UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

LABORATORY STUDY TO DETERMINE THE EQUILIBRIUM BEACH PROFILE FOR FIGARDEN RESERVOIR--CENTRAL VALLEY PROJECT, CALIFORNIA

Hydraulics Branch Report No. Hyd-475

DIVISION OF ENGINEERING LABORATORIES

OFFICE OF ASSISTANT COMMISSIONER AND CHIEF ENGINEER
DENVER, COLORADO

JULY 27, 1962

CONTENTS

CONTENTS--Continued

FOREWORD

The study described in this report was conducted in the Division of Engineering Laboratories, Bureau of Reclamation, Denver, Colorado, during the months of June and July 1960. The beaching tests were performed by E. R. Zeigler and R. A. Dodge, Jr. under the direct supervision of E. J. Carlson, all of the Sediment Investigations Unit of the Hydraulics Branch.

The Soils Engineering Branch made standard tests to determine soil characteristics and to develop methods for handling and controlling the placement of the soil test sections.

SUMMARY

This report describes a study made to determine the equilibrium beach profiles of the shore of Figarden Reservoir resulting from wave action. A sloping beach made of sand similar to Figarden Reservoir material was built into a hydraulic model and waves were allowed to impinge on it. An equilibrium slope was produced by allowing the waves to erode the sand, forming a beach. Two types of waves were used and two beach profiles were obtained.

It was determined that the shape and location of a beach can be expressed in dimensionless parameters which include beach slope, wave runup distance, beach length necessary for wave dissipation, and the bulking of beach material after erosion. Correlation of these parameters with original data consisting of wave characteristics and soil properties made it possible to predict an equilibrium beach profile at the edge of Figarden Reservoir.

Because of the success attained on this brief study, it is believed that useful design criteria for predicting the location and shape of beach profiles for any reservoir could be obtained by further laboratory studies using other types of soil.

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

Office of Assistant Commissioner
and Chief Engineer
Division of Engineering
Laboratories
Hydraulics Branch
Denver, Colorado
July 27, 1962

Laboratory Report No. Hyd-475
Compiled by: R. A. Dodge
Checked by: E. J. Carlson
Reviewed by: A. J. Peterka
Submitted by: H. M. Martin

LABORATORY STUDY TO DETERMINE THE EQUILIBRIUM BEACH PROFILE FOR FIGARDEN RESERVOIR--CENTRAL VALLEY PROJECT

INTRODUCTION

Figarden Dam and Reservoir site is in the project planning stage. It will be part of the Central Valley Project, and will be located downstream from Friant Dam on the San Joaquin River. The reservoir will be about 12 miles long and will have a maximum width of about 2 miles.

The amount of right-of-way necessary to prevent beaching action from damaging private property surrounding the reservoir was of vital concern. Conferences held with personnel from the Region, the Hydraulics Branch, and Design Division of the Denver Office of the Assistant Commissioner and Chief Engineer resulted in estimates that the equilibrium beach slope would be in the range 1:5 to 1:20. The Hydraulics Branch was requested to conduct a model study to determine the equilibrium beach slope for the Figarden Reservoir.

PRELIMINARY INVESTIGATIONS

Climatological Data for Reservoir Area

Because the dam did not yet exist, it was necessary to predict the wave heights to be encountered in the reservoir. This was done by using wind data to determine wave occurrences and characteristics. An inspection of climatological data for the Figarden Reservoir area showed that the maximum wind was northwest at 43 miles per hour, recorded December 1949. The mean wind for the years 1921 to 1950 was 6.1 miles per hour from the same direction.

Significant Waves for Reservoir

Using the above-mentioned wind data and Bretschneider's relationship[1] for deepwater waves, the significant wave height was determined for the reservoir. Significant wave height is defined as the average of the highest one-third of the waves observed. The significant wave length and period are the values associated with the significant wave height.

The wave length (L) of deepwater waves is related to the period (T) by:

$$L = \left(\frac{g}{2\pi}\right) T^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where (g) is the acceleration of gravity. Bretschneider[1] states that when D/T^2 is less than 2.5, the waves are affected by the bottom. Sverdrup and Munk[2] state that deepwater waves will occur when L/D is less than 2 and shallow-water waves will occur when L/D is greater than 25. Other investigators have found the effects of the bottom on the waves are insignificant for values of L/D up to 7.

The significant wave for the maximum wind encountered at the reservoir site would be a wave having a height of 3.0 feet and a wave length of 54 feet. The significant wave for the mean wind at the reservoir site would be a wave having a height of 0.28 foot and a wave length of 8.8 feet. The periods of these waves would be 3.2 and 1.3 seconds, respectively.

Reservoir Beach Slope Prediction

Prediction of the equilibrium beach slope, the slope at which the sand material remains stable, was made using Bascom's[3] data. Bascom's data is based on a "reference sand size," which is defined as the mean particle size of the beach soil at the mean stillwater line of an established beach. In using Bascom's data to predict the beach slopes of a reservoir, the reference sand size is unknown. Therefore, the assumption was made that the mean particle size at the mean stillwater line is the same, both before and after equilibrium is reached. This assumption implies that there is no particle size segregation during beaching action. The minimum probable beaching slope determined from Bascom's data for Figarden Reservoir for the mean wind and fetch of 2 miles, was 1:10.

Types of Beach Profiles Possible

An article by J. W. Johnson[4] states there are two different types of beach profiles, one an ordinary beach, and the other a storm

[1] Numbers refer to the Bibliography at the end of the report.

beach. The ordinary beach has no distinct offshore bar formed by wave action, whereas the storm beach generally has an offshore bar and possibly one or more intermediate bars.

The type of beach profile that occurs, is determined by the steepness factor H_o/L_o of the approaching deepwater wave. H_o is the wave height and L_o is the wave length. The subscript (o) denotes incoming waves. According to Johnson, storm profiles always occur when H_o/L_o is greater than 0.03 and ordinary profiles always occur when H_o/L_o is less than 0.025. For values of H_o/L_o between these two values, either beach might exist. The H_o/L_o value for Figarden Reservoir, for the mean wave determined from the wind data, was 0.032.

Johnson also states, "The similarity of profiles obtained from comparable setups and the close agreement between the stable slopes resulting from these tests with a given material were both indicative of the fact that a small-scale study of wave action on various materials could be used in studying full-scale wave action on identical materials."

IMPLICATIONS OF PRELIMINARY INVESTIGATION

The preliminary investigations indicated that small-scale equilibrium beach studies could be conducted without scaling the beach material. Existing laboratory equipment is capable of producing waves that have magnitudes equivalent to the expected prototype mean wave, making it possible to use 1:1 scaling in the study. However, it was decided to check for similarity for the equilibrium beach and for the earlier stages of beach development by using two different size waves.

When considering the entire beach wave encroachment problem, the knowledge of only the equilibrium beach slope is insufficient to predict the region to be affected. Other factors or parameters are needed such as, runup distance and length of beach necessary to dissipate the wave energy. The model study was programed to determine these parameters.

THE MODEL STUDY

Test Apparatus

The beaching studies were conducted in the Hydraulics Branch's 70-foot-long wave flume. This flume contains wave-producing equipment to make wave erosion studies and had been provided with the necessary filters and absorbers to prevent undesirable reflective interference. Figure 1 shows the wave machine and wave flume. The flume and the wave machine are described in detail in Hydraulic Laboratory Report No. Hyd-465. 5/

To study direct onshore beach erosion, a 1-foot-wide test section was constructed along one wall of the flume, Figure 2. A sloping floor was installed, Section B-B of Figure 2, and filled with soil, Section A-A, Figure 2, to provide a beach test section 16 feet long and 2 feet deep. The constructed test facility is shown in the photograph of Figure 3. Beach profiles were measured using a point gage with a swivel foot. The swivel allowed the foot to rest on a slope to give an average reading. The entire point gage was made to slide on a supporting channel which was marked for horizontal distances. The supporting channel could be moved allowing beach profiles to be measured at intervals as closely as desired.

Soil Characteristics

Soil used in the beach test section, assembled and mixed by personnel in the Soils Engineering Branch, corresponded to the average soil found at the reservoir site, classified as medium sand. The "Phi Probability" size analysis, plotted in Figure 4, showed a geometric mean grain diameter of 0.57 mm. "Phi Mean" (M_ϕ) was +0.83, Phi Mean standard deviation (σ_ϕ) was 1.0, "Phi Skewness" for the large particles (K_ϕ) was -0.5, and the Phi Skewness for the fine particles (K'_ϕ) was +1.5. A standard mechanical analysis was also plotted and is shown in Figure 14T.

Placing the Soil

The soil was placed in the flume with 20-percent moisture content and hand tamped to obtain the required density. The initial slope of the beach at the beginning of each test was 1:1.5, as shown in Figures 2 and 5. When the wave flume was filled with water to an operational depth of 1.5 feet, Figure 6, it was noted that the 1:1.5 slope was close to the angle of repose for the saturated soil.

Wave Characteristics

Two separate tests were conducted. The first placement of soil was exposed to a wave having a wave height of 0.15 foot, and wave length of 4.24 feet, called Wave No. 1. For the second test, the soil was removed and new soil was again placed as described above. The second placement was exposed to a wave having a height of 0.26 foot and wave length of 9.10 feet, called Wave No. 2. The properties of these waves, along with those for the prototype wave, are listed in Table 1. Wave parameters discussed earlier for Waves

No. 1 and 2 and a prototype wave computed from Bretschneider's relationships are also included in the table. Wave No. 2 is nearly equivalent to the computed mean prototype wave.

ANALYSES OF MODEL DATA

Beach Profile Plots

Profiles of the beaching slopes were measured at various times during the two wave tests. After 1, 600 minutes of exposure to the smaller (0.15 foot) wave, the beach profile became stable and additional exposure produced no additional significant erosion. The larger (0.26 foot) wave produced a stable beach profile after approximately 2, 400 minutes.

The progressive development of the equilibrium beach profile for the larger wave is plotted in Figure 7. The time versus progressive development of the beach for the smaller wave was not plotted but the time intervals are proportionally smaller. Equilibrium beach profiles for both wave tests are plotted in Figure 8.

Dimensionless Beach Profiles

To compare the beaches formed by each wave, the profiles were plotted on a single graph using dimensionless coordinates. The stillwater line was used as the origin, and the (X) and (Y) coordinates were divided by the wave length (L_o) to make them dimensionless, Figure 9. The plot verifies Johnson's4/ analysis, and shows that the equilibrium beach profiles in the stillwater line region will be similar with respect to wave lengths for different size waves for a given beach sand when plotted nondimensionally. The equilibrium beach slope, determined from the dimensionless plots in Figure 9 was 1:10 in the stillwater line region.

According to Johnson's criteria, Wave No. 1 was in the storm class and Wave No. 2 was in the transition range near the lower limit of the storm wave class. The beach profiles obtained in this study agreed with criteria determined in Johnson's4/ study.

Runup Factor

In Figure 9, it is apparent that the coordinates of the runup end point when plotted in dimensionless form are nearly the same for both waves. To further substantiate this conclusion, two additional plots were made. The first, in dimensionless coordinates, shows runup distance from the original waterline plotted against the number of waves. The second, also in dimensionless coordinates, shows the horizontal distance of the stillwater line migration from its original position versus the number of waves. Both curves, Figure 10, indicate that the two waves were dynamically similar during early stages of beach development and after an equilibrium profile had been reached. The vertical distance between curves was defined as the dimensionless runup factor and is shown in Figure 11 plotted against the number of waves.

Wave Dissipation Length Parameter

The length of beach required to dissipate the wave energy was considered for both waves in terms of the number of waves. The wave dissipation length was arbitrarily defined as the horizontal distance between the point farthest from the stillwater line where the depth equaled the wave height, and the end point of the wave runup. The dissipation length was plotted in dimensionless form and is shown in Figure 12. Here again, both waves produced similar dissipation lengths for both early stages of beach development and for the equilibrium beach profile.

Volumetric Erosion Parameter

To further substantiate that a small-scale beaching study may be conducted with prototype beach soil material, the beaching data for the two laboratory waves were compared in terms of a dimensionless volumetric parameter. This parameter was defined as $\frac{V_e}{L_o H_o^2}$ where (V_e) is the volume of soil eroded. The other terms are described previously. The volumetric parameter for both waves, plotted in Figure 13, shows that both waves eroded nearly identical volumes of beach material.

Bulking Factor

It was noted during the tests that the soil eroded from the beach had a tendency to increase in volume after it was redeposited. This factor (called bulking) was defined as the volumetric ratio of beach deposition to beach erosion. During the early stages of beach formation, the bulking factor was 1.35; at equilibrium beach stage, the bulking factors for both waves were asymptotic to a value of 1.15. This showed a consolidation of the deposited beach material with time.

Size Segregation

A particle size segregation analysis of the soil in the equilibrium beach which had been exposed to Wave No. 1 was made. Core samples were taken at the locations shown in Figure 14 and size analyses were made of 1/2-inch layers sliced from the cores. This procedure could not be used for Sample 1B, located just downslope from the erosion bank, because the deposit of fines was only one-eighth inch thick with some pebbles resting on top. The 1/8-inch layer was analyzed with and without the pebbles and the effect of the pebbles is reflected in the size analysis shown in Figure 14-1B. By comparing Figures 14-1B, 14-2B, and 14-3B, it is seen that the thickness of deposits finer than the original soil increased in thickness in the down beach slope direction. The fine deposited material reached a thickness of 2-1/2 inches at the point where Sample 3B was taken, on top of the bar. From Figure 14-3B, it is apparent that the grain size on the bar became progressively coarser as the core sample depth increased.

The lower slope, downslope from Core 3B, showed distinct stratification with respect to grain size. Two core samples were obtained, one at the centerline and the other at one edge of the test section. The particle size analyses of the 1/2-inch layers varied considerably and the individual curves often crossed each other. The limits of size analysis variation are shown in Figure 14S. The average of all grain-size analysis made of the lower slope samples were coarser than the original material. The undisturbed portion, the segregated fine portion, and the segregated coarser portion of the equilibrium beach cross section for Wave No. 1 are shown in Figure 15.

Comparison with Bascom's Data

A comparison was made between Bascom's 3/ data and the data obtained in this study to determine the minimum probable equilibrium beach slope. A reference sand particle size which is the median size of sand particles at the stillwater line is related to the slope of the beach face. From the size analysis of the surface beach material at the stillwater line plotted on 1B, Figure 14, the median size of sand particles was estimated to be 0.4 mm. Using this value as an ordinate and intersecting Bascom's curve for "minimum probable slope" Figure 16, the probable equilibrium beach slope is seen to be 1:23. This contrasts with the 1:10 slope determined in this study. However, when the latter data (0.4 mm and slope 1:10) were plotted on Bascom's curve the test point was found to fall within the scatter of Bascom's data. Bascom points out that as beaches build and erode, the slope of the beach face at the reference point will change considerably, apparently in response to the H/L factor of the waves. An eroding beach will flatten and a building beach will steepen. These factors explain the scatter of Bascom's data.

BEACH PROFILE PREDICTION FOR FIGARDEN RESERVOIR

To predict the equilibrium beach profile for Figarden Reservoir, a simplified version of the dimensionless profile obtained during the tests can be used. The simplified profile is obtained by assuming a straight-line beach having a 1:10 slope as determined in this study; the corresponding horizontal dimensionless dissipation length is 0.675, and the dimensionless runup distance is 0.150. The erosion bank is essentially vertical and the deposit face has a slope equivalent to the submerged angle of repose for the soil.

A design wave is then selected and its wave length is used to convert the simplified dimensionless profile to a geometric profile. It is suggested that the significant wave be used; defined by Sverdrup and Munk2/ as the wave having the average height and period of the highest one-third of the total number of waves observed.

If wave data are lacking, available wind data and Bretschneider's method1/ can be used to compute wave heights and wave lengths. The position of the beach profile is found by trial and error, making the cross-sectional area of erosion equal to the cross-sectional area of deposition divided by the equilibrium bulking factor.

The beach prediction method can be modified to account for a rising and falling water surface level. This would be done by making a series of erosion and deposition balances. However, allowances should be made for time intervals below those necessary for an equilibrium beach to be formed. It seems logical that the ultimate beach would have the equilibrium slope sufficiently long to include the range of depth fluctuation plus the distance necessary to dissipate the action of the design wave. The runup portion of the beach would be above the maximum water surface. As an alternate solution, the actual profile could be used instead of the simplified profile. However, this increases the difficulty of balancing deposits with erosion.

IMPLICATIONS OF THE STUDIES

This study verifies Johnson's4/ analysis that equilibrium studies can be conducted with small-scale models using prototype beach material. Also, the study demonstrates that models of this type provide useful data for earlier stages of beach development as well as for the equilibrium condition.

The beach prediction method described in this report can be used for any reservoir beaching area composed of noncohesive homogeneous material. General prediction curves of slope, runup, dissipation distance and bulking, all plotted versus the initial median particle diameter are required. The standard deviation of the particles from the median size is a necessary third parameter to account for sorting or segregation of particle sizes during beaching action. The skewness on the large particle end of the distribution curve may be of significance when armoring or pebbling of beaches is of concern. The geometry of the storm class beach can also be determined in a nondimensional form with respect to wave length and plotted versus soil particle distribution properties. All necessary data can be obtained in the laboratory in a manner similar to that used in this study to determine the equilibrium beach profile for Figarden Reservoir.

CONCLUSIONS

Specific conclusions concerning Figarden Reservoir beach are: The equilibrium beach slope will be approximately 1:10. The horizontal runup distance will be 0.150 times the wave length or for the prototype mean wave it would be 1.3 feet. The horizontal distance from the stillwater line and the place where the water reaches a depth equal to the wave height will be 0.525 times the wave length, or 4.6 feet. The position of the beach will be determined by the initial shore profile both above and below the water surface and can be located using the method described in this report.

BIBLIOGRAPHY

1. Bretschneider, C. L., "Revisions in Wave Forecasting: Deep and Shallow Water," Proceedings of Sixth Conference on Coastal Engineering, Council on Wave Research, University of California, 1958, pages 30-67.

2. Sverdrup, H. U. and W. H. Munk, "Wind, Sea and Swell: Theory of Relationships for Forecasting," Publication No. 601, Hydrographic Office, U.S. Navy Department, 1947.

3. Bascom, W. N., "The Relationship Between Sand Size and Beach-face Slope," Transactions American Geophysical Union, Volume 32, No. 6, December 1951.

4. Johnson, J. W., "Scale Effects in Hydraulic Models Involving Wave Motion," Transactions American Geophysical Union, Volume 30, No. 4, August 1949.

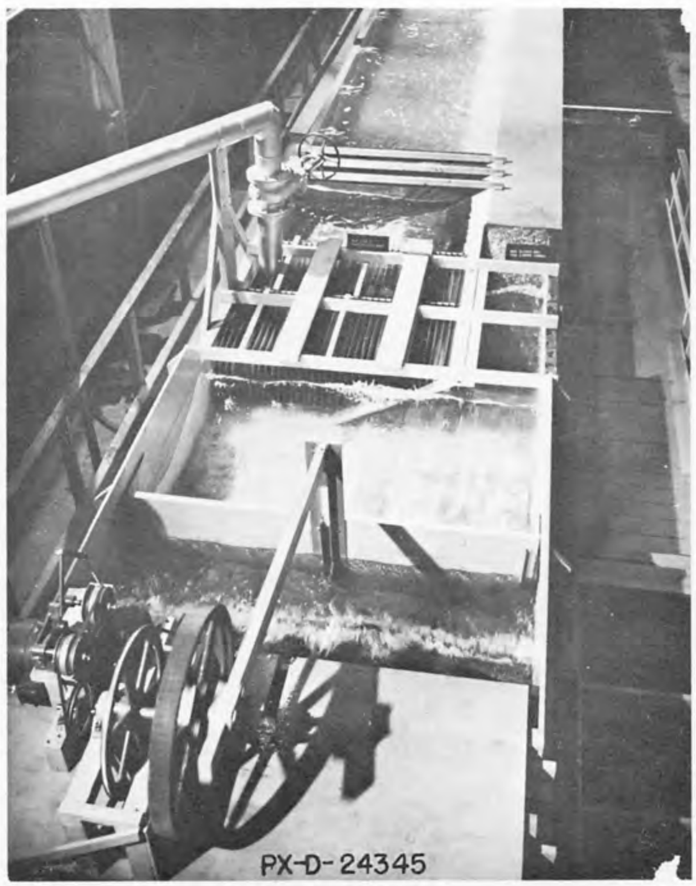
5. Carlson, E. J., and W. W. Sayre, "Progress Report No. 1--Canal Bank Erosion Due to Wind-generated Water Waves," Report No. Hyd-465.

Table 1

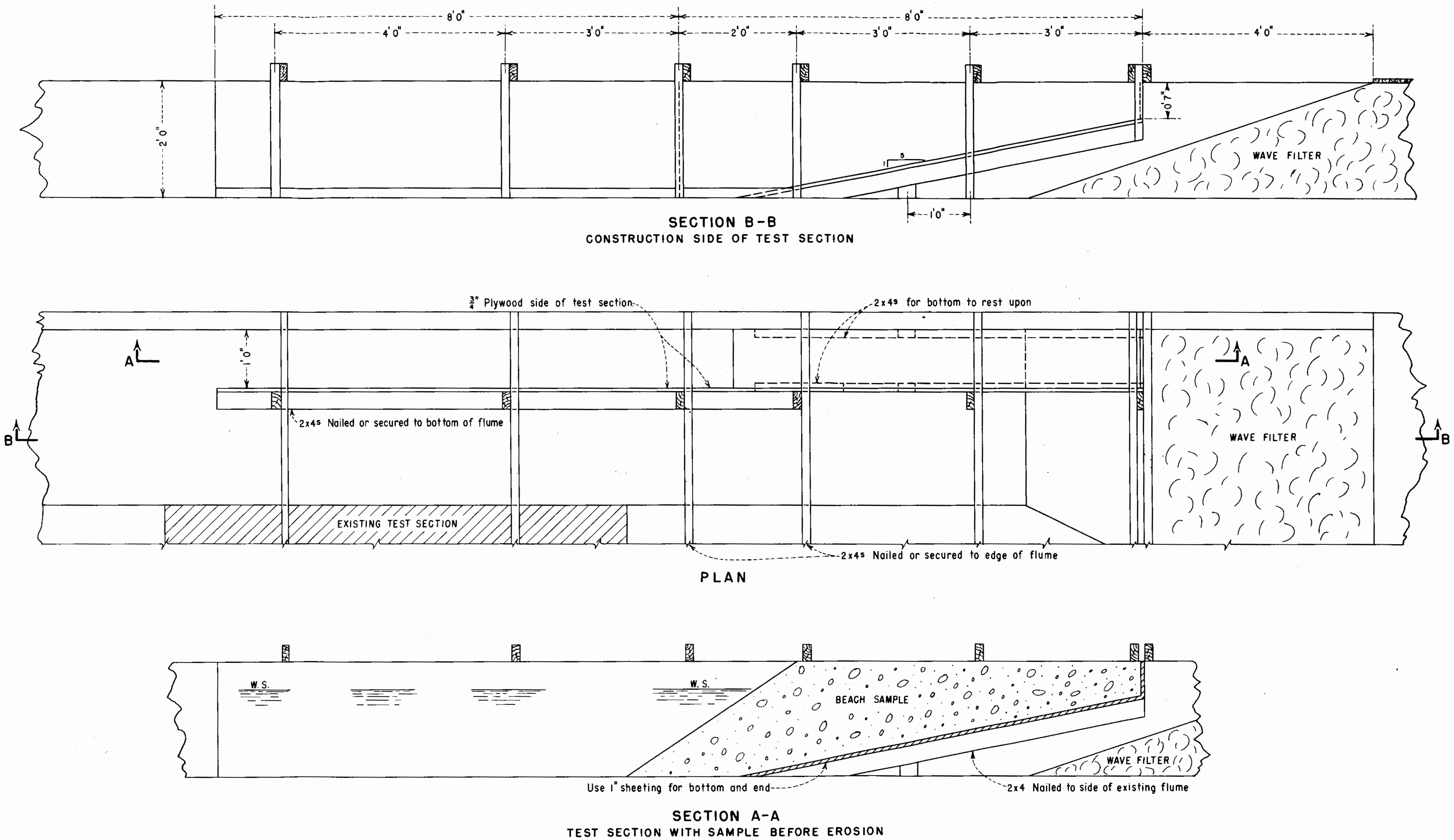
WAVE PROPERTIES

Wave No.	H_o wave height (feet)	L_o wave length (feet)	T_o period (sec)	D_o stillwater depth (feet)	$\frac{L_o}{D_o}$	Steepness factor H_o/L_o	D_o/T_o^2 feet per second^2
1	0.153	4.24	0.934	1.5	2.83	0.0360	1.70
2	0.257	9.10	1.46	1.5	6.07	0.0282	0.70
*Proto-type	0.28	8.8	1.30	--	--	0.032	--

*Values determined from Bretschneider's data1/ using the mean wind of 6.1 miles per hour.



WAVE MACHINE AND FLUME



MODEL FLUME WITH TEST BEACH SECTION

Figure 3

MODEL FLUME AND TEST SECTION

635

EL-103
(2-59)
Bureau of Reclamation

PHI PROBABILITY GRAPH

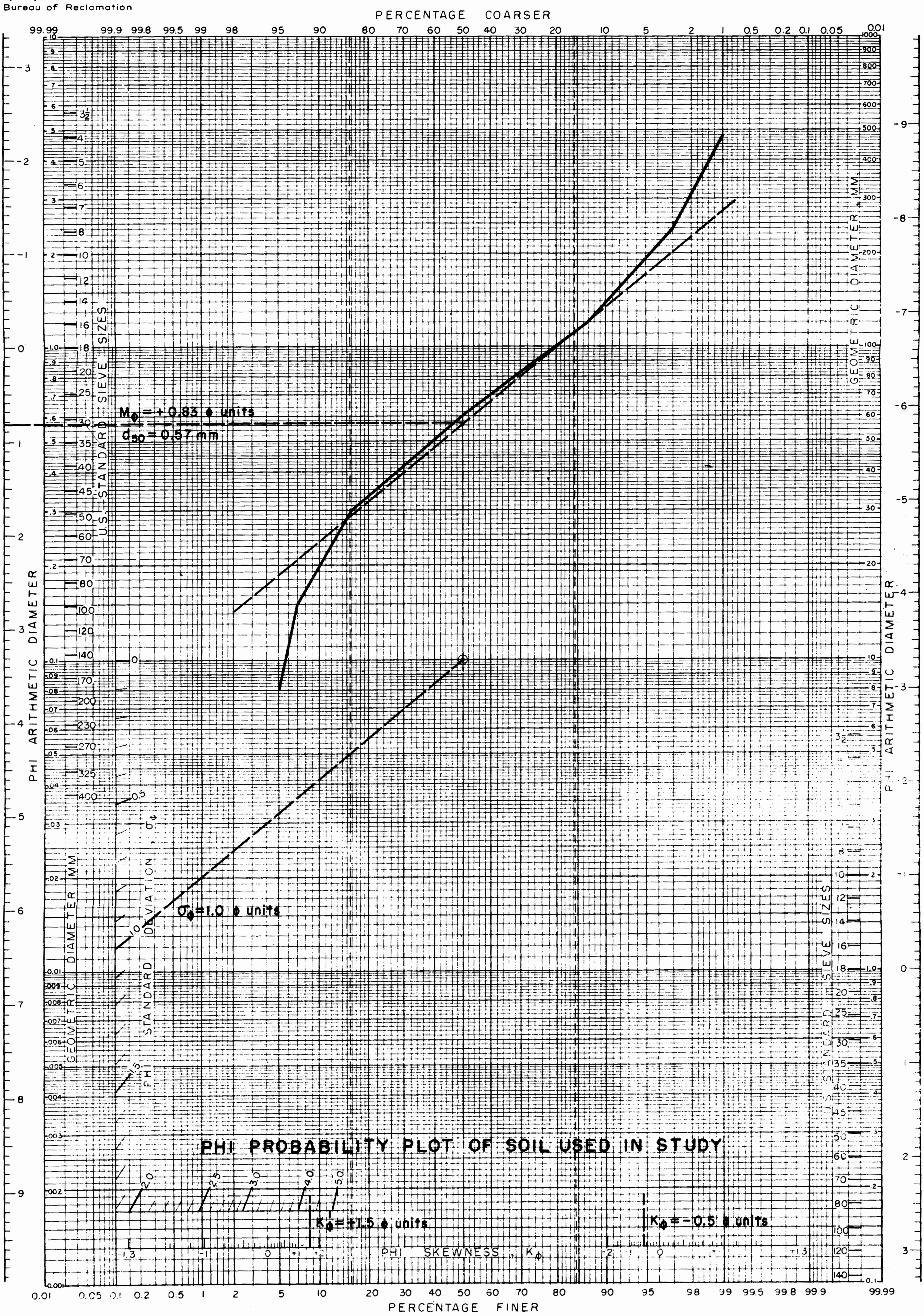
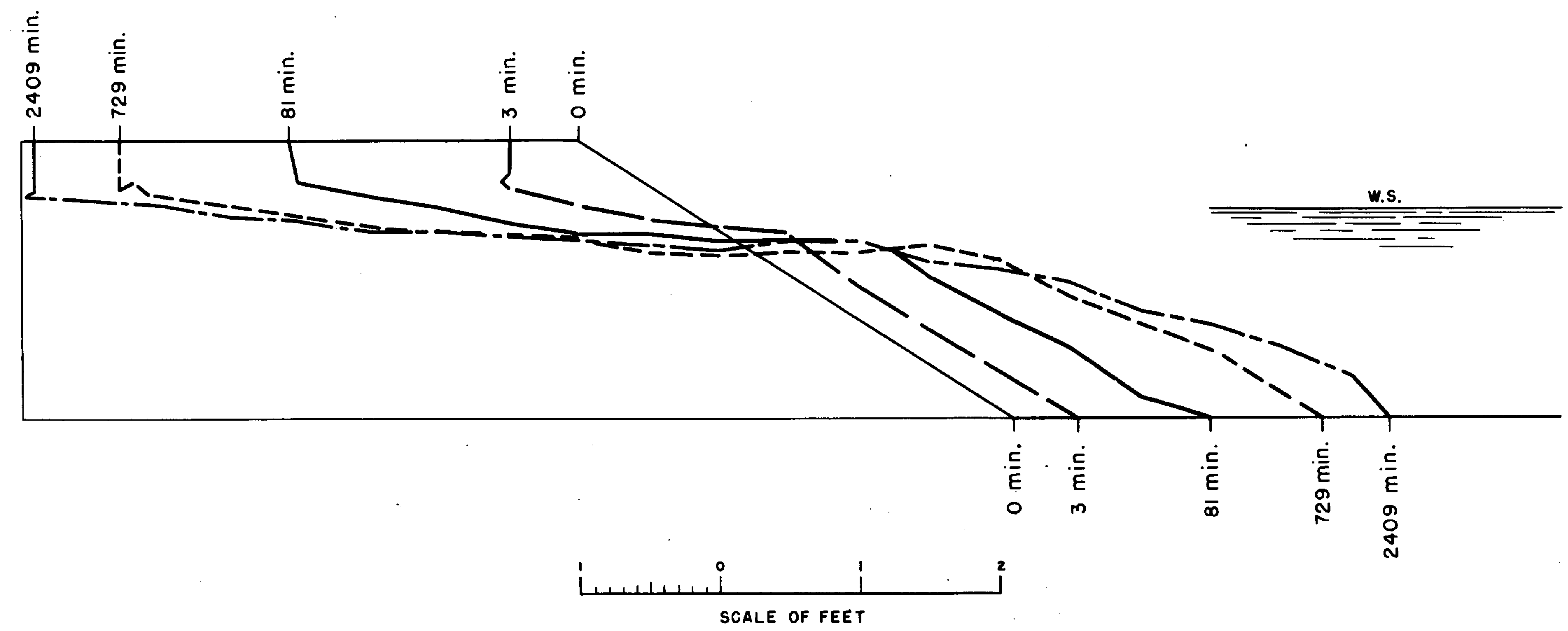


FIGURE 4
REPORT HYD. 475

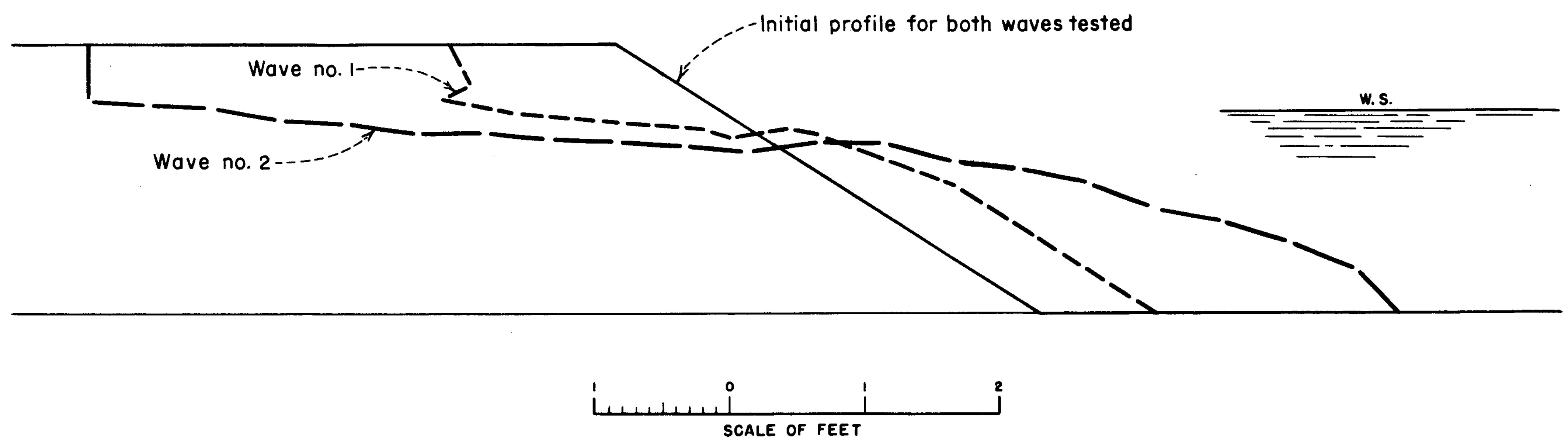
SOIL MATERIAL ON INITIAL TEST SLOPE OF 1:1.5

TEST SECTION IN THE FLUME WITH WATER
AT STILL WATER LEVEL



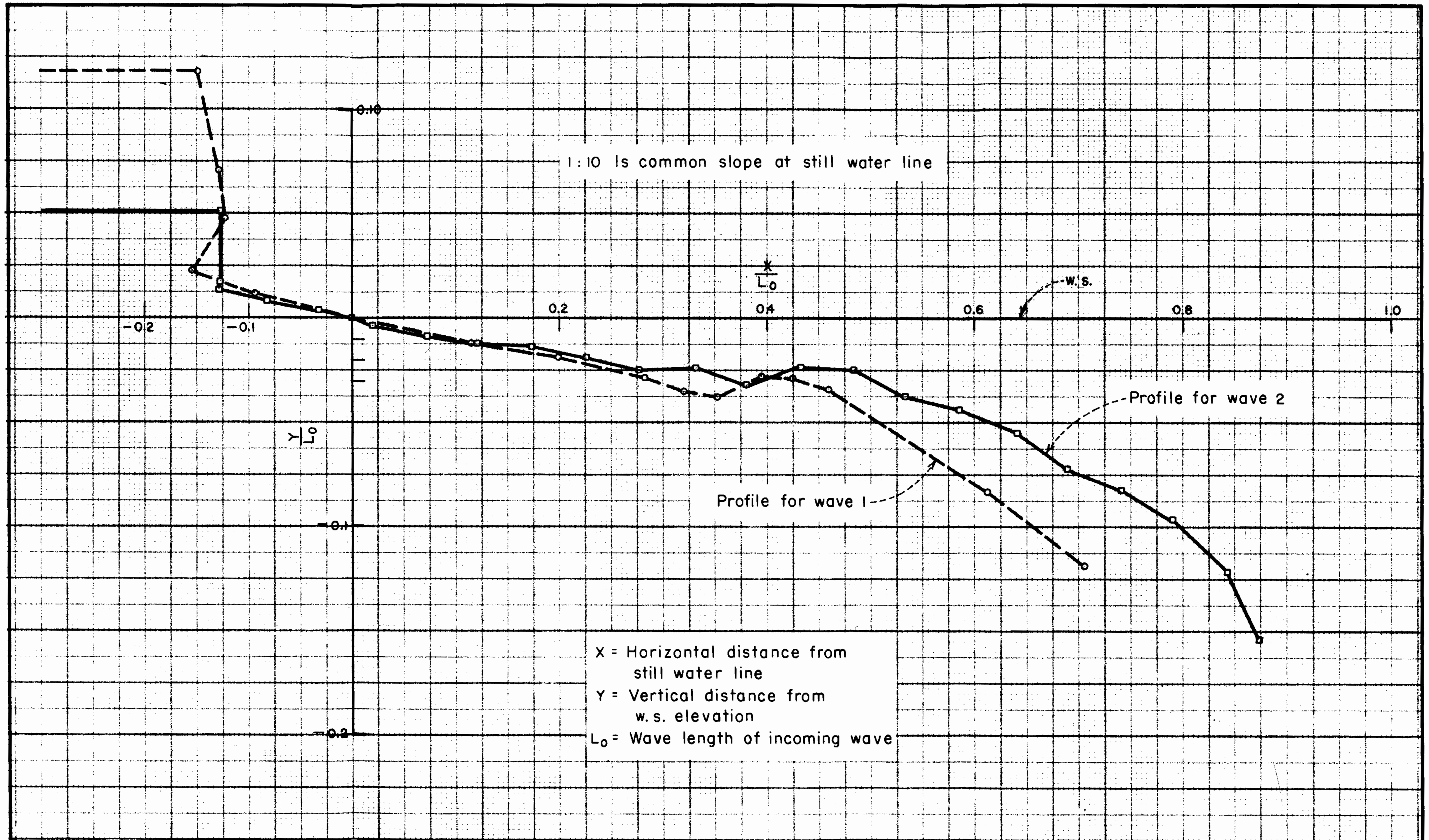
BEACH PROFILES AT PROGRESSIVE TIMES FOR WAVE NO. 2

635

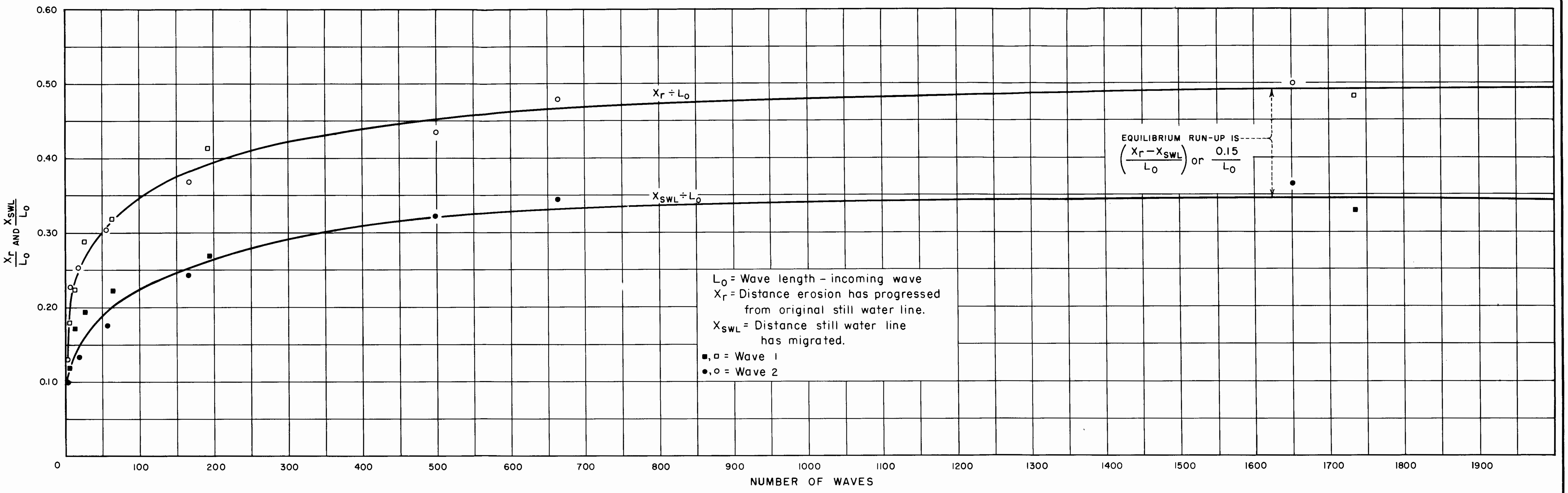


EQUILIBRIUM BEACH PROFILES

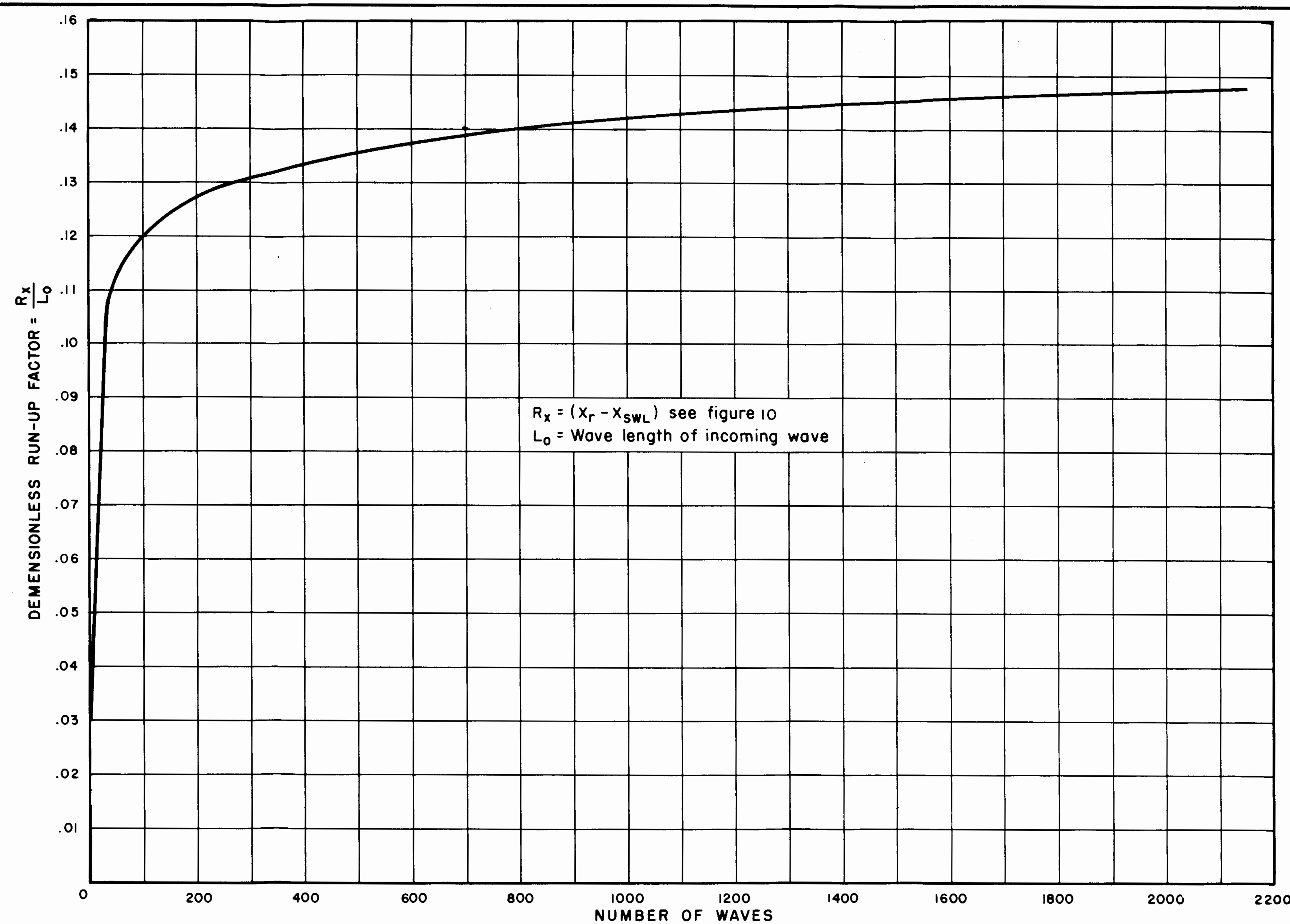
635



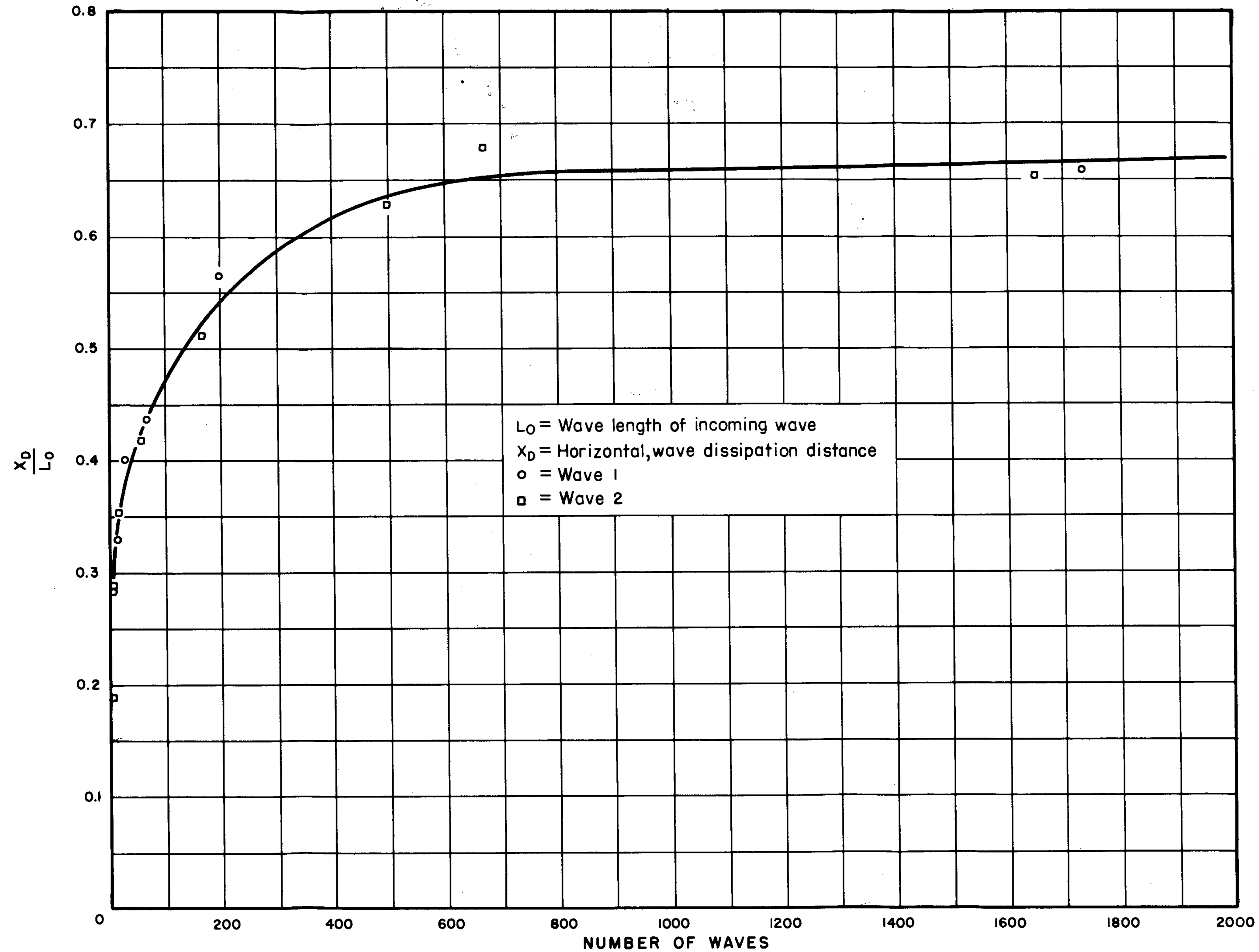
DIMENSIONLESS PLOTS OF EQUILIBRIUM BEACH PROFILES



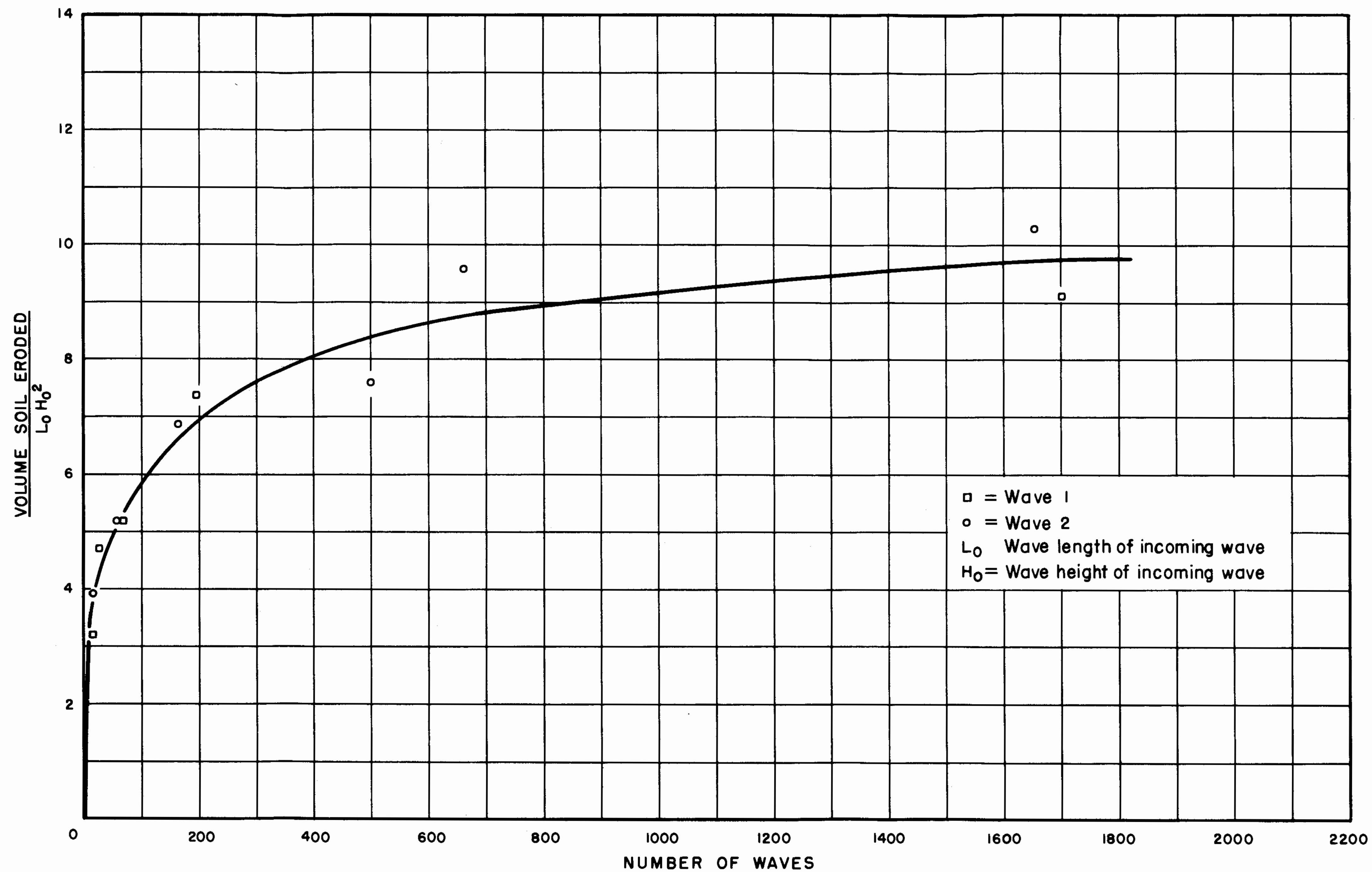
EROSION PROGRESSION AND STILL WATERLINE MIGRATION
WITH RESPECT TO INITIAL WATERLINE VERSUS THE NUMBER OF WAVES



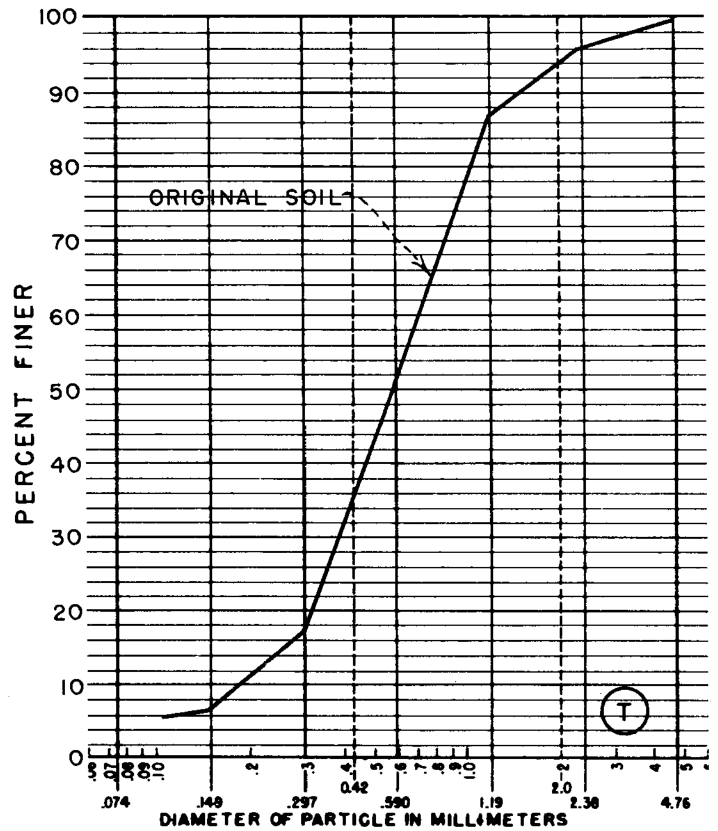
RUNUP FACTOR VERSUS NUMBER OF WAVES

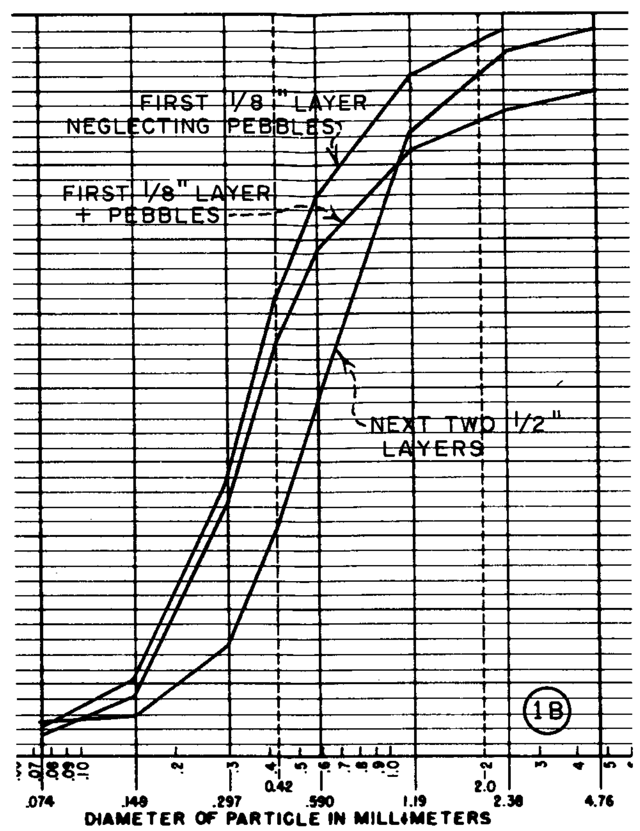


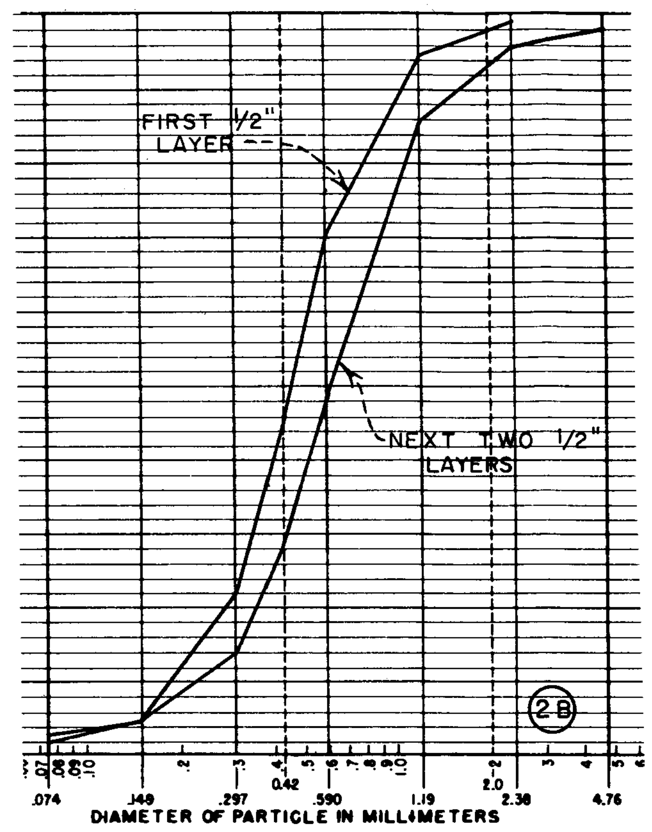
DISSIPATION LENGTH PARAMETER VERSUS NUMBER OF WAVES

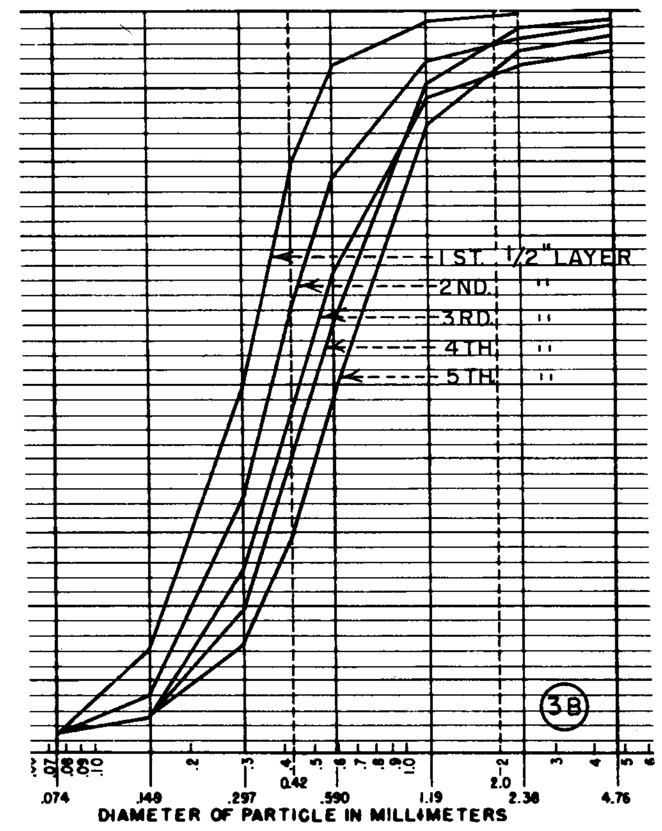


VOLUMETRIC PARAMETER VERSUS NUMBER OF WAVES

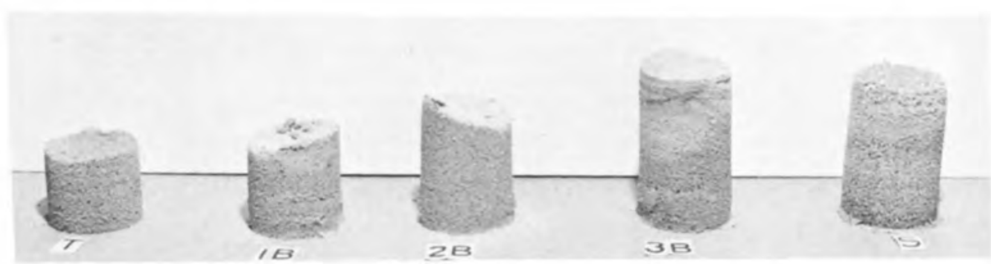


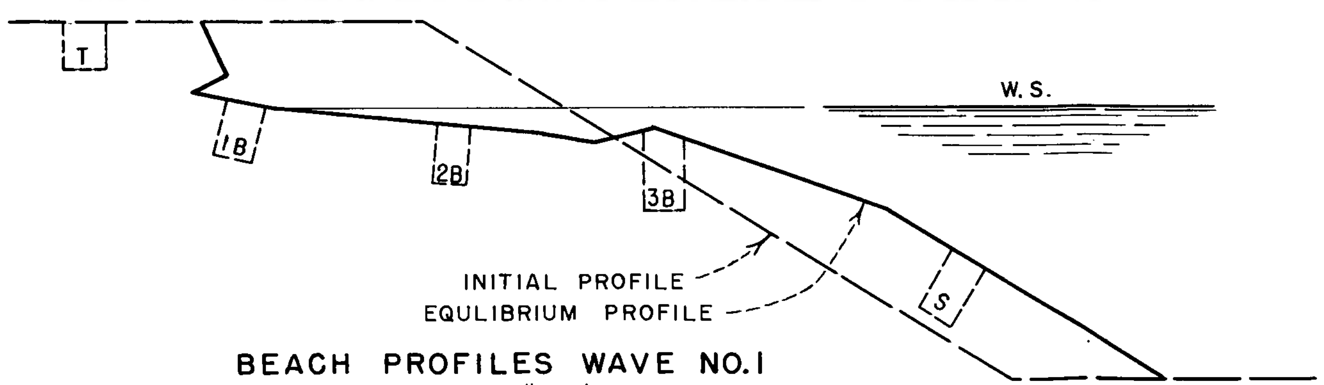






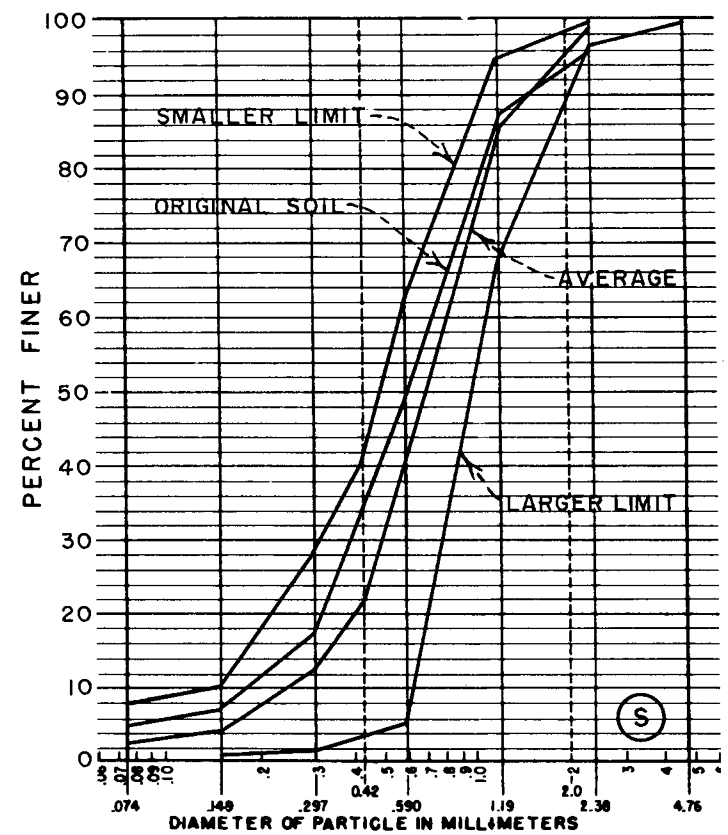
CORE SAMPLES



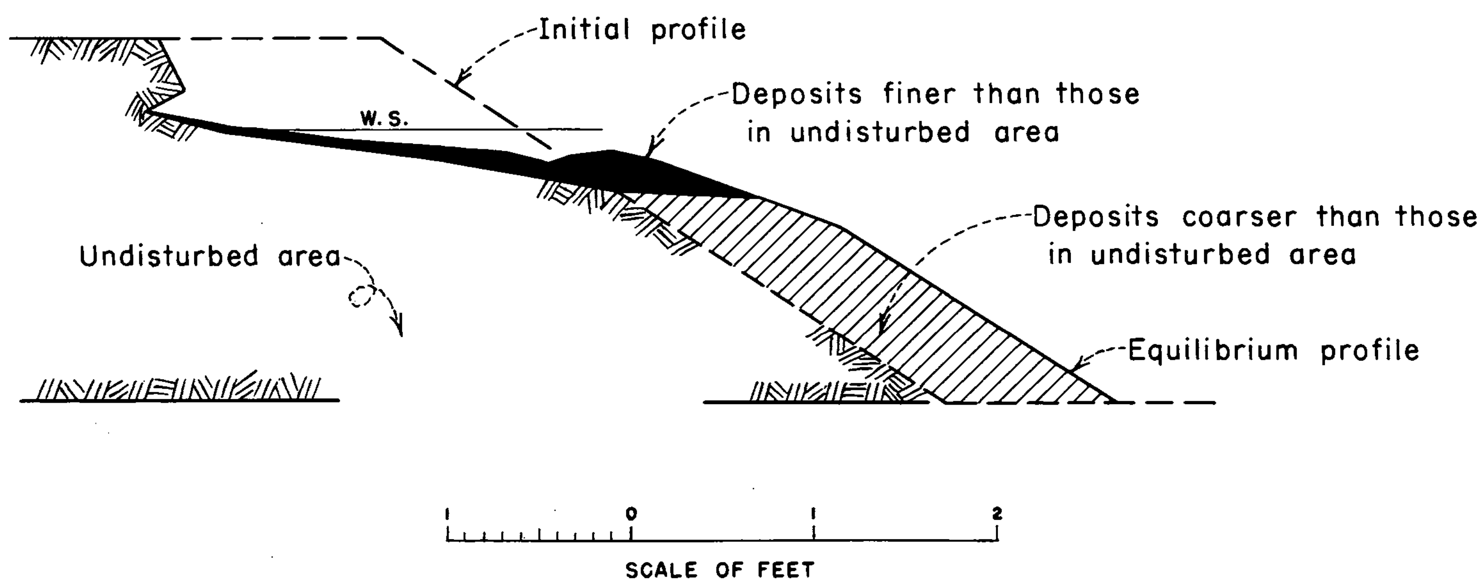


BEACH PROFILES WAVE NO. 1
SCALE 1" = 1'

EQUILIBRIUM BEACH WAVE NO. 1

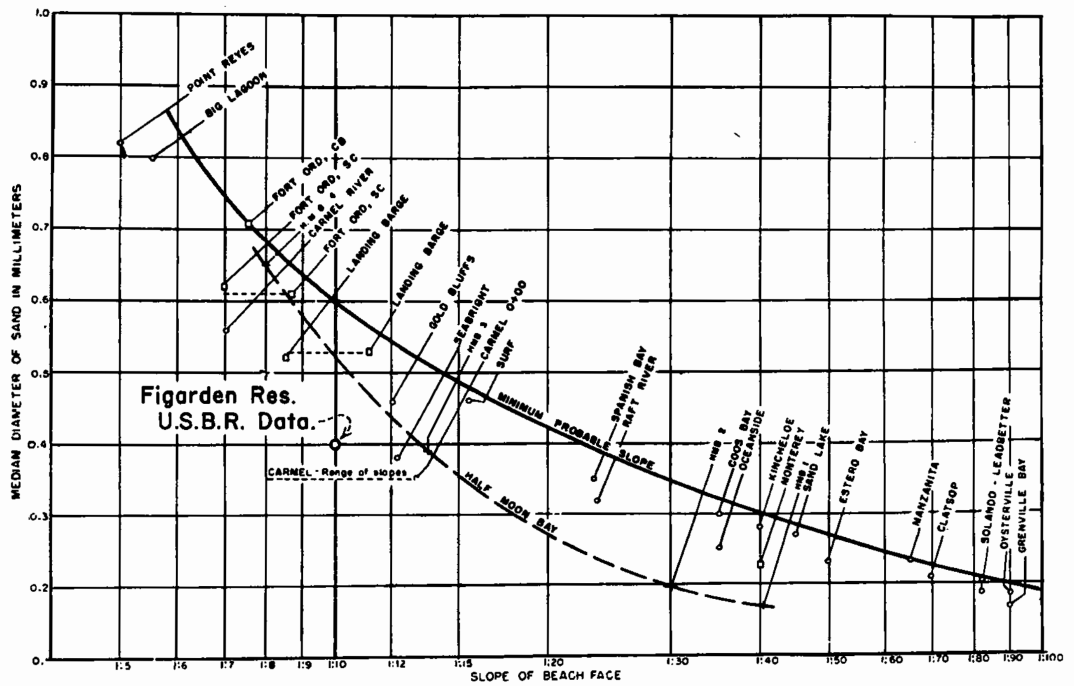


SIZE ANALYSES OF SOIL MATERIAL AT VARIOUS LOCATIONS
ON THE EQUILIBRIUM BEACH FOR WAVE NO. 1



CROSS-SECTION SHOWING SEGREGATION OF SOIL SIZES FOR WAVE NO. 1

FIGURE 15
REPORT HYD. 475



BASCOM'S EQUILIBRIUM BEACH SLOPE CURVE3/