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Evaluation of variation of instantaneous velocity and reynolds stress due to spherical obstruction in a fluid flow

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ABSTRACT : When a flow passes through a protruding particle, all the turbulent parameters of the fluid subjected to change. So the effect of flow past a protruding particle of spherical shape over a gravel bed was investigated experimentally. All experiments were performed in a 12 m in length, 0.9 m in width and 0.71 m deep horizontal flume. The slope was maintained at 1 in 1400, and depth of water level was 15 cm with gravel size of 2.6 mm. Three balls of 2cm, 3cm and 4 cm diameter was kept in the test section as the protruding particle. The time-averaged velocity components were measured by the Acoustic Doppler Velocimeter (ADV), Vectrino. The point of interest lies in at 3d upstream and 0.5d, 1.0d, 1.5d, 2.5d, 3.5d, 5.5d, 8.0d downstream from the edge of the ball at various depth, where d is the diameter of the ball. At each section velocity measurements were taken at various vertical intervals. The experimental results have shown that the turbulent flow parameters affect significantly due to protruding particle. The velocity and the Reynolds stress of flow at bottom is negative at immediate downstream of the ball which reduces gradually till 2.5d downstream and both are fully recovered after 8d downstream of the section.

KEY WORDS : Turbulence, Flow separation, Time averaged velocity, Reynolds stress

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River and unlined channels are subjected to continuous change. Flowing water erodes, transports and deposits sediment, altering its bed elevation and adjusting its boundaries. Similarly it is also subjected to various obstructions in the flow as a result flow parameters like velocity, Reynolds stress changes (Grass, 1971). Since most important flows are turbulent, advanced instruments along with analytical capability can visualize the flow behavior due to any obstruction. In turbulent flow, unsteady vortices appear on many scales and interact with each other. Drag due to boundary layer skin friction increases. The structure and location of boundary layer separation often changes, sometimes resulting in a reduction of overall drag. In fluid dynamics turbulent flow is a fluid regime characterized by chaotic and stochastic property changes. This includes low momentum diffusion and rapid variation of pressure and velocity in space and time. In turbulent flow, unsteady vortices appear on many scales and interact with each other. Drag due to boundary layer skin friction increases. The structure and location of boundary layer separation often changes, sometimes resulting in a reduction of overall drag. The presence of turbulent flow structures at a broad range of spatial and temporal scales has long been recognized in rivers (Matthes, 1947). In the turbulent boundary layer, flow structures exist in the form of low speed streaks, ejections and sweeps that comprise the bursting process in the inner region and of large-scale structures in the outer region. These structures were first identified through flow visualization (Kline *et al.,* 1967; Grass, 1971).

The basic structure of flow past a sphere has been experimentally investigated using a variety of approaches, including flow visualization. The flow is characterized by unsteady vortex shedding with the most of the large scale vorticity originating from the shear layer which separate from sphere surface .These vortices and their own potential instabilities in turn dictate much of the resulting flow field. As the flow is get disturbed due to protruding particle over gravel bed hence the resultant velocity distribution, Reynolds shear stress as well as velocity spectra changes. Vertical distributions of the time-averaged velocity in gravel-bed flows can be highly variable within zone of influence. But after few distance downstream of protruding particle the original flow structure is recovered.

While there is no theorem relating Reynolds number to turbulence, flows with high Reynolds numbers usually become turbulent, while those with low Reynolds numbers usually remain laminar. For open channel flow, a Reynolds number above about 2000 will most likely correspond to turbulent flow, while a Reynolds number below 500 indicates laminar flow. The region in between (500 < Re < 2000) is called the transition region. In turbulent flow, unsteady vortices appear on many scales and interact with each other. Drag due to boundary layer skin friction increases. The structure and location of boundary layer separation often changes, sometimes resulting in a reduction of overall drag. Turbulence causes the formation of eddies of many different length scales. Most of the kinetic energy of the turbulent motion is contained in the large scale structures. This process continues creating smaller and smaller structures which produces a hierarchy of eddies (Schmid, 2001). Eventually this process creates structures that are small enough that molecular diffusion becomes important and viscous dissipation of energy finally takes place. Although it is possible to find some particular solutions of the Navier-Stokes equations governing fluid motion, all such solutions are unstable at large Reynolds numbers (Falco, 1977). It is the ability to generate new vorticity from old vorticity that is essential to turbulence. And only in a three-dimensional flow is the necessary stretching and turning of vorticity by the flow itself possible (Roy *et al.*, 2004).

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In gravel-bed Rivers as well as in channels the hydrodynamics are strongly influenced by the heterogeneous topography of the bed, composed of discrete particles, bed forms, and roughness elements of various shapes, sizes, and orientations (Kirkbride, 1993). Hence, in the present study it was aimed to determine spatial distribution of velocity and Reynolds stress at upstream and downstream section of protruding particle over the gravel bed till it achieve the zone of recovery.

METHODOLOGY

This experiment was carried out in Hydraulic and Water resources Engineering Laboratory of the Indian Institute of Technology, Kharagpur, West Bengal, India. Experiments were performed in a horizontal, re-circulating flume with a rectangular cross-section of 12 m length, 0.9 m width and 0.71 m deep. At the test section, the side walls of the flume were made of transparent glasses. At the inlet section of the flume concrete stilling basin was provided through which water enters into the flume. The stilling basin consisted of one perforated baffle wall and two vertical steel screens covering the full cross section for damping the flow turbulence and waves. An adjustable tailgate was installed at the downstream end of the flume to control the flow depth. The flume was connected to the water supply system comprised of a constant head reservoir about a height of 4 m above the ground level, an inlet tank, a large underground reservoir and the pumps. The water was pumped to the constant head reservoir and supplied to the inlet tank through the valve fitted at their junction. A calibrated V-notch weir was fitted at the inlet tank through which water entered into the flume via stilling basin.

The sediment of d_{50} value which is equals to 2.6 mm was placed uniformly in the flume and a constant slope of almost 1 in 1400 was made over the sediment. The bed level was checked using a point gage. The experiments were performed by placing a perfectly spherical steel ball of diameter 4 cm over the sediment bed. Then similar experiment was carried on 2cm and 3cm balls (Fig. A). The discharge into the flume was regulated by a valve fitted at the junction of constant head reservoir and inlet tank and decided using calibrated V-notch fitted at the inlet tank. Instrument carriage carrying a vernier point gage with an accuracy of ±0.1 mm was used for the measurement of bed level and water surface level above the bed. The Vectrino Velocimeter was used for the measurement of instantaneous three-dimensional component of velocity. The experimental data were collected using a 5 cm down looking Vectrino – A new generation 3D water velocity sensor. The Vectrino is a high-resolution acoustic velocimeter used to measure 3D water velocity in a wide variety of applications from the laboratory to the field with an acoustic

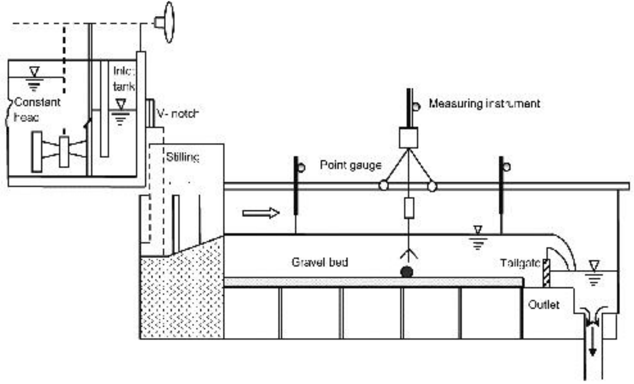

Fig. A : Schematic diagram of the experimental set-up

frequency of 10 MHz. The Vectrino was fastened to instrument carriage securely so that it can move freely both longitudinal and transverse direction. Our point of interest was lying at various longitudinal sections such as 3d upstream and 0.5d, 1.0d, 1.5d, 2.5d, 3.5d, 5.5d, 8.0d downstream from the edge of the ball at various depth, where d is the diameter of the ball (Fig. B). The vertical measurements were taken at an interval of 0.125m up to an height of 3 cm above virtual bed level was reached. Then an interval of 0.250 cm was used followed by 0.5 cm till a height of 5 cm and 10 cm was reached.

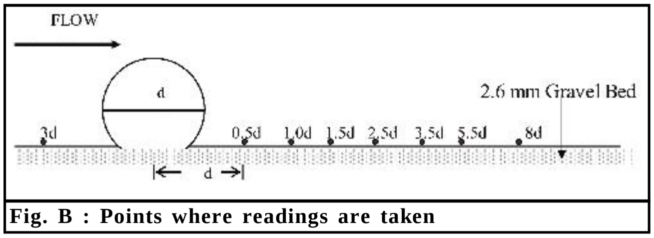

Fig. B : Points where readings are taken

RESULTS AND DISCUSSION

Velocity measurements for all experimental runs were taken. It was observed that, the obstruction of the flowing stream by a protruding particle caused a three-dimensional separation of flow, as it travels through the particle, forming a vortex flow. Drag due to boundary layer skin friction increases. The structure and location of boundary layer separation often changes, sometimes resulting in a reduction of overall drag. Thus, stream wise velocity changed its direction while flow past the sphere. In present experimental runs, the vertical distributions of time averaged stream wise velocity component were plotted. Almost similar pattern was observed for all the three balls (Fig. 1-3). Due to flow separation negative stream wise velocity was observed in immediate downstream of spherical ball which is at 0.5 times diameter of ball and attain significant recovery by 2.5d downstream. In all the cases, the negative velocity was in lower depth below 2 cm. However, with increase in size of ball, greater is the depth of negative velocity, due to greater flow separation caused by the balls. In successive experimental readings taken along downstream, the original velocity profile is approached with increasing downstream distance and fully recovered almost after 8 times diameter of ball. For different ball diameter, the variation in velocity for various locations for different balls is giving a similar pattern. Flow separation increases with size of obstruction, for a given flow rate. The pattern in the variation of longitudinal velocity shows negative immediately after the obstruction and then achieved recovery (Fig. 4). The negative velocity in the immediate downstream has significant effect on the scouring occurred in soil is due to different types of forces act between soil particles which causes the dislodgement of particles.

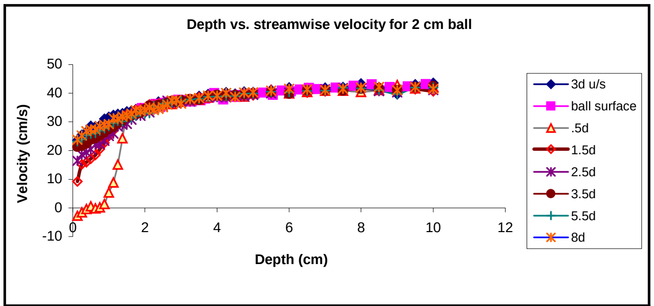

Fig. 1 : Velocity-depth variation at various locations for the ball of 2 cm diameter

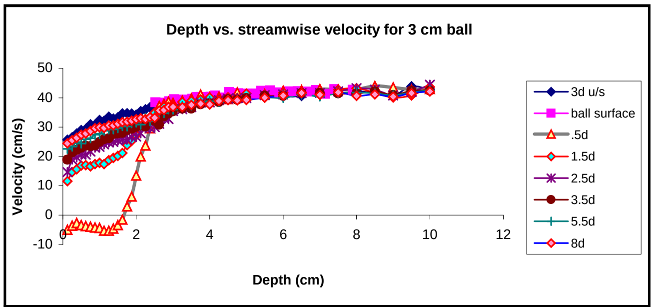

Fig. 2 : Velocity-depth variation at various locations for the ball of 3cm diameter

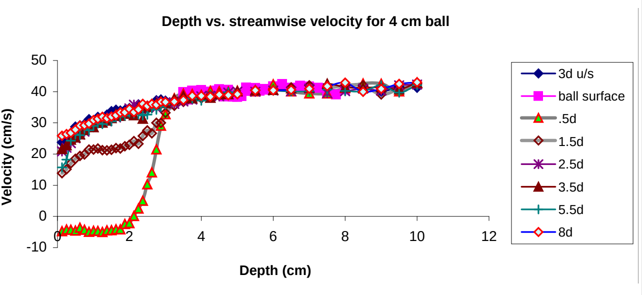

Fig. 3 : Velocity-depth variation at various locations for the balls of 4 cm diameter

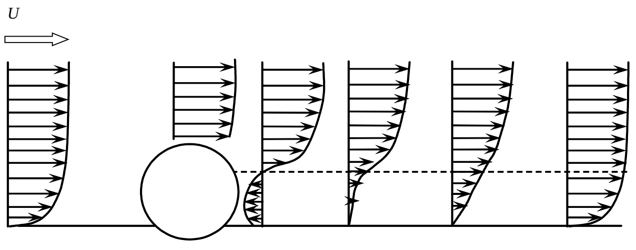

Fig. 4 : Variation of velocity longitudinally due to flow past the sphere

The Reynolds stresses is the stress tensor in a fluid due to the random turbulent fluctuations in fluid momentum. The stress is obtained from an average over these fluctuations. Reynolds stresses and can be expressed as a stress tensor called Reynolds stress tensor given as

Where σ_1, σ_2, σ_3 are are normal stresses in (x, y, z) directions and τ_{12}, $\tau_{13,}$ $\tau_{21,}$ $\tau_{23,}$ $\tau_{31,}$ τ_{32} are Shear stresses. 1',2',3' are the fluctuations of instantaneous streamwise, transverse and vertical velocity components respectively. Value of Reynolds stresses changed its sign due to reversal of flow just immediate downstream of spherical ball (Fig. 5). As a result of flow separation and hence velocity box averaged shear stress reduced near the bed level. At 0.5 d upstream, it shows maximum negative Reynolds stress.

$$\begin{bmatrix} \pm_1 & 2_{12} & 2_{13} \\ 2_{21} & \pm_2 & 2_{23} \\ 2_{31} & 2_{32} & \pm_3 \end{bmatrix} = -° \begin{bmatrix} \overline{1'1'} & \overline{1'2'} & \overline{1'3'} \\ \overline{2'1'} & \overline{2'2'} & \overline{2'3'} \\ \overline{3'1'} & \overline{3'2'} & \overline{3'3'} \end{bmatrix}$$

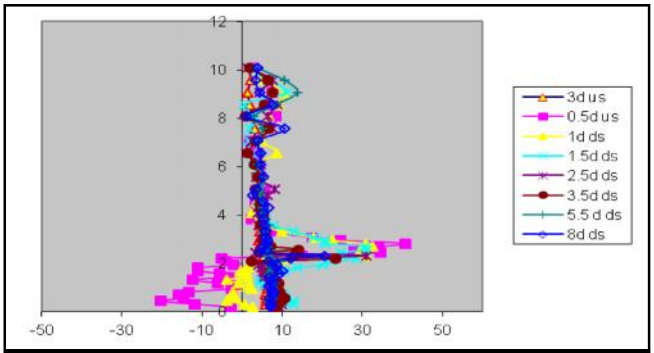

Fig. 5 : Box averaged shear stress for 4 cm ball

Conclusion :

There is significant change in velocity in the downstream of protruding particle due to flow separation. The velocity near bed just immediate downstream of the protruding particle is negative. There is gradual shifting of velocity from highly negative value near bed level at just after protruding particle to normal velocity level as in upstream of 2.5d of protruding particle. So finally velocity is recovered after certain distance which is almost 8 times diameter of the protruding particle. There is gradual shifting of box averaged Reynolds stress from highly negative value near bed level at just after protruding particle to normal level as in upstream of protruding particle. So finally both velocity and stress recovered after certain distance which is almost 8 times diameter of the protruding particle. There is a study needed to show the longitudinal variation of velocity for different size and shape of objects and a mathematical model can be developed to understand fluid behaviour.

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