UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

CANAL BANK EROSION BY SURFACE WATER WAVES GENERATED IN A LABORATORY FLUME

Hydraulic Laboratory Report No. Hyd-506

DIVISION OF RESEARCH

OFFICE OF CHIEF ENGINEER
DENVER, COLORADO

June 11, 1963

CONTENTS

CONTENTS--Continued

FOREWORD

The studies described in this report were carried out as part of the Lower Cost Canal Lining Program and were conducted in the Division of Research, Bureau of Reclamation, Denver, Colorado, during the months of March through May 1960. The erosion tests were performed by Eugene R. Zeigler and R. A. Dodge, Jr., under the direct supervision of E. J. Carlson, all of the Sediment Investigations Unit, Special Investigations Section of the Hydraulics Branch. H. M. Martin is Chief of the Hydraulics Branch. R. J. Willson was Chairman of the Lower Cost Canal Lining Committee when these studies were conducted.

The soil for these studies came from Kennewick Main Canal, Yakima Project, Washington. The Soils Engineering Branch made standard soil tests for determining soil characteristics and for handling and controlling placement of soil test sections.

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

Office of Chief Engineer
Division of Research
Hydraulics Branch
Denver, Colorado
June 11, 1963

Laboratory Report No. Hyd-506
Compiled by: R. A. Dodge, Jr.
Checked by : E. J. Carlson
Reviewed by: A. J. Peterka
Submitted by: H. M. Martin

CANAL BANK EROSION BY SURFACE WATER WAVES GENERATED IN A LABORATORY FLUME

SUMMARY

The purpose of these studies was to determine the erosive effect of gravity water waves on earth material obtained from the Kennewick Main Canal, Yakima Project, Washington. The soil is classified as a fine silt having practically no cohesive qualities. Three placements of the soil were made in a side-slope test section of a canal represented in a wave flume. Each placement received the same kind and degree of compaction but was subjected to the action of a different wave produced by a wave generator. The amount of bank erosion was measured and the relationship of the volume of eroded soil was determined with respect to wave length, wave period, wave height, and the time of exposure to waves.

INTRODUCTION

Canal bank erosion resulting from wind generated water waves in canals creates problems which are both bothersome and costly. Consequently the Lower Cost Canal Lining Committee of the Bureau of Reclamation formulated a general program to investigate the problem. The general aims of this investigation were the development of: (1) criteria for predicting the characteristics of waves that occur in canals, (2) a laboratory wave flume in which canal waves and the resulting bank erosion can be reproduced under controlled conditions, (3) a better understanding of the mechanics of canal bank erosion by waves, (4) a classification of various soil properties with respect to erosion by wave action, (5) methods and design criteria for stabilizing canal banks susceptible to damage by wave action, and (6) correlations between laboratory and field studies.

This report deals with the first four of these points and also presents the results of a series of laboratory wave erosion tests on a nonplastic soil.

PRELIMINARY INVESTIGATIONS

REVIEW OF LITERATURE

Very little research has been done on the subject of wind waves in canals. In recent years, however, an increasing amount of research has been undertaken on the generation of wind waves in oceans, lakes, reservoirs, and laboratory flumes.

Prior to World War II, prediction of wave characteristics was dependent on empirical relations developed by Stevenson17/, 1874, Gaillard6/, 1904, Molitor14/, 1935, and others. Most of these formulas express wave height as a function of wind velocity and fetch, which is defined as the length of the reach of water over which the wind blows at a particular velocity. None of these empirical relations are intended to be applicable over a wide range of wind and fetch conditions.

During World War II, investigation of the problem was accelerated because of the interest of the armed forces in amphibious operations. By a combination of theoretical, dimensional, and empirical analysis, Sverdrup and Munk18/, 1947, derived relationships in which wave characteristics, such as height, length, celerity, and period are expressed as a function of fetch, wind velocity, and wind duration. Wind duration is defined as the interval of time during which wind velocity exists. Their findings are expressed in the relationships between various dimensionless parameters which combine the wave, wind, and fetch characteristics. Hirschberg9/, 1949, Johnson12/, 1950, and others have shown that these parameters may be readily obtained by application of the Buckingham Pi Theorem and dimensional analysis.

Although the Sverdrup-Munk relationships were derived for the purpose of predicting the characteristics of ocean waves, Johnson11/, 1948, 12/, 1950, Bretschneider2/, 1952, 3/, 1954, 4/, 1958, Sibul 16/, 1955, and others have shown that with minor modifications, the Sverdrup-Munk analysis is also applicable to bodies of water such as lakes, reservoirs, and laboratory flumes where the fetch dimensions are limited. The results of the Sverdrup-Munk analysis were modified by Bretschneider4/.

According to the Sverdrup-Munk analysis, the transfer of energy from wind to waves occurs by the push of the wind against the wave crests and by the drag of the wind on the water. The push, or normal pressure is the dominating factor in the early stages of wave growth. The drag force is primarily responsible for the continued growth of waves, even when the wave celerity exceeds the wind velocity. Forces tending to retard the growth of waves are the normal pressure when the wind velocity is less than the wave celerity, and viscous shear, the latter being of negligible importance. Thus, the waves continue to grow until equilibrium is reached between the energy added by shear and that lost by air resistance.

Wave growth is limited by wind velocity and either fetch length or wind duration. In relatively short fetches, maximum wave growth is achieved in a short time and the length of fetch is usually the limiting factor. In very long fetches, wind duration usually controls.

Sverdrup and Munk made another important contribution by introducing the concept of the significant wave. Natural wave trains are seldom uniform with respect to wave height and wave period. The significant wave is defined statistically as the wave having the average height and period of the highest one-third of the total number of waves observed. The Sverdrup-Munk-Bretschneider analysis is based on the concept of the significant wave.

Deepwater wave conditions exist when the ratio of the wave length to the depth L/y is less than two. When L/y becomes greater than two, the waves begin to "feel" bottom and the wave height and period are reduced accordingly.

Bretschneider3/, 1954, has extended the Sverdrup-Munk analysis to cover certain cases of shallow water waves by taking into account energy dissipation due to bottom friction and percolation.

Sibul 16/, 1955, in a series of experiments with wind waves in a laboratory channel demonstrated that the depth begins to affect the wave height when the ratio of the depth to wave height y/H becomes less than five. A reduction in wave period becomes noticeable when L/y becomes greater than five. Sibul's experiments included both smooth and rough bottom conditions. Results appeared to be independent of bottom roughness.

Hufft10/, 1958, in another series of laboratory experiments with wind waves in shallow water, obtained results showing that observed wave heights for L/y ratios up to about five do not differ appreciably from those predicted by the Sverdrup-Munk-Bretschneider curves for deepwater conditions. Wave periods, lengths, and celerities were found to be in substantial agreement with their deepwater counterparts over the entire range of experimental conditions which included L/y ratios up to about seven.

Saville15/, 1954, developed a method for estimating the effect of fetch width in limiting the growth of waves. It is generally recognized that where the width of the fetch is limited by land forms, waves are significantly lower than those that would be expected from the same generating conditions over more open water. It is also known that waves are generated not only in the immediate direction of the wind, but also at various angles with the wind direction. Thus, the wave characteristics measured at a particular point are dependent not only on the energy components in a direction coincident with the wind direction but also on those components from various angles to the wind direction. The actual wave chacteristics at the point will result from the summing up of all these components.

Saville used several alternate assumptions in his analysis, but obtained the best results by assuming that the wind effectiveness varies as the cosine of the angle up to 45° on either side of the wind direction, and has no effect for angles greater than 45°. Saville established a graphical relationship for a rectangular fetch in which the ratio of the effective fetch to the actual fetch F_e/F is expressed as a function of the ratio of the fetch width to the actual fetch length W/F.

WAVE STUDIES BY U.S. BUREAU OF RECLAMATION

An earlier wave erosion study conducted by the Hydraulics Branch was reported in "Hydraulic Model Studies to Determine Required Cover Blanket to Prevent Fine Base Material from Leaching Due to Wave Action--Kennewick Main Canal, Yakima Project, Washington," Report No. Hyd-381, 19/. In this study it was determined that for a silty base material, the protective cover must be fine enough to prevent leaching of the base material through it, and that particles on the exposed surface of the protective cover must be of sufficient size and weight to resist displacement by wave action.

Other Bureau wave erosion studies are recorded in "Progress Report No. 1--Canal Bank Erosion Due to Wind Generated Water Waves," Report No. Hyd-465, 20/. The conclusion in this report, applicable to soils of low plasticity such as inorganic clays and silts, are listed as follows:

a. When started, the erosion of a homogeneous embankment by a uniform wave train tends to continue as a geometric progression of time.

b. The rate of erosion is dependent primarily on the wave height and the density to which the soil has been compacted. Compaction above 95 percent of the Proctor maximum density greatly reduces the erosion rate.

c. Wetting and drying cycles have a deteriorating effect on the resistance of an embankment to erosion. This is caused by the disruptive effect of slaking on the soil structure and occurs when dried soil is subjected to immersion. Freezing and thawing cycles seem to have a similar, though not as severe, effect.

In another wave erosion study, "Laboratory Study to Determine the Equilibrium Beach Profile for Figarden Reservoir--Central Valley Project, California," Hydraulic Laboratory Report No. Hyd-475, 21/, it is demonstrated that the shape and location of an equilibrium beach can be expressed in dimensionless terms for both model and prototype, in terms of the incoming wave length.

THE GENERAL PROGRAM FOR THIS STUDY

The purpose of this study was to determine the erosion effect of gravity waves on earth material obtained from Kennewick Main Canal. The following program was formulated. Three placements of the soil were to be made on a 1-1/2:1 sloping side of a canal. Each placement was to be subjected to a wave of different wave steepness; this may be expressed as the ratio of wave height to wave length (H/L). The soil density of the placements were to be the maximum obtainable within the flume and test section container. Because the density was to be constant for the three placements it would be possible to determine the relationships of bank erosion to wave length, wave period, wave height and time of exposure to waves. Finally the results of this study were to be compared with those of Progress Report No. I, Hyd-465, 20/, previously discussed.

THE LABORATORY STUDIES

TEST APPARATUS

The bank erosion studies were conducted in the 70-foot-long wave flume in the hydraulic laboratory. The flume contained the wave producing equipment and had been provided with the necessary filters and absorbers to prevent undesirable reflective interference. Figure 1 shows schematic sketches of the wave channel and equipment. Figure 2(a) shows the wave generator and filters. Figure 2(b) shows the wave absorber at the downstream end of the channel. The test area in which the soil was placed was constructed in the 1-1/2:1 side slope of the canal as shown in Section B-B, Figure 1. The length of the test area was 8 feet and the depth was 6-1/2 inches. Figure 3 shows the section where the test soil was placed.

CHARACTERISTICS AND PLACEMENT OF SOIL

Classification and Soil Gradation

The soil used in this study was taken from locations between Station 246+75 and 249+00 on Kennewick Main Canal, Yakima Project, Washington. The soil was a cohesionless silt and is classified as a nonplastic soil in the ML group of the Unified Soil Classification System. A logarithmic-probability graph method, 22/, for describing the mechanical analysis of soils was used in this study. A log-probability graph for the Kennewick soil is plotted in Figure 4, M_ϕ for the soil was 5.18, and the standard phi-deviation σ_ϕ was 1.58. The phi-skewness for the fines K'_ϕ was 3.0 and the phi-skewness for coarse particles K_ϕ was 1.3. The geometric mean size was 0.028 mm.

Compaction Properties and Tractive Force Resistance

The compaction properties of Kennewick Main Canal soil are shown in Figure 5. The equivalent maximum dry density of the soil is 100.1 pounds per cubic foot at an optimum moisture content of 21.0 percent, based on the dry weight of the soil. The moisture versus penetration resistance curve is also presented in Figure 5. The soil was subjected to a tractive force machine test, 22/, and the critical tractive force was found to be 0.024 lb/ft^2. The compaction properties of Driftwood-Meeker soil which was previously tested and reported in Hyd-465, 20/, are also shown in Figure 5. Comparison with the Kennewick soil is made and discussed later in this report.

Preparation of Soil and Placement in Erosion Test Section

The soil was prepared for placing in the erosion test section by breaking up the lumps and forcing it through a 1/2-inch screen. The moisture content was adjusted by adding water, mixing, and allowing the mixture to age at least 1 week under a plastic sheet before placing.

The soil was compacted into the test section with an airhammer. Blows of the hammer were transmitted through a 2- by 6-inch plank which was slowly moved over the entire test section, Figure 6. The soil was compacted in layers not exceeding 2 inches in thickness. When near grade, the embankment was screeded with a steel straightedge. Some small low areas were filled in by hand tamping.

Soil Density Samples

After each soil placement, 4 ring density samples were obtained along the compacted embankment at an elevation of 1.5 feet from the bottom of the wave flume. Thus, for the 3 placements, 12 samples were obtained. The average density for the 12 samples was 93.4 percent of the maximum obtainable. The average absolute deviation from this value was 1.05 percent. The maximum absolute deviation from this value was 3.6 percent.

Saturation Effects on Embankment

After the density sample holes were refilled with soil, the canal was filled slowly with water to a depth of 1.5 feet. The compacted soil was allowed to saturate overnight. As the soil became saturated, it expanded, and colloidal material leached out between the coarser particles into the canal prism. Formations were deposited at the base of the side slope which looked much like the alluvial fans encountered in geology, Figure 7. The embankment settled and a slight crack formed just above the waterline.

WAVES USED IN STUDY

Generated Waves

Three generated wave forms were used, one for each soil placement. The direction of wave travel for the three waves was along the canal axis. The wave characteristics are completely summarized in Table 1. The wave heights were 0.18, 0.20, and 0.38 feet, respectively, with corresponding wave lengths of 6.8, 3.2, and 4.7 feet. The flatness ratios (L/H) for these same waves were 37.8, 16.0, and 12.4.

Edge Waves

Edge waves and their related transverse oscillations are natural characteristics of waves in trapezoidal canals and are induced by the sloping banks of the trapezoidal cross section, Section B-B, Figure 1. The variation in wave phase caused by the sloping banks of the canal causes a node to occur at some distance from the water's edge. The node distance, Z_e, is a function of the L/Y ratio and increases as the ratio increases. L is the wave length and Y is the depth of water.

In addition to the change in phase, there is also a change in the wave height along the water's edge. Since edge waves occur in the bank erosion region, their properties are also included in Table 1. Edge waves and their properties are described in greater detail in Progress Report No. 1, Hyd-465, 20/.

Wave variables were not measured during these studies but were set by means of previous calibrations of the wave producing equipment and flume, 20/.

DATA OBTAINED

Profile Measurements

Bank profile measurements were made following exposure to the waves shown in Table 1. The bank profiles were obtained using a swivel foot attached to a point gage assembly, Figure 8, mounted to slide along a support channel scaled for horizontal distances. The volumes of eroded material, computed for each bank profile measurement, are listed in Table 1. Testing was stopped when the soil test layer had been eroded completely through at one point on any profile. A typical profile of the wave erosion obtained during a test is shown in the sketch and photograph in Figure 9.

Analysis of Data

The input variables considered in the analysis of data were wave height (H) from crest to trough, wave length (L), wave period (T), and (t), the interval of time the soil samples were exposed to the waves. The output variable considered in the analysis was the measured value of erosion (E), in volume per unit length of canal (one bank only).

Since this study involved one particular type of soil, and compaction was essentially constant, the following functional relationship was assumed to exist

$$E = f_1 (H, L, T, t) \qquad (1)$$

By means of dimensional analysis, this relationship was reduced to the more compact form

$$E/H^2 = f_2 \, (t/T, \; L/H) \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

(E/H^2) will be called the volume-of-erosion parameter throughout the remaining portion of this report. (t/T) will be designated as the time parameter and is identical to the number of waves to which the soil is exposed. (L/H) is the reciprocal of the wave steepness and will be called the wave flatness. These parameters were computed and are listed in Table 1 and plotted in Figure 10. Straight lines were fitted by eye to these computed points. The equation for this set of lines was determined to be

$$\left(\frac{E}{H^2}\right) = 5.7 \times 10^{-4} \left(\frac{t}{T}\right)\left(\frac{L}{H}\right)^{2/3} \ldots\ldots\ldots\ldots\ldots \quad (3)$$

The symbols are as previously defined. Thus the amount of erosion in Kennewick Main Canal soil can be computed for any wave and time of wave exposure, within the limits of the laboratory data. These limits can be determined from the data points in Figure 10. Another limitation, not apparent in the figure, is the fact that all waves traveled along the length of the canal.

COMPARISON OF RESULTS WITH PREVIOUS STUDIES

In previously reported studies, laboratory wave erosion data were obtained for Driftwood-Meeker soil; compaction properties are shown in Figure 5. These data are analyzed and presented in Progress Report No. 1 "Canal Bank Erosion Due to Wind Generated Water Waves," Hydraulic Report No. Hyd-465, 20/. The wave erosion data were obtained using the same laboratory apparatus and techniques used in conducting the wave erosion studies with the Kennewick soil. Furthermore, one soil placement, reported in Progress Report No. 1, was subjected to nearly the same combination of wave form and soil compaction used in the Kennewick study. Therefore, it is possible to compare the Kennewick soil with the Driftwood-Meeker soil in regard to their resistance to wave erosion. To make this comparison, the parameters of Equation 2 were plotted for both soils in Figure 11. This plot demonstrates that the Kennewick soil is much more sensitive to wave erosion than the Driftwood-Meeker soil.

Since a common combination of wave form and soil compaction was used for both studies, the causes for the difference in wave erosion resistance must be soil properties other than compaction. The effect of compaction on erosion resistance has been discussed in more detail in Progress Report No. 1, 20/. The properties for both soils are given in Table 2. Column 2 of this table shows that the Kennewick soil was nearly three times larger in mean grain diameter than the Driftwood-Meeker soil. Despite the larger particles, the Kennewick soil was less resistive to erosion as shown in Figure 11. Therefore, it must be inferred that when a soil is in the clay-to-silt class, some property or properties other than grain size must predominate when considering wave erosion. If it can be assumed that the partical size or mean diameter has a minor effect, it must follow that all the log-normal properties are also of minor importance when dealing with soils in the clay-to-silt class. This leaves the cohesive property or the plasticity index as the dominant factor since the other factors are intrinsically related to either the grain distribution factors or to the plasticity index or both. Therefore, the zero plastic limit appears to be the predominant factor in causing the Kennewick soil to be less resistant to wave erosion.

CONCLUSIONS

1. Equation (3) can be used to predict, within the limits of the laboratory data, the amount of erosion of Kennewick soil produced by water waves traveling along the length of a canal having 1-1/2:1 side slopes.

2. Figure 11 and Table 2 demonstrate that, other than the degree of compaction, the plasticity index of a soil in the silt-to-clay class is probably the dominant soil property when considering resistance to water wave erosion.

3. Figure 11 and Table 2 show that the mean diameter of the individual particles is of minor importance in a silt-to-clay class of soil when considering resistance to wave action.

APPENDIX

BIBLIOGRAPHY

1. Biesel, F. and Suquet, F., "Laboratory Wave-generating Apparatus," La Houille Blanche, Vol 6, No. 2, 1951, pages 147 to 165 (translated by Meir Pilch, SAF Hydraulic Laboratory, University of Minnesota)

2. Bretschneider, C. L., "The Generation and Decay of Wind Waves in Deep Water," Transactions AGU, Vol 33, No. 3, June 1952, pages 386 to 392

3. Bretschneider, C. L., "Generation of Wind Waves Over a Shallow Bottom," Corps of Engineers, Beach Erosion Board, T. M. No. 51, 1954

4. 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 to 67

5. Carlson, E. J., "Gravel Blanket Required to Prevent Wave Erosion," Proceedings ASCE, Journal of the Hydraulics Division, Vol 85, No. HY 5, May 1959

6. Gaillard, D. D., "Wave Action in Relation to Hydraulic Structures," Professional Paper No. 31, Corps of Engineers, U.S. Army, U.S. Government Printing Office, Washington, D.C., 1904

7. Hanson, E. T., "The Theory of Ship Waves," Royal Society of London, Proceedings, Series A, Vol III, 1926, page 491

8. Herbich, J. B., "Experimental Studies of Wave Filters and Absorbers," Project Report No. 44, St. Anthony Falls Hydraulic Laboratory, University of Minnesota, 1956

9. Hirschberg, L., "Wave Action in Relation to the Design of Hydraulic Structures," M. S. Report, Colorado State University, 1949

10. Hufft, J. C., "Laboratory Study of Wind Waves in Shallow Water," Proceedings ASCE, Proceedings Paper 1765, September 1958

11. Johnson, J. W., "The Characteristics of Wind Waves on Lakes and Bays," Transactions AGU, Vol 29, No. 5, October 1948, pages 671 to 681

12. Johnson, J. W., "Relationships Between Wind and Waves, Abbots Lagoon, California," Transactions AGU, Vol 31, No. 3, June 1950, pages 386 to 392

13. Lamb, Horace, "Hydrodynamics," Sixth Edition, Cambridge University Press, 1932, pages 446 to 450

14. Molitor, D. A., "Wave Pressures on Sea Walls and Breakwaters," Transactions ASCE, Vol 100, 1935, page 984

15. Saville, T., Jr., "The Effect of Fetch Width on Wave Generation," Corps of Engineers, Beach Erosion Board, T. M. No. 70, 1954

16. Sibul, O., "Laboratory Study of the Generation of Wind Waves in Shallow Water," Corps of Engineers, Beach Erosion Board, T. M. No. 72, 1955

17. Stevenson, T., "Design and Construction of Harbors: A Treatise on Maritime Engineering," Edition 2, Edinburgh, 1874

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

19. U.S. Department of Interior, Bureau of Reclamation, "Hydraulic Model Studies to Determine the Required Cover Blanket to Prevent Fine Base Material from Leaching Due to Wave Action--Kennewick Main Canal, Yakima Project, Washington," Hydraulic Laboratory Report No. Hyd-381, June 195[illegible]

20. U.S. Department of Interior, Bureau of Reclamation, "Progress Report No. 1--Canal Bank Erosion Due to Wind Generated Water Waves," Hydraulic Laboratory Report No. Hyd-465, January 1961

21. U.S. Department of Interior, Bureau of Reclamation, "Laboratory Study to Determine the Equilibrium Beach Profile for Figarden Reservoir--Central Valley Project, California," Hydraulic Laboratory Report No. Hyd-475, July 1962

22. U.S. Department of Interior, Bureau of Reclamation, "Progress Report No. 3, Canal Erosion and Tractive Force Study (Correlation of Laboratory Test Data)--Lower-cost Canal Lining Program," Appendices I and II, Hydraulic Laboratory Report No. Hyd-464, October 1960

SYMBOLS

σ_ϕ	Standard deviation in phi standard units
E	Volume of erosion
F	Fetch
F_e	Effective fetch
f	Denotes functional relationship
ϕ	Subscript denoting log-normal distribution properties
H	Wave height
H_e	Edge wave height
K'_ϕ	Skewness of fines
K_ϕ	Skewness of coarse particles
L	Wave length
M_ϕ	Phi mean
T	Wave period
t	time of exposure to waves
W	Fetch width
Y	Depth of water
Z_e	Edge wave node distance

Table 1

SUMMARY OF DATA AND ANALYSIS

Main Wave				Edge Wave		Erosion	Parameters		
Wave height H (ft)	Wave length L (ft)	Wave period T (sec)	Time elapsed t (sec)	Wave height H_e (ft)	Node distance Z_e (ft)	Volume erosion E* (cu ft)	Number of waves t/T	Wave flatness L/H	Erosion parameter E/H^2
0.18	6.8	1.2	300	0.16	1.05	0.055	250	37.8	1.70
			600			0.104	500		3.21
			900			0.155	750		4.79
			1,560			0.271	1,300		8.36
0.20	3.2	0.8	300	0.15	0.45	0.072	375	16.0	1.80
			600			0.112	750		2.80
			900			0.160	1,130		4.00
0.38	4.7	1.0	300	0.25	0.75	0.136	300	12.4	0.94
			540			0.212	540		1.47
			840			0.357	840		2.48
			1,020			0.435	1,020		3.02

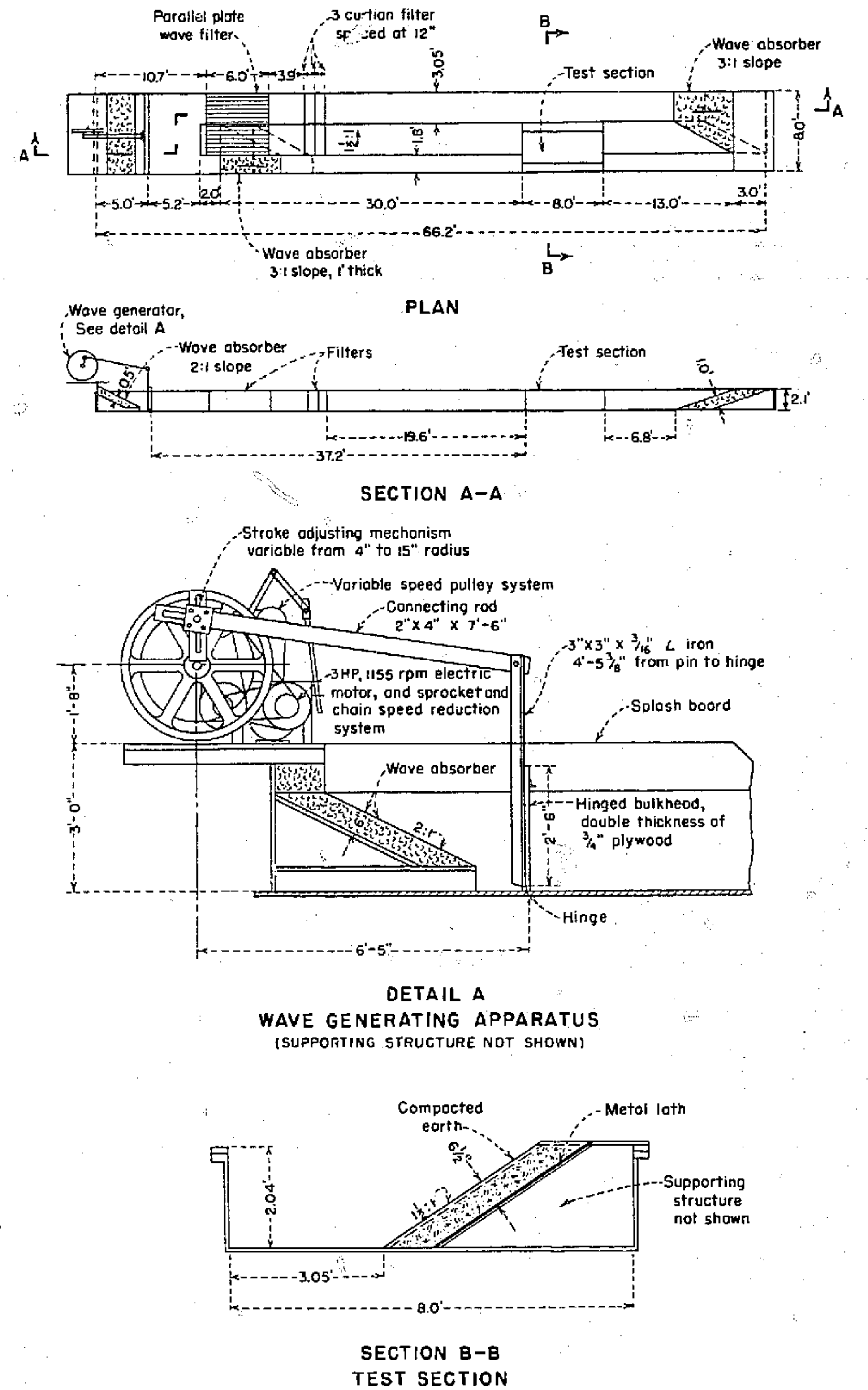
*E = Volume of soil eroded per foot of canal per bank

Table 2

COMPARISON OF SOIL PROPERTIES

Soil	Grain diameter mm	Log normal properties				Plasticity index	Critical tractive force lb/ft-2	Classi-fication	Liquid limit	Shrink-age limit	Percent of maximum com-paction
		$M\phi$	σ_ϕ	$K\phi$	$K'\phi$						
Kennewick*	0.028	5.17	1.58	+1.31	+3.00	None	0.024	ML	None	21.4	93.4
Driftwood-Meeker[ψ]	0.010	6.62	2.35	+1.31	+0.40	12.1	0.110	CL	32.8	15.3	95

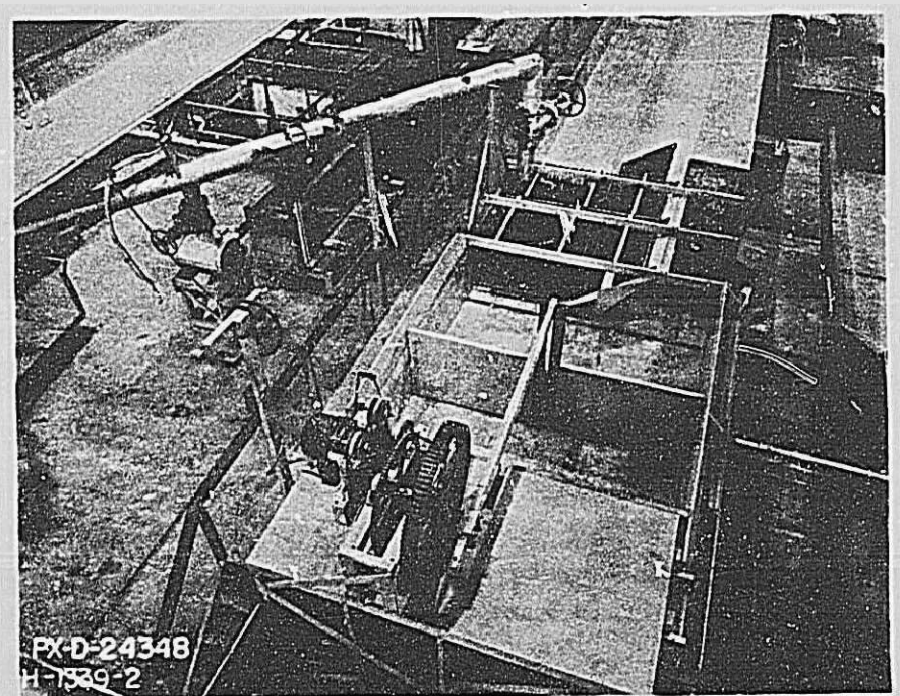
*Sample 18F-1192
ψ Sample 18F-1191



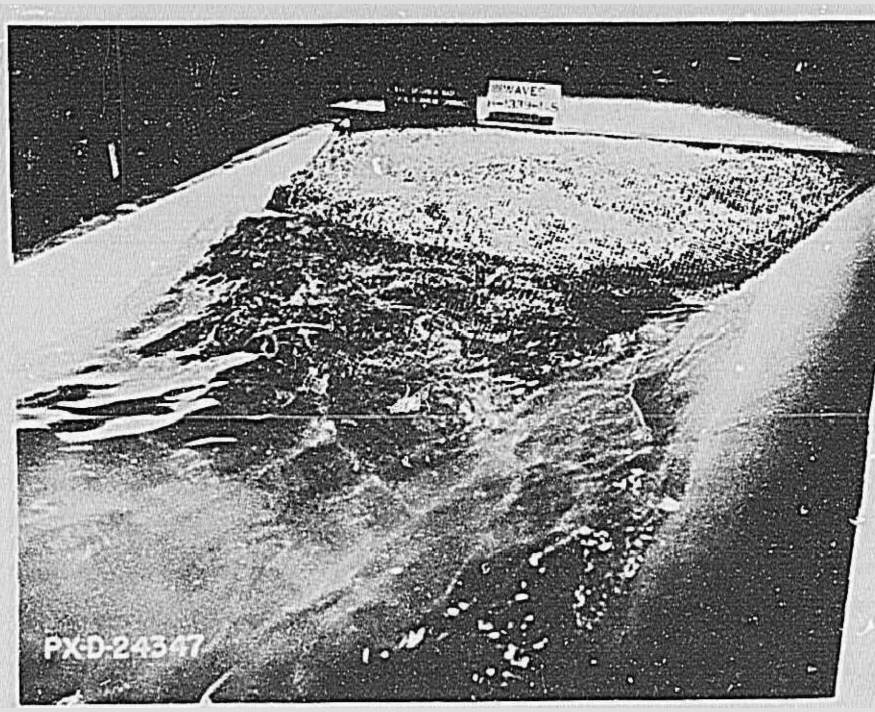
LABORATORY WAVE CHANNEL AND EQUIPMENT-SCHEMATIC SKETCHES

565

FIGURE 2
Report Hyd-506

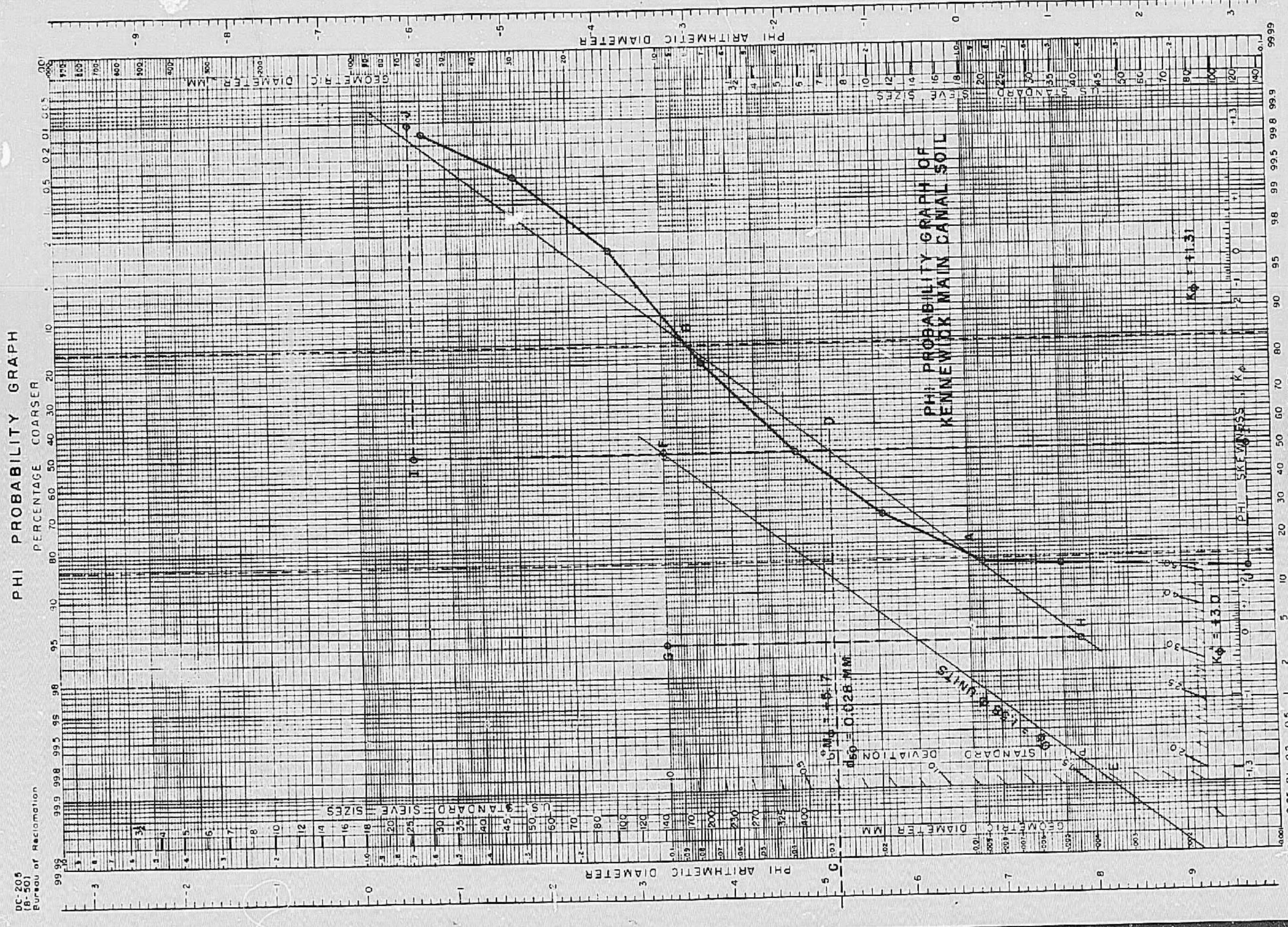


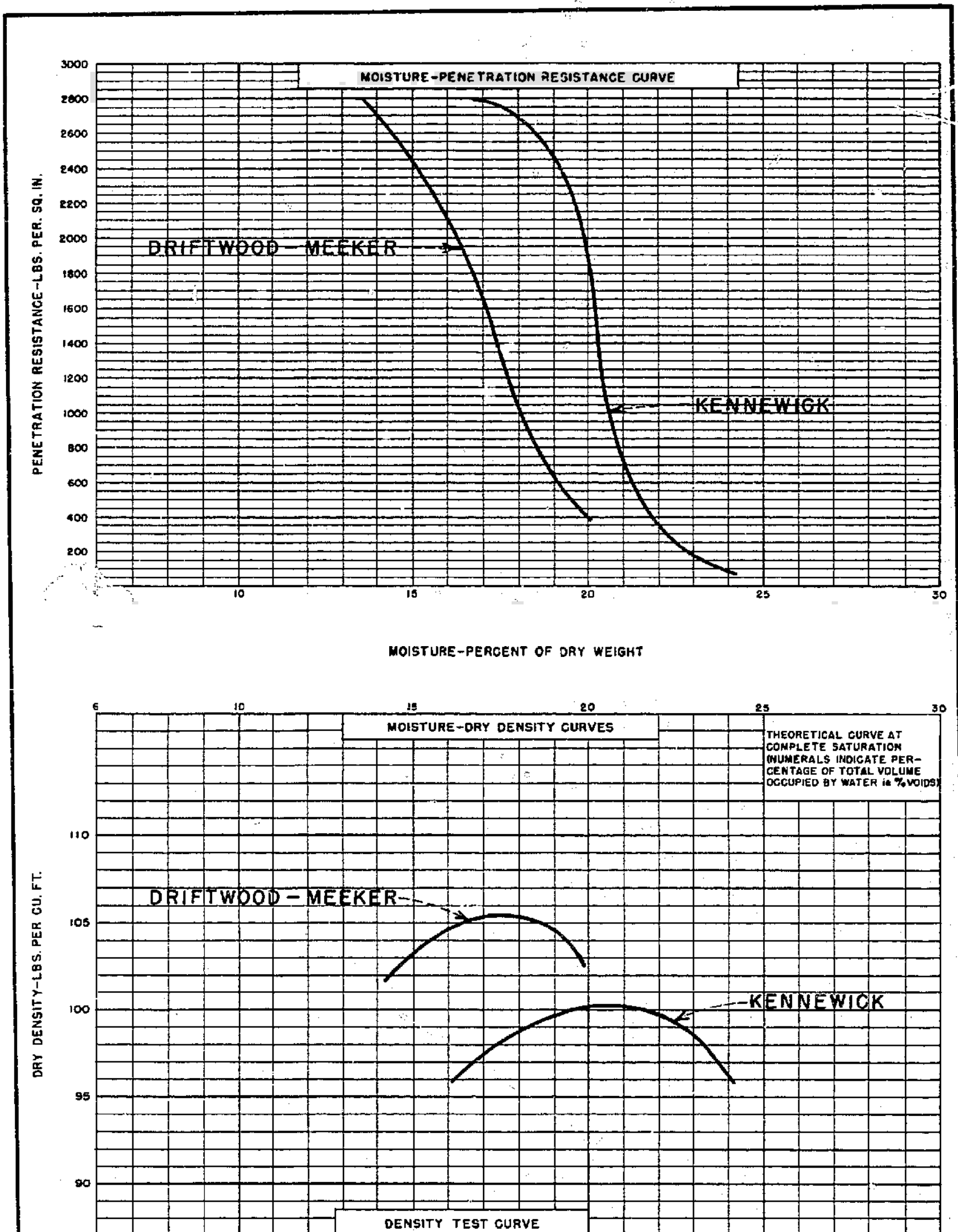
(a) Wave generator



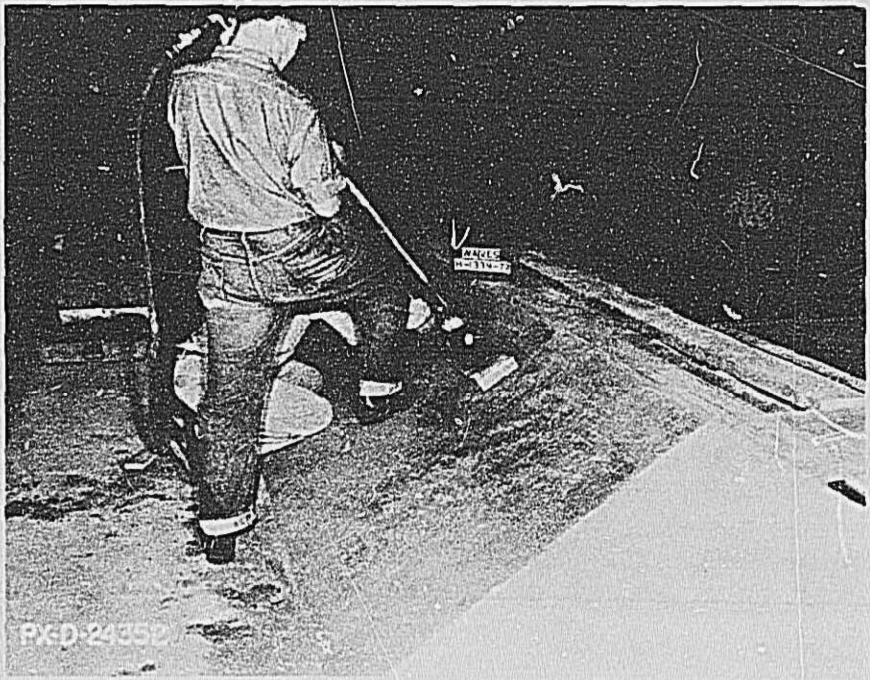
(b) Absorber at
downstream end
of channel

LABORATORY EQUIPMENT


PHI PROBABILITY GRAPH
PERCENTAGE COARSER
PERCENTAGE FINER
PHI ARITHMETIC DIAMETER
GEOMETRIC DIAMETER MM
U.S. STANDARD SIEVE SIZES
PHI STANDARD DEVIATION
PHI SKEWNESS, K_ϕ
PHI PROBABILITY GRAPH OF
KENNEWICK MAIN CANAL SOIL
$K_\phi = +1.31$
$K_\phi = +3.0$
$M_\phi = +5.7$
$d_{50} = 0.028$ MM
$\sigma_\phi = 1.8$ ϕ UNITS
DC-205
(8-50)
Bureau of Reclamation



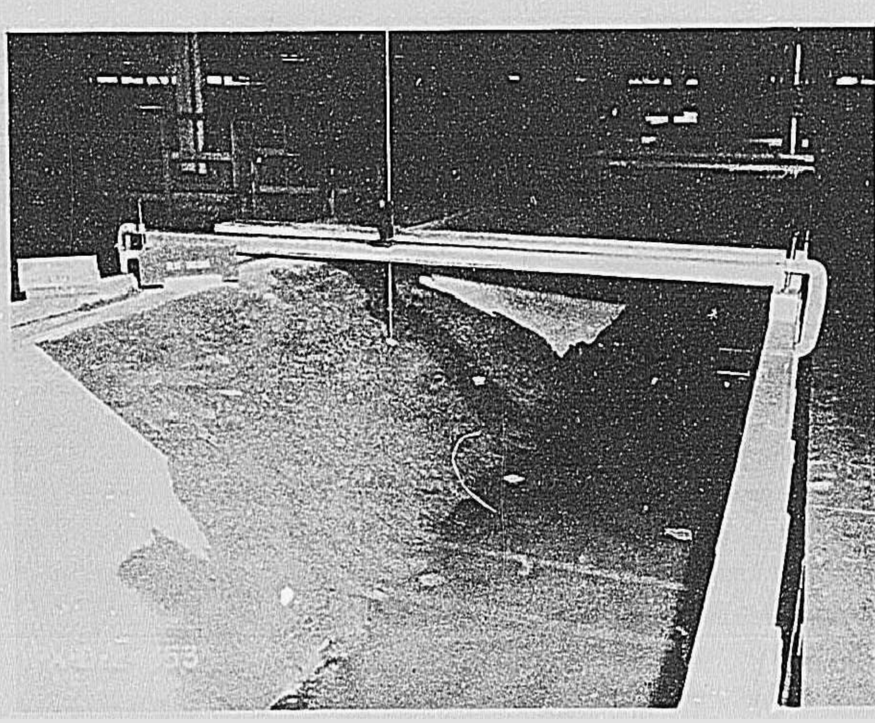
COMPACTION PROPERTIES OF SOILS



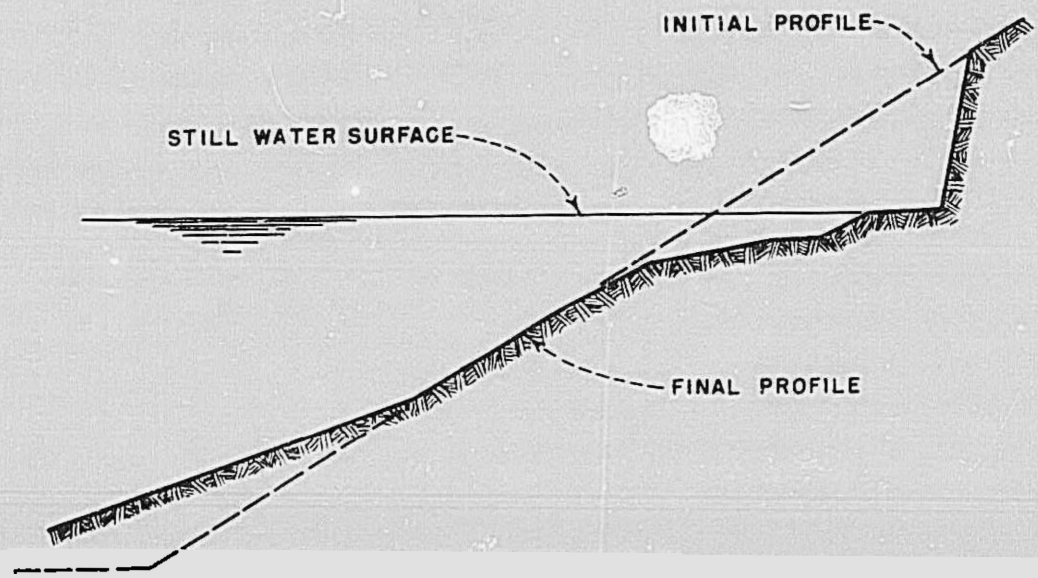
Soil being compacted in test section

FIGURE 7
Report Hyd-506

Fan-like formation on test section
caused by saturation leaching



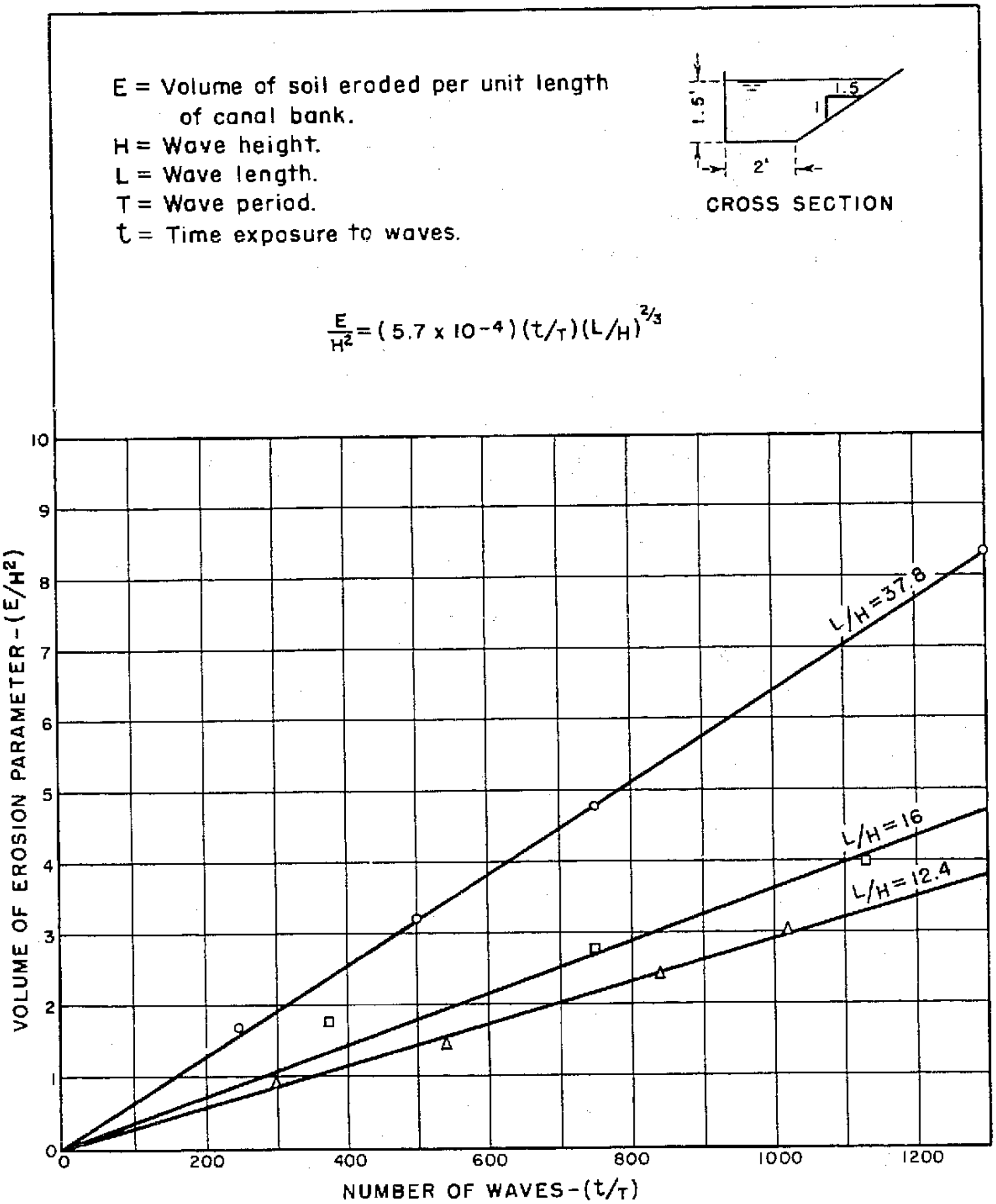
Equipment for measuring
erosion cross sections



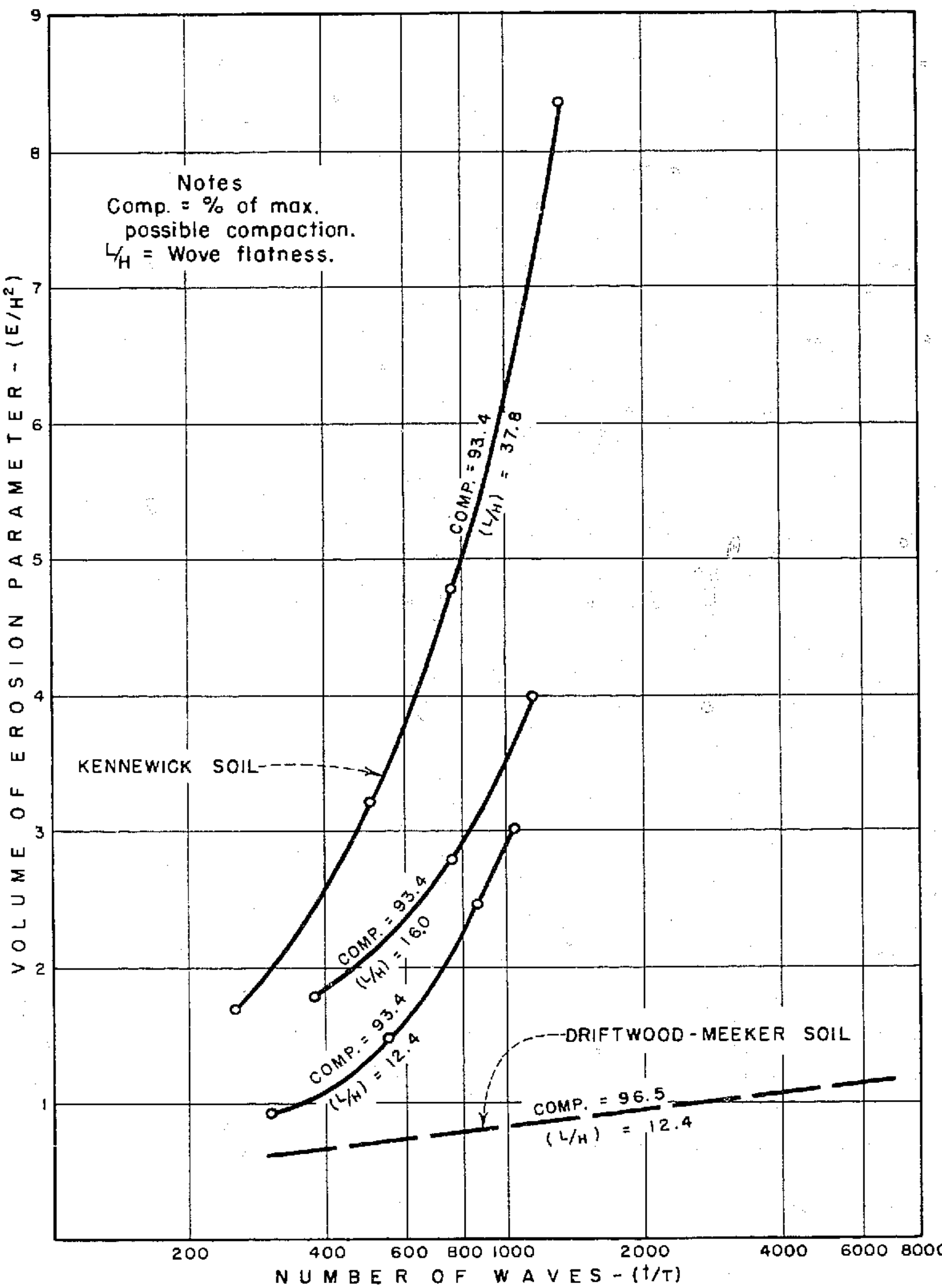
(a) CROSS SECTION

(b) VIEW LOOKING TOWARDS WAVE GENERATOR

TYPICAL WAVE EROSION



WAVE EROSION CHARACTERISTICS FOR KENNEWICK SOIL
93.4 % OF MAX COMPACTION



COMPARISON OF WAVE EROSION PROPERTIES
KENNEWICK SOIL WITH DRIFTWOOD-MEEKER SOIL