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Fractional Critical Shear Stress at Incipient Motion in a Bimodal Sediment

Yusron Saadi[1]

Abstract: The objective of this research was to examine and to quantify the stability of mixed grain sediment beds previously exposed to different time length of uniform antecedent flow hydrograph. The assessment of bed stability was carried out based on the observation of temporal pattern of eroded sediment during two identical stability tests with time varying flow and higher peak discharge. This was linked to the movement of individual sediment fractions to obtain fractional critical shear stress in a bimodal sediment mixture. The stability tests suggest a considerable increased in the stability of individual grain. Longer exposure time by antecedent flow clearly had an influence in the increasing stability of the bed. The increased rate of fractional critical shear stress during stability tests varied between 16 % and 35 % in the coarse mode whilst in the fine mode the rate of increase varied between 27 % and 39 %.

Keywords: critical shear stress, bimodal sediment, antecedent flow, stability test.

Introduction

In mixed grain size deposits, the initiation of motion of a given size sediment with various grain size fractions is affected by the presence of the other sizes. This adjusts the entrainment thresholds and thus the transport of sediment mixtures in open channels. The finer fractions are sheltered by the coarse fractions, and the coarser particles are exposed more to the action of flow due to their more exposed position. A range of friction angles demonstrates that grains within a size fraction can generate a range of resisting forces. This variability was at its greatest with the finer size fractions particularly when the sediment beds were water worked, with no upstream sediment supply rather than on mechanically scrapped flat beds [1]. Current prediction methodologies rely on the calculation of time-averaged quantities of flow in order to predict sediment movement. It is believed that the incipient motion of sediment particles is sensitive to the fluctuating fluid forces. Modern equipment used for flow velocity measurement now allow researchers to investigate near bed turbulence over sediment deposits [2]. However, the problem of defining critical flow conditions associated with the initial instability and entrainment of bed sediment particles is not as simple as thought. It has long been realised that different threshold methods give different values of the critical shear stress for initiation of grain motion. This has mainly been due to the different methods of defining the threshold of movement even in the relatively simple case of sediments that are nearly uniform in size.

The aim of these experiments was to examine and to quantify the stability of the armour bed caused by an increase in the time length of exposure as mixed grain sediment bed were exposed to antecedent flow hydrograph with constant and uniform flow rate. The pattern of individual transport rate was observed to obtain the fractional critical shear stress of a bimodal mixture.

Literature Review

In hydraulic engineering, determining the critical condition for sediment incipient motion and the sediment transport rate is very important. Natural river sediments are generally non-uniform and the bed-load movement in such case is quite complex. In this condition, the coarse particles on the bed are easier to be entrained than the uniform sediment of equivalent sizes, because they have higher chance of exposure to the flow and experience larger fluid dynamic forces than they would if they were in a uniform sediment bed. The situation is reversed for the fine particles, in which transport of a particular size of smaller particles will be less than that if the bed were composed of uniform sediments of the same size. This condition is likely to occur due to the fact that the finer particles are more likely sheltered and entrapped behind or below coarser particles. The smaller particles remain immobile for certain period of time until set in motion by turbulent burst or dislodgement of sheltering particles [3,4,5]. Therefore, the effect of the presence of one size on the transport rate of another in case of non-uniform

[1] Department of Civil Engineering, University of Mataram, NTB-Indonesia
E-mail: yoessaadi @yahoo..co.id

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sediment must be very carefully taken in the modelling of non-uniform sediment transport.

Wiberg and Smith [6] discussed that particles at the surface of a poorly sorted bed could have critical shear stresses differ significantly from the critical shear stress associated with that particle when placed on a well-sorted bed of the same size. The difference is primarily due to the relative protrusion of the particle into the flow along with differences in the particle angle of repose or bed pocket geometry, that results from having a mixture of grain sizes on the bed. This work was confirmed by Kirchner et al [7] where friction angles for a range of individual grains from different size fractions were estimated. Their observations indicated that for a given grain size on a given bed the critical shear stress was a wide distribution rather than a single value. A more fundamental problem is that the bed shear stress is a fluctuating quantity, and one cannot precisely define a value below which there is no motion [8]. Therefore, the criterion of initial motion needs to be defined so that determinations of the critical shear stress for different fraction of sediment mixture are comparable. Later study by Shvidchenko et al [9] indicated a further finding on the application of mean grain size. They suggested that the shear stress at incipient motion of median sized grains in mixtures was found to be the same as for uniform sediment of this size and was consistent with available flume and field data.

The initial motion threshold, or critical shear stress for incipient motion of individual fractions is estimated by producing a least square trend which is fitted to the estimated reference shear stress line. The reference transport method requires nominating the value of a transport rate parameter and fitting lines to data from each size fraction to determine the corresponding dimensionless critical shear stress. The values of dimensionless critical shear stress should be decreased for the larger fractions and increased for the smaller fraction with respect to values appropriate for the size being considered in a homogenous bed [10]. This method has the advantages that it may be measured for all fractions in a mixture regardless of the distribution of individual fraction critical shear stress within the mixture and does not depend on sampling individual, rare large grains in transport and because it is based on a transport rate, it is on a consistent basis with the threshold between partial transport and fully mobile transport [11]. Parker et al. [12] define the reference transport rate in terms of a constant value of the fractional transport parameter [8,13]. The value of fractional transport parameter is arbitrarily chosen to be equal to 0.002 and formalised by the use of least-squares log-log regression to fit each dimensionless bed-load parameter and Shields stress correlation [12].

Experimental Procedures

The laboratory experiments were carried out in a re-circulating glass sided tilting flume, which was 18.4 metres long, 0.5 metres wide and 0.5 metres deep (Figure 1). In all tests no sediment was input at the upstream inlet to the flume. The concept was to carefully place the mixture that was fully mixed using the electric mixer. The mixing time length was three minutes long enough to produce a well-mixed sediment bed. The mixing process was repeated until the amount of mixture was sufficient to fill the 12.5 m length of mobile bed section in the flume. The total mass of sediment used for each antecedent flow experiment was 310 kg. The mixtures had two modes with fine mode and coarse mode being at approximately 0.355 mm and 5.6 mm with d_{16} = 0.65 mm, d_{50} = 5.19 mm, and d_{84} = 7.61 mm. The geometric standard deviation σ_g was 3.42. This

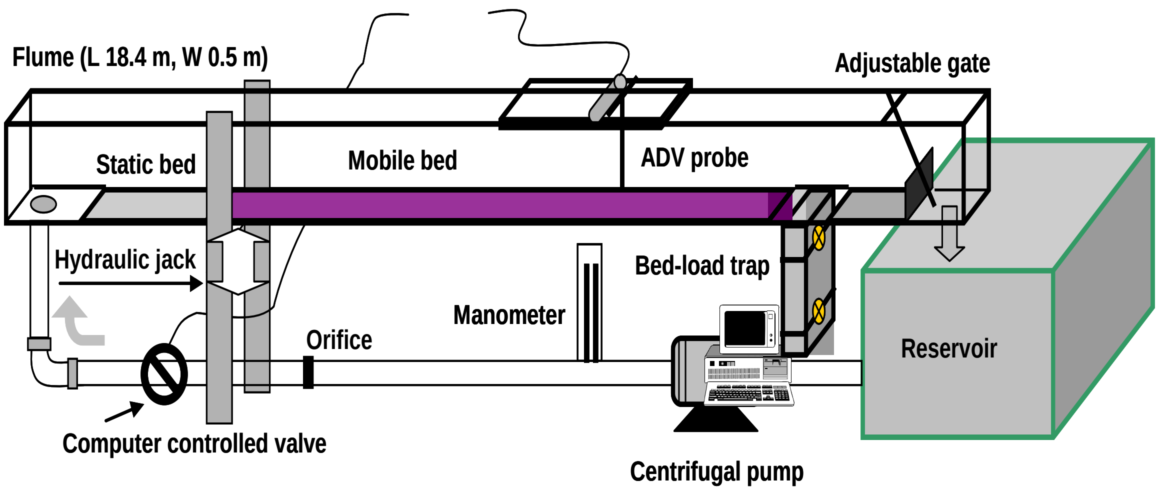

Fig. 1. Sketch of the experimental set up

bimodal sediment mixture was scrapped flat along the bed using a metal scrapper, which ran on two parallel measurement rails to give a bed surface with the same slope of the flume, i.e. 1 in 250.

Different time lengths of constant flow hydrographs were applied in antecedent flow experiments. The length was divided into two different durations as indicated by the number given in the name of experiment, i.e. AF-3 for 3-hour and AF-6 for 6-hour steady antecedent flow respectively. A constant flow rate of 0.0338 m^3/s was applied to both antecedent flow hydrographs. The gate at downstream end of the flume was adjusted during the initial stage of steady flow experiments so that experiment was started with a uniform flow depth. The stability of the beds was observed by the application of two relatively short identical stability hydrographs following each antecedent flow test. In this case stability test ST-3 was applied to the bed formed by 3-hour long steady antecedent flow hydrograph AF-3 and stability test ST-6 used to test the stability of the bed formed by 6-hour steady antecedent flow hydrograph AF-6. The flow rate of stability hydrographs increased from base flow of 0.0075 m^3/s to a peak flow rate of 0.0375 m^3/s in a time of 60 minutes. It then took a further 60 minutes to return to the base flow rate. The assessment of bed stability was carried out by examination of the temporal pattern of eroded sediment at 10 minutes intervals. Table 1 gives the details of experimental arrangement.

Results and Discussion

Transport Rate

The observation of transport rates throughout the antecedent flow AF-3 and AF-6 indicates that both tests produced almost identical rates of bed-load transport in the first three hours of time elapsed. Table 2 shows that the level of decreasing rates from the first to the second hour of both antecedent flow tests changed quite significantly. The rates in the second hour were less than half of the rates in the first hour of AF-3 and half the rates of the first hour of AF-6 respectively. The bed started to increase its stability as indicated by smaller decreases in the transport rates in the third hour, which was also the last hour of antecedent flow AF-3. The increased in the bed stability was more evident in the remaining hours of longer antecedent flow test. It was suspected that during these stages the bed started to develop an armoured bed where the bed load transport rate almost constant during the last three hours of AF-6.

The pattern of transport rate shown in Table 2 suggest that different level of beds stability to some extent were established as a result of continuous constant flow exposure with the discharge of 0.0338 m^3/s to the bed with different time length of antecedent flow tests. However, the pattern of transport alone was unable to provide more information in detail on the armouring process and the resulting bed stability. It was therefore decided to test both the bed structures by applying two identical short stability hydrographs with time varying flow in which the peak discharge was higher than the discharge applied during the antecedent flow tests. In this case the stability test ST-3 was applied to the bed formed by antecedent flow AF-3 and the stability test ST-6 applied to the bed formed by antecedent flow AF-6.

The observation of high transport rates throughout the stability test ST-3 indicates that the bed formed by the shorter duration was less stable than the bed formed by the longer duration of antecedent flow test. As seen in Figure 2, when the identical stability test applied to the bed formed by 6-hour antecedent flow, the transport rate during the stability hydrograph ST-6 was still moderately high but noticeably less than the production in the stability test ST-3. This suggests that the longer tests with a constant discharge established a more stable bed. Figure 2 also shows that although both steady

Table 1. Details of experimental arrangement

Descriptions	Antecedent flow tests		Stability tests	
	AF-3	AF-6	ST-3	ST-6
Discharges (m^3/s)	0.0338	0.0338	0.0075 – 0.0375	0.0075 – 0.0375
Durations (hours)	3	6	2	2
Flow hydrograph	Steady	Steady	Unsteady	Unsteady
Number of bed-load samples	18	36	12	12

Table 2. Transport pattern as a function of time during antecedent flow tests

Time elapsed (hour)			1st hour	2nd hour	3rd hour	4th hour	5th hour	6th hour
AF-3	(3 hrs)	Amount (gr)	45.28	20.41	17.16	n/a	n/a	n/a
		Rate (gr/s/m)	0.40	0.18	0.15	n/a	n/a	n/a
AF-6	(6 hrs)	Amount (gr)	42.98	21.53	15.27	10.33	8.34	7.80
		Rate (gr/s/m)	0.38	0.19	0.13	0.09	0.07	0.07

antecedent flow experiments produced different level of bed stability, only the higher discharges during the stability tests were able to destabilise the previously formed armoured bed. The transport rate during the stability tests generally increased with increasing discharges. However at the peak discharges the peak value of transport rate was not attained. It was only when the discharge passed its peak, at time elapsed 60 minutes, the transport rate was significantly increased. At the beginning of falling limb in ST-3 (time elapsed 60-70 minutes or between T60 - T70) the transport rate was 3.19 gr/s/m or more than 100 % higher from 1.58 gr/s/m observed during the similar level of discharge at the end of rising limb (time elapsed 50-60 minutes or between T50 - T60).

The peak discharge of stability test ST-6 produced a maximum transport rate of 1.26 gr/s/m (time elapsed T60 - T70). This was 50 % above the transport rate shortly before the discharge attained its peak (0.83 gr/s/m at time elapsed T50 - T60). The transport rates measured at the same level of discharges during the falling limb were always higher than those in the rising limb. Overall, the average transport rate during 60 minutes of the rising limb (time elapsed T0 - T60) was 0.18 gr/s/m and this increased to 0.32 gr/s/m during the same period of falling limb (time elapsed T60 - T120).

The observations of stability test ST-3 also suggest that during the initial low discharges (time elapsed T10 - T20) the flow eroded only the finer grains. At these stages the available fluid forces were not sufficient to transport grains in the coarse mode, i.e. 4.0, 5.6 and 8.0 mm. These grains started to appear in transport at time elapsed 30 minutes of the rising limb (see Table 3). When water discharge increased at time elapsed T50 or 10 minutes before the peak discharge, significantly more coarse particles on the bed moved. The coarse mode dominated the transported bed load until time elapsed T80. This suggests that the grains in the coarse mode started to move when the fluid forces were strong enough to transport them, therefore the transport was highly size selective.

The removal of sheltered smaller grains continued as the flow strength increased. An increasing proportion of the grains in the fine mode, i.e. 0.25, 0.355 and 0.5 mm, entrained into transport and the level of exposure of larger grains increased and becoming less stable and easy to remove. This can be explained by examination of the pattern of transport during the increasing and declining flow rates as presented in Table 3. In the last 10 minutes rising limb of stability test ST-3 the proportion of transport in the fine mode to the total transport was 5.17 % (45.13 grams) and increased to 7.71 % (67.28 grams) in the first 10 minutes of falling limb. Within the same duration, the proportion of grains in the coarse mode increased significantly from 12.35 % (107.78 grams) to 28.07 % (244.92 grams). Supporting this observation was the fact that lower available fluid forces at time elapsed 80 minutes in the falling limb (T80) were able to move and transport more grains in the coarse mode than in the fine mode (see Table 3 and Figure 3). At time elapsed T90 the proportion of grains transported in the coarse mode decreased to almost similar level of grains in the fine mode and was gradually reduced within the next 30 minutes where bed load was dominated by fine grains until

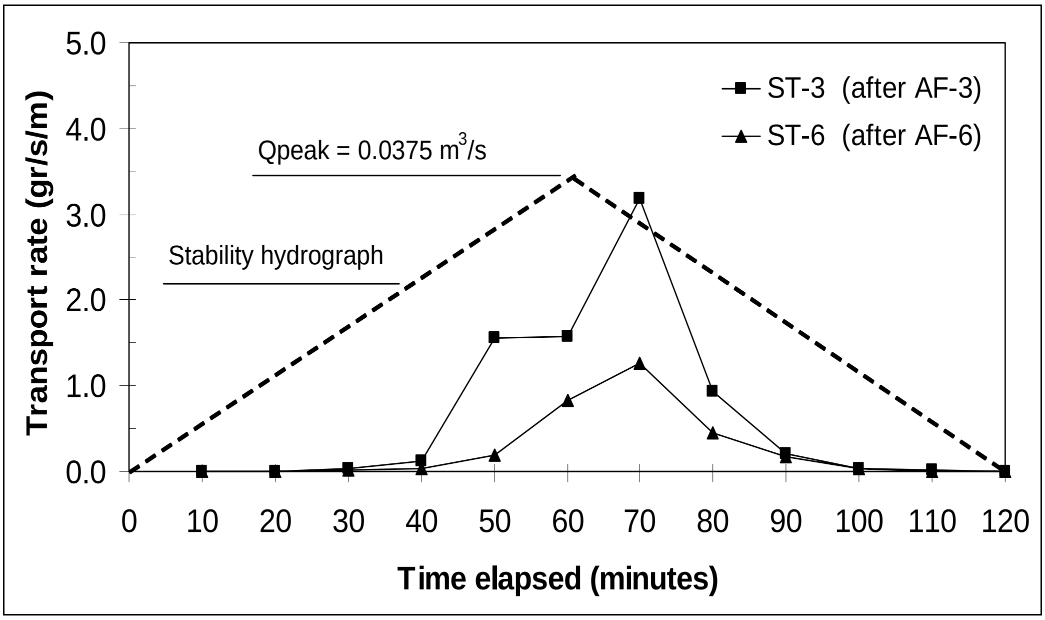

Fig. 2. Bed load transport rate pattern during stability tests (Note: hydrograph not to scale)

stability hydrograph ended. It is worth noting that a decrease in the coarse fraction of bed-load in the falling limb is believed to be solely due to the decreasing fluid forces rather than the changes in the availability of coarse grains on the bed surface.

Almost similar to the finding in stability test ST-3, the transport at lower flow rates (time elapsed T10, T110 and T120) in stability test ST-6 composed entirely grains in the fine mode (see Table 3 and Figure 4). At time elapsed T20 a small amount of 4 mm grain was found in transport whilst the coarse mode at time elapsed T30 and T40 represented only by grains of 5.6 mm with the amount less than grains in the fine mode. It was at time elapsed T50 when all grains in the coarse mode appeared and started to dominate the transported bed load. This occurred at a latter time than experienced in stability test ST-3. Following the disruption by peak discharge the contribution of coarse grains in bed load transport was immediately evident at time elapsed T70 to T90, and then diminished during the lower discharges, i.e. T100, T110 and T120 respectively.

As seen in Table 3 a significant increased in the coarse mode is apparent as the flow rate approaching its peak in stability test SF-6. At time elapsed T50, T60 and T70 the amount of grains in the coarse mode subsequently increased from 13.40 grams to 69.11 grams and 108.71 grams. Although the amount of grains in the fine mode was also increased in the corresponding time elapsed, these grains were proportionally decreased. The amount of transported grains in the fine mode at time elapsed T50 and T60 were 6.85 grams and 18.37 grams. After the peak flow rates, a small increased was noticed when 21.70 grams was transported at time elapsed T70. At the lower flow rates (time elapsed T80) the amount of grains in the coarse mode decreased to 33.75 grams. The amount of finer mode was also decreased (11.73 grams). Although the flow rates had similar level between time elapsed T50 and T80, the higher amount of transport at the latter time indicates the influence of destabilising process during the peak flow rates. In the last 30 minutes of falling limb (time elapsed T90 to T120) the bed load transport was clearly dominated by fine mode.

In term of the total amount of bedload, a significant amount of coarser grains was transported during both stability tests. In ST-3 only 22 % of the total bed load contained grains of fine mode in comparison to 63% of grains in coarse mode whilst ST-6 transported 70% grains in the coarse mode in comparison to 21% of grains in the fine mode. These findings suggest that the stability tests was very efficient at moving the coarse materials which means during both stability tests the coarser grains were anticipated more mobile than the finer grains.

Table 3. Fractional transported bed load (grams) during stability tests ST-3 and ST-6

Grain size (mm)	Test	Time elapsed T (minutes)											
		Rising limb						Falling limb					
		10	20	30	40	50	60	70	80	90	100	110	120
8.0	ST-3	0.00	0.00	0.00	2.06	19.64	4.53	8.06	2.85	0.00	0.00	0.00	0.00
	ST-6	0.00	0.00	0.00	0.00	2.66	8.57	11.24	5.16	0.85	0.00	0.00	0.00
5.6	ST-3	0.00	0.00	1.85	3.86	66.36	65.85	149.17	36.03	4.56	0.25	0.11	0.00
	ST-6	0.00	0.00	0.46	0.12	6.86	47.12	73.76	22.05	6.78	0.00	0.00	0.00
4.0	ST-3	0.00	0.00	0.00	2.03	33.91	37.40	87.69	18.89	3.64	0.76	0.00	0.00
	ST-6	0.00	0.40	0.00	0.00	3.88	13.42	23.71	6.54	3.52	0.45	0.18	0.00
2.8	ST-3	0.00	0.17	0.22	0.28	8.85	9.66	19.45	5.67	1.71	0.05	0.06	0.04
	ST-6	0.00	0.00	0.04	0.07	0.39	2.27	4.55	1.28	0.74	0.33	0.02	0.00
2.0	ST-3	0.00	0.04	0.10	0.16	4.70	3.64	8.56	2.91	0.66	0.05	0.01	0.00
	ST-6	0.01	0.02	0.00	0.04	0.20	0.77	1.31	0.70	0.25	0.05	0.05	0.00
1.4	ST-3	0.00	0.02	0.08	0.17	3.34	3.37	6.06	2.44	0.58	0.07	0.05	0.01
	ST-6	0.02	0.00	0.01	0.02	0.14	0.77	1.41	0.73	0.31	0.05	0.04	0.02
1.0	ST-3	0.00	0.06	0.09	0.30	3.32	3.41	5.92	2.52	0.68	0.15	0.11	0.01
	ST-6	0.03	0.01	0.02	0.04	0.23	1.03	1.74	0.91	0.40	0.15	0.02	0.02
0.71	ST-3	0.03	0.07	0.13	0.50	4.17	5.24	8.38	3.60	1.07	0.31	0.30	0.03
	ST-6	0.05	0.02	0.09	0.20	0.59	2.07	2.84	1.62	0.87	0.31	0.09	0.02
0.5	ST-3	0.04	0.16	0.40	1.48	11.13	15.56	22.28	10.08	3.42	1.00	0.35	0.12
	ST-6	0.06	0.10	0.30	0.78	2.03	6.58	7.60	4.47	2.13	0.89	0.26	0.08
0.355	ST-3	0.05	0.18	0.59	1.90	13.41	21.10	30.12	12.74	4.67	1.17	0.14	0.10
	ST-6	0.06	0.10	0.44	1.27	3.14	8.28	9.59	5.22	2.43	0.99	0.30	0.09
0.25	ST-3	0.03	0.13	0.28	0.96	5.91	8.47	14.88	5.42	2.05	0.52	0.04	0.05
	ST-6	0.02	0.09	0.13	0.57	1.68	3.51	4.51	2.04	0.82	0.34	0.10	0.02
0.15	ST-3	0.03	0.08	0.06	0.17	1.05	1.33	2.50	0.93	0.32	0.08	0.02	0.02
	ST-6	0.01	0.01	0.05	0.07	0.33	0.58	0.96	0.30	0.12	0.05	0.01	0.01

Note: Top and bottom shades represent grains in the coarse and fine mode

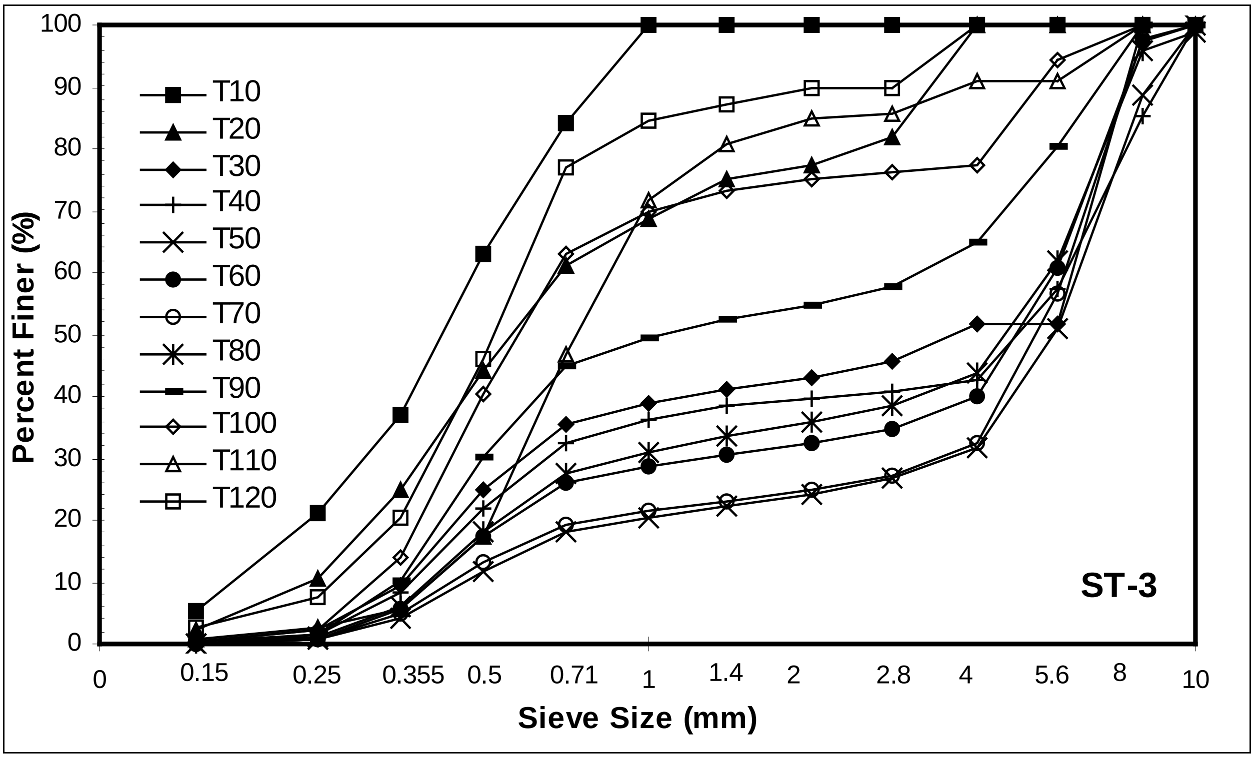

Fig. 3. Grain size distribution of transported bedload for stability test ST-3

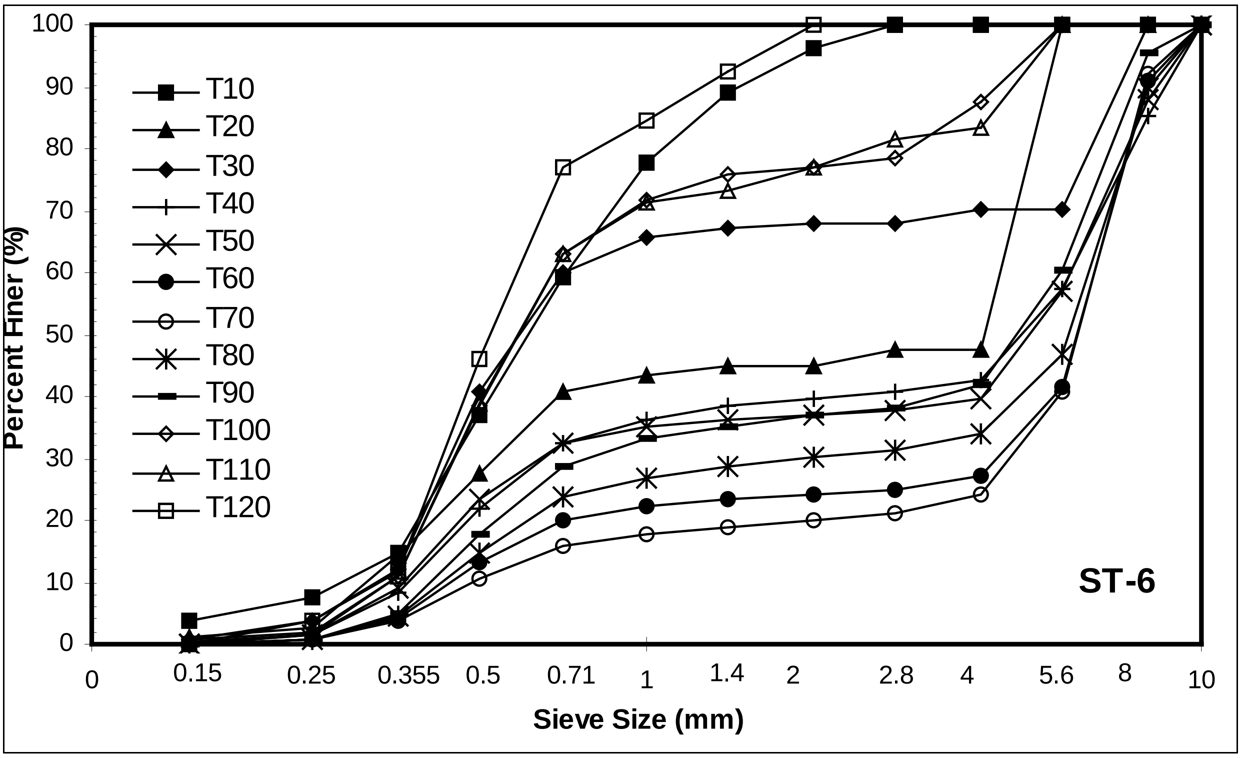

Fig. 4. Grain size distribution of transported bedload for stability test ST-6

Fractional Threshold of Motion

It is clear in the previous section that the threshold of motion of individual grain size fraction, particularly the coarse mode fractions, is an important factor in determining whether a water worked deposit would remain stable. It is therefore decided to examine the threshold of motion for individual grain size fractions for each test in which measurement should cover different level of discharges during the stability flow. This is done to meet the primary requirement used to select the data to be examined that the fractional transport rates were well measured over a wide range, including very low transport rates near incipient motion. The sufficient sampling was also performed to account for variability of fractional transport rates over a variety of time elapsed with an interval of ten minutes. The critical shear stress for incipient motion of individual grain size fraction, τ_{ci}, was estimated from the shear stress parameter, τ_{ri}*, that produces a small, non-dimensional reference transport rate, W_{ri}*. This method involves fitting a transport function to the sediment transport data for each fraction. The values of τ_{ri}* is defined such that W_{ri}* equals to a low reference value of 0.002 for each grain size fraction. One of the advantages of this method is that because the proportion of available sediment is considered, it can be applied on a consistent basis for the estimation of threshold during both situations of partial transport and fully mobile transport.

The non-dimensional reference transport rate, W_{ri}*, and the shear stress parameter, τ_{ri}*, were determined as follows

$$W_{ri}^{*} = \frac{q_{bi}\left(\frac{\rho_s}{\rho} - 1\right)g}{f_i \rho_s U_*^{3}} \tag{1}$$

$$\tau_{ri}^{*} = \frac{\overline{\tau_i^{'}}}{\left(\frac{\rho_s}{\rho} - 1\right)\rho g D_i} \tag{2}$$

where q_{bi} is fractional bedload transport rate for grain size fraction i (gr/s/m), ρ_s is sediment density (kg/m^3), ρ is density of water (kg/m^3), g is the acceleration due to gravity (m/s^2), f_i is proportion of grain size fraction i on the bed, U_* is bed shear velocity (m/s), $\overline{\tau_i^{'}}$ is time-averaged bed shear stress for grain size fraction i (N/m^2) and D_i is grain size fraction i (mm).

The value of time-averaged shear stress was calculated by averaging the large number of calculated instantaneous shear stress values obtained from measurement

$$\overline{\tau_i^{'}} = \sum_i^n \frac{\rho u^{'} v^{'}}{n} \tag{3}$$

where $u^{'}$ and $v^{'}$ are the fluctuating component of velocity in streamwise and vertical directions (m/s) and n is the large number of measurement.

These procedures gave the values of shear stress parameter, τ_{ri}*, for stability tests ST-3 and ST-6. The values of τ_{ri}* were then used to determine the critical shear stress, τ_{ci}, for individual grain size fraction as follows

$$\tau_{ci} = \tau_{ri}^{*}\left(\frac{\rho_s}{\rho} - 1\right)\rho g D_i \tag{4}$$

Figure 5 and Figure 6 present the shear stress parameter, τ_{ri}*, that produces a small, non-dimensional reference transport rate, W_{ri}* = 0.002, whereas Tabel 4 gives the summary of the critical shear stress, τ_{ci}, for incipient motion of individual grain size.

Table 4 shows the variation of critical shear stress τ_{ci} with grain size. This suggests that the individual grain fraction moves at different level of flow strength. As expected from the measurement of bedload transport rates (see Figure 2) the stability test ST-3 which applied to the bed formed by antecedent flow AF-3 indicated lower critical shear stresses for all grain sizes than that of stability test ST-6 which applied to the bed formed by antecedent flow AF-6. Table 4 also shows that grains in the fine mode for stability test ST-3 had a relatively consistent increased in critical shear stress with increasing grain size but the coarse mode had an inconsistent pattern. A much lower threshold of motion for fine grains was produced by the stability test ST-3. Individual grains started to move at lower critical shear stresses. This is an indication that the bed was not sufficiently stable in comparison to the bed formed by antecedent flow AF-6. It is suspected that the antecedent flow test with the duration of 3 hours (AF-3) still produced a bed with many unsheltered fine grains. Relatively stable and sheltered fine grains are only likely to be obtained with duration longer than 3 hours as the stability test ST-6 transported less amount of grains in this mode. These grains have critical shear stress almost 30 % higher than that of ST-3.

The coarser grains produced more complex pattern in which the level of increase in the threshold of motion varied between grain sizes. Grain size 5.6 mm was the most stable grain in the coarse mode. Three hours difference of exposure to the constant flow rates increased the critical stress to 35 % from

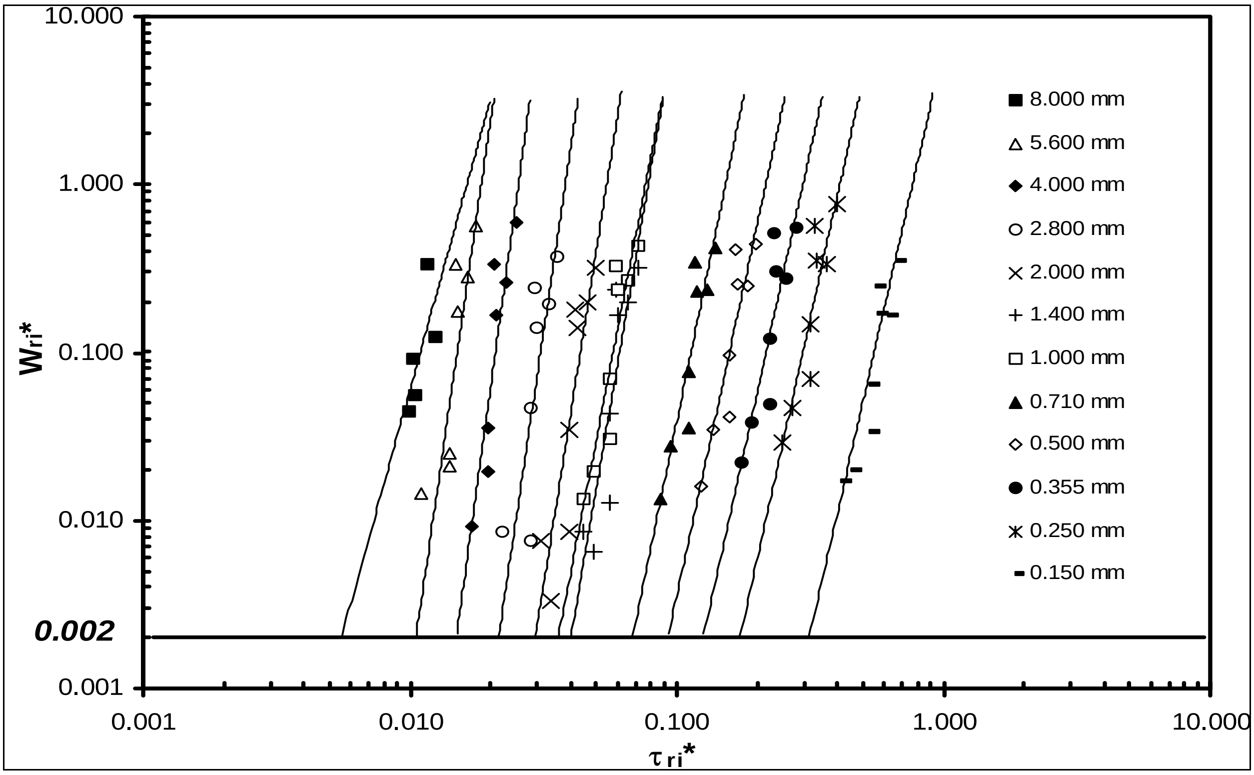

Fig. 5. Dimensionless shear stress parameter, τ_{ri}*, obtained from low reference transport rate, W_{ri}* = 0.002, for stability test ST-3

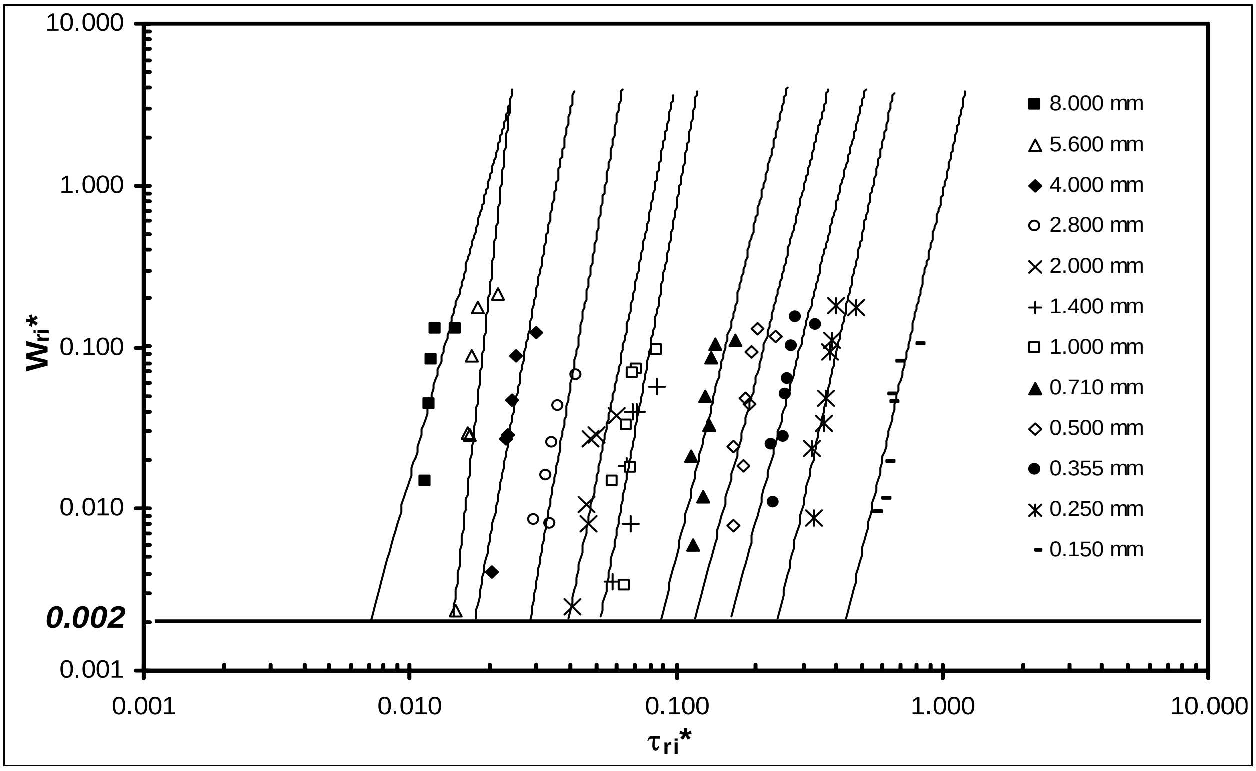

Fig. 6. Dimensionless shear stress parameter, τ_{ri}*, obtained from low reference transport rate, W_{ri}* = 0.002, for stability test ST-6

0.977 N/m^2 in the stability test ST-3 to 1.319 N/m^2 in the stability tests ST-6. Although grain size 8 mm displayed similar level of increased between both stability tests, their critical shear stress was considerably lower than the other two grains sizes in the coarse mode, i.e. 5.6 mm and 4.0 mm. It is believed that these grains were weaker because of the level of exposure to the flow increased as grains in the fine mode continued to be transported during both stability tests. Grain sizes 4 mm were more stable in which the increased in critical shear stress were less than the other grains in the coarse mode. The critical shear stress of grain sizes 4 mm was 0.975 N/m^2 during the stability test ST-3 and increased 16 % to 1.130 N/m^2 during the stability tests ST-6.

Grain sizes other than the fine and the coarse mode were also seen to have a significant increased in their critical shear stress between stability tests ST-3 and ST-6. The level of increased were considerably high between 28 to 47%. However, the increased values of critical shear stress is not a strong and sole indication that these grains had stabilised in the way the fine and the coarse grains had. It is suspected that the availability of these grains in the mixture also influence the ability of the flow to transport them. Less amount of certain grains size available on the bed are less likely to be moved and transported throughout the course of the stability test by the fluid forces.

Conclusions and Recommendations

Conclusions

The research enables some conclusion to be drawn as the following:

1. Different levels of transport rate are produced by the identical stability tests. The beds formed by antecedent flow test AF-3 were weaker than the beds formed by antecedent flow test AF-6. This means different duration of antecedent flow clearly had an influence on the bed stability. The similarity of both stability tests is that the falling limb transported more bed load than the rising limb. This reflects the ability of the peak flow rates to destabilise the armoured bed structure formed by the antecedent flow tests.
2. It is apparent that during the stability test ST-3 and ST-6 grains in the coarse mode did not make a continuous contribution to the bedload and only started to move when the fluid forces had increased sufficiently. However, the contribution of this mode in the total amount of bedload was considerably high. The increasing level of mobility of the coarser grains was thought to be due to their enhanced exposure. The level of exposure left by antecedent flow increased when the peak discharge of stability test removed the finer grain size around the coarse grains. This created a less stable formation of larger grains, and allowed the destabilisation process to be enhanced.
3. The stability of grain size fraction increased considerably after 3-hour longer of bed exposure by antecedent flow. These indicated by noticeable increased in the fractional critical shear stress during stability tests. In the coarse mode the increased rate varied between 16 % and 35 % whilst in the fine mode the increased rate varied from 27 % to 39 %. Grains other than these two modes increased their critical shear stress from 28 % to as much as 47%.

Recommendations

Examination of fractional critical shear stress in this study was based on reference transport rate and shear stress parameter. Certain grains may be less stable after flow exposure change their protrusion and orientation on the bed. It is therefore a method corresponds to the observation of grains exposure need to be developed as this will allow an investigation of the changes in the bed surface structure and to link it with the movement of individual grain.

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