On the Virtual Wall Height in Open channel Flow with Large Relative Roughness

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ABSTRACT

In order to apply the logarithmic velocity distribution law to open channel flows with rough beds, it is necessary to define the equivalent roughness and the virtual wall height. In previous studies the equivalent roughness and the virtual wall height have been estimated with a measured velocity distribution. However, when the relative roughness is large, the region where the logarithmic velocity distribution should hold is restricted in a narrow region of a flow. In the flow with large scale relative roughness, therefore, an error of estimation of the virtual wall height from the velocity distribution necessarily becomes large, and the virtual wall height must be determined with the wall shear stress measured directly. From this point of view we measured the wall shear stress directly using a servo typed shear stress meter, and examined the virtual wall height. In spite of the same arrangement of the roughness elements, the virtual wall height depends on the relative depth and the slope of the flume.

1. INTRODUTION

The examination on the law of resistance in open channel flows is a general and important problem in hydraulics. Many studies have concerned with the law, and many results have been obtained. In those results, a monument is Prandtl-Kármán's logarithmic velocity distribution law, which was presented as the velocity distribution in a turbulent boundary layer and based on the mixing length theory.

To apply the logarithmic velocity distribution law to open channel flows, it is necessary to define the equivalent roughness and the virtual wall height. Many studies of the open channel flows have concerned with gentle slopes of the flume and the small scale relative roughness. In recent years, in view of actual hydraulic problems, it has been examined to apply the logarithmic velocity distribution law to flows in a flume with large scale relative roughness and steep slopes. When the relative depth is smaller than about 10, there have been many questions for the application of the logarithmic velocity distribution law1)~4). In these recent works, the virtual wall height and the equivalent roughness are estimated from a measured velocity distribution. However, when the relative depth of the flow is small, limited is a region where the logarithmic velocity distribution law should be valid. It is, therefore, clear that the

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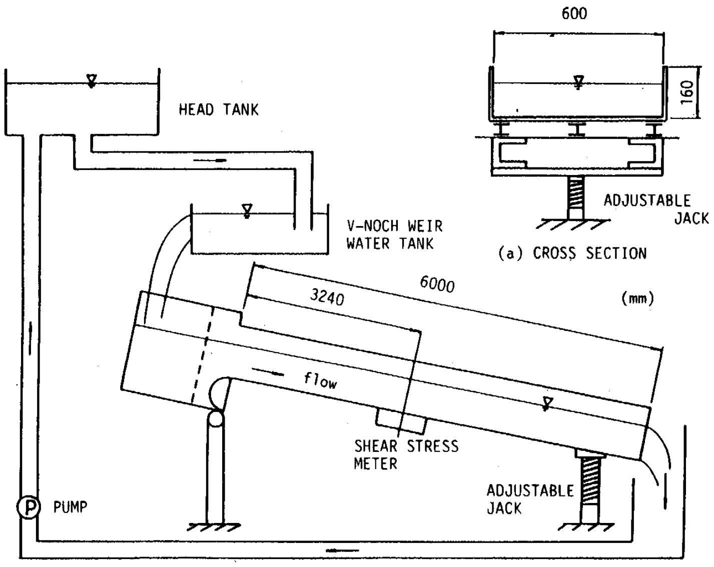
estimation of the virtual wall height and the equivalent roughness have large errors.

The logarithmic velocity distribution law originally contains an approximation with an artificial boundary condition of complicated flows in the vicinity of the wall and an estimation of the resistance law with one type of velocity distribution. Therefore, it is necessary to clear characteristics of the flow in the vicinity of the wall and the extent of the region where the logarithmic velocity distribution law is valid. Typical length scales in the flow are the depth of the flow H, the equivalent roughness k_s, and ν / u_*, where u_* the friction velocity, and ν the kinematic viscosity. Because there are three length scales in the problem on the investigation of the law of resistance in the flow with large scale roughness, we should treat the law under some condition with which we change the values of one parameter and fix those of the another parameters. From this point of view, we measured the wall shear stress directly using a servo typed sheare stress meter, and examined only the virtual wall height. In spite of the same arrangement of the roughness elements, the virtual wall height depends on the relative depth and the slope of the flume.

2. EXRERIMENTAL APPARATUS AND METHOD

Experiments were carried out using a rectangular flume made of transparent acrylic resin, 60cm wide, 17cm deep, and 6.0m long. The slope of the flume can be changed. The flume and a water circulation system are schematically shown in Fig. 1. In the experiments we used two types of the bed in the flume. One is the acrylic resin which surface is smooth. The other is a rough bed. Lightweight aggregate, which mean diameter is 12mm, was stuck on the resin. In the experiments, because the flow is nonuniform, the water depth was measured with static pressure tube which



(a) CROSS SECTION

(b) LONGITUDINAL SECTION

Fig. 1 Definition sketch.

were set on three positions in the transverse direction and on six points, which are at intervals of about 0.58m from the point which distance is 1.7m from the upper end, in the longitudinal direction. The water depths are extrapolated from the data with the method of least squares, in which a quadratic curve was used, and shapes of the water surface are determined. From the depth and the water surface gradient, the gradient of energy was calculated. In the experiments, the slope of the flume was varied from 1/800 to 1/50. The wall shear stress were measured with a servo typed shear stress meter (model SM-101, KEISOKUGIKEN) that was set at a point which is 3.2m distant from the upper end. The shear stress meter is sketched in Fig. 2. The mechanism of the measurment with the shear stress meter is as follows. When the shear stress acts on the shear table (the size is 8cm×8cm), the table shifts from a point of equilibrium. The shift is measured with the detection part. The servo amplifier and the driven part make electrically a restoring force in proportion to the shift, then the shear table is returned to the eqilibrium position. We have the data of the shear stress using a relation between the shear stress and the voltage which concerns with the restoring force.

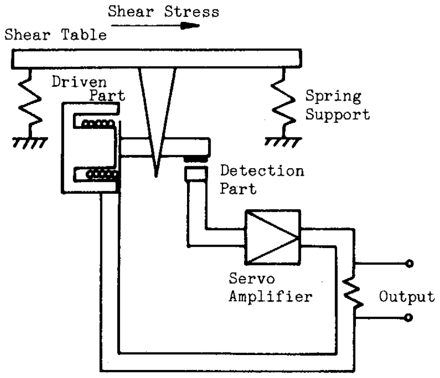


Fig. 2 Schematic diagram of the shear stress meter.

3. EXPERIMENTAL RESULTS

3. 1 Calibration of the shear stress meter

Relationship between the output voltage of the shear stress meter V_0 and the friction velocity u_* is shown in Fig.3. The friction velocity u_* is given as follows ;

$$u_* \doteq \sqrt{gRI_e}\,, \tag{1}$$

where g the acceleration due to gravity, R the hydraulic radius, and I_e the gradient of energy. A curve in the figure is extrapolated with the method of least squares. According to the figure, when the slope of the flume is set in a range of 1/800–1/50, the relationship between the friction velocity and the output can be indicated with

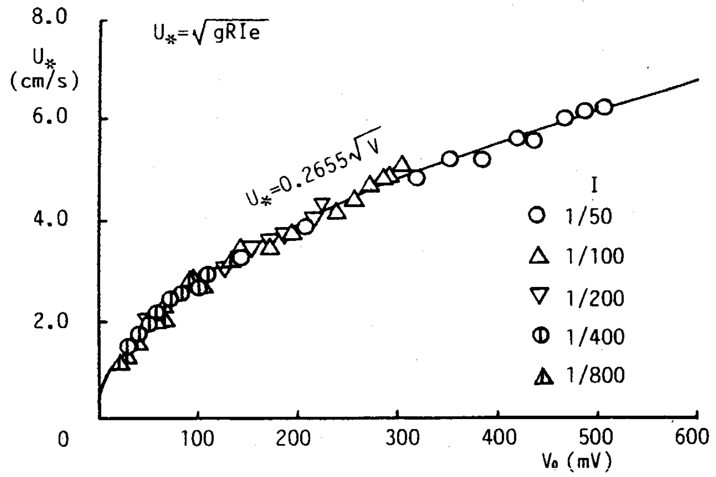


Fig. 3 Calibration curve.

one curve and dose not depend on the slope. When the slope of the flume is larger than 1/25, the meter was not able to adjust the equilibrium position. We could not use the meter, when the slope is larger than 1/25.

3.2 Friction coefficient with smooth bed

In Fig. 4, the friction coefficient $f=8gRI_e/V^2$ is plotted against the Reynolds number VH/ ν , where curved lines denote a relation between them in a turbulent flows and straight line denotes that in laminar flows. Ishihara et al.[5] carried out experiments using a flume with steep slopes and smooth beds, and have introduced the Froude number as well as the Reynolds number in the law of resistance in turbulent flow in an open channel. They have found that the bottom slope has an important role on the law of resistance in a flume with a steep slope. Using the data in the region $Re<10^4$ in Fig. 4, we can recognize a tendency that the law of resistance is influenced by bottom slopes. However, since the shear stress is small and accuracy of its measurement is insufficient, this tendency should be investigated precisely in future.

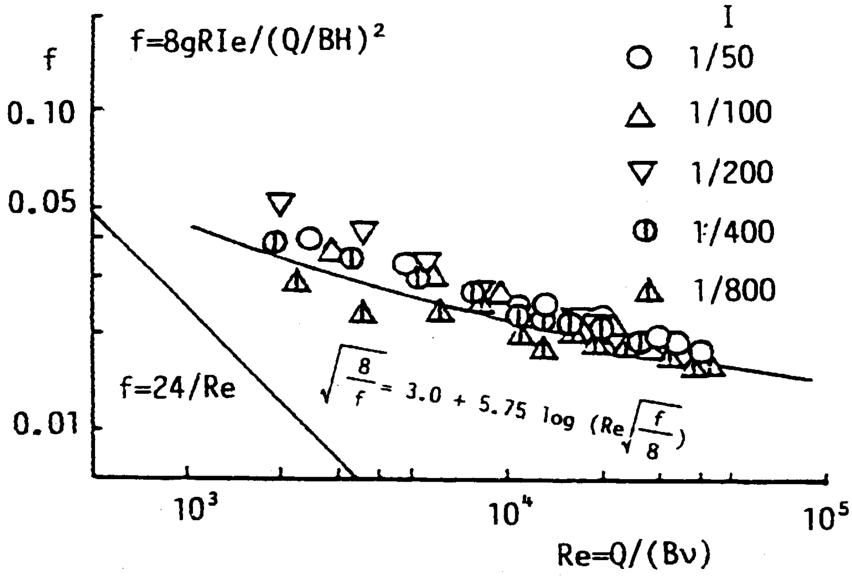


Fig.4
Relation between the Reynolds number VH/ ν and the friction coefficient in the flume with smooth bed, V=Q/(BH) the averaged velocity, Q the discharge, and B the width.

3. 3 Virtual wall height

Using the energy gradient, the depth H is derived from the friction velocity u_* measured with the shear stress meter. The virtual wall height α will be defined here as a value of (H–h) divided by the diameter of the roughness element d, where h is a depth from the top of the roughness element to the water surface. The virtual wall height is shown schematically in Fig.5, and the values of the virtual wall height in the experiments are plotted against H/d in Fig. 6. In investigations of the averaged velocity distribution at the large relative depth comparatively, some constant values of the virtual wall height have been provided ; $\alpha = 0.20$ by Einstein et al.[6], $\alpha = 0.25$ by Iwagaki[7], and Tsuchiya[8]. In the present experiments, however, the value of α has a minimum value at H/d=3~4, and it increases rapidly as the relative depth becomes small. Under the same value of H/d, the value of α becomes small as the slope of the flume becomes steep, except a case which slope is 1/800. The virtual wall height depends on the slope. From this point of view the law of resistance on a rough bed is related with the slope as well as a result on a smooth bed mentioned by Ishihara et al.[9] At H/d=3~4, the value of the virtual wall height is nearly zero. This means that in such a flows the water bed is placed seemingly at the top of the roughness elements, and the flow between the roughness elements dose not contribute to the law of resistance due to the logarithmic velocity distribution law.

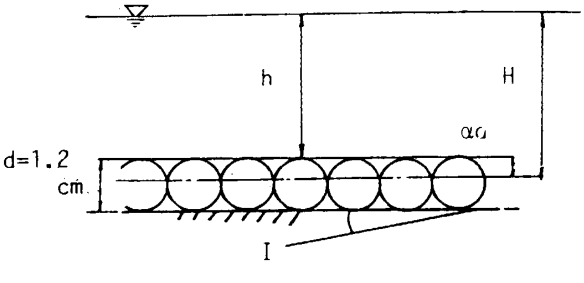


Fig. 5 Definition sketch of the virtual wall height.

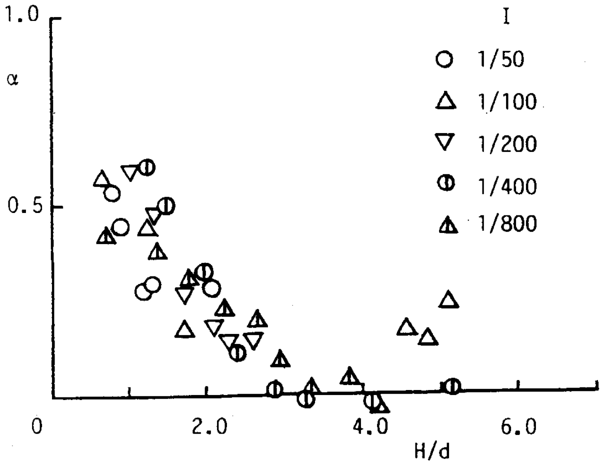


Fig. 6 Relation between the virtual wall height and H/d.

The present experimental condition was H/d<5, though the previous studies have dealt with the problem under conditions $H/k_s > 10$. We are, therefore, preparing systematic experiments about the problems with large relative roughness.

3. 4 Friction coefficient with rough bed

Relationship between the Reynolds number and the friction coefficient f_r is shown in Fig. 7. When the Reynolds number is smaller than 5000, the friction coeffi-

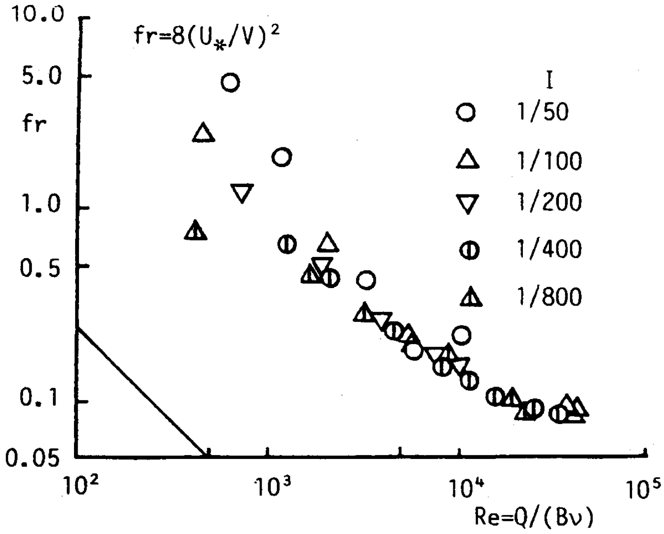


Fig.7
Relation between the Reynolds number and the friction coefficient in the flume with rough bed.

cient dose not depend on the slope of the flume but on the Reynolds number. However, when the Reynolds number is larger than 5000, the steeper the slope is, the larger the friction coefficient is.

4. CONCLUSION

The characteristics of the shear stress meter with the method of zero detection was examined in the flume with a smooth bed. Using the meter, we measured directly the wall-shear stress on the rough bed. As follows are results on the virtual wall height and the friction coefficient with the large scale roughness.

1. Although it has been thought that the virtual wall height depends only on the arrangement of roughness elements in the previous studies, the virtual wall height varies with the change of the values of H/d and the slope of the flume.
2. When the slope of the flume is small, the friction coefficient in the flume with large scale roughness dose not depend only on VH/ν and H/k_s in the Moody diagram but also on the slope of the flume.

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