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Experimental Study of Sediment Incipience Under Complex Flows*

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Abstract: Sediment incipience under flows passing a backward-facing step was studied. A series of experiments were conducted to measure scouring depth, probability of sediment incipience, and instantaneous flow velocity field downstream of a backward-facing step. Instantaneous flow velocity fields were measured by using Particle Image Velocimetry (PIV), and an image processing method for determining probability of sediment incipience was employed to analyze the experimental data. The experimental results showed that the probability of sediment incipience was the highest near the reattachment point, even though the near-wall instantaneous flow velocity and the Reynolds stress were both much higher further downstream of the backward-facing step. The possible mechanisms are discussed for the sediment incipience near the reattachment point.
Keywords: sediment transport; local scour; complex flows; particle image velocimetry; sediment incipience

Understanding the mechanisms of sediment incipience is important for the study of sediment transport and local scouring process. Critical incipient conditions for sediment movement have been studied extensively in the past mainly for relatively simple flows. Pioneer work on the sediment incipient conditions was done by Shields (1936)[1], who attributed the sediment incipience to the mean bed shear stress. The critical mean bed shear stress to move sediment particles can be determined from the well-known Shields diagram. The original data of Shields (1936)[1] showed considerable scatter, and the Shields curve should be interpreted as the mean of the data in a narrow band (Buffington (1999)[2]).

In order to evaluate the critical incipient shear stress or shear velocity for sediments of different properties (cohesive or cohesionless), a large number of empirical formulae were developed (e.g., Rijn (1984)[3], Dou (1999)[4], Cheng (2004)[5], Cao *et al*(2006)[6]). Although much work has been done on the sediment incipience, no universal theory exists at present that can provide accurate predictions of sediment incipience under various flow conditions, including complex flow conditions where large vortices exist. Main difficulties in the study of the sediment incipience come from two aspects: a) sediment incipience is not well-defined for complex flows; b) mechanisms of sediment incipience are not well-understood.

Traditionally, sediment incipient conditions were obtained from one of the following methods: a) visual observations of motion of sediment grains; b) bulk sediment transport rates; c) probability of sediment incipience. In early studies of sediment transport, the sediment incipient conditions were obtained mainly from visual observations. Based on visual observations, Kramer (1935)[7] defined three types of sediment incipient conditions, namely, weak transport, medium transport and general transport (see Beheshti and Ataie-Ashtiani (2008)[8]). One problem with visual observations is that sediment incipient conditions are determined subjectively by individual investigators. In recent studies, methods based on either bulk sediment transport rates (e.g., Rijn (1984)[3]) or probability of sediment incipience (e.g. Neill and Yalin (1969)[9], Dancey *et al* (2002)[10]) are widely adopted to obtain the sediment incipient conditions. Compared with the methods based on visual observations, the results obtained by the other

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two methods are more objective, but implementation of these two methods can be difficult for certain complex flows.

In the past, mean bed shear stress was widely used to discuss the hydrodynamic mechanisms that cause sediment grains to move. Majority of past researches on the sediment incipience focused on the determination of critical incipient mean shear stress. Recently Lyn (1995)[11] and Liu and Huhe (2003)[12], in their studies on sediment incipience under turbulence generated by oscillating grid, reported that sediment grains could be picked up under the condition of zero mean bed shear stress. The concept of bursting process that has been widely used in the study of turbulence was introduced recently to the study of sediment incipience and transport by several authors (Cao (1996)[13], Keshavarzy and Ball (1999)[14], Sechet and Guennec (1999)[15], Marchioli and Soldati (2002)[16]), who discussed the roles of sweeps and ejections in sediment incipience. Most of the early studies of sediment incipience focused on unidirectional stream flows. In the numerical studies of the local scour under complex flows, most researches adopted in their simulations the sediment incipient conditions obtained from unidirectional flows (e.g. Liang *et al* (2005)[17]). To our knowledge, very little experimental study has been done to determine the sediment incipient conditions under complex flows that have both flow separation and reattachment associated with large scale vortices. The mechanism of sediment incipience under complex flows is one of the areas in the study of sediment transport that needs further in-depth research.

Separation and reattachment associated with large vortices can be found in steady flows passing a backward-facing step. In this study, flows over a backward-facing step were employed to study the sediment incipience. A series of experiments were conducted to measure the instantaneous flow velocity fields and the probability of sediment incipience, and to record scouring process downstream of the backward-facing step. The probability of sediment incipience downstream of the backward-facing step was determined from our experimental data by analyzing sequential frames recording the positions of individual sediment particles. Possible hydrodynamic mechanisms of sediment incipience under complex flows will be tentatively discussed with the help of instantaneous flow velocity fields downstream of the step that were measured by using Particle Image Velocimetry (PIV).

1 Experimental apparatus and methods

Experiments were carried out in a Perspex flume, which had a test section of 6 m long, 0.4 m wide and 0.4 m deep. In our experiments, the working water depth was fixed at 0.3 m. Turbulent intensity at the inlet of the flume was lower than 0.3% and the adjustable flow velocity could vary continually from 0.05 m/s to 1.0 m/s. A backward-facing step of height 0.025 m was placed at the middle of the flume. A set of experiments were carried out to measure the velocity field using PIV (SM2-MicroVec V2.0 PIV system developed by Beijing Macro-Space Company). Hollow glass beads of diameter 5 μm were used as tracer particles, which were introduced to the flow through an array of 1 mm holes equally distributed along a horizontal thin pipe(of a diameter 3 mm) placed at 1.5 m upstream of the step. 1.5 W semiconductor laser was used to provide a thin light sheet and the thickness of the laser sheet was about 1 mm. The resolution of the CCD camera used in the PIV system was 640×480 pixels and the grabbing speed was 200 frames per second. The flow field (vertical or horizontal) downstream of the step was divided into four small regions (field of view, or FOV) so that each FOV could be covered by the CCD camera to provide the required spatial resolution. For vertical flow field, the size of each FOV was 70 mm×52 mm; for horizontal flow field, the size of each FOV was 85 mm×64 mm. Accordingly, the mesh size for calculating velocity vector was about 1.7 mm×1.7 mm for all vertical flow fields and 2.1 mm×2.1 mm for all horizontal flow fields. To illuminate the flow field in the vertical plane, the laser light sheet entered the water from the bottom of the flume. To illuminate the flow field in the horizontal plane, the laser light sheet entered the water from one side of the flume. The nearest horizontal velocity field that could be measured in our experiments was 0.5 mm above the bottom.

Separate sets of experiments were also carried out to study the probability of sediment incipience. A sketch of the experimental apparatus is shown in Fig.1. To prepare the sediment bed, a sediment container was arranged immediately downstream of the step. The sediment container was a Perspex box of 1.0 m long, 0.38 m wide and 0.05 m deep. Uniform glass beads of density 2 500 kg/m^3 and diameter 0.165 mm were filled in the sediment container to form a sediment bed of a thickness same as the inner depth of the sediment container. First, the sediment bed was carefully prepared using a special tool to make sure that the sediment bed surface was as horizontal and flat as possible, and then the laser light sheet was carefully adjusted so that it was tangent to the surface of the sediment bed. In this way the sediment particles on the bed surface could be illuminated (it is possible that some sediment particles were in the shadows of other sediment particles). As the bottom was occupied by sediment grains in these experiments, a CCD camera of resolution 768×576 pixels was placed above the flow to record images of sediment particles through a horizontal, transparent plate whose lower surface was adjusted to touch the still water surface. The CCD camera could grab up to 25 frames per second. The sketch of the system used to measure the probability of sediment incipience is shown in Fig.2.

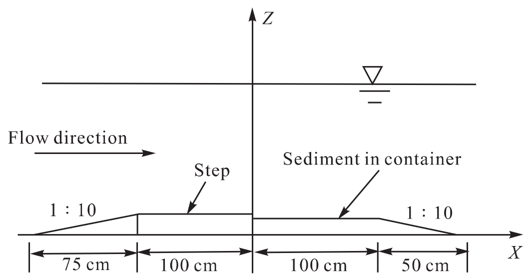


Fig.1 The sketch of the experimental apparatus

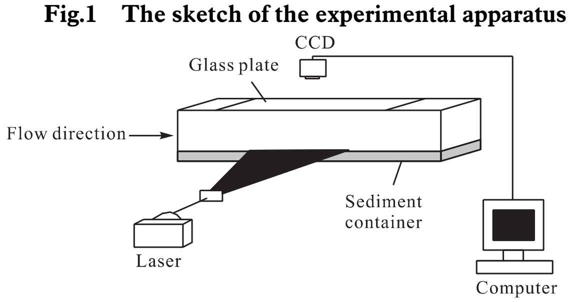


Fig.2 The system to measure the probability of sediment incipience

All sediment particle images recorded by the CCD camera were stored on a computer as digital images. Based on these digital images, the number of sediment particles on each pair of frames can be calculated by marking the pixels occupied by each individual sediment particle (e.g., Wang *et al* (1994)[18]). Pairing of particles on a pair of frames can be done by examining the following cross-correlation coefficient (Soria *et al* (1999)[19])

$$R(\Delta I,\Delta J)=\frac{\iint_{\Omega} g_1(I,J)g_2(I+\Delta I,J+\Delta J)\mathrm{d}I\mathrm{d}J}{\left(\iint_{\Omega} g_1^2(I,J)\mathrm{d}I\mathrm{d}J\iint_{\Omega} g_2^2(I+\Delta I,J+\Delta J)\mathrm{d}I\mathrm{d}J\right)^{1/2}} \tag{1}$$

where I, J are the coordinates of pixels in the frame; $g_1(I,J)$, $g_2(I,J)$ are the grey scales of the pixel (I,J) in the first and the second frame, respectively; Ω is the collection of all pixels occupied by one particle. In our measurements, the time interval Δt between two adjacent frames was 0.04 s. The displacement of an identified particle α recorded in a pair of frames is denoted by $\Delta \boldsymbol{x}_\alpha$, which can be determined by multiplying a scale factor with $(\Delta I,\Delta J)$. The values of $(\Delta I,\Delta J)$ can be determined by requiring that the cross-correlation coefficient $R(\Delta I,\Delta J)$ takes its maximum value at $(\Delta I,\Delta J)$. With known $\Delta \boldsymbol{x}_\alpha$ and Δt, the velocity of this particle can be computed simply by $\boldsymbol{U}_\alpha=\Delta \boldsymbol{x}_\alpha/\Delta t$.

If the velocity of a sediment particle is greater than 1 mm/s, this sediment particle is regarded as a moving particle in this study. A statistical analysis was carried out to compute the probability of sediment incipience averaged over a small region (field of view) of size 10 mm×7.5 mm. Let N_m^k be the number of moving sediment particles in the kth pair of frames and N_t^k the total number of the sediment particles in the same pair of frames, the averaged probability of sediment incipience for the kth pair of frames can be calculated by

$$P_k = N_m^k / N_t^k \tag{2}$$

When we determine N_t^k and N_m^k, there are two extreme scenarios that must be considered separately: (1) the velocity of a sediment particle is very small, and (2) the velocity of a sediment particle is very high. The first scenario has been discussed before and now we discuss the second scenario. When the velocity of a particle is very high, it is possible that the image of this particle cannot be found in the second frame, resulting in a very small cross-correlation coefficient. Fortunately, we only need to know whether or not a sediment particle is moving when we calculate the probability of sediment incipience, not the absolute velocity of a sediment particle. If the maximum cross-correlation coefficient of a sediment particle image under consideration is lower than a threshold value R_{cr}, we say the particle in the first frame has moved out of the second frame. In this study, we took the threshold value as R_{cr}=0.5, which was determined by assuming the particles touching the edge of the first frame will have their centers right on the edge of the second frame. Therefore, we can determine whether or not a sediment particle is moving from the velocity and cross-correlation coefficient of a sediment particle image, and obtain the number of total particles in kth pair of frames (N_t^k) and the number of the moving particles in the same pair of frames (N_m^k).

The profile of the sediment bed downstream of the step can be obtained by using a simple visualization method. In this method, the laser sheet in the vertical plane enters the water from the flume top; the intersection of the laser sheet and the sediment bed can be recorded by CCD camera from the side to provide the time-history of the sediment bed profile.

2 Results and discussion

2.1 Flow velocity field

We studied in our experiments the flow velocity fields at three different Reynolds numbers, defined by $Re = U_0 D/\nu$, where U_0 is inlet velocity, D is the step height and ν the kinetic viscosity of the fluid. The instantaneous flow velocity field at Re=5 000 is reported here. Fig.3 shows one typical instantaneous flow velocity field on the vertical plane measured by PIV. The complex vortex structures downstream of the step can be clearly observed. After averaging all the measured instantaneous flow fields over a time interval of 3 s (600 frames), the mean flow field downstream of the step can be obtained. Fig.4 shows the mean velocity profiles on the vertical plane at three different locations downstream of the step, along with those computed by Le *et al* (1997)[20]. It can be seen that the measured mean velocity profiles agree well with those obtained by direct numerical simulation of Le *et al* (1997)[20].

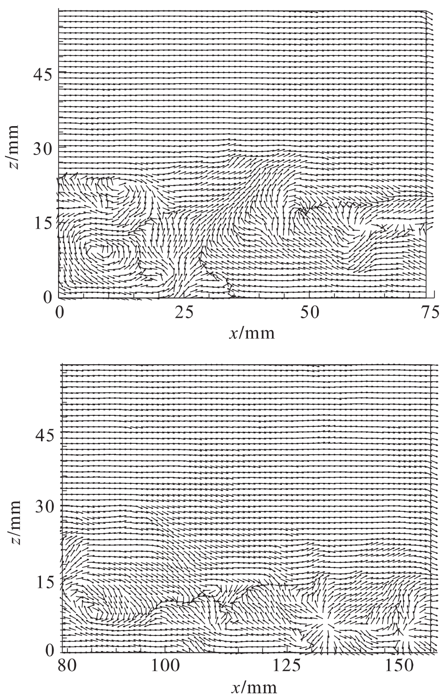
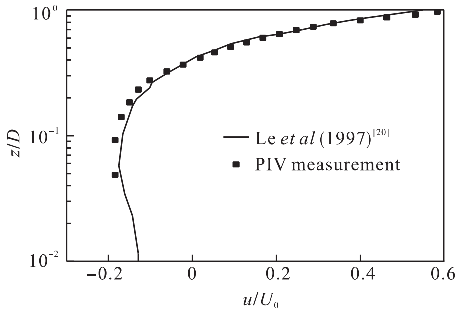
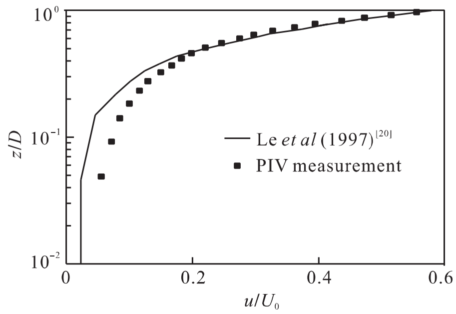


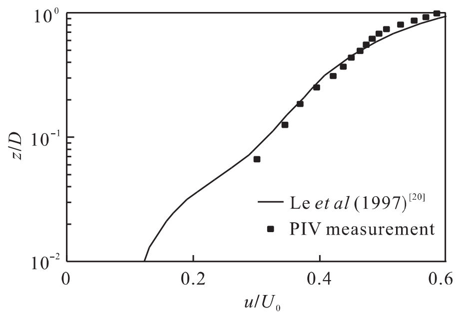
Fig.3 Instantaneous velocity field downstream of the step on the vertical plane



(a) x/D=4



(b) x/D=6



(c) x/D=12.5

Fig.4 Mean streamwise velocity profiles at three locations

Reattachment length X, the horizontal distance between the step and the reattachment point, is an important parameter for backward-facing flows and it has been studied extensively by many researchers (e.g. Armaly *et al* (1983)[21], Jovic and Driver (1994)[22], Le *et al* (1997)[20]). Armaly *et al* (1983)[21] studied the effects of Reynolds number (Re) on the reattachment length. They found that the reattachment length first increased with Re when Re<1 200, then decreased with Re when 1 200<Re<6 600, and eventually approached a constant when Re>6 600. For Re=5 000, the reattachment length X varied slightly from 6.0D to 6.3D (Armaly *et al* (1983)[21], Jovic and Driver (1994)[22], Le *et al* (1997)[20]). According to measured mean velocity profiles, the reattachment lengths in our experiments can be obtained by $\left.\partial\overline{u}/\partial z\right|_{z=0}=0$ (Le *et al* (1997)[20]). The reattachment length in our experiments was found to be about 6*D*.

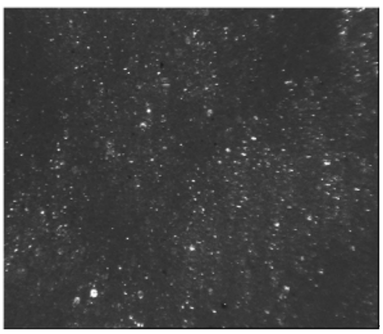
2.2 Probability of sediment incipience

The probability of sediment incipience downstream of the step was studied for three inlet mean velocities U_0 =0.15, 0.20, 0.25 m/s, respectively. The Reynolds number in our experiments was in the range of $1\,200 < Re < 6\,600$, for which flow transition from laminar flow to turbulence occurred (Armaly *et al* (1983)[21]). The sediment particle motion is stochastic in nature, and can be described by the probability of sediment incipience defined by Eq.(2). The probabilities of sediment incipience were measured at 8 different positions x=5, 8, 15, 22.5, 27.5, 32.5, 37.5, 40 cm, where x is the horizontal distance from the step.

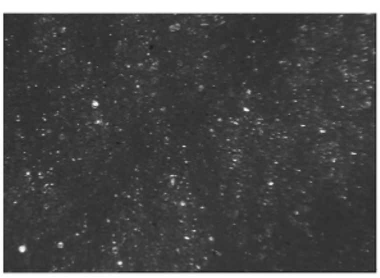
In our experiments, the total number of identified sediment particles in one pair of frames was 60—100 (see Fig.5). 100 pairs of frames were recorded for each test run, resulting in 6 000—10 000 sediment particles for statistical analysis, i.e., the probability of sediment incipience in the field of view is calculated by

$$P=\sum_{k=1}^{100}N_m^k\Big/\sum_{k=1}^{100}N_t^k \tag{3}$$

where N_m^k, N_t^k are the number of moving particles and the number of total particles in the kth pair frames, respectively. To further reduce the measurement errors,we repeated each test condition 4 times.



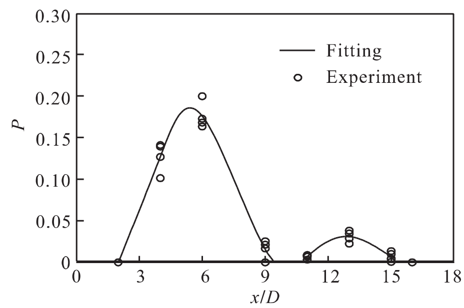
(a) The first frame (10 mm×7.5 mm)



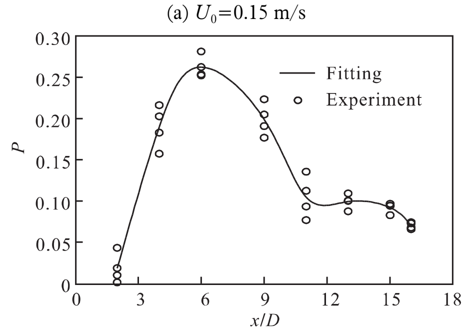
(b) The second frame(10 mm×7.5 mm)

Fig.5 The grey scale image of sediment particles (time interval between two adjacent frames is 0.04 s)

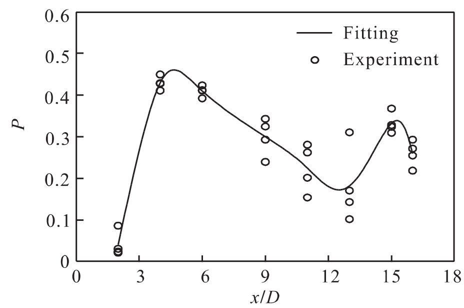
The probabilities of sediment incipience determined for 8 regions downstream of the step are shown in Fig.6. The scatter in the experiment data is expected due to the random nature in sediment particle motion. However, all experiment data confirmed that the maximum probability of sediment incipience occurred at a location 4*D*—6*D* away from the step (where *D* is the step height). For U_0=0.15 m/s and 0.20 m/s, the maximum probability of sediment incipience occurred at a location about 6*D* away from the step. For stronger current of U_0=0.25 m/s, the maximum probability of sediment incipience occurred at a location about 4*D* away from the step. It has been found in previous research on backward-facing step flows that the reattachment length is typically about 6*D* for Re=5 000 (Armaly *et al* (1983)[21], Jovic and Driver (1994)[22], Le *et al* (1997)[20]). In our experiments, Reynolds number ranges from 3 750 to 6 250, thus it can be concluded that the maximum probability of sediment incipience downstream of the step occurs in a region close to the reattachment point of the flow.



(a) U_0=0.15 m/s



(b) U_0=0.20 m/s



(c) U_0=0.25 m/s

Fig.6 Distribution of probability of sediment incipience downstream of the step

The evolution of the bed profile downstream of the step was also recorded by a CCD camera for 2 h to study the scouring process. Fig.7 shows the bed profiles at two instants: $t=10$ min and $t=2$ h. From Fig.7(b), it can be seen that the scour hole occupies the region of $4D<x<8D$ and the maximum depth of the scour hole occurs around $x=5.5D$, which is also the location of the reattachment point and the location where the probability of sediment incipience takes its maximum.

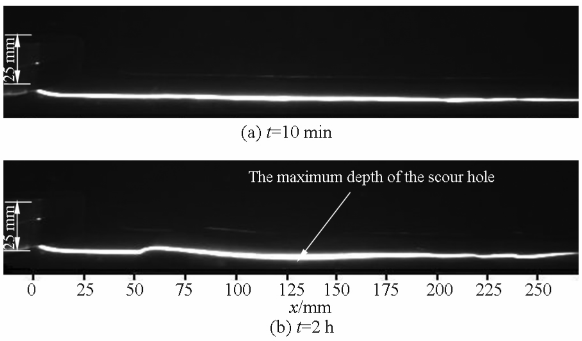


Fig.7 The bed profile downstream of the step ($U_0=0.25$ m/s)

It is well-known that the following condition must be satisfied at the reattachment point:

$$\frac{\partial \bar{u}}{\partial z}\Big|_{z=0}=0 \tag{4}$$

where $\bar{u}$ is the mean stream-wise velocity and z is the vertical distance measured from the bed. Eq.(4) implies that the mean bed shear stress at the reattachment point is zero if the concept of eddy viscosity is used to compute the Reynolds stress. Reynolds stress can also be computed by the correlation of turbulent fluctuations, i.e., $\overline{u'v'}$, where u' is horizontal velocity fluctuation, v' is vertical velocity fluctuation. The experimental results of Jovic and Driver (1994)[22] and direct numerical simulations of Le *et al* (1997)[20] showed that $\overline{u'v'}$ was high at the reattachment point, with maximum Reynolds stress $\overline{u'v'}$ occurring at $x=10D$. Therefore, the concept of eddy viscosity, which is well-defined for unidirectional flows, may not be suitable for complex flows where large scale vortices exist. The locations of maximum probability of sediment incipience and locations of maximum depth of scour holes found in our experiments are significantly different from the locations of the maximum Reynolds stress given by Jovic and Driver (1994)[22] and Le *et al* (1997)[20], suggesting that even the concept of Reynolds stress is not sufficient to explain the sediment incipience and scouring process in complex flows such as flows passing a backward-facing step. It is hypothesised that the flow acceleration and the pore pressure in the sediment bed might play an important role in the sediment incipience condition. Further study is needed to understand the mechanism of the sediment incipience near the reattachment point.

3 Conclusions

The probability of sediment incipience downstream of backward-facing step was measured using an image processing technique. The maximum probability of sediment incipience was found to occur near the flow reattachment point, which was also the location where the maximum depth of the scour hole occurred. Mean bed shear stress and Reynolds stress could not provide satisfactory explanation to our experimental results. Further study is needed to understand the mechanism of the sediment incipience near the reattachment point.

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