DEPARTMENT OF THE ARMY CORPS OF ENGINEERS

BEACH EROSION BOARD
OFFICE OF THE CHIEF OF ENGINEERS

# EFFECT OF BOTTOM ROUGHNESS ON WIND TIDE IN SHALLOW WATER

TECHNICAL MEMORANDUM NO. 95

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## FOREWORD

When the wind blows over a water surface, in addition to generating waves it induces a surface current in the general direction of the wind movement; this results in a piling up of water at the leeward side of the water body and a lowering of water level at the windward side (for an inclosed body of water). This deviation from still-water level caused by the wind-driven currents, called wind set-up or wind tide, may reach significant proportions (9 and 10-foot rises above still water level being not uncommon for Lake Okeechobee, Florida during hurricanes, for example) and represents a very important factor in shore protection design. Several methods of computing these set-ups have been derived, but all, of necessity, assume smooth bottom conditions; it is known, however, from observation at Lake Okeechobee and elsewhere that a rough bottom, or aquatic plants growing up through the water can affect the set-up to a significant degree. This report presents the results of a laboratory study of the effect of bottom roughness on both run-up and wave generation, utilizing equally spaced strips of window screening to represent the roughness.

Results of this study show that the roughness increased the set-up over smooth bottom conditions by as much as two times when the water depth was slightly above the roughness top, though decreasing it to a negligible amount when the water depth was about half way up on the roughness strips. Wave heights were not appreciably affected for large depths over the roughness tops, but were reduced for small depths; generally wave heights could be predicted adequately by using an "effective" depth equal to the depth over the roughness.

This report was prepared at the Wave Research Laboratory of the Institute of Engineering Research at the University of California in Berkeley in pursuance of contract DA-49-055-eng-31 with the Beach Erosion Board which provides in part for a research investigation of the interaction between wind and water surface in shallow water. The author, E. G. Tickner, is a Research Engineer at that institution.

The work done on this study was supported jointly by the Jacksonville District, Corps of Engineers, and the Beach Erosion Board. The funds were allocated from the Civil Works Investigation Program of the Office, Chief of Engineers under projects CW166 and CW167, "Study of Waves and Wind Tides in Shallow Water", and from project funds for the Central and Southern Florida Flood Control Project.

Views and conclusions stated in the report are not necessarily those of the Beach Erosion Board.

This report is published under authority of Public Law 166, 79th Congress, approved July 31, 1945.

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# EFFECTS OF BOTTOM ROUGHNESS ON WIND TIDE IN SHALLOW WATER

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## ABSTRACT

Wind tide and wave conditions in shallow water were studied in a laboratory channel with a rough bottom. Common window screen arranged in strips, 0.10 foot in height, across the channel was used to simulate a vegetative roughness as often found in shallow lakes and bays. This roughness increased the set-up over a smooth bottom condition by a factor of about 2 when the water depth was slightly above the top of the roughness. When the water depth was half way up on the roughness strips, the set-up was 0.08 of that for the smooth bottom conditions with the same depth. The wave heights are not affected by the roughness if the ratio of the still-water depth to the roughness height is greater than 4, but when the ratio is less than 4, waves predicted by using the "effective depth" in the channel compare favorably with those predicted for a smooth bottom where the depth is equivalent to the effective depth.

## INTRODUCTION

The wind, blowing over a body of water, generates waves and the shearing stress on the water surface causes a surface current in the direction of the wind. The surface current is balanced by a back-flow in the lower part of the channel. There is little resistance to back-flow in deep water, but in shallow water the back-flow is restricted by the bottom roughness. It is then necessary for the water surface to "set-up" to create a pressure head at the leeward end of the body of water to overcome the bottom resistance.

This problem of wind tides has been treated theoretically and empirically by many investigators. The wind tides and water surface slopes have been measured and analyzed in nature in the Baltic Sea by Palmen(1)*, Palmen and Lourila(2), and in numerous inland lakes by Hellstrom(3). The most complete data available for a large variety of conditions are the Lake Okeechobee data, as obtained and published by the Corps of Engineers, U. S. Army(4). The latter data have been used by numerous investigators such as Hellstrom(3), Langhaar(5), and Saville(6) to develop or verify various theories concerning wind tides. Small laboratory investigations have been completed by Keulegan(7,8), Hellstrom(3), Francis(9) and Sibul(10,11,12). Van Dorn(13) completed a study of wind tides in a large outdoor pond.

*See References, page 24.

All of the laboratory investigations were completed, insofar as it is known, with a smooth bottom condition with the exception of the experiments by Sibul[10]. Bottom conditions in natural bodies of water vary considerably. Parts or all of the bottom of these bodies may be covered with vegatation. Naturally more knowledge is required on the effects of vegetation upon waves and set-up. The experiments discussed below were conducted using four different bottom conditions, three of which were intended to simulate vegetation; they were a. smooth bottom, b. roughness spacing of 0.80 foot, c. roughness spacing of 0.40 foot, d. roughness spacing of 0.20 foot. The roughness was common window screen which extended up from the bottom 0.10 foot. Each of the conditions of roughness was combined with a variety of water depths and wind velocities.

## DEFINITIONS

The definitions used in this report are listed below and shown in Figure 1.

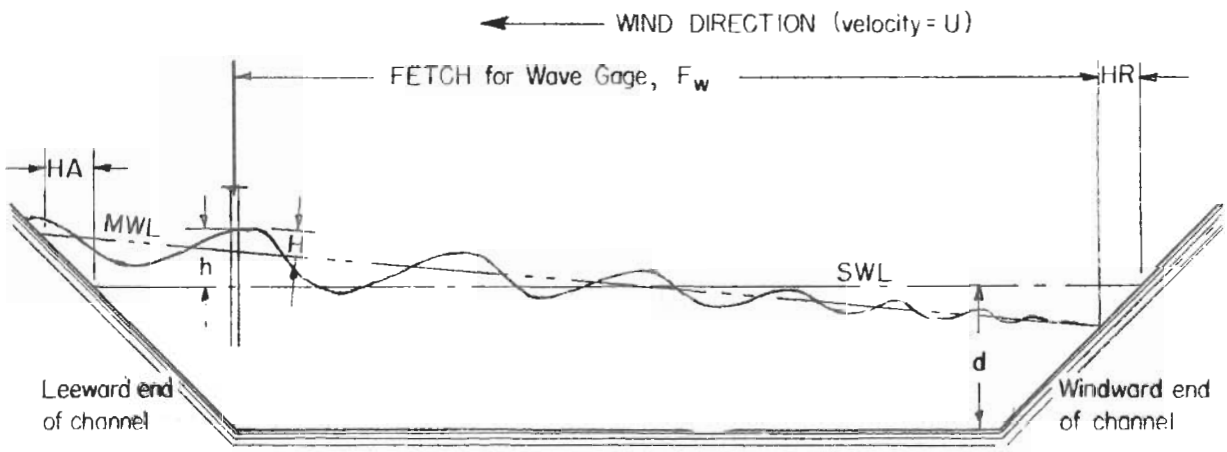



FIGURE 1

A - amplification factor, hr/hs
b - height of roughness = 0.10 foot
d - still water depth in feet
$d_e$ - effective depth, the difference between the SWL and the roughness height, b
F - fetch, defines as the distance parallel to the wind direction measured from the equilibrium shore line (when the body of water is under wind action) to the point of set-up measurements
g - acceleration of gravity, 32.17 ft./sec.$^2$
h - wind set-up above the SWL in feet
$h_s$ - wind set-up in the smooth bottom channel
$h_r$ - wind set-up in the rough bottom channel

$h_{20}$ - wind set-up in the rough bottom channel, with $\Delta$ = 0.20 foot

$h_{40}$ - wind set-up in the rough bottom channel, with $\Delta$ = 0.40 foot

$h_{80}$ - wind set-up in the rough bottom channel, with $\Delta$ = 0.80 foot

H = wave height in feet

$H_a$ - average wave height, in feet

$H_{ae}$ - Sibul's average wave height taken with smooth bottom conditions for the equivalent effective depth

$H_{as}$ - Sibul's average wave height taken with smooth bottom conditions for a specific depth

$H_{1/3}$ - significant wave height in feet

$H_{e/s}$ - Sibul's significant wave height taken with smooth bottom conditions for the equivalent effective depth

$H_{s/3}$ - Sibul's significant wave height taken with smooth bottom conditions for a specific depth

HA - horizontal advancement in feet

HR - horizontal retreat in feet

L - horizontal distance across the water surface

MWL - mean water level

n - Manning's roughness coefficient

SWL - still water level (surface of the water with no wind or wave action)

U - average center-line wind velocity in feet/second

$\Delta$ - spacing between successive wire screen roughness in feet.

## LABORATORY EQUIPMENT

Experiments were performed in a channel 1 foot wide, 60 feet long, and 1.28 feet deep, as shown in Figure 2a. The channel was constructed of wood, with one side made of plate-glass for observational purposes. The wind was generated by a blower mounted at one end of the channel, which was driven by a synchronous AC motor. By varying the inlet area of the blower the wind velocity in the channel was varied from 0 to 50 feet per second. A honeycomb at the entrance straightened the wind flow and a beach with a slope of 1:20 graudally guided the wind onto the water surface. The leeward beach guided the wind out of the channel and also served to break the waves to prevent reflections. The wind was metered by a venturi section, and the velocity distribution of the wind at the mid-point was taken with a pitot tube. The wave characteristics were measured by a resistance type wave gage near the end of the channel (Figure 2).

Piezometers were located along the center-line at five positions, as shown in Figure 2a. These piezometers were used to determine the water depth and the pressure in the channel above the atmospheric pressure. The difference in readings between successive piezometers permitted the drop in pressure along the channel to be computed. These data also were used to correct the piezometer readings for pressure drop and thereby obtain the true water surface profile. Two draft gages

were placed at two of the piezometer positions, so that an immediate check could be made on the piezometer readings for pressure drop. If the two types of observations did not agree, the piezometer was checked for a clogged line or for an air leak.

Common 1/16-inch mesh window screen was used as the roughness to simulate vegetation (Figure 3). This cloth was cut so as to extend across the bottom of the channel and stand 0.10 foot high. The strips of screen were stapled to the bottom of the channel at even spaces. By varying the distance between screens, the relative roughness of the bottom could be changed.

The Manning's roughness coefficient, n, was determined for each screen spacing by a series of tests with steady uniform flow in a laboratory flume. Figure 4 shows the relationship between Manning's n and screen spacing for several depths.

Figure 5 shows the general arrangements of the experimental equipment with wire roughness and recorders in place.

## PROCEDURE

The channel was filled and the true water level was determined from piezometer readings. The blower then was started and the inlet area was adjusted until a predetermined venturi reading was reached. Conditions were allowed to reach steady-state, and then readings were made on the piezometers, draft gages, venturi meter and the pitot tube. Simultaneously a wave recorder was operated to obtain a record of 300 waves.

Tests were made with both smooth and rough bottom conditions using the following parameters:

1. The smooth bottom surface was painted with a white oxide primer paint; this surface had a Manning's n roughness of 0.016.

2. The bottom roughness spacing was varied as follows: 0.20, 0.40 and 0.80 foot. The values of Manning's n for the rough bottoms is shown in Figure 4.

3. The wind velocity was varied as follows: 10, 15, 20, 25, 30 and 35 feet/second.

4. The water depth was varied as follows: 0.350, 0.300, 0.250, 0.200, 0.150, 0.100 and 0.050 foot.

Other recordings that were made during the tests were: water temperatures, wet and dry bulb thermometer readings, and the barometric pressure.

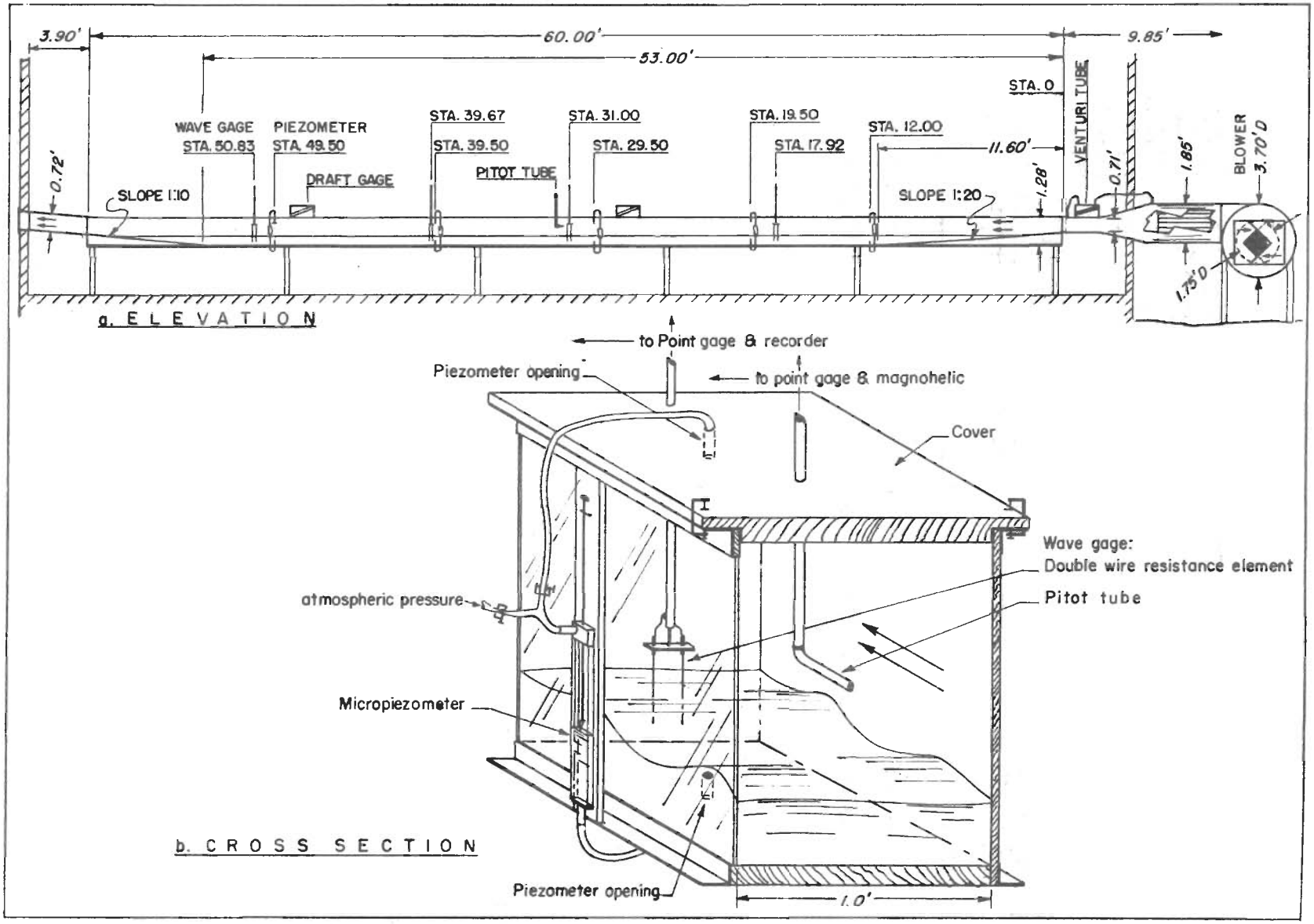



FIGURE 2. GENERAL LABORATORY SET-UP FOR STUDY OF WIND TIDE IN SHALLOW WATER

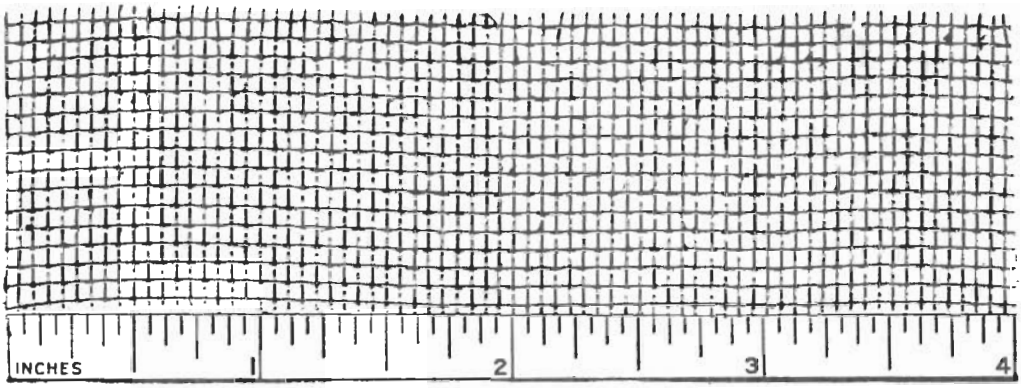



FIGURE 3. ENLARGED VIEW OF WINDOW SCREEN USED AS A CHANNEL BOTTOM ROUGHNESS.

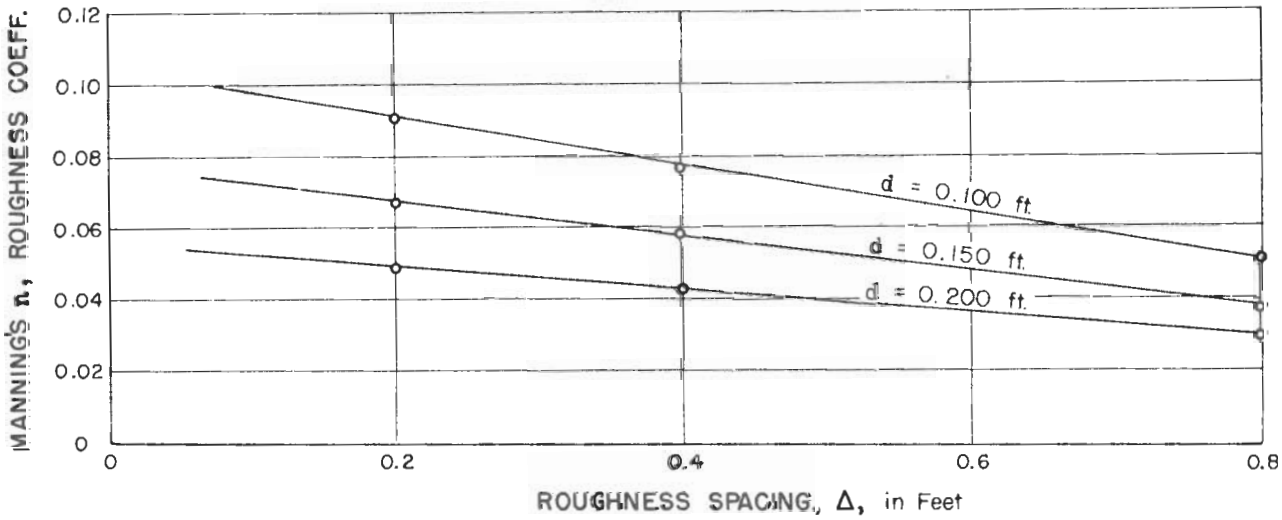
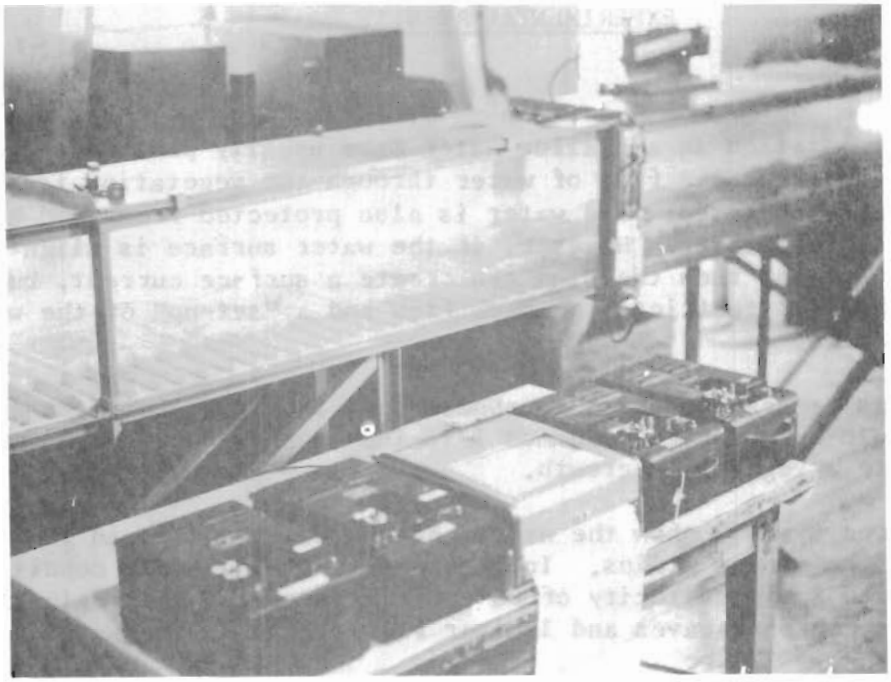
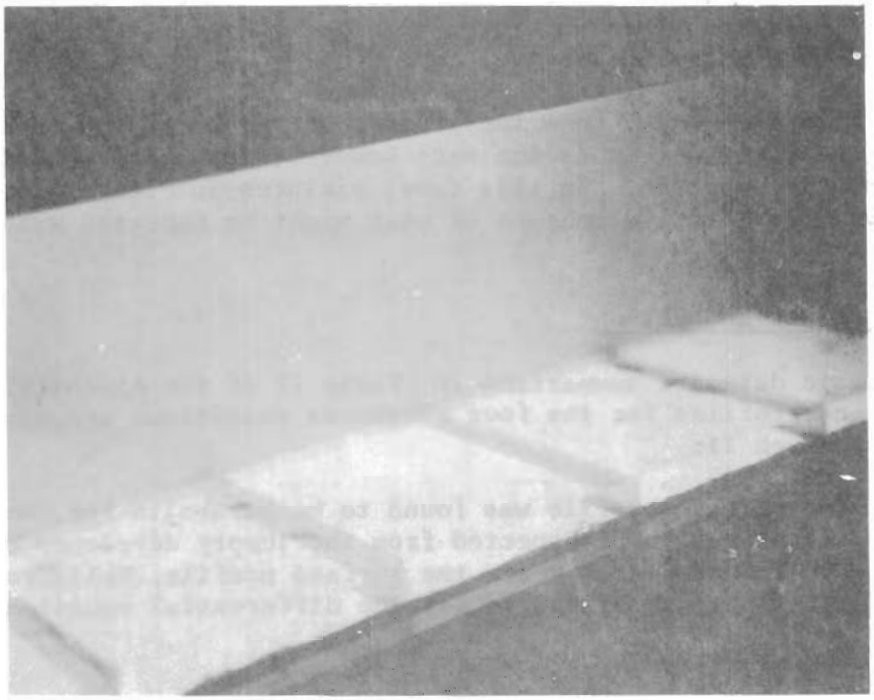



FIGURE 4. MANNING'S n ROUGHNESS COEFFICIENT AS A FUNCTION OF ROUGHNESS SPACING Δ



a. Laboratory channel with wave recording equipment in foreground. (Screen spacing, $\Delta$, = 0.20 foot; water depth, d, = 0.35 foot; wind velocity, U, = 25 feet/second)



b. Closeup view of roughness screens with spacing of 0.80 foot and water surface at top of screens.

FIGURE 5 GENERAL ARRANGEMENT OF EXPERIMENTAL EQUIPMENT

## EXPERIMENTAL RESULTS

### General

The vegetation in a shallow water lake usually protrudes from the water surface, and the flow of water through the vegetation is restricted or sometimes inhibited. The water is also protected from wind action by the same vegetation. However, if the water surface is slightly above the growth, then the wind can create a surface current, but the vegetation still restricts the back flow and a "set-up" of the water surface occurs.

It was desired to use a roughness such that the above characteristics could be observed. Common 1/16-inch mesh window screen was used to simulate a vegetative growth.

Figures 6 and 7 show the nature of the water motion in the vicinity of one of the screen strips. In Figure 6, a steady-state condition exists, with a wind velocity of only 2 feet/second. This velocity is too low to generate waves and laminar flow occurs in the water.

In Figure 7, an unsteady flow occurs. This figure was prepared from a sequence of motion pictures that were taken shortly after the blower was started; these pictures in Figure 7 were taken just prior to the appearance of surface waves. Since it takes a period of time for the velocity to build up to a steady-state condition, laminar flow occurs for most of the sequence. However, when a steady-state condition was reached, surface waves and turbulent flow of the water existed which contributed to dispersing the dye.

Both Figures 6 and 7 show the effects of the roughness upon restricting the flow when it is laminar; however, in nature turbulent flow is usually expected. In this case, pictures in Figure 6 and 7 merely give a qualitative measure of what might be expected with turbulent flow.

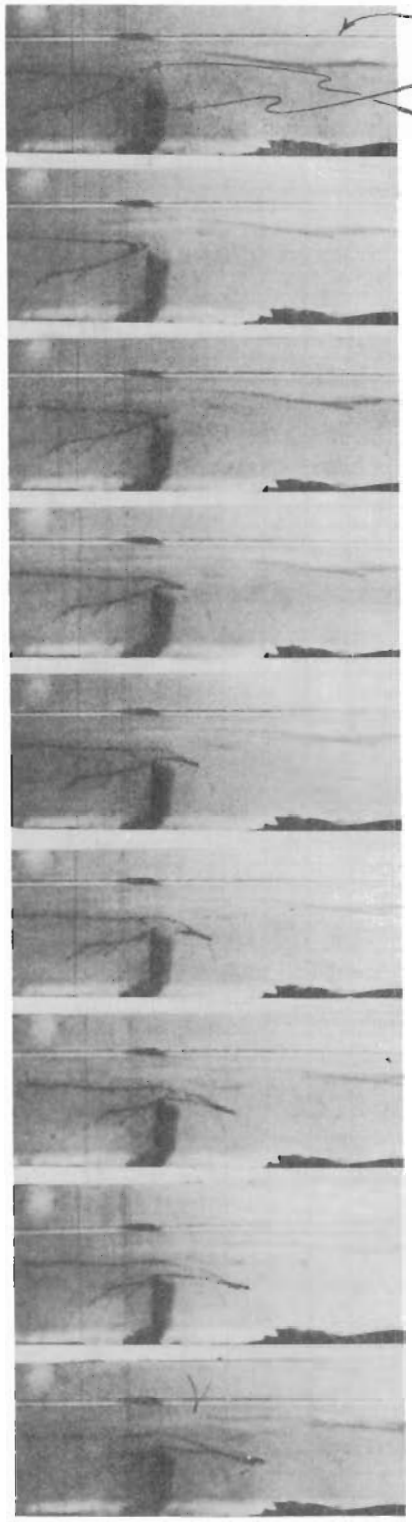
### Surface Profiles and Set-up

The basic data are summarized in Table II of the Appendix. The water surface profiles for the four roughness conditions are plotted in Figures 8 through 11.

The water-surface profile was found to be parabolic for the smooth bottom conditions, as to be expected from the theory developed by Hellstrom[3]. In order to develop the surface profile, Hellstrom started with the Euler-Navier equations to get the differential equation.

$$\frac{d\,z_s}{d\,x} = \frac{\lambda \tau_s}{\gamma z_s} \qquad (1)$$

Integration of this equation gives the relationship



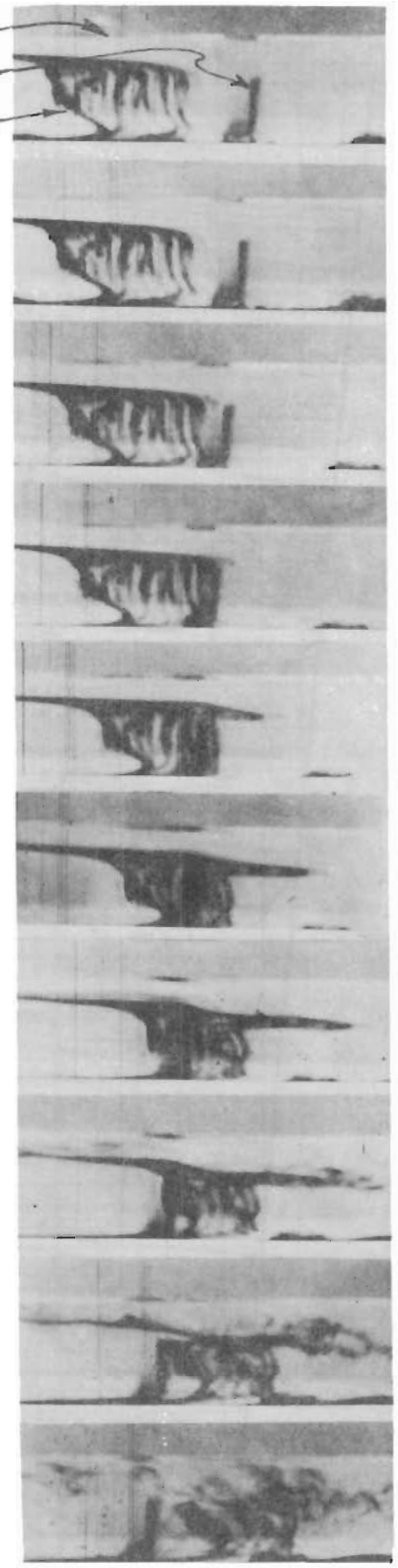



FIG. 6 Laminar Flow Over A Bottom Roughness.

FIG. 7 Unsteady Flow Over A Bottom Roughness.

FIGS. 6 & 7.
PHOTOGRAPHS SHOWING WATER MOTION NEAR A BOTTOM ROUGHNESS

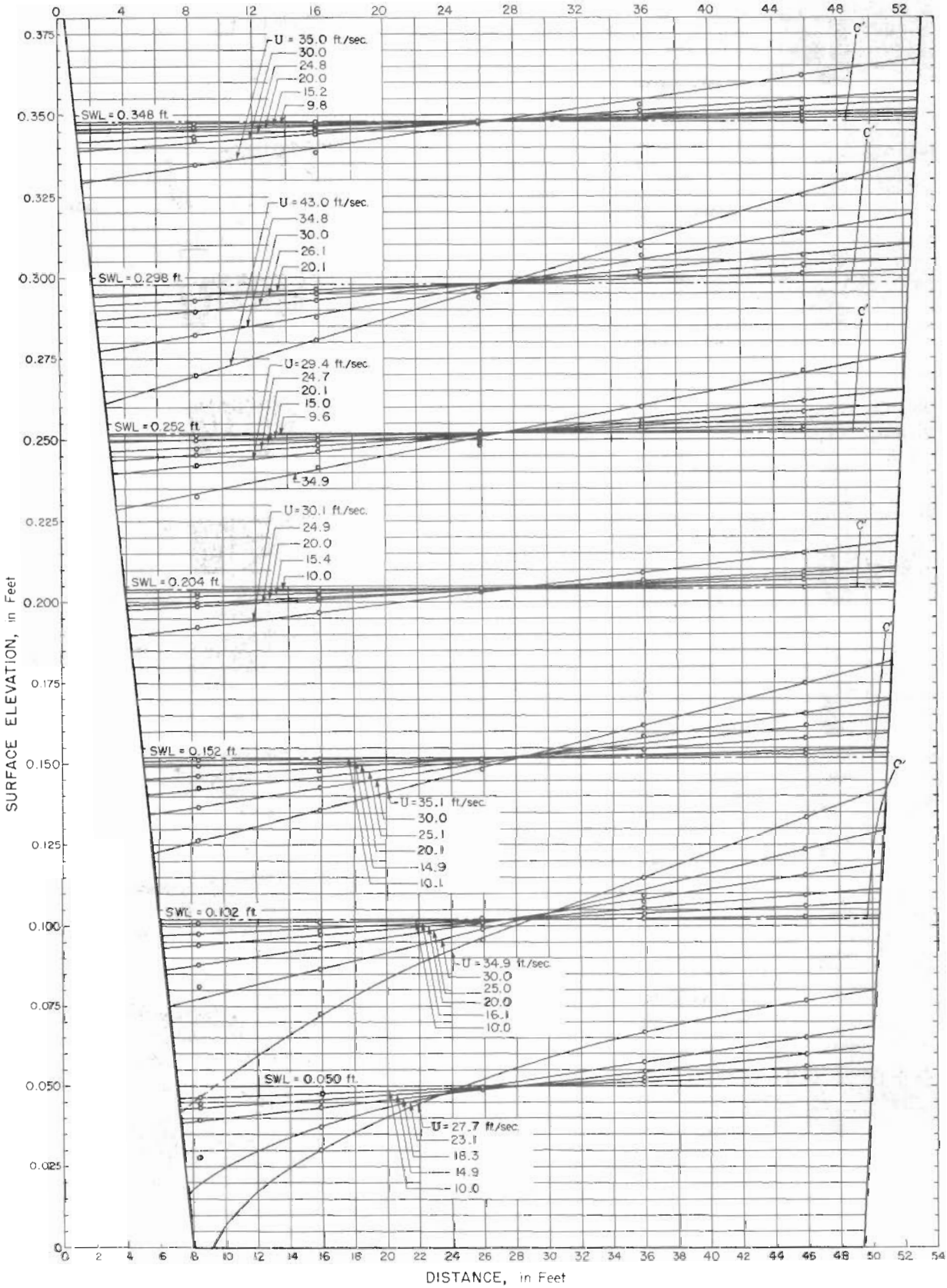



FIGURE 8. WATER SURFACE PROFILES ALONG A SMOOTH BOTTOM CHANNEL WITH VARIOUS WIND VELOCITIES AND WATER DEPTHS

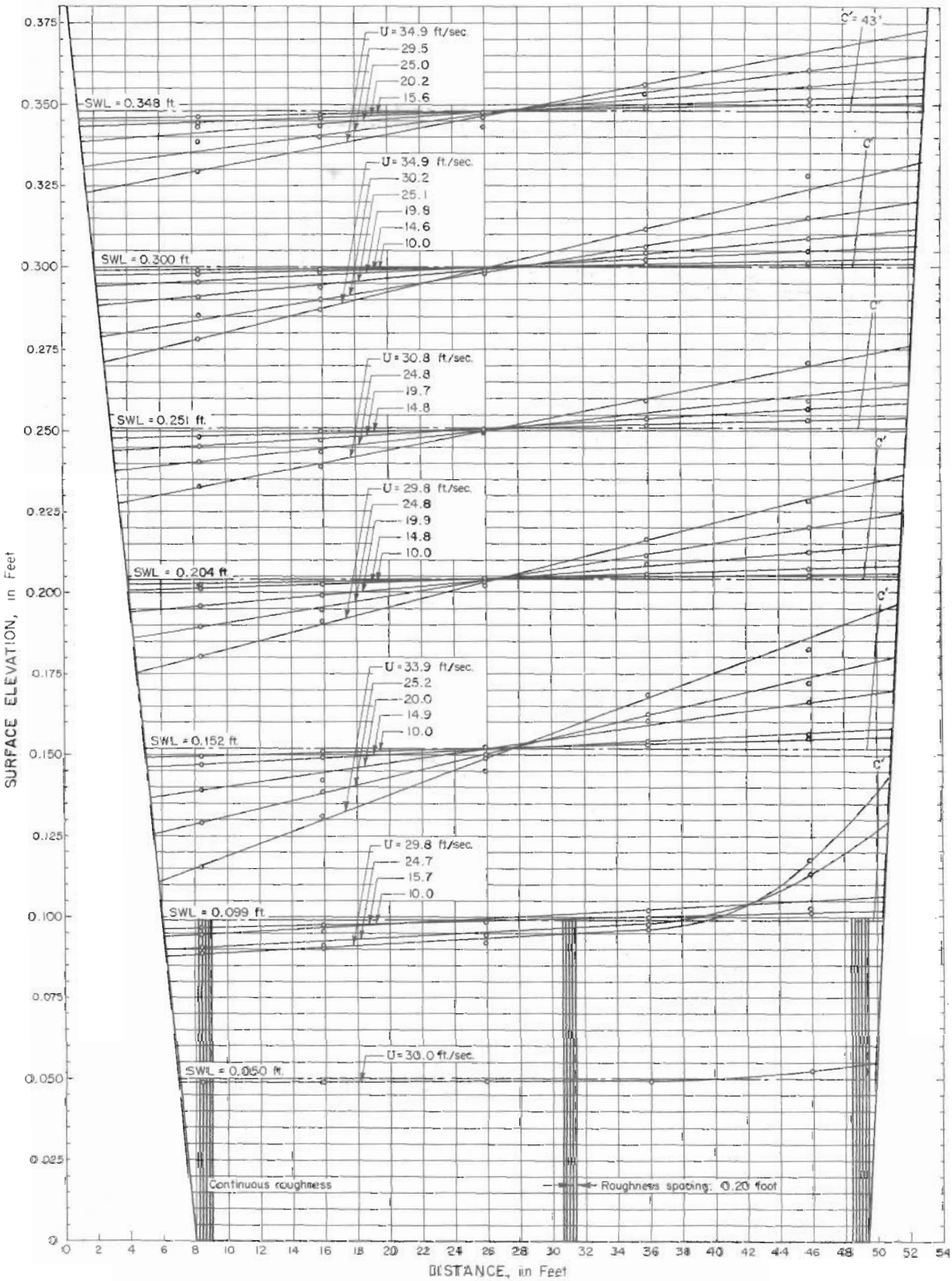



FIGURE 9. WATER SURFACE PROFILES ALONG A ROUGH BOTTOM CHANNEL ($\Delta = 0.20'$) WITH VARIOUS WIND VELOCITIES AND WATER DEPTHS

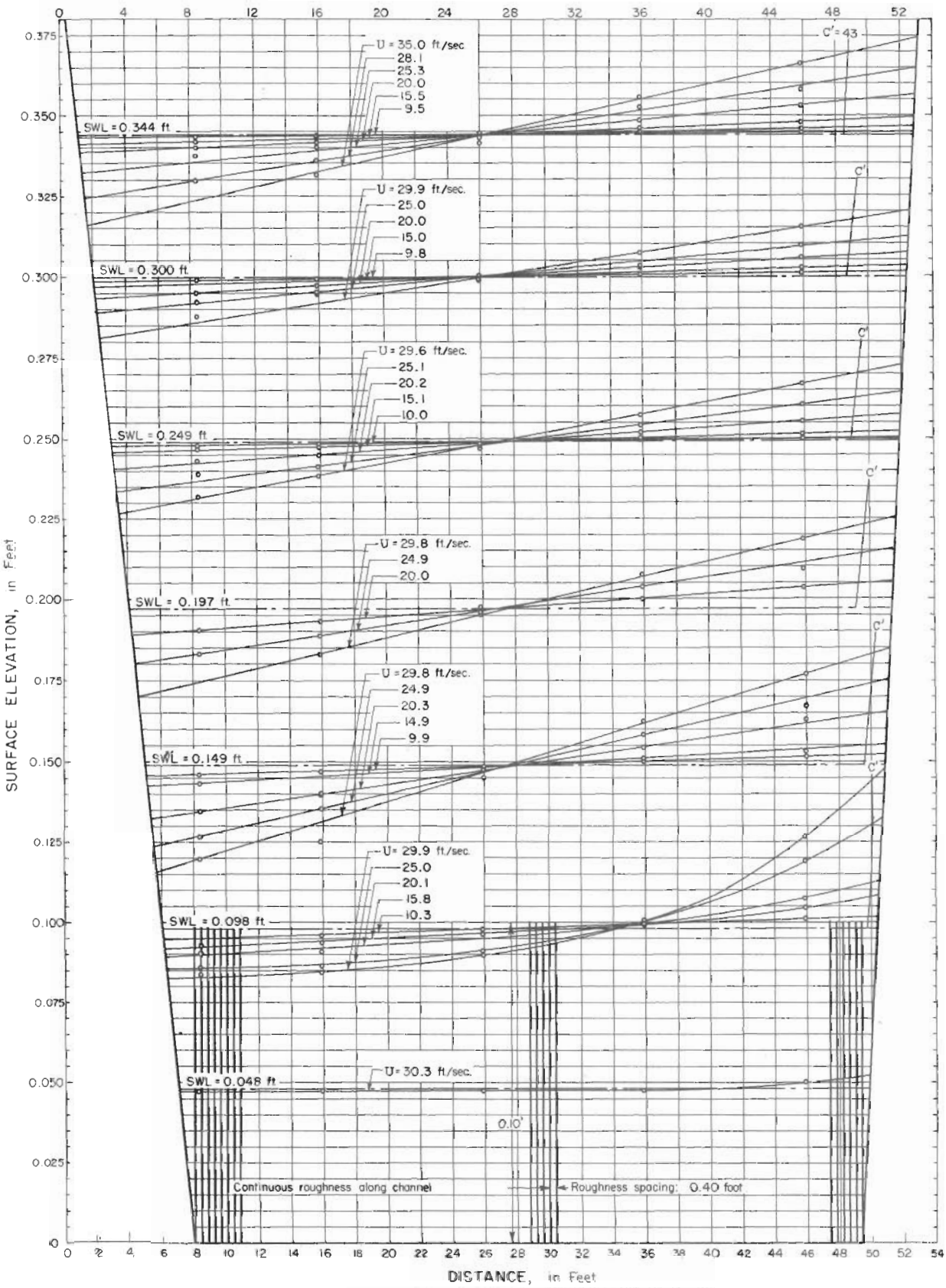



FIGURE 10. WATER SURFACE PROFILES ALONG A ROUGH BOTTOM CHANNEL ($\Delta = 0.40'$) WITH VARIOUS WIND VELOCITIES AND WATER DEPTHS

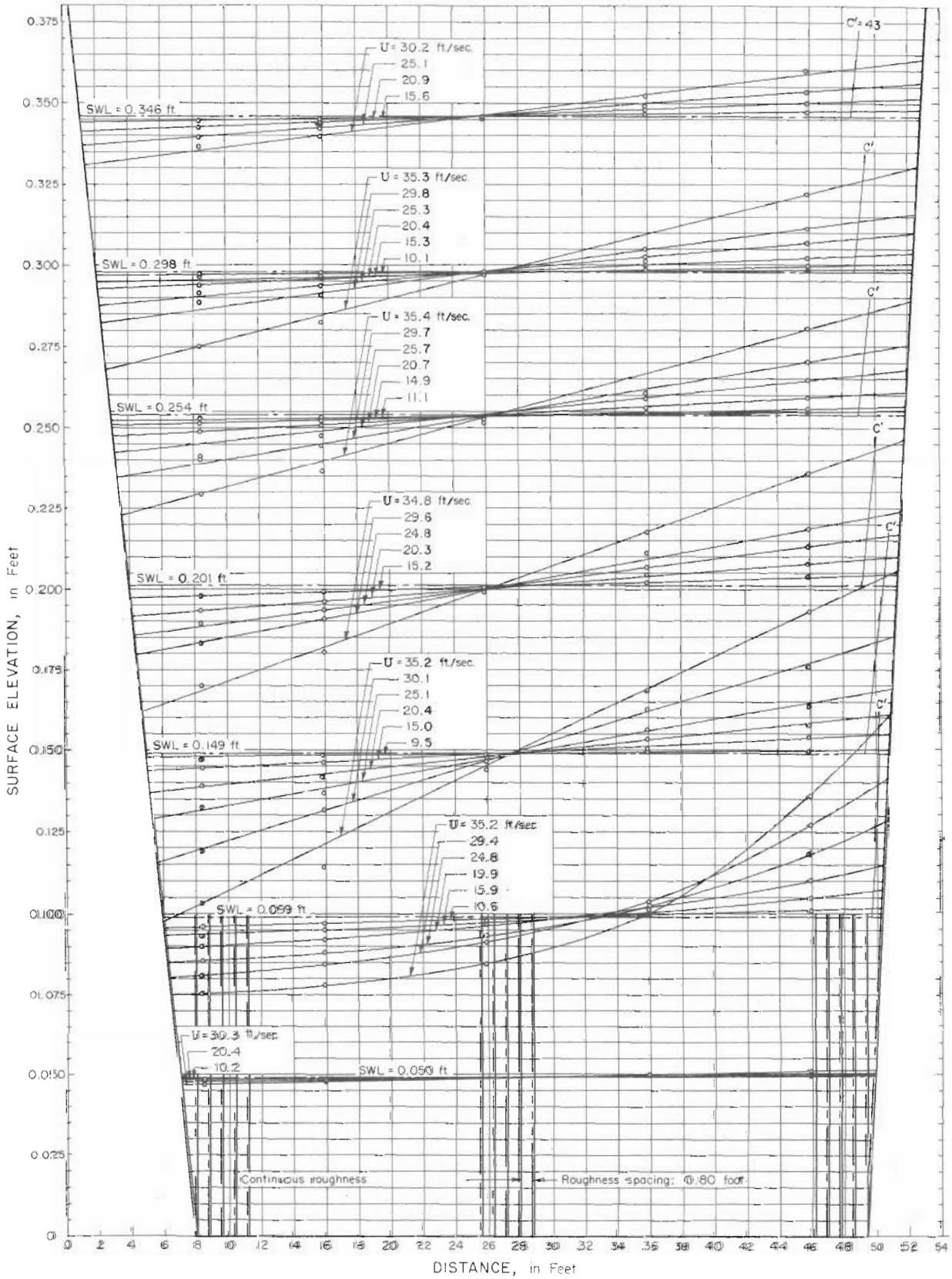



FIGURE 11. WATER SURFACE PROFILES ALONG A ROUGH BOTTOM CHANNEL ($\Delta = 0.80'$) WITH VARIOUS WIND VELOCITIES AND WATER DEPTHS

$$z_s^2 = \frac{2 \lambda \tau_s}{\gamma} (x + C_1) \tag{2}$$

When the water depth is great in comparison with the set-up, the water surface approaches a plane surface. In this case, the water depth can be assumed as a constant value, d, and equation (2) reduces to

$$\frac{d z_o}{d x} = \frac{\mu k}{\gamma d} \tag{3}$$

integration of which gives

$$z_o = \frac{\mu k}{\gamma d} x + C_2 \tag{4}$$

If the body of water is in an ideal rectangular shaped channel of length L, with a still water depth of d, the constant of integration can be determined as follows:

$$\int_0^L \left(\frac{\mu k}{\gamma d} x + C_2\right) dx = Ld; \quad C_2 = d - \frac{\mu k L}{2 \gamma d} \tag{5}$$

However, if the channel is of some other shape (see Figure 1) the constant $C_2$ becomes complicated in form and involves variables such as: the slope of the beaches, and the distances HR and HA. However, the effect of all of these are negligible in comparison to the overall channel length; so with the limit of engineering accuracy, we may write

$$z_o = \frac{\mu k}{\gamma d} + d - \frac{\mu k L}{2 \gamma d} \tag{6}$$

and

$$h = z_o - d = \frac{\mu k}{\gamma d} \left( x - \frac{L}{2}\right) \tag{7}$$

If the maximum water slope is considered, the angle of the surface with respect to the horizontal is equal to 8 minutes. In this case, x can be replaced by the fetch, F, and equation (7) then becomes

$$h = \frac{K}{d} \left(F - \frac{L}{2}\right) \tag{8}$$

To compare h for various depth and wind velocities, $(F - \frac{L}{2})$ is set equal to a constant, C. For convenience we write

$$(2F - L) = 2C = C' \tag{9}$$

C' was chosen to be 43 feet, because it was the maximum constant distance that could be used for all depths. This value is the length of the channel at minimum depth. About 90 percent of the water surface profiles are linear; so even though this is not an accurate basis for comparing 10 percent of the runs, it gives us a common basis for comparing all the data.

For the purposes of design, the set-up is, of more interest than the water surface profiles. Figure 12 has been prepared as cross-plots from Figures 8 through 11 to show set-up as a function of wind velocity with the water depth as a parameter. These graphs indicate that for a given depth the set-up increases more rapidly with an increase in velocity at higher velocities than with lower velocities.

In Figure 13, the set-up is plotted against the still water depth with wind velocity as a parameter. This figure shows that for a constant velocity, the set-up increases with a decrease in water depth. The relationships for the rough bottom conditions are similar to those for a smooth bottom at the large water depths.

For small water depths the curves for the rough bottom have a definite set-up limit which is the same for all roughness conditions. This point of maximum set-up occurs at a water depth of 0.10 foot, which is the condition where the water surface is just at the top of the roughness screens. When the water depth is less than the height of the roughness, the set-up rapidly decreases with water depth until at a depth of half of the roughness height the set-up is negligible.

Figure 14 presents a more convenient comparison of the same curves shown in Figure 13. In this comparison the set-up was measured at a location, C' (see Figures 8 through 11). This C' location should be used in the cases where the water surface profiles are linear, but it can be used in the non-linear cases too. This comparison of the different roughnesses for the non-linear cases can be done because at a constant depth the fetch, length of the still water surface, and the wind velocities were held constant. These plots show that at high wind velocities there is little difference in the set-up with roughness. Also, the set-up was much greater with the roughnesses than for a smooth bottom for depths greater than 0.10 foot. The set-up for a spacing $\Delta = 0.80$ is noticeably smaller than the other two roughnesses as the wind velocity decreases. At low wind velocities the set-up for a spacing $\Delta = 0.80$, is the same as for a smooth bottom, except for depths less than 0.10 foot.

To compare the set-up under smooth and rough bottom conditions for various wind velocities, the ratios of the set-ups have been computed and summarized in Figure 15. This ratio has been designated as an amplification factor. It is noted in Figure 15a that this factor is relatively small, average value = 0.08, because the water depth is less than the height of the roughness. Under this condition the wind is unable to act effectively on the water surface.

In those tests in which the water surface was greater than the roughness height the amplification factor is a function of the roughness spacing for wind velocities up to 20 feet/second (Figure 15b). For wind velocities greater than this value, the set-up caused the roughness strips in the windward part of the channel to become exposed. The effect of this condition was to reduce the shear stress on a part of the water

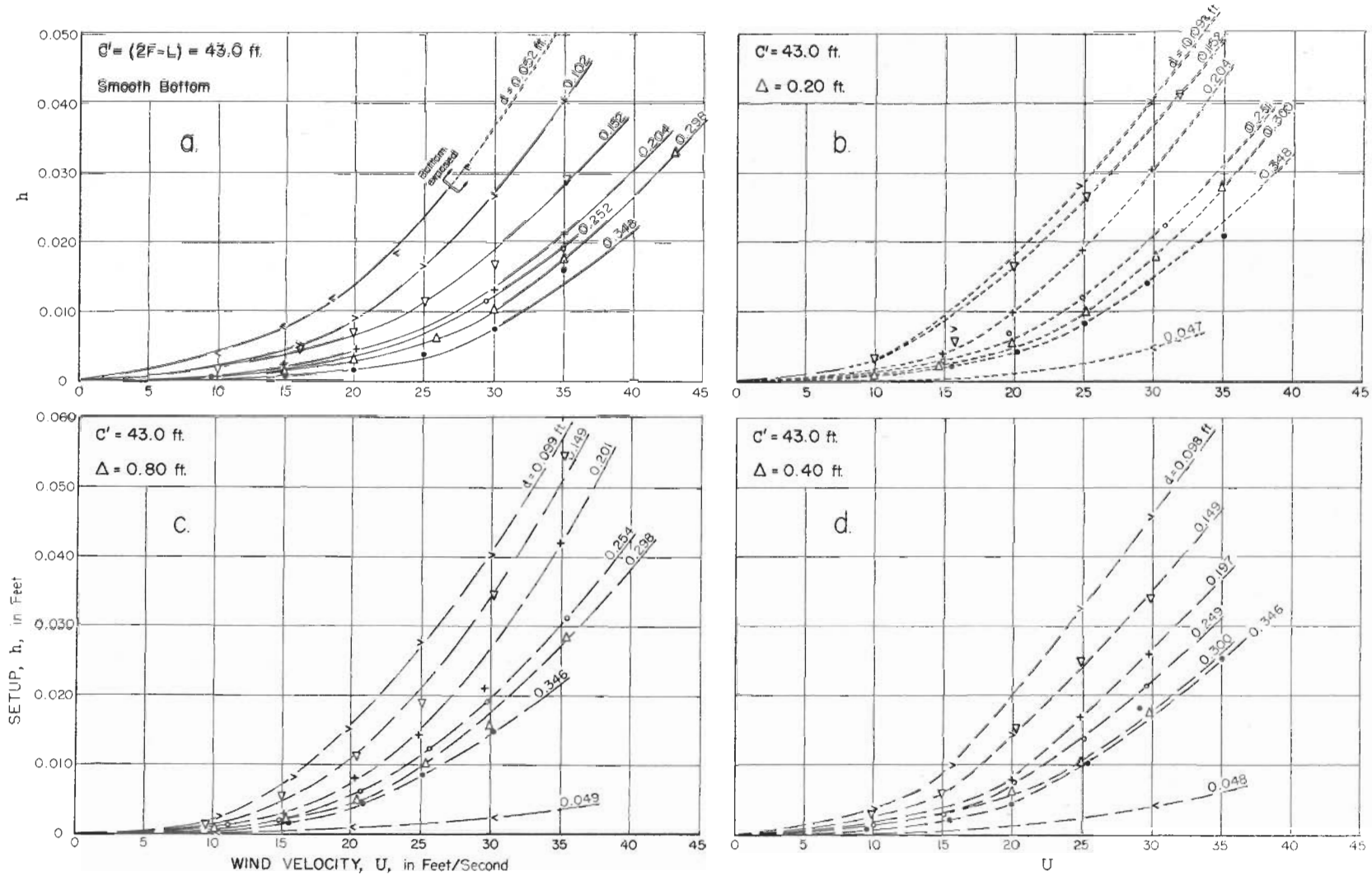



FIGURE 12. WIND SET-UP AS A FUNCTION OF WIND VELOCITY FOR VARIOUS BOTTOM ROUGHNESSES AND WATER DEPTHS

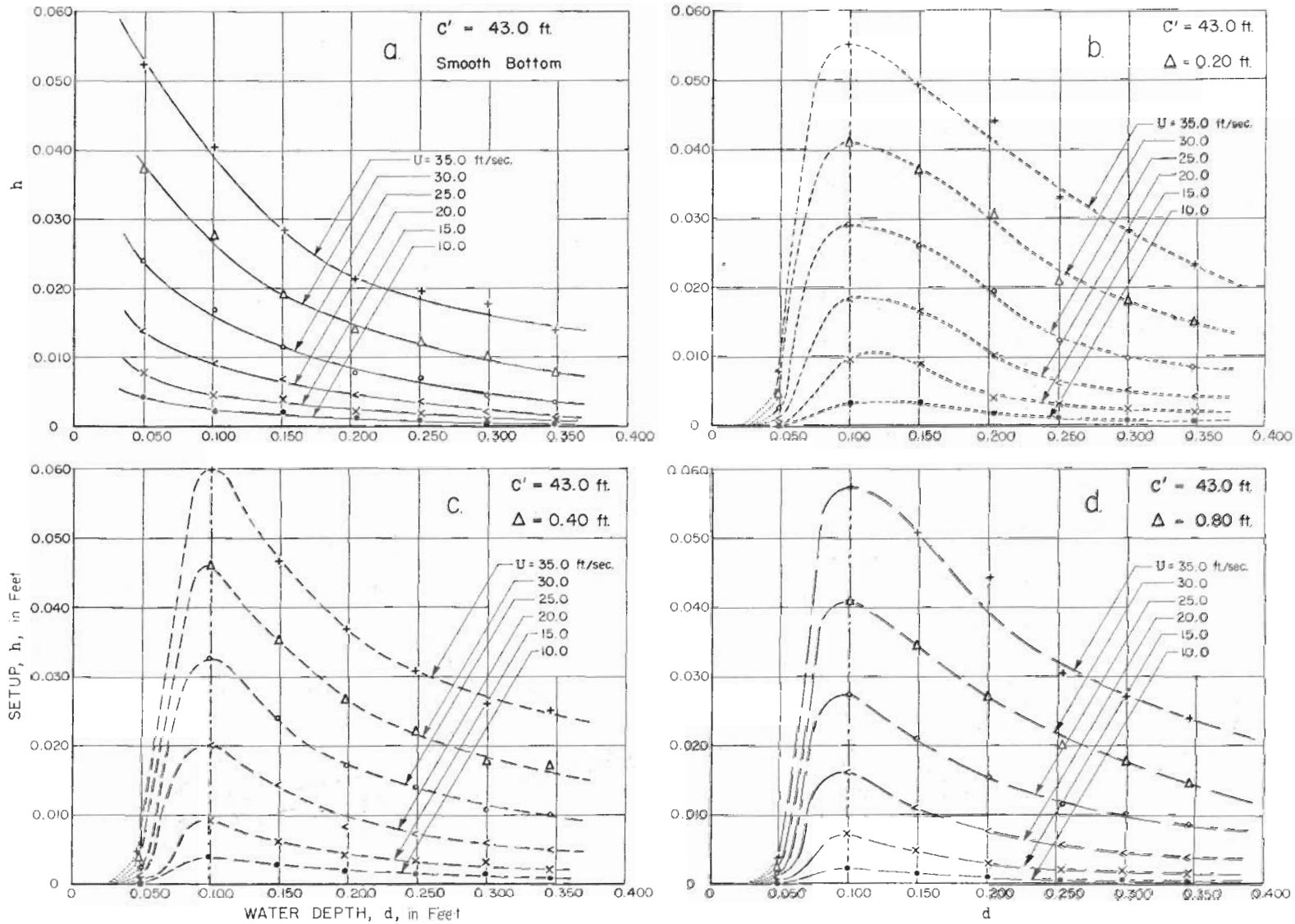



FIGURE 13. WIND SET-UP AS A FUNCTION OF WATER DEPTH FOR VARIOUS BOTTOM ROUGHNESSES AND WIND VELOCITIES

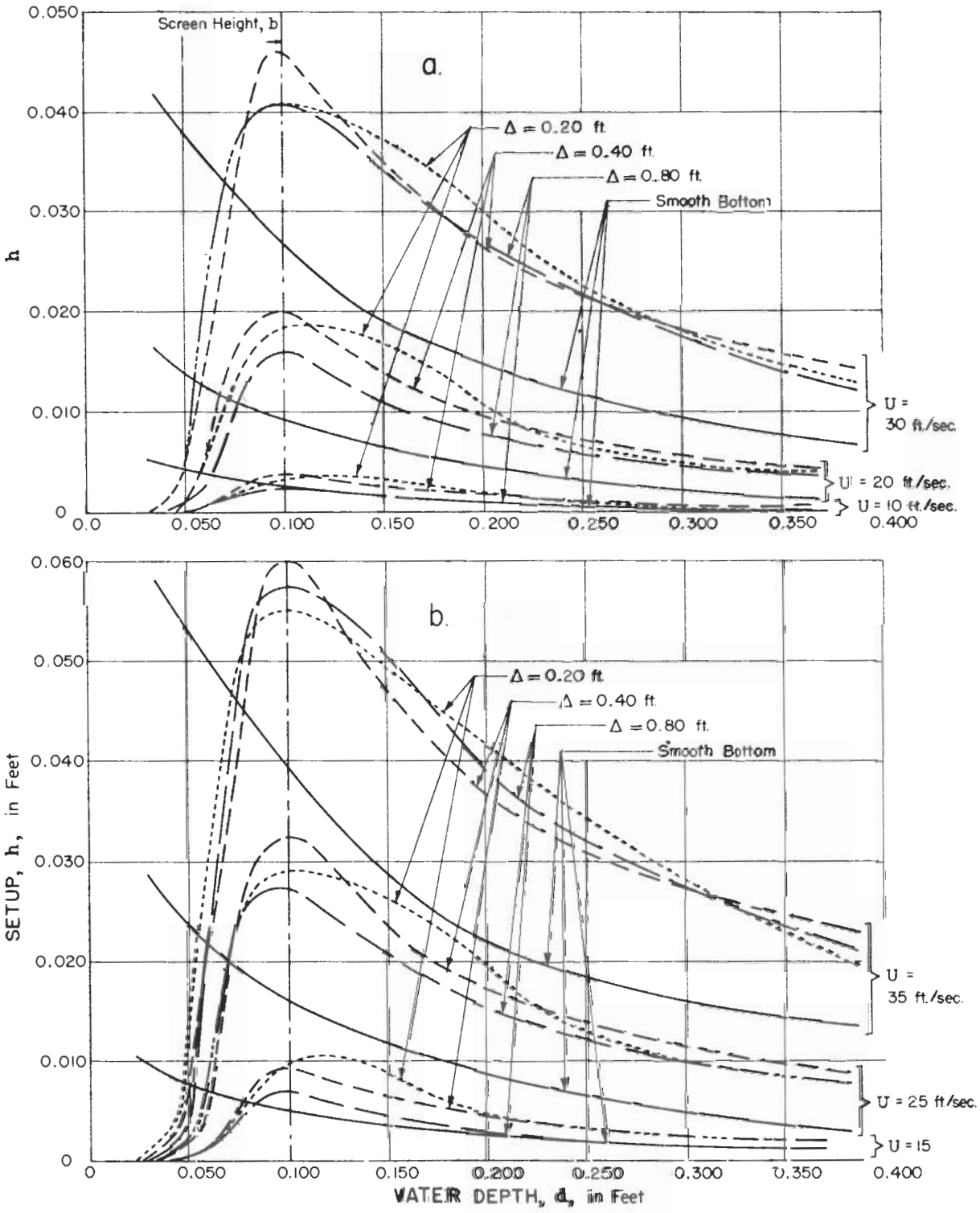



FIGURE 14. WIND SET-UP AS A FUNCTION OF WATER DEPTH FOR VARIOUS BOTTOM ROUGHNESSES AND WIND VELOCITIES

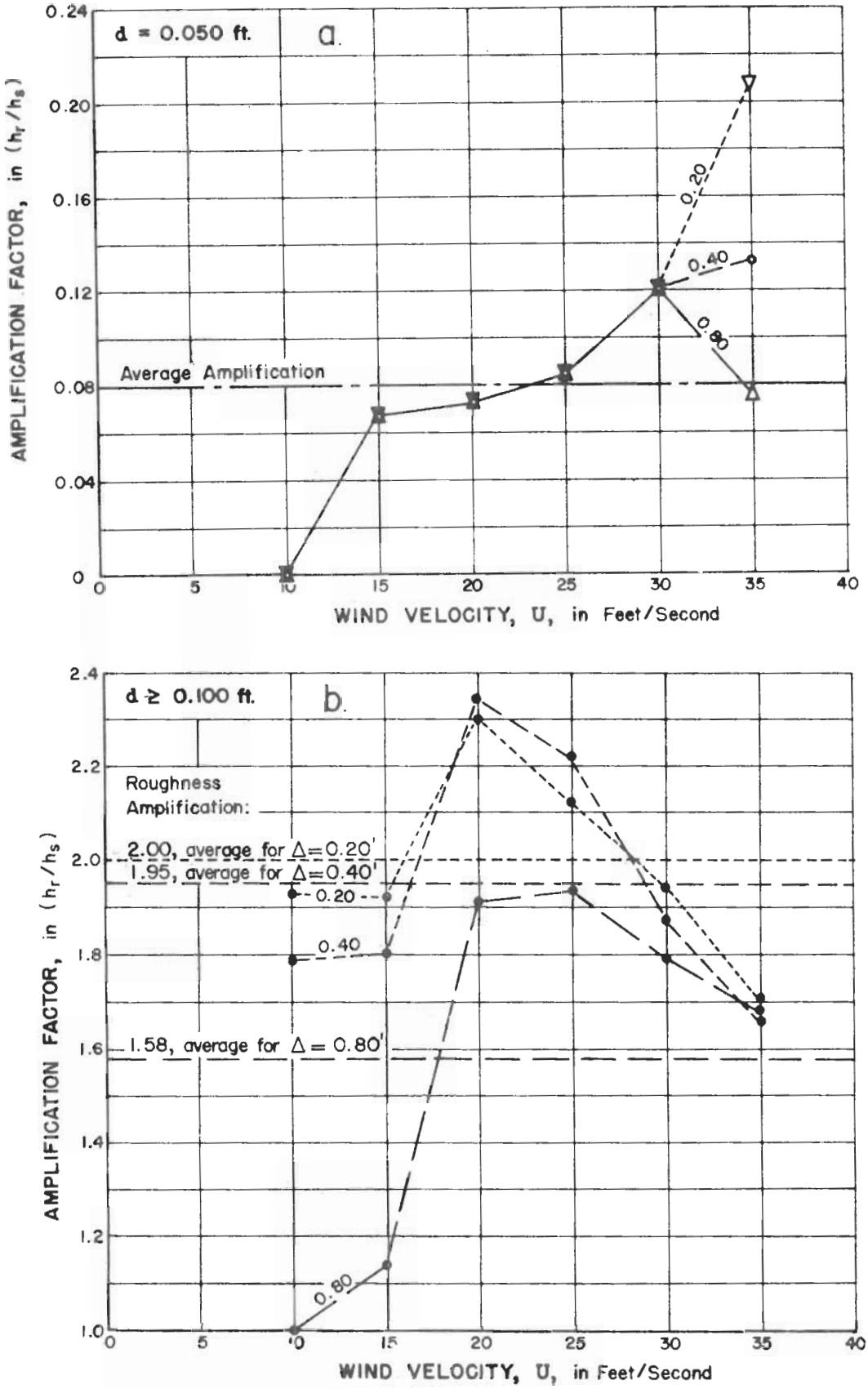



FIGURE 15. AMPLIFICATION FACTOR OF SET-UP AS A FUNCTION OF WIND VELOCITY

surface and thereby cause a smaller increase in set-up with a given increase in velocity than would occur at velocities lower than 20 feet per second.

The various data on set-up are summarized in Figure 16 with the ratio of set-up to still water depth, h/d, plotted as a function of $U^2/Fg$. Figure 16a presents these terms for the smooth bottom condition, and Figure 16b presents the terms for the various rough bottom conditions. It is evident that a family of curves exists with the ratio of water depth to roughness height being a parameter. The curves are approximately parallel with the exception of the curve for a water depth of 0.05 foot under the rough bottom condition. For a particular water depth, the experimental points fall on a single line regardless of roughness.

## Wave Characteristics

Measurements of wave heights and periods were made at a location near the end of the channel by a resistance type instrument (Figure 2a). The records from the recorder were analyzed for the significant wave height and compared with those taken previously by Sibul[11] in the same channel under smooth bottom conditions. As might be expected, the wave heights which occurred with the roughnesses used in these experiments were less than the heights observed by Sibul. When the ratio of water depth to roughness height was greater than about 4, the effect of the bottom roughness in reducing wave heights was relatively small, but when the water depth approached the height of the roughness the wave height was reduced appreciably. When the water depth was less than the roughness height no waves were formed.

If the distance between the still water level and the top of the roughness screens is considered to be the "effective depth", $d_e$, the wave heights occurring in these tests correspond to those occurring in the smooth bottom tests of Sibul[11] with the same wind velocity and a water depth equal to $d_e$. The channel and location of wave gages were the same in both tests. A comparison of data obtained in the present tests with that obtained by Sibul is shown in Table I. For example, in Run 71 the water depth was approximately 0.15 foot, which gave an effective depth, $d_e$, of 0.05 foot. Considering the effective depth, the percentage derivation of the wave heights in these tests and the Sibul experiments have been calculated for Run 71 as follows:

### Sample Calculations for Run #71

| | Experimental wave ht.: | Sibul's wave heights: | |
|---|---|---|---|
| | | for $d = d_e = 0.05'$ | for $d = 0.015'$ |
| $d = 0.15$ | | | |
| $b = 0.10$ | $H_a = 0.030$ ft. | $H_{ae} = 0.023$ ft. | $H_{as} = 0.055$ ft. |
| $d = d - b = 0.05$ | $H_{1/3} = 0.038$ ft. | $H_{e/3} = 0.039$ ft. | $H_{s/3} = 0.084$ ft. |

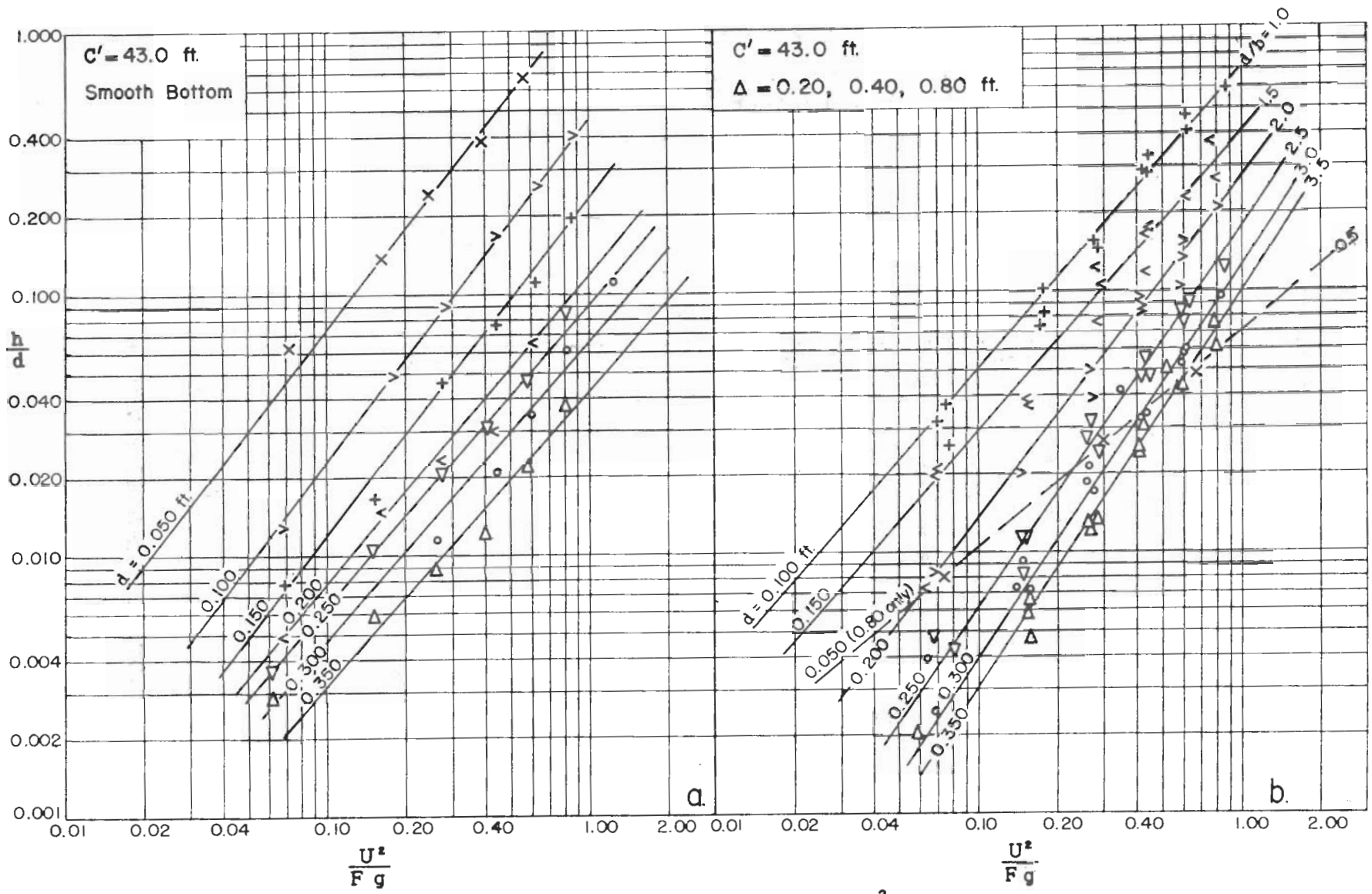



FIGURE 16. $\frac{h}{d}$ *versus* $\frac{U^2}{Fg}$

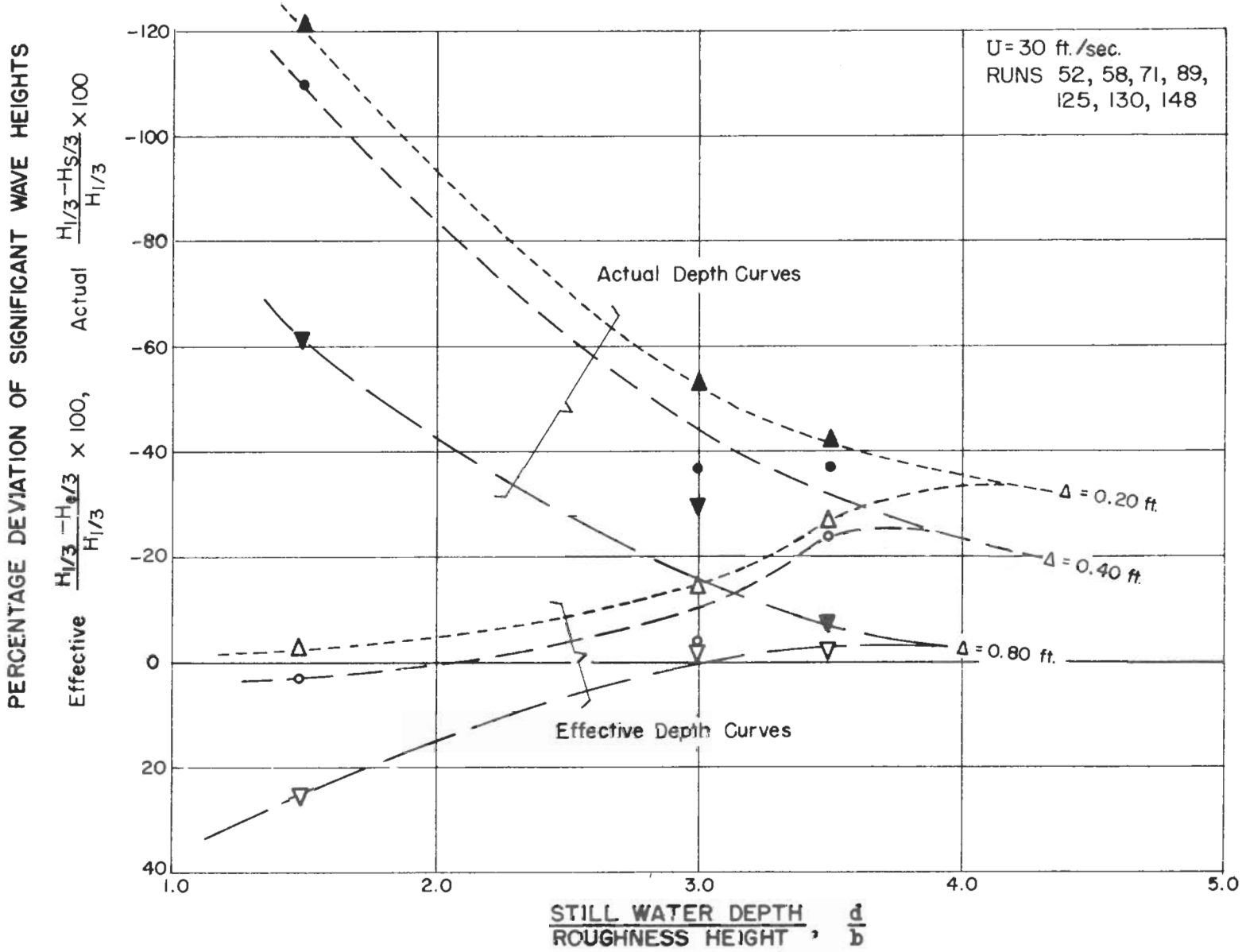



FIGURE 17. PERCENTAGE DEVIATION OF SIGNIFICANT WAVE HEIGHTS AS A FUNCTION OF d/b.

Percent deviation "effective depth" method:

Average H

$$\frac{H_a - H_{ae}}{H_a} = \frac{0.030 - 0.023}{0.030} = +\ 23.3\%$$

Significant H

$$\frac{H_{1/3} - H_{e/3}}{H_{1/3}} = \frac{0.038 - 0.039}{0.038} = -\ 2.6\%$$

Percent deviation "actual depth comparison":

$$\frac{H_a - H_{as}}{H_a} = \frac{0.030 - 0.055}{0.030} = -83.3\%$$

$$\frac{H_{1/3} - H_{s/3}}{H_{1/3}} = \frac{0.038 - 0.084}{0.038} = -\ 121\%$$

Considering the significant wave height the percentage deviation was -2.6%. If, on the other hand, the data are compared with Sibul's data for a depth equal to 0.15 foot the percentage deviations become relatively large; that is, the percentage deviations are -83.3 percent and -121 percent for the average and significant wave heights, respectively. The minus sign indicates that the wave heights in the present tests were less than those in the Sibul tests.

A summary of the percentage deviation of the significant wave heights in the present tests and the Sibul tests is shown in Figure 17. This figure graphically summarizes the data for all tests in which water depth and roughness spacing were the principal variables.

## CONCLUSIONS

1. When the water depth is equal to the height of the roughness, a critical condition occurs in both set-up and wave generation.

2. When the water depths were equal to or greater than the roughness height the average set-up was 2.0, 1.95 and 1.58 times that for a smooth bottom for roughness spacings of 0.20, 0.40 and 0.80 foot, respectively.

3. When the water depth is less than the roughness height the average wind stress becomes progressively smaller as the depth is decreased. When the water depth was one-half the roughness height the set-up was 0.08 the set-up with a smooth bottom.

4. When the ratio of water depth, d, to the roughness height, b, is greater than approximately 4, the wave heights do not appear to be affected by the bottom roughness. For ratios of d/b less than 4, but greater than 1.0, the wave heights can be predicted with a fair degree of accuracy from the smooth bottom relationships if the effective depth, d, is used in calculations.

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## APPENDIX

### TABLE I

| Run No. | d ft. | d ft. | U ft./sec. | Δ ft. | Experimental Wave Heights ft. $H_a$ | $H_{1/3}$ | Sibul's Wave Hts. for Equiv. Eff. Depth ft. $H_{ae}$ | $H_{e/3}$ |
|---|---|---|---|---|---|---|---|---|
| 71 | 0.150 | 0.050 | 33.9 | 0.20 | 0.030 | 0.038 | 0.023 | 0.039 |
| 58 | 0.300 | 0.200 | 30.2 | 0.20 | 0.063 | 0.090 | 0.071 | 0.103 |
| 52 | 0.350 | 0.250 | 29.5 | 0.20 | 0.068 | 0.102 | 0.094 | 0.130 |
| 111 | 0.150 | 0.050 | 29.8 | 0.40 | 0.027 | 0.040 | 0.023 | 0.039 |
| 92 | 0.300 | 0.200 | 29.9 | 0.40 | 0.067 | 0.100 | 0.071 | 0.103 |
| 89 | 0.350 | 0.250 | 28.1 | 0.40 | 0.070 | 0.105 | 0.094 | 0.130 |
| 148 | 0.150 | 0.050 | 30.1 | 0.80 | 0.035 | 0.052 | 0.023 | 0.039 |
| 130 | 0.300 | 0.200 | 29.8 | 0.80 | 0.073 | 0.105 | 0.071 | 0.103 |
| 125 | 0.350 | 0.250 | 30.2 | 0.80 | 0.106 | 0.140 | 0.094 | 0.130 |

| Run No. | Sibul's Wave Hts. for Depth d ft. $H_{as}$ | $H_{s/3}$ | % Deviation Using Eff. Depth Method ave. H $\frac{H_a-H_{ae}}{H_a}$ | signif. H $\frac{H_{1/3}-H_{e/3}}{H_{1/3}}$ | % Deviation Using Actual Depth d ave. H $\frac{H_a-H_{as}}{H_a}$ | signif. H $\frac{H_{1/3}-H_{s/e}}{H_{1/3}}$ |
|---|---|---|---|---|---|---|
| 71 | 0.055 | 0.084 | +23.3% | -2.6% | -83.3% | -121 % |
| 58 | 0.114 | 0.137 | -12.7 | -14.4 | -81.0 | -52.2 |
| 52 | 0.100 | 0.144 | -38.2 | -27.4 | -47.1 | -41.2 |
| 111 | 0.055 | 0.084 | +14.8% | +2.5 | -104 % | -110 % |
| 92 | 0.114 | 0.137 | - 6.0 | -3.0 | - 55.2 | - 37.0 |
| 89 | 0.100 | 0.144 | -34.2 | -23.8 | - 42.0 | - 37.1 |
| 148 | 0.055 | 0.084 | +34.2% | +25.0% | -57.1% | -61.5% |
| 130 | 0.114 | 0.137 | + 2.7 | + 1.9 | -56.2 | -30.5 |
| 125 | 0.100 | 0.144 | +11.3 | + 7.1 | + 5.7 | - 2.9 |

## TABLE II. SUMMARY OF RESULTS

| Run No. | U ft./sec. | F ft. | h ft. | d ft. | b ft. | $U^2/Fg$ | $h/d \times 10^2$ | d/b | Bottom Condition |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 1 | 9.8 | 47.5 | 0.0010 | 0.352 | | 0.0628 | 0.284 | | Smooth |
| 2 | 15.2 | | 0.0020 | 0.350 | | 0.151 | 0.571 | | |
| 3 | 20.0 | | 0.0030 | 0.349 | | 0.262 | 0.860 | | |
| 4 | 24.8 | | 0.0042 | 0.349 | | 0.402 | 1.203 | | |
| 5 | 30.0 | | 0.0075 | 0.346 | | 0.589 | 2.17 | | |
| 6 | 35.0 | | 0.0163 | 0.344 | | 0.801 | 4.74 | | |
| 7 | 40.3 | | -- | 0.343 | | -- | -- | | |
| 8 | 9.9 | 46.7 | -- | 0.300 | | -- | -- | | Smooth |
| 9 | 15.1 | | -- | 0.300 | | -- | -- | | |
| 10 | 20.1 | | 0.0034 | 0.298 | | 0.267 | 1.14 | | |
| 11 | 26.1 | | 0.0062 | 0.298 | | 0.454 | 2.08 | | |
| 12 | 30.0 | | 0.0103 | 0.297 | | 0.600 | 3.47 | | |
| 13 | 34.8 | | 0.0182 | 0.297 | | 0.807 | 6.13 | | |
| 14 | 43.0 | | 0.0331 | 0.298 | | 1.233 | 11.11 | | |
| 15 | 9.6 | 46.0 | 0.0009 | 0.252 | | 0.062 | 0.357 | | Smooth |
| 16 | 15.0 | | 0.0027 | 0.252 | | 0.152 | 1.071 | | |
| 17 | 20.1 | | 0.0052 | 0.252 | | 0.273 | 2.06 | | |
| 18 | 24.7 | | 0.0078 | 0.253 | | 0.412 | 3.08 | | |
| 19 | 29.4 | | 0.0115 | 0.252 | | 0.584 | 4.56 | | |
| 20 | 34.9 | | 0.0215 | 0.249 | | 0.823 | 8.63 | | |
| 21 | 10.0 | 45.3 | 0.0010 | 0.204 | | 0.069 | 0.490 | | Smooth |
| 22 | 15.4 | | 0.0030 | 0.204 | | 0.162 | 1.47 | | |
| 23 | 20.0 | | 0.0047 | 0.204 | | 0.274 | 2.30 | | |
| 24 | 24.9 | | 0.0060 | 0.204 | | 0.425 | 2.94 | | |
| 25 | 30.1 | | 0.0131 | 0.204 | | 0.621 | 6.42 | | |
| 26 | 10.1 | 44.5 | 0.0012 | 0.152 | | 0.071 | 0.789 | | Smooth |
| 27 | 14.9 | | 0.0025 | 0.152 | | 0.155 | 1.645 | | |
| 28 | 20.1 | | 0.0070 | 0.152 | | 0.282 | 4.60 | | |
| 29 | 25.1 | | 0.0116 | 0.152 | | 0.440 | 7.63 | | |
| 30 | 30.0 | | 0.0170 | 0.152 | | 0.629 | 11.12 | | |
| 31 | 35.1 | | 0.0290 | 0.150 | | 0.861 | 19.3 | | |
| 32 | 10.0 | 43.7 | 0.0013 | 0.102 | | 0.071 | 1.28 | | Smooth |
| 33 | 16.1 | | 0.0048 | 0.103 | | 0.184 | 4.85 | | |
| 34 | 20.0 | | 0.0091 | 0.103 | | 0.284 | 8.84 | | |
| 35 | 25.0 | | 0.0168 | 0.101 | | 0.443 | 16.6 | | |
| 36 | 30.0 | | 0.0267 | 0.102 | | 0.638 | 26.2 | | |
| 37 | 34.9 | | 0.0405 | 0.102 | | 0.864 | 39.7 | | |

TABLE II (cont.)

| Run No. | U ft./sec. | F ft. | h ft. | d ft. | b ft. | $U^2/Fg$ | $h/d \times 10^2$ | d/b | Bottom Condition |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 38 | | | | | | | | | |
| 39 | | | | | | | | | |
| 40 | Data not analyzed | | | | | | | | |
| 41 | | | | | | | | | |
| 42 | | | | | | | | | |
| 43 | 10.0 | 43.0 | 0.0037 | 0.051 | | 0.073 | 7.25 | | Smooth |
| 44 | 14.9 | | 0.0070 | 0.051 | | 0.161 | 13.7 | | |
| 45 | 18.3 | | 0.0120 | 0.050 | | 0.243 | 24.0 | | |
| 46 | 23.1 | | 0.0185 | 0.049 | | 0.387 | 37.8 | | |
| 47 | 27.7 | | 0.0303 | 0.050 | | 0.556 | 60.6 | | |
| 48 | -- | | -- | -- | | -- | -- | | |
| | | | | | | | | | Rough Bottom |
| 49 | 15.6 | 47.5 | 0.0023 | 0.350 | 0.10 | 0.159 | 0.657 | 3.50 | $\Delta$=0.20 |
| 50 | 20.2 | | 0.0042 | 0.350 | | 0.267 | 1.20 | 3.50 | |
| 51 | 25.0 | | 0.0086 | 0.347 | | 0.409 | 2.48 | 3.47 | |
| 52 | 29.5 | | 0.0142 | 0.346 | | 0.569 | 4.10 | 3.46 | |
| 53 | 34.9 | | 0.0210 | 0.344 | | 0.797 | 6.10 | 3.44 | |
| 54 | 10.0 | | 0.0008 | 0.348 | | 0.065 | 0.230 | 3.48 | |
| 55 | 14.6 | 46.7 | 0.0022 | 0.301 | 0.10 | 0.142 | 0.731 | 3.01 | 0.20 |
| 56 | 19.8 | | 0.0056 | 0.301 | | 0.261 | 1.86 | 3.01 | |
| 57 | 25.1 | | 0.0100 | 0.299 | | 0.420 | 3.34 | 2.99 | |
| 58 | 30.2 | | 0.0173 | 0.299 | | 0.608 | 5.79 | 2.99 | |
| 59 | 34.9 | | 0.0281 | 0.299 | | 0.812 | 9.40 | 2.99 | |
| 60 | 10.2 | 46.0 | -- | -- | 0.10 | -- | -- | -- | 0.20 |
| 61 | 14.8 | | 0.0029 | 0.251 | | 0.148 | 1.155 | 2.51 | |
| 62 | 19.7 | | 0.0069 | 0.251 | | 0.262 | 2.75 | 2.51 | |
| 63 | 24.8 | | 0.0121 | 0.250 | | 0.416 | 4.84 | 2.50 | |
| 64 | 30.8 | | 0.0225 | 0.250 | | 0.641 | 9.00 | 2.50 | |
| 65 | 10.0 | 45.3 | 0.0017 | 0.203 | 0.10 | 0.069 | 0.837 | 2.03 | 0.20 |
| 66 | 14.8 | | 0.0041 | 0.203 | | 0.150 | 2.02 | 2.03 | |
| 67 | 19.9 | | 0.0101 | 0.203 | | 0.271 | 4.98 | 2.03 | |
| 68 | 24.8 | | 0.0189 | 0.200 | | 0.421 | 9.45 | 2.00 | |
| 69 | 29.8 | | 0.0303 | 0.200 | | 0.608 | 15.15 | 2.00 | |
| 70 | -- | | -- | -- | | -- | -- | -- | |
| 71 | 33.9 | 44.5 | 0.0422 | 0.152 | 0.10 | 0.803 | 27.7 | 1.52 | 0.20 |
| 72 | 25.2 | | 0.0268 | 0.154 | | 0.444 | 17.4 | 1.54 | |
| 73 | 10.0 | | 0.0032 | 0.154 | | 0.070 | 2.08 | 1.54 | |
| 74 | 14.9 | | 0.0058 | 0.151 | | 0.155 | 3.84 | 1.51 | |
| 75 | 20.0 | | 0.0169 | 0.152 | | 0.280 | 11.1 | 1.52 | |

TABLE II (cont.)

| Run No. | U ft./sec. | F ft. | h ft. | d ft. | b ft. | $U^2/Fg$ | $h/d \times 10^2$ | d/b | Bottom Condition |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 76 | 10.0 | 43.7 | 0.0032 | 0.100 | 0.10 | 0.071 | 3.20 | 1.00 | 0.20 |
| 77 | 15.7 | | 0.0073 | 0.099 | | 0.174 | 7.37 | 0.99 | |
| 78 | -- | | -- | -- | | -- | -- | -- | |
| 79 | 24.7 | | 0.0282 | 0.097 | | 0.432 | 29.1 | 0.97 | |
| 80 | 29.8 | | 0.0398 | 0.097 | | 0.630 | 40.9 | 0.97 | |
| 81 | 15.0 | 43.0 | too small | 0.050 | 0.10 | -- | -- | 0.50 | 0.20 |
| 82 | 20.1 | | " | 0.051 | | -- | -- | 0.51 | |
| 83 | 25.0 | | " | 0.052 | | -- | -- | 0.52 | |
| 84 | 30.0 | | 0.0052 | 0.052 | | 0.653 | 11.1 | 0.52 | |
| 85 | 9.5 | 47.4 | 0.0007 | 0.346 | 0.10 | 0.059 | 0.202 | 3.46 | $\Delta = 0.40$ |
| 86 | 15.5 | | 0.0020 | 0.346 | | 0.157 | 0.578 | 3.46 | |
| 87 | 20.0 | | 0.0045 | 0.346 | | 0.262 | 1.30 | 3.46 | |
| 88 | 25.3 | | 0.0105 | 0.345 | | 0.419 | 3.04 | 3.45 | |
| 89 | 28.1 | | 0.0173 | 0.343 | | 0.517 | 5.04 | 3.43 | |
| 90 | 35.0 | | 0.0256 | 0.339 | | 0.801 | 7.55 | 3.39 | |
| 91 | repeated in Run 93 | | | | | | | | |
| 92 | 29.9 | 46.7 | 0.0174 | 0.302 | 0.10 | 0.596 | 5.76 | 3.02 | 0.40 |
| 93 | 9.8 | | 0.0012 | 0.301 | | 0.064 | 0.399 | 3.01 | |
| 94 | 15.0 | | 0.0028 | 0.300 | | 0.150 | 0.933 | 3.00 | |
| 95 | 20.0 | | 0.0063 | 0.299 | | 0.267 | 2.11 | 2.99 | |
| 96 | 25.0 | | 0.0104 | 0.297 | | 0.417 | 3.50 | 2.97 | |
| 97 | 10.0 | 45.9 | 0.0012 | 0.249 | 0.10 | 0.0677 | 0.482 | 2.49 | 0.40 |
| 98 | 15.1 | | 0.0029 | 0.249 | | 0.154 | 1.165 | 2.49 | |
| 99 | 20.2 | | 0.0075 | 0.248 | | 0.273 | 3.02 | 2.48 | |
| 100 | 25.1 | | 0.0137 | 0.250 | | 0.426 | 5.48 | 2.50 | |
| 101 | 29.6 | | 0.0212 | 0.248 | | 0.593 | 8.55 | 2.48 | |
| 102 | -- | | -- | -- | | -- | -- | -- | |
| 103 | -- | | -- | -- | | -- | -- | -- | |
| 104 | 20.0 | 45.1 | 0.0076 | 0.197 | 0.10 | 0.276 | 3.86 | 1.97 | 0.40 |
| 105 | 24.9 | | 0.0170 | 0.196 | | 0.428 | 8.67 | 1.96 | |
| 106 | 29.8 | | 0.0261 | 0.195 | | 0.613 | 13.4 | 1.95 | |
| 107 | 9.9 | 44.5 | 0.0030 | 0.149 | 0.10 | 0.069 | 2.01 | 1.49 | 0.40 |
| 108 | 14.9 | | 0.0058 | 0.150 | | 0.155 | 3.87 | 1.50 | |
| 109 | 20.3 | | 0.0154 | 0.148 | | 0.289 | 10.4 | 1.48 | |
| 110 | 24.9 | | 0.0250 | 0.149 | | 0.433 | 16.8 | 1.49 | |
| 111 | 29.8 | | 0.0341 | 0.149 | | 0.615 | 22.9 | 1.49 | |

TABLE II (cont.)

| Run No. | U ft./sec. | F ft. | h ft. | d ft. | b ft. | $U^2/Fg$ | $h/d \times 10^2$ | d/b | Bottom Condition |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 112 | 10.3 | 43.7 | 0.0036 | 0.098 | 0.10 | 0.075 | 3.68 | 0.98 | 0.40 |
| 113 | 15.8 | | 0.0100 | 0.098 | | 0.177 | 10.2 | 0.98 | |
| 114 | 20.1 | | 0.0144 | 0.097 | | 0.286 | 14.8 | 0.97 | |
| 115 | 25.0 | | 0.0325 | 0.099 | | 0.443 | 32.8 | 0.99 | |
| 116 | 29.9 | | 0.0458 | 0.098 | | 0.634 | 46.7 | 0.98 | |
| 117 | 10.3 | 43.0 | too small | 0.050 | | -- | -- | 0.50 | 0.40 |
| 118 | 15.1 | | " | 0.050 | | -- | -- | 0.50 | |
| 119 | 20.1 | | " | 0.049 | | -- | -- | 0.49 | |
| 120 | 30.3 | | 0.0042 | 0.048 | | 0.666 | 8.75 | 0.48 | |
| 121 | -- | 47.4 | -- | -- | 0.10 | -- | -- | -- | $\Delta$=0.80 |
| 122 | 15.6 | | 0.0016 | 0.345 | | 0.159 | 0.464 | 3.45 | |
| 123 | 20.9 | | 0.0046 | 0.344 | | 0.286 | 1.34 | 3.44 | |
| 124 | 25.1 | | 0.0085 | 0.348 | | 0.412 | 2.44 | 3.48 | |
| 125 | 30.2 | | 0.0147 | 0.346 | | 0.596 | 4.25 | 3.46 | |
| 126 | 10.1 | 46.7 | 0.0007 | 0.298 | 0.10 | 0.068 | 0.245 | 2.98 | 0.80 |
| 127 | 15.3 | | 0.0021 | 0.298 | | 0.156 | 0.705 | 2.98 | |
| 128 | 20.4 | | 0.0051 | 0.298 | | 0.277 | 1.71 | 2.98 | |
| 129 | 25.3 | | 0.0103 | 0.298 | | 0.427 | 3.46 | 2.98 | |
| 130 | 29.8 | | 0.0157 | 0.298 | | 0.592 | 5.27 | 2.98 | |
| 131 | 35.3 | | 0.0282 | 0.298 | | 0.831 | 9.46 | 2.98 | |
| 132 | 11.1 | 46.0 | 0.0011 | 0.255 | 0.10 | 0.083 | 0.431 | 2.55 | 0.80 |
| 133 | 14.9 | | 0.0021 | 0.254 | | 0.150 | 0.827 | 2.54 | |
| 134 | 20.7 | | 0.0062 | 0.254 | | 0.289 | 2.44 | 2.54 | |
| 135 | 25.7 | | 0.0122 | 0.252 | | 0.446 | 4.84 | 2.52 | |
| 136 | 29.7 | | 0.0191 | 0.252 | | 0.596 | 7.58 | 2.52 | |
| 137 | 35.4 | | 0.0313 | 0.255 | | 0.847 | 12.27 | 2.55 | |
| 138 | -- | | -- | -- | | -- | -- | -- | |
| 139 | 15.2 | 45.2 | 0.0030 | 0.201 | 0.10 | 0.159 | 1.49 | 2.01 | 0.80 |
| 140 | 20.3 | | 0.0083 | 0.201 | | 0.283 | 4.13 | 2.01 | |
| 141 | 24.8 | | 0.0165 | 0.200 | | 0.422 | 8.25 | 2.00 | |
| 142 | 29.6 | | 0.0210 | 0.203 | | 0.602 | 10.34 | 2.03 | |
| 143 | 34.8 | | 0.0421 | 0.201 | | 0.832 | 20.9 | 2.01 | |
| 144 | 9.5 | 44.5 | 0.0011 | 0.150 | 0.10 | 0.0631 | 0.733 | 1.50 | 0.80 |
| 145 | 15.0 | | 0.0056 | 0.149 | | 0.157 | 3.76 | 1.49 | |
| 146 | 20.4 | | 0.0112 | 0.148 | | 0.291 | 7.57 | 1.48 | |
| 147 | 25.1 | | 0.0180 | 0.151 | | 0.440 | 11.9 | 1.51 | |
| 148 | 30.1 | | 0.0345 | 0.149 | | 0.633 | 23.1 | 1.49 | |
| 149 | 35.2 | | 0.0546 | 0.147 | | 0.866 | 37.1 | 1.47 | |

TABLE II (cont.)

| Run No. | U ft./sec. | F ft. | h ft. | d ft. | b ft. | $U^2/Fg$ | $h/d \times 10^2$ | d/b | Bottom Condition |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 150 | 10.6 | 43.7 | 0.0026 | 0.100 | 0.10 | 0.079 | 2.60 | 1.00 | 0.80 |
| 151 | 15.9 | | 0.0082 | 0.100 | | 0.179 | 8.20 | 1.00 | |
| 152 | 19.9 | | 0.0153 | 0.099 | | 0.281 | 15.45 | 0.99 | |
| 153 | 24.8 | | 0.0277 | 0.098 | | 0.436 | 28.3 | 0.98 | |
| 154 | 29.9 | | 0.0403 | 0.098 | | 0.634 | 41.1 | 0.98 | |
| 155 | 35.2 | | 0.0580 | 0.097 | | 0.878 | 59.8 | 0.97 | |
| 156 | 10.2 | 43.0 | 0.0004 | 0.049 | 0.10 | 0.0754 | 0.816 | 0.49 | 0.80 |
| 157 | 20.4 | | 0.0013 | 0.049 | | 0.302 | 2.65 | 0.49 | |
| 158 | 30.3 | | 0.0024 | 0.049 | | 0.666 | 4.90 | 0.49 | |

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