BEACH EROSION BOARD
OFFICE OF THE CHIEF OF ENGINEERS

LABORATORY STUDY
OF WIND TIDES
IN SHALLOW WATER

TECHNICAL MEMORANDUM NO. 61

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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. 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 in 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 observations at Lake Okeechobee and elsewhere that a rough bottom, or aquatic plants growing up through the water affect the set-up to a significant degree. These laboratory tests were made to enable some quantitative indication to be made of the importance of bottom effects and its dependence on such things as depth and wind strength. A considerable number of observations were made, and the data obtained should be of considerable interest to those involved in the design of structures where set-up over a rough bottom is important.

The empirical forecasting method given in the end of the report is but one possible method of obtaining set-up values and, while supported by the data presented in the report, does not appear to warrant preference over the more generally used step-integration methods given by Hellstrom, Keulegan, or Thijsse also discussed in the report and which have been successfully applied to a very large range of conditions in the field.

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

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LABORATORY STUDY OF WIND TIDES IN SHALLOW WATER

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ABSTRACT

Wind tides and wave conditions in shallow water were studied in a laboratory channel. The experiments were conducted with smooth and rough bottom conditions, and with strips of cheese cloth in the channel to simulate the roughness effects of vegetation in nature. The results indicate a rapidly increasing set-up when the still-water depth decreases below a certain limit. There were no indications that the bottom roughness affects the set-up for relatively deep water; in very shallow water, however, the rougher bottom conditions result in higher set-ups. The trend is especially pronounced for higher wind velocities. For the shallowest still-water depth (0.05 foot) used in the experiments, the set-up 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 set-up observed with a smooth bottom.

INTRODUCTION

When wind is blowing over a water surface it generates waves, the heights and periods of which are a function of wind intensity, wind duration, depth, and fetch. In addition to generating waves, the wind produces a tangential stress at the water surface with a resulting surface current in the general direction of the wind. In deep water, this current is balanced by the backflow in the lower layers. In shallow water, however, the backflow is affected by the roughness of the bottom and the water will "set-up" to the leeward until a sufficient pressure head is reached to balance the effect of bottom roughness. The more shallow the water, the more the bottom affects the backflow of water, and the higher the relative set-up must be to create an equilibrium condition between the wind generated current on the surface and the backflow along the bottom.

In limited bodies of water such as lakes, rivers, bays, and seas, wind tides have been measured and found to vary from a few inches for light winds to many feet in extreme cases involving hurricane winds over shallow bodies of water. Wind tides are capable of creating vast destruction when levees and dikes are not sufficient to withstand the combined action of wind tides and waves. For the proper design of shore protecting structures, the design engineer must be able to predict the most critical condition for the given locality. The problem has been treated by numerous investigators theoretically as well as empirically.

Wind tides and water surface slopes have been measured and analyzed in nature in the Baltic by Palmen¹/_{*} and Palmen and Laurila²/_/, and in numerous inland lakes by Hellstrom³/_/. The most complete data available for a large variety of conditions is the Lake Okeechobee data, obtained by the Corps of Engineers, U. S. Army⁴/_/. The latter data have been used by numerous investigators such as Hellstrom³/_/, Langhaar⁵/_/, Saville⁶/_/, etc., to develop or verify various theories concerning wind tides. Small scale laboratory investigations have been completed by Keulegan^{7,8}/_/, Hellstrom³/_/ and Francis⁹/_/. Dorn¹⁰/_/ has made a study in a large outdoor pond. Keulegan and Dorn, in their studies, demonstrated (by eliminating waves in some tests by the use of detergents) that two effects of the wind are involved: the surface traction of the wind, and the form resistance of the waves.

All of the laboratory investigations were completed, insofar as is known with a smooth bottom condition. For the natural bodies of water, however, the roughness of the bottom may have varied considerably; perhaps from being smooth sand on some occasions to being covered with dense vegetation on others. To study the effect of bottom roughness upon the characteristics of wind tides and the generation of waves, the experiments discussed below were completed using three different conditions of bottom roughness, i.e., a) smooth bottom, b) rough bottom, and c) rough bottom with strips of cheese cloth in the channel to simulate the effect of the roughness of vegetation in nature. Each of the conditions of roughness were combined with several depths of water.

DEFINITIONS

The definitions used in this report are shown in Figure 1.

- A — the angle between the wind direction and tidal axis (A = 0 for the laboratory studies).
- B — a coefficient in Boussinesq's formula expressing the roughness of the boundary.
- F — the fetch in feet; the distance from the leeward still-water shore line to the point the set-up was measured.
- H — wave height in feet.
- I — the gradient of the flow (Chezy formula).
- K — a coefficient in Boussinesq's formula which depends upon the characteristics of the fluid.
- M — a coefficient depending upon the flow velocity (for low velocities $M = 25$).
- MWL — the mean-water-level (see Figure 1).
- N — the planform factor which takes the converging or diverging planform of the lake or channel into consideration.
- R — hydraulic radius in feet.
- S — the difference in windward and leeward water-surface elevations in feet, when the bottom at the windward end is not exposed.

* Numbers indicated by _/ refer to references listed on page 38.

- S' — the elevation of the MWL at the leeward shore above the horizontal bottom when the bottom at the windward end is exposed.
- S_1 — set-up (difference in windward and leeward water surface elevations) due to the skin friction between wind and water surface.
- S_2 — set-up (difference in windward and leeward water surface elevations) due to the form resistance of the waves.
- U — the wind velocity in ft/sec.
- U_0 — the "formula characteristic velocity" in ft/sec. It is about 1.3 times the wind velocity necessary to start waves and was introduced by Keulegan⁽⁷⁾ and given as 14.4 ft/sec. for the depth of 0.13 foot; 13.75 ft/sec. for $d = 0.20$ ft.; 12.4 ft/sec. for $d = 0.26$ ft; 11.8 ft/sec. for $d = 0.36$ ft; and 11.5 ft/sec. for $d = 0.475$ ft.
- SWL — the still-water-level; the surface of the water if all wave and wind action were to cease.
- d — still-water depth in feet.
- g — the acceleration of gravity (32.17 ft/sec²).
- h — the wind set-up above SWL in ft. (the bottom at windward shore not exposed).
- h' — the wind set-up above SWL in ft. (the bottom at windward shore is exposed).
- k_s — equivalent sand roughness in feet.
- n — Manning's roughness coefficient.
- p — pressure in lbs/ft².

FIGURE 1.

u — wind velocity component in x-direction.
 u_1 — velocity at the boundary in Boussinesq's equation.
 u_s — the velocity at the water surface.
 v — velocity component in y-direction.
 w — velocity component in z-direction.
 x — distance along x-axis.
 y — distance along y-axis.
 z — distance along z-axis.
 z_s — the distance from the bottom to MWL.
 γ — unit weight of water.
 ϵ — eddy viscosity.
 λ — a coefficient depending upon the turbulence in flow.
 μ — coefficient of viscosity.
 ρ — density of the fluid.
 τ_b — shear stress on the bottom.
 τ_s — shear stress on the water surface.

THEORETICAL DEVELOPMENT

The analysis of wind tide data involves numerous variables which include the wind velocity and the energy transfer between the air and water, which in turn depend upon the wave conditions, temperature gradients, etc.^{11/}. The depth and the geometrical shape of the body of water and the configuration and roughness of the bottom are other factors of importance. The stratification (layers of different density) of water may influence the results considerably, and in very large bodies of water the rotation of the earth^{12,13,14/}, and the variation of atmospheric pressure to the surface elevation and directions of currents may also be important. To solve the problem theoretically, several assumptions must be made which include the flow conditions and viscosity at and near the air-water boundary. Several investigators have studied this problem using different approaches and assumptions. The most complete analysis so far available is that of Hellstrom^{3/}. In his treatment, he applied the Euler-Navier equation as given for the motion of a viscous incompressible fluid of a constant temperature, i.e.,

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

$$\text{and } \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0.$$

Here u , v , and w are the velocity components, parallel to the co-ordinate axes x , y , and z at the time t ; ρ is the density of fluid; p the pressure;

μ the coefficient of viscosity; and X, Y, and Z the components of Coriolis' forces due to the rotation of the earth and gravity. Coriolis' forces act at right angles to the direction of the velocity, toward the right in the northern, and toward the left in the southern hemisphere. When ω denotes the angular velocity of the earth (7.29×10^{-5}), and ζ the latitude, then for the northern hemisphere $X = -2 v \omega \sin \zeta$, and $Y = 2 u \omega \sin \zeta$. To solve Equation (1) the following assumptions are made: a) the flow is laminar, b) the depth is constant and small, c) the water surface slope is small, d) the pressure depends upon the depth below the surface only, e) the wind is constant, and f) the motion is steady and so the velocities are independent of time. Finally, the following expressions for the velocities u and v were obtained:

$$u = \frac{\gamma}{\mu} \frac{\partial z_s}{\partial x} \left(\frac{z^2}{2} - z_s z \right) + \frac{\tau_s}{\mu} z \quad (2)$$

$$v = \frac{\gamma}{\mu} \frac{\partial z_s}{\partial y} \left(\frac{z^2}{2} - z_s z \right). \quad (3)$$

For incompressible fluids:

$$\int_0^{z_s} u \, dz = 0 \quad \text{and} \quad \int_0^{z_s} v \, dz = 0 \quad (4)$$

hence

$$\frac{\partial z_s}{\partial x} - \frac{3}{2} \frac{\tau_s}{\gamma z_s} = 0 \quad \text{and} \quad \frac{\partial z_s}{\partial y} = 0 \quad (5)$$

or, as z_s is dependent on x only,

$$\frac{\partial z_s}{\partial x} = \lambda \frac{\tau_s}{\gamma z_s} \quad (6)$$

where $\lambda = 3/2$.

Equation (6) is the fundamental equation which is identical for the various investigators, regardless of the method of derivation, and is the basic formula for computing the wind effect. This formula demonstrates also that for lakes of shallow depth, the rotation of the earth has an insignificant effect on results. This is demonstrated also by the fact that Keulegan⁷ arrived at the same results, although he neglected the effect of Coriolis' force in the original equation. According to Ekman¹², the rotation of earth will reduce the gradient of water surface in the ratio of 0.98 when the depth of water is 150 to 300 feet; in the ratio 0.77 when the depth is 400 to 750 feet; and by 0.66 when the depth is infinite. For Lake Geneva, Forel¹⁵ found that the direction of surface current in the water was the same as that of the wind direction, and that the return current along the bottom had a direction opposite to that of the surface current. This demonstrates that in lakes of reasonable

size and depth, the rotation of the earth has a negligible effect on the direction of the currents.

A combination of Equations (2) and (3) with (5) gives the velocities u and v of the water particles, provided that laminar flow exists; i.e.,

$$u = \frac{3}{4} \frac{\tau_s}{\mu z_s} z^2 - \frac{\tau_s}{2\mu} z \quad (7)$$

$$v = 0. \quad (8)$$

The velocity distribution curve in Equation (7) is parabolic with zero velocities at $z = 0$ and $z = 2/3 z_s$, and the maximum return velocity at $z = 1/3 z_s$.

The distribution of velocities may be studied also by dividing the total current into a drift-(caused by the wind) and a gradient-current (caused by the set-up). For the drift current, the water surface remains horizontal and the pressure will be independent of x , so from Equation (1)

$$\mu \frac{d^2 u}{dz^2} = 0 \quad (9)$$

On the other hand, for the gradient current the pressure depends upon the gradient $\frac{\partial p}{\partial x} = \gamma \frac{\partial z_s}{\partial x}$ and Equation (1) gives

$$\mu \frac{\partial^2 u}{\partial z^2} = \gamma \frac{\partial z_s}{\partial x} \quad (10)$$

for the gradient current. The solution of Equations (9) and (10) gives

$$u = \frac{\tau_s}{\mu} z_s \quad (11)$$

for the drift current, and

$$u = \frac{\gamma}{\mu} \frac{\partial z_s}{\partial x} \left(\frac{z^2}{2} - z_s z \right) \quad (12)$$

for the gradient current. The mean velocity for the gradient current can be found by integrating Equation (12) between $z = 0$ and $z = z_s$, as

$$u_m = -\frac{1}{3} \frac{\gamma}{\mu} \frac{\partial z_s}{\partial x} z_s^2. \quad (13)$$

According to Equation (13), the mean velocity of the gradient current is directly proportional to the gradient $\frac{\partial z_s}{\partial x}$ of the water surface.

For turbulent flow, however, the mean velocity is proportional to the square root of the gradient as demonstrated by the Chezy formula.

The combination of Equations (11) and (12) gives the total velocity distribution, and is identical to Equation (2).

The same results as given by Equations (2), (6) and (7) can be obtained by considering the state of equilibrium of acting forces as demonstrated by Hellstrom^{3/} and illustrated in Figure 2. The equations were established by:

- (a) taking the sum of forces in x direction.
- (b) taking the sum of forces in y-direction.
- (c) taking the moments around point O.

FIGURE 2.

In Figure 2, P_1 and P_2 are the total pressure forces, and F_1 and F_2 the total shear forces on the sides of element dx , which can be computed for a viscous incompressible fluid of constant temperature according to the laws of hydrodynamics. $\tau_s dx$ is the wind force on the free surface, and $\tau_b dx$ is the frictional force

at the bottom. The resultant solution from this force balance is:

$$-\frac{dz_s}{dx} = \frac{2\tau_s}{\gamma z_s} - 2\mu \frac{u_s}{\gamma z_s^2} \quad (14)$$

Equation (14) demonstrates that the total gradient results from a combination of static-(first term) and flow-(second term) conditions. By replacing u_s (water surface velocity) in Equation (14) with an expression as found from Equation (7) for $z = z_s$, we obtain an equation identical to Equation (6).

Summarizing the findings for laminar flow, the equation for the water-surface gradient for limited bodies of water of reasonable depth is defined by Equation (6), and the frictional force per square unit at the bottom, τ_b , is half the value of the wind drag force, τ_s , on the surface. The coefficient, λ , in Equation (6) is equal to $3/2$ for laminar flow.

Turbulent Flow

Equation (6) was derived without consideration of turbulence, which exists in practically all important cases. Equation (13) demonstrates, as mentioned previously, that the mean velocity, u_m , caused by the set-up of the leeward end is directly proportional to the water surface gradient $\frac{\partial z_s}{\partial x}$. Chezy, however, established in 1775 the empirical formula for turbulent flow ($u_m = C\sqrt{RI}$) where the mean velocity is proportional to the square root of the gradient. Application of Equation (13) for turbulent flow gives values which are far too high. Any attempt to apply the theories

of laminar flow to turbulent flow will encounter the assumption that the coefficient of viscosity is constant and independent of the velocity. It is very difficult to establish average values for they vary with the flow condition throughout the fluid.

According to Boussinesq^{16,17,18/}, turbulent motion can be expressed by Equation (1) when, instead of a constant coefficient of viscosity, μ , a coefficient ϵ is introduced which depends upon the nature of fluid as well as upon the flow condition. is usually called the eddy viscosity. Boussinesq puts

$$\epsilon = \frac{\rho g}{K} \sqrt{B} z_s u_1 \quad (15)$$

where K is a coefficient depending upon the characteristics of fluid, B expresses the roughness of the boundary, and u_1 is the velocity at the boundary. Hellstrom^{3/}, by determining u_1 , obtains

$$\epsilon = \frac{z_s \sqrt{\gamma}}{K} \sqrt{\gamma \frac{dz_s}{dx} z_s - \tau_s} \quad (15a)$$

Rewriting the first part of Equation (1), then

$$\rho \left(\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} \right) = \rho X - \frac{\partial p}{\partial x} + \left[\frac{\partial}{\partial x} \left(\epsilon \frac{\partial u}{\partial x} \right) + \frac{\partial}{\partial y} \left(\epsilon \frac{\partial u}{\partial y} \right) + \frac{\partial}{\partial z} \left(\epsilon \frac{\partial u}{\partial z} \right) \right] \quad (16)$$

The rest of Equation (1) can be modified in an analogous manner. Assuming now that the coefficient of turbulence can be expressed through Equation (15), and that the frictional force at the bottom is equal to

$$\tau_b = \rho g B u_1^2 \quad (17)$$

the velocity distribution K obtained as

$$u = \frac{K \sqrt{\gamma}}{z_s \sqrt{\gamma \frac{dz_s}{dx} z_s - \tau_s}} \frac{dz_s}{dx} \frac{z^2}{2} - \frac{K}{z_s \sqrt{\gamma} \sqrt{\gamma \frac{dz_s}{dx} z_s - \tau_s}} \left(\gamma \frac{dz_s}{dx} z_s - \tau_s \right) z - \frac{\sqrt{\gamma \frac{dz_s}{dx} z_s - \tau_s}}{\sqrt{\gamma B}} \quad (18)$$

And finally, integrating the velocity u over the entire depth,

$$\frac{dz_s}{dx} = \lambda \frac{\tau_s}{\gamma z_s} \quad (19)$$

Equation (19) has exactly the same form as found for laminar flow. The coefficient varies, however, depending upon the flow condition. Hellstrom gives

$$\lambda = \frac{3}{2} \frac{(K \sqrt{B} + 2)}{(K \sqrt{B} + 3)} \quad (20)$$

When $K \sqrt{B} \rightarrow \infty$, then $\lambda \rightarrow 3/2$; this case represents the laminar flow condition, and Equation (20) is identical with Equation (6). When $K \sqrt{B} \rightarrow 0$, $\lambda \rightarrow 1$; hence

$$1 \leq \lambda \leq 1.5. \quad (21)$$

Boussinesq estimates for water, $K = 45 \text{ m}^{1/2}/\text{sec.}$ and

$$B = \frac{9}{(3 M R^{1/6} - K)^2} \quad (22)$$

where $M = 25$ for lakes where the velocity is low.

A combination of Equations (18) and (19) gives a different form of equation for the velocity u

$$u = \frac{K \lambda \tau_s}{2 \sqrt{\gamma} \sqrt{\tau_s (\lambda - 1)}} \left(\frac{z}{z_s} \right)^2 - \frac{K \sqrt{\tau_s (\lambda - 1)}}{\sqrt{\gamma}} \left(\frac{z}{z_s} \right) - \frac{\sqrt{\tau_s (\lambda - 1)}}{\sqrt{\gamma B}} \quad (23)$$

Equation 23 demonstrates that the velocity u is directly proportional to the square root of the wind force on the water surface, hence proportional to the wind velocity.

Applications of the Theory

Most investigators give the differential equation for the free water surface affected by a constant wind force in a form identical to Equation (19). The application of this equation to the computation of wind tides has various forms; that is,

1. Hellstrom integrates Equation (19) to get

$$z_s^2 = \frac{2 \lambda \tau_s}{\gamma} (x + C_1) \quad (24)$$

FIGURE 3.

Finally, the set-up, h , can be computed from Equation (26)

$$h = \sqrt{\frac{2\lambda\tau_s}{\gamma} (x + C_1)} - d. \quad (26)$$

The nodal-line can be computed from Equation (26) for $h = 0$.

When the depth is great as compared with set-up, Hellstrom gives the formula

$$h = \frac{\lambda\tau_s}{\gamma d} \left(x - \frac{F}{2}\right) \quad (27)$$

The nodal-line for (27) is at $x = F/2$ and the set-up at the windward shore, $x = 0$, is:

$$h_{x=0} = \frac{\lambda\tau_s F}{2\gamma d} \quad (28)$$

and at the leeward shore, $x = F$

$$h_{x=F} = \frac{\lambda\tau_s F}{2\gamma d} \quad (28a)$$

Equation (24) indicates that the water surface is parabolic in form and may be written in coordinates ζ and ξ as follows:

$$\zeta_s^2 = \frac{2\lambda\tau_s}{\gamma} \xi \quad (25)$$

Equation (25) is plotted in Figure 3. Hellstrom calls Equation (25) the "Characteristic Water Surface Parabola". The next step is to cut out a portion of the parabola in length F so that the area between the curve and the x -axis is equal to Fd (shaded area in Figure 3), where F is the length of the channel and d the still-water depth. The so-found distance between the z - and ζ -axis gives the constant C_1 as indicated in Figure 3. The case where the bottom is not exposed is represented by Figure 3a, and C_1 is a positive value. Figure 3b represents the case $C_1 = 0$, wherein the water surface at the beginning of the channel has the same elevation as the bottom. The case with an exposed bottom is given in Figure 3c, and here C_1 is negative.

2. Langham's analysis^{5/} is based on the momentum principle, separating the effect into statical and dynamical components. The statical tide is the tide that the wind would maintain if it persisted indefinitely; the tide due to the seiches is called the dynamical tide. He gives two different formulas for statical tides, depending upon the magnitude of the wind tides.

(a) For small tides where the bottom is not exposed he gives the formula:

$$h_x = F = \frac{\tau_s F}{2\gamma d} \quad (29)$$

where $h_x = F$ indicates the wind tide above the original still-water at the leeward shore. The formula is identical to Equation (28a), as presented by Hellstrom for $\lambda = 1$.

(b) For the case where part of the windward bottom is exposed:

$$S' = \sqrt[3]{\frac{3 \tau_s F d}{\gamma}} \quad (30)$$

S' in Equation (30) indicates the depth above the horizontal bottom, and at the leeward shore. The set-up above SWL is $h' = S' - d$. Equation (30) determines the statical tide in any lake that does not have a pronounced taper of planform, provided that the wind is so strong that the bottom is exposed at the windward end. This equation indicates that the depth of water at the leeward end of the lake varies as the two-thirds power of the wind velocity and as the cube root of the length of the lake.

The Jacksonville District, Corps of Engineers, U. S. Army^{19/} have found numerous applications for Equation (30). During their investigation it was found necessary, however, to change a constant in this equation. They give the formula as

$$h_x = F^1 = \sqrt[3]{\frac{3.373 \tau_s F d N}{\gamma}} - d \quad (31)$$

h' in this formula gives the set-up above SWL for the case when a portion of the windward bottom is exposed. N in Equation (31) is the so-called planform factor which takes into consideration the converging or diverging planform of the lake or channel. For the case where the body of water has a constant width, the planform factor $N = 1$. For a converging planform, $N > 1$, and for a diverging planform $N < 1$.

3. Keulegan^{7/} derives a differential equation for the water surface which is identical to that of Equation (19). He gives the definition for the coefficient λ as:

$$\lambda = \frac{\tau_b}{\tau_s} + 1 \quad (32)$$

For purely viscous laminar flow, $\lambda = 1.5$ and the equation takes an identical form with Equation (6). For turbulent flow Keulegan adopted temporarily the value, $\lambda = 1.25$.

In his experimental study, Keulegan separated the total set-up S into two parts; (a) S_1 , the set-up due to skin friction between wind and water surface; and (b) S_2 , the set-up due to the form resistance of the waves. S is defined as the difference between the water-surface elevations at the windward and the leeward ends of the channel.

$$S = S_1 + S_2. \quad (33)$$

The set-up without the wave action was found to be

$$S_1 = C_2 \times 10^{-6} \frac{U^2 F}{g d} \quad (34)$$

and the set-up due to the waves,

$$S_2 = C_3 \frac{(U - U_0)^2 F}{g d} \left(\frac{d}{F}\right)^{\frac{1}{2}} \quad (35)$$

Keulegan gives further, $C_2 = 3.3 \times 10^{-6}$, and $C_3 = 2.08 \times 10^{-4}$, so the total set-up will be

$$S = \left[3.3 \times 10^{-6} \frac{U^2}{g d} + 2.08 \times 10^{-4} \frac{(U - U_0)^2}{g d} \left(\frac{d}{F}\right)^{\frac{1}{2}} \right] F \quad (36)$$

U_0 is referred to by Keulegan as the "formula characteristic velocity", and is approximately 1.3 times the lowest wind velocity necessary to start waves. Keulegan determined U_0 as a function of water depth. The values given by him for U_0 are plotted in Figure 4, and are connected by a curve. Equation (36) was established using small-scale laboratory experiments.

Formula Characteristic Velocity vs. Depth of Water

FIGURE 4.

Keulegan states further that the critical wind velocity for the genesis of waves on a large body of water is about one third as great (somewhat more than 3 ft/sec.) as the corresponding values obtained in laboratory channels, and so U_0 may be omitted in Equation (36) without causing a large error. The set-up formula for the large bodies of water is then given as:

$$S = 3.3 \times 10^{-6} \left[1 + 63 \left(\frac{d}{F} \right)^{\frac{1}{2}} \right] \frac{U^2 F}{g d} \quad (37)$$

and it applies when the body of water approximates the shape of a rectangular channel of uniform cross-section.

4. In addition to the above formulas for wind tides in shallow water, there are a variety of other formulas which are generally identical in form but vary in the constants to be used. Among these the Zuider Zee formula should be mentioned. Originally the formula was given as 20

$$S = \frac{U^2 F}{800 d} \quad (38)$$

where S is again the difference in windward and leeward water-surface elevations, U is the wind velocity in miles per hour, F is the fetch in miles, and d the depth in feet. The formula (38) was later modified²¹ to

$$h = \frac{U^2 F}{1400 d} \cos A \quad (39)$$

Here h is the set-up in feet above the original still-water elevation at the leeward end, U is in miles per hour, F is in miles, and d is in feet. A is the angle between the wind and tidal axis.

The Beach Erosion Board formula (6) was presented as:

$$S = \frac{k \lambda \rho_a U^2 F}{\rho g d} \cos A \quad (40)$$

S represents here the difference in water-surface elevations at windward and leeward sides of the lake, ρ_a is the air density, k is a numerical constant approximately equal to 0.003, λ is as defined above in Equation (32) and A denotes the angle between the wind and the fetch.

LABORATORY EQUIPMENT AND PROCEDURE

Experiments were performed in a channel 1 foot wide, 60 feet long and 1.28 feet deep, as shown in Figure 5a. The length of the channel was about 60 feet, essentially the same as that used by Keulegan⁷, but the width (1 foot) was approximately three times greater and the depth (1.25 feet) somewhat larger than that used by Keulegan (0.93 foot). 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, driven by an a.c. motor. The wind velocities could be varied from 0 to approximately 50 ft/sec. by varying the air intake area at the blower. To straighten the wind flow upon entering the channel, a honeycomb was set between the blower and the channel. To guide the wind gradually on and off the water surface, a sloping beach (slope approximately 1:15) was set at the beginning and the end of the channel, as shown in Figure 5a. The downwind (leeward) beach served also as a wave absorber to reduce the effect of wave reflection. The discharge of air was measured by a Venturi meter mounted as shown in Figure 5a. The Venturi meter was used to obtain approximately the desired wind velocity. The final wind velocity measurements were made, however, by using Pitot tubes mounted on point gages.

Piezometer openings were installed on the top and the bottom of the channel at five locations along the centerline. The openings were connected to Piezometers, as shown in Figure 5b, so that both the water depth and the total pressure, above atmospheric, could be read directly. The difference between the two readings gave the inside air pressure, and the drop in pressure between successive piezometers was used to determine corrections to be applied to the measured water-surface profiles. To check the latter measurement, three draft gages were connected to the piezometer opening on the top of the channel at the locations of micropiezometers 1, 3, and 5 as shown in Figure 5a, and the pressure readings were made simultaneously with those of the micropiezometers. These two readings always agreed very closely. Any difference indicated a faulty connection or a clogging of the piezometer opening, and corrections were made at once.

The wave heights and periods were measured at four locations, as indicated in Figure 5a, by the use of parallel-wire resistance elements connected to Brush recorders. A section of the channel is pictured in Figure 6. The photograph shows a piezometer, pitot tube, draft-gage, and a wave gage with a brush recorder.

Procedure

The desired wind velocity was obtained by adjusting the air inlet or the blower to the proper size. The blower then was shut off and the ends of the channel were closed so that no air movement could occur in the channel and influence the initial still-water elevation. When the water surface had calmed completely, the still-water elevation was determined at the location of each of the five piezometers. The blower then was started and the wind velocity profiles obtained at the three locations along the channel, as shown in Figure 5a. In later tests, only the wind velocity profile at the middle of the channel was obtained. After letting the blower run at least a half an hour, and when there was every indication that the flow condition had stabilized the surface profile was measured. Because of side wall friction and the energy transfer from wind to waves, the pressure in the channel drops gradually as the wind passes through the channel, and the measured water-surface profiles are

FIGURE 5 - GENERAL LABORATORY SET-UP FOR STUDY OF WIND TIDES IN SHALLOW WATER

FIGURE 6 · A SECTION OF THE CHANNEL SHOWING MICROPIEZOMETER (1), PITOT TUBE (2), DRAFT GAGE (3), WAVE GAGE (4), AND BRUSH RECORDERS (5)

FIGURE 7 · EXPANDED METAL LATH USED FOR CHANNEL BOTTOM ROUGHNESS

FIGURE 8 · CHEESECLOTH STRIPS USED IN CHANNEL TO SIMULATE VEGETATION

the result of combined action of wind drag and pressure differences. To eliminate the effect of the variable pressure, the pressures were measured at each of five piezometers, as already described, and the measured surface profiles were corrected using the average pressure from these five measurements as their basis.

Experiments were performed using three different bottom roughnesses.

1. A smooth bottom was represented by the original bottom, painted with white oxide primer paint. The roughness for this type of bottom was determined in a laboratory flume and was found to be $k_s = 0.0135$ foot in equivalent sand roughness, and the Mannings $n = 0.0116$. The experiments were completed with eight different depths (0.05; 0.075; 0.100; 0.150; 0.200; 0.250; 0.300; and 0.370 ft.) each of which was combined with 5 different wind velocities (approximately 11; 15; 20; 25; and 33 ft/sec.).

2. A rough bottom condition was obtained by covering the smooth painted bottom with a $7/8$ in. expanded metal lath, as shown in Figure 7. The equivalent sand roughness k_s was found to be 0.0635 foot, and the Mannings $n = 0.0207$. The experiments were made with 5 different depths (0.050; 0.075; 0.100; 0.200; and 0.370 ft.) each combined with five different wind velocities.

3. A combination of the rough bottom and cheese cloth in the channel was introduced to simulate the roughness effect of vegetation in nature. The cheese cloth was fastened to the bottom across the entire width of the channel. The top of the cloth was made to float by the use of a thin piece of balsawood. The buoyancy of the cloth was kept to a minimum so that it could easily follow the current and the motion of water particles, as do natural grasses. The height of the cloth was approximately 0.30 foot, and constant for all runs; hence, for the deepest depth of 0.37 foot used in the experiments, the top of the cloth was slightly below the SWL and for shallower depths it floated at SWL. One piece of cloth was used for each linear foot of channel. The arrangement is shown in Figure 8.

The experiments for this condition were performed using four different depths (0.05; 0.10; 0.20; and 0.37 ft.) each combined with the same five wind velocities used in the previous experiments.

RESULTS AND DISCUSSION

The basic data are summarized in Table I and the water-surface profiles plotted in Figures 9-11. (Table I appears at end of report.)

The water surface profiles were found to be parabolic, as was to be expected. The parabolic shape of the profiles was most pronounced for the combination of shallow water depths and high wind velocities. For the case of relatively deep water and relatively low wind velocities, the parabolic shaped water surface was found to be relatively flat, and could

a.

b.

c.

d.

FIGURE 9, a-d · SURFACE PROFILES

e.

f.

g.

h.

FIGURE 9, e-h · SURFACE PROFILES

FIGURE 10 SURFACE PROFILES

U = Wind velocity in feet/second Channel with rough bottom and cheesecloth weeds
Beach slopes 1:15

FIGURE 11. SURFACE PROFILES

FIGURE 12. COMPARISON OF MEASURED WATER SURFACE PROFILES WITH THEORY

with sufficient accuracy be replaced by a plane (compare with assumptions for Equations 27 and 28). The theoretical water surface profiles as given by Equation (24) were compared with laboratory measurements in Figure 12 for two depths and three conditions of bottom roughness. The wind shear stress τ_s in Equation (24) was evaluated from wind velocity profiles as previously described (11). The coefficient λ was also determined experimentally (11). The values for τ_s and λ in Equation (24) were obtained from Table I, Reference 11, under the given run numbers, as were the actual measurements for the given run. The constant C_1 was evaluated by the method given by Hellstrom^{3/}, and described by Equation (24). The agreement between the actual measurements and the theory was found to be good except for Run 70 in Figure 12e, where the measured profile was about 30 percent steeper than the theory indicated. For cases with exposed bottom, the extent of exposure was not always predicted accurately, and it seemed that the extent of exposure was greater than the theory predicted. This may be a phenomenon which depends upon the experimental condition and such effects as surface tension, etc. In laboratory experiments it is very hard to determine the exact location of the water line on a level bottom. Also the surface tension may have a considerable effect in the very shallow region. The observed water

FIGURE 13.

velocity distribution curves in Figure 14 for depths 0.37 foot and 0.11 foot. No attempt was made to measure the actual flow velocities. Various qualitative observations (observing the motion of tiny particles)

surface in the region of the water line has very often the shape shown by the heavy line in Figure 13, and the water line is determined at a' instead of a .

The velocity distribution of the water flow is given by Equation (23) for turbulent flow. This equation was used to plot the theoretical

FIGURE 14.

indicated, however, that the flow in wind direction was concentrated in

a narrow region just below the water surface. The velocities on the water surface seemed to be higher than predicted by the theory, declining rapidly with depth. The approximate observed velocity distribution curve has been indicated in Figure 14. The curve should be considered as qualitative only, and as such it indicates the shape of the curve, but not the absolute values of velocity.

Current directions and intensities can be visualized by a study of Figures 15 to 17, where strips of cheese-cloth were used to simulate vegetation. Figures 15 and 16 represent the case of relatively deep water (0.37 ft.) as compared with the height of the cloth, and the top of the cloth (approximately 0.30 ft. high) floats slightly below the still-water surface (see Figure 16a). When the wind velocity was increased, the magnitude of the drift and return flow also increased. The effect of the return flow along the bottom was to incline the cloth in the direction opposite to that of the wind (marked with an arrow in the pictures). The effect of the return current was to pull the buoyant top of the cloth below the water surface. At higher wind velocities, the entire cloth was subjected to the action of the return flow (see Figures 15 and 16 c;d). In Figure 17 the water is shallow (0.10 ft.) as compared with the height of the cloth (0.30 ft.). For lower wind velocity the cloth usually became inclined in the same direction as the wind, but at times it became inclined in the opposite direction (see Figure 17a), depending upon the buoyancy at the top of the cloth. In some cases the balsawood on the top of the cloth extended out of the water and was subjected to additional wind drag. When the wind velocity was increased above a certain magnitude, return flow was great enough to pull the top of the cloth below the water surface and out of the region of drift. Under these circumstances, the cloth reversed direction and inclined in the direction opposite to that of the wind (see Figure 17b).

In most practical cases, one is not as interested in the exact shape of the water surface profile as in the maximum elevations to be expected along the leeward shores. Because of this, only the set-up near the leeward shore is considered in the following discussion. The set-ups were measured at the location of Piezometer 5 (see Figure 5a) which was located near the toe of the leeward beach in a constant depth of water. The fetch, F , is the distance from the still water beach line at the windward shore to the point of measurement at Piezometer 5. The relationship between set-up and wind velocity is presented in Figures 18 and 19. It can be seen that smooth curves fit the experimental points in a satisfactory manner. In Figure 20 the set-up as a function of the depth of water is given for 5 different wind velocities (10; 15; 20; 25; and 30 ft/sec.). The correlation between runs with slightly different wind velocities and fetch lengths was obtained by graphical interpolation of the experimental values. Figure 20 demonstrates clearly that the set-up increases rapidly when the depth of water decreases below a certain value. This "critical" depth seems to be related to wind velocity with the stronger the wind, the deeper the critical depth.

The various theoretical formulas, as discussed in a previous section, were compared with experimental results in Figures 21 and 22. In general,

FIGURE 15 · RELATIVELY DEEP WATER
AS COMPARED WITH THE LENGTH OF CLOTH

FIGURE 16 · CLOSE-UP OF CLOTH

FIGURE 17 · RELATIVELY SHALLOW WATER
AS COMPARED WITH THE LENGTH OF CLOTH

FIGURES 15, 16, 17 · CONDITION WITH CHEESECLOTH
IN CHANNEL TO SIMULATE VEGETATION

FIGURE 18 · WIND SET-UP AS A FUNCTION OF
WIND VELOCITY FOR VARIOUS BOTTOM ROUGHNESSES

FIGURE 19. WIND SET-UP AS A FUNCTION OF WIND VELOCITIES FOR SEVERAL DEPTHS AND ROUGHNESSES

FIGURE 20 · WIND SET - UP AS A FUNCTION OF DEPTH FOR SEVERAL WIND VELOCITIES

Fig. 21

Fig. 22

COMPARISON OF VARIOUS THEORIES WITH EXPERIMENTAL LABORATORY RESULTS

the formulas could be divided into two groups: (a) the formulas giving the difference S between the water-surface elevation at the windward and the leeward shore, and (b) the formulas giving the set-up, h , at the leeward shore above the SWL. In addition to these two groups, the Langhaar exposed bottom formula, as given by Equation (30) should be considered separately. The set-up in this formula is essentially the difference between the windward and leeward water-surface elevations, but the windward water-surface elevation must be taken in this case to be the elevation of the exposed horizontal bottom. Because the bottom is horizontal, this elevation remains a constant for all conditions of exposed bottom. Plotting the set-up against the wind velocity (Figure 21a), Langhaar's formula for exposed bottom results in a curve which has a slope that decreases with increasing wind velocity. The other formulas for non-exposed bottoms result in a curve with a slope which increases as the wind velocity increases. To distinguish between the exposed bottom and the non-exposed bottom formulas, the set-up as measured above the horizontal bottom for exposed bottom formulas is indicated by S' and the set-up above the SWL is indicated by h' , rather than S and h .

The formulas in groups (a) and (b) cannot always be interchanged by setting $S = 2h$. This can be done only when the wind effect is small; that is, when the surface profile approaches a straight line and the nodal point is located half way between the windward and leeward shore. When the wind effect increases, the profile will assume a parabolic shape and the nodal point will move toward the windward shore, as can be seen from Equation (26) and as has been demonstrated by the laboratory experiments (Figures 9 to 11).

Group (a) is represented in Figures 21a and 22a. The experimental curves in these figures were plotted using data from Figures 9 a-e. The experimental data were compared with the Langhaar and the Keulegan theories, and the Zuider Zee formula. Keulegan's formula seems to fit the data the best when the water is not too shallow and the surface profile approaches more or less a straight-line. Langhaar's formula gives a better fit for cases with very shallow water, as is the case shown in Figure 21a. Keulegan's formula is also fairly reliable in this case, provided that the bottom is not exposed. For exposed bottom conditions, use of Keulegan's formula may lead to overestimation of the set-up, depending upon the degree of exposure. Langhaar's theory shows good agreement when the curve of the non-exposed bottom theory is followed until it intersects the curve of the exposed bottom theory and then the latter is followed. The exposed bottom theory seems to give somewhat smaller values than measured, so that the change of the constant 3.0 in Equation (30) to 3.373, as introduced by the Corps of Engineers in Equation (31), may be recommended. The wind shear stress τ_s in Langhaar's formula was taken from Figure 11 of Reference 11., and represents an average of the actual measurements for the same experiments and conditions. For different cases, the accuracy of prediction will obviously depend very much upon the proper estimation of wind shear stresses at the water surface.

U_0 , in Keulegan's formula, was given in Reference 7 for five different depths of water. These data were plotted in Figure 4 in this report and a smooth curve was drawn through them. This curve was used to determine U_0 for the given particular cases.

The Zuider Zee formula as given by Equation (38) also has been compared with measurements (Figures 21a and 22a). It can be seen in both figures that use of the formula leads to an underestimation of the set-up for laboratory experiments.

The set-up, h , above the SWL has been compared with the formulas of group (b) in Figures 21b and 22b. Langhaar's formula actually belongs to group (a), but as has been pointed out, $S = 2h$ when the surface profile approaches a straight line. The experimental data were obtained at the location of Piezometer 5 and plotted as given in Table I.

The revised Zuider Zee formula (Equation 39) gives the best agreement for shallow water (Figure 21b), while for deeper water it leads to underestimations of the set-up for laboratory experiments. Use of Langhaar's formula leads to overestimations of the set-up for shallow water. The overestimation may be due to the assumption that $h = S/2$. In actual cases, however, $h < S/2$ when the wind effect is large as compared with the depth of water. In deep water, use of Langhaar's formula seems to lead to underestimation of the set-up, especially for higher wind velocities.

Langhaar's theory does not consider the increase in form drag due to the presence of waves. In shallow water the wave heights are usually small and so the increase in form drag may be negligible, while in deeper water and for higher waves, it has to be included in computations. This is demonstrated in Figure 22a, where use of Langhaar's formula leads to underestimations of set-up for higher wind velocities, while use of Keulegan's formula, where the increase in form drag due to the waves is included, leads to results which fit the experimental curve very closely.

The effect of bottom roughness has been demonstrated in Figures 18 to 20. When the bottom roughness was increased from $n = 0.012$ for the smooth bottom to $n = 0.021$ for the bottom covered with expanded metal lath, the set-up at the leeward end did not change, except for very shallow depths, as has been shown in Figure 18 a and 20. For the shallowest still-water depth (0.05 foot) used in this set of experiments, the set-up was further increased by adding cheese cloth in the channel to simulate vegetation; then the shape of the curve indicating the set-up in Figure 20 was changed slightly. Figure 20 indicates that for deeper water depths the set-up may be smaller than for the smooth bottom, but in shallow water it seems to be definitely higher. For the depth 0.05 foot the set-up was approximately 20 percent higher than the set-up for the smooth bottom. The slope of the set-up curve was steeper when the cheese cloth was present than was the slope of the set-up curve for the smooth bottom.

Qualitative observations indicated that the time necessary to reach equilibrium set-up at the leeward end of the channel was longer for the

rougher bottom. For the experiments with cheese cloth, it was found that the time to reach equilibrium was much longer than was the case for the experiments with the smooth bottom. On the other hand it was found that the roughness acted to dampen oscillations. For the smooth bottom the set-up usually exceeded for a short time the equilibrium position when the wind was started, and came to rest only after many oscillations about the equilibrium. When the blower was turned off a bore was established which was reflected back and forth in the channel many times. The bottom roughness acted to dampen this bore so that the water surface became calmed much more rapidly for rough bottom conditions than for the smooth bottom.

Natural lake beds are very often covered with reeds and saw-grass which may be very dense and extend a considerable distance above the water surface; even the wind distribution and intensity above the lake may be affected. The reeds and saw-grass cannot follow the flow as easily as seaweed does (Figures 15 to 17), and so the flow may be considerably different for this condition. At the present time there are no data available to indicate what effect these types of vegetation have on wind tides. Further study should cast more light on this important phase of the problem.

Derivation of an Empirical Relationship

A consideration of the various terms of the formulas shows that the following dimensionless arrangement can be used to represent the relationship between the set-up and the other variables:

$$\left(\frac{h}{d}\right) = f'\left(\frac{U^2}{Fg}\right) .$$

These dimensionless parameters were used to plot all the data on a log-log scale in Figure 23. The experimental points in this figure fit a family of straight lines fairly well, indicating that the relationship has the following form:

$$\left(\frac{h}{d}\right) = f(F/d) \left(\frac{U^2}{Fg}\right)^a \quad (41)$$

The " $f(F/d)$ " and " a " were evaluated from Figure 23 for various conditions and replotted in Figure 24 as functions of the fetch-depth relationship. There is some scatter of experimental points in Figure 24, but in general the points fit a straight line. By extending the data beyond the laboratory limits, the average line in Figure 24a was used to determine " $f(F/d)$ " for Lake Okeechobee, Baltic and Ringskobing Fjord. Using the available data for the above named bodies of water, 3,4,6,22 an average value for " a " was computed for each case and plotted in Figure 24b. The points so determined closely fit the same straight line as determined by the laboratory experiments. Provided that the relationship is valid for other conditions in nature, one could determine from Figure 24 " $f(F/d)$ " and " a " for the given fetch-depth relationship F/d . Applying

FIGURE 23 · h/d versus U^2/Fg

FIGURE 24 · F/d versus $f(F/d)$ & a versus F/d

this value in Equation (41), the set-up can be predicted. To simplify the computations, Equation (41) together with Figure 24 were used to draw a nomographic chart (Figure 25, Parts I and II). Figure 25, Part I can be used for laboratory experiments and for the smaller bodies of water, while Part II of Figure 25 is useful for larger lakes.

To describe the applications of Figure 25, the following three examples are given:

1. Assume that we are using the nomographic chart to predict the set-up in a laboratory channel similar to that used in our experiments. The data are as follows: Wind velocity, $U = 25$ ft/sec.; Fetch, $F = 45$ ft.; and depth of still water, $d = 0.10$ ft. From these data: $U^2/Fg = 4.32 \times 10^{-1}$ and $F/d = 450$.

Enter the left side of Figure 25, Part I, with $U^2/Fg = 4.32 \times 10^{-1}$ and turn the ray by 90 degrees (as shown by the dotted line) each time it meets the line for $F/d = 450$ until we obtain $h/d = 0.21$ in the right portion of the chart. Knowing $d = 0.10$ foot, we compute $h = 0.021$ foot. Comparison with Figure 20 indicates that this value agrees very closely with the measured value.

2. Using the graph for a large lake, we use Part II of Figure 25. Let us assume $U = 50$ ft/sec.; $F = 35$ mi. $= 185,000$ ft.; $d = 8.0$ ft. From this data we have $U^2/Fg = 4.20 \times 10^{-4}$, and $F/d = 23,100$. Entering the graph with the given U^2/Fg , we obtain $h/d = 0.278$, hence $h = 2.23$ ft.

3. For the third example, let us assume that the lake is the same as in Example 2, but the wind velocity is $U = 80$ ft/sec. Hence we have $U^2/Fg = 1.08 \times 10^{-3}$ and $F/d = 23,100$. The resultant $h/d = 0.67$, and $h = 5.35$ ft.

The graphs in Figure 25 may be used for lakes with uniform or nearly uniform depths and widths across the entire fetch, and the tide axis parallel to the wind direction.

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FIGURE 25-a · NOMOGRAM FOR THE DETERMINATION OF WIND TIDES
PART I

FIGURE 25-b · NOMOGRAM FOR THE DETERMINATION OF WIND TIDES
PART II

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TABLE I - SUMMARY OF DATA

RUN NO.	DATE	BOTTOM ROUGHNESS	WATER DEPTH, d — feet	AVE. WIND VELOCITY, U — feet/second	AIR TEMPERATURE — °F	BAROMETRIC PRESSURE — inches of Hg	UNIT WT. OF AIR — pounds/foot ³	PT. OF MEASUREMENT FROM STILL WATER SHORELINE — feet	CORRECTED CHANGE IN SURFACE ELEV. DUE TO WIND EFFECT — feet x 10 ⁻²	DIST. FROM WINDWARD SHORE TO 1st RIPPLES — ft.	HORIZ RETREAT OF WINDWARD SHORELINE — feet	HORIZ. ADVANCE OF LEEWARD SHORELINE — feet
1	2	3	4	5	6	7	8	9	10	11	12	13
1-5	1953 Nov. 2	These runs were made to study the characteristics of the channel; no water involved.										
6	10	smooth	0.096	23.0	57	30.030		4.36 14.37 24.38 34.38 44.38	-1.48 -0.49 0.187 0.74 1.22			
7	11	smooth	0.10	13.7	63.5	30.132		4.46 14.47 24.48 34.48 44.48	-0.427 -0.194 0.016 0.292 0.331			
8	12	smooth	0.0985	9.80	62	30.084		4.46 14.47 24.48 34.48 44.48	-0.254 -0.122 -0.0098 0.115 0.220			
9	Dec. 22	smooth	0.072	34.5	54	30.408		4.26 14.27 24.28 34.28 44.28	bottom exposed -1.43 -0.97 2.41 3.52			
10	23	smooth	0.068	33.8	60	30.593		4.25 14.26 24.27 34.27 44.27	-- -1.22 0.85 2.26 3.31			
11		smooth	0.060	37.0	58	30.594		4.24 14.25 24.26 34.26 44.26	bt'm expos'd — 0.872 3.179 5.347			

Table I (cont.)

RUN NO.	DATE	BT'M RGH'NESS	d - feet	U - ft./sec.	AIR TEMP. - °F	BAR. PRESS. - in. of Hg	UNIT WT. OF AIR - lbs./ft. ³	PT. OF MEASURE, - feet	CHANGE IN SURF. ELEV. - ft. x 10 ⁻²	DIST. TO 1st RIPPLES - feet	HORIZ. RETREAT - feet	HORIZ. ADVANCE - feet
1	2	3	4	5	6	7	8	9	10	11	12	13
12	1954 Jan. 14	smooth	0.370	10.05	55	30.150		7.01 17.02 27.03 37.03 47.03	-0.140 -0.065 0.098 0.040 0.106			
13	15	smooth	0.368	14.10	52.5	30.206		7.18 17.19 27.20 37.20 47.20	-0.156 -0.047 0.028 0.038 0.104			
14		smooth	0.367	19.25	52.5	30.206		7.21 17.22 27.23 37.23 47.23	-0.251 -0.113 0.028 0.280 0.543			
15		smooth	0.365	25.6	52.5	30.206		7.21 17.22 27.23 37.23 47.23	-0.755 -0.374 0.075 0.500 1.200			
16	18	smooth	0.367	33.4	48.4	29.970		7.13 17.14 27.15 37.15 47.15	-2.56 -1.18 0.25 1.03 2.43			
17	20	smooth	0.300	33.0	53.0	30.012		6.46 16.47 26.48 36.48 46.48	-1.89 -1.39 0.030 0.780 1.83			
18		smooth	0.301	25.2	53.0	30.012		6.34 16.35 26.36 36.36 46.36	-0.89 -0.45 0.05 0.51 0.85			
19	21	smooth	0.300	20.3	48.0	30.334		6.39 16.40 26.41 36.42 46.42	-0.54 -0.28 +0.00 0.30 0.54			

1	2	3	4	5	6	7	8	9	10	11	12	13
20	21	smooth	0.301	16.30	48	30.334		6.36 16.37 26.38 36.38 46.38	-0.26 -0.11 0.03 0.16 0.26			
21	22	smooth	0.301	11.20	48	30.050		6.39 16.40 26.41 36.42 46.42	-0.09 -0.03 0.02 0.04 0.09	7.00	0.03	0.08
22	25	smooth	0.251	31.2	52.5	30.174		5.81 15.82 25.83 35.83 45.83	-2.354 -1.190 -0.067 1.094 2.124	0.80	0.45	1.30
23		smooth	0.251	25.0	52.5	30.174		5.89 15.90 25.91 35.91 45.91	-1.011 -0.532 -0.082 0.515 0.907	1.50	0.23	0.70
24	26	smooth	0.251	20.4	50.0	30.318		5.81 15.82 25.83 35.83 45.83	-0.639 -0.334 -0.068 0.150 0.611	2.35	0.13	0.46
25	Feb. 15	smooth	0.250	15.2	53.5	30.260		5.84 15.85 25.86 35.86 45.86	-0.321 -0.138 -0.010 0.138 0.240	3.60	0.08	0.16
26	16	smooth	0.251	11.1	48.3	30.068		5.73 15.74 25.75 35.75 45.75	-0.141 -0.062 +0.00 -0.039 0.141	6.40	--	--
27		smooth	0.200	10.7	48.3	30.068	0.0771	5.39 15.40 25.41 35.41 45.41	-0.203 0.009 0.039 0.157 0.229	6.50	0.08	0.05
28	18	smooth	0.200	15.80	57	30.492	0.0780	5.36 15.37 25.38 35.38 45.38	-0.364 -0.151 -0.036 0.112 0.410	3.50	0.02	0.14

Table I (cont.)

RUN NO.	DATE	BT'M RGH'NESS	d - feet	U - ft./sec.	AIR TEMP. - °F	BAR. PRESS. - in. of Hg	UNIT WT. OF AIR - lbs./ft. ³	PT. OF MEASURE. - feet	CHANGE IN SURF. ELEV. - ft. x 10 ⁻²	DIST. TO 1st RIPPLES - feet	HORIZ. RETREAT - feet	HORIZ. ADVANCE - feet
1	2	3	4	5	6	7	8	9	10	11	12	13
29	1954 Feb. 18	smooth	0.200	20.0	57	30.492	0.0784	5.36 15.37 25.38 35.38 45.38	-0.787 -0.426 -0.0426 0.312 0.705	2.25	0.17	0.22
30	19	smooth	0.201	24.3	62.4	30.510	0.0784	5.35 15.36 25.37 35.37 45.37	-1.145 -0.568 0.039 0.604 1.037	1.15	0.22	0.42
31	23	smooth	0.202	30.5	68.2	30.326	0.0754	5.38 15.39 25.40 35.40 45.40	-2.45 -1.238 -0.112 1.187 2.203	--	--	--
32	25	smooth	0.153	28.7	74.0	30.128	0.0753	4.91 14.92 24.93 34.93 44.93	-3.045 -1.391 0.187 1.565 2.736	0.65	0.65	1.00
33		smooth	0.152	24.0	74.0	30.128	0.0745	4.83 14.84 24.85 34.85 44.85	-1.453 -0.646 0.105 0.781 1.401	0.90	0.22	0.55
34	26	smooth	0.151	20.5	69.8	30.084	0.0766	4.78 14.79 24.80 34.80 44.80	-0.906 -0.433 0.056 0.512 0.892	2.80	0.09	0.27
35		smooth	0.151	15.5	69.8	30.084	0.0751	4.78 14.79 24.80 34.80 44.80	-0.518 -0.312 -0.008 0.210 0.443	3.70	0.02	0.22
36		smooth	0.151	10.9	69.8	30.084	0.0750	4.80 14.81 24.82 34.82 44.82	-0.217 -0.135 -0.043 0.069 0.174	5.40	0.02	0.07

1	2	3	4	5	6	7	8	9	10	11	12	13
37	Mar. 1	smooth	0.101	31.5	68.3	29.926	0.0747	4.32 14.33 24.34 34.34 44.34	-5.384 -1.788 0.722 2.717 4.606	0.50	2.56	1.45
38		smooth	0.101	24.4	68.3	29.926	0.0742	4.23 14.24 24.25 34.25 44.25	-2.113 -0.846 0.203 1.132 1.890	1.00	0.22	0.43
39	2	smooth	0.101	20.4	69.8	29.948	0.0757	4.25 14.26 24.27 34.27 44.27	-1.246 -0.521 0.124 0.715 1.207	1.90	0.13	0.27
40		smooth	0.101	15.8	69.8	29.948	0.0753	4.28 14.29 24.30 34.30 44.30	-0.751 -0.318 0.059 0.377 0.696	4.0	0.02	0.18
41		smooth	0.101	11.4	69.8	29.948	0.0751	4.25 14.26 24.27 34.27 44.27	-0.299 -0.157 0.033 0.131 0.295	6.8	0.01	0.03
42	3	smooth	0.051	30.3	52.3	30.072	0.0771	3.86 13.87 23.88 33.88 43.88	bottom exposed 0.548 3.278 5.367	0.40	17.00	1.02
43		smooth	0.051	23.9	52.3	30.072	0.0772	3.79 13.80 23.81 33.81 43.81	bottom exposed -1.253 0.709 2.136 3.150	1.20	7.63	0.47
44		smooth	0.051	19.9	52.3	30.072	0.0768	3.81 13.82 23.83 33.83 43.83	-2.546 -0.787 0.417 1.401 2.175	2.40	2.15	0.37
45	4	smooth	0.051	16.0	51.5	30.248	0.0780	3.81 13.82 23.83 33.83 43.83	-1.207 -0.436 0.220 0.804 1.335	5.00	0.16	0.18

Table I (cont.)

RUN NO.	DATE	BT'M ROUGHNESS	d - feet	U - ft./sec.	AIR TEMP. °F	BAR. PRESS. - in. of Hg	UNIT WT. OF AIR - lbs./ft. ³	PT. OF MEASURE. - feet	CHANGE IN SURF. ELEV. - ft. x 10 ⁻²	DIST. TO 1st Ripples - feet	HORIZ. RETREAT - feet	HORIZ. ADVANCE - feet
1	2	3	4	5	6	7	8	9	10	11	12	13
46	1954 Mar. 4	smooth	0.051	11.2	51.5	30.248	0.0778	3.80 13.81 23.82 33.82 43.82	-0.584 -0.223 0.108 0.394 0.577	12.5	0.06	0.03
47	Apr. 15	smooth	0.073	12.25	68.0	30.202	0.0755	4.08 14.09 24.10 34.10 44.10	-0.37 -0.17 0.03 0.10 0.36	5.7	0.04	0.08
48		smooth	0.073	17.25	74.0	30.202	0.0747	4.08 14.09 24.10 34.10 44.10	-0.95 -0.46 0.03 0.47 0.95	3.75	0.11	0.25
49		smooth	0.074	21.95	71.0	30.202	0.0750	4.08 14.09 24.10 34.10 44.10	-1.79 -0.81 0.04 0.70 1.53	1.70	0.26	0.36
50		smooth	0.074	25.80	71.0	30.202	0.0750	4.08 14.09 24.10 34.10 44.10	-2.93 -1.19 0.15 0.86 2.31	--	0.43	0.52
51	16	smooth	0.073	32.65	69.0	30.342	0.0753	4.08 14.09 24.10 34.10 44.10	bottom exposed -2.20 0.84 3.11 5.25	0.20	8.93	1.25
52	19	rough	0.073	11.80	65.0	30.048	0.0756	4.01 14.02 24.03 34.03 44.03	-0.52 -0.22 0.03 0.31 0.49	6.0	0.04	0.05
53	20	rough	0.074	16.85	59.0	30.118	0.0767	4.07 14.08 24.09 34.09 44.09	-1.06 -0.53 0.10 0.56 0.97	4.50	0.12	0.16

1	2	3	4	5	6	7	8	9	10	11	12	13
54	Apr. 20	rough	0.074	21.15	63.0	30.118	0.0761	4.04 14.05 24.06 34.06 44.06	-2.02 -0.86 0.18 0.95 1.63	2.0	0.24	0.26
55		rough	0.074	25.60	63.0	30.118	0.0761	4.00 14.01 24.02 34.02 44.02	-3.93 -1.39 0.44 1.73 2.43	0.75	2.79	0.44
56		rough	0.074	31.80	63.0	30.118	0.0761	4.01 14.02 24.03 34.03 44.03	bottom exposed -3.22 0.96 3.58 5.77	0.20	12.35	1.43
57	21	rough	0.051	11.75	58.0	30.020	0.0765	3.86 13.87 23.88 33.88 43.88	-0.94 -0.40 0.02 0.38 0.69	10.0	0.16	0.16
58		rough	0.051	16.70	63.0	30.020	0.0758	3.84 13.85 23.86 33.86 43.86	-1.86 -0.68 0.11 0.84 1.44	5.20	1.25	0.18
59		rough	0.050	21.25	67.0	30.020	0.0752	3.74 13.75 23.76 33.76 43.76	bottom exposed -0.83 0.67 1.83 2.71	2.0	6.88	0.33
60		rough	0.051	25.50	64.0	30.020	0.0752	3.75 13.76 23.77 33.77 43.77	bottom exposed -2.49 0.48 2.24 4.51	1.0	12.79	0.44
61		rough	0.051	32.35	64.0	30.020	0.0756	3.79 13.80 23.81 33.81 43.81	bottom exposed 0.28 3.70 5.70	--	20.33	0.94
62	22	rough	0.099	11.45	56.0	29.940	0.0766	4.34 14.35 24.36 34.36 44.36	-0.35 -0.20 -0.02 0.19 0.32	--	0.01	0.02

Table I (cont.)

RUN NO.	DATE	BTM ROUGHNESS	d - feet	U - ft./sec.	AIR TEMP. - °F	BAR. PRESS. - in. of Hg	UNIT WT. OF AIR - lbs./ft. ³	PT. OF MEASURE. - feet	CHANGE IN SURF. ELEV. - ft. x 10 ⁻²	DIST. TO 1st RIPPLES - feet	HORIZ. RETREAT - feet	HORIZ. ADVANCE - feet
1	2	3	4	5	6	7	8	9	10	11	12	13
63	1954 Apr. 22	rough	0.099	16.50	61.0	29.940	0.0758	4.32 14.33 24.34 34.34 44.34	-0.77 -0.45 0.03 0.40 0.75	4.30	0.07	0.17
64		rough	0.099	21.10	63.0	29.940	0.0756	4.32 14.33 24.34 34.34 44.34	-1.51 -0.68 +0.00 -0.75 1.35	2.20	0.22	0.27
65		rough	0.099	25.55	62.0	29.940	0.0757	4.28 14.29 24.30 34.30 44.30	-2.62 -1.06 0.17 1.23 2.11	0.95	0.32	0.43
66		rough	0.099	32.40	62.0	29.940	0.0757	4.28 14.29 24.30 34.30 44.30	bottom exposed -1.61 1.15 3.31 5.41	0.10	5.32	1.65
67	23	rough	0.201	11.50	61.0	29.956	0.0759	5.32 15.33 25.34 35.34 45.34	-0.28 -0.08 0.03 0.08 0.18	5.80	0.01	0.07
68	26	rough	0.202	16.80	60.0	30.102	0.0766	5.33 15.34 25.35 35.35 45.35	-0.42 -0.23 +0.00 -0.22 0.46	4.0	0.04	0.19
69		rough	0.202	21.05	63.0	30.102	0.0761	5.34 15.35 25.36 35.36 45.36	-0.76 -0.38 +0.00 -0.35 0.77	2.0	0.13	0.29
70		rough	0.201	25.70	65.0	30.102	0.0757	5.34 15.35 25.36 35.36 45.36	-1.33 -0.64 -0.01 0.63 1.18	1.20	0.22	0.46

1	2	3	4	5	6	7	8	9	10	11	12	13
71	Apr. 26	rough	0.201	32.50	67.0	30.102	0.0754	5.32 15.33 25.34 35.34 45.34	-2.72 -1.43 -0.25 1.17 2.59	--	0.49	--
72	27	rough	0.372	11.70	57.0	29.876	0.0763	7.21 17.22 27.23 37.23 47.23	-0.10 -0.08 -0.04 -0.01 0.07	5.0	0.08	0.17
73		rough	0.372	16.55	57.5	29.876	0.0763	7.14 17.15 27.16 37.16 47.16	-0.19 -0.12 -0.07 0.10 0.20	2.50	0.05	0.21
74	28	rough	0.372	21.25	58.0	30.070	0.0767	7.17 17.18 27.19 37.19 47.19	-0.41 -0.25 -0.06 0.18 0.44	2.0	0.16	0.32
75		rough	0.370	26.20	63.0	30.070	0.0759	7.17 17.18 27.19 37.19 47.19	-1.16 -0.32 0.05 0.55 1.07	0.85	0.24	0.69
76		rough	0.370	33.80	67.0	30.070	0.0753	7.16 17.17 27.18 37.18 47.18	-3.00 -0.83 0.10 1.31 2.88	0.65	0.65	--
77	May 4	rough with weeds	0.373	11.70	59	30.074	0.0765	7.20 17.21 27.22 37.22 47.22	-0.36 -0.14 0.01 0.11 0.25	5.00	0.08	0.07
78		rough with weeds	0.372	16.80	59	30.074	0.0765	7.20 17.21 27.22 37.22 47.22	-0.42 -0.27 -0.18 0.28 0.42	2.70	0.13	0.36
79	5	rough with weeds	0.372	21.70	62	30.046	0.0760	7.19 17.20 27.21 37.21 47.21	-0.59 -0.32 -0.07 0.25 0.65	1.90	0.20	0.37

Table I (cont.)

RUN NO.	DATE	BT'M RGH'NESS	d — feet	U — ft./sec.	AIR TEMP. — °F	BAR. PRESS. — in. of Hg	UNIT WT. OF AIR — lbs./ft. ³	PT. OF MEASURE. — feet	CHANGE IN SURF. ELEV. — ft. X 10 ⁻²	DIST. TO 1st RIPPLES — feet	HORIZ. RETREAT — feet	HORIZ. ADVANCE — feet
1	2	3	4	5	6	7	8	9	10	11	12	13
80	1954 May 5	rough with weeds	0.373	26.30	67	30.046	0.0753	7.18 17.19 27.20 37.20 47.20	-0.93 -0.54 -0.09 0.45 1.01	0.85	0.29	0.77
81		rough with weeds	0.373	34.0	67	30.046	0.0753	7.19 17.20 27.21 37.21 47.21	-2.35 -1.51 -0.40 0.79 2.42	0.60	0.61	—
82		rough with weeds	0.201	33.40	70	30.046	0.0748	5.40 15.41 25.42 35.42 45.42	-3.83 -1.95 -0.22 1.43 3.26	0.65	0.67	—
83	6	rough with weeds	0.201	24.70	56	29.980	0.0768	5.44 15.45 25.46 35.46 45.46	-1.42 -0.74 0.03 0.72 1.33	1.60	0.31	0.40
84		rough with weeds	0.201	20.20	60.5	29.980	0.0761	5.44 15.45 25.46 35.46 45.46	-0.76 -0.39 -0.10 0.40 0.83	2.70	0.18	0.22
85		rough with weeds	0.202	15.90	57	29.980	0.0766	5.42 15.43 25.44 35.44 45.44	-0.25 -0.11 -0.02 0.02 0.28	3.60	0.08	0.05
86		rough with weeds	0.201	11.25	60	29.980	0.0761	5.42 15.43 25.44 35.44 45.44	-0.15 -0.05 -0.02 0.07 0.11	7.00	0.06	0.02
87	7	rough with weeds	0.101	11.95	54	29.944	0.0770	4.37 14.38 24.39 34.39 44.39	-0.23 -0.11 +0.00 0.11 0.23	—	0.03	0.01

1	2	3	4	5	6	7	8	9	10	11	12	13
88	May 7	rough with weeds	0.101	17.0	57	29.944	0.0765	4.37 14.38 24.39 34.39 44.39	-0.61 -0.30 -0.04 0.28 0.61	6.00	0.10	0.05
89		rough with weeds	0.101	21.85	61	29.944	0.0759	4.37 14.38 24.39 34.39 44.39	-1.35 -0.72 -0.06 0.64 1.41	2.15	0.23	0.22
90		rough with weeds	0.100	25.90	61	29.944	0.0759	4.37 14.38 24.39 34.39 44.39	-2.72 -1.19 0.09 1.21 2.21	1.40	0.41	0.42
91		rough with weeds	0.100	33.60	66	29.944	0.0752	4.37 14.38 24.39 34.39 44.39	bottom exposed -2.38 0.99 3.64 5.95	--	6.91	0.70
92	10	rough with weeds	0.051	11.05	58	30.196	0.0770	4.24 14.25 24.26 34.26 44.26	-0.67 -0.27 0.04 0.33 0.53	--	0.09	0.08
93		rough with weeds	0.051	16.0	60.5	30.196	0.0766	3.87 13.88 23.89 33.39 43.89	-1.56 -0.68 -0.04 0.75 1.46	16.0	0.18	--
94		rough with weeds	0.051	20.20	61	30.196	0.0765	3.87 13.88 23.89 33.89 43.89	bottom exposed -0.78 0.52 1.67 2.69	--	5.91	0.31
95		rough with weeds	0.051	24.50	66	30.196	0.0757	3.87 13.88 23.89 33.89 43.89	bottom exposed -1.39 0.57 2.54 4.10	1.50	11.91	0.52
96		rough with weeds	0.051	31.40	62	30.196	0.0763	3.87 13.88 23.89 33.89 43.89	bottom exposed -0.09 4.17 6.82	1.20	20.41	0.96

9593 092