.30	491	1.33	151.0
4.0	.105	.084	.005	○	5.35	1965	2.11	491	1.28	151.0
4.0	.165	.132	.008	○	10.30	3089	3.16	771	2.00	238.0
4.0	.165	.132	.008	○	10.70	3089	3.08	771	2.14	238.0
3.0	.175	.158	.017	□	8.05	2082	3.36	518	1.92	160.0
3.0	.175	.158	.017	□	8.22	2082	3.17	518	1.92	160.0
3.0	.105	.095	.010	○	5.75	1252	2.50	312	1.12	96.2
3.0	.105	.095	.010	○	5.75	1252	2.40	312	1.12	96.2
2.5	.260	.250	.040	□	6.50	2287	3.84	570	1.60	177.0
2.5	.260	.250	.040	△	6.50	2287	4.04	570	1.44	177.0
2.5	.380	.366	.059	△	11.85	3349	4.60	834	3.04	259.0
2.5	.380	.366	.059	△	11.50	3349	4.50	834	2.98	259.0
2.5	.350	.338	.054	△	10.30	3093	4.04	770	2.56	239.0
2.5	.350	.338	.054	△	10.70	3093	4.14	770	2.67	239.0
2.0	.380	.393	.099	—	12.80	2299	4.04	574	3.57	177.0
2.0	.380	.393	.099	—	12.60	2299	4.14	574	3.68	177.0
2.0	.310	.320	.080	△	6.31	1872	3.36	467	1.81	144.0
2.0	.310	.320	.080	—	6.70	1872	3.46	467	1.76	144.0
2.0	.145	.150	.037	□	3.82	877	1.53	219	1.28	67.5
2.0	.145	.150	.037	□	4.00	877	1.44	219	1.33	67.5
1.5	.135	.147	.065	△	4.20	485	2.11	121	0.96	37.4
1.5	.135	.147	.065	△	4.40	485	2.02	121	0.91	37.4
1.5	.220	.240	.106	—	6.92	792	2.70	196	1.87	61.2
1.5	.220	.240	.106	—	7.11	792	3.00	196	1.92	61.2
1.5	.370	.403	.179	×	10.50	1330	3.84	330	3.10	103.0
1.5	.370	.403	.179	×	10.95	1330	3.65	330	3.00	103.0
1.0	.275	.290	.290	×	6.54	425	2.50	105	1.60	32.7
1.0	.275	.290	.290	×	6.70	425	2.59	105	1.55	32.7
1.0	.360	.380	.380	◆	7.51	557	2.11	139	1.87	42.9
1.0	.360	.380	.380	◆	7.72	557	2.30	139	1.97	42.9
1.0	.470	.495	.495	◆	8.50	725	2.50	180	2.34	55.9
1.0	.470	.495	.495	◆	8.62	725	2.69	180	2.40	55.9
1.0	.535	.564	.564	◆	8.81	826	3.26	206	2.67	63.7
1.0	.535	.564	.564	◆	8.81	826	3.26	206	2.67	63.7
1.0	.535	.564	.564	◆	9.01	826	3.08	206	2.72	63.7

TABLE 5 (continued)

ROUGHENED SLOPES - LABORATORY DATA

Slope 1 on 6

Size of Slope Material					$1\frac{1}{2}$" - 3"		3" - 6"	
T	H	H_o'	$\frac{H_o'}{T^2}$	Symbol	$\frac{R}{d}$	$\frac{H_o'T^2}{d^2}$	$\frac{R}{d}$	$\frac{H_o'T^2}{d^2}$
4.0	.105	.084	.005	○	0.58	42.4	0.40	15.0
4.0	.105	.084	.005	○	0.53	42.4	0.42	15.0
4.0	.165	.132	.008	○	0.83	66.6	0.52	23.6
4.0	.165	.132	.008	○	0.80	66.6	0.50	23.6
3.0	.175	.158	.017	□	0.80	45.0	0.50	15.8
3.0	.175	.158	.017	□	0.91	45.0	0.46	15.8
3.0	.105	.095	.010	○	0.58	27.1	0.36	9.5
3.0	.105	.095	.010	○	0.53	27.1	0.38	9.5
2.5	.260	.250	.040	□	1.07	49.2	0.47	17.5
2.5	.260	.250	.040	△	1.04	49.2	0.50	17.5
2.5	.380	.366	.059	△	1.28	72.1	0.43	25.6
2.5	.380	.366	.059	△	1.33	72.1	0.45	25.6
2.5	.350	.338	.054	△	1.28	66.5	0.82	23.6
2.5	.350	.338	.054	△	1.25	66.5	0.80	23.6
2.0	.380	.393	.099	—	1.33	49.5	0.92	17.6
2.0	.380	.393	.099	—	1.39	49.5	0.92	17.6
2.0	.310	.320	.080	△	1.17	40.3	0.73	14.3
2.0	.310	.320	.080	—	1.22	40.3	0.73	14.3
2.0	.145	.150	.037	□	0.67	18.9	0.50	6.7
2.0	.145	.150	.037	□	0.72	18.9	0.48	6.7
1.5	.135	.147	.065	△	0.64	10.4	0.47	3.7
1.5	.135	.147	.065	△	0.69	10.4	0.48	3.7
1.5	.220	.240	.106	—	0.80	17.0	0.65	6.1
1.5	.220	.240	.106	—	0.69	17.0	0.68	6.1
1.5	.370	.403	.179	×	1.28	28.6	0.82	10.2
1.5	.370	.403	.179	×	1.31	28.6	0.85	10.2
1.0	.275	.290	.290	×	0.75	9.1	0.57	3.2
1.0	.275	.290	.290	×	0.80	9.1	0.60	3.2
1.0	.360	.380	.380	◆	0.93	11.9	0.70	4.3
1.0	.360	.380	.380	◆	0.93	11.9	0.72	4.3
1.0	.470	.495	.495	◆	1.20	15.6	0.85	5.5
1.0	.470	.495	.495	◆	1.20	15.6	0.83	5.5
1.0	.535	.564	.564	◆	1.17	17.8	0.68	6.3
1.0	.535	.564	.564	◆	1.22	17.8	0.70	6.3

TABLE 5 (continued)

ROUGHENED SLOPES – LABORATORY DATA

Slope 1 on 8

Size of Slope Material					¼" – 3/8"		½" – ¾"		¾" – 1½"	
T	H	H'_o	$\frac{H'_o}{T^2}$	Symbol	$\frac{R}{d}$	$\frac{H'_oT^2}{d^2}$	$\frac{R}{d}$	$\frac{H'_oT^2}{d^2}$	$\frac{R}{d}$	$\frac{H'_oT^2}{d^2}$
4.0	.115	.092	.006	○	4.40	2153	1.34	537	0.70	165.0
4.0	.120	.096	.006	○	4.04	2246	1.44	560	0.70	173.0
4.0	.185	.148	.009	○	6.13	3463	3.26	864	1.01	266.0
4.0	.180	.144	.009	○	5.74	3370	3.16	841	1.07	259.0
3.0	.195	.176	.019	□	5.55	2319	2.30	577	1.01	178.0
3.0	.190	.171	.019	□	5.17	2254	2.30	560	1.12	173.0
3.0	.115	.104	.011	○	4.40	1371	1.34	341	0.54	105.0
3.0	.120	.108	.011	○	4.21	1423	1.44	354	0.64	109.0
2.5	.235	.227	.036	□	3.83	2077	2.88	518	0.75	160.0
2.5	.240	.232	.037	□	3.45	2123	2.88	529	0.85	164.0
2.5	.440	.424	.068	△	8.90	3880	3.84	967	0.75	300.0
2.5	.450	.434	.069	△	9.00	3971	3.93	990	0.80	307.0
2.5	.360	.347	.065	△	6.90	3175	2.02	791	1.44	245.0
2.5	.350	.337	.054	△	6.90	3084	2.30	768	1.55	238.0
2.0	.390	.403	.101	—	8.05	2357	2.98	588	1.60	181.0
2.0	.400	.414	.103	—	7.27	2421	2.69	604	1.50	186.0
2.0	.290	.300	.075	△	7.67	1755	2.30	438	1.01	135.0
2.0	.295	.305	.076	△	7.27	1784	2.30	445	0.91	137.0
2.0	.145	.150	.037	□	5.35	877	1.44	219	0.43	67.5
2.0	.140	.145	.036	□	4.98	848	1.34	212	0.53	65.2
1.5	.155	.169	.075	△	4.60	557	1.44	138	0.69	43.1
1.5	.150	.164	.073	△	4.21	541	1.44	135	0.75	41.8
1.5	.220	.240	.106	—	8.42	792	1.53	197	1.07	61.2
1.5	.210	.229	.101	—	8.04	756	1.63	188	1.12	58.3
1.5	.370	.403	.179	×	6.50	1330		330	0.91	103.0
1.5	.360	.392	.174	×	6.50	1293		321	0.96	100.0
1.0	.225	.290	.290	×	4.98	425	1.53	105	0.53	32.7
1.0	.270	.285	.285	×	5.17	417	1.63	104	0.75	32.2
1.0	.400	.422	.422	◊	4.98	618	1.53	154	1.01	47.7
1.0	.410	.432	.432	◊	5.17	632	1.63	158	1.12	48.8
1.0	.450	.475	.475	◊	5.37	695	1.91	173	1.18	53.7
1.0	.460	.495	.485	◊	5.75	711	2.02	177	1.23	54.8
1.0	.530	.560	.560	◊	6.90	820	2.11	204	1.18	63.3
1.0	.520	.549	.549	◊	7.28	804	2.30	200	1.28	62.0

TABLE 5 (continued)

ROUGHENED SLOPES - LABORATORY DATA

Slope 1 on 8

Size of Slope Material					$1\frac{1}{2}$" - 3"		3" - 6"	
T	H	H'_o	$\frac{H'_o}{T^2}$	Symbol	$\frac{R}{d}$	$\frac{H'_o T^2}{d^2}$	$\frac{R}{d}$	$\frac{H'_o T^2}{d^2}$
4.0	.115	.092	.006	○	0.24	46.5	0.22	16.5
4.0	.120	.096	.006	○	0.26	48.5	0.23	17.2
4.0	.185	.148	.009	○	0.43	74.7	0.43	26.5
4.0	.180	.144	.009	○	0.45	72.7	0.45	25.7
3.0	.195	.176	.019	□	0.51	50.1	0.32	17.6
3.0	.190	.171	.019	□	0.53	48.7	0.30	17.1
3.0	.115	.104	.011	○	0.186	29.6	0.13	10.4
3.0	.120	.108	.011	○	0.32	30.7	0.12	10.8
2.5	.235	.227	.036	□	0.53	44.7	0.28	15.9
2.5	.240	.232	.037	□	0.56	45.7	0.27	16.2
2.5	.440	.424	.068	△	0.90	83.5	0.83	29.6
2.5	.450	.434	.069	△	0.96	85.5	0.90	30.4
2.5	.360	.347	.055	△	0.56	68.3	0.58	24.3
2.5	.350	.337	.054	△	0.68	66.3	0.55	23.6
2.0	.390	.403	.101	—	0.80	50.8	0.53	18.1
2.0	.400	.414	.103	—	0.83	52.2	0.60	18.5
2.0	.290	.300	.075	△	0.59	37.8	0.50	13.4
2.0	.295	.305	.076	△	0.69	38.4	0.57	13.6
2.0	.145	.150	.037	□	0.35	18.9	0.45	6.7
2.0	.140	.145	.036	□	0.37	18.3	0.41	6.5
1.5	.155	.169	.075	△	0.35	12.0	0.33	4.3
1.5	.150	.164	.073	△	0.37	11.6	0.30	4.2
1.5	.220	.240	.106	—	0.72	17.0	0.41	6.1
1.5	.210	.229	.101	—	0.66	16.2	0.45	5.8
1.5	.370	.403	.179	×	0.48	28.6	0.30	10.2
1.5	.360	.392	.174	×	0.45	27.8	0.30	10.0
1.0	.275	.290	.290	×	0.37	9.1	0.45	3.2
1.0	.270	.285	.285	×	0.48	8.9	0.48	3.2
1.0	.400	.422	.422	◆	0.53	13.2	0.45	4.7
1.0	.410	.432	.432	◆	0.58	13.6	0.48	4.8
1.0	.450	.475	.475	◆	0.50	14.9	0.66	5.3
1.0	.460	.485	.485	◆	0.56	15.2	0.73	5.4
1.0	.530	.560	.560	◆	0.88	17.6	0.50	6.2
1.0	.520	.549	.549	◆	0.85	17.3	0.57	6.1

TABLE 5 (continued)

BIBLIOGRAPHY

Beach Erosion Board, Corps of Engineers, Shore Protection Planning and Design, Tech. Report No. 4, 1961.

Bertram, G. E., Stone For Slope Protection Against Wave Action, Crushed Stone Journal, March 1962.

Hudson, R. Y., Laboratory Investigations of Rubble Mound Breakwaters, Proc. of Waterways and Harbours, A.S.C.E., Vol. 85, Paper No. 2171, 1959.

Kuiper, Prof. E., Flood Control, University of Manitoba (unpublished), page F 17.

Linsley, Kohler, and Paulus, Applied Hydrology, fifth edition, 1949.

Longstreth, T. M., Understanding the Weather, first edition.

Savage, R. P., Wave Run-up on Roughened and Permeable Slopes, Journal of Waterways and Harbours Division, Proc. Paper 1640.

Saville, T. Jr., Wave Run-up on Shore Structures, Journal of Waterways Division of the A.S.C.E., Vol. 82, April 1956.

Thysse and Schijf, Ocean Navigation Communication IV, XVII, International Navigation Congress Section II.

U. S. Army, Corps of Engineers, Concepts of Surface Wind Analysis and Record Wind Velocities, Project CW 178, Tech. Bulletin No 1, 1959.