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Direct measurement of bottom shear stress under high-velocity flow conditions

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ABSTRACT

The objectives of the present research are to accurately measure bottom shear stress under high-velocity flow conditions. To achieve high-velocity flow conditions, a laboratory-scale flume has been specially built in which flow velocity can reach over 3 m s^{-1}. Also an instrument that can directly measure bottom shear stress has been developed and validated. Then, the flow resistance has been estimated by simultaneously measuring flow velocity and bottom shear stress. It appears that the shear stress is indeed proportional to velocity squared and also to Reynolds number. On the other hand, Manning's *n* value and the skin friction factor are more or less uniform across all experimental cases.

1. Introduction

Mean velocity and tractive stress are the two most important flow characteristics in evaluating and designing river bank stability measures (see e.g. [11] and [16]). In steady uniform flow, bottom shear stress, τ, averaged over channel surface area is often estimated from momentum balance (e.g. [7]):

$$\tau = \rho g R S, \tag{1}$$

where ρ is the density of water, g the gravitational acceleration, R the hydraulic radius of the channel cross-section, and S the energy slope, which is the same as the bottom slope as well as the water surface slope for uniform flow.

However, the structure of overbank flow in a compound channel is very complicated due to both vertical and streamwise vortices and the associated secondary flows [10]. With the additional effects of meandering river channel and the uneven channel surface roughness, spatial and temporal distributions of shear stress could be significantly different from that estimated from Eq. (1). This calls for a means to accurately measure shear stress locally.

In literature, there are mainly four kinds of approaches in measuring the bottom shear stress: (i) direct force measurement on the bottom (e.g. [2,8,15], and [12]); (ii) estimating from the measured near-bed turbulence (e.g. [3]); (iii) estimating from scalar diffusion at the bottom, such as thermal diffusion (e.g. [14]) or electrodiffusion (e.g. [13]); and (iv) estimating from the measured velocity profile near the bottom (e.g. [6] and [5]).

It is possible to obtain reasonable result using the last kind of method, especially in laminar flow (e.g. [9]) through high-resolution velocity measurement, but it is usually very difficult to resolve the viscous sub-layer in high-Reynolds-number turbulent flow. In a well-developed turbulent flow on a flat boundary, the velocity profile near the bottom may be fitted with the law of the wall to determine the friction velocity and thereby the bottom shear stress, although there are some uncertainties involved in the fitting [3]. Furthermore, it is known that the logarithmic velocity law is no longer valid in the vicinity of the river channel bank [10], whereas it is indeed the region of our interest. Also, methods using scalar diffusion often require a separate velocity measurement close to the probe to resolve the directional information. Therefore in the present research, we only consider the first two methods and provide further reviews on the two methods below.

To our best knowledge Ippen and Mitchell [8] are the first to directly measure bottom shear stress under surface waves. Their shear test plate was made of 1 ft^2 aluminum plate which was flush mounted on the bottom of the wave tank. The plate was connected to a force gage by a 3/4 in. diameter round steel rod, which was again enclosed by 1 in. diameter Lucite tube that was fixed separately from the force measurement system. An aluminum container was placed beneath the test plate, which was filled with mercury up to the underside of the test plate to prevent wave-induced flow under the plate. The pressure force acting over the

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thickness of the plate was estimated by repeating the same experiments with different thicknesses of the plate (1/8 and 3/8 in., respectively). Finally shear force was obtained by subtracting the pressure force from the total measured force. Overall their experimental result showed good agreement with the available theory, but the pressure force was more than 50% of the total force, reducing the sensitivity in the shear force measurement. Also the instrumentation is rather intrusive because of the steel rod and its Lucite casing penetrating through the depth of water.

Recently, Barnes et al. [2] used a shear plate (0.1 m long, 0.25 m wide, 0.73 mm thick) in their bore-driven swash experiments. The whole instrumentation system is contained in a Perspex cell, which is flush mounted on the beach surface making it practically non-intrusive. The test plate was supported by six ball bearing rollers to prevent any displacement normal to the beach, while allowing tangential displacement. At the same time four sway legs that were clamped to the underside of the plate and extended to the base of the cell provided stiffness to limit the tangential displacement less than 1 mm. The displacement was measured using an eddy current probe, from which the total force was estimated. Pressure force was estimated by the two pressure sensors on both sides of the cell. Due to the small side area of the test plate, the estimated pressure force was typically an order-of-magnitude less than the total force in their experimental conditions. The cell was completely filled with water, and it is maintained that the surface tension in the 1 mm gap between the test plate and the Perspex cell could hold the water even when the test plate was in dry condition. Also the authors stated that the induced flow inside the cell was minimal, but no detailed information was provided.

Further consideration on the effect of pressure-gradient force in the use of a shear plate under a transient flow is discussed in [12]. They suggest that a constant value could be used for the fraction of the streamwise pressure gradient that acts on the shear plate even for unsteady flow conditions. Their shear plate is validated for turbulent flat boundary layer, in which the pressure-gradient force is negligible, and for surface solitary wave, where the pressure-gradient force could be dominant especially when the crest of the wave passes the location of the instrument. Overall the performance of the methodology was encouraging, although discrepancies were noticed when the flow was highly unsteady and the pressure gradient changed sign.

Biron et al. [3] compares different ways of estimating bottom shear stress from velocity and turbulence measurements both in simple and complex flows. Other than using the reach-averaged bottom shear stress (i.e. Eq. (1)) or the law of the wall, they used Reynolds shear stress and turbulent kinetic energy to indirectly determine the bottom shear stress.

The present research is motivated by the practical need to assess the safety and the stability of river embankment revetments using laboratory facility. Especially we are interested in high-water revetments under flooding conditions, which are characterized by high-velocity flow. To meet the requirements, we have specially built a laboratory-scale water flume, in which high-velocity flow conditions can be achieved. The key component of the flume is the pressurizing chamber at the upstream end where the water is pressurized and fed into the straight channel essentially as a wall jet to create high-velocity flow. The maximum flow velocity can be as high as 2.7 $\mathrm{m\,s^{-1}}$ without slope and 3.5 $\mathrm{m\,s^{-1}}$ with slope in typical water depth of order 0.1 m.

Furthermore, an instrument, so-called the shear plate, has been built which can be flush mounted to the channel bed and directly measure the bottom shear stress. The design closely follows the one described in [2], except that the dimension of our shear plate is comparable to a typical river revetment to meet the purpose of our research. Our instrument is validated against the indirect methods described in [3] using the turbulence data in a simple boundary-layer flow. We emphasize that the flow velocities used in our experiments is much higher than those found in literature. Most previous works have been done with velocity less than 1 $\mathrm{m\,s^{-1}}$. After validating the instrument, we report another set of experimental results in which we estimate the flow resistance from the shear stress and velocity data. It appears that the shear stress is indeed proportional to velocity squared and also to Reynolds number. On the other hand, Manning's n value and the skin friction factor are more or less uniform across all experimental cases.

In the next section, we will describe the above-mentioned facility in detail. In Section 3, we report two sets of experimental data, which are used for validation of the experimental setup and for accurate estimation of flow resistance, respectively, as well as further discussion. Finally, concluding remarks are given in Section 4.

2. Methods

2.1. Generation of high-velocity flows in a laboratory flume

A flume has been built at the Environmental Water Resources Laboratory in the Department of Environmental Science and Engineering at Inje University, South Korea. The water flume is made of smooth acrylic sheets (20 mm thick) and supported by protruded aluminum frame, measuring 6 m long, 0.3 m wide and 0.3 m deep. The slope of the flume can be adjusted to any angle between −5° and 5° (see Fig. 1).

The water flow is supplied by a submerged water pump (power: 30 hp; maximum capacity: 0.2 $\mathrm{m^3\,s^{-1}}$) through 5 hoses. Each hose is fitted with an adjustable valve and the flow rate is controlled by adjusting opening of the valves. The feed water first enters into the pressurizing chamber before flowing into the working section of the flume so that a very high flow velocity (2.7 $\mathrm{m\,s^{-1}}$ without slope and 3.5 $\mathrm{m\,s^{-1}}$ with slope in typical water depth of order 0.1 m) can be achieved. Between the pressurizing chamber and the working section of the flume, there is a sluice gate. Opening of the gate can also be adjusted so that the flow velocity as well as the flow depth can be further controlled.

The flow rate is measured by an ultrasonic flowmeter (Ulsoflow 309P) and it essentially varies linearly with the number of open valves:

$$Q = 0.013N_v, \tag{2}$$

where Q is the flow rate in $\mathrm{m^3\,s^{-1}}$, and N_v is the number of open valves. Note that each valve can be partially open and N_v can be any number between 0 and 5, not necessarily just positive integers. Now, given the water depth (h), we can estimate the Froude number (Fr) of the flow as a function of N_v:

$$\mathrm{Fr} = \frac{Q}{Wh}\frac{1}{\sqrt{gh}} = \frac{0.013N_v}{W\sqrt{gh^3}}, \tag{3}$$

where $W = 0.3$ m is the width of the channel. For $h = 0.1$ m, Eq. (3) reduces to $\mathrm{Fr} = 0.44N_v$, therefore the flow is supercritical for $N_v \geq 2.3$. Under supercritical condition, we observed that the water depth does not vary noticeably within the 5 m reach of the channel.

The Reynolds number (Re_h) based on the water depth can also be estimated:

$$Re_h = \frac{Q}{Wh}\frac{h}{\nu} \approx 4.3 \times 10^4 N_v, \tag{4}$$

where, $\nu = 10^{-6}\ \mathrm{m^2\,s^{-1}}$ is the kinematic viscosity of water. We emphasize here again that we are interested in the high-water