THE EFFECTS OF THE SEDIMENT BED THICKNESS ON THE INCIPIENT MOTION OF PARTICLES IN A RIGID RECTANGULAR CHANNEL

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ABSTRACT

The problem of determining critical condition for incipient motion has been long considered for alluvial channels. Mohammadi (2005), stated that the majority of research work on sediment researchers have been concentrated on beds formed of the same mobile sediment, only a few including Novak and Nalluri (1975-1991), Ojo (1978), Alvareza (1990), and El-Zaemey (1991), Mohammadi (2005), Ab. Ghani et al. (2008) attempted to analyze the incipient motion of different sizes of sediment over fixed beds. The aims of this study are to gain an improved understanding of the incipient motion processes and to provide improved incipient motion relationships. This can be achieved by investigating the important parameters governing the incipient motion of particles touching each other and resting in one layer ($t_s = d_{50}$) and in several bed thicknesses. The results of the experiments demonstrate that the sediment thickness and the sediment particles size are significantly affects the incipient motion of the sediments. Comparisons with the previous studies were done and the experimental results are used to derive a new equations taking into account the effects of deposits thickness, for critical bed shear stress and critical velocity.

Keywords: Incipient motion, Rigid channel, Sediment transport, Threshold condition

1. INTRODUCTION

The incipient motion forms an integral part of the understanding of sediment transport. It is involved in many geomorphic and hydraulic problems such as local scour stable channel design, and the purification of public water supply . These problems can only be handled when the incipient motion is fully understood. The beginning of sediment motion is difficult to define, this difficulty is a consequence of a phenomenon, which is random in both time and space. This suggests, as observed by Shields (1936), that the process of incipient motion is statistical in nature, as such there is no unique critical condition for which motion begins as the condition is reached. The definition and measurement of the incipient motion for sediment have been a problem for many years. Several definitions has been given in previous work such as, Kramer (1935) defined the incipient motion in weak, medium and general movement where movement is occurring in all parts of the bed at all time, also Neil and Yalin (1969), Yalin (1977), among others. Shafai, et.al., (1991), They considered the observation of the first rock movement as the criterion for incipient motion. Novak and Naluri (1975) identified incipient motion by a slight sliding and/or tossing (or both) of the particles and an occasional bigger movement of one or two particles. Ojo [16] Adopted almost the same definition given by Novak and Novak et.al (1975). El-Zaemey [6] considered the movement of at least two particles as the criterion for incipient motion.

M. Ashiq et.al., [14] recommended that incipient motion considered when large number of sediment particles start to move over a large part of the bed. It is worthwhile remembering that each investigator used different experimental techniques. The criterion used for the determination of the incipient motion is subjective (Andrey et.al., [9]) as it is based on the observation of each investigator.

It can be summarized that the studies of the incipient motion or the beginning of movement of sediment show that there is two possible definition of the incipient motion: **a**) the first category is based on minimum transport rate, such as work by Kramer (1935) and Shields (1936), Day (1980), Parker and Klingeman (1982) **b**) The second definition constitutes of the visual observation of particles motion on the bed (Kramer 1935, Yalin et.al 1979. The latest one had been adopted in the present study.

2. EQUIPMENTS AND EXPERIMENTAL PROCEDURE

The experiments were performed in a rectangular flume 300 mm wide, 10m long and 450 mm deep, re-circulated water was supplied to the flume through an inlet tank. The sides of the flume were made of glass enabling observation of the movement of bed particles, the horizontal slope can be changed by moving the flume along its axis in the downstream, up and down (decrease and increase the slope) using a mechanical jack placed near the outlet of the flume. A tail gate was provided at the end of the flume to adjust the depth of the flow.

In order to study the effect of sediment thickness on the process of incipient motion, the sediment particles were initially positioned in one layer (i.e. sediment thickness, $t_s = d_{50}$). The particles were then placed in different thickness, namely 5 mm, 10mm, and 24 mm over the whole width of the channel along a test section located in the middle of the channel. In each test, the flow was slightly increased, while maintaining uniform flow by adjusting the dawn stream gate. This incipient motion of sediment particles was characterized according to Kramer (1935) by general movement of particles in all parts of the test section. When the value of the bed friction velocity just exceeds the critical value for incipient of motion, the particles will begin to move, after the threshold condition occurred the discharge, flow depth, and the slope were recorded. A slight increase in the flow discharge was made ensuring that the erosion of the sediment particles has taken place.

Total of 120 experiments were done for all these thicknesses of sediment bed. The ranges of experimental work are $0.20<v_c$ (m/s)< 0.6, $0.55<d_{50}$ (mm) 4.78, $s_s=2.50$, $13< y_o$ (mm) < 170 where v_c is the critical velocity, d_{50} is the mean sediment size, s_s= the specific gravity of sediment and y_o the flow depth. Different bed slopes were utilized.

The entrainment, transportation and deposition of sediment depends fully as much upon the hydraulic characteristics of the flow as the properties of the sediment, such properties may be classed as: particles size, sediment density, and specific gravity of sediment. Generally, size has been found to represent a sufficiently complete description of the sediment particles for many practical purposes Yang [10]. The properties of sediment used are shown in table 1

Size, d_{50} (mm)	Density, ρ_s (kg /m^3)	Specific Gravity, S_s
0.55	2569	2.569
0.97	2502	2.502
1.80	2460	2.460
3.09	2400	2.40
4.78	2301	2.301

Table 1 characteristics of the sediments

4. AVAILABLE INCIEPIENT MOTION CRITERION

4.1 Rigid boundary

R. Mayerle et. Al. (1992) stated that factors such as: hydraulic radius, channel cross section, conveyance roughness, sediment concentration, grain size, and cohesivity influence sediment transport over rigid boundaries, Also the flow depth, averaged velocity, boundary shear stress, to name only some of the most important ones. According to Ab. Ghani et.al [17],[3], the deposits thickness significantly affects the channel's ability to erode the sediment deposits. It has to be motioned that, Critical velocity (v_c) or shear stress(τ_c) is normally used to describe the incipient motion of sediments in both rigid and loose boundary. An extensive experimental work in circular and rectangular channels by Novak & Nalluri [1] using different sizes of non cohesive sediment, they proposed:

$$\frac{v_c}{\sqrt{g\,d_{50}(s_s-1)}} = a\left(\frac{d_{50}}{R}\right)^{b} \tag{1}$$

Where d_{50} is the mean sediment size, R flow hydraulic radius, g the gravity acceleration constant, s_s the specific gravity of sediment, and a and b depends on the configuration of bed whether there are single/touching particles.

El-zaemey [6] conducted experimental work in a circular channel having a flat rigid bed utilizing several sizes of non-cohesive sediments and obtained the following equation:

$$\frac{v_c}{\sqrt{g\,d_{50}(s_s-1)}} = 0.75\left(\frac{d_{50}}{R}\right)^{-0.34} \tag{2}$$

4.2 Loose boundary

Majority of the works on incipient of motion and sediment transport deal with alluvial channels. A good deal of information could be found in standard textbooks such as Vanoni (1975), Graf (1984), Garde-Ranga Raju (1985), Van Rijn (1989), and Raudkivi (1991), Yang (1996)[10].

Among the methods available, the Shields curve (1936) who has been credited as the first person to express the incipient motion condition for the case of uniform grains on a flat bed, and relates dimensionless bed shear stress to dimensionless Reynolds number i.e:

$$\tau_{c^*} = \frac{\tau_c}{\rho g(s_s-1)d} = F(R_{e^*}) = F\left(\frac{v_* d}{\nu}\right) \tag{3}$$

In which $\tau = \rho g R s$ is the bed shear stress (g is the gravitational acceleration, R is the hydraulic radius of the bed, s is the bed slop), s_s relative density of sediment, and d is the grain size, $v_* = \sqrt{\frac{\tau_c}{\rho}}$ donates shear velocity where ρ is the fluid density, and ν donates kinematics viscosity of water.

Shields (1336) empirically established his relationship using flume data (Figure 1), which has a distinct form for hydraulically smooth, transitional, and rough surfaces, indicating a minimum value of $\tau_{c^*} = 0.03$ at $R_e \approx 10$ and a constant value of $\tau_{c^*} = 0.06$ above $R_e \approx 400$. The Shields curve has been accepted as a suitable criterion for the incipient of uniform sediment motion Andrey et.al., (2000),. Van Rijn (1984) proposed the following function to express the Shields curve:

$$\frac{\tau_c}{\rho g(s_s-1)d_{50}} = f(D_{gr}) \tag{4}$$

Where D_{gr} is the dimensionless grain diameter which is:

$$D_{gr} = d_{50}\left[\frac{g(s_s - 1)}{v^2}\right]^{1/3} \qquad (5)$$

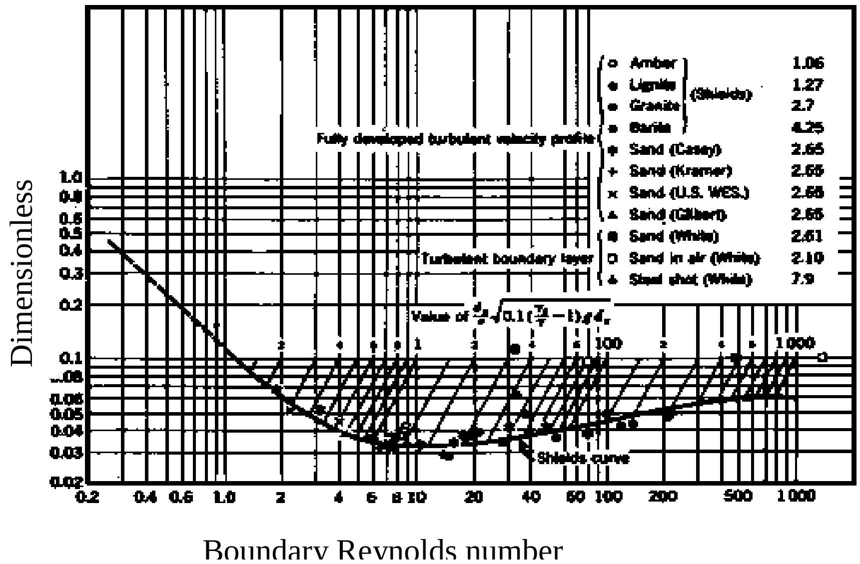

Figure1-Shields'diagram for incipient of motion (Vanoni, 1975)

5. RESULTS AND DISCUSSION

The assessment of the equations by Novak and Nalluri (1984) and El-zaemey (1991) for bed thicknesses equals the sediment particles size were done, It can be seen from Figure 2 which shows the relationship between the measured and predicted velocity that a very good agreement was obtained with v_c given by El-zaemey's equation (2), the average discrepancy ratio (computed/measured v_c) over 30 tests was 1.01, which indicate that the presence of a flat rigid bed in a circular channel tends to simulate the incipient motion condition in a rigid rectangular channel. It should be mentioned that El-zaemey [6] used a similar range of sediment sizes as those of the present study, which gives the indication of the validity of equation (2) to predict the critical velocity over circular and rectangular conveyance. However the less agreement obtained with equation (1) could be attributed to the high resistance to flow as the number of rows of particles increase. As the number of rows decreases, strong irregularities in the water surface become obvious which increase the acceleration above the particles and force early motion.

For the present work, the same function was employed and a simple linear regression analysis was performed. The following relationship was obtained:

$$\frac{v_c}{\sqrt{g\, d_{50}(s_s - 1)}} = 0.937\left(\frac{d_{50}}{R}\right)^{-0.255} \qquad (6)$$

With r = 0.93, $R^2 = 0.86$

Another equation based on the same function (Ackers et al, 1973, Garde et al, 1985) [17] was employed in this study and, the best fit obtained can be expressed as the following:

$$\frac{v_c}{\sqrt{g\,d_{50}(s_s-1)}} = -0.523\ln\left(\frac{d_{50}}{R}\right) + 0.476 \qquad (7)$$

With r = 0.92, $R^2 = 0.85$

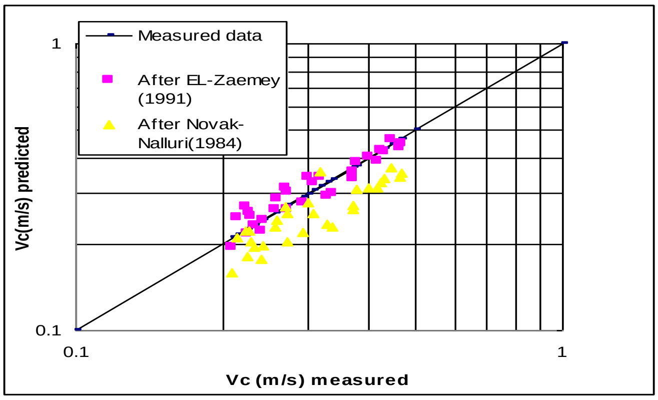

Fig 2 Comparison between the measured vs. computed critical velocity($t_s = d_{50}$)

With the increasing of sediment bed thickness (t_s), i.e,. sediment particles are positioned in different thickness (5, 10, 24 mm).Figures 3,4, and 5 shows that the prediction of Vc by equation (2) and equation (1) becomes less accurate, and the deviation from the measured data is gradually become obvious, therefore, new equation is needed to take into account the presence of different thickness of sediment particles.

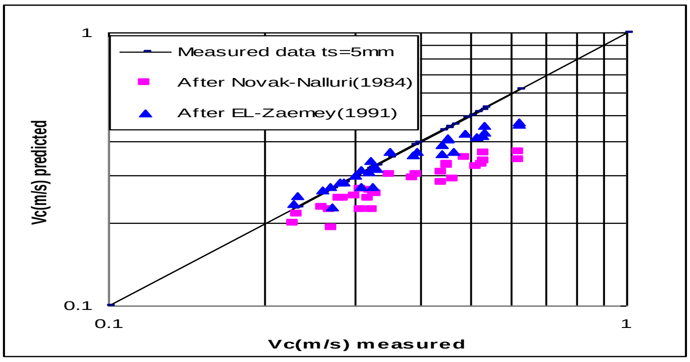

Fig 3 Comparison between the measured and computed v_c (t_s = 5mm)

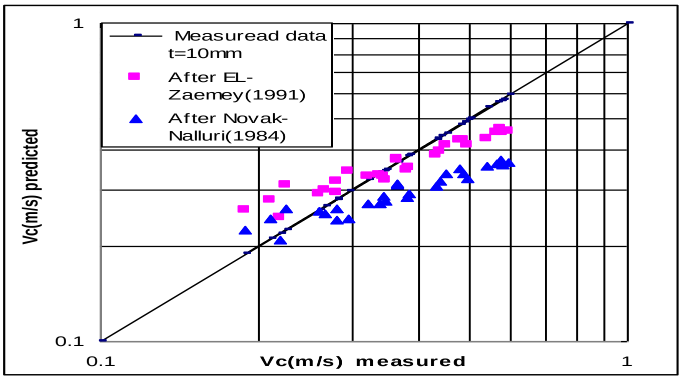

Fig 4 Comparison between the measured and computed v_c (t_s = 10mm)

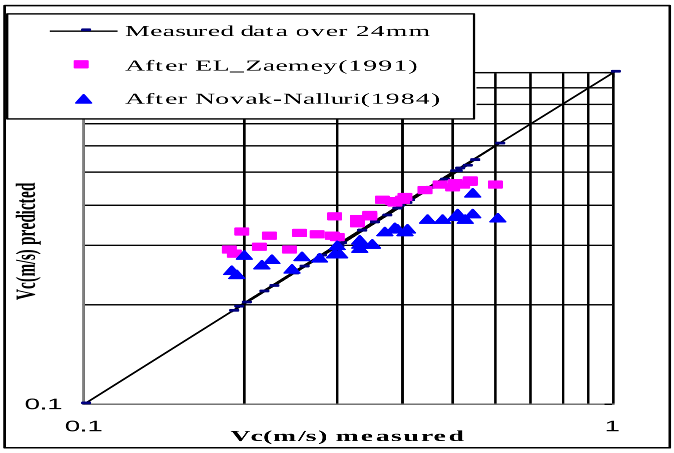

Fig 5 Comparison between the measured and computed v_c (t_s = 24mm)

Having considered several function relationships to analyze the present and data from previous studies, the best-fit models representing the different bed thicknesses are listed in Table 2

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Type of data	Best-fit Equation	No of data	r
$t_s = d_{50}$	$\frac{v_c}{\sqrt{g\,d_{50}(Ss-1)}} = 0.937\left[\frac{d_{50}}{R}\right]^{-0.255}$	30	0.93
t_s = 5 mm	$\frac{v_c}{\sqrt{g\,d_{50}(Ss-1)}} = 1.248\left[\frac{d_{50}}{R}\right]^{-0.197}$	30	0.89
t_s = 10 mm	$\frac{v_c}{\sqrt{g\,d_{50}(Ss-1)}} = 1.3\left[\frac{d_{50}}{R}\right]^{-0.19}$	30	0.85
t_s = 24 mm	$\frac{v_c}{\sqrt{g\,d_{50}(Ss-1)}} = 1.09\left[\frac{d_{50}}{R}\right]^{-0.217}$	30	0.836
All data at	$\frac{v_c}{\sqrt{g\,d_{50}(Ss-1)}} = 1.074\left[\frac{d_{50}}{R}\right]^{0.814}$	120	0.814

Table 2 Developed new incipient motion criterion using Vc approach

Yang (1969) stated that the important factors in the determination of incipient motion are the shear stress τ,, specific gravity of sediment, sediment size d_{50}, the kinematic viscosity ν, and gravitational acceleration g. these five quantities are grouped together in equation (3).

Employing the present experimental data over one layer, the shear Reynolds (Re_*) number was plotted against dimensionless shear stress (τ_*), together with the Shields curve, as shown in Figure 6. The present data seen to be below Shields curve. It can also be noticed that (τ_*) decreases as Re_* increase for smooth rigid bed unlike in movable beds (Shields curve), and as the sediment particles size decrease, the data shows a tendency towards Shields curve. Which confirm that the Shields approach is suitable for small sediment size but not so for larger sizes as noticed by Mohammadi 2005 [5].

A simple liner regression was performed using the formula of Equation (3) and the best fit was found to be

$$\frac{\tau_c}{\rho g(S_s - 1)d} = 0.067\left(R_{e^*}\right)^{-0.425} \tag{8}$$

With r = 0.90 and $r^2 = 0.81$

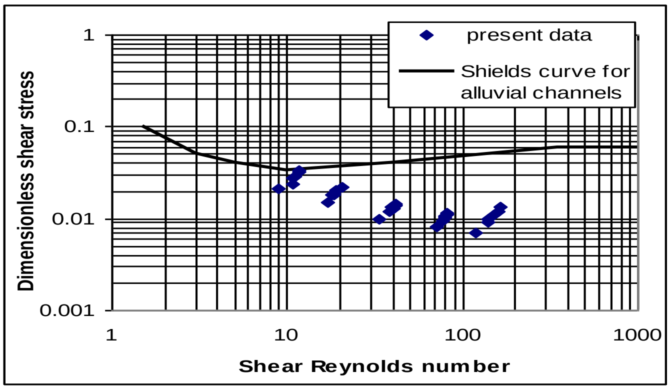

Figure 6. Comparison between the present study and Shields curve

The same approach has been employed to study the effect of sediment bed thickness on the initiation of motion and to check the suitability of using Shields curve as the criterion for incipient motion. The dimensionless shear stress and Reynolds number were plot versus each other for different bed thicknesses, the results in the incipient of motion are given in Figures 7, 8, and 9. It is clearly seen as expected that the critical shear stress required to move the sediment particles increases with the sediment particle thickness and decreases with the water flow depth.

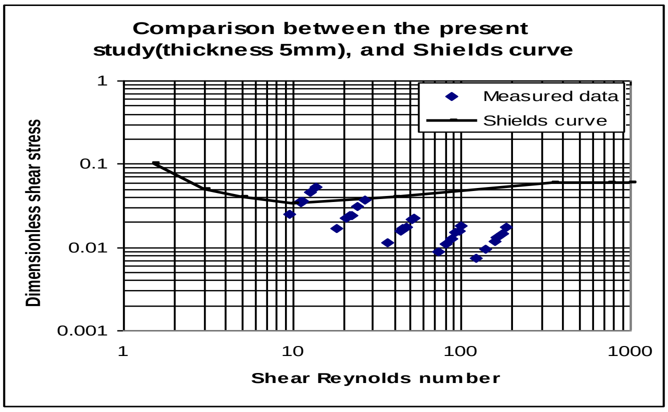

Figure 7. Shields curve vs. present study (t_s = 5mm)

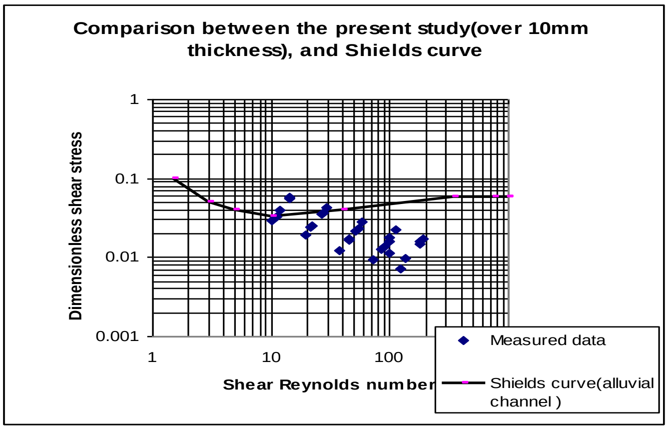

Figure 8. Shields curve vs. present study (t_s = 10mm)

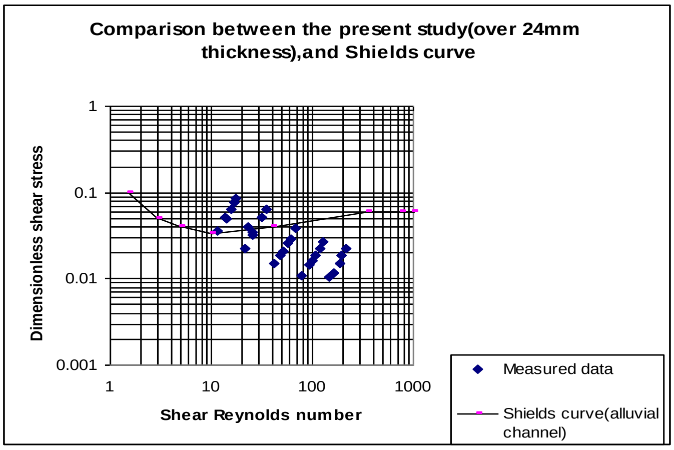

Figure 9. Shields curve vs. present study (t_s = 24mm)

An attempt was then made to consider the effect of sediment thickness on the incipient of motion relationships. By utilization of equation (3), the parameter $\frac{t_s}{y_0}$ (where t_s is the sediment thickness and y_0 is the water depth) was incorporated to reflect the influence of sediment thickness while the effect of the flow resistance due to the present of sediment beds thicknesses is incorporated in the over all friction factor λ_0, which calculated using the Darcy- Weisbach's equation:

$$\lambda_o = \frac{8gRs}{v^2} \qquad (9)$$

Where λ_o is known as a Darcy- Weisbach's friction factor, s_0 is longitudinal bed slop, and R is the hydraulic radius, R = A/p where A is the flow cross section area, p is the wetted perimeter.

The resulted equations for each thickness were given in Table 3 together with the universal equation. It has to be mentioned that high value of r indicate the significant of the sediment thickness on incipient motion.

Type of data	Best-fit Equation	No of data	r
t_s = 5 mm	$\frac{\tau_c}{\rho g d_{50}(Ss-1)} = 0.547[R_{e*}]^{-0.332}[\lambda_o]^{0.667}\left[\frac{t_s}{y_0}\right]^{0.048}$	30	0.95

t_s = 10 mm	$\frac{\tau_c}{\rho g d_{50}(Ss-1)} = 0.219\left[R_{e*}\right]^{-0.078}\left[\lambda_o\right]^{0.054}\left[\frac{t_s}{y_0}\right]^{0.955}$	30	0.93
t_s = 24 mm	$\frac{\tau_c}{\rho g d_{50}(Ss-1)} = 0.673\left[R_{e*}\right]^{-0.353}\left[\lambda_o\right]^{0.682}\left[\frac{t_s}{y_0}\right]^{0.396}$	30	0.85
All data at	$\frac{\tau_c}{\rho g d_{50}(Ss-1)} = 0.315\left[R_{e*}\right]^{-0.235}\left[\lambda_o\right]^{0.349}\left[\frac{t_s}{y_0}\right]^{0.285}$	90	0.96

Table 3. Development of new incipient motion and criterion

6. CONCLUSION

From the foregoing the following conclusion are drawn

1. In a situation where sediment are touching each other resting in one layer, there would be greater friction between them. This friction increases with the increases of sediment size and the thickness of sediment which will bind the particles together as well. Hence a higher value of shear stress or velocity will be required to erode the sediment

2. experimental results using one layer , 5mm, 10mm, and 24 mm shows that the particles are eroded at lower shear stress and critical velocity than that predicted by Shields criterion for wide alluvial channels

3. it's observed that as the sediment thickness decrease the data shows tendency towards Shields curve. The Shields criterion thus overestimates threshold conditions for rigid beds.

4. The thicker the sediment layer is the higher the velocity is needed to erode them

2. the critical velocity required for particles movement is a function of particle size (d_{50}), hydraulic radius (R), water density (ρ) sediment density (ρ_s) and acceleration due to gravity (g)

5. Evaluation of available incipient motion criteria show that they can not take into account the effect of sediment bed thickness. However, the new developed equations with high values of r can be used to determine the thickness of sediment deposit which can be eroded by the existing system. They can also be used to obtain the required slopes of the conveyance to ensure no permanent deposition of sediment over a period of time

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