WIND SETUP PARAMETERS

A Thesis

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by

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SYNOPSIS

A laboratory investigation was undertaken of the factors determining the rise in water level encountered when wind blows towards the shore of a shallow body of water. The factors were evaluated for bodies of water of uniform dimensions and for bodies of water of irregular surface areas and bottom configurations. On the basis of the laboratory observations and a theoretical analysis of the phenomenon, methods of predicting the rise in water level for a specific wind velocity and body of water are proposed in Chapter V.

ACKNOWLEDGEMENTS

I would like to acknowledge the assistance received from the National Research Council in providing funds for the laboratory investigation and from Professor E. Kuiper under whose direction the funds were placed.

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LIST OF SYMBOLS AND DEFINITIONS

A	-	the angle between the wind direction and tidal axis.
B	-	a coefficient in Boussinesq's formula indicating the roughness of a boundary.
F	-	fetch in feet, the distance from the windward shore.
K	-	a coefficient in Boussinesq's formula indicating the characteristics of a fluid.
M	-	a coefficient dependent on flow velocity.
N	-	a plan shape factor dependent on the shape of the water surface area (U.S. Corps of Engineers).
R	-	hydraulic radius in feet.
S	-	wind setup value in feet.
S_1	-	wind setup due to skin friction between wind and water surface.
S_2	-	wind setup due to the form resistance of waves.
U	-	the wind velocity in feet per second .
U_o	-	Keulegan's "characteristic formula velocity".
V	-	the wind velocity in feet per second.
a	-	a coefficient dependent on the ratio of fetch to depth of a body of water.
d	-	still water depth in feet.
g	-	acceleration of gravity in feet/sec.^{2}
h	-	wind setup in feet (bottom at windward shore not exposed).
h'	-	wind setup in feet (bottom at windward shore exposed).

m	-	distance along "m" axis.
n	-	distance along "n" axis.
p	-	pressure in pounds per square foot.
Z_s	-	distance from the bottom to the mean water level.
γ	-	unit weight of water.
ϵ	-	a coefficient depending on the eddy viscosity.
λ	-	a coefficient depending on the turbulence of flow.
μ	-	a coefficient of viscosity.
ρ	-	density of a fluid in pounds/cubic foot.
τ_b	-	shear stress on the bottom.
τ_s	-	shear stress on the water surface.

CHAPTER I

INTRODUCTION

A significant factor in the safe design of dams and dykes is the selection of freeboard (i.e) the vertical distance between the maximum still water level and the top of the structure. With many of these structures overtopping would mean failure, and failure, major disaster. It is desirable to select the freeboard with as much accuracy as possible, firstly for safety and secondly for economy. One of the components of freeboard that must be evaluated is the rise in water level encountered when a wind blows towards a structure or shore. This phenomenon is defined as wind setup at the leeward shore. In actual cases the setup may vary from a few inches in short deep lakes to several feet in long shallow lakes. Values of over six feet have been observed on Lake Erie, a typical example of the latter case.

Investigations into predicting wind setup have been undertaken from both the theoretical and empirical approach. Investigators have included Hellstrom (1941), U.S. Corps of Engineers (1945), Langhaar (1951), Keulegan (1951), and Sibul (1954). In nearly all investigations the theoretical analysis deals with an idealized body of water seldom encountered in nature. This presents the problem of modifying the theoretical predictions to apply to natural bodies of water. The fundamental difficulties are determining allowances for non-uniform depths of water, irregular plan shapes of some natural bodies of water, and increased obstruction on the bottom of shallow lakes. Surges that occur after the wind has begun to blow are also of significance in predicting the maximum water level.

The purpose of this thesis is to investigate briefly as many determining factors of wind setup as possible. To accomplish this a theoretical analysis of the wind setup phenomena has been made followed by a summary of the present methods of relating the theoretical predictions to natural bodies of water. From this point a laboratory investigation was undertaken that encompassed idealized conditions as well as some of the irregularities encountered under natural conditions.

CHAPTER II

THEORETICAL WIND SETUP ANALYSIS

When wind blows over a water surface a tangential stress develops between the wind and water. The stress generates waves and causes a surface current in the general direction of the wind. In addition, a pressure head is built up at the leeward end of the body which generates and sustains a return current in the opposite direction of the surface current (see Figure I). The pressure head is formed by the water surface assuming a slight slope upwards towards the leeward shore. The amount the water surface changes is defined as the wind "setup". The phenomenon is synonomous with wind "piling" at the leeward shore.

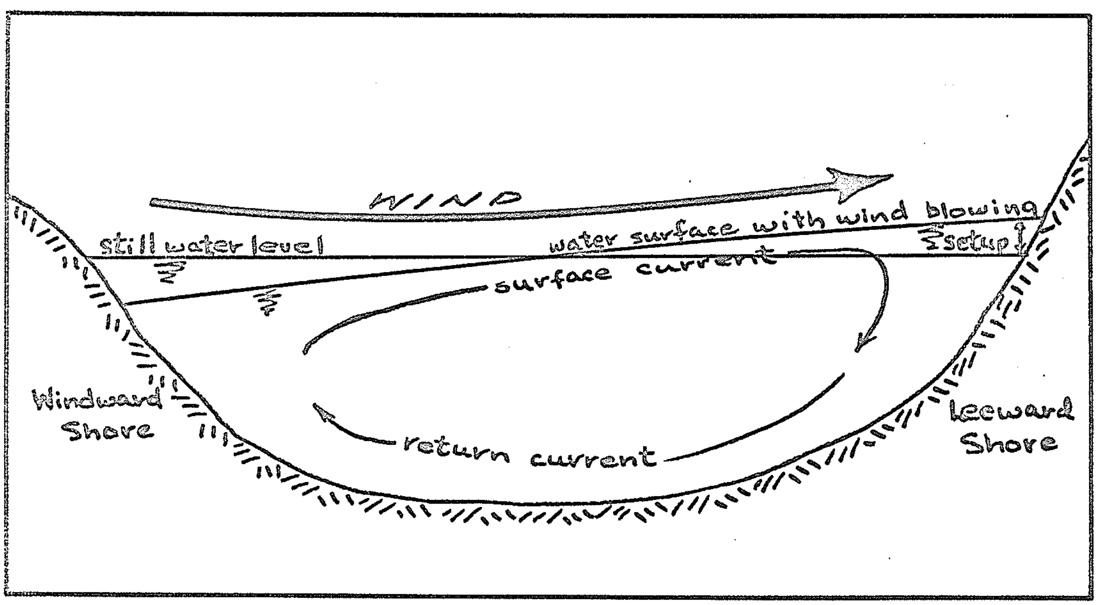


FIGURE I. WIND SETUP PHENOMENON

Wind Setup Formula

The development of a wind setup formula involves a number of factors. Some of the more significant include wind velocity, the transfer of energy from wind to water, length or fetch of water on which the wind acts, depth of water, plan shape of the body of water, bottom shape and roughness, wave height and period, currents, variations in atmospheric pressure, and the rotation of the earth.

One of the most comprehensive theoretical treatments of the phenomenon was proposed by Hellstrom in 1941[1]. He applied the basic Euler-Navier equation for the three dimensional motion of a viscous incompressible fluid, (i.e)

$$\begin{aligned}
\rho\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}\right) &= \rho X-\frac{\partial p}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right)\\
\rho\left(\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}\right) &= \rho Y-\frac{\partial p}{\partial y}+\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right) \qquad (1)\\
\rho\left(\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}\right) &= \rho Z-\frac{\partial p}{\partial z}+\mu\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right)
\end{aligned}$$

To simplify equation (1) Hellstrom made the following assumptions:

(a) the flow is laminar,

(b) the depth is constant and small,

(c) the water surface slope is small,

(d) the pressure distribution is hydrostatic,

(e) the wind velocity and direction is constant,

(f) all motion is steady and equilibrium is established.

He then solved the equation to obtain the differential equation for the free water surface as:

$$\frac{\partial z_s}{\partial x} = \lambda \frac{\tau_s}{\gamma z_s} \tag{2}$$

Equation (2) is the basic equation presented by most investigators regardless of the method of derivation. A derivation that is more readily visualized based on the same assumptions as Hellstrom has made in his analysis is as follows:

If equilibrium conditions prevail, a small portion of unit width and length "dx" of the lake shown below may be isolated.

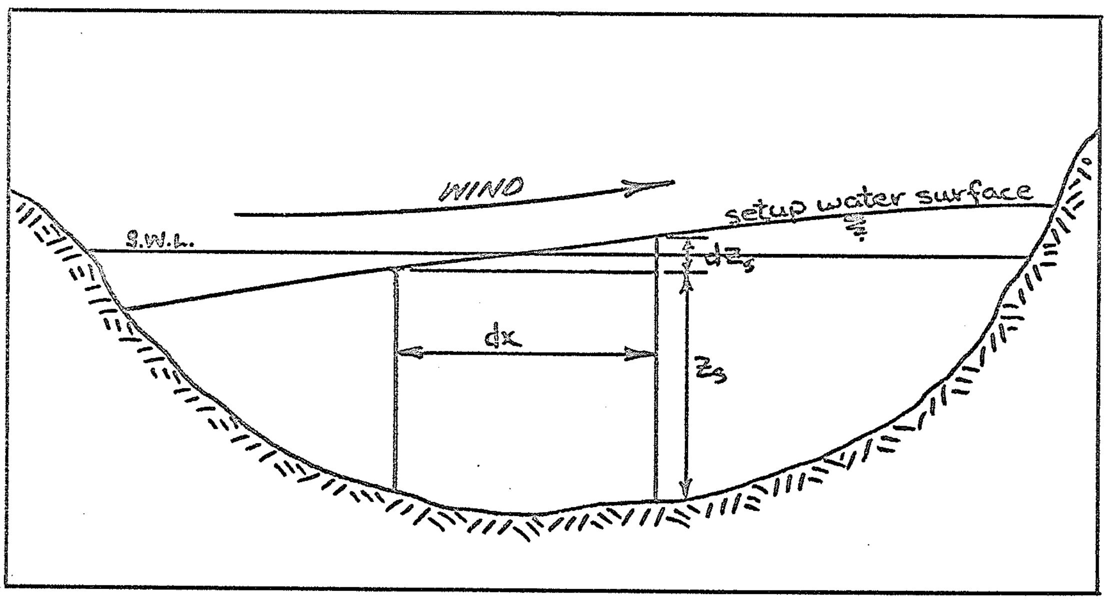


FIGURE II WIND SETUP ANALYSIS

The forces acting on this portion are shown in Figure III:

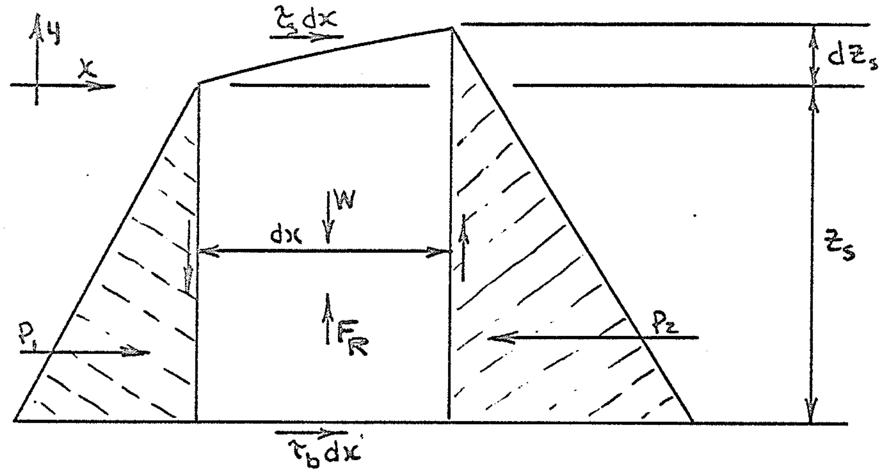


FIGURE III WIND SETUP FORMULA

For equilibrium: $\Sigma F_x = 0$

Writing $\Sigma F_x = 0$

$$P_1 + \tau_s dx + \tau_b dx - P_2 = 0$$

$$\text{OR } (\tau_s + \tau_b) dx = \tfrac{1}{2}\gamma (z_s + dz_s)^2 - \tfrac{1}{2}\gamma (z_s)^2$$

$$= \tfrac{1}{2}\gamma (2 z_s dz_s + dz_s^2)$$

IF dz_s is very small, $dz_s^2 \doteq 0$

$$\therefore (\tau_s + \tau_b) dx = \gamma z_s dz_s \text{, OR}$$

$$\frac{dz_s}{dx} = \frac{\tau_s + \tau_b}{\gamma z_s} \tag{3}$$

The bottom stress, τ_b, is a function of the wind stress expressed by the following relationship:

$$\frac{\tau_b}{\tau_s} + 1 = \lambda \tag{4}$$

Equation (3) can now be written as:

$$\frac{dz_s}{dx} = \lambda \frac{\tau_s}{\gamma z_s} \tag{5}$$

Equation (5) for the free water surface is now in the same form as derived by Hellstrom (Equation (2)).

Turbulent Flow

Equations (2) and (5) were derived on the assumption that all flow is laminar. This is seldom the case under natural conditions. Investigations by Boussinesq[2,3,4] into turbulent flow indicate that the factor λ in equations (2) and (5) varies with the degree of turbulence of flow. When the flow is laminar, λ has a value of 1.5 and when completely turbulent 1.0, (i.e.) $1.0 \leq \lambda \leq 1.5$ Hellstrom gives

$$\lambda = \frac{3}{2} \frac{(K\sqrt{B} + 2)}{(K\sqrt{B} + 3)} \tag{6}$$

where $K = 45 \; m^{1/2}/sec.$

and $$B = \frac{g}{(3MR^{1/6} - K)^2} \tag{7}$$

where $M \doteq 25$ for lakes and reservoirs of low velocity and R = the hydraulic radius.

Summarizing the above, it is evident that the factor in equations (2) and (5) must be evaluated by equations (6) and (7) derived empirically by Boussinesq and Hellstrom to conform the water surface equation with the existing turbulence of flow.

Wind Shear Stress

The wind shear stress factor in equations (2) and (5) was investigated by Sibul in 1954[8]. On the basis of a theoretical analysis and laboratory observations he proposed the wind shear stress relationship to be:

$$\tau_s = 5.65 \times 10^{-6} \, U^{2.15} \tag{8}$$

where 'U' is the average wind velocity. Equation (8) will be used to evaluate the results of this investigation.

CHAPTER III

APPLYING THE THEORETICAL WIND SETUP ANALYSIS

Equation (5), the differential equation for a free water surface affected by a constant wind force, must be integrated to obtain numerical wind setup values. There have been several approaches to this problem, three of which will be considered for a theoretical body of water of unit width and uniform depth.

<u>The Ideal Case</u>

1. Hellstrom integrates equation (5) to obtain:

$$z_s^2 = \frac{2\lambda \tau_s}{\gamma}(x + c_1) \tag{9}$$

Equation (9) indicates the water surface is parabolic in form and may be written in coordinates of <u>m</u> and <u>n</u> as:

$$n^2 = \frac{2\lambda \tau_s}{\gamma}(m) \tag{10}$$

Equation (10) is plotted in Figure IV illustrating Hellstrom's "Characteristic Water Surface Parabola".[1] To locate a particular portion of the water surface parabola that represents a specific case, two characteristics of the case are utilized, the fetch and "still" water depth. As shown in Figure IV the area between the curve and x-axis must equal the product of the fetch and still water depth since the volume of water does not increase or decrease due to the wind force. The distance between the <u>m</u>-axis and the Z_s - axis is represented by C_1.

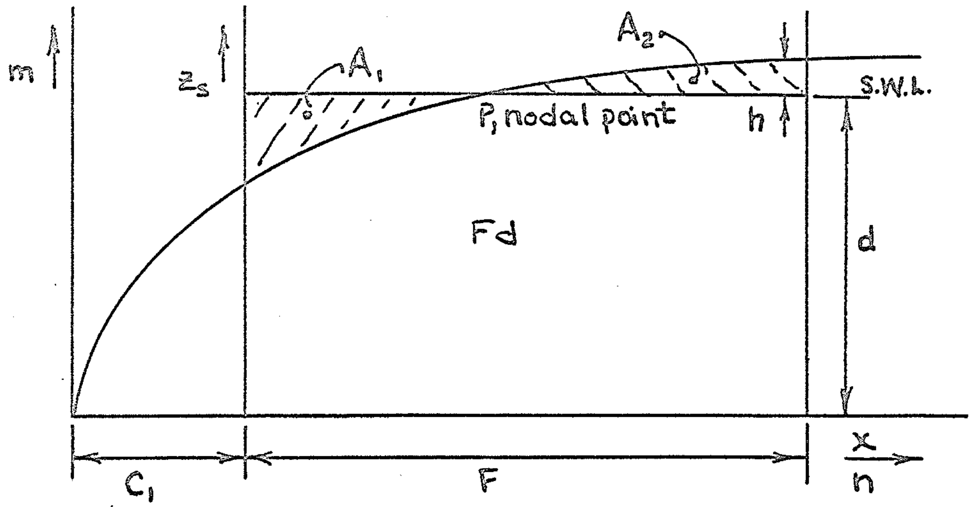


FIGURE IV CHARACTERISTIC WATER SURFACE PARABOLA-HELLSTROM

Figure IV represents a particular case where the bottom of a body of water is not exposed, giving C_1 a positive value. Figure V shown below represents the case where C_1 equals zero, (i.e) the water surface at the beginning of the lake has the same elevation as the bottom. The third case that may be encountered is illustrated in Figure VI where the bottom of the lake is exposed giving C_1 a negative value. The setup "h" can be isolated by forming equation (11)

$$h = \sqrt{\frac{2\lambda \tau_s}{\delta} (x + c_1)} - d \qquad (11)$$

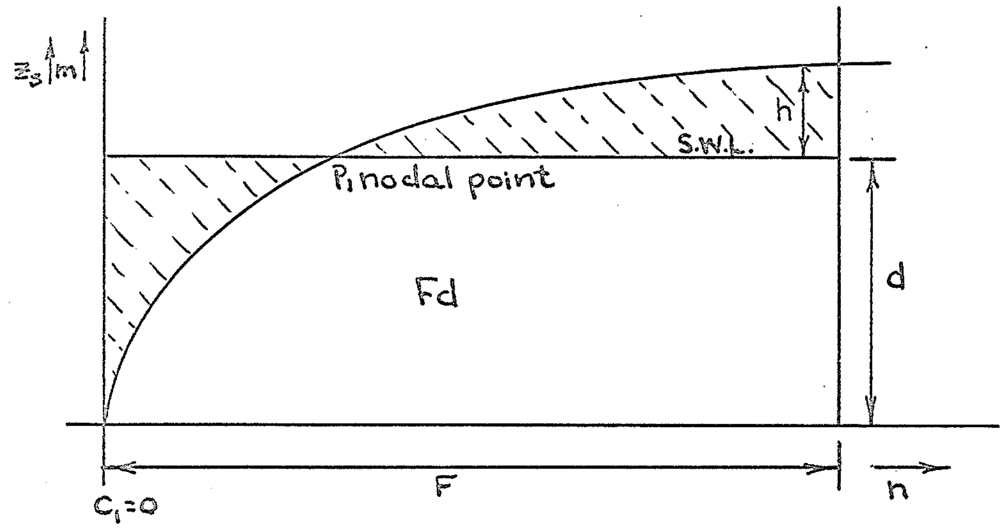


FIGURE V CHARACTERISTIC WATER SURFACE PARABOLA-HELLSTROM

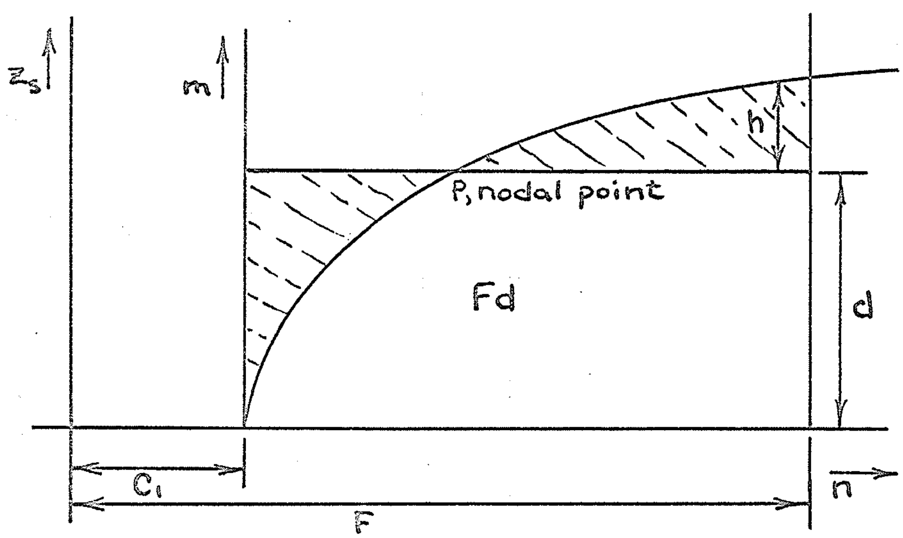


FIGURE VI CHARACTERISTIC WATER SURFACE PARABOLA-HELLSTROM

The nodal point "p" may be obtained from equation (11) by setting $h = 0$.

When the depth is large compared to the setup, Hellstrom proposes that the nodal point occurs at F/2. The setup equation for the windward shore then becomes:

$$h_{x=o} = \frac{\lambda \tau_s}{\gamma d} (x - F/2) \qquad (12)$$

At the leeward shore where x = F

$$h_{x=F} = \frac{\lambda \tau_s}{2\gamma d} F \qquad (13)$$

Equation (13) coincides with the setup formula proposed by Langhaar[5].

$$h_{x=F} = \frac{\tau_s F}{2\gamma d} \qquad (14)$$

where he has assumed the factor λ equals one if the setup is small and the depth relatively great.

2. Keulegan conducted a laboratory investigation of the wind setup phenomenon in 1951[6]. He also derived the basic differential equation for the water surface in the form of equations (2) and (5). Keulegan proposed the factor λ in the equation has a value of 1.5 for laminar flow and 1.25 for turbulent flow. In his investigation he separated the total setup "S" into two parts:

1. S_1, the setup due to skin friction between the wind and water surface and,
2. S_2, the setup due to the form resistance of the waves.

Keulegan's setup "S" is defined as the difference between the water surface elevations at the windward and leeward shores.

He proposed the setup without wave action as:

$$S_1 = C_2 \frac{U^2 F}{gd} \tag{15}$$

and the setup due to waves as:

$$S_2 = C_3 \frac{(U-U_o)^2}{gd} \left(\frac{d}{F}\right)^{1/2} \tag{16}$$

The constants C_2 and C_3 were given as $C_2 = 3.3 \times 10^{-6}$ and $C_3 = 2.08 \times 10^{-4}$. The total setup is then the sum of S_1 and S_2 or:

$$S = F\left[3.3\times10^{-6}\frac{U^2}{gd} + 2.08\times10^{-4}\frac{(U-U_o)^2}{gd}\left(\frac{d}{F}\right)^{1/2}\right] \tag{17}$$

The factor "U_o" is referred to by Keulegan as the "formula characteristic velocity" of the wind. It is approximately 1.3 times the lowest wind velocity needed to start waves. The value of "U_o" was established by his experiments as varying with depth. This is illustrated in Figure VII.

For larger bodies of water under actual conditions Keulegan proposed the factor U_o be ignored. The formula for larger bodies of water then becomes

$$S = 3.3\times10^{-6}\left[1 + 63\left(\frac{d}{F}\right)^{1/2}\right]\frac{U^2F}{gd} \tag{18}$$

3. The Zuider Zee[7] and Beach Erosion Board[9] formulae for wind setup are similar. They may be derived from the basic equation for

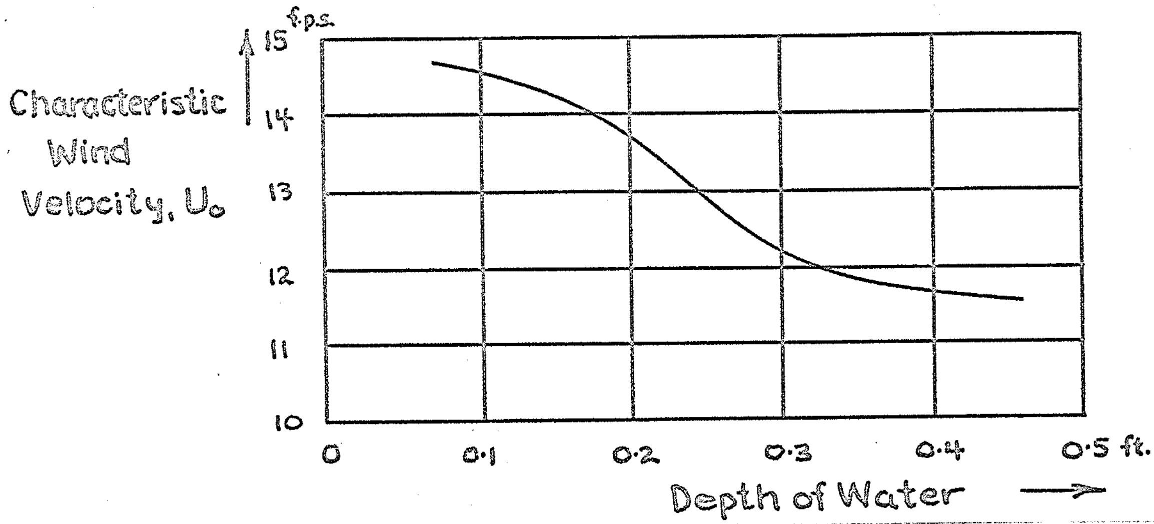


FIGURE VII CHARACTERISTIC WIND VELOCITIES-KEULEGAN

the water surface profile by applying several empirical constants. The Zuider Zee formula is

$$h = \frac{V^2 F}{C\,d} \cos A \qquad (19)$$

where h is the setup in feet above the still water elevation at the leeward shore, U is in miles per hour, and F is in miles. In deriving equation (19) the following assumptions were made:

(a) the bottom stress is only a small fraction of the wind stress and may be ignored and,

(b) the wind stress is proportional to the square of the velocity of the wind.

The value of "C" has been observed to be 1400 in field investigations.

The Beach Erosion Board[13] proposes a similar equation with slightly different constants and factors:

$$S = \frac{K \lambda \rho_a U^2 F}{\rho g d} \cos A \tag{20}$$

where ρ_a is the air density and k is a numerical constant approximately equal to .003.

Modifications of the Ideal Case

The previous wind setup formulae were based on theoretical bodies of water of uniform dimensions and characteristics. Theoretical setup predictions must be modified when applied to the irregular conditions encountered in most natural bodies of water. Information presently available on this aspect may be briefly summarized as follows:

1. Irregular Dimensions

Allowances for irregular plan shapes and irregular depths have been proposed by several investigators, notably the Beach Erosion Board of the U.S. Corps of Engineers[9]. The suggested method for predicting wind setup values where non-uniform dimensions are encountered could best be described as mechanical integration. In essence, it is recommended that the body of water be broken up into sections of uniform width and depth, the setup values computed for each section using the general setup formula, and the water surface elevations adjusted to form a continuous water surface. Some adjustments in elevations may then be required to ensure the volume of water raised above the still water depth is equal to the volume of water depressed below the still water depth.

Other investigators have proposed factors by which the setup values from theoretical formulae may be multiplied to allow for irregular dimensions. Usually these factors apply to a specific body of water under observation for a period of years. From the observations, actual setup values are compared with the theoretical predictions and a factor is evaluated. The success of this method hinges on the period of observation and the specific case considered. Where new bodies of water are to be impounded, setup predictions must be based on a theoretical analysis only.

2. Bottom Roughness and Irregularities

A laboratory study by Sibul in 1954[10] has indicated the effects of bottom roughness and weeds on wind setup in shallow water. His experiments were conducted in a small wind tunnel with smooth and rough bottom conditions. Strips of cloth placed in the channel were used to simulate vegetation. Sibul summarized his findings as follows:

> "The results indicate a rapidly increasing setup when the still water depth decreases below a certain limit. There were no indications that the bottom roughness affects the setup for relatively deep water. In very shallow water, however, the rougher bottom conditions result in higher setups. The trend is especially pronounced for higher wind velocities. For the shallowest still water depth (0.05 ft) used in the experiments, the setup was approximately 10 percent higher for the rough bottom and approximately 20 percent higher when strips of cheese cloth were used in the

> channel to simulate the roughness effect of vegetation, than the setup observed with a smooth bottom".[10]

The preceding sections have briefly outlined the theoretical and empirical information available on the analysis of the wind setup phenomenon. No attempt has been made to present a complete and detailed review of the findings and recommendations of previous investigators. It is hoped that the present state of the wind tide phenomenon knowledge has been indicated. For detailed accounts of a specific investigation the reader is referred to the bibliography.

CHAPTER IV

LABORATORY INVESTIGATION

A series of laboratory experiments were performed to investigate the wind setup phenomenon with actual observations. The tests, thirty-five in all, were primarily concerned with measuring the water surface profiles of a small body of water under various setup conditions. They may be roughly divided into two categories; investigation of the general or theoretical case and investigation of the natural or irregular case. The testing apparatus was constructed and the tests run over a period of seven months in 1963. Information obtained from the tests is tabulated in Appendices A and B. The laboratory apparatus and testing procedure is briefly outlined in this chapter and considered in detail in Appendix C.

Laboratory Apparatus:

Essentially the apparatus consisted of a wind tunnel, 46 feet long, 3 feet wide, and 2 feet deep. The tunnel, actually a converted hydraulic flume, was dammed off at either end allowing a depth of water of 0.5 feet to be impounded. Air was drawn through the tunnel over the water surface with a variable centrifugal fan. Manometers, reading to the thousandth of a foot, were spaced along the glass-walled tunnel to record the water surface elevations at various fetches. An adjustable passage between the manometers and tunnel was used to dampen out the wave motion of the water. A carriage mounted on rails running the length of the tunnel carried a wave recording probe, a pitot tube, a static tube, and a point gauge. Access into the tunnel was possible through small ports in the top of the tunnel during tests. The top was removable for adjustments between tests. The following measurements were made with the above equipment:

1. water surface elevations : manometers and point gauge
2. wind velocities and distribution : pitot tube
3. static pressure : static tube and manometers
4. wave heights and periods : wave recording probe and oscilliscope.

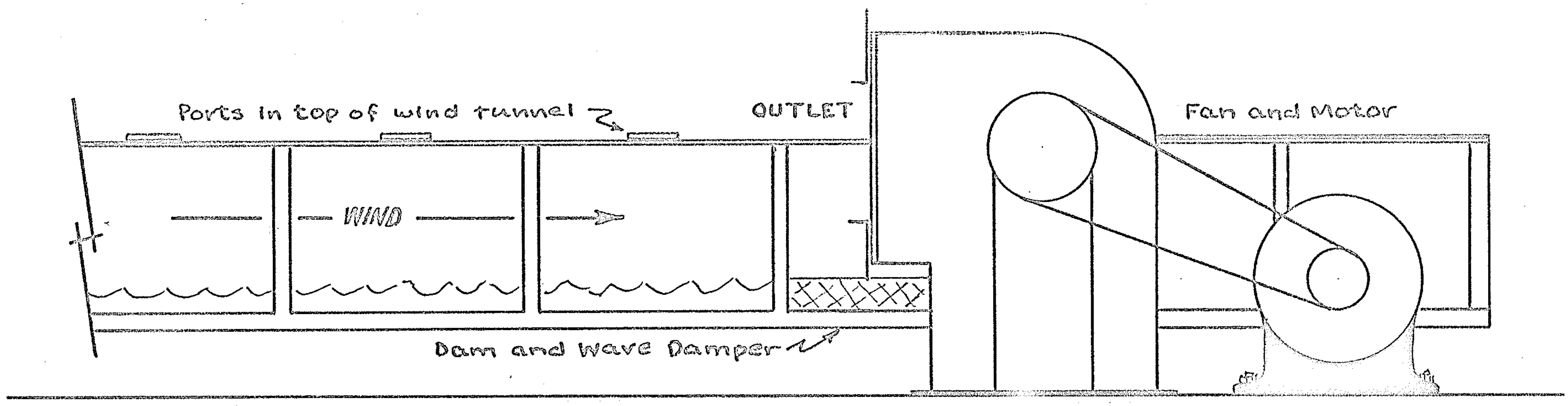
Bottom and plan shapes were moulded with fine sand and low retaining walls. In addition to the above equipment an electric timing clock was used to record the times of measurements and the durations of the tests.

The apparatus allowed five parameters to be varied; wind velocity, depth of water, fetch, plan shape, and bottom shape. The plan and bottom shapes were limited by the tunnel dimensions and the setup measuring devices. Illustrations of the equipment and brief descriptions are included at the end of this chapter (see Figure VIII and Illustrations I to V).

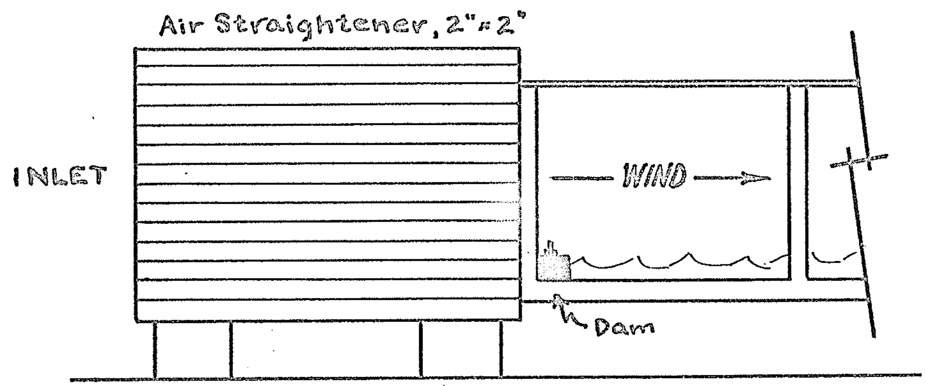
Testing Procedure

Tests were run for the various conditions in the following manner: The particular condition to be investigated was constructed in the tunnel. The tunnel was then sealed, the water was allowed to settle, and the mean water levels were recorded. The wind was introduced and the initial setup was recorded in magnitude and time of occurrence. Velocity and static pressure traverses were taken at stations along the tunnel. After conditions in the tunnel had reached a steady state, the water surface elevations and wave characteristics were recorded. This was usually an hour or so after the test had begun. The tests were repeated several times and the values averaged to give the results as tabulated in Appendices A and B. Illustrations VI and VII at the end of this chapter show the water surface during a test and a moulded plan shape prior to a test.

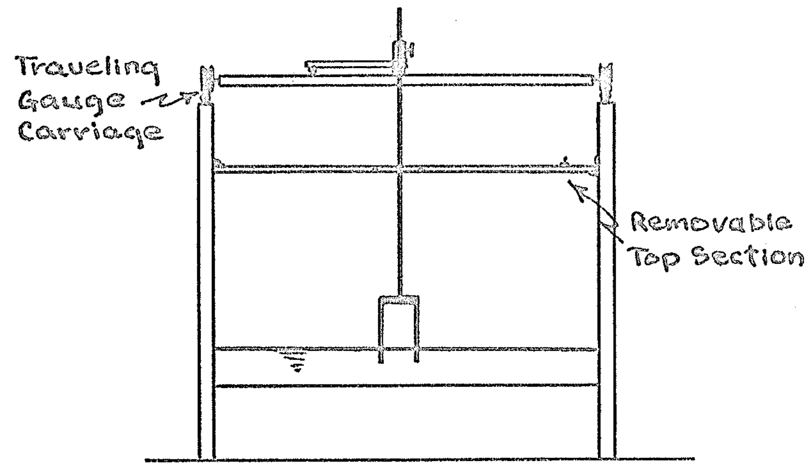
LABORATORY APPARATUS: WIND SETUP INVESTIGATION



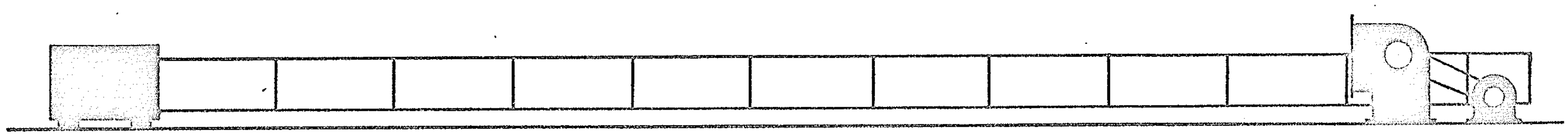
OUTLET END OF WIND TUNNEL



INLET END OF WIND TUNNEL



CROSS-SECTION OF WIND TUNNEL



ELEVATION OF WIND TUNNEL TO SCALE: 46 FT. LONG, 3 FT. WIDE, 2 FT. DEEP

FIG. VIII

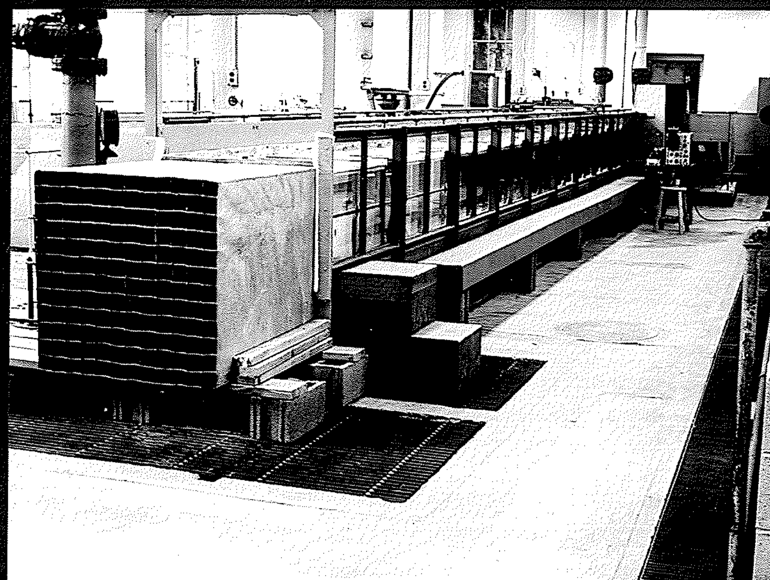


ILLUSTRATION I: General view of the laboratory testing tunnel. Note the "egg-crate" air straightener at the inlet, the glass walls and plywood top of the tunnel, and the centrifugal fan at the outlet. The air enters the tunnel through the straightener on the left side of the photograph, proceeds down the tunnel over the water surface, and is drawn out of the side of the tunnel by the fan. The air velocity is adjusted by varying the area of the fan outlet.

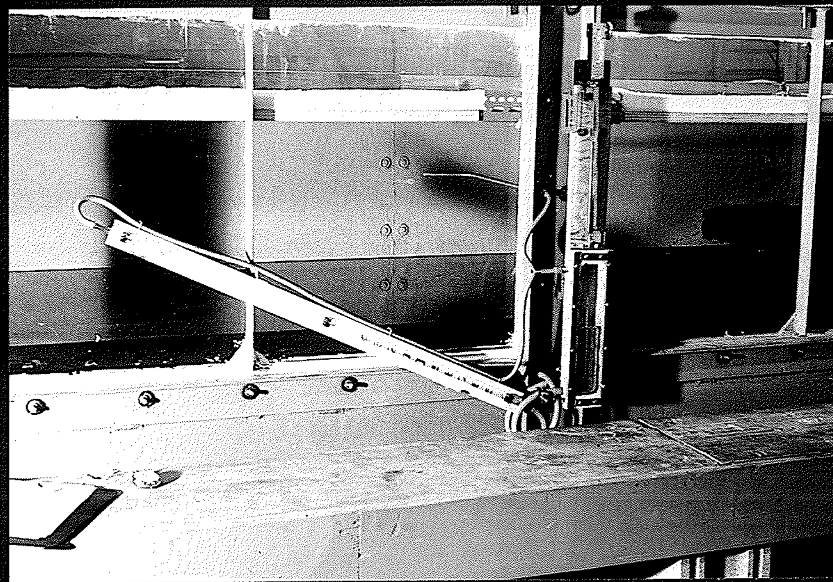


ILLUSTRATION II: Manometers used in measuring the water surface elevations. The vertical manometer is used to obtain accurate long-term setup values when wave motion is established. The sloping manometer is used for measuring the initial setup where time measurements require no lag or delay between the water elevation in the tunnel and in the manometer tube. Note the static tube in the tunnel connected to the manometer case to equalize the pressure in the tunnel and in the manometer. As indicated by the calm water surface, there is no test in progress at the time the photograph was taken.

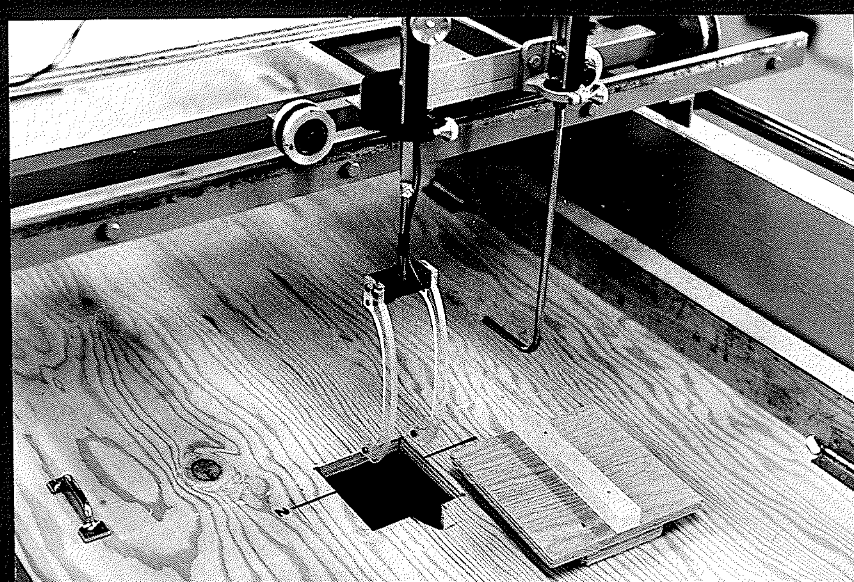


ILLUSTRATION III: Wave recording probe and pitot tube. Note the fine wires stretched between the plexiglass arms of the probe. Movement of the water surface up and down the wires records the wave heights and periods. Both instruments are mounted on staff gauges that enables them to be set at different depths in the tunnel.

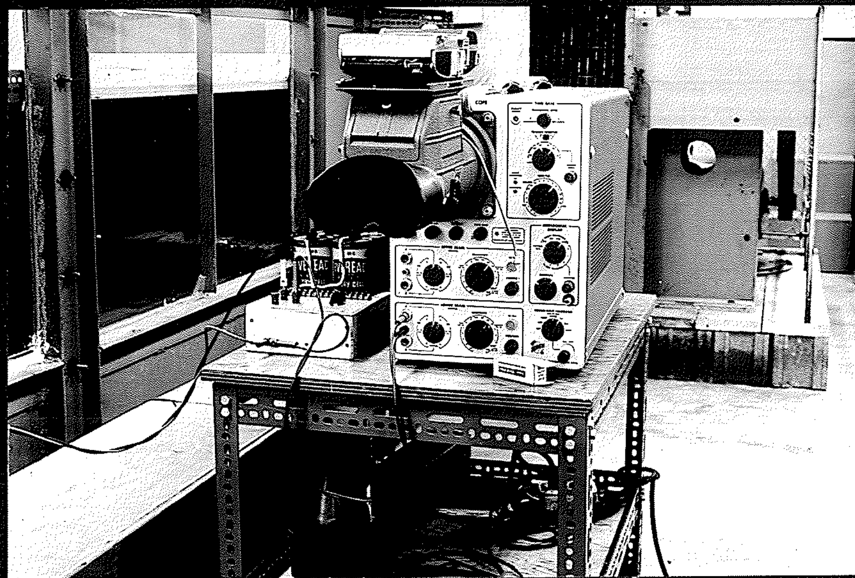


ILLUSTRATION IV: Wave recorder. Wave forms are recorded on the oscilliscope screen (not shown). In the photograph a Land camera is mounted over the screen to record the wave heights and periods on film.

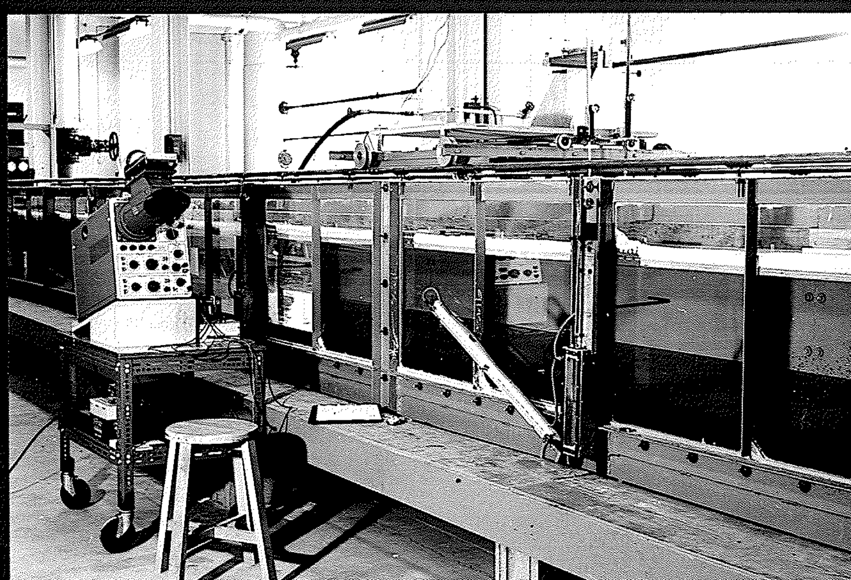


ILLUSTRATION V: Measuring instruments in position. At the location shown, the wind velocity, static pressure, water surface elevation, and wave data will be taken. The pitot tube, wave recorder probe, and point gauge are mounted on a moveable carriage that enables them to be used at any location in the tunnel.

ILLUSTRATION VI: The water surface during a test. The waves shown were generated by a wind velocity of 30 feet per second. The depth of water is 0.4 feet.

ILLUSTRATION VII: A modified plan form. This photograph shows the "stepped" plan form used in test 28, stage II. The plan form is molded in sand that is retained by small cantilevered plywood walls. The photograph is taken from the leeward end of the water surface.

CHAPTER V

RESULTS AND CONCLUSIONS

Wind setup laboratory tests were selected with the following three objectives in mind:

1. The tests and test results should be within the range of accuracy of the available measuring devices and laboratory apparatus. To accomplish this, high wind velocities and shallow water depths were utilized.

2. There should be a number of tests for which the setup condition may be theoretically predicted. As has been indicated in previous chapters, uniform or idealized conditions of wind setup may be obtained from several theoretical formulae. The first 19 tests were run with uniform conditions and compared with their calculated counterparts. As a result of this comparison, more confidence was placed in the suitability of the testing apparatus, the limits of accuracy of the apparatus were indicated, and the value of results obtained for presently non-predictable setup conditions was reassured.

3. There should be sufficient tests of non-uniform setup conditions to indicate the possibility of converting or extending the present methods of setup prediction to deal with non-uniform conditions. The last 20 tests were selected to approach this objective.

The discussion of test results has been divided into two parts, Part A dealing with setup tests under uniform conditions and Part B dealing with setup tests under non-uniform conditions. Part A has been further subdivided into three topics dealing with the general characteristics of wind setup, the derivation of an empirical setup relationship, and the comparison of the observed setup values with those calculated by the available setup formulae. Part B has been subdivided into three sections dealing with the variation of setup with time, the effect of irregular depths of water, and the effect of irregular plan shapes of bodies of water.

PART A : WIND SETUP UNDER UNIFORM CONDITIONS

1. The General Characteristics of Wind Setup.

The characteristics of wind setup under uniform conditions may be evaluated by considering the theoretical setup formulae proposed in Chapters II and III. In accordance with these relationships, wind setup varies proportionally with fetch, the inverse of depth, and the square or near square of the wind velocity. The first 19 tests were run to evaluate these characteristics. In addition, several complete water surface profiles were measured to illustrate the balance between the volume of water raised above the still water level and the volume of water depressed below the still water level.

A plot of wind velocity versus setup at the leeward shore is illustrated in Graph I, page 42. A series of wind velocities acting on a particular depth and fetch of water produce wind setup values that lie on a parabolic curve. As indicated by Sibul's wind shear stress formula (8) given in Chapter II, the setup varies with the wind velocity to a power slightly greater than two.

A plot of depth versus setup at the leeward shore is illustrated in Graph II. Three straight lines have been drawn through the setup values, each representing a specific wind velocity. The values indicate the setup varying linearly with the inverse of depth in agreement with the theoretical prediction.

A plot of fetch versus setup at the leeward shore is illustrated in Graph III. In this case fetch refers to the total fetch of the body of water. Only three tests were run due to the construction required to shorten the fetch in the wind tunnel but the results fell on a straight line. This indicates the linear variation of setup with fetch as derived theoretically.

Graph IV illustrates the water surface profile and volume balance for two typical tests of the first nineteen. The profiles start steeply from the windward shore and gradually flatten as they approach the leeward shore. This is in agreement with the profiles recorded by Sibul[10] and Keulegan[6] and Hellstrom's "Characteristic Water Surface Profile" presented in Chapter III. The profiles also illustrate the balance between the volume of water raised and the volume of water depressed from the still water level. This is indicated as equal areas between the water surface profiles and the still water level in the graph since the width of the body of water is uniform.

2. An Empirical Wind Setup Relationship.

The derivation of an empirical wind setup formula for uniform conditions involves the curve fitting of the results of the first 19 tests. It was found after several trials that the plotting of two dimensionless terms, setup over depth and wind velocity squared over fetch times the acceleration of gravity, against one another, produced a readily applied setup formula,

$$\left(\frac{S}{d}\right) = f\left(\frac{V^2}{Fg}\right) \tag{21}$$

When the results were plotted on logarithmic ordinate and abscissa graphs they formed a series of straight lines for similar values of fetch over depth, F/d. The lines for specific values of F/d were parallel indicating the relationship to be of the power form

$$\frac{S}{d} = a\left(\frac{V^2}{Fg}\right)^b \tag{22}$$

In equation (22) the slope "b" is similar for all lines and "a" is some function of F/d. The plotted values and lines are illustrated in Graph V, page 46, When the curves were evaluated the following values of "a" and "b" were obtained (see Table I).

TABLE I

CURVE FITTING FOR EMPIRICAL SETUP RELATIONSHIP

F/d	a	b
350	0.1750	1.22
175	0.0687	1.22
116.7	0.0348	1.22

The results indicate equation (22) may be written as

$$\frac{S}{d} = a\left(\frac{V^2}{Fg}\right)^{1.22} \tag{23}$$

Since both the "a" and F/d values define a particular line in Graph V, "a" was plotted versus F/d on logarithmic graph paper (Graph VI). The values lay on a straight line indicating the relationship to be of the form

$$a = m\left(\frac{F}{d}\right)^{n} \tag{24}$$

When the curve in Graph VI was evaluated "m" was found to be 2.8×10^{-5} and "n" was found to be 1.5. Equation (24) can now be written as

$$a = 2.8 \times 10^{-5}\left(\frac{F}{d}\right)^{1.5} \tag{25}$$

With equations (23) and (25) or Graphs V and VI a theoretical value for setup at the leeward shore may be obtained by the following procedure.

1. Evaluate F/d from the dimensions of the particular body of water.
2. Obtain the value of "a" from equation (25).
3. Obtain the value of S/d from equation (23).
4. Knowing "d", the value of "s", the leeward shore setup, may be obtained.

To follow the above procedure only the dimensions of the body of water and the wind velocity to be considered must be known. However, projection of the empirical relationship based on the wind tunnel observations to natural bodies of water should be made with caution. The ratio of setup to total depth of 0.2 to 0.4 in the laboratory tests is out of proportion to that anticipated under natural conditions. The water surface profile under the exaggerated laboratory conditions assumes a definite parabolic shape which does not conform to the assumptions made for natural bodies of water of a shallow slope and relatively flat water surface. This would cause a significant underestimate of the setup value by the empirical relationship as demonstrated in the following section. However, for small scale laboratory tests and conditions of a relatively high setup to depth ratio, the empirical predictions will be of value.

3. Comparison of Observed Results with Present Theoretical Predictions.

The wind setup values observed in the first 16 tests were compared with values calculated by the methods outlined in Chapters II and III. The formulae used in calculating the theoretical values may be summarized as follows:

1. Hellstrom and Langhaar

$$h = \sqrt{\frac{2\lambda\tau_s}{\gamma}(x + c_1)} - d \qquad (11)$$

2. Keulegan

$$S = F\left[3.3 \times 10^{-6}\frac{U^2}{gd} + 2.08 \times 10^{-4}\frac{(U-U_0)^2}{gd}\left(\frac{d}{F}\right)^{\frac{1}{2}}\right] \qquad (17)$$

3. Zuider Zee

$$h = \frac{V^2 F}{1400\, d}\cos A \qquad (19)$$

4. Nomographs formed by Sibul in his laboratory investigation of wind setup[10].

To facilitate comparison, setup at the leeward shore was plotted against wind velocity for depths of 0.1, 0.2, 0.3, and 0.4 feet producing Graphs VII to X. All tests were run with a fetch of 32 feet.

The graphs illustrate the observed setup values as being slightly less than the theoretical values for the shallowest depth but agreeing fairly well for the other depths. In any case, the observed values are within the range of variation of the different theoretical predictions. In the case of the shallowest depth, the parabolic form of the water surface was extremely pronounced. This has the effect of decreasing the leeward shore setup and increasing the windward shore depression to maintain the volume balance between water raised and water depressed from the still water level. The assumption of a plane water surface with a nodal point at F/2 and equal variation from the still water level at the windward and leeward shores is not applicable to this case. However, this is one of the assumptions on which some of the theoretical predictions are based, leading to an over-estimate of the leeward setup for extremely shallow depths and high wind velocities. In support of this, Hellstrom's formulae for leeward setup only, give results that agree closely with the observed values. In contrast, Keulegan's formula gives the setup as the difference in elevation between the windward and leeward shore water levels that is assumed to be twice the value for a particular shore. This produces results that are significantly higher than the observed values.

In summary, the observed setup values are similar to the theoretical predictions in both magnitude and behavior with the exception of exaggerated setup conditions where the water surface profiles assume a pronounced parabolic shape.

PART B : WIND SETUP UNDER NON-UNIFORM CONDITIONS

Part B will deal with wind setup phenomena for which little or no theoretical development is available. The test results discussed in Part A of this chapter have indicated the laboratory apparatus capable of producing a setup phenomenon similar in magnitude and behavior to theoretical predictions. With this reassurance, the procedure in Part B will be reversed. On the basis of laboratory observations an effort will be made to formulate a theoretical treatment of wind setup under non-uniform conditions.

1. The Variation of Setup With Time

As developed in preceding chapters, the wind setup phenomenon is created by the wind exerting a tangential force on the water surface. Due to the action of the wind, the water surface assumes a positive slope to the leeward shore and a rotational current is generated. The energy imparted by the wind is thus utilized in creating and maintaining the sloping water surface, and in very shallow depths, overcoming resistance to the return current in the rotational flow. In deeper depths some of the energy is dissipated by the turbulence of the rotational flow. The theoretical formulae derived to describe the phenomenon are based on the entire system being in equilibrium (i.e), the slope is stable and the velocity of the rotational flow is constant. If the phenomenon is considered just after the wind has begun to act on the body of water and just before the rotational flow has begun to dissipate some of the imparted energy, it may be possible that an initial setup may be created that is higher than the final setup when the entire system is in equilibrium.

The first fifteen tests were run with both the initial and long term setups recorded. In addition, qualitative observations were made of the point at which the return current was generated. It was observed that as soon as the wind began to act on the water surface, an initial setup was created that reached a maximum value an instant before the return current was generated. The setup then diminished as the return current became established to the final setup value measured over an hour later.

The initial setup behaved in accordance with the same theoretical parameters as the long-term setup but differed in magnitude. When the initial setup was plotted versus the long-term setup it formed a straight line relationship that in nearly all cases indicated the value to be exactly twice the long-term value. The plot is shown in Graph XI, page 52, where the observed points are very nearly split by a straight line at a slope of 2 to 1. The time of the initial peak was found to vary with the magnitude of the initial setup as shown in Graph XII.

For laminar conditions of flow, the wind shear stress on the water surface was presented as twice the bottom shear stress in formula (4), Chapter II. The Reynolds Number for the conditions of flow observed in the laboratory varied from 1,000 for the shallowest depth to 5,000 for the deepest depth indicating the flow to be in the laminar range. Thus, the total energy imparted to the body of water was twice the energy dissipated by the frictional resistance opposing the rotational current on the bottom. However, before the flow conditions become established, no return current is generated and no energy is being dissipated by the bottom resistance. This would indicate that twice the setup should be expected initially as twice the energy is available to create it. A similar situation was created by Sibul[10] in his tests of the effect of obstruction to the return current. When he had all but eliminated the return current he observed a significant increase in setup.

In projecting the laboratory observations to natural bodies of water there are two significant factors to consider, the conditions of flow and the relative depths of water. In the laboratory, laminar flow and extremely shallow depths made the bottom shear resistance an important factor in the setup phenomenon. In natural bodies of water neither of these conditions would be expected. It is proposed by Hellstrom, Langhaar, Sibul, and in the Zuider Zee formula that the bottom shear stress may be ignored under natural conditions due to the return current existing at some level above the bottom and the conditions of turbulent flow. Allowances for increased initial setup should therefore be confined to cases where laminar flow and extremely shallow depths exist. In effect, these conditions confine the allowance to theoretical and small scale laboratory investigations.

2. The Effect of Non-Uniform Water Depths

The theoretical analysis of wind setup is based on a body of water of uniform depth throughout. Since this is seldom encountered under natural conditions, some modifications must be made to allow for the effect of irregular depths. The simplest approximation would be to use the mean or average depth of a body of water in the setup formula. A more refined approximation has been proposed by the United States

Corps of Engineers[9] wherein the body of water is broken up into sections of average depth. Since these methods have been used with success in the past this aspect of wind setup analysis was only briefly investigated.

The laboratory tests were chosen to be examples of the setup conditions for non-uniform depths, the setup conditions for a uniform mean depth, and the setup conditions for a series of sections of mean depth. The configurations tested may be summarized as follows:

Test 31 : a uniform depth of 0.2 feet was tested,

Test 32 : a bottom sloping from 0 feet at the windward shore to 0.4 feet at the leeward shore was tested,

Test 33 : an approximation of the bottom slope of test 32 with two equal steps of 0.1 and 0.3 feet of uniform depth was tested,

Test 34 : a bottom sloping from 0.4 feet at the windward shore to 0 feet at the leeward shore was tested,

Test 35 : an approximation of the bottom slope of Test 34 was tested with two equal steps of 0.1 and 0.3 feet of depth was tested.

A comparison of the water surface profiles of Tests 31, 32, and 33 is shown in Graph XIII, page 53, and of Tests 31, 34 and 35 in Graph XIV.

The results indicate an error of 30 to 50 percent in the setup values may be encountered if only one mean depth of a non-uniform body of water is used as an approximation to the actual condition. However, dividing the body into several sections of uniform depth produced results that closely approximated those of the original condition. This would indicate the validity of the following method of dealing with conditions of non-uniform depth.

1. Divide the fetch of the body of water into sections and determine the average depth for each section.
2. Calculate the setup and water surface profile for each section.
3. Adjust the elevation of each section to make the water surface continuous.
4. Adjust the elevation of the entire profile to make the volume of water raised equal to the volume of water depressed from the still water level.
5. Repeat the above procedure if the final average depths with the setup profile are substantially different from the initial average depths. The average depths from the previous approximations should be used in subsequent trials.

A comparison of the proposed method of setup prediction with the laboratory observations is made in Table II.

TABLE II

NON-UNIFORM DEPTH MODIFICATIONS

Test	Depth	Observed Setup	Theoretical Setup (Hellstrom)
33	0.1	.017	.015
35	0.1	.017	.015
31	0.2	.008	.007
33	0.3	.004	.005
35	0.3	.008	.005

Although the laboratory values are slightly distorted with the exaggerated setup conditions, the trend of the results is in agreement with the "step" method of setup analysis for bodies of water of irregular depth.

3. The Effect of Non-Uniform Plan Shapes of Bodies of Water

The tests of the preceding section indicated a method of modifying the depth factor in the wind setup formulae to allow for the effect of irregular depths. In the case of irregular widths or plan shapes of a body of water, there is no factor in the existing setup formulae that may be modified. It is assumed that the body of water is of uniform or unit width. However, in natural bodies of water it has been observed that the plan shape of the body may significantly effect the wind setup magnitude.

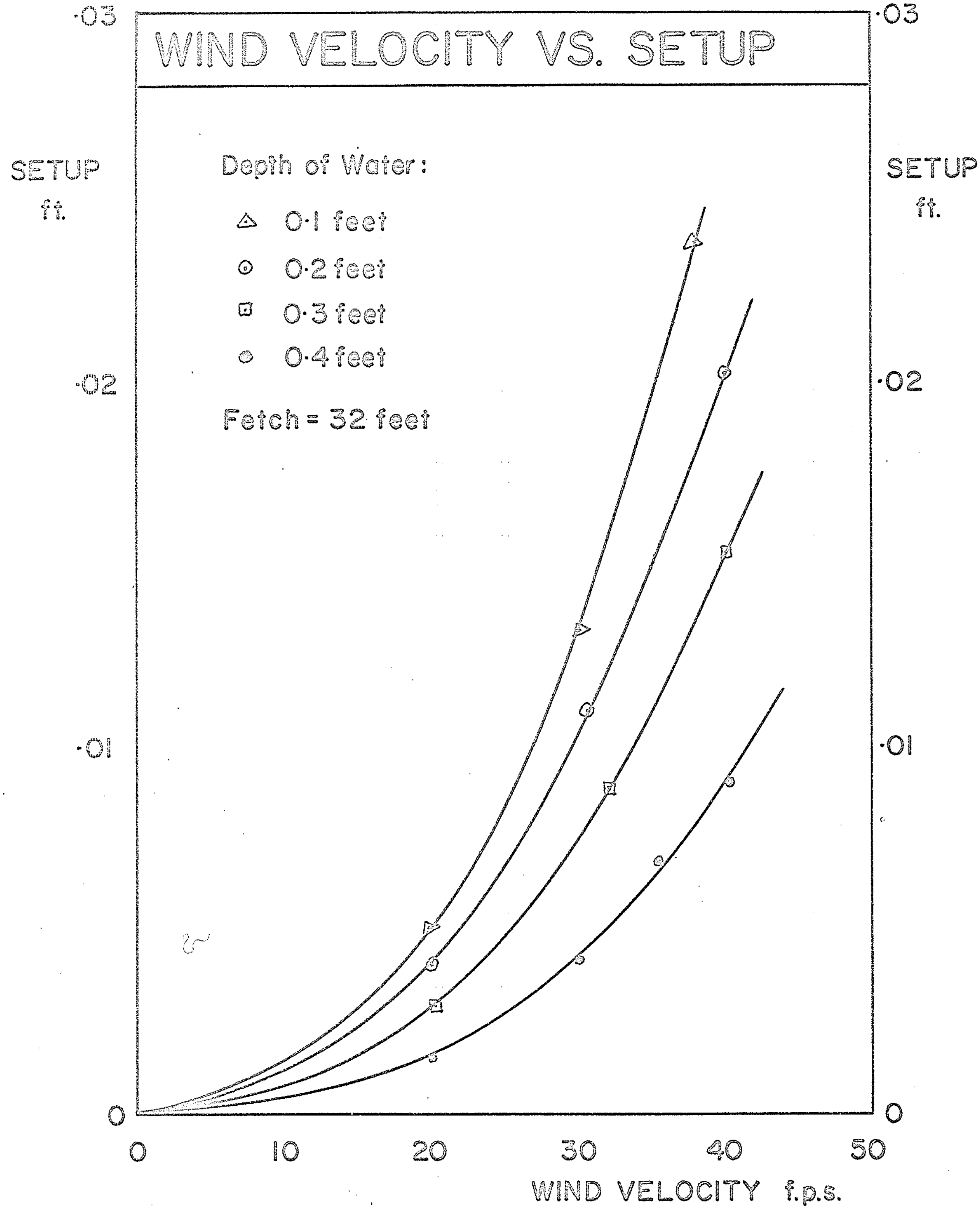
The tests run in the laboratory to investigate the effect of non-uniform shapes may be divided into three groups; rectangular, triangular, and "stepped" rectangular shapes. In the series of tests with triangular plan shapes, the leeward setup exceeded the theoretical predictions by 30 to 40 per cent. The tests were run with gradually varied plan dimensions to discover if some factor depending on the shape of the triangle by which the theoretical setup could be multiplied existed. The "stepped" rectangular plan shapes were derived by breaking the triangular shapes into sections of uniform width as suggested by previous investigators. Typical water surface profiles for the various shapes are plotted in Graphs XV to XVIII, pages 54 and 55.

The setup produced by the rectangular shape shown in Graph XV closely approximates that predicted by the setup formulae. The setup conditions produced by the various triangular shapes were very nearly equal and no factor dependent on the shape of triangle was observed. The "stepped" rectangular shapes produced wind setup of a similar magnitude to the triangular shapes but since no plan shape factor exists in the theoretical setup analysis the approximation is of little value. However, when all the water surface profiles are compared, it is seen that they are very nearly identical in slope and shape if elevations are disregarded. To illustrate this, the profiles were plotted in Graph XIX as passing through a common elevation at the mid-point of the fetch. Graph XIX demonstrates that the profiles are identical regardless of the plan shape, if all other conditions are similar. In addition, the results of Graph XV indicate the profiles may be predicted theoretically in slope and shape. However, to predict the magnitude of the setup at a specific shore the elevation of the sloping water surface must be determined. To accomplish this, the volume balance principle demonstrated in the first section of this chapter will be utilized. If the entire profile is known in slope and shape it may be adjusted in elevation until the volume of water raised equals the volume of water depressed from the still water level. In Graphs XX and XXI the water surface profiles for a rectangular and a triangular shape were plotted and the displaced volumes computed. In both cases the volumes raised equalled the volumes depressed to within a few percent.

Based on the above observations, the following procedure is proposed to modify the setup analysis for bodies of water with irregular plan shapes.

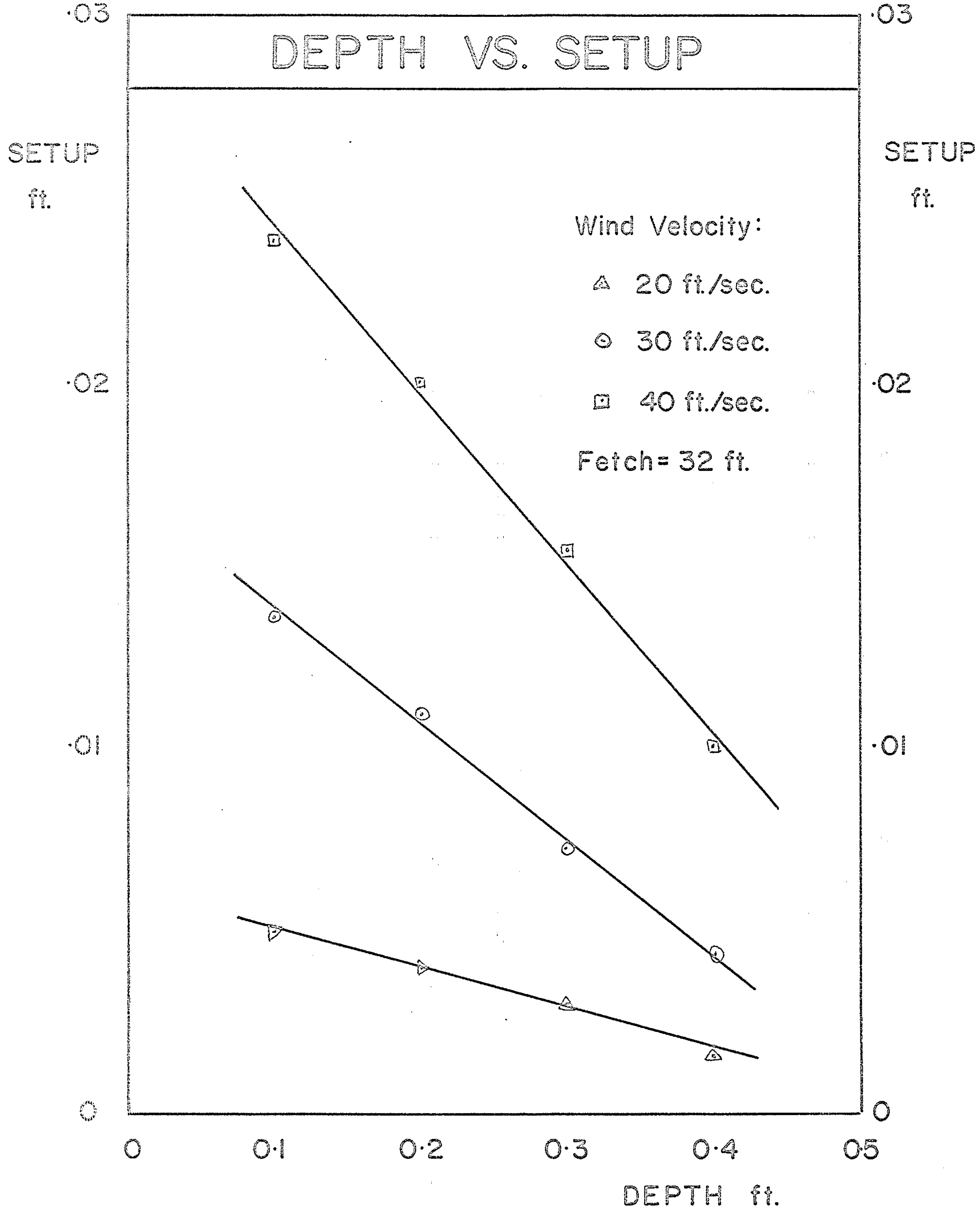
1. Compute the slope and shape of the water surface profile for the longest continuous fetch in the direction of the wind with the theoretical setup formulae.
2. Superimpose the sloping water surface on the mean water level and adjust the entire profile up or down until the volume depressed equals the volume raised from the still water level. The volumes may be determined by a mechanical integration for the varying widths.
3. Repeat the above procedure if the average depths of the body of water vary substantially from the initial values. The average depths from the previous approximations should be used in subsequent trials.

In the sections of this chapter the results of the setup investigation have been reviewed and design methods for wind setup under various conditions have been proposed. The design methods will not be further extracted and summarized as they should be applied with a full knowledge of their derivation and conditions of occurrence.



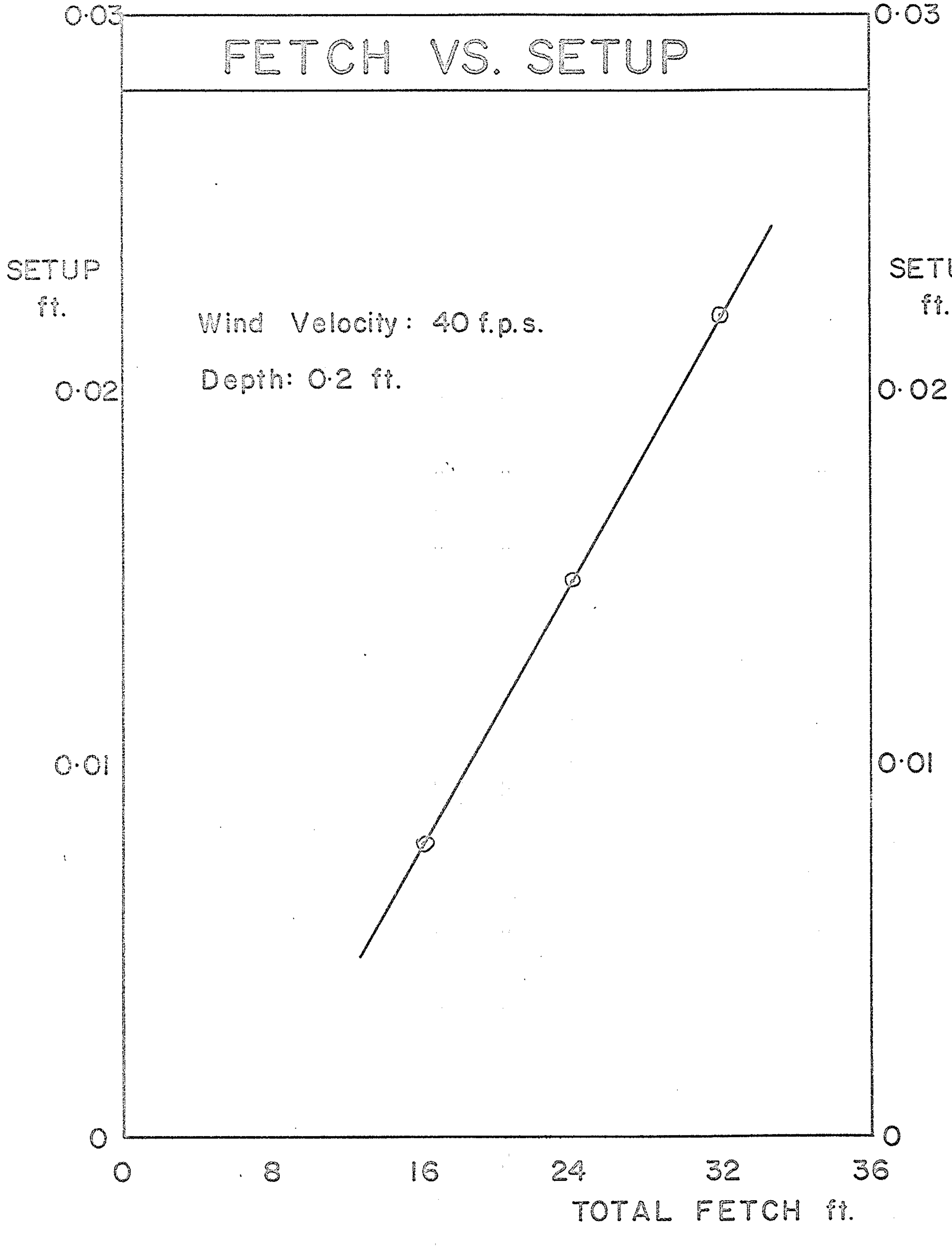
RESULTS AND CONCLUSIONS
SETUP CHARACTERISTICS

GRAPH I



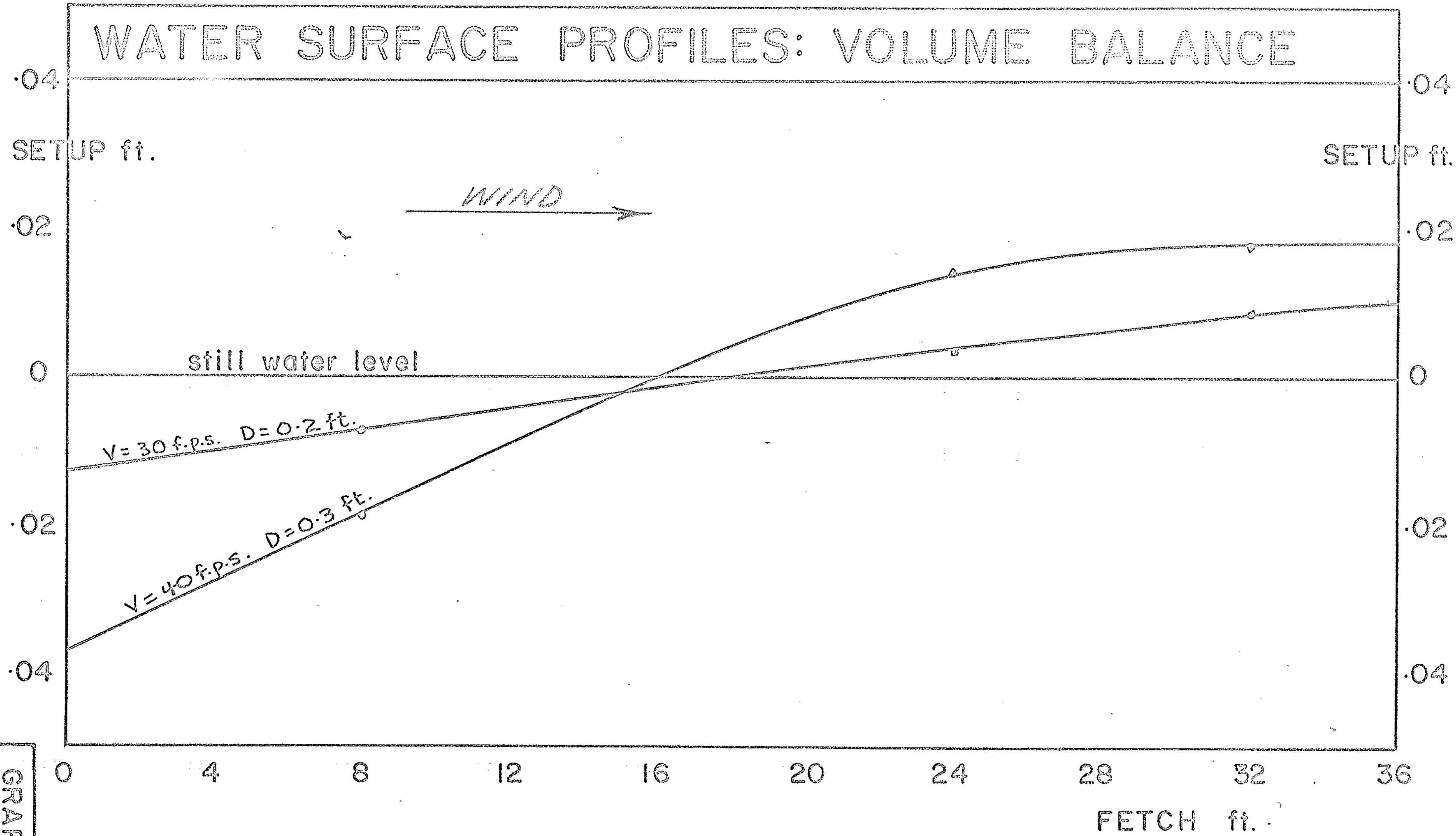
RESULTS AND CONCLUSIONS
SETUP CHARACTERISTICS

GRAPH II

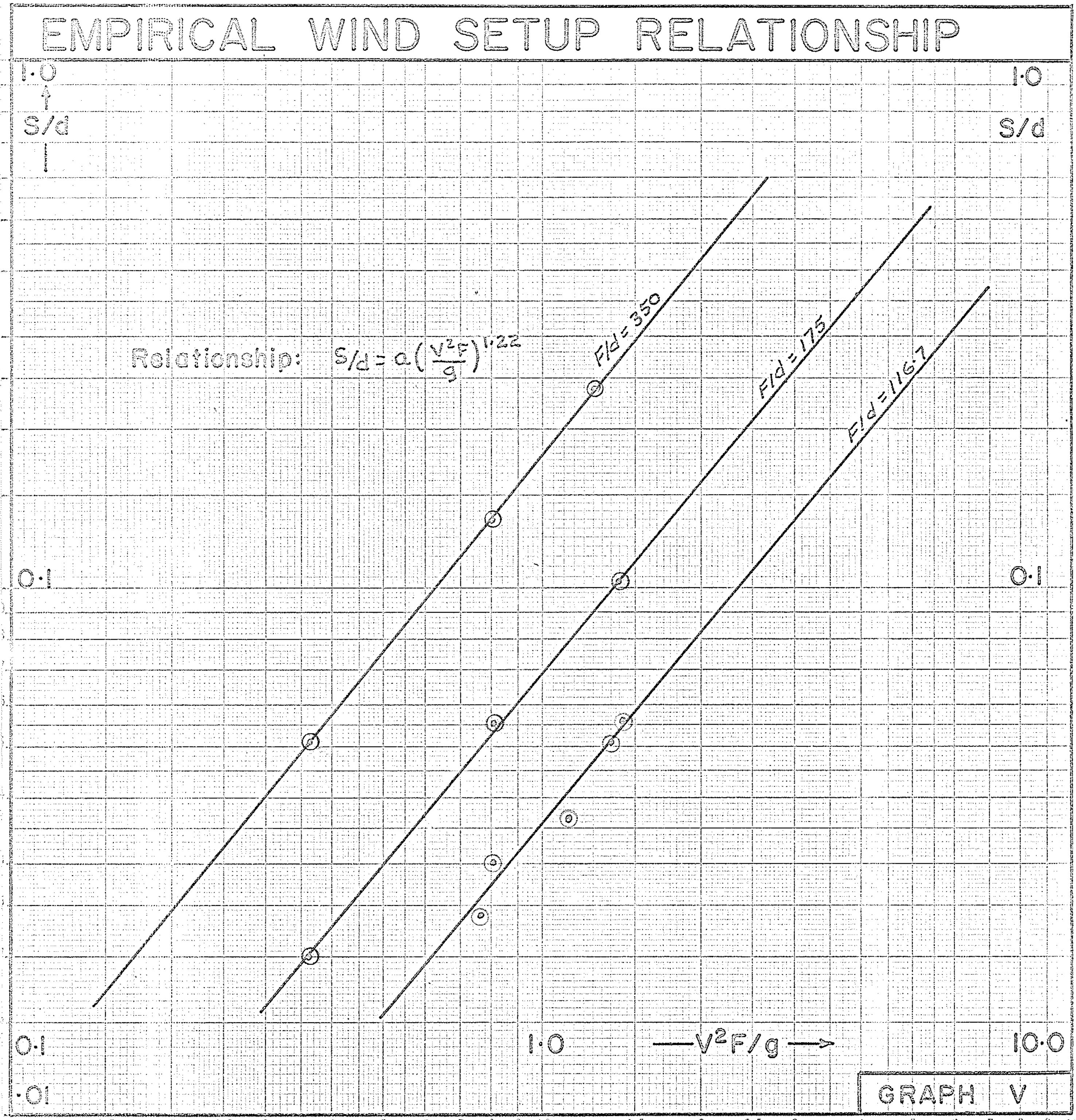


RESULTS AND CONCLUSIONS
SETUP CHARACTERISTICS

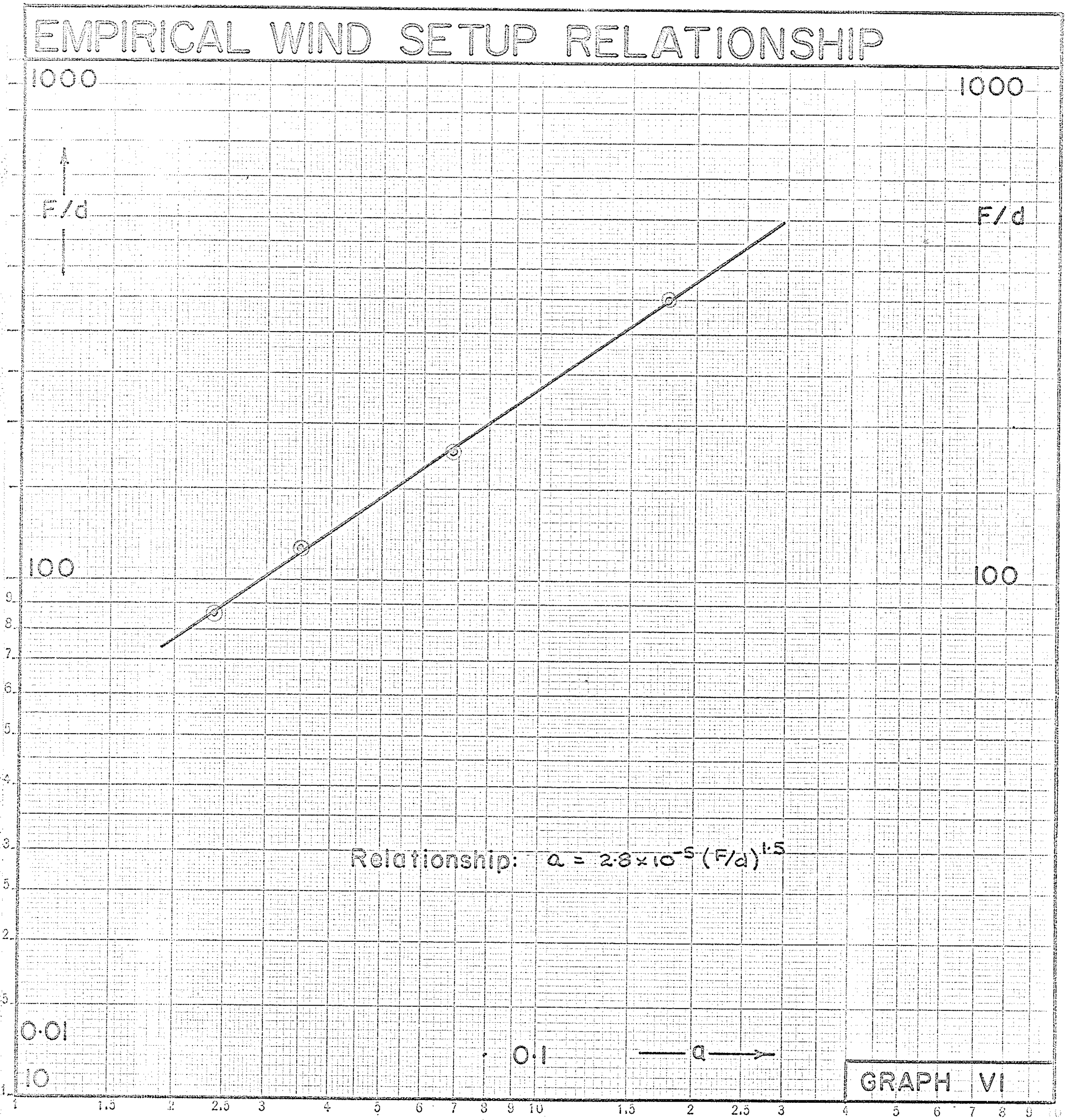
GRAPH III

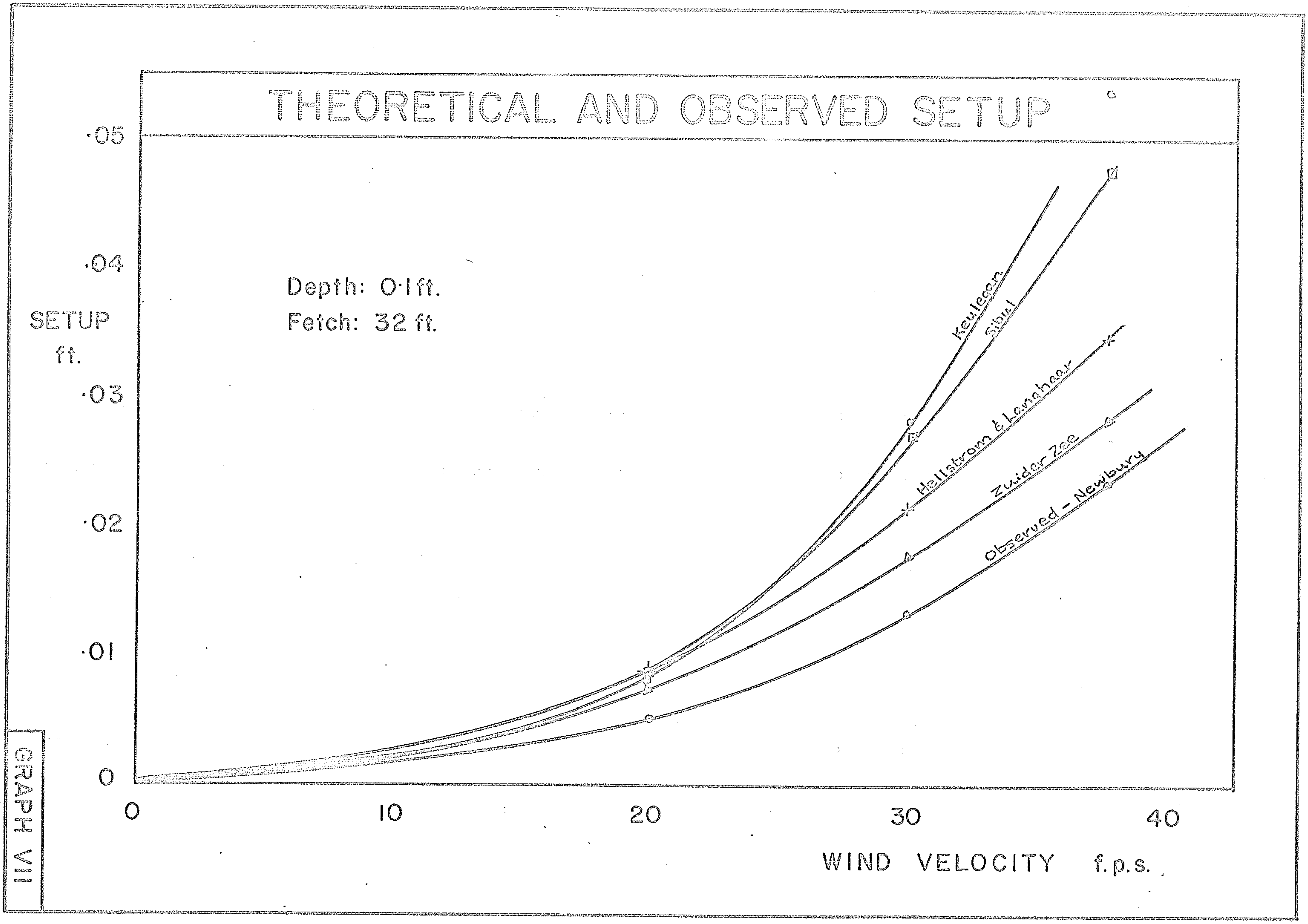

WATER SURFACE PROFILES: VOLUME BALANCE
SETUP ft.
SETUP ft.
WIND
still water level
V = 30 f.p.s. D = 0·2 ft.
V = 40 f.p.s. D = 0·3 ft.
·04
·02
0
·02
·04
0
4
8
12
16
20
24
28
32
36
FETCH ft.

GRAPH IV



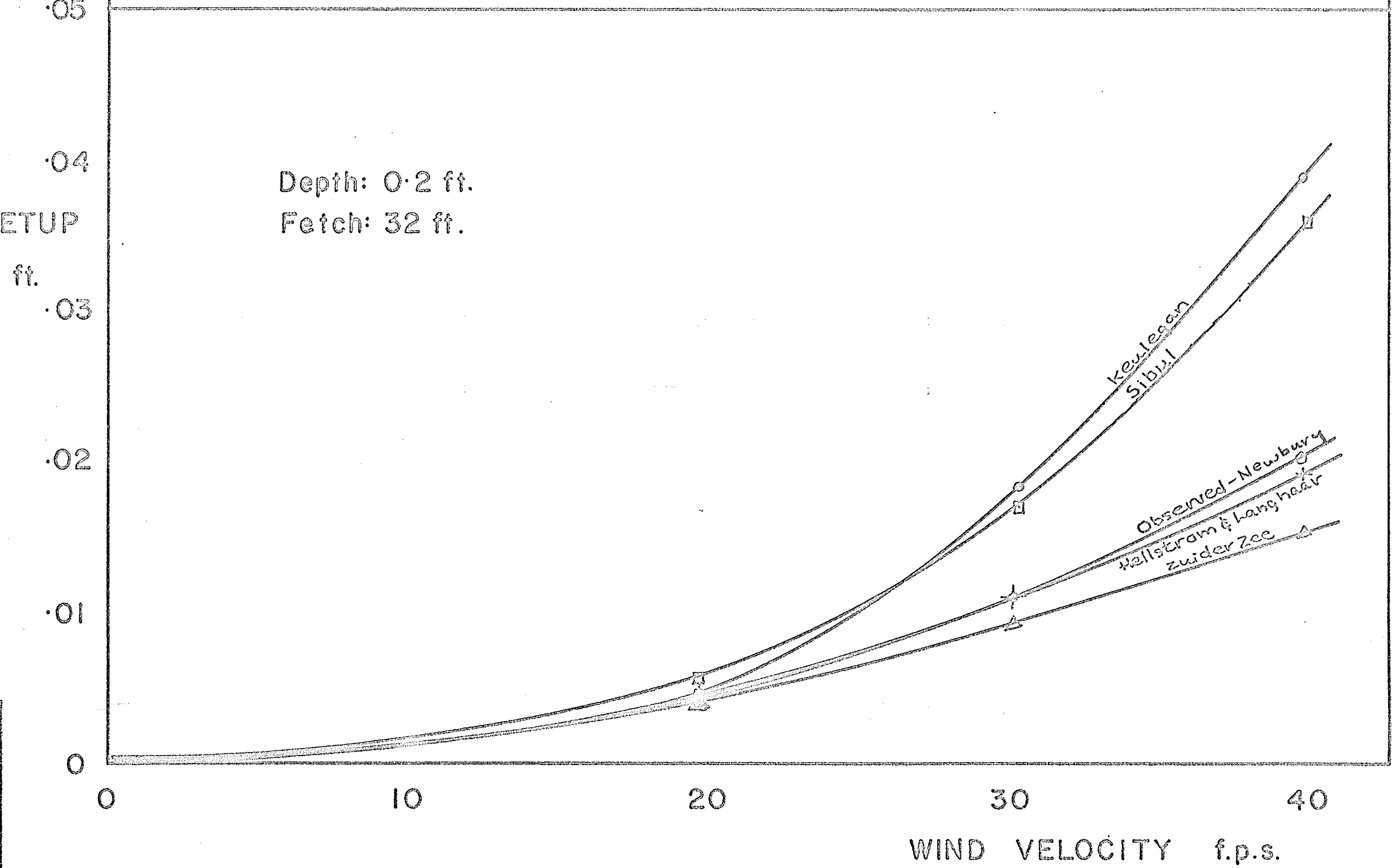
EMPIRICAL WIND SETUP RELATIONSHIP
1·0
S/d
0·1
Relationship: $S/d = a\left(\frac{V^2F}{g}\right)^{1.22}$
F/d = 350
F/d = 175
F/d = 116·7
0·1
1·0
—V²F/g →
10·0
·01
GRAPH V


EMPIRICAL WIND SETUP RELATIONSHIP
1000
1000
F/d
F/d
100
100
Relationship: $a = 2.8 \times 10^{-5} (F/d)^{1.5}$
0.01
0.1
— a →
10
GRAPH VI

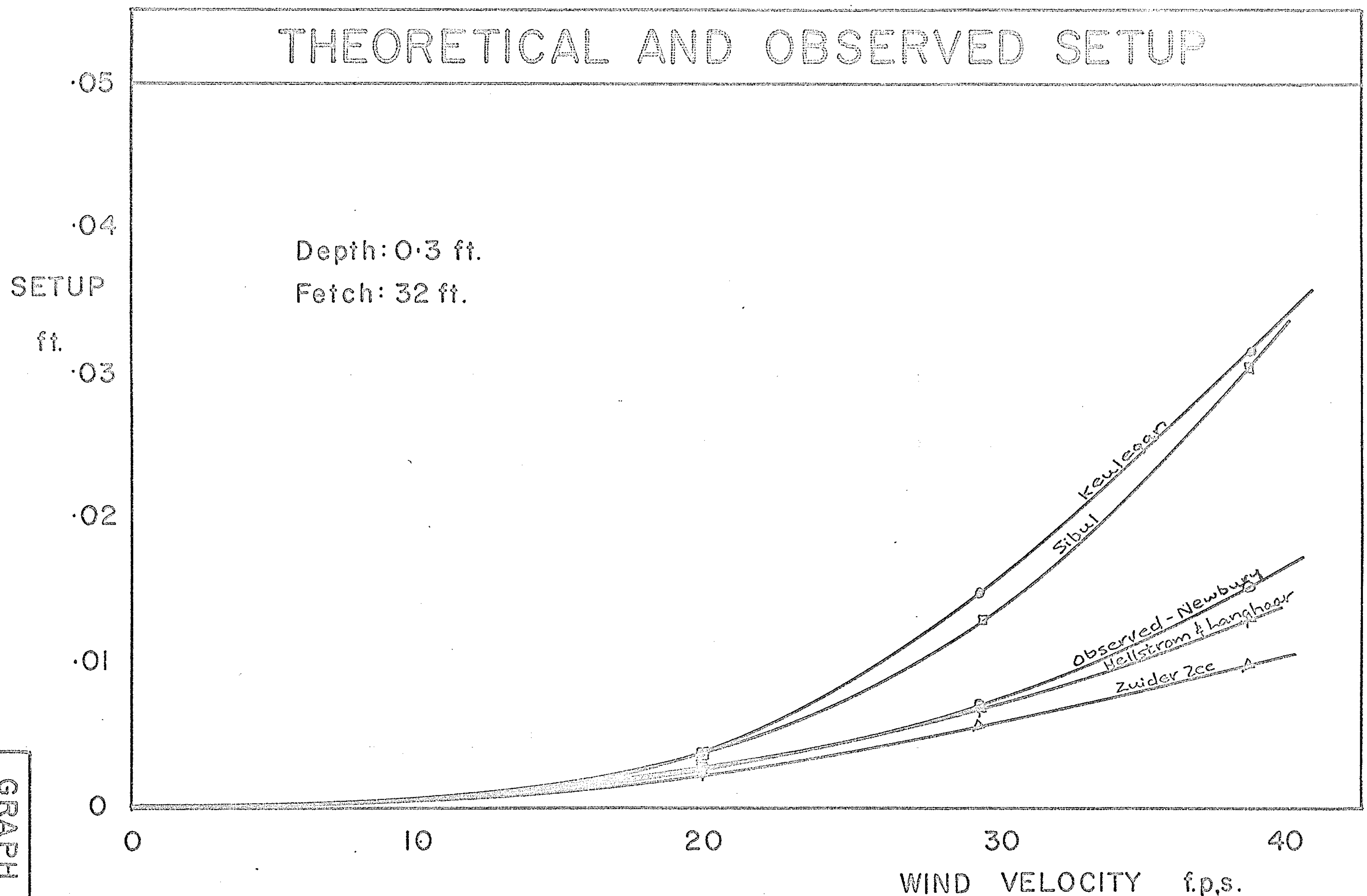

THEORETICAL AND OBSERVED SETUP
Depth: 0·1 ft.
Fetch: 32 ft.
SETUP ft.
·05
·04
·03
·02
·01
0
0
10
20
30
40
WIND VELOCITY f.p.s.
Keulegan
Sibul
Hellstrom & Langhaar
Zuider Zee
Observed – Newbury

GRAPH VII

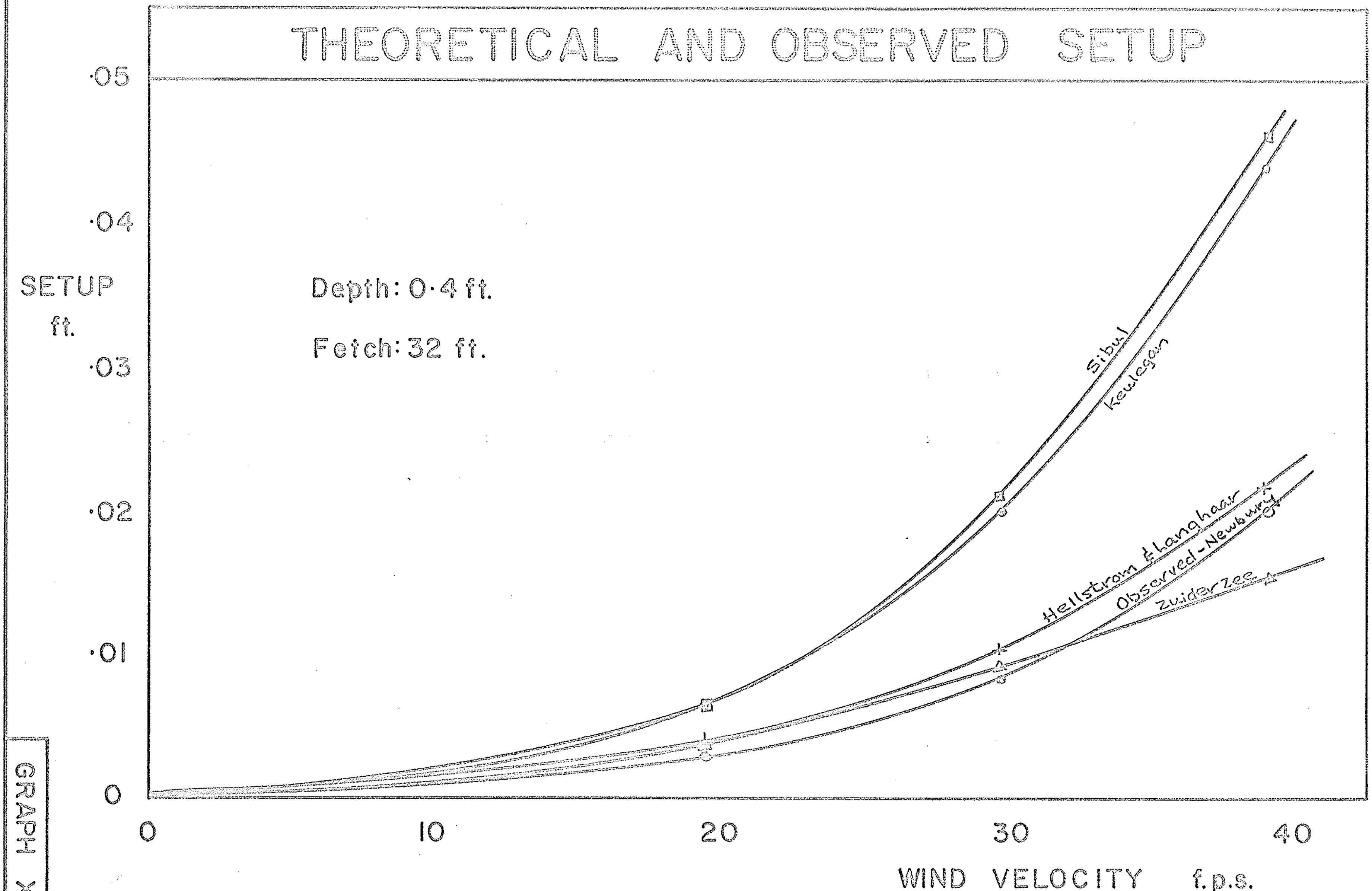
THEORETICAL AND OBSERVED SETUP



GRAPH VIII

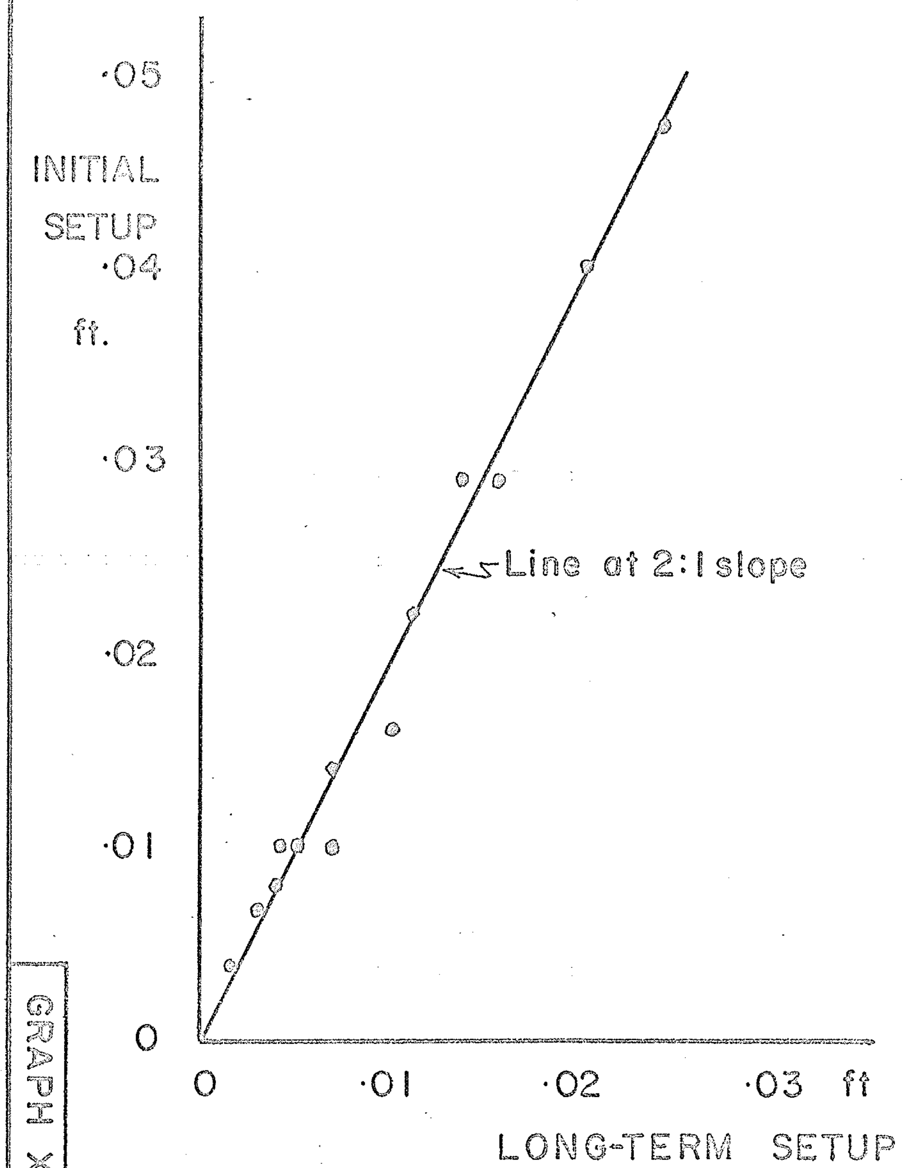

THEORETICAL AND OBSERVED SETUP
SETUP ft.
·05
·04
·03
·02
·01
0
Depth: 0·3 ft.
Fetch: 32 ft.
Keulegan
Sibul
Observed - Newbury
Hellstrom & Langhaar
Zuider Zee
0
10
20
30
40
WIND VELOCITY f.p.s.

GRAPH IX


THEORETICAL AND OBSERVED SETUP
SETUP ft.
·05
·04
·03
·02
·01
0
Depth: 0·4 ft.
Fetch: 32 ft.
Sibul
Keulegan
Hellstrom & Langhaar
Observed - Newbury
Zuiderzee
0
10
20
30
40
WIND VELOCITY f.p.s.

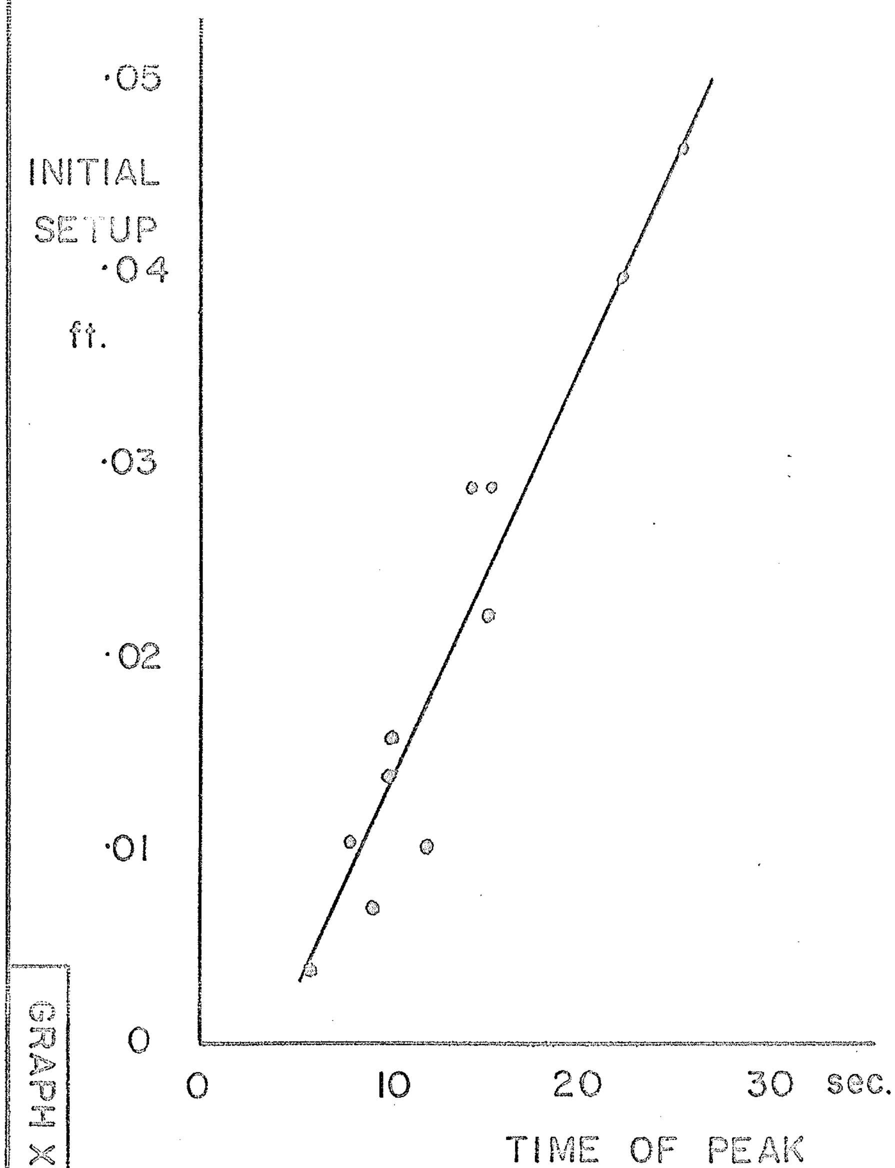
GRAPH X

INITIAL VS. LONG-TERM SETUP



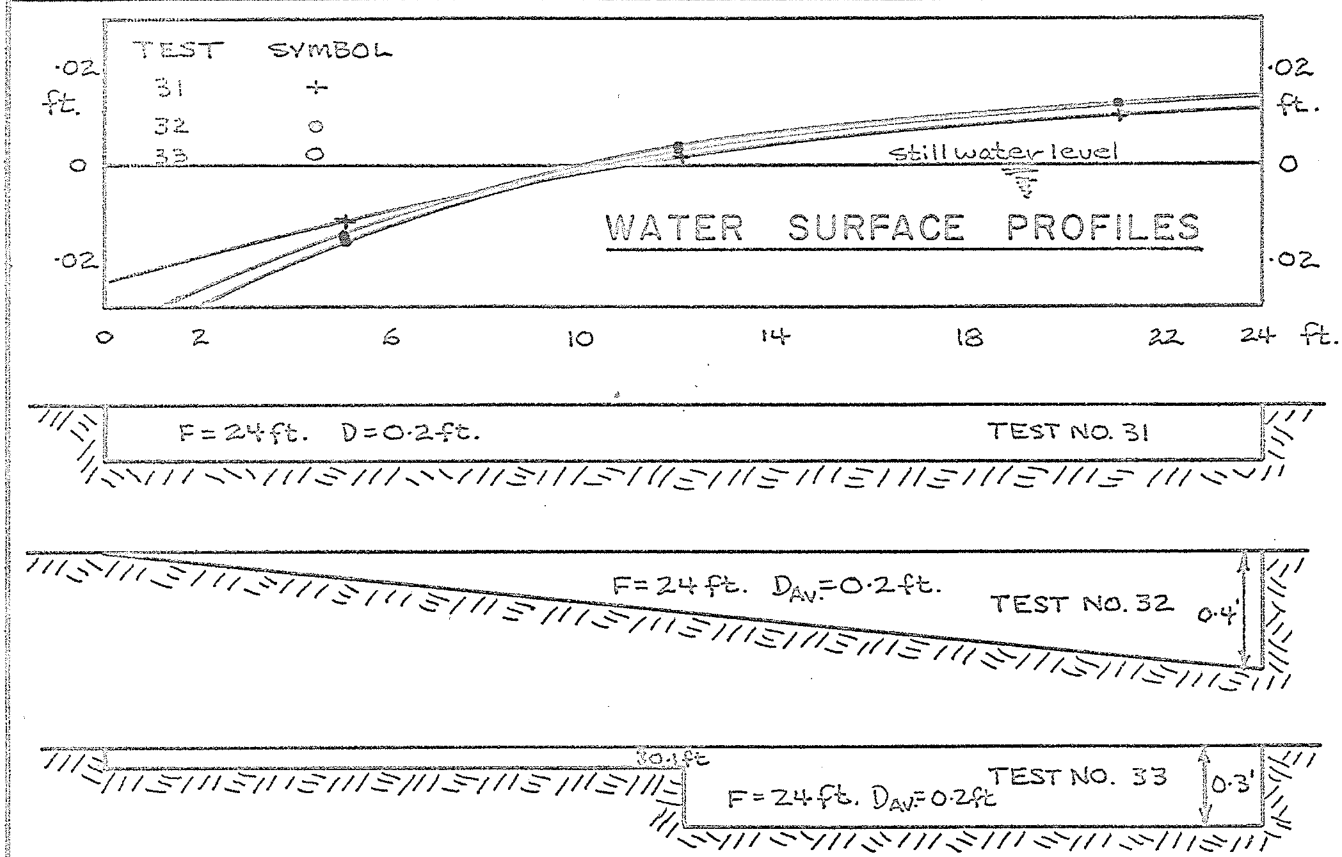
GRAPH XI

INITIAL SETUP VS. TIME

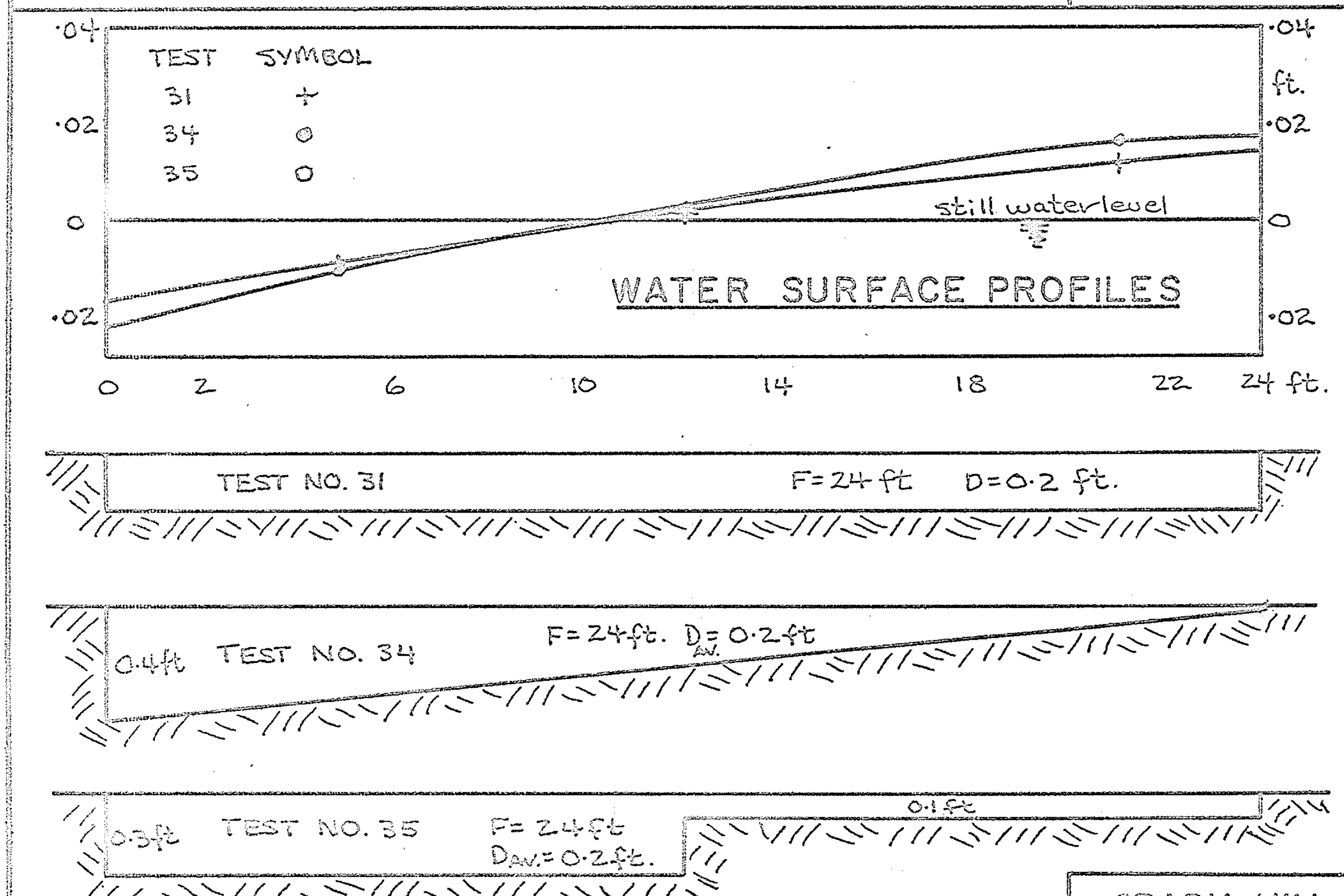


GRAPH XII

SETUP WITH IRREGULAR DEPTHS

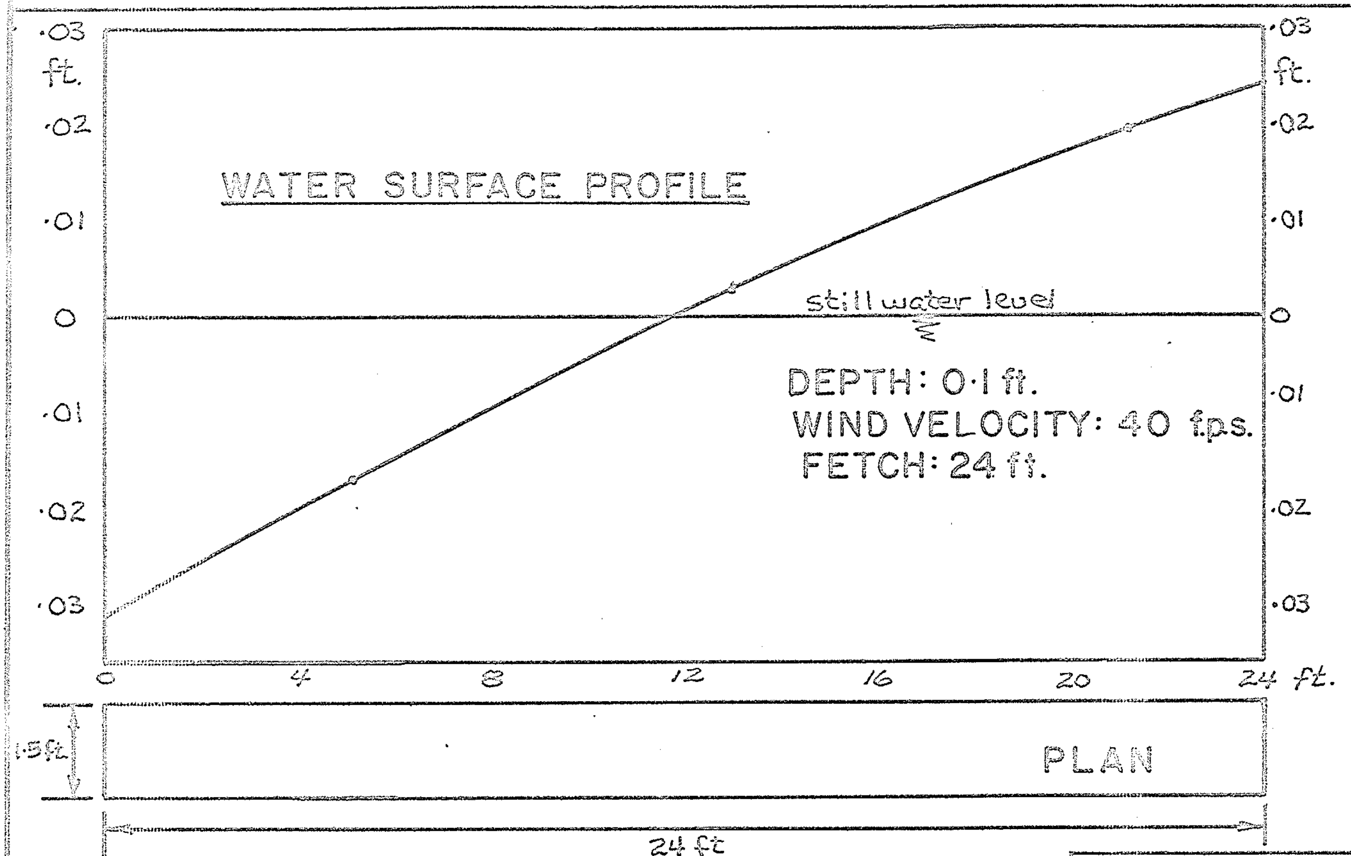


GRAPH XIII

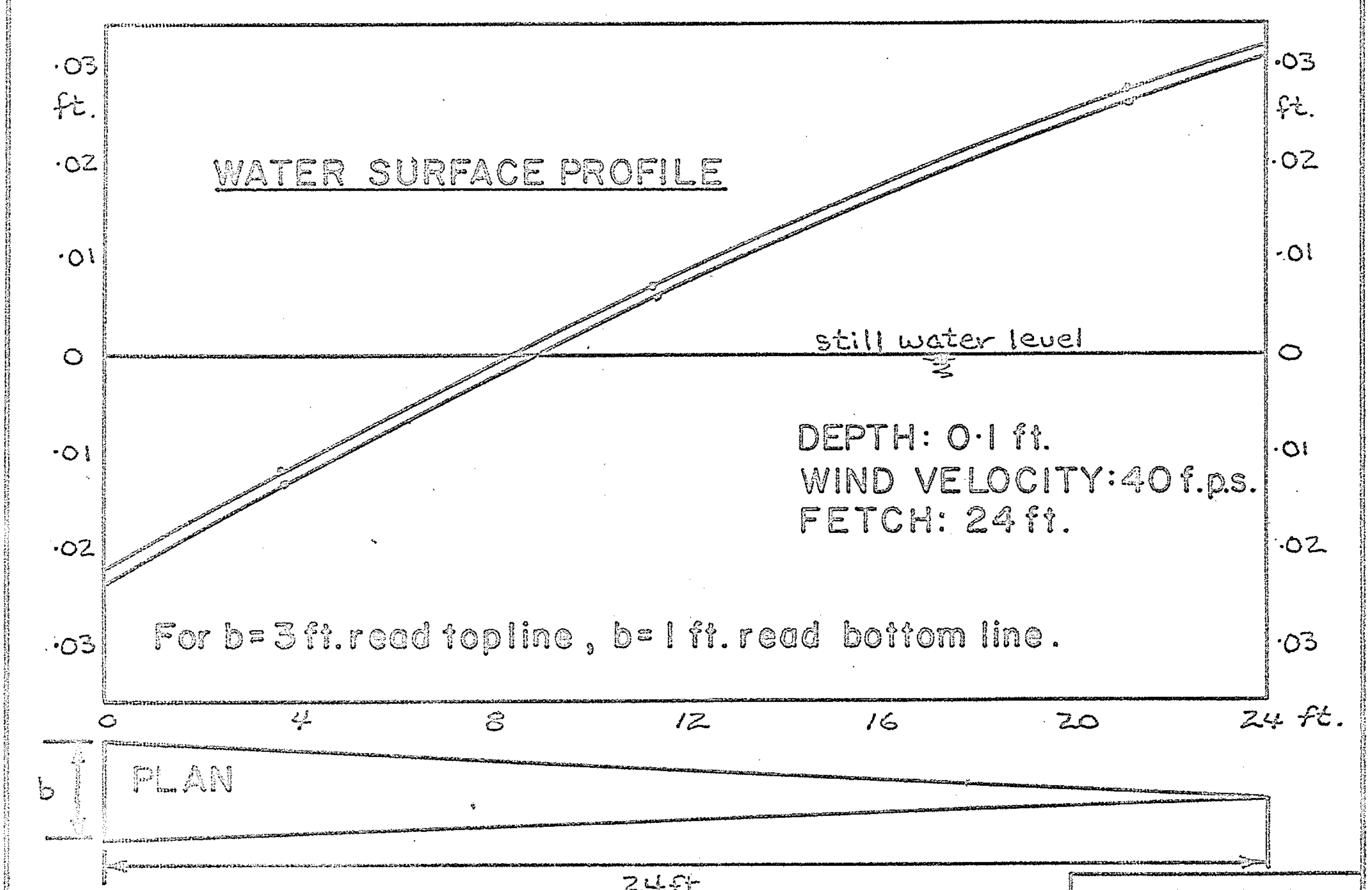


GRAPH XIV

SETUP WITH IRREGULAR PLAN SHAPES

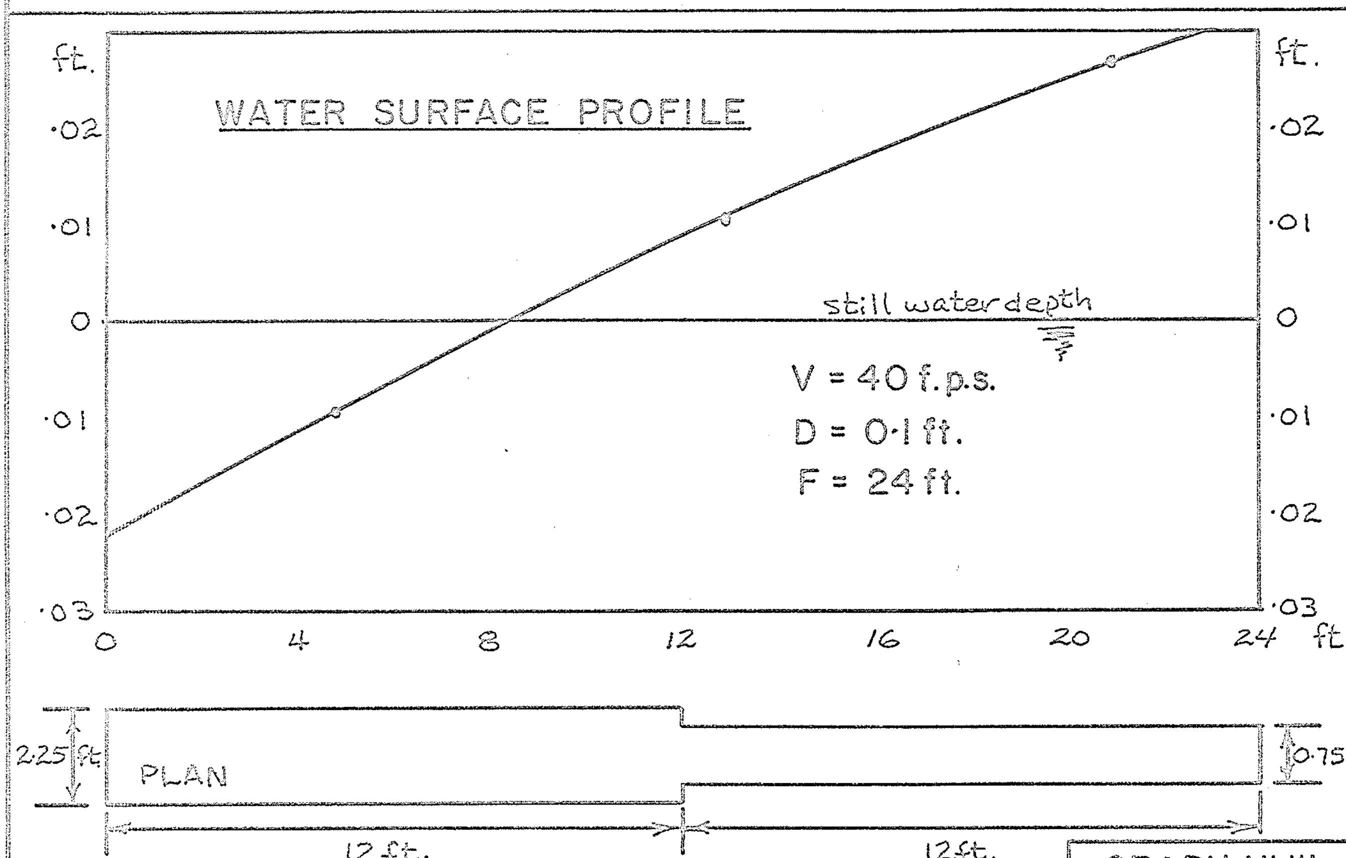


GRAPH XV

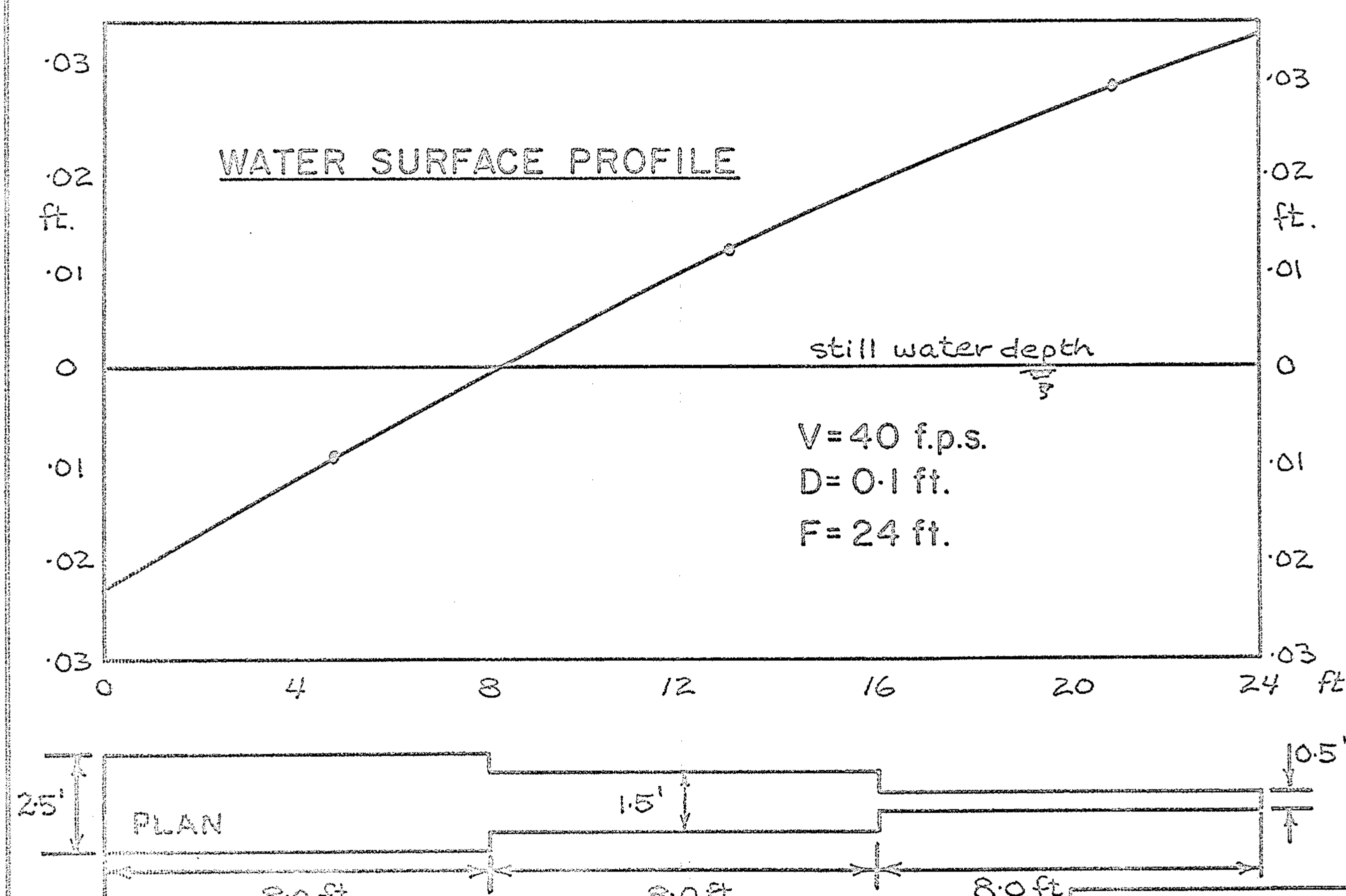


GRAPH XVI

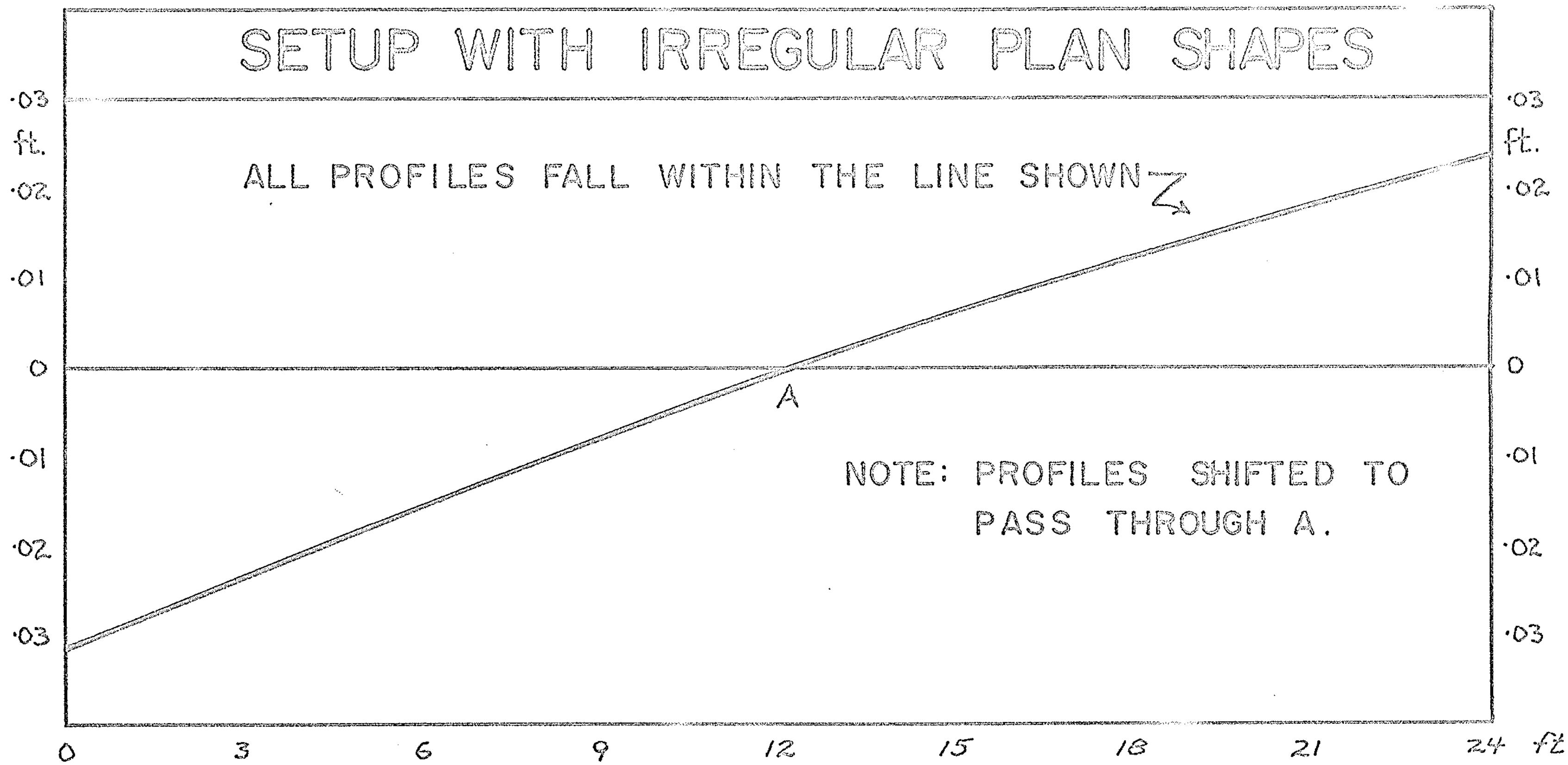
SETUP WITH IRREGULAR PLAN SHAPES



GRAPH XVII



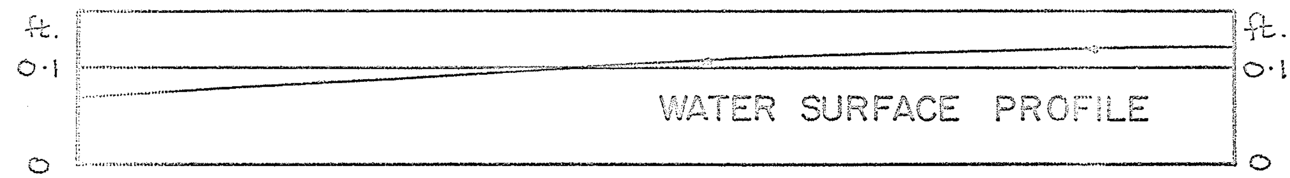
GRAPH XVIII

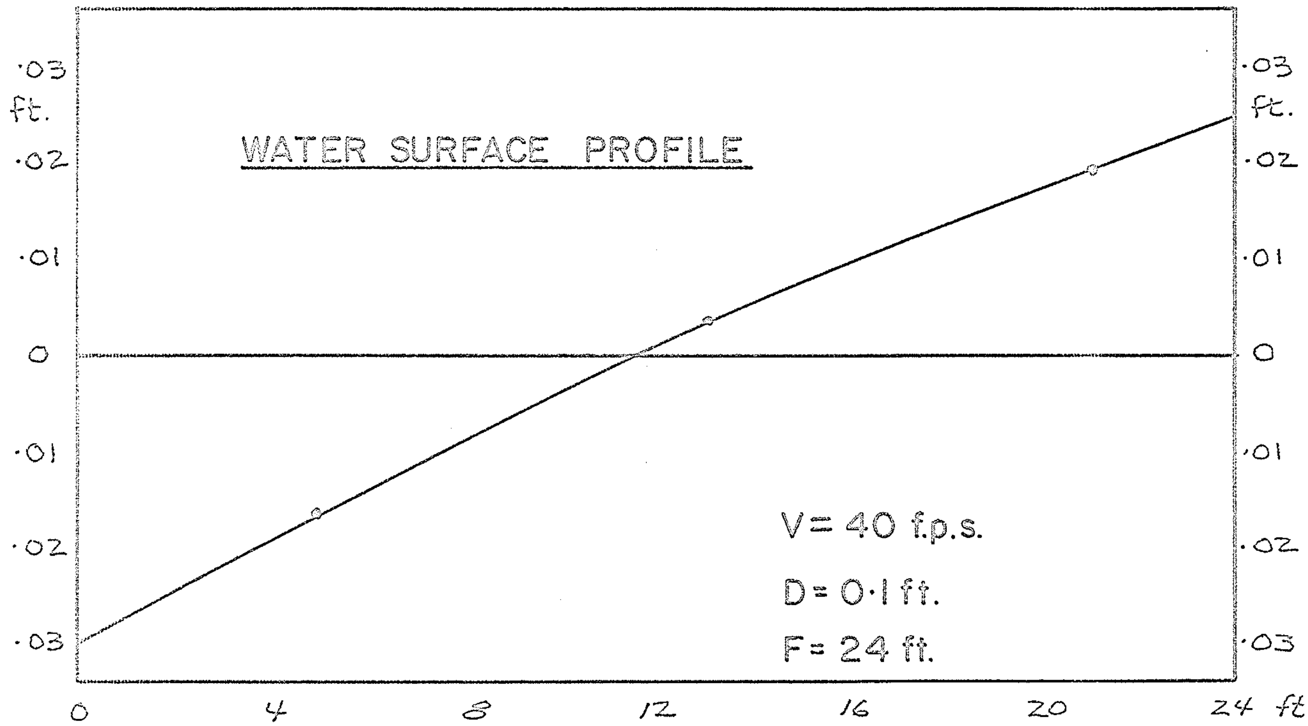


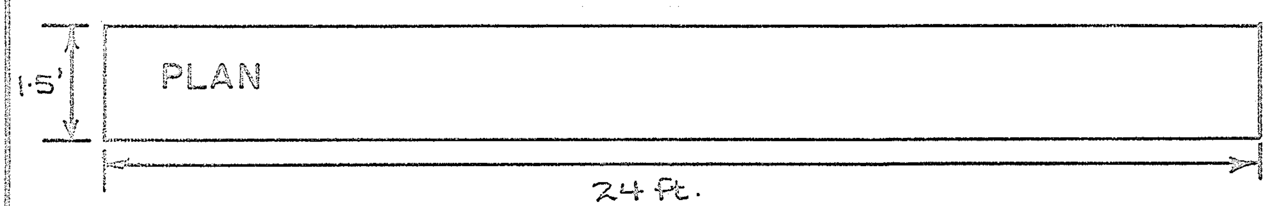
PLOT OF WATER SURFACE PROFILES FOR TESTS 20 TO 30.

GRAPH XIX

VOLUME BALANCE: IRREGULAR PLAN SHAPE



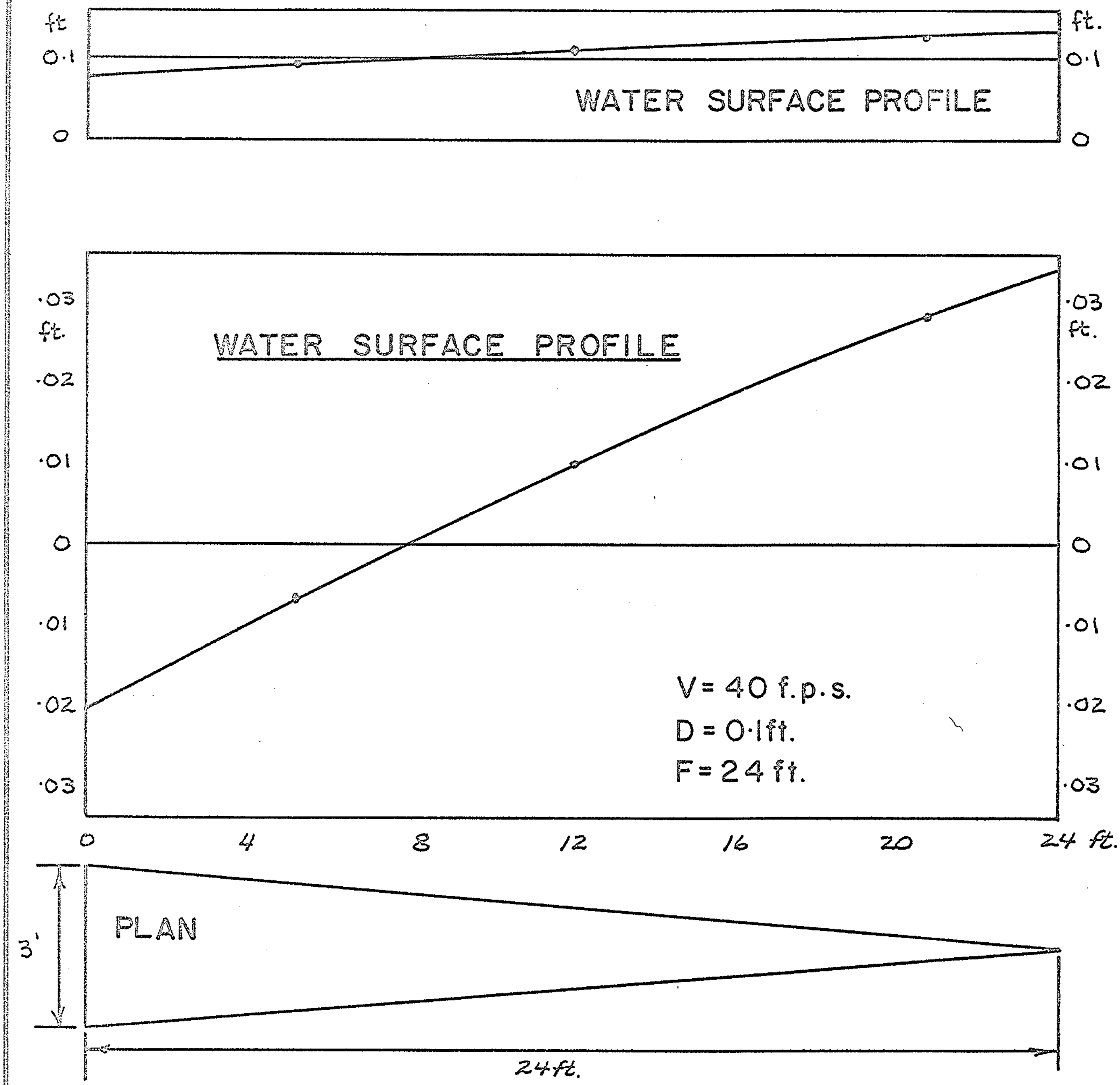




Depth ft.	−·027	−·022	−·017	−·012	−·007	−·002	+·003	+·008	+·011	+·016	+·019	+·023	ΣVOL. ft³
Width ft.	1·5	1·5	1·5	1·5	1·5	1·5	1·5	1·5	1·5	1·5	1·5	1·5	
+ VOL.							·005	·012	·017	·024	·028	·033	+·119
− VOL.	·040	·033	·025	·017	·010	·003							−·128

GRAPH XX

VOLUME BALANCE: IRREGULAR PLAN SHAPE



Depth ft.	−·018	−·012	−·008	−·002	+·003	+·007	+·012	+·017	+·021	+·025	+·028	+·032	ΣVOL. ft.³
Width ft.	2·88	2·63	2·38	2·13	1·88	1·63	1·38	1·13	0·88	0·63	0·38	0·13	
+ VOL.					·006	·011	·017	·018	·019	·016	·011	·004	+·102
− VOL.	·052	·031	·019	·004									−·106

GRAPH XXI

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APPENDICES

TABLE III

WIND SETUP LABORATORY DATA

Test No.	Date	Wind Velocity	Total Fetch	Mean Depth	Mean Width	Distance From Wind-ward shore	Wind** Setup		Bottom Con-figuration	Plan Con-figuration
	1963	ft/sec.	feet	feet	feet	feet	$ft \times 10^{-2}$	T*		
1	2	3	4	5	6	7	8	9	10	11
1	Aug.12	19.9	35.0	0.1	3.0	32.0	+1.05 +0.51	I F	Flat	Rectangular
2	Aug.13	29.8	35.0	0.1	3.0	32.0	+2.92 +1.33	I F	Flat	Rectangular
3	Aug.14	37.5	35.0	0.1	3.0	32.0	+4.68 +2.38	I F	Flat	Rectangular
4	Aug.15	39.6	35.0	0.2	3.0	32.0	+4.00 +2.02	I F	Flat	Rectangular
5	Aug.16	30.2	35.0	0.2	3.0	32.0	+2.20 +1.10	I F	Flat	Rectangular
6	Aug.17	19.8	35.0	0.2	3.0	32.0	+0.75 +0.40	I F	Flat	Rectangular
7	Aug.19	19.8	35.0	0.3	3.0	32.0	+0.71 +0.31	I F	Flat	Rectangular
8	Aug.20	29.4	35.0	0.3	3.0	32.0	+1.00 +0.72	I F	Flat	Rectangular
9	Aug.21	38.6	35.0	0.3	3.0	32.0	+2.90 +1.55	I F	Flat	Rectangular
10	Aug.22	34.4	35.0	0.4	3.0	32.0	+1.41 +0.71	I F	Flat	Rectangular
11	Aug.23	19.6	35.0	0.4	3.0	32.0	+0.40 +0.15	I F	Flat	Rectangular

Test No	Date	Wind Velocity	Total Fetch	Mean Depth	Mean Width	Distance From Windward shore	Wind** Setup		Bottom Configuration	Plan Configuration
	1963	ft/sec.	feet	feet	feet	feet	ft x 10^{-2}	T*		
1	2	3	4	5	6	7	8	9	10	11
12	Aug.24	29.9	35.0	0.4	3.0	32.0	+1.07	I	Flat	Rectangular
							+0.42	F		
13	Aug.26	39.1	35.0	0.4	3.0	32.0	+1.60	I	Flat	Rectangular
							+1.00	F		
14	Sept.3	39.6	35.0	0.3	3.0	8.0	-1.93	F	Flat	Rectangular
						16.0	-0.20	F		
						24.0	+1.35	F		
						32.0	+1.70	F		
15	Sept.4	35.8	35.0	0.3	3.0	8.0	-1.40	F	Flat	Rectangular
						16.0	-0.37	F		
						24.0	+0.52	F		
						32.0	+1.08	F		
16	Sept.5	30.0	35.0	0.3	3.0	8.0	-1.08	F	Flat	Rectangular
						16.0	-0.13	F		
						24.0	+0.31	F		
						32.0	+0.91	F		
17	Sept.9	39.4	32.0	0.2	3.0	5.0	-2.06	F	Flat	Rectangular
						13.0	-0.73	F		
						21.0	+0.71	F		
						29.0	+2.02	F		
18	Sept.12	39.6	24.0	0.2	3.0	5.0	-1.42	F	Flat	Rectangular
						13.0	+0.02	F		
						21.0	+1.05	F		
19	Sept.16	37.6	16.0	0.2	3.0	5.0	-0.58	F		
						13.0	+0.46	F		

Test No	Date	Wind Velocity	Total Fetch	Mean Depth	Mean Width	Distance From Wind-ward shore	Wind** Setup		Bottom Con figuration	Plan Con-figuration
	1963	ft/sec	feet	feet	feet	feet	ft x 10-2	T*		
1	2	3	4	5	6	7	8	9	10	11
20	Sept.23	40.4	16.0	0.2	1.5	5.0	-0.60	F	Flat	Triangular 3 ft base at windward shore
						13.0	+1.20			
21	Sept.28	39.6	24.0	0.2	1.5	5.0	-1.24	F	Flat	Triangular 3 ft base at windward shore
						13.0	+0.35	F		
						21.0	+2.00	F		
22	Oct.1	37.5	24.0	0.1	1.5	5.0	-0.77	F	Flat	Triangular 3 ft base at windward shore
						13.0	+1.15	F		
						21.0	+2.78			
23	Oct.4	37.5	24.0	0.1	1.25	5.0	-0.80	F	Flat	Triangular 2.5 ft. base at windward shore
						13.0	+1.10	F		
						21.0	+2.73	F		
24	Oct.7	37.5	24.0	0.1	1.0	5.0	-0.85	F	Flat	Triangular 2.0 ft. base at windward shore
						13.0	+1.10	F		
						21.0	+2.65	F		
25	Oct.9	37.5	24.0	0.1	0.75	5.0	-0.90	F	Flat	Triangular 1.5 ft base at windward shore
						13.0	+1.05	F		
						21.0	+2.62	F		
26	Oct.11	37.5	24.0	0.1	0.50	5.0	-0.90	F	Flat	Triangular 1.0 ft base at windward shore
						13.0	+1.00	F		
						21.0	+2.60	F		
27	Oct.14	37.0	24.0	0.1	1.50	5.0	-0.87	F	Flat	Two 12 ft. rectangular sections of 2.25 ft and 0.75 ft width.
						13.0	+1.10	F		
						21.0	+2.70	F		

Test No	Date	Wind Velocity	Total Fetch	Mean Depth	Mean Width	Distance from Windward shore	Wind** Setup		Bottom Configuration	Plan Configuration
	1963	ft/sec	feet	feet	feet	feet	ft x 10^{-2}	T*		
1	2	3	4	5	6	7	8	9	10	11
28	Oct.17	37.0	24.0	0.1	1.50	5.0 13.0 21.0	-0.92 +1.20 +2.93	F F F	Flat	Three 8 ft rectangular sections of 2.5 ft, 1.5 ft, 0.5 ft. width
29	Oct.21	37.5	24.0	0.1	1.50	5.0 13.0 21.0	-1.70 +0.30 +1.90	F F F	Flat	Rectangular
30	Oct.23	35.0	24.0	0.1	3.0	5.0 13.0 21.0	-1.40 +0.20 +1.50	F F F	Flat	Rectangular
31	Oct.28	39.1	24.0	0.2	3.0	5.0 13.0 21.0	-1.20 +0.10 +1.15	F F F	Flat-sand bottom	Rectangular
32	Oct.31	39.1	24.0	0.2	3.0	5.0 13.0	-1.50 +0.30 +1.30	F	Sloping bottom 0.0 ft. windward to 0.4 ft leeward	Rectangular
33	Nov.2	39.1	24.0	0.2	3.0	5.0 13.0 21.0	-1.60 +0.40 +1.30	F	Two 12 ft flat sections of 0.1 ft and 0.3 ft.	Rectangular

Test No.	Date	Wind Velocity	Total Fetch	Mean Depth	Mean Width	Distance from Wind-ward shore	Wind** Setup		Bottom Con-figuration	Plan Con-figuration
	1963	ft/sec	feet	feet	feet	feet	ft x 10-2	T*		
1	2	3	4	5	6	7	8	9	10	11
34	Nov.5	39.1	24.0	0.2	3.0	5.0	-1.20	F	sloping bottom 0.4 ft wind-ward to 0.0 ft leeward	Rectangular
						13.0	+0.23	F		
						21.0	+1.60	F		
35	Nov.7	39.1	24.0	0.2	3.0	5.0	-1.06	F	Two 12 ft flat sections of 0.3 ft and 0.1 ft.	Rectangular
						13.0	+0.10			
						21.0	+1.55			

*T, column 9, denotes I, initial setup value or F, final setup value.

**Corrected for static pressure differential in wind tunnel.

APPENDIX B : SUMMARY OF WIND GENERATED WAVE CHARACTERISTICS

Measurements of the wave characteristics of the first fourteen tests of the laboratory investigation were taken with the recording device described in Appendix C. A summary of the measurements is included in Table IV to be used in further investigations of wind setup and investigations of wind generated waves in shallow water.

TABLE IV

WIND GENERATED WAVE CHARACTERISTICS

Test No	Average Wind Velocity	Uniform Depth	Uniform Width	Total Fetch	Distance From Wind ward Shore	Average Height of waves*	Average Period of Wave
	ft/sec.	ft.	ft.	ft.	ft.	ft.	sec.
1	2	3	4	5	6	7	8
1	19.9	0.1	3.0	35.0	26.5	0.038	0.30
2	29.8	0.1	3.0	35.0	26.5	0.044	0.40
3	37.5	0.1	3.0	35.0	26.5	0.048	0.41
4	39.6	0.2	3.0	35.0	26.5	0.078	0.50
5	30.2	0.2	3.0	35.0	26.5	0.055	0.43
6	19.8	0.2	3.0	35.0	26.5	0.033	0.33
7	19.8	0.3	3.0	35.0	26.5	0.056	0.36
8	29.4	0.3	3.0	35.0	26.5	0.065	0.42
9	38.6	0.3	3.0	35.0	26.5	0.088	0.50
10	34.4	0.4	3.0	35.0	26.5	0.100	0.47
11	19.6	0.4	3.0	35.0	26.5	0.060	0.42
12	29.9	0.4	3.0	35.0	26.5	0.090	0.43
13	39.1	0.4	3.0	35.0	26.5	0.120	0.50
14	39.6	0.3	3.0	35.0	6.5	0.035	0.33
					16.5	0.070	0.40
					26.5	0.094	0.50
					33.5	0.106	0.61

* Peak to trough

APPENDIX C : LABORATORY APPARATUS

The construction and operation of the laboratory apparatus will be described in this section to assist further investigations of the wind setup phenomenon and wave generation in the same laboratory. The equipment used is neither refined nor permanent, but it is readily available.

1. Wind Tunnel.

(a) Construction: The wind tunnel was constructed by installing a removeable cover on a 50 foot hydraulic flume. The flume consisted of glass and steel panels bolted to vertical steel channels at four foot intervals. The panels were arranged to make one side of the flume completely glass allowing the entire fetch to be observed during the tests. The flume and panels are shown in Illustrations IX and X, page 73 .

The top installed on the flume was made of $\frac{3}{4}$ inch plywood sections four feet in length hinged to one wall of the flume. Sections of, or the entire top, could be swung open for adjustments in the wind tunnel between tests. Access into the tunnel during a test was possible through small ports cut into the top of the plywood sections. The flume with two top sections installed is shown in Illustration XI.

Small dams that could be adjusted in height were installed to impound water in the bottom of the tunnel, one at the inlet and one 35 feet along the flume. The dams were made of laminated boards and caulking compound bolted to the floor of the flume. Adjustments in height were made by increasing or decreasing the number of boards. At the leeward end of the fetch, a wave damper made of plastic tubing was attached to the top of the dam to prevent the breaking waves carrying over the dam into the fan.

Air was drawn through the tunnel by a 36 inch centrifugal fan driven by a 10 horsepower motor. The flume was permanently covered over at the outlet end to form a chamber 3 feet by 3 feet by 12 feet from which the air was drawn. The inlet of the fan was attached to one wall of the chamber by removing a panel from the flume and replacing it with a fitted plywood adapter. The adapter is shown in Illustration XII prior to attaching the top of the chamber. The fan and motor were bolted to a raised cinder-block base at the side of the flume. An air straightener was placed over the inlet end of the tunnel to obtain a flow of air parallel to the water surface and sides of the tunnel.

(b) Operation: Prior to each test, the top of the tunnel was opened and the particular situation to be tested was moulded in fine sand. The top was then closed and water was added to the desired depth. Measurements of elevation were made with a point gauge attached to a moveable carriage on top of the tunnel. The fan was turned on and the wind velocity was adjusted to the desired value by opening or closing the fan outlet. The fan was then turned off and the water was allowed to stand until all surges were damped out. The mean water level was recorded on all manometers and the situation was ready to be tested. Following the tests the water was drained from the tunnel and the next situation was constructed.

2. Water Level Manometers

(a) Construction : Manometers were attached to the sides of the tunnel at various fetches to record the water levels before and during the tests. The manometers were made of wooden rectangular cases with plexiglass sides. The cases were made air tight with caulking compound. The bottom of the manometers were connected to a valved tube leading to the water in the tunnel. The air space above the water was connected to a static tube in the air flow in the tunnel. This made the static pressure in the tunnel equal to the static pressure above the water in the manometer case and hence the water surface elevations equal. The water levels in the manometers were determined with a point gauge extending through the top of the manometer case. The stem of the point gauge passed through a lubricated rubber gasket to keep the case air-tight. Readings could be determined to the nearest one thousandth of a foot with the point gauge vernier scale.

(b) Operation: Before the fan was turned on, the still water levels were recorded on all manometers. During a test the connecting tube between the manometer and water in the tunnel was gradually valved down until the wave fluctuation was damped out and a steady mean water level was obtained. For initial setup readings the manometer valves were opened to obtain the time and peak of each surge.

3. Wave Recorder

In principle the wave recorder consisted of two fine wires extending below the water surface in an electrical circuit. As the waves passed the probes and the water moved up and down the wires, the length of wire through which the current passed changed, changing the total resistance of the electrical circuit. This varied the voltage across a constant resistance in the circuit. The change in voltage was then calibrated with the change in water level against the wire probes and measured with an oscilliscope. The circuit is shown schematically in Figure IX below:

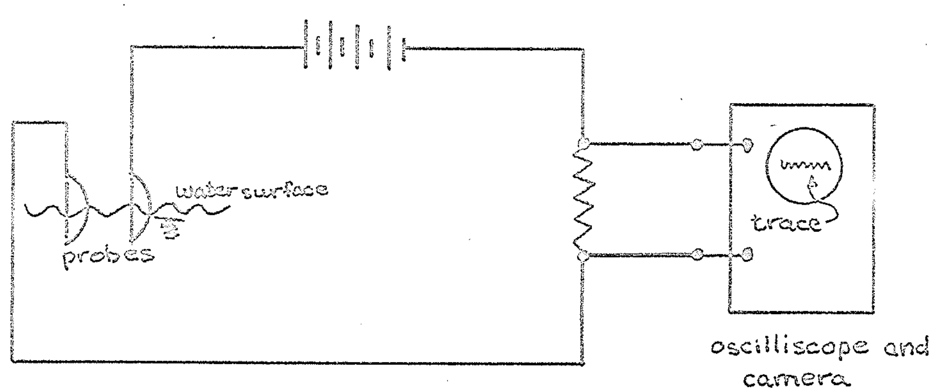

FIGURE IX : WAVE RECORDER CIRCUIT

(a) Construction : The wire probes were mounted about 4 inches apart between two plexiglass arms. The arms were attached to the staff of a point gauge allowing them to be extended into the tunnel and water. The probes were connected to the circuit on a moveable bench beside the wind tunnel. The fluctuations in voltage across a constant resistance in the circuit was recorded with a camera and oscilliscope.

(b) Operation : Before each test, the voltage fluctuation was calibrated with the fluctuation in water level. This was done by lowering the probe a known amount while the water surface was calm and observing the change in voltage. The sensitivity of the oscilloscope was adjusted to give a significant indication of the wave magnitude on the screen. With the test in progress, the trace of the wave fluctuation was photographed with a Polaroid Land camera (see Illustration VIII). In the photograph, the number of peaks for a known time may be counted to determine the period of the waves. The average magnitude of the waves may be measured directly on the photograph and converted to feet by the calibration constant.

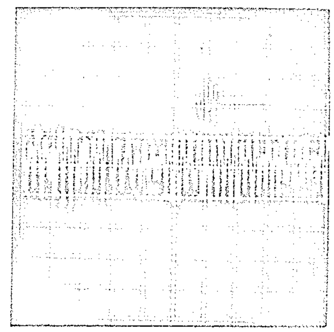

ILLUSTRATION VIII
OSCILLISCOPE WAVE TRACE FOR TEST NO.10

4. Standard Equipment

In addition to the specially constructed apparatus described, several standard measuring devices were used in the investigation. These include rack and pinion mounted point gauges, static tubes, pitot tubes, and draft gauges. The point gauges were used to determine depths of water and the dimensions of plan and bottom configurations constructed in the tunnel. The pitot tubes were used for wind velocity measurements and the static tubes were used for pressure measurements inside the tunnel.

ILLUSTRATION IX: Hydraulic flume prior to construction. The flume was converted to a wind tunnel by installing a temporary plywood top.

ILLUSTRATION X: Glass and steel side panels of hydraulic flume during construction. When completed, one side of the wind tunnel was entirely glass.

ILLUSTRATION XI: Installation of top panels of wind tunnel. The panels were opened as shown between tests for alterations in the wind tunnel. Small ports were cut in the panels for access during a test.

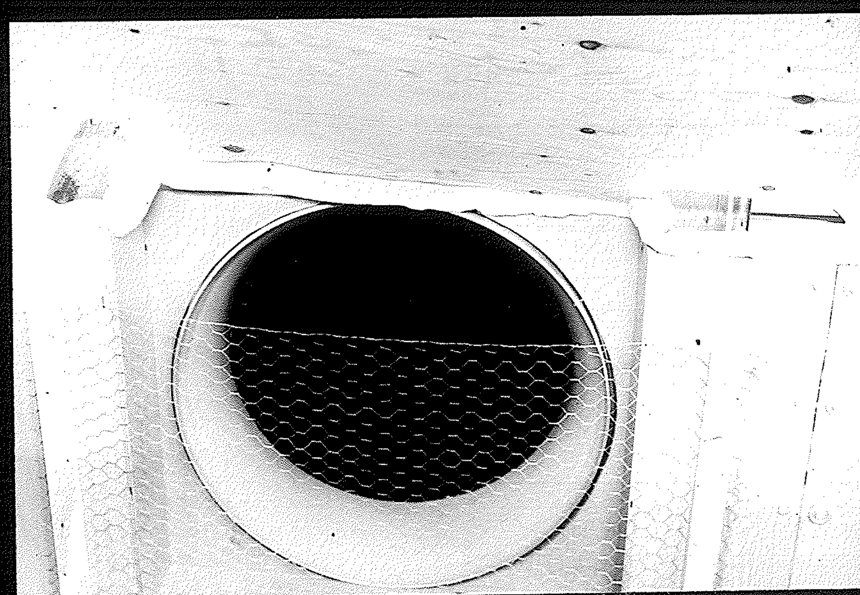

ILLUSTRATION XII: Fan inlet adapter. Air was drawn through the tunnel and into the chamber shown.