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EXPERIMENT STUDY ON SEDIMENT INCIPIENCE IN BACKWARD-FACING STEP FLOW

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ABSTRACT: Flow over a backward-facing step was studied to investigate the effect of large-scale vortex structures on sediment incipience. The transient flow velocity field at the downstream of the backward-facing step was obtained using the technique of Particle Tracking Velocimetry (PTV). The optical amplification technique was employed to measure the instantaneous flow velocities near the bed and the instantaneous bed shear stress was given. The experimental observations revealed a new insight into the oscillation of the large-scale structure and the three-dimensional characteristics of the flow. In particular, very high turbulence intensity, instantaneous horizontal velocity near the bed and the bed shear stress near the reattachment point were observed. The sediment incipient probability obtained from the sequent images of sediment particles near the bed indicates that the critical instantaneous shear stress of the sediment incipience is independent of flow conditions.

KEY WORDS: backward-facing step flow, coherent structure, sediment incipience, Particle Tracking Velocimetry (PTV)

1. INTRODUCTION

For investigating the problems such as sediment transport, local scour, etc., it is of primary importance to understand the mechanism of sediment incipience, which has been extensively studied. In most researches, the sediment incipience has been attributed to the mean bed shear stress or mean lift force. Up to now, a great deal of research efforts has been devoted to establishing the relationship between the sediment transport and the mean shear stress or unit stream power [1-4]. However, some investigations showed that the sediment particles could be picked up as the mean lift force imposed on the sediment particles is not large enough to make them suspend [5] and the sediment incipience could occur even though the mean bed shear stress approaches zero [6].

Recently more and more researchers began to be concerned about the effect of coherent structure on sediment incipience. One of these research efforts is the introduction of the concept of bursting process in the study of sediment incipience and transport. Cao [7] calculated the pick-up flux from the bed according to the average bursting period and spatial scales. Keshavarzy[8] applied the image processing technique to investigate the relationship of the sediment incipient probability and the probability distributions of the high instantaneous bed shear stress in the case of sweeps. By conducting the coupled Laser Doppler Velocimetry (LDV) measurements of the instantaneous velocity near the wall and real time measurements of sand

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particle trajectories at the bottom, Sechet and Guennec [9] demonstrated the involvement of the coherent structures in bed load transport. It was assumed that two transport modes exist at the wall: the dominant transport by ejections and the sweeps involved in the removal of particles on the wall. Marchioli [10] studied the motion of particles in the boundary layer through Direct Numerical Simulation (DNS) and found that particles are transferred by sweeps in the wall region, whereas ejections transfer particles from the wall region to the outer flow. Zhong et al. [11] classified particles moving in the bed load layer into two groups, one being lifted up by ejections, the other being carried back to the bed via sweepings. By calculating the upward and downward fluxes of particles, they obtained the particle concentration in the bed load layer.

All these studies, however, have been still limited to the condition of the wall boundary layer. In the case of local scouring, the separation of boundary layer exists, and large-scale vortex structures are often generated in the free shear layer and interact with the wall. The influence of the large-scale vortices on sediment incipience becomes very important. More recently, some scholars numerically investigated the effects of the vortices on sediment transport [12, 13]. Unfortunately, few experimental researches on the sediment transport in the case of large-scale vortices have been carried out and the critical condition of the sediment incipience under the action of large-scale vortex structures is still not very clear.

Flow over a backward-facing step, in which the separation and the reattachment of the boundary layer exist, is a perfect flow model to study the role of the large-scale vortex structures in the sediment incipience and transport. So the influence of large-scale vortex structures on sediment incipience is studied in this article. The instantaneous flow velocity field at the downstream of the backward-facing step is measured by the Particle Tracking Velocimetry (PTV) and the instantaneous bed shear stress was calculated by the instantaneous flow velocity field near the wall. The variation of image gray scale is used to judge whether the sediment on the bed is moving or still. The critical instantaneous shear stress of sediment incipience under the action of large-scale vortex structures is obtained by analyzing the probability of the sediment incipient motion.

2 . EXPERIMENTAL APPARATUS AND METHODS

Experiments were carried out in the water tunnel of the Key Laboratory of Turbulence and Complex Systems at Peking University. The observation section of the tunnel is a 6 m long, 0.4 m wide and 0.4 m deep Perspex flume. The turbulence intensity at the inlet of the flume is lower than 0.3%. The flow velocity range is 0.05 m/s-1.0 m/s. A step of 0.025 m height was placed at the middle of the flume. A sediment container, which is a 1.0 m long, 0.3 m wide and 0.05 m deep Perspex box, was located at the downstream of step. The plastic particles with densities 1.4×10^3 kg/m^3 and diameters 0.5 mm were filled in the sediment container to form sediment bed (see Fig.1). In order to measure the instantaneous flow velocity field, the PTV technique was employed. The pollen with the density 970 kg/m^3 and the diameter 40 μm was used as the tracer particles, which are feeding at a distance 1.5 m upstream of the step. An Argonion laser with the power of 5 W was employed to generate the light sheet. The flow velocity field in the vertical plane was measured by letting light sheet enter from the top of the flume, while the horizontal flow velocity was measured by letting the light sheet enter from one side of the flume.

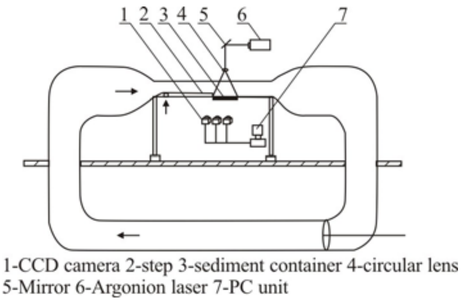


Fig. 1 Sketch of experimental apparatus

Three Charge-Coupled Device (CCD) cameras were used to record the images of the large-scale structures at the downstream of the step. The images recorded in the CCD cameras were simultaneously grabbed and stored in the memory of the PC unit under the control of the software. The images from different CCD cameras were combined into one large image. According the combined image, the instantaneous flow velocity field with the range of 9*H* at the downstream of the step could be measured, where H is the height of the step.

The optical amplification technique was employed to measure the flow velocity field near the bed. A len with the focus 75 mm was used to magnify the image. The resolution of image is 72 pixels/mm. According to the horizontal instantaneous flow velocity components u_x, u_y near the bed, the instantaneous bed shear stress τ is calculated by the logarithmic law

$$\frac{\sqrt{u_x^2 + u_y^2}}{u_*} = 2.5 \ln \frac{u_* z}{\nu} + 5.5 \qquad (1)$$

where $u_* = \sqrt{\dfrac{\tau}{\rho_w}}$. In order to calculate u_*, the value of z must be determined. It is known that the logarithmic law is valid only as $z_{cr}^* = \dfrac{u_* z}{\nu} > 30$, where the value of z_{cr}^* depends on the flow conditions. So it is a better choice to let $\dfrac{u_* z}{\nu} \approx 30$. In our experiments, z was chosen as 2 mm, which could satisfy $\dfrac{u_* z}{\nu} \approx 30$ in most cases.

In order to study the incipience and suspension of the sediment at different stream wise positions at the downstream of the step, the light sheet was first set entering from the top of the flume. The image of the sediment bed and the suspended sediment particles were recorded. The grids shown in Fig. 2 were adopted to judge the incipience of the sediment. The bottom of the grids were the sediment bed, and the size of the grid was 0.005 m × 0.005 m. The height of the gravity center of the sediments in one grid h_c was calculated by the formula

$$h_c = \frac{\sum_{i=1}^{n} h_i g_i}{\sum_{i=1}^{n} g_i} \qquad (2)$$

where g_i is the gray scale of a pixel, h_i is the height of the pixel and n is the total number of pixels in the grid. The events of the sediment incipience were then determined by the derivation of h_c with respect to time $\dfrac{\mathrm{d}h_c}{\mathrm{d}t}$. In the case of $\dfrac{\mathrm{d}h_c}{\mathrm{d}t} > 0$, most of sediments in the grid are suspended and there is an incipient event occurring in the grid. In the case of $\dfrac{\mathrm{d}h_c}{\mathrm{d}t} < 0$, most of sediments in the grid are depositing and there is no incipient event in the grid. In the case of $\dfrac{\mathrm{d}h_c}{\mathrm{d}t} = 0$, the sediments in the grid are still and no incipient event occurs in the grid. Divided the time occupied by the incipient events by the observing time, the probability of the sediment incipience in a grid can be obtained.

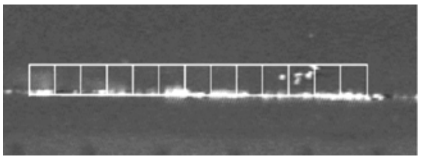


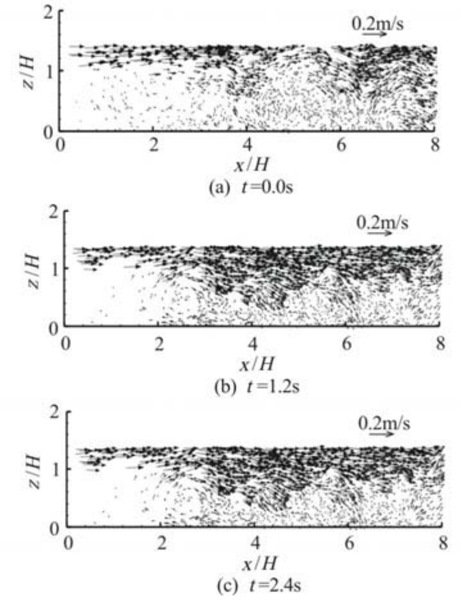
Fig. 2 The grids adopted to judge the sediment incipience

3. RESULTS AND DISCUSSIONS

3.1 *Flow characteristics*

The turbulent flow at the downstream of the step was measured in order to investigate the mechanism of the sediment incipience under the influence of large-scale vortex structures. The Reynolds number *Re* in the experiment is 5×10^3, where *Re* is defined as $Re = \dfrac{U_0 H}{\nu}$, U_0 is the mean velocity at the inlet and ν is the kinematic viscosity.

The instantaneous flow velocity field at the downstream of the step is characterized by the unsteady large-scale structure and three-dimensional features. It was observed in the experiments that free-shear layer emanating from the step rolls up and forms large-scale structure due to the Kelvin-Helmholtz (K-H) instability. The large-scale structure continues to grow and interacts with the bed near the reattachment point. Consequently, the reattachment point travels further downstream as the large-scale structure grows in its scale and strength until a detachment of the large-scale structure from the step occurs causing a sudden decrease of the reattachment length. Figure 3 shows the transient velocity field in the vertical plane at the downstream of the step. The oscillating process of the large-scale structure is clearly evident in the figure. For measuring the oscillating range of the large-scale structure, the instantaneous reattachment point is defined as the location of $\frac{\partial u_x}{\partial z}\Big|_{z=0} = 0$, where u_x is the stream wise velocity. The position of the instantaneous reattachment point is obtained from the transient velocity field in the vertical plane. It is found that the instantaneous reattachment point oscillates from $4.6H$ to $6.8H$ for $Re = 5\times10^3$. These results agree with the numerical results of Friedrich[14] and Le[15].



(a) t=0.0s

(b) t=1.2s

(c) t=2.4s

Fig. 3 The transient flow velocity field at the downstream of the step

In the oscillating range of the large-scale structure, the turbulence intensity is found to be higher due to the existence of high intensity large-scale vortices. Figure 4 shows the stream wise and vertical turbulent root-mean-square velocity u', v' at the downstream of the step. It is shown that the turbulence intensity depends on the movement of the large-scale vortices. It can be seen that the turbulent root-mean-square velocity is small in the region of $0 \le x \le 2H$ close to the step since the large-scale vortices have not developed. As the distance away from the step is greater than $2H$, the large-scale vortices begin to develop and the turbulent root-mean-square velocities increase rapidly. In the region near the reattachment point, the large-scale vortices have fully developed and the turbulent root-mean-square velocities reach the maximum value. At further downstream of the reattachment point, however, the turbulent root-mean-square velocities begin to decrease due to the break-up and subsequent dissipation of the large-scale vortices. It is also shown in Fig. 4 that the stream wise root-mean-square velocity is higher than the vertical component in the region near the bed, indicating the deformation of the large-scale vortices near the bed. The strong interaction of the large-scale vortices and the bed in the region near the reattachment point tends to induce very high instantaneous flow velocity near the bed (see Fig. 5) , A direct consequence of such high instantaneous flow velocity due to the strong interaction of large-scale vortices and the bed is the occurrence of the sediment incipience.

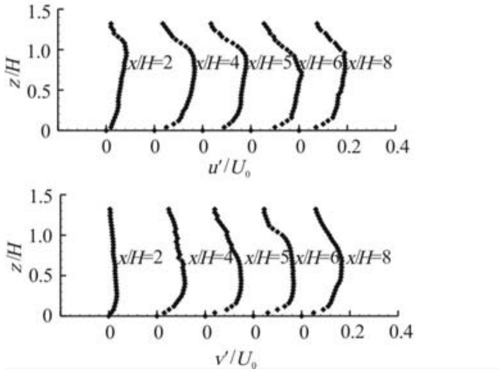


Fig.4 Turbulent root-mean-square velocity at the downstream of the step

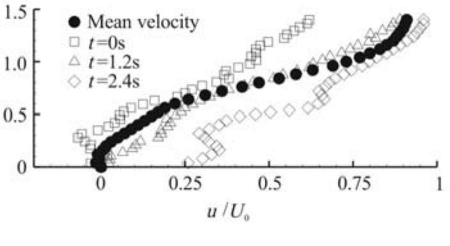


Fig. 5 The profiles of instantaneous stream wise velocity near the reattachment point x/H=6.0

The instantaneous flow velocity field in the horizontal plane shows the three-dimensional characteristic of the flow (see Fig. 6). Due to the instability of the flow, the Tollmien-Schlichting (TS) wave forms in the free-shear layer emanating from the step and the flow velocity (y) in the span wise direction exhibits similar periodic variation (see Fig. 6(a)). The span wise vortices are distorted with the development of the T-S wave and three-dimensional vortices form at the downstream of the step. These three-dimensional vortices interact with the bed near the reattachment point as the free-shear layer rolls up. The strong interaction of the three-dimensional vortices with the bed appears to induce very high span wise velocity near the bed. Figure 6 shows the very high span wise velocity near the bed in the oscillating range of the large-scale structure. The same phenomenon was also found by Le[15] using the DNS. So the three-dimensional characteristic of the flow is also a contributor to the very high instantaneous velocity near the bed in oscillating range of the large-scale structure.

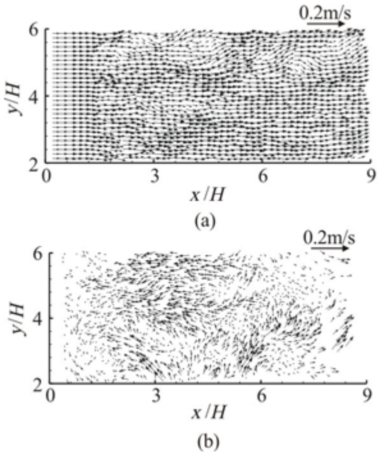


Fig. 6 The instantaneous flow velocity field in the horizontal plane

The instantaneous bed shear stress τ was calculated based on the instantaneous flow velocity in the horizontal plane of 2 mm above the bed, and the results are shown in Fig.7. It is seen that the instantaneous bed shear stress in the region of $0 \le x \le 2H$ close to the step is very low. This is due to the low velocity and turbulence intensity in this region. As the distance away from the step is greater than $2H$, the higher bed shear stress region is observed with the increase of turbulence intensity. In the region near the reattachment point, as can be seen in Fig.7, the instantaneous bed shear stress reaches as high as 3 times of that at the far down stream of the step. So the effect of turbulence and the interaction of large-scale vortices on the sediment incipience may be manifested by the instantaneous bed shear stress.

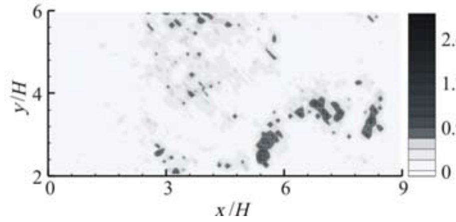


Fig. 7 The instantaneous bed shear stress at the downstream of the step (τ_0: bed shear stress at far down stream)

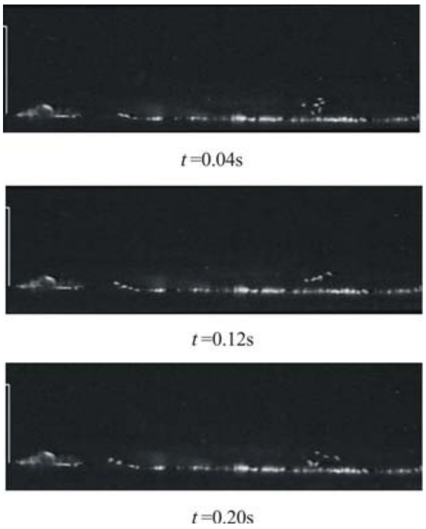
3.2 *Probability of sediment incipience*

In the turbulent flow field, the incipience of the sediment is uncertain. So the incipient probability P_i is introduced to describe the phenomenon of the sediment incipience. The probability of the sediment incipience is obtained from the time occupied by the sediment particles suspension event, which is calculated based on the sequent images of sediment particles near the bed (see Fig. 8). The images shown in Fig. 8 are 0.04 s equally apart. An event of sediment particles suspension and the following depositing event are observed in Fig. 8. It is found that the time occupied by the suspension event is shorter than that occupied by the depositing event. Figure 9 shows the distribution of the sediment incipient probability at the downstream of the step. It is seen that very few sediment incipience events occur in the region of $0 \le x \le 2H$ close to the step. As the distance away from the step is greater than $2H$, the sediment incipience events start to occur and the probability of sediment incipience begins to increase. In the region near the reattachment point ($\approx 6H$) the probability of sediment incipience reaches its maximum despite very low mean flow velocity near the bed in this region. At the further downstream of the reattachment point, the probability of sediment incipience remains relatively high. So the mean bed shear stress cannot be the criterion of sediment incipience as the large-scale vortex structures exist. The instantaneous bed shear stress is assumed to be the criterion of sediment incipience in this article. If this assumption is right, there must exist a critical instantaneous shear stress τ_c satisfying the following equation anywhere

$$P\{\tau > \tau_c\} = P_i \tag{3}$$

where $P\{\tau > \tau_c\}$ is the probability of

$\tau > \tau_c$ .Figure 9 shows that the distribution of $P\{\tau > 0.12 \text{ N/m}^2\}$ is almost the same as the distribution of the sediment incipience probability at the downstream of the downstream of the step. Therefore, the critical instantaneous shear stress of the sediment in the present experiment is 0.12 N/m^2 and the sediment will be picked up if the instantaneous bed shear stress is greater than 0.12 N/m^2. It should be noted that the critical instantaneous shear stress is only dependent on the sediment. For a given sediment, there is only one critical instantaneous shear stress under all flow conditions. A large number of experiments are required in order to obtain the critical instantaneous shear stress for different sediments.


t=0.04s

t=0.12s

t=0.20s

Fig. 8 The sequent images of sediment particles near the bed

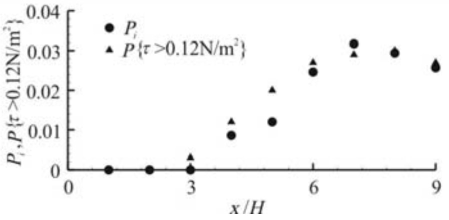


Fig. 9 The distribution of incipience probability and the probability of $\tau > \tau_c$ at the downstream of the step

4. CONCLUSION

Flow and the incipience of sediment suspension at the downstream of a backward-facing step have been experimentally studied. The oscillation of the large-scale structures and the three-dimensional characteristics of the flow have been observed in the experiments. The interaction of the large-scale vortices and the bed is found to induce very high turbulent intensity and instantaneous horizontal flow velocity near the bed, and further to result in the incipience of sediment suspension. The higher instantaneous span wise velocity near the bed induced by stream wise vortex is also found to be important for the sediment incipience. It is concluded that the instantaneous bed shear stress can be taken as the criterion of sediment incipience for the flow with strong turbulence and vortices. There exists one and only one critical instantaneous shear stress under all flow conditions for given sediment.

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