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Influence of decelerating flow on incipient motion of a gravel-bed stream

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Abstract. An experimental study on incipient motion of gravel-bed streams under steady-decelerating flow is presented. Experiments were carried out in a flume with two median grain sizes, $d_{50} = 16{\cdot}7$ mm for a fixed-bed case and $d_{50} = 8$ mm for a mobile bed case. In addition, an effort is made to determine a simplified method for the estimation of bed shear stress in decelerating flow over fixed and mobile beds for use in field situations. From the observation of eleven fixed-bed and nine mobile-bed velocity profiles, it is revealed that the parabolic law method (PLM) and the Reynolds stress method are comparable for estimation of shear velocity in general. Also, the results show that the shear stress distribution adopts a convex form over fixed and mobile beds. Due to this form the critical Shields parameter value for decelerating flow is less than the reported values in literature.

This paper supports Buffington & Montgomery (1997) statement that less emphasis should be given on choosing a universal shields parameter, and more emphasis should be given on choosing defendable values based on flow structure.

Keywords. Incipient motion; gravel-bed; decelerating flow; Shields parameter; parabolic law.

1. Introduction

The movement of sediment along a channel has been the most challenging problem to hydraulicians. Incipient motion of the bed sediment refers to the beginning of movement of bed particles. There are some difficulties in defining the incipient conditions precisely. The accurate measurement of water discharge in a channel at which the incipient motion occurs is a subjective criterion. In addition, the difficulty of observing sediment particles at the initiation of motion is another reason for the lack of general definition of incipient motion. Incipient motion of stream-beds is a fundamental aspect of river mechanics that has applications to a wide variety of research problems, such as stable channel design, scouring of river-beds, etc. Usually most investigators use a standard or modified form of the critical Shields parameter

(τ_{*c}) to define incipient motion of a given sediment size. The Shields parameter or dimensionless shear stress is defined as $\tau_* = \tau/[(\gamma_s - \gamma)d_{50}]$, where τ is the bed shear stress, d_{50} is the median diameter of sediment particles; and γ_s and γ are the specific weights of sediment and water, respectively.

Shields (1936) showed that τ_{*c} for uniform sediments varies with critical particle Reynolds number Re_{*c} and that attains a constant value of 0·06 for $\mathrm{Re}_* > 500$. The critical particle Reynolds number is defined as $\mathrm{Re}_{*c} = u_{*c}k_s/\nu$, where u_{*c} is critical shear velocity for incipient motion, that is $(\tau_c/\rho)^{0 \cdot 5}$; ρ is the mass density of water; k_s is the Nikuradse's equivalent roughness, being assumed to be d_{50}; and ν is kinematic viscosity. Several investigators (Garde & Ranga Raju 1985, Buffington & Montgomery 1997, Wilcock 1988, 1992 and Lavelle & Mofjeld 1987) analysed data on critical shear stress. They showed that the divergence between various methods and departure of experimental data from these. They stated that one reason of scatter in various studies is the definition of critical condition employed by different investigators. Also, the other reason of divergence is the fact that each investigator carried out his experiments in a limited range of sediment size. Also,when the material is nonuniform, it is extremely difficult to define the condition of incipient motion. In this condition the coarse particles would move relatively easily and the smaller ones move less readily because they will be sheltered. (Garde & Ranga Raju 1985). Therefore, it is important to find out the representative grain size in a mixture for critical condition. Likewise, it is interesting to know whether the critical shear stress calculated in this manner is smaller or larger than the critical shear force for uniform material of the same grain size. Aki and Sato (see Iwagaki 1956) showed that critical shear stress for non-uniform material will be smaller than the critical shear stress for uniform material of the same median size.

There have been number of additions and modifications on the shields curve in later period. Limited experiments by Fernandez Luque & Van Beek (1976) and Ikeda (1982) showed that the critical shear stress required for the initial movement of sediment on a stream-wise sloping bed decreases with increasing in slope. Using a larger data set, Yalin & Karahan (1979) reported that τ_{*c} is 0·045 for rough turbulent flow, and it was in conformity to the finding of Miller *et al* (1977), who compiled flume data from various sources. Song & Graf (1994) carried out research on the effect of uniform flow in open channels with movable gravel-bed. Dey (1999) put forward a theoretical model for the threshold of sediment motion on stream-wise sloping beds considering the equilibrium of a solitary sediment particle. Furthermore, experimental studies with gravel-beds were put forward by Mizuyama 1977, Bathurst *et al* 1987, Andrews & Parker (1987), Wiberg & Smith 1987, Andrews (1994), Chiew & Parker 1994, Church *et al* 1998, Patel & Ranga Raju 1999, Dey & Debnath 2000, Dey & Raju (2002) and Mueller *et al* 2005.

Over the eight decades, the incipient of motion of uniform flow have been extensively investigated (Baffington & Montgomery 1997). However, to the authors' knowledge there is no study on the influence of decelerating flow on incipient motion of gravel-bed channels. This kind of flow can be especially considered during low flows that water travels through a series of pool sections in gravel-bed rivers. Therefore, the primary objective of the present study is to investigate the effect of decelerating flow (velocity decreases in the stream-wise direction) on the incipient of motion of sediment. Since measurements of the Reynolds stress are difficult to make in the field, an attempt is made to present a simple alternative which can be easily applied to gravel-bed rivers. Finally, application of the Shields diagram to predict the incipient motion is investigated for decelerating flow over a gravel-bed channel.

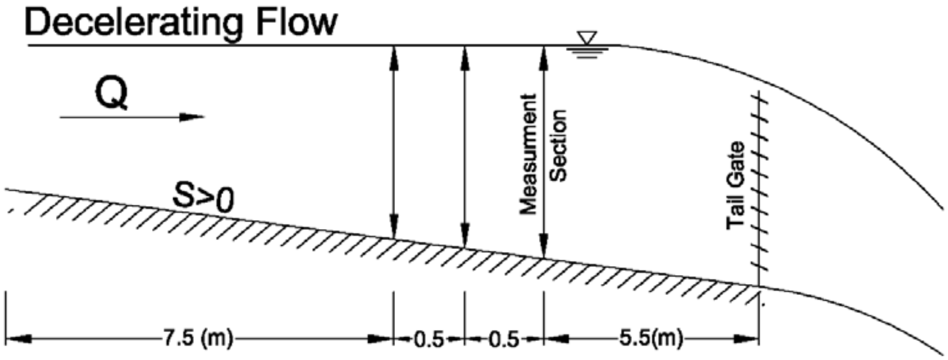

Figure 1. Sketch of experimental set-up for decelerating flow.

2. Experimental set-up and procedure

The tests were conducted in a 14 m long rectangular, glass-walled flume having 0·6 m width and 0·5 m depth. The slope of the flume was set to a horizontal position, with desired bed slopes developed by adjusting the sediment fill within the flume. There was an adjustable gate to keep the desired flow depth. To ensure the establishment of fully developed turbulent flow, the measuring reach was located downstream of the section where the upper limit of the boundary layer reaches the water surface.

Water depths are measured with a mobile point gage limnimeter. To verify that the flow is nonuniform, water depth is measured at three sections: 6·50, 6·0, and 5·50 m from the downstream end of flume (figure 1). The test section is located 5·50 m from the downstream end of the flume. Grid damps the oscillation observed within the head-box, which ensures stabilized flow conditions at the flume entrance. Subsequently, the flow passes over the gravel-bed above the flume's measuring reach and drops at its downstream end into a collection tank linked to the sumps. Decelerating flow is tried to be reached by operating the downstream tail gate and positive channel slopes. Large (positive) values of channel slope, greater than its critical value were generally taken for decelerating flows. In decelerating flow, depth of flow increases towards downstream, therefore in a flume with a constant width, velocity decreases in flow direction. In this case, the longitudinal pressure gradient is positive ($\mathrm{d}p/\mathrm{d}x > 0$).

To obtain various bottom slopes; they were adjusted by varying the thickness of the gravel layer along the flume (minimum thickness of 50 mm). Flow discharge was calculated from the discharge curve of the intermediate tank's weir. The experiments were conducted under steady non-uniform (decelerating flow condition) for two cases: fixed bed (eleven velocity profile) and mobile bed (nine velocity profiles). The reason of investigating the fixed bed case in this study is to compare the Reynolds stress distribution and Shields parameter values (non-critical values) with mobile bed case under decelerating flow. In fact only for mobile bed the incipient motion can be observed and no particle motion is considered for fixed bed channel. To achieve the mobile bed situation, the experiments were started with small flow discharge, at the condition of the bed observed. It was found that the materials comprising the bed were stationary for small discharges. Then, the flow discharge was increased to a certain value, and it was found that sediment particles just started moving. This condition is known as the condition of incipient motion of the sedimentary particles. In fact, in visual study which was adopted in this research, flow is typically increased gradually until grain observed to move from plan bed surface (Yalin & Karahan 1979). Visual observation depends on investigator's definition of how much movement constitutes initial motion (Neill & Yalin 1969, Wilcock 1988). In this study several grains motion was observed in measuring reach. However, it should be mentioned that theoretically the threshold should be defined as zero bed-load transport rate, but it is not meaningful in practical situation (Wu *et al* 2000). Many experiments show that even if the flow strength is much weaker than the critical condition proposed by Shields, there are still some sediment particles moving on the bed (e.g. Han & He 1984). An acoustic Doppler velocimeter was used for velocity measurements. The correlation between signal-to-noise ratio (SNR) and signal amplitude were recorded in the ADV file for each probe beam. For accurate measurements, the correlation coefficient for each signal beam should have values between 70% and 100%. Also, for measuring mean velocities, the signal-to-noise ratio (SNR) should be 5 or higher. The WinADV program was used for filtering the data after measurements and other post-processing analyses. Data with average correlation coefficients lower or equal than 70% were excluded. A three-beam average of correlation was used for filtering. The range of sample time was set between 5 and 7 min. The sample reporting rate 21 Hz was used, while the acoustic frequency was 10 MHz.

The tests were run for two different gravel sizes, a fixed bed with a median grain size of $d_{50} = 16{\cdot}7$ mm and, a mobile bed with $d_{50} = 8$ mm. There is no sediment motion for fixed bed case (profiles 1 to 11 in table 1) then the reported dimensionless shear stress (τ^*) is a non-critical value. The critical shear stress values for mobile bed were reported in second part of table 1 (profiles 12 to 20). As seen from table 1, the differences between non-critical and critical shear stresses are small. This is typical in gravel bedded channels (Parker *et al* 1982)

Table 1. Experimental data.

Profile No.	Q (L/s)	S_o	h (m)	u_m (m/s)	Fr	Re	u_{*uw} (m/s)	u_{*PLM} (m/s)	τ_{*uw} (N/m^2)
Fix Bed ($d_{50} = 16{\cdot}7$ mm)									
1	50	1·5	0·2	0·563	0·4	111841	0·052	0·056	0·01
2	50	1·5	0·19	0·589	0·43	111103	0·059	0·058	0·013
3	60	1·5	0·2	0·61	0·44	121168	0·06	0·061	0·013
4	70	1·5	0·2	0·662	0·47	131386	0·072	0·087	0·019
5	80	1·5	0·2	0·764	0·55	151722	0·081	0·089	0·024
6	90	1·5	0·2	0·875	0·62	173843	0·089	0·099	0·029
7	40	0·75	0·22	0·34	0·23	74194	0·03	0·035	0·003
8	50	0·75	0·21	0·451	0·32	91793	0·041	0·04	0·006
9	60	0·75	0·17	0·627	0·49	105857	0·062	0·07	0·014
10	70	0·75	0·19	0·668	0·49	124787	0·061	0·05	0·013
11	80	0·75	0·2	0·745	0·53	147886	0·058	0·068	0·012
Mobile Bed ($d_{50} = 8$ mm)									
12	50	0·75	0·13	0·733	0·65	94645	0·056	0·052	0·024
13	60	0·75	0·14	0·787	0·68	107867	0·057	0·077	0·025
14	70	0·75	0·15	0·817	0·67	121753	0·057	0·055	0·025
15	80	0·75	0·17	0·833	0·64	140597	0·055	0·078	0·023
16	85	0·75	0·19	0·86	0·63	160489	0·05	0·057	0·019
17	60	1·5	0·17	0·726	0·57	121192	0·059	0·052	0·027
18	70	1·5	0·18	0·758	0·57	135581	0·054	0·067	0·023
19	80	1·5	0·2	0·8	0·57	158936	0·05	0·06	0·02
20	85	1·5	0·21	0·785	0·54	165997	0·061	0·058	0·029

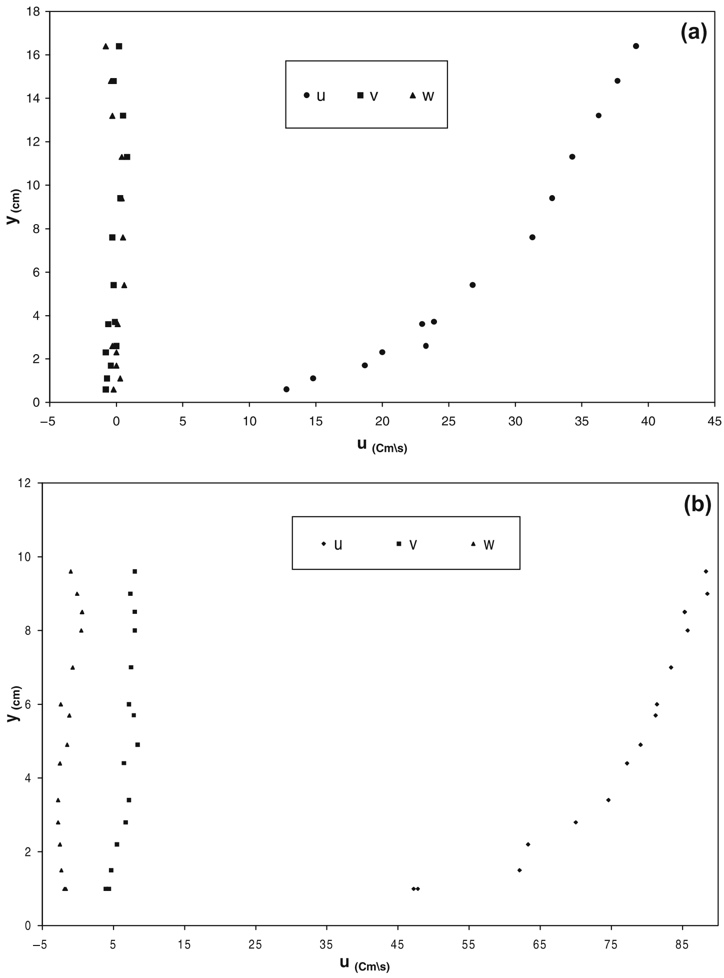

Figure 2. **(a)** Flow velocity distribution over fixed-bed channel; and **(b)** Flow velocity distribution over mobile bed channel.

because of approximately bankfull-threshold nature of bed mobility (Buffington 1995). The geometric standard deviation σ_g of particle size distribution given by $(d_{84}d_{16})^{0\cdot5}$ was less than 1·4 for the nearly-uniform sediments used in this study. The measuring cross section of velocity was situated on the distance of 8·5 m from flume entrance. The water depth, defined as the distance from the bed level to the water surface. The reference level can be found by trial–error in a way that the parabolic law reproduces adequately the measured velocity profile. Blinco & Partheniades (1971) and Tu & Graf (1992) obtained the reference level 0·25 d_{50} under top of the particles. The position of the bed reference was determined 0·25 d_{50} under the top of gravel particles in this study. The adjustment of channel bed slope was carried out manually in such way that the thickness of gravel was 5 cm in channel downstream and its thickness in the upstream depended on the required slope. Considering the flow conditions, two slopes of 0·75% and 1·5% were selected for this study.

Velocity measurements were carried out in the middle part of flume and at least fourteen points velocity were taken for each profile. The measuring arrangement is that near the bed, the inner layer zone was approximately $y/h < 0{\cdot}2$ (Afzalimehr & Anctil 2001) where resolution of the measurement was 4 mm at 8 points and from there after it was 20 mm. Figure 2 shows the flow velocity distributions over fixed and mobile beds. The shape of the profiles is similar to that observed by Kironoto & Graf (1995) and Song & Graf (1994) for decelerating flow over gravel-bed streams. However, the lateral and vertical components of velocity distribution differ more from one another for the mobile-bed case. This can be attributed to larger near-bed turbulent intensity for the mobile-bed stream. It should be stressed that Song & Graf (1994) and Kirnoto & Graf (1995) did not study the effect of decelerating flow on the incipient of motion, but they tried to investigate the influence of decelerating flow on the turbulent structure such as the turbulence intensities, eddy viscosity, mixing length and other turbulence characteristics. The experimental data are summarized in table 1 in which Q = flow discharge (lit/s); S_o = bottom slope, h = flow depth (m); u_m = average flow velocity (m/s); Fr = Froude number defined by $u_m/(gh)^{0{\cdot}5}$, and Re = Reynolds number that is $u_m h/\nu$.

3. Bed shear stress estimation

This quantity is defined as $\tau = \rho\, u_*^2$. Since ρ is a constant for water, therefore with estimation of shear velocity (u_*) the bed shear stress can be calculated. Several methods are available to estimate the bed shear stress of non-uniform flows, such as the Reynolds stress method (Kirnoto & Graf 1995; Song & Graf 1994), the parabolic law method (Afzalimehr & Anctil 1999) and the log-law method (Afzalimehr & Anctil 2001). In general, the log-law applies only for the data near-bed where considerable uncertainty exists in the measurement, such as the determination of the reference bed level, especially for gravel-beds (Afzalimehr & Anctil 2000). On the other hand, the parabolic law is applied when the data are far from the bed and consequently less sensitive to the reference bed level and velocity measurement. The bed shear stress estimated using the Reynolds stress distribution is independent of the velocity measurements and the log-law hypothesis in which flow is in equilibrium. Here the flow equilibrium refers to a flow condition that does not depend on the upstream conditions and the velocity profiles and turbulent characteristics do not change along the flow direction. The parabolic law, in contrast to the log law may be applied even if equilibrium is not reached (Chen 1991). According to Barenblatt (1982), the parabolic law works as well as the log law, although it is often taken into account as purely empirical approach. Furthermore, the law of the wall does not hold even for high Reynolds number and is an approximate representation of measured data. Therefore, in this study, the law of the wall will not be applied for estimation of shear velocity.

The shear velocity is estimated using the parabolic law by the data of the outer layer and the following equation (Afzalimehr & Anctil 1999):

$$u_{*PLM} = \frac{\Omega u_{\max}}{\lambda} \tag{1}$$

where Ω is the slope of the regression equation between $u/u_{\max}$ and $[1 - (y + 0{\cdot}25d_{50}/h + 0{\cdot}25d_{50})]^2$; u is the mean point velocity at the distance y measured from the reference level, $u_{\max}$ is the maximal velocity at the water surface; and λ is a constant that depends on the deviation point of the outer layer from the inner layer (x) in each velocity profile which is defined as follows (Afzalimehr & Anctil 1999):

$$\lambda = \frac{2{\cdot}5}{2x(1-x)} \tag{2}$$

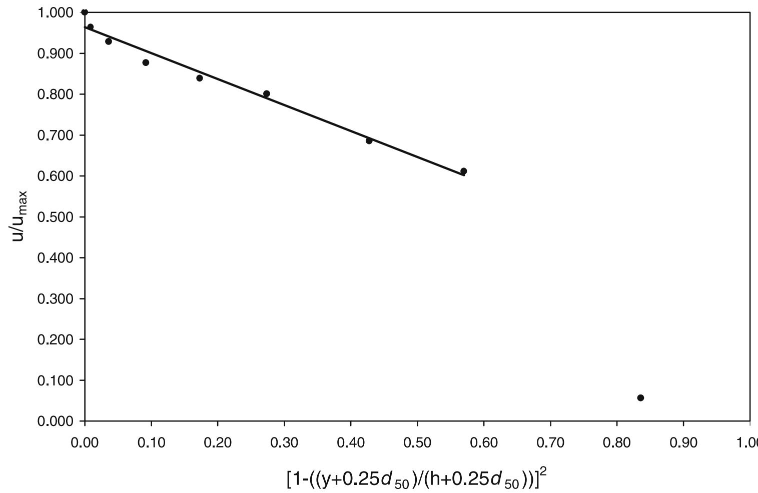

Figure 3. Fitness of the parabolic law to the outer layer data.

Afzalimehr & Anctil (1999) showed that the parabolic law method fits nicely to the outer region data ($y/h > x$) over a fixed-gravel-bed. Furthermore, figure 3 shows the fitness of the parabolic law method to the outer layer data ($y/h > x$) for the mobile bed in this research.

To estimate shear velocity using the Reynolds stress, first the mean value of the Reynolds stress for each point is estimated as follows:

$$\overline{u'w'} = \frac{1}{N}\sum_{i=1}^{i=N} u'w' \tag{3}$$

where u' and w' are the root mean square values of the velocity fluctuations in the longitudinal and in the vertical directions and N is the number of observations at each sample point (almost 7500 for this study). Then, by extrapolating, using a polynomial regression fit to the Reynolds stress profiles until the reference level, the corresponding intercept at $y = 0$ is taken as bed shear stress ($\tau = \rho u_*^2$). In this paper, the Reynolds stress method is applied to determine the Shields parameter.

4. Results

4.1 *Reynolds stress distribution*

The prediction of critical shear stress related to incipient motion is very important in hydraulics of sediment transport. In fact, the bed shear stress is pertinent to estimate the sediment threshold and bed load of sediments. Since the thickness of the layer, where the viscous shear stress is important, is small in comparison to the flow depth for flow over gravel-beds, the Reynolds stress can be estimated as the total shear stress $\tau = \rho\overline{u'w'}$.

In figure 4, the Reynolds stress profiles for decelerating flow over fixed and mobile beds are plotted against of y, where y is the distance from the reference level of channel bed. Data

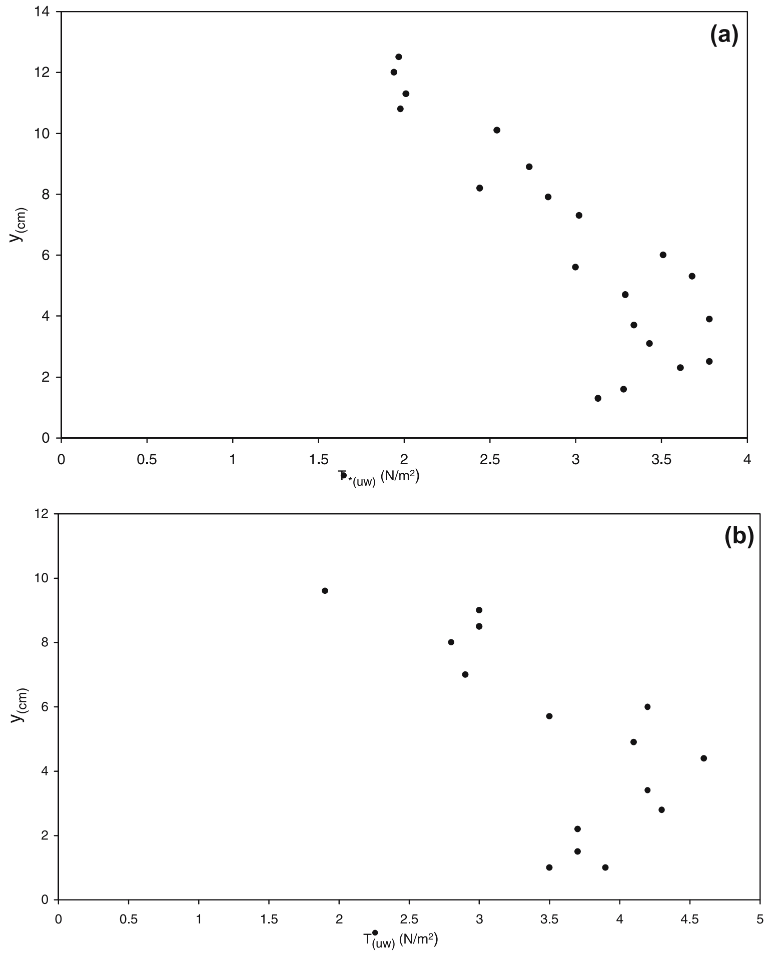

Figure 4. **(a)** Reynolds stress distribution over fixed-bed channel; and **(b)** Reynolds stress distribution over mobile bed channel.

scattering is pronounced in decelerating flow due to air bubbles appearing in the decelerating flow (Kironoto & Graf 1995).

For decelerating flow over fixed and mobile beds, the Reynolds stress is maximal at a certain distance above the bed and decreases monotonically towards the water surface, therefore the profile shapes become convex. However, for the case of uniform flow with a specific depth, the Reynolds stress vanishes at the wall and decreases linearly with increasing distance from the wall (Song *et al* 1994). For decelerating flow, a convex distribution can be justified using the Navier–Stokes equation in which $\partial p/\partial x = \partial \tau/\partial y$ (Cousteix 1989). Since the longitudinal pressure gradient ($\partial p/\partial x$) increases in the stream-wise direction for a decelerating flow, therefore vertical shear stress distribution ($\partial \tau/\partial y$) has a positive sign that is an increase in τ near the bed (see figure 4). On the other hand, no specific pattern for $v'w'$ and $u'v'$ distributions exist in decelerating flow over fixed as well as mobile beds. In this case the distributions have tendency to be zero along the flow depth.

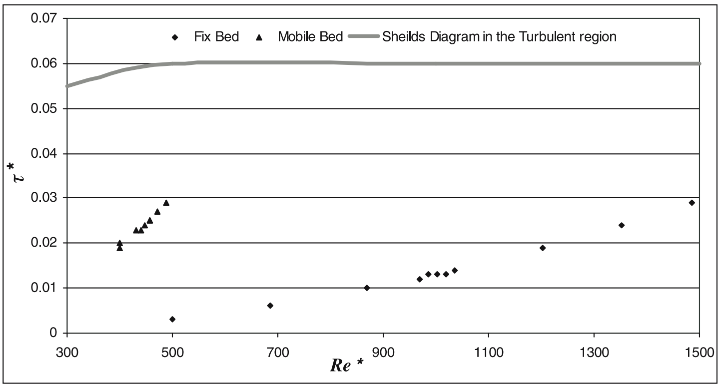

Figure 5. Comparison of the experimental data with the curve (τ^* versus Re^*) proposed by Shields in rough-turbulent regime.

4.2 *Shields parameter*

Shields' original data have evolved over time because of drafting errors and personal interpretations by later workers (Buffington 2000). In fact, the Shields diagram was obtained in a flume with fully developed turbulent flow, using sediment ranging in size from 0·4 mm to 3·4 mm. A variety of bed forms and relative roughnesses were present during Shields' experiments (Baffington 2000). Because he did not account for the form drag caused by these roughness elements, values of dimensionless critical shear stress determined from stress-transport extrapolation may have been overestimated. The sediment used by Shields and his other data sources were not uniform in size and shape. This may also explain some of the scatter of dimensionless critical shear stress values reported by Shields.

The commonly quoted value of $\tau_{*c} = 0{\cdot}06$ for rough turbulent flow reflects a single data point within the overall swath of Shields data (1936). According to Neill (1968), this large value of τ_{*c} can be due to some non-uniformity in sediments used in laboratory studies and also due to the fact that the same probability of movement may not have existed at the critical condition for different sediment sizes. In addition, it should be noticed that reported value $\tau_{*c} = 0{\cdot}06$ in literature generally predicts high stresses that likely represent instantaneous rather than time averaged critical shear stress (Buffington *et al* 1992).

Figure 5 shows the functional relationship between τ_* and Re_* for the 20 data in this study and suggested diagram by Rouse (1949) and other investigators (Buffington & Montgomery 1997; Shvidchenko & Pender 2000) on flumes with a flat bed in the turbulent region of large Reynolds number $\mathrm{Re}_* > 300$. In fact, Rouse (1949) promoted Shields' work by fitting a line through the data. Rouse fit of the data diverges toward the upper envelop at higher critical boundary Reynolds number values, approaching $\tau^*c = 0{\cdot}06$ at $\mathrm{Re}^* > 500$.

Examination of the computed Shields parameters for each of the nine velocity profiles measured over the mobile-bed stream indicates that all the data lie under the Shields curve in figure 5. This is due to convex form of the Reynolds stress distribution for decelerating flow which has smaller bed shear stress than that reported in literature for uniform flow. In addition, the values of less than $\tau_{*c} = 0{\cdot}03$ for nine velocity profiles measured over the mobile bed shows that the experiments were conducted for weakly mobile bed condition, as mentioned by Nikora & Goring (2000). For example in profiles 16 and 19 of table 1, the Shields parameters are less than minimum value of incipient motion that is 0·02 (Konrad *et al*

2002) for gravel-bed streams. However, in the both velocity profiles (16 and 19), movement of particles was observed. This result is in agreement with above explanation that in decelearting flow the critical shear stress has smaller values than that reported for uniform flow condition. Therefore, it seems that there is no universal value for τ_{*c} in rough turbulent flow in open channels as mentioned by Buffington and Montgomery (1997). Although, it may consider a range for τ_{*c} which depends on experiment conditions.

In the turbulent region of large particle Reynolds numbers ($\mathrm{Re}_* > 300$), the laminar sublayer is interrupted by the particle size. As seen in figure 5, for the hydraulically rough boundary, the Shields diagram shows a constant value of 0·06 being independent of the particle Reynolds number Re_*. However, the results of this study (solid triangles on figure 5) indicate that for $\tau_{*c} = 0{\cdot}02$ which is under the Shields curve, the bed was mobile and movement of particles was observed. This underestimation in Shields diagram reflect a variety of factors such as different in bed material properties (i.e. shape, rounding) neglect of roughness elements (size), method of shear stress determination, sampling technique used to estimate grain size distribution and difference in flow properties arising from changes in bed roughness and channel gradient as reported by Ashida & Bayazitt 1973, Bathurst *et al* 1987, Graf 1991. Likewise, incipient motion of non-spherical particles is affected by their orientation with respect of to the down stream flow direction (Carling *et al* 1992). Platy grains used in this study tend to have low incipient motion thresholds as mentioned by Mantz (1977). Also, the methods used to calculate shear stress can affect the Shields parameter. In some investigations shear stress is determined as a simple depth-slope product (e.g. Powell & Ashworth 1995), while in other research bed shear stress is estimated from velocity profile (e.g. Nezu & Nakagawa 1993). These methods can result in different estimate of shear stress and the Shields parameter particularly for non-uniform flow condition through a study reach (Afzalimehr & Anctil 1999). Therefore, to obtain more realistic insight for calculation of shear stress and thus the critical Shields parameter values, it is vital to analyse the shear stress distribution for non-uniform flow. Therefore, an important explanation is related to the effect of flow structure on incipient motion. In fact, this study shows that when there is a positive pressure gradient in flow direction of a reach (decelerating flow), the Shields parameter is smaller than that proposed by Shields for zero pressure gradient (uniform flow). The decelerating flow influence is presented by convex shear stress distribution in which near the bed, critical shear stress is smaller than the critical value of linear shear stress distribution for uniform flow, as reported in original Shields diagram. Likewise, the Task Committee on preparation of sedimentation manual (1966) and Neill (1968) had already observed that $\tau_{*c} = 0{\cdot}06$ in completely rough boundary is on the high side and true critical condition may occur at lesser value that is $\tau_{*c} = 0{\cdot}06$. Therefore, one can state that the experimental data are in complete disagreement with the Shields diagram, which is not at all uncommon for gravel-beds, as it was reported in the literature (Andrews & Kuhnle 1993, Dey & Raju 2002).

5. Discussion

Shear velocity estimation using two approaches is presented in the table 1. Also, figure 6 shows that the estimated shear velocity by the parabolic law method (u_{*PLM}) and the Reynolds stress method (u_{*uw}) are comparable. However, there are some exceptions, such as profiles 13 and 15 over the mobile-bed streams. In figure 6, the middle line is the line of perfect agreement and the two other lines show $\pm 25\%$ of deviation from the line of perfect agreement. The similarity of the two approaches indicates that the PLM method can be used to simplify

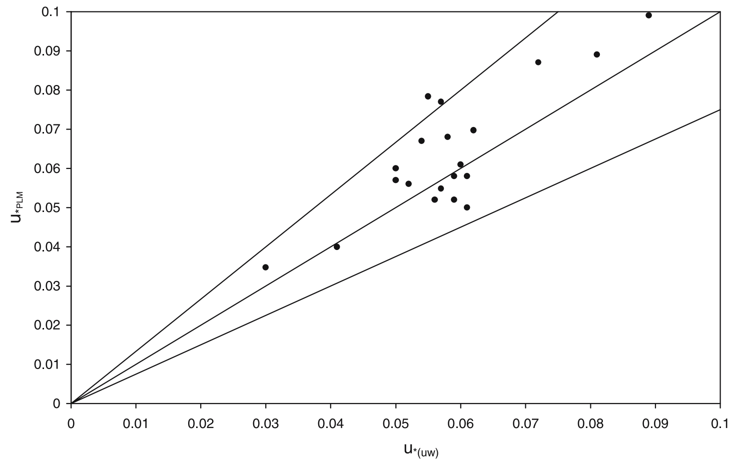

Figure 6. Comparison of calculated shear velocity from the Reynolds stress and the parabolic methods.

field measurements. It should be mentioned that the parabolic law method can be applied for one-dimentional flows using the outer region data of mean velocity profiles. However, the Reynolds stress method needs to calculate the root mean square values of velocity fluctuations in longitudinal and vertical directions. Also, the parabolic law method can be applied with simple instruments such as a currentmeter, while the Reynolds stress method requires the advanced measuring equipment such as ADV.

According to Yalin & Karahan (1979) for a rough turbulent flow, where the size of the largest macro turbulent eddies is comparable with flow depth, these eddies have some influence on the critical stage. As a result, some investigators claim that relative flow depth h/d_{50} should be considered as the additional variable for estimating τ_{*c} and that the removable scatter in the Shields diagram may be due to the omission of the relative flow depth. However, the results of this study do not indicate any correlation between τ_* and the relative depth h/d_{50}. For example, for the largest relative flow depth over the fixed-bed stream (profile 6 in table 1) with $S_o = 1{\cdot}5\%$, $Q = 0{\cdot}09\,\mathrm{m}^3/\mathrm{s}$, and $u_m = 0{\cdot}875$ m/s, particle motion was not observed, then $\tau_* = 0{\cdot}029$ is a non-critical value. It should be noticed that for the profile 6, $d_{50} = 16{\cdot}7$ mm therefore, the resistance to motion in the profile 6 is large.

This analysis indicates that less emphasis should be given on choosing a universal τ_{*c} values for of fully turbulent flow and high relative flow depth typical of gravel-beds as mentioned by Buffington and Montgomerey (1997). It is necessary to give more emphasis on flow structure (decelerating or uniform) and choosing defendable values for particular application, given the observed methodological biases, uses of each approach and systematic influence of sources of uncertainty associated with different methods and experimental conditions.

6. Conclusions

Experiments were conducted to determine the effect of decelerating flow on the incipient motion of a gravel-bed channel. The results show that:

(i) The Reynolds stress distribution over fixed and mobile beds has a convex form. Due to this form, τ_{*c} value for decelerating flow is less than the reported values in literature.

(ii) The parabolic law method presents a good agreement with the Reynolds stress method for calculating the shear velocity.
(iii) The Shields diagram overestimates τ_{*c} for decelerating flow condition.
(iv) There is no correlation between τ_{*c} and the relative flow depth for decelerating flow over a gravel-bed channel.
(v) More emphasis should be given in selecting defendable values of τ_{*c} for particular application with considering the flow structure.

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List of symbols

d_{16}	16% finer particle diameter;
d_{50}	Median diameter of sediment particles;
d_{84}	84% finer particle diameter;
Fr	Froude number defined by $u_m/(gh)^{0\cdot5}$;
g	Gravitational acceleration;
h	Flow depth;
h/d_{50}	Relative flow depth;
k_s	Nikuradse's equivalent roughness;
N	Number of observations at each sample point;
Q	Flow discharge;
Re	Reynolds number that is $u_m h/\nu$;
Re_*	Particle Reynolds number $u_* d_{50}/\nu$;
$S_\circ$	Bottom slope;
u	Mean point velocity at the distance y measured from the reference level;
u'	Root mean square value of the velocity fluctuations in the longitudinal direction;
u_m	Average flow velocity;
$u_{\max}$	Maximum point velocity at the distance y measured from the reference level;
u_*	Shear velocity;
u_{*c}	Critical shear velocity;
u_{*PLM}	Shear velocity estimated by the parabolic law method;
u_{*uw}	Shear velocity estimated by the Reynolds stress method;
$\overline{u'w'}$	Mean value of the Reynolds stress for each point;
v'	Root mean square value of the velocity fluctuations normal to the longitudinal direction;
w'	Root mean square value of the velocity fluctuations in the vertical direction;
x	Deviation point of the inner layer from the outer layer;
y	Distance from the reference level of channel bed;
γ	Specific weight of water;
γ_s	Specific weight of sediment;
λ	A constant in the parabolic law method;
ν	Kinematic viscosity;
ρ	Mass density of water;

σ_g Geometric standard deviation; $(d_{84}/d_{16})^{0\cdot5}$;
τ Total shear stress $\tau = \rho\overline{u'w'}$;
τ_{*c} Critical Shields parameter;
τ_c Critical bed shear stress;
Ω Slope of regression equation between $u/u_{\max}$ and $[1-(y+0\cdot25d_{50}/h+0\cdot25d_{50})]^2$.

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