Experimental Analysis of Incipient Motion for Uniform and Graded Sediments

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Abstract: So far, few studies have focused on the concept of critical flow velocity rather than bed shear stress for incipient sediment motion. Moreover, few studies have focused on sediment mixtures (graded sediment) and shape rather than uniform sediment for incipient motion condition. Different experiments were conducted at a hydraulic laboratory at the University of Guilan in 2015 to determine hydraulic parameters on the incipient motion condition. The aim of this study is to conduct a comparison between uniform and graded sediments, and a comparison between round and angular sediments. Experiments included rounded uniform bed sediments of 5.17, 10.35, 14 and 20.7 mm, angular uniform sediment of 10.35 mm, and graded sediment. Results demonstrated that angular sediment has a higher critical shear velocity than rounded sediment for incipient motion. Results also showed that for a given bed sediment, although critical shield stress and relative roughness increased with the bed slope, the particle Froude number (based on critical velocity) decreased. In terms of the sediment mixture, the critical shear stress (V_c*) was higher for the graded sediment than for the three finer uniform sediment sizes. The finer fractions of the mixture have a higher particle Froude number than their corresponding uniform sediment value, while the coarser fractions of the mixture showed a lower stability than their corresponding uniform sediment value. Results demonstrated that the reduction in the particle Froude number was more evident in lower relative roughness conditions. The current study provides a clearer insight into the interaction between initial sediment transport and flow characteristic, especially particle Froude number for incipient motion in natural rivers where stream beds have different gravel size distribution.

Keywords: incipient motion; graded sediment; uniform sediment; critical flow velocity; relative roughness

1. Introduction

Coarse bedload transport and especially incipient motion of stream-bed materials is one of the most relevant and practical processes to investigate for hydraulic engineers, fluvial geomorphologists and ecologists. Accurately predicting sediment transport rates is important in geoscience [1], stable channel design [2], environmental management, river restoration [3], debris-laden flood hazard mitigation [4], and landscape evolution [5]. The incipient motion of sediment is defined as the condition at which a sediment particle is entrained. The hydrodynamic condition for determining the movement of sediments is generally defined in terms of critical shear stress [6]. Shields [6] proposed a practical way

of assessing the critical shear stress based on extrapolation of negligible bedload transport; this technique is widely used (along with low bedload reference values) although it remains subject to several uncertainties [7]. Indeed, many researchers have attempted to modify or improve the approach, especially for steep and coarse-sediment streams and rough turbulent flow conditions [8–13]. Identifying the conditions at which a particle can be considered entrained is an issue in itself. Shields [6] used zero or small observable transport rate, whereas other researchers defined threshold visually as the first displacement of single particle [14], scattered particle movement [15], weak movement [16], and general movement [17].

Using uniform coarse sediment, Shevidchenko and Pender [9] revealed that the critical flow condition for uniform sediment motion depends on grain size and the flow depth to grain diameter ratio (also called relative submergence or relative flow depth) [relative submergence was also revealed as a function of the river (channel) slope by Recking [10]]. Wan Mohtar [18] investigated the effect of turbulence and vortex oscillation on incipient motion of semi-spherical sediment particles with density of 1.2 and 2.5, due to the fact that turbulence parameters can have a great effect on the incipient motion. Some researchers suggest using the flow velocity rather than shear stress for determining the incipient sediment motion [12]. The suggested equations are usually based on experimental data and dimensional analysis and can be written as follows [19]:

$$\frac{V_c}{\sqrt{[g(s-1)d]}} = a\left(\frac{Y}{d}\right)^m \tag{1}$$

where Vc is incipient motion flow velocity, g is gravitational acceleration, s is specific gravity of the sediment ($s = \rho_s/\rho_w$), d is sediment particle size, Y is the flow depth, ρ_s is fluid density, ρ_w is sediment density and a and m are coefficient which are calculated using experimental data under free flow condition. The left term of the equation is known as critical particle Froude number or densimetric Froude number, which was introduced by Hamill [20]. Gogus and Defne [21] investigated the effect of particle shape on incipient motion of solitary sediment with different shapes, revealing that incipient motion depends on sediment shape, except for particle size and relative submergence. Khozeymehnezhad and Shafai Bejestan [22] investigated incipient motion of 12 uniform sediment sizes in three slopes of 0.5, 1, and 1.5%. Agudo et al. [23] studied the impact of neighborliness of finer and coarser grains on initiation movement of the grains, revealing that protective surface layer has an impact on incipient motion of sediment particles. Najafi-Mood et al. [24] investigated flow velocity of incipient motion of non-uniform sediments, showing that particle stability decreases with increasing slope, and decreasing uniformity of sediments. In addition, Sadegh Safari et al. [25] showed that cross-sectional shape, including trapezoidal, rectangular, circular, U-shape, and V-bottom cross-section smooth channels using four different size-sands, was an important factor in incipient motion of sediment. They analyzed data using both shear stress and velocity approaches. Lamb et al. [26] investigated whether the critical Shield stress for incipient motion depends on bed slope. They showed that flow velocity and turbulent fluctuations are responsible for the slope dependency resulting from coincident increase in the relative roughness. Prancevic and Lamb [27] also showed that the main reason for increasing critical Shield stress with slope is relative roughness, and regardless of relative roughness, the steeper the slope, the smaller the critical Shield stress. Roušar et al. [28] also investigated the incipient motion of coarse uniform sediments including parameters like the grain Reynolds number, the relative submergence, the longitudinal bed slope, and the angle of repose. They showed that the effect of bed slope and angle of response are more important than grain Reynolds number and relative submergence. Wan Mohtar et al. [11] examined incipient sediment motion of uniform sediments in a turbulent fluctuation condition. They represented the Shields parameter using turbulent strength, and illustrated both turbulent fluctuations and shear velocity parameters in the same way to promote incipient sediment motion, and also, turbulent fluctuations are better predictors than the commonly used critical shear velocity.

Cheng et al. [12] investigated the critical flow velocity for incipient sediment motion in open channel flow in a rigid emergent vegetation condition, showing that critical flow condition can be presented in a simple form of the densimetric Froude number.

The literature review revealed that a number of studies have been conducted on critical flow velocity of sediment particles, but only a few have used graded sediment mixtures, which dominate in coarse natural gravel-bed rivers. Most researchers used the conceptual framework of the Shields diagram, trying to refine the values of predicted incipient conditions for entrainment. Here, we focus instead on studying critical flow velocity and its impacts on incipient motion of non-uniform sediments. This study attempts to compare the incipient motion of uniform and graded sediments, since the impact of fractions on incipient motion of graded sediment is usually underestimated. Therefore, the main objectives of the current study are: (1) to investigate incipient motions of uniform and graded bed sediments, (2) to study the impact of inter-granular fractions on incipient motion in comparison to the counterpart uniform particle, and (3) to compare incipient motion of rounded and angular bed sediments of the same size.

2. Materials and Methods

In the current study, a visually-based 30 cm distance of continuous movement of a certain number of particles (i.e., more than five) over a surface area has been considered as the incipient motion criteria for sediment in all tests [9].

2.1. Effective Variables

Using the Buckingham π Theorem, the incipient motion of non-uniform sediments can be considered to depend on critical flow velocity (V_c), water depth (Y), median diameter of particles (d_{50}), bed slope (S), fluid density (ρ_w), dynamic viscosity (μ), particle submerged density ($\rho_s - \rho_w$) and gravitational acceleration (g) as follow:

$$F^* = \frac{V_c}{\sqrt{[g(s-1)d_{50}]}} = f_1(d_{50}/Y, S, \mathrm{Re}) \tag{2}$$

where f_1 is a function to be determined experimentally, F^* is the particle densimetric Froude number or particle stability parameter, d_{50}/Y is relative roughness (or particle's size parameter), and Re is the Reynolds number. For high Re number fully developed turbulent flow (typical of river flows), the Re parameter can be neglected. Comparing Equation (2) with Equation (1), it can be seen that there is an additional dependence on S in our analysis, which we have considered in our experiments.

2.2. Flume Set-Up

A series of experiments were conducted in a 12 m long (with an effective working length of 5 m), 0.5 m wide, and 0.5 m deep tilting water-recirculating flume with glass walls (Figure 1). At the upstream end of the flume, some nets were placed to slow down the incoming flow current to the flume. The sediments in the loose section of the flume were leveled flat, with a thickness of ~ 5–6 d_{50} prior to each experiment; the bed was carefully leveled using screed-board riding on the flume rails. To prevent local scour and backwater, fixed roughened bed sections with the same size in a movable bed each experiment, were placed for 4 m near the inlet and 2.8 m near the outlet of the flume. The length of the movable bed was 5 m and a trap 0.5 m long and 0.3 m wide was placed at the end of the movable bed. More details on the experimental runs are presented in Khosravi et al. [29].
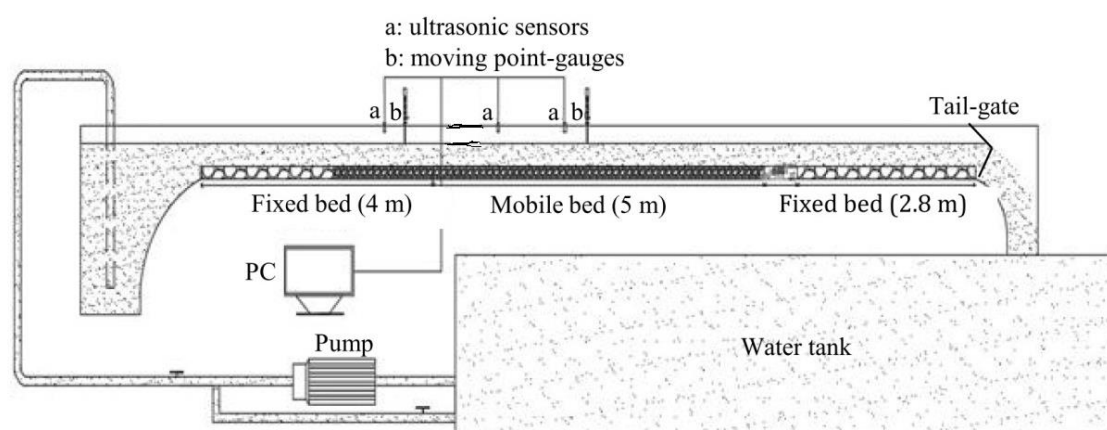
Figure 1. Experimental flume set-up (not to scale) [29].

Depending on sediment diameter, experiments were run with slopes of 0.005, 0.0075, 0.01, 0.015, 0.02, 0.03, 0.0325, and 0.035 m/m. The flow regime was controlled by tailgate at the outlet end of the flume. The water level was measured by two point gauges and three ultrasonic sensors with frequency of 25 Hz and with accuracy of ± 1 mm. The first sensor and point gauge were established in the fixed bed to measure the correct water level during the movable bed washing.

Four rounded uniform sediment classes, 5.17, 10.35, 14, and 20.7 mm were used to create the graded sediment mixture of d_{50} and mean size of 12.5 mm and 13.57 mm, respectively. An angular uniform sediment with mean size of 10.35 mm was also used (Table 1). The rounded sediment had a specific gravity of 2.567 and the angular sediment had a specific gravity of 2.4.

Table 1. Physical properties of bed sediments used in this study.

Sediment Type	Fraction, mm	d_{50}	σ_g	Sediment Size (d), mm	Density, kg/m^3	Porosity	Grain Shape
Fine gravel	4.75–5.6	-	-	5.17	2391	0.4	Rounded
Lower Medium Gravel	9.5–11.2	-	-	10.35	2375	0.4	Rounded
Lower Medium Gravel	9.5–11.2	-	-	10.35	2400	0.45	Angular
Higher Medium Gravel	13–15	-	-	14	2900	0.45	Rounded
Coarse gravel	19–22.4	-	-	20.7	2552	0.43	Rounded
Graded (mixture)	4.75–22.4	12.5	1.7	13.57	2567	0.37	Rounded

2.3. Experimental Procedure

With the flume set at the desired slope, the tailgate was raised and the flume was filled with water from its downstream end. Then the flow was gradually increased to the desired value and uniform flow was always maintained during each run. Then the flow discharge was gradually increased until reaching the incipient motion of sediment condition. Next, all required information (such as, Y, Vc, and so on) for calculating incipient motion recorded. Discharge calculated through volumetric method at the end of the flume (i.e., $\forall/t$, where $\forall$ is the volume of the water and t is the time of measuring). The flow conditions for incipient

motion of each bed sediment are shown in Table 2. More details on the experimental runs are presented in Khosravi et al. [29].

Table 2. Range of hydraulic conditions and sediment transport rates.

Sediment Size (mm)	Slope (m/m)	Flow Depth (cm)	Mean Velocity (m/s)	Froude Number	$q^*(*10^{-5})$
5.17	0.005, 0.0075, 0.01, 0.015	9, 6, 4, 3.5	0.92, 0.83, 0.75, 0.68	0.97–1.6	6, 8, 3, 53
10.35-R	0.01, 0.015, 0.03	8, 7, 4	1.11, 1.10, 1.05	1.2–1.65	31, 7, 50
10.35-A	0.015– 0.0175, 0.03	8, 7, 4	1.3, 1.2, 1.07	1.28–1.71	13, 28, 52
14	0.015, 0.02, 0.03	8.5, 6.5, 4.5	1.30, 1.19, 1.10	1.4–1.8	18, 6, 17
20.7	0.03, 0.0325, 0.035	8, 6, 5	1.66, 1.42, 1.35	1.8–1.93	25, 33, 15
Graded	0.015, 0.02, 0.03	10, 7, 5	1.51, 1.25, 1.25	1.52	13, 19, 29

R is rounded and A is angular shaped sediments.

The critical mean flow velocities for incipient motion of sediment have been estimated using the measured discharge by the wetted area (A) (i.e., $V = Q/A$). The mean sediment transport rate was calculated from the volume of sediments accumulated in the trap during the experiment. Because the aim was to investigate the incipient motion, sediments were not fed from upstream. After each experiment (the total duration T of each experiment was about 30 min), the transported sediment was collected from the trap, then dried by oven and finally weighed. Following this, the Einstein bed load parameter was estimated as [9]:

$$q* = \frac{q}{\rho_s \sqrt{(s-1)gd^3}} \tag{3}$$

where q is unit sediment transport rate and can be calculated as follow:

$$q = \frac{G}{b \times T} \tag{4}$$

where G is the dried weight of collected bed sediment and b is the flume width. The grain Reynolds number was calculated as follows:

$$Re* = \frac{V_* \times d}{v} \tag{5}$$

where, V_* is the shear velocity, d is the sediment diameter and v is the kinematic viscosity of water ($v = \mu/\rho$ where μ is water dynamic viscosity). The shear velocity was calculated as $V_* = \sqrt{\tau/\rho}$ with shear stress obtained as $\tau = \rho g R_b S$ where R_b is the hydraulic radius which is calculated based on Shvidchenko and Pender [9] where the side wall effect is considered. The critical Shield stress for incipient motion ($\tau*$) was calculated as follows:

$$\tau* = \frac{\tau}{g(\rho_s - \rho_w)d} \tag{6}$$

3. Results

3.1. Determination of the Most Effective Factors on Sediment Transport

In order to determine the most effective factors (among slope, particle diameter, flow depth, flow velocity and shear stress) on both incipient motion and sediment transport rate, 19 experiments with different sediment sizes, sorting, slopes, and flow depths were carried out (see Table 2). We used the statistical package for social sciences (SPSS) to compute the Pearson correlation coefficient, a parametric method measuring the linear correlation

between two variables X and Y as follows (e.g., between bed slope and sediment transport rate):

$$r = \frac{N\sum XY - \sum X \sum Y}{\sqrt{\left[N\sum X^2 - (\sum X)^2\right]\left[N\sum Y^2 - (\sum Y)^2\right]}} \tag{7}$$

where r is the Pearson correlation coefficient, N is the number of observations in each dataset, $\sum xy$ is sum of the products of paired scores, $\sum x$ is sum of X scores, and $\sum Y$ is sum of Y scores.

In terms of the strength of relationship (i.e., between dependent and independent variables), the value of the correlation coefficient varies between +1 and −1, where +1 is total positive linear correlation, 0 is no linear correlation, and −1 is total negative linear correlation. The Pearson correlation coefficient shows that the highest correlation coefficient for sediment transport was found with flow velocity (0.757), followed by shear stress (0.717), bed slope (0.504), sediment diameter (0.315), and flow depth (0.269), with p-values of 0, 0.007, 0.02, 0, and 0, respectively. Although flow velocity is rarely investigated compare to Shields number for incipient motion, flow velocity is much more effective than shear stress (based on the r result), and thus, in the present study flow velocity criteria is applied for incipient motion investigation.

The correlation between independent variables showed that the highest correlation was between flow velocity and shear stress (0.92), followed by bed slope with shear stress (0.88), sediment diameter with shear stress (0.83), bed slope with sediment diameter (0.82), flow velocity with bed slope (0.7), flow velocity with sediment diameter (0.67) and flow depth with sediment diameter (0.009) at the 5% significance level.

3.2. Critical Shear Velocity

The results of the critical shear velocity as a function of bed slope and sediment diameter are shown in Figure 2a,b. For all experiments including uniform and graded bed sediments (except for the coarse grain diameter of 20.7 mm), the steeper the bed slope, the higher the critical shear velocity, while this is the opposite for coarse grain diameter of 20.7 mm. This may result from the effect of grain Reynolds number. For rounded particles of 5.17 mm, increasing the bed slope S from 0.005 to 0.015 caused a 16.2% increasing in V^*_c; for the 10.35 mm particles, an increase in S from 0.01 to 0.03 induced a V^*c increase of 20.75%; for the 14 mm sediment, an increase in S from 0.015 to 0.03 led to a 6.2% increase in V^*c; and for the 20.7 mm a slope increasing from 0.03 to 0.035 resulted in V^*c decreasing by 18.35%. For the angular 10.35 mm size, an increase of slope from 0.015 to 0.03 led to the critical shear velocity increase by 9.5%; and, finally, Vc increased by 3.4% for the graded bed sediments and with slopes ranging from 0.015 to 0.03.

A comparison between rounded and angular bed sediments of 10.35 mm showed that the angular sediments had critical shear velocities 6.8% and 8.7% higher than rounded bed sediment for bed slopes of 0.015 and 0.03, respectively. A comparison between graded and rounded bed sediment showed that incipient motion shear velocity of the graded bed sediment was higher than that of the uniform sediments of 5.17, 10.35, and 14 mm, but lower than the incipient motion shear velocity for the 20.7 mm uniform bed material. The results showed that coarser bed sediment diameter had higher critical shear velocity (Figure 2b), with an increase in grain Reynolds number of 61.7%, 32.5%, and 42.6% (from 5.17 mm to 10.35, from 10.35 mm to 14, and from 14 mm to 20.7), leading to an increase in critical flow velocity of 23.7%, 9.0%, and 23.12%, respectively.
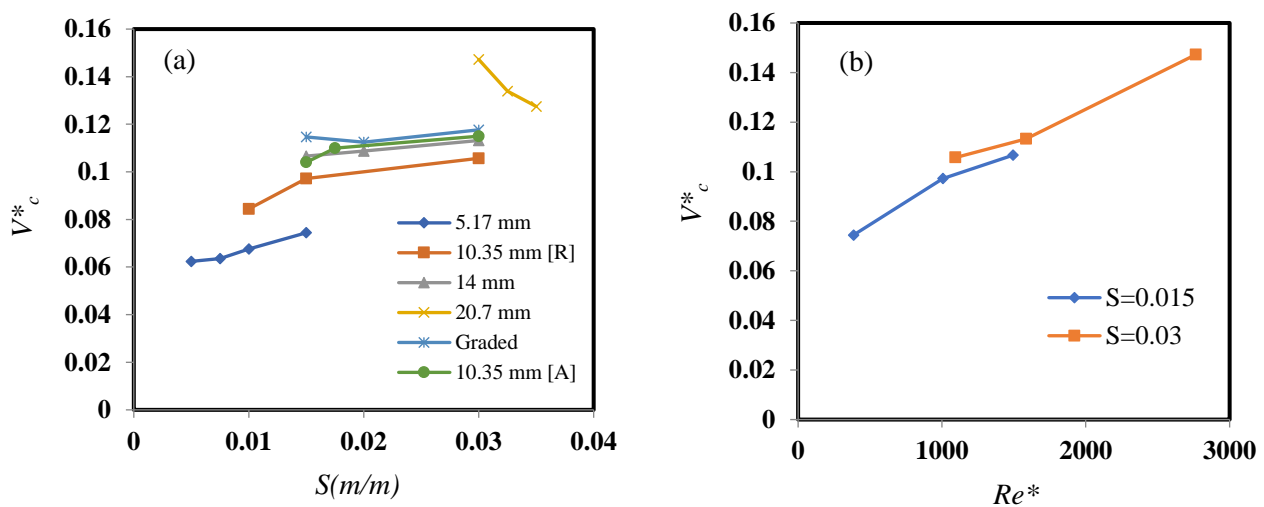
Figure 2. Critical shear velocity as a function of bed slope (**a**) and grain Reynolds number (**b**).

3.3. Ratio of Critical Flow Velocity to Critical Shear Velocity (V_c/V_c^*)

Figure 3 shows an initial decrease in V_c/V_c^* with increasing grain Reynolds number for fixed slopes of 0.015 and 0.03 (Figure 3). The increase in Re^* corresponds to a sediment size increase from 5.17 to 14 mm. However, with a further increase in Re^* (and an increase in sediment size from 14 to 20.7 mm), the ratio of V_c/V_c^* increased. For a given grain size sediment and incipient motion condition, an increase in bed slope led to a reduction in critical flow velocity (Figure 3). In addition, with increasing bed slope (from 0.015 to 0.03), the value of V_c/V_c^* was reduced by 12.4% and 17% for bed sediment sizes of 10.35 and 14 mm, respectively.
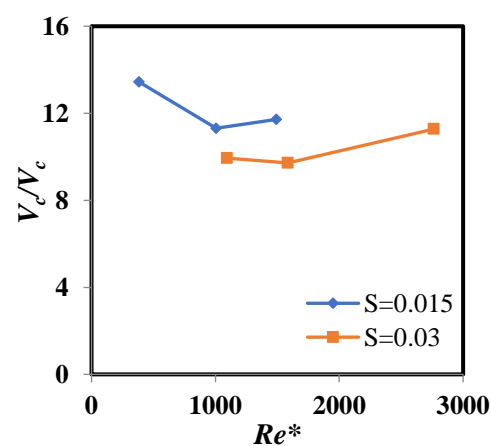

Figure 3. Relationship between V_c/V_c^* and Re^* for different bed sediments in fixed slopes of 0.015 and 0.03.

3.4. Critical Shields Stress for Graded and Uniform Sediment

Critical Shields stress versus bed sediment diameter is shown in Figure 4, for each uniform sediment size and its corresponding fraction in the graded sediment bed. For sediment sizes of 5.17, 10.35, and 14 mm, the critical Shields stress for the fractions within the graded mixture is higher than that for the corresponding uniform counterpart bed (Figure 4a); however, the critical Shields stress for 20.7 mm sediment fraction of the graded bed is less than that of the corresponding uniform sediment (Figure 4b) (results refer to different slopes).
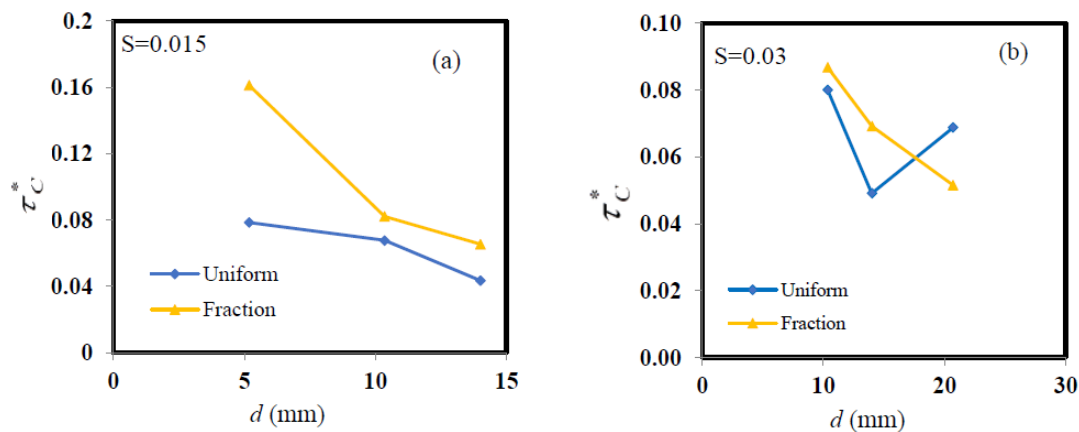
Figure 4. Critical Shields stress against of sediment diameter in bed slope of 0.015 (**a**) and 0.03 (**b**).

In the graded sediments, the finer fractions (5.17, 10.35, and 14 mm) had a higher critical Shields stress than the coarser fraction (20.7 mm). In other words, to induce incipient motion, finer fractions need a higher critical Shields stress than the coarser fraction due to a hindering effect, while the coarser fraction is more exposed and therefore needs a lower Shields stress. For instance, for a given bed slope of 0.015 m/m, as the diameter decreases 0.5 times (from 10.35 mm to 5.17 mm), 0.73 times (from 14 mm to 10.35 mm), and 0.67 times (from 20.7 mm to 14 mm), the critical Shields stress increases 2, 1.2, and 1.5 times, respectively (Figure 5a). For each size fraction in the graded bed, the critical Shields stress increases with increasing slope (Figure 5a), but decreases with increasing relative depth (Figure 5b). In incipient motion conditions for graded sediment, with equal Shields stress, the finer the fraction, the higher the relative depth and also, in equal relative submergence, the finer the fraction, the higher the critical Shields stress.
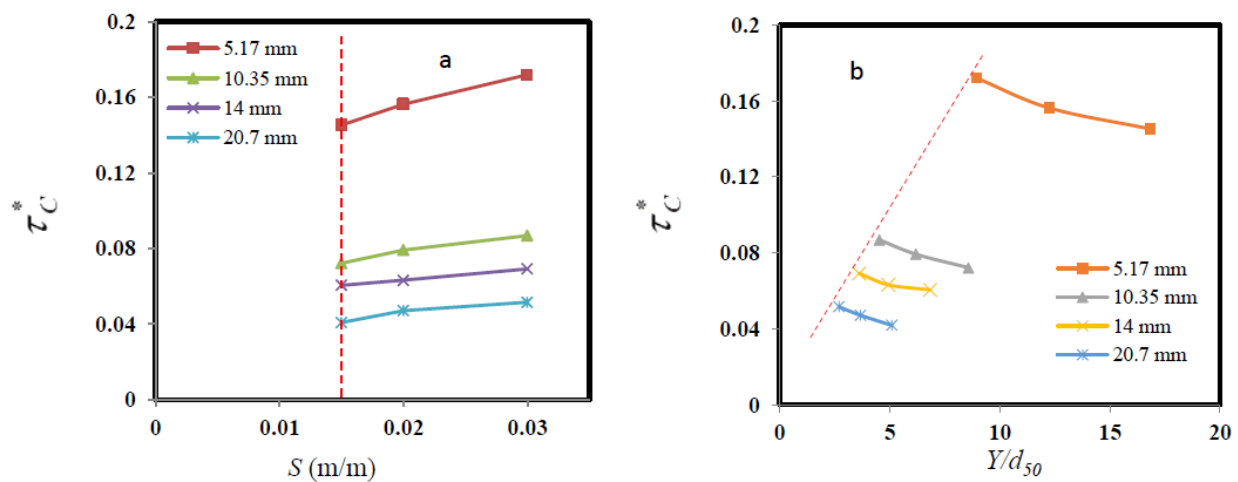

Figure 5. Critical Shields stress as a function of bed slope (**a**) and relative submergence (**b**) for each fraction in graded sediment.

3.5. Particle Densimetric Froude Number

Figure 6 shows a comparison between the particle densimetric Froude number of rounded and angular sediments of the same size (10.35 mm) versus relative roughness. This figure shows that the angular bed sediments are 13.6% and 18.7 % more stable than the rounded ones in both slopes (0.015 and 0.03), and that as the relative roughness increases, the stability of the rounded particle bed suffers from a more severe reduction than that of the angular sediment bed. The incipient motion conditions of angular shaped sediments

are higher than for rounded particles of the same size, in accordance with Gogus and Defne [21] and Gomez [30].
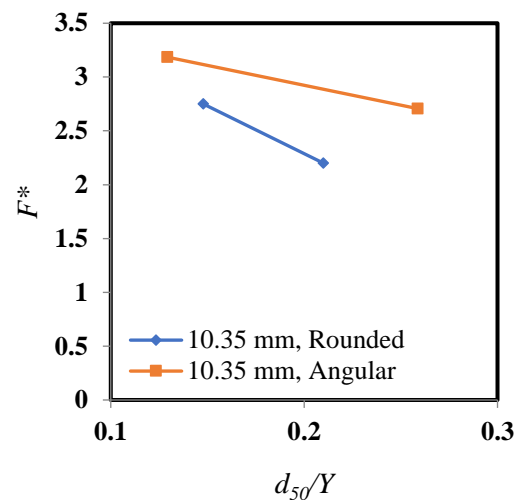

Figure 6. Comparison between particle Froude number for uniform rounded and angular sediments of 10.35 mm.

These results show that for the 5.17 mm bed sediment, a three-fold increase in bed slope from 0.005 to 0.015 m/m, led to a decrease of 18% in the particle Froude number. Increasing the bed slope three times, from 0.01 to 0.03 m/m in bed materials of 10.35 and 14 mm caused a reduction of 8.7% and 6.5% in the particle Froude number respectively. The particle Froude number for particles of 20.7 mm was reduced by 18.6% when bed slope was increased 1.16 times (from 0.03 to 0.035 m/m), and finally for the graded sediment, a two-fold increase in bed slope (from 0.015 to 0.03) led to a 20% reduction of the particle Froude number.

A comparison between the rounded uniform sediment beds and same size fractions in the graded bed, in incipient motion conditions, showed that the fractions of 5.17, 10.35, and 14 mm in the graded bed had higher particle Froude numbers than the corresponding particles in the uniform beds. Therefore, these fractions are more stable than the uniform sediment counterparts (Figure 7), as the particle Froude number of rounded uniform sediments of 5.17, 10.35, and 14 mm were 29.8%, 22.4%, and 29.4% lower than that of graded bed fractions. The comparison between the slopes of the two curves in Figure 8 shows that the rate of reduction of the uniform sediment particles' Froude number with increasing relative roughness is more severe than that of the fraction's particle Froude number.

The comparison between the particle Froude number of uniform and fractions of 10.35, 14, and 20.7 mm in a bed slope of 0.03 m/m (Figure 7) shows that the sediment fractions of 10.35 and 14 mm were more stable on the graded bed than on the uniform counterpart bed. However, the uniform sediment of 20.7 mm had a higher particle Froude number (7.5% more stable) than the fraction of the same size in the graded bed (Figure 8).
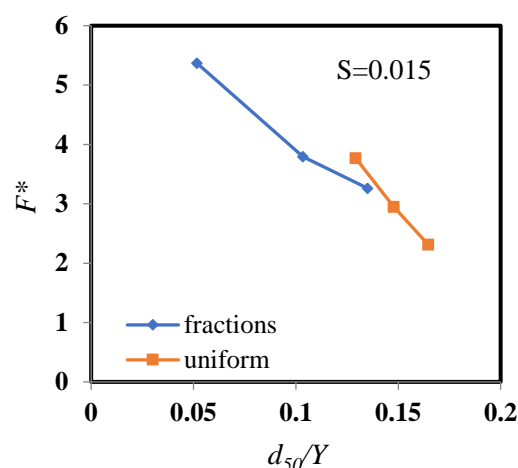
Figure 7. Comparison between the particle Froude number of the uniform and graded fractions corresponding to 5.17, 10.35, and 14 mm in a bed slope of 0.015.
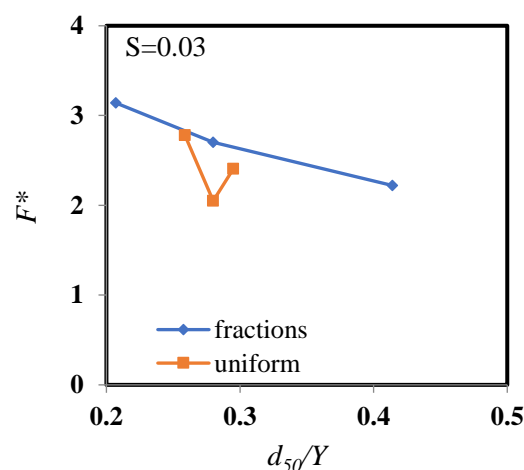

Figure 8. Comparison between particle Froude number for sediment sizes of 10.35, 14, and 20.7 mm in the fractions of the graded and uniform beds with a slope of 0.03.

4. Discussion

Although the correlation coefficients for flow velocity and shear stress are close to each other, flow velocity shows a higher Pearson correlation coefficient to sediment transport rate. The flow velocity was thus preferred to shear stress to analyze incipient motion of sediment in this paper. However, it is worth noting that we used the depth-averaged flow velocity, and the near bed flow field velocity would likely have a higher correlation with sediment transport rate.

4.1. Effect of Flow Velocity, Shear Velocity and Shield Stress on Incipient Motion Condition

The critical Shield stress tends to increase with bed slope due to a reduction of near bed mean flow velocity and turbulent fluctuation in a steeper slope resulting from an increase in relative roughness [26,30]. In addition, changes in the ratio of V_c/V_c^* would imply a non-constant roughness value. The relationship between the particle Froude number and bed slope showed that for a given bed sediment, the steeper the bed slope, the lower the particle Froude number. Moreover, for a given bed sediment diameter, the higher the relative roughness, the lower the particle Froude number.

A comparison between rounded uniform bed sediments revealed thatthe coarser the grain diameter, the higher the particle Froude number at a given relative roughness, except for a bed sediment of 14 mm,. The lowest stability of the 14 mm sediment bed may be due to

the fact that this particle's shape is more rounded than the others, and the highest stability of the 20.7 mm bed may be due to its greater diameter than the others. The particle Froude number of the graded sediment was higher than the rounded uniform sediments of 5.17, 10.35, and 14 mm, and lower than 20.7 mm. The higher stability of graded materials than the sediments of 5.17, 10.35, and 14 mm may be related to the existence of a coarser fraction of 20.7 mm and the lower stability of sediment diameter of 20.7 mm may be associated with the presence of finer fractions in graded bed sediment.

The reduction in particle Froude number for a given bed sediment is mainly due to the increased bed slope and to a reduction in water depth, which cause an increase in relative roughness. Previous research uncoupled the effect of bed slope from relative roughness for incipient motion conditions [26,27], and showed that by increasing the bed slope (increased relative roughness), the critical Shield stress increases. This would appear counterintuitive, as at a higher slope the particles would be less easily entrained. Prancevic and Lamb [27] showed that if the relative roughness is not taken into account, the critical Shield stress decreases at higher slopes and particles are more easily entrained. However, Figure 9a shows that by increasing the bed slope and relative roughness, the particle Froude number decreases, as suggested also by Prancevic and Lamb [27] and Lamb et al. [26]. Thus, it appears that the only reason for the increase of critical Shield stress with bed slope is the increase of relative roughness. With increasing relative roughness, the slope of stability curve decreases for both uniform and graded sediments. This shows that significant decrease in the slope of this trend occurs for lower relative roughness or for lower slope value (Figure 9).
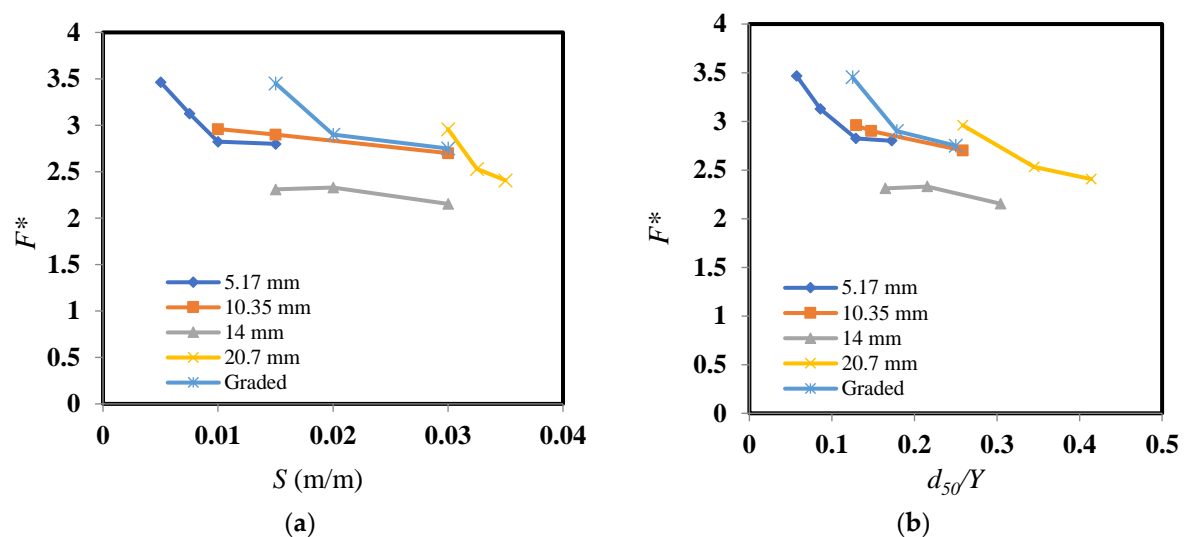

Figure 9. Particle Froude number as a function of bed slope (**a**) and relative roughness (**b**) for uniform and graded bed sediment.

4.2. Comparison between Uniform Sediment and Counterpart Sediment Fractions of Graded Bed

The main reason for higher critical flow velocity of fractions than for the uniform particles' counterpart is hiding and protrusion effects (e.g., [10,31–34], as the finer fraction hides within the coarser fraction and requires a larger force (via flow velocity or Shield stress) for movement in comparison to the uniform sediment. The opposite is true for the coarse fraction, which is more exposed to flow and can move more easily. Generally, graded bed sediment (with d_{50} of 12.5 mm) has a lower mean size but higher critical flow velocity than the 14 mm material. This is due to the fact that the coarse fraction of 20.7 mm caused graded bed sediment to be more stable, thus showing a higher critical flow velocity for incipient motion in comparison to rounded bed sediment, even with a higher sediment diameter (e.g., sediment of 14 mm).

Regarding the graded sediment, the finer fractions in the mixture were more stable than their uniform counterparts due to the presence of a coarser fraction; however, the coarser fraction in the same mixture was less stable than its uniform counterpart due to the presence of the finer fractions (Figure 9a,b). This is due to the shielding phenomenon, in which coarse sediments act as a shielding layer that protects the finer sediment from movement [23,35] but at the same time is more exposed to the flow forces.

4.3. Comparison with Previous Results

The results of the current study can be compared to Najafi-Mood et al. [24], Straub [35], and Neil [14]. This comparison revealed differences in terms of d_{50}/Y between the current study and the literature results, probably due to differences in bed sediment diameter and bed slope, as coarser sediment was used for the current study. However, the F^* values for both sediments were very close to each other (Figure 10).
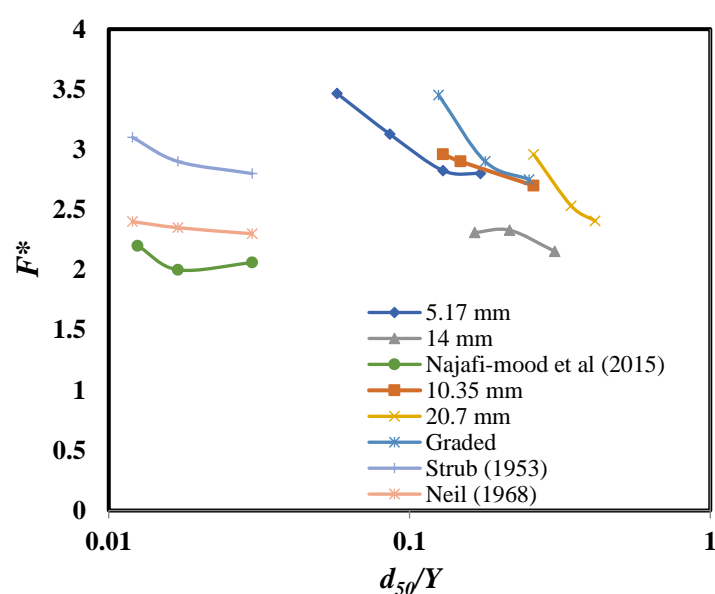

Figure 10. Comparison between results of current study with other researchers.

The main limitation of the current research is likely the use of mean flow velocity, as the near-bed flow field is responsible for bed movement in an incipient motion condition [36–38]. Particle image velocimetry (PIV) can be used to measure the near bed flow field to determine its effect on incipient motion of stream bed.

Further recommendation for future work includes the use of graded sediment beds with identical d_{50} but different mixtures of sizes, and also different uniform particles with the same densities but different diameters, to allow comparison of the effects on flow hydraulic and incipient motion of sediment.

5. Conclusions

In the current study, the incipient motions of three different types of sediments including rounded sediments (5.17, 10.35, 14, and 20.7 mm), angular uniform sediments (20.35 mm), and graded bed sediments (mixture of rounded uniform sediment in equal proportions) were investigated. The results of Pearson correlation coefficient showed that the impact of flow velocity on sediment transport and incipient motion is as important as shear stress. Dimensional analysis indicated the effect of flow velocity on incipient motion. To investigate the impact of relative roughness on critical flow velocity in a given bed sediment, some experiments have been performed for different bed slopes, indicating that the steeper the slope, (and consequently the higher relative roughness), the lower the critical flow velocity (or the higher the critical shear velocity). Results revealed that with an increase in grain Reynolds number, critical shear velocity increases linearly.

Results also showed that angular sediments have a higher critical shear velocity than rounded sediments in an incipient motion condition. Findings of V_c/V_c* against the grain Reynolds number suggested that a graded bed sediment on a given bed slope has a higher V_c/V_c* than uniform sediments of 5.17, 10.35, and 14 mm. In incipient motion condition, the finer the fraction, the higher the Shields stress and relative submergence. Particle Froude number analysis showed that the greater the bed slope and relative roughness, the lower the particle Froude number will be for a given bed sediment. Comparison between uniform sediment and its counterpart fraction of the same size revealed that finer fractions in graded sediment are more stable than their uniform counterparts; however, coarser fractions in graded sediment are less stable than their uniform counterparts. The reduction in the particle Froude number was more marked in lower relative roughness.

The current study provides a clearer insight into the interaction between incipient sediment transport and flow characteristics, especially critical flow velocity, in an incipient motion condition in a natural river and stream beds with a different gravel size distributions. The results of the current study also provide a better understanding of the effect of intergranular fractions in graded sediment beds, and the effect of differences in behavior between the graded beds and beds with uniform particles, particularly during conditions of incipient motion.

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