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REVIEW OF THE PREVIOUS STUDIES ON WIND STRESS APPLIED ON A LAKE SURFACE

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SYNOPSIS

This paper is a review of the recent researches on the wind stress apllied on a water surface. Previous works concerning with this subject have been conducted in connection with the development of wind waves. The wind stress, on the other hand, has a distinctive feature to generate a water current. This current is usually called as a wind drift, drift current or wind-driven current. The current plays an important role in the water circulation of a lake or bay where the contribution from the tidal current is not so large.

In this study, the mechanism of momentum transfer from wind to water surface is examined in connection with the development of wind waves.

The air flow over water waves has characteristics similar to the boundary layer flow over a rigid boundary. The length scale of turbulence can be closely related to short waves with the size of waves which are generated in a wind-wave tank.

INTRODUCTION

Recently, water pollution in lakes are increasing and the preservation of natural environment is strongly advocated. In making a plan for an improvement of water quality in a lake, it is necessary to predict a flow pattern in the lake by an appropriate method such as numerical calculations. The lake current is mainly caused by a wind stress applied on a water surface. The validity of the calculated results of the current, therefore, depends mainly on the accuracy in estimating the wind stress. A tangential wind stress applied on a free surface can be represented as follows

$$\tau_a = \rho_a C_D U_z^2 \qquad (1)$$

where τ_a= wind shear stress; ρ_a= density of air; U_z= wind velocity measured at the height z from the water surface; and C_D= drag coefficient. Generally, C_D is represented as a single-valued function of U_z. In calculating a current velocity in a lake, the wind field on the lake is usually represented by a wind velocity and direction observed at the neighbouring observatory station. According to Eq.1, the wind stress is constant over the whole numerical region if the wind velocity is considered to be constant. Therefore, in a shallow lake where a thermocline does not exist, the vertically averaged flow pattern in horizontal direction depends only on the water depth. However, is it sufficient to regard that the wind stress is constant over the whole region of the lake? How much the error would be expected from the above assumption? Those are the main subjects to be examined in this study.

The main reason why a wind stress is not uniform can be considered as follows;

a) Non-uniformity of the representative wind velocity : This comes not only from the irregularity of the surrounding topography of the ground but also from the existence of a sea/land breeze, slope and valley winds and the passage of a front. In Japan, the configuration of the ground is usually so complicated that the effect of the latter sometimes dominates.

b) Wind wave development is in the initial stage : Surface shear stress of the wind is affected by the conditions of wind waves. As the fetch is relatively short in a lake, the growth rate of wave height is large.

c) Distribution of the current is not uniform : As a lake water is bounded, wind-driven current can be either co-current or counter current to the wind depending on the water depth. Wind waves are affected by these currents and the shear stress varies because of the interaction between waves and wind.

In regard to a), studies on the sea/land breeze near the lake Kasumigaura is being conducted (10). In connection with b), Tsuruya et al. ((34),(35)) have investigated experimentally the effect of return flow of wind-driven current and of the presence of current on the wind shear stress. Present study summerizes the studies concerning the item b).

REVIEW OF THE RESEARCHES ON WIND STRESS

Wind stress is affected not only by the wind condition but also by the situation of wind waves and current there. Wind waves interact not only with wave components but also with current and have an influence on the wind stress. Therefore, in estimating the wind stress it is important to understand the total mechanism of momentum transfer from wind to water surface. There still remain many problems to be investigated, for example, the mechanism of air streams above wind waves, wave-wave and wave-current interactions and momentum transfer from air to waves and current. Present study summerizes the previous works concerning the momentum transfer from air to water surface. After specifying the total view of this problem the authors present the subjects for a future study in the estimation of the wind stress.

Wind velocity distribution

A large numbers of measurements of wind velocity distribution over the water surface have been made in the fields and experimental flumes. Almost all the results support the logarithmic distribution as in the case of wind profiles above solid surface (26). The mean velocity profiles near the air-water interface, then, can be written as

$$\frac{U_z}{u_*} = \frac{1}{\kappa}\ln\left(\frac{z}{z_0}\right) \qquad (2)$$

where u_*= friction velocity of wind; κ= von Kármán constant; and z_0= roughness length.

An example of measured wind profiles in the field is shown in Fig.1 (14). Measurements of wind profiles over the water surface have been made in the

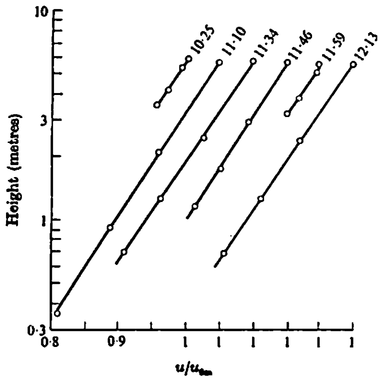

Fig. 1 Mean velocity profile in the field (by Kondo et al. (14))

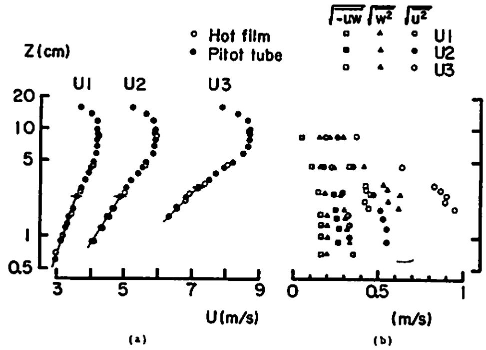

Fig. 2 Mean velocity profile in a wind-wave tank (by Kawamura et al.(12))

laboratory ((3),(12),(37)) as well as in the field ((14),(23),(28),29)). Figure 2 shows an example of measured wind profiles in the laboratory (12).

It is well known that a turbulent boundary layer over a solid surface can be divided into two regions; namely, the wall region (10~20% of the boundary layer thickness) and the outer region(80~90% of it). The region where the log-law can hold strictly is the wall region. In Fig.2, we can admit that the wind profile can be divided into two regions. Measurements of the Reynolds stress show that the shear stress near the water surface is nearly constant and simultaneous measurements of mean wind profiles indicate that the Reynolds stress and shear stress calculated from the inclination of the mean wind profile give the same value. It can be deduced from the result that even in the region above the water surface, the wall law can hold and the wind velocity distribution follows the log-law. Some investigators have reported that the wind velocity near the water surface becomes greater than the logarithmic distribution ((25),(31)), though it is not clearly recognized in Figs.1 and 2. This is known as a "kink". Mitsuyasu (20) has explained that the kink originates from the interaction between wind waves and air stream, and it can be easily produced when wind waves are one-dimensional and has a regular profiles. However, when wind waves have three-dimensional properties, the kink cannot be easily produced. Phillips(26) has explained that the deformation of wind velocity originates from the existence of long waves. As stated above, the region where the logarithmic law can hold is confined within the wall region and besides upper part than that where interactions between waves and air flow occur. Strictly speaking, therefore, the region where the logarithmic law can hold is restricted to the narrow region, but the logarithmic distribution can be regarded as the universal law to express the wind velocity distribution above the water surface.

Drag coefficient

There are several methods in estimating the wind stress (32). Among these methods, the following three methods give relatively reliable values, namely, wind profile method, eddy correlation method, and dissipation technique method. All these three methods utilize the characteristics of the wall region in estimating the wind stress. Miyake et al. (23) have demonstrated that in the ocean, the results obtained from these three methods are coincident within the experimental errors for nearly neutral conditions.

Figure 3 shows the relationship between drag coefficient C_D and wind velocity U_{10} (34). Some fluctuations can be recognized in the experimental data by Tsuruya et al.(34) and the differences between the other authors are also remarkable. In representing the drag coefficient Charnock suggested the following relation

$$z_0 = b u_*^2/g \qquad (3)$$

where b = Charnock constant. Equation 3 represents that the roughness parameter z_0 of the water surface is a single-valued function of the wind stress. It is known that Eq.3 expresses the relation between measured wind velocity and drag coefficient C_D in an average. Wu (39) has given an physical explanation for the Charnock relation as follows "If the breaking waves support the wind stress, the wave slopes can be considered as constant. The roughness parameter z_0 corresponds to the scale of these waves. As a result, it can be easily verified that the Charnock relation and the dispersion relationship are equivalent." However, it is known from many investigations that the constant b in Eq.3 varies widely. If we substitute the constant b in Eq.3 into Eq.2 we can readily recognize that Eq.3 represents the single-valued relation between C_D and U_{10} . Namely, wide scatter of the drag coefficient C_D against U_{10} is identical with that of the Charnock constant b. This indicates that the condition of water surface cannot be prescribed by a wind condition only. The reason of the wide scatter of C_D against U_{10} comes from the fact that we adopted the above mentioned indirect method in estimating the wind shear stress because it is very difficult to measure the shear stress directly. Wind stress may be affected by another factors such as ; (1) wind velocity, (2) stratification of air, (3) fetch, (4) waves and (5) wind-driven current or steady current. About the item (1),it is well known that the wind stress depends on the wind velocity as can be seen in Fig.3. In the figure, plotted data shows wide scatter and the water surface shifts from smooth to rough at the region where U_{10} is 5~8m/s. About the item (2), correction can be made by using the temperature which is measured simultaneously with the wind velocity if the air condition is not neutral. About the item (3), in the case of a lake, as the horizontal scale is from hundreds meter to tens kilometer and wind waves are in the condition of initial stage, the wind stress may change according to the fetch. Although Kraus (16) and Safaie (27) have described that the drag coefficient C_D does not depend on the fetch, they did not confirm it with the field data. Sheppard et al.(28) have shown that in the range of the fetch 2~22km, C_D does not depend on fetch. Smith (29) has shown that the value of C_D becomes large as the fetch decreases but the tendency is not remarkable. From the above discussion it can be said that the drag coefficient C_D vary widely and no distinct dependence of C_D on the fetch is obtained. Moreover, it can be said that the water surface shifts from smooth to rough when U_{10}=5~8m/s.

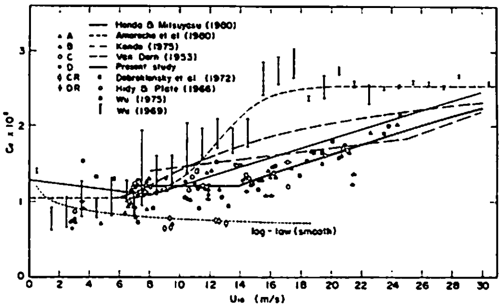

Fig. 3 Relation between C_D and U_{10} (Tsuruya et al. (34))

Relationship between wind stress and short waves

According to Tsuruya et al. (34), a transition from smooth water surface to rough occurs at U_{10}=7m/s, and corresponding shear velocity u_* is 23cm/s. Although the value of u_*=23cm/s slightly differs with each investigator, it corresponds to the minimum phase velocity of water waves. Therefore, it can be considered that this value has a physical meaning. Wu(38) has reported that airflow separation from wind waves occurs when the phase velocity of water waves is less than the friction velocity of air. On the other hand, Banner and Melville (1) have conducted an experiment in order to investigate the separation of the airflow over standing wave train produced by the water flow over a submerged smooth cylinder and pointed out that airflow separation is closely related to the breaking of waves. Melville (19) has shown that the friction velocity u_* is approximately equal to the phase velocity of the breaking waves because the turbulent velocity fluctuations over a train of small-scale waves are dominated by the breaking process. Moreover, he has obtained the expression for z_0 by making use of the condition of the maximum wave height of short waves proposed by Banner and

Phillips (2) in the presence of wind-driven current and orbital velocity of long waves as

$$\left.\begin{aligned} & z_0 \approx M\zeta^* u_*^2/g \\ & \zeta^* = \frac{1}{2\alpha^2}\left[\ \alpha - \left\{1 - \left(1 - \frac{\gamma(2-\gamma)}{(1-\delta)^2}\right)^{1/2}\right\}\right]^2 \\ & \alpha = c_0/C, \quad \delta = u_0/C, \quad \gamma = q_0/C \end{aligned}\right\} \qquad (4)$$

where M= constant(0.1~1); c_0= phase speed of short waves; C= phase speed of long waves; u_0 = maximum orbital velocity of long waves; and q_0= wind drift in the absence of swell. Comparing with the data measured by Sheppard et al. (28), Melville has shown that z_0 can be expressed well by Eq.4 which reduces to Charnock relation in the absence of wind drift and swell. If Eq.4 is valid, it can be thought that a cause for a scatter of b mentioned in the previous section may be the wind drift and swell. In regard to airflow separation from wind waves, Kawai (11) has shown that it occurs in spite of no breaking wave. It may be true, however, that small scale waves which are in the situation of nearly breaking have a great influence on the wind stress ((15),(24)). Figure 4 shows the ratio of the significant wave height to the physical roughness length measured in a wind-wave tank and in the ocean. It can be read from the figure that the ratio is almost unity in the wind-wave tank, but it is $10^2 \sim 10^3$ in the ocean. This tacitly shows that even in the presence of long waves, the short waves prescribe the physical roughness of water surface.

From the above discussion,it became evident that the wind stress is closely related to the short waves which are observed in a wind-wave tank. Hence, we can recognize that in the ocean, we must take an interaction of short wave and long waves into consideration because both wave exist simultaneously.

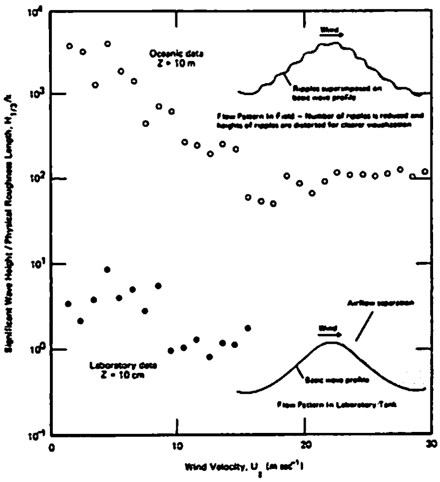

Fig. 4 Comparison between significant wave height and roughness height, and illustrations of different airflow patterns in laboratory tanks and in the field (by Wu (38))

Interaction between long and short water waves

The interaction between long and short water waves closely relates to the growth mechanism of wind waves. Mitsuyasu and Honda (21) have measured the growth of mechanically generated water waves under wind action both for pure water (tap water) and for water containing a surfactant. The use of a surfactant suppresses the growth of the wind waves up to fairly high wind speeds. Figure 5 shows the relationship between the dimensionless growth rate β/f (β is the measured growth rate and f is the frequency of regular waves generated by the wave maker) and the dimensionless friction velocity u_*/C (C is the phase velocity of regular waves). The best-fit relation for pure water is given by

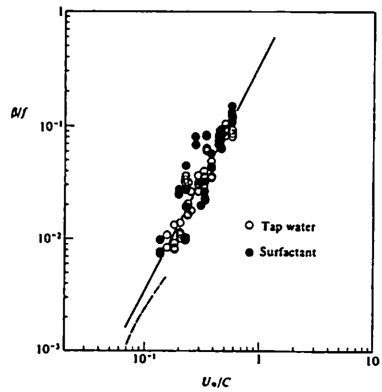

Fig. 5 Plot of β/f versus u_*/C (by Mitsuyasu and Honda (21))

$$\beta/f=0.34(u_*/C)^2 \quad (0.1<u_*/C<1) \tag{5}$$

which is shown in Fig.5 by a solid straight line. For water containing a surfactant, the measured growth rate is smaller than that for pure water, but the friction velocity of the wind is also small. If the friction velocity u_* is estimated from the measured wind profile, Eq.5 also holds approximately for water containing a surfactant. These results suggest that the growth of the regular waves by wind is uniquely related to the friction velocity of the wind and that the short waves play an important role in the transfer mechanism of momentum from wind to waves.

After the field study, which showed that the rate of wave growth was considerably greater than that predicted by Miles, the modification of Miles' theory and the proposals of new theory have been attempted to explain the discrepancy ((5),(6),(7),(9),(17),(18)). An important idea common to these theories is how the effects of short waves are described. For example, Gent (7) has proposed a numerical model for the flow in a deep turbulent boundary layer over water waves considering the turbulent fluctuations in the air flow which were not considered in Miles' theory. In Gent's theory it became evident that if z_0 is allowed to vary with the position along the waves, the fractional rate of energy input can be significantly increased for small amplitude waves. This indicates that the distribution and behavior of short waves over long waves are important to account for the momentum transfer from wind to waves.

Partition of wind stress into waves and drift current.

We have described the previous works concerning with wind stress, namely, the total momentum transfered from wind to water surface. In considering the drift current, it is necessary to examine how the wind stress is distributed into waves and the drift current.

Table 1 shows the ratio of momentum flux to the wave field τ_w to the total momentum flux across the interface τ_a estimated by several authors (Tsuruya et al. (34)). In Table 1 the authors can be devided into two groups. One group is represented by Dobson (4), Snyder et al. (30) and Hsu et al. (8). They have estimated τ_w by measuring the air pressure fluctuation above water waves and water surface elevation simultaneously, then the value of τ_w indicate direct momentum transfer to waves. They concluded that wind waves support more than 40% of the total wind stress. The authors in another group, on the other hand, estimated the ratio τ_w/τ_a to be less than 20%. In this case they have estimated τ_w from the rate of change of momentum of wind waves and then τ_w expresses the momentum advected away by wind waves.

Table 1 Values of τ_w/τ_a estimated by several authors (by Tsuruya et al. (34))

Author	τ_w/τ_a
Starr(1947)	10
Stewart(1961)	20
Korvin-Kroukovsky(1965)	7
Hamada et al.(1966)	15(14-16)
Wu(1968)	20(12-30)
Dobson(1971)	80(±30)
Imasato et al.(1971)	(2-15)
Imasato et al.(1973)	7(3-10)
Taira(1972)	5(3-10)
Toba(1978)	$G=G_0[1-\mathrm{erf}(b_T T^*)]$
Hsu et al.(1981)	42
Snyder et al.(1981)	57
Ura(1984)	(0-10)
Tsuruya et al.(1983)	7(2-20)

Mitsuyasu (22) has interpreted that the great difference of τ_w/τ_a between the two groups does not originated from the errors of measurements, but indicates an basic mechanism of momentum transfer from wind to water surface. Then he has suggested a new dynamical model : A large fraction of the momentum flux to the water surface first takes the form of wave momentum, but wave instability and succeeding wave breaking eventually converts most of it into the momentum of the surface turbulent flow, and only a small residue is retained by wind waves.

We must substanciate the above model, but it can be considered from the previous works that the momentum advected by waves is 5~6% of the total momentum transfered from wind to water surface, and most of the wind stress are converted into the momentum of drift current.

CONCLUDING REMARKS

From the above discussions the mechanism of momentum transfer from wind to water surface can be considered as follows.

The air flow over water waves has characteristics similar to the boundary layer flow over a rigid boundary, though the interaction between air flow and wave motion exists (13). Hence the length scale of turbulence can be represented by the roughness parameter z_0, and z_0 is closely related to short waves with the size of waves which are generated in a wind-wave tank. In the field, short waves usually ride on large waves and characteristics of short waves are varied because of the influence of large waves and drift current. Thus short waves play an important role directly or indirectly in the momentum transfer from wind to water surface.

Further investigation will be necessary how the short waves are influenced by dominant waves.

This study describes the results of the investigation concerning the item b) which is a part of the workings that have been mentioned in the INTRODUCTION.

The plans of the future study for the another items are as follows;

a) Local winds such as sea/land breeze, slope and valley wind will be investigated and then numerical calculation will be used to investigate how much these winds affect the water flow in a lake.

c) Studies on the development of wind waves generated on water currents have been made by Tsuruya et al. In the ocean it is important to investigate the development of wind waves generated on water currents. In the lake we can utilize the results to estimate the variation of wind stress in the presence of water currents.

The workings of the present group is being done as a part of the activities of the working groups of the younger researchers supported by the Committee of Hydraulics,JSCE.

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APPENDIX-NOTATION

The following symbols are used in this paper:

b = Charnock constant;

c_0 = phase speed of short waves;

C = phase speed of long waves;

C_D = drag coefficient;

M = constant (0.1~1);

q_0 = wind drift in the absence of swell;

u_0 = maximum orbital velocity of long waves;

U_z = wind velocity measured at the height z from the water surface;

u_* = friction velocity of wind;

z_0 = roughness length;

κ = von Kármán constant;

ρ_a = density of air;

τ_a = wind shear stress.