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DIMENSIONLESS CRITICAL SHEAR STRESS EVALUATION FROM FLUME EXPERIMENTS USING DIFFERENT GRAVEL BEDS

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ABSTRACT

Flume experiments were conducted using four different gravel beds ($D_{50} = 12$–39 mm) and a range of marked particles (10–65 mm). The shear stresses were evaluated from friction velocities, when initial movement of marked particles occurred. Two kinds of equations were produced: first for the threshold of initial movement, and second for generalized movement. Equations of the type $\theta_c = a(D_i/D_{50})^b$, as proposed by Andrews (1983) are applicable even if the material is relatively well sorted. However, the values of a and b are lower (respectively 0·050 and −0·70) for initial movement. Generalized movement requires a higher shear stress ($a = 0{\cdot}068$ and $b = -0{\cdot}80$).

D_{90} of the bed material and y_0 (the bed roughness parameter) were also used as reference values in place of D_{50}. They produced lower values than in natural streams, mainly owing to the fact that the material used in the flume is better sorted: clusters are less well developed and the bed roughness is lower.

KEY WORDS Gravel bed Flume experiments Critical shear stress Entrainment

INTRODUCTION

Shear stress is generally accepted as a criterion for initiation of movement of bed material, based on the establishment of reasonable reliable critical shear stress equations. Such equations were first obtained from experiments conducted in sand-bedded flumes. When subsequent attempts to extend these equations to gravel and pebble fractions were made, discrepancies soon appeared (Wilcock, 1967; Baker and Ritter, 1975). Indeed, in the case of gravel and pebbles, some factors come into play which are not significant in the case of sandy material. These include the shapes of the particles and the fact that, in a heterogeneous bed, certain phenomena peculiar to pebble beds are apparent. First, imbrication and grouping in clusters tend to offer greater resistance to erosion and thus, as shown by Reid and Frostick (1984), tend to retard entrainment of the material. Second, and conversely, protrusion factors revealed by Fenton and Abbott (1977) tend to favour initial entrainment for relatively low shear stress, owing to the increased exposure of grains.

It has proved difficult to integrate these factors into existing equations. However, Shield's dimensionless criterion (θ_c), where $\theta_c = \tau_c/\rho_s - \rho_f)gD$, allows analysis of these effects. In this equation, $\theta_c = 0{\cdot}06$ when $Re^* > 200$ (which is generally the case in natural rivers and even in flumes), and thus fits with the equation $\tau_c \propto D$. However, this value of $\theta_c = 0{\cdot}060$ has been challenged. For example, Miller *et al.* (1977) and Yalin and Karahan (1979) both proposed a value of $\theta_c = 0{\cdot}045$, while Neill (in Andrews, 1983) found a value of $\theta_c = 0{\cdot}030$. Additionally, the constancy of θ_c has been questioned, Andrews (1983) suggesting an equation of the type:

$$\theta_c = a\left(\frac{D_i}{D_{50}}\right)^b \tag{1}$$

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where the Shields factor (θ_c) varies as a function of the relationship between the size of the surface particles involved (D_i) and the diameter of the underlying material constituting the bed (D_{50}).

In this type of equation, the coefficient *a* represents Shield's standard dimensionless coefficient (θ_c) in homogeneous sediment conditions when $D_i/D_{50} = 1$. Also, the negative sign of the exponent *b* indicates that values of θ_c diminish as D_i increases. The equation proposed by Andrews (1983) includes both the effects of imbrication factors and protrusion factors, as shown earlier in a different form by Church (1978). More recent studies, notably by Komar (1987), Ferguson *et al.* (1989) and Ashworth and Ferguson (1989) confirm the validity of this approach even if, as we shall see later, the values of coefficients and exponents sometimes differ significantly.

Furthermore, Richards (1988) and Robert (1990) propose an equation of similar type, but in which θ_c varies as a function of the ratio D_i/y_0, where y_0 is the bed roughness height which is involved in the calculation of the friction velocities u^*. This equation is very close to that of Wiberg and Smith (1987), based on theoretical analysis.

Experiments on selective gravel entrainment were conducted in flume by Day (1980) using a small size material (< 5 mm), and by Bathurst *et al.* (1987) with entrainment equations based on the flow discharge rather than bed stresses. Carling *et al.* (1992) also undertook flume experiments to measure the entrainment of individual clasts, the objective being to test the mechanical grain-pivoting equations. But most equations proposed for heterogeneous beds are based on research conducted in rivers, where D_i represents the size of material collected either in a sampler or in a sediment trap, i.e. where the material is already in motion. However, in a natural river it is not always possible to encounter widely differentiated bed types nor to follow very precisely the movement of the bedload. Experimental conditions in a flume offer the advantage of changing the composition of the material that forms the bed. Additionally, it is possible to watch the exact initial movement of particles and to estimate the proportion of material set in motion. This paper therefore reports on results from a series of experiments conducted in a flume using four types of bed, differentiated by the size of the bed material. These experiments are intended to complement research undertaken into pebble-bedded rivers of Upland Belgium (Petit, 1987, 1988).

CHARACTERISTICS OF THE FLUME

The experiments were conducted in a flume at the Physical Geography Department of Uppsala University. The operational length of the flume is 6 m and its width is 0·5 m. The longitudinal gradient can be varied from 0 to 35 per thousand. The discharge can reach 400 l s^{-1}. Current velocity was measured using an Ott-C2 current meter fitted with a 3 cm diameter impeller, and by an electromagnetic probe capable of measuring and recording instantaneous current velocities to within 1 cm of the bed. The bed and walls of the flume are made of plexiglass. In the first set of experiments, pebbles were laid on the bed and glued in place. These pebbles were placed edge-to-edge and slightly inclined upstream, and had $D_{50} = 19{\cdot}6$ mm (Table I). The pebbles chosen for use offered a compact and relatively well-rounded shape ($C/B > 0{\cdot}6$ and $B/A > 0{\cdot}7$ in the Zingg classification). In the second set of experiments, loose beds were used in which the pebbles were not glued down but merely placed over the bed of the flume in a continuous layer so that they could settle and position themselves in a manner similar to a natural setting. In this second series, three types of beds

Table I. Characteristics of the different beds

D_{50} (mm)	D_{90} (mm)	$\frac{D_{90}}{D_{50}}$	y_0 (mm)	$\frac{y_0}{D_{50}}$
12·8	14·7	1·15	1·7	0·13
19·6	28·5	1·45	1·8	0·092
24·2	30·8	1·27	3·6	0·15
39·2	43·5	1·11	4·4	0·11

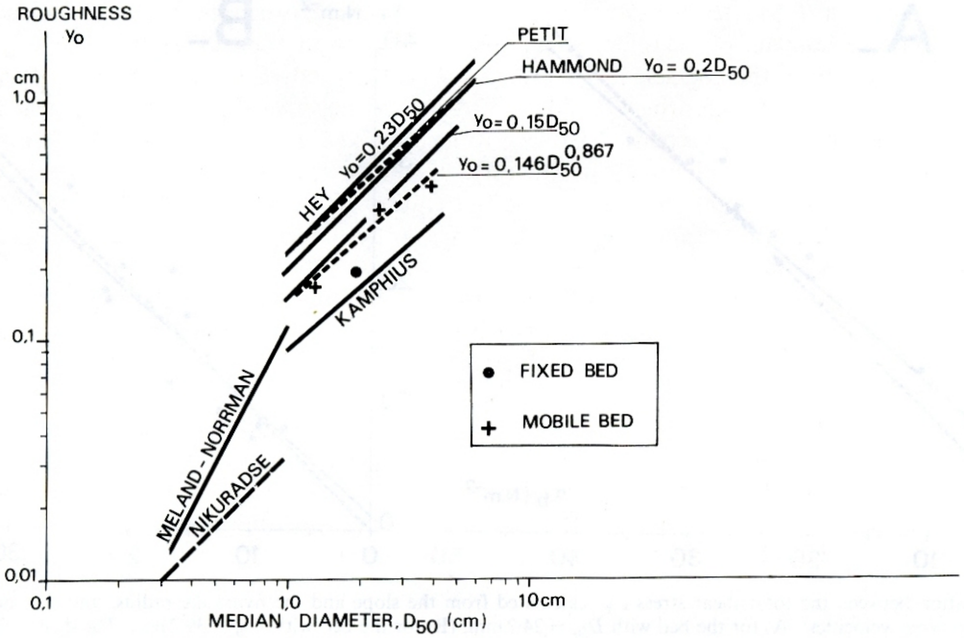

Figure 1. Relation between the roughness height y_0 and the diameter of the particles

were used, the essential difference being in the sizes of the bed material employed (Table I). With these four different beds, experiments were carried out using marked pebbles of known diameter. Nearly 100 pebbles ranging from 10 to 65 mm in diameter were used, being selected from the same material as that which constituted the flume bed (granite from the Uppsala esker).

The side wall effect was corrected following the procedure advocated by Vanoni (1975). Furthermore, the virtual bottom of the bed was considered to be at $0{\cdot}7\,D_{90}$ above the level at which the particles are laid out, which is consistent with results obtained in other studies (Kamphuis, 1974; Komar and Li, 1988). Shear stress (τ^*) was evaluated from friction velocities:

$$\tau^* = u^{*2}\rho \tag{2}$$

where ρ is the density of fluid and u^* is the friction velocity arrived at from the following equation:

$$\frac{u}{u^*} = 2{\cdot}5 \ln \frac{y}{y_0} \tag{3}$$

where u is the velocity measured at a distance y above the virtual bottom of the flume and y_0 is the roughness parameter characterizing the bottom of the bed.

More detailed discussion of the methodology employed, the choice and variation of parameters, and the degree of equality between shear stress evaluated by this method and the grain shear stress (τ') involved in the initiation of movement and the transport of sediments may be found in Petit (1989). However, note that the parameter y_0 was obtained by application of the law of the wall, i.e. by analysis of velocity gradients in close proximity to the bed (less than 0·2 total depth). The values of y_0 are obviously a function of the diameter of the material forming the bed (see Table I) and, consistent with recent research (Hey, 1979; Hammond *et al.* 1984; Petit, 1990), they diverge significantly from the values originally proposed by Nikuradse (1933) for sandy beds (albeit homogeneous ones).

As Figure 1 shows, the values obtained in a flume come close to those obtained by different authors for gravel-bed streams. The roughness values tend to settle around the equation $y_0 = 0{\cdot}15\,D_{50}$, whereas in a natural river the y_0/D_{50} ratio is about 0·2–0·25 (Hey, 1979; Petit, 1990), with values sometimes beyond

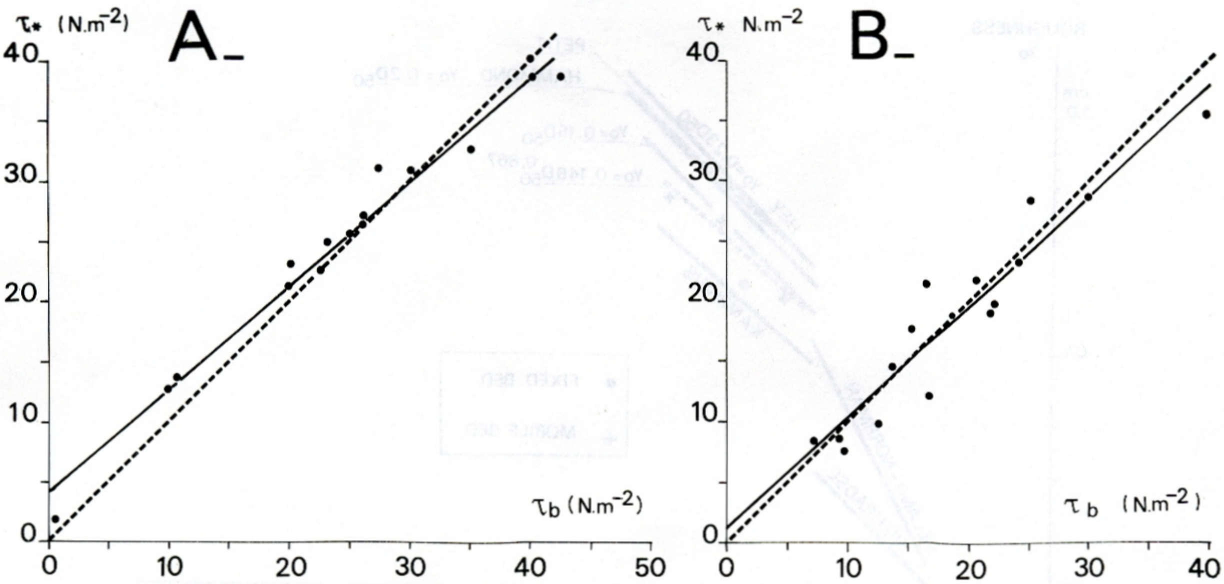

Figure 2. Relation between the total shear stress (τ_b) calculated from the slope and the hydraulic radius, and the shear stress (τ^*) evaluated from shear velocities: (A) for the bed with $D_{50} = 24{\cdot}2$ mm; (B) for the bed with $D_{50} = 39{\cdot}2$ mm. The dashed lines represent perfect agreement. The solid lines are least square regressions

0·33 (Ferguson *et al.*, 1989) but usually less than 0·5 (Ferguson and Ashworth, 1992). The ratio y_0/D_{50} was highlighted by Robert (1990) as a good indicator of bed roughness, and varies basically as a function of packing and sorting of the bed material. The low values of y_0/D_{50} obtained in the flume result from the fact that the pebbly material used to create the different beds was taken from a clearly defined range of pre-selected and therefore better graded pebbles, which influences the roughness of the bed. The superior grading of the material forming the bed of the flume emerges clearly from the D_{90}/D_{50} relationship, which is below 1·3 in the flume whereas in a natural river it generally exceeds 2·0 and even 3·0 (Ashmore, 1988). Furthermore, y_0 obtained for the fixed bed in the flume ($D_{50} = 19{\cdot}6$ mm) appears abnormally low as compared with the other values, and this is clearly connected with the artificial layout of the pebbles.

Since the equations linking shear stress τ^* calculated from friction velocities (Equations 2 and 3), which require y_0, and shear stress τ_b evaluated from the water surface gradient and hydraulic radius (known to represent the grain shear stress τ' for flat beds) are particularly well defined, and since the lines obtained by regression are all very close to the line of perfect agreement (Figure 2), it appears that the values for y_0 are correctly established for both beds. The values of y_0 and the equality between τ^* and τ_b were revealed during preliminary tests carried out on each of the experimental beds. During these tests the slope of the flume was varied from 5 to 20 per thousand and the discharges from 6 to 200 l s^{-1} so as to obtain a fairly broad range of shear stress. Furthermore, the values of y_0 obtained for each of the beds represent the average of some 30 measurements taken at different points along the flume for different rates of discharge. For a given bed, no systematic variation of this parameter was noted either in relation to location or to discharge.

EXPERIMENTAL PROCEDURE

For each of the four bed types, runs were undertaken with different slopes and discharges. Before each run, the marked pebbles were arranged on the bed at different locations along the flume. Modifications in the case of each marked pebble were monitored: initiation of movement, cessation of movement and also absence of movement. Point shear stresses were calculated at each location where the marked elements were found, even when the flow failed to initiate movement. Almost a dozen runs were made with each bed, with any pebbles which had been displaced being restored to their original positions each time.

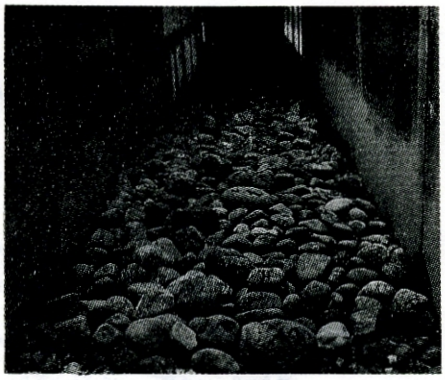

Figure 3. Downstream view of the flume with the 39·2 mm bed material. Marked pebble '12' is 60 mm in diameter (in the foreground) 'H' is 40·8 mm, '1' is 59·6 mm, 'F' (just below) is 38·9 mm and '14' is 32·1 mm (in the background)

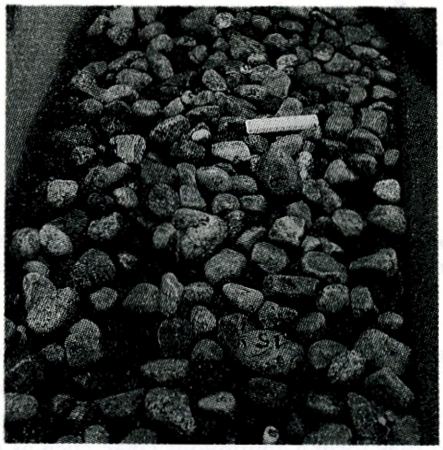

Figure 4. Disposition of marked pebbles (D_{50} of the bed is 39·2 mm). Marked pebble '6' is 37 mm in diameter. '15' is 55 mm. '12' and '17' (see arrow) are 16·6 mm and 27·8 mm, respectively. The folding rule is 10 cm in length

Figure 5. Downstream view of the flume with the 24·2 mm bed material. Marked pebble '2' is 65·4 mm in diameter, '20' is 21·8 mm and '12' is 16·6 mm (close to the folding rule)

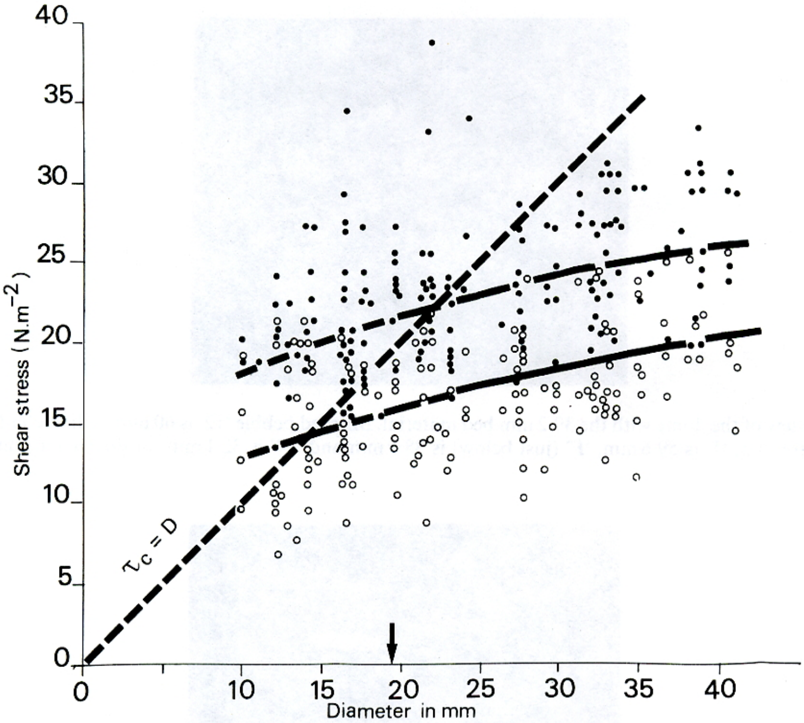

Figure 6. Relation between the shear stress and the diameter of particles for the bed with $D_{50} = 19{\cdot}6$ mm. The arrow on the x axis represents the medium bed particle diameter. Open circles represent no movement, while closed data points represent movement

The position of particles in relation to the bed-layer, and whether or not particles are in isolation, both have a strong influence on their entrainment (Naden, 1987). It is therefore important to stress that the marked pebbles were placed on the bed of the flume; they were not isolated, since they received support from other particles, but neither did they form a continuous layer, such as that forming the bed (Figures 3–5).

When all observations of both initiation and absence of movement were plotted on a single graph of critical shear stress versus diameter of particles, it was found that two more or less parallel curves could be drawn (Figure 6). For each bed, relations between θ_c and D_i/D_{50} were estimated by ordinary least squares regressions (Figure 7):

(1) for a lower limit, involving those points where movement was observed with the weakest shear stresses; and

(2) for an upper limit, involving points where no movement was observed even with the highest shear stresses.

Some 15 points were thus selected for each regression, and correlation coefficients were excellent on every occasion ($r > 0{\cdot}98$). The upper curve represents the limit of shear stress above which movement of material is certain (nearly 100 per cent of marked elements are set in motion). Conversely, the lower curve represents the limit of shear stress below which movement cannot occur or, in other words, the limit which gives the onset of movement of particles, it being understood that only a limited percentage (on the order of 20 per cent) of the particles will be in motion at the time. It would seem justifiable to make this distinction, which is consistent with the comments of Wilcock (1988) concerning the concept of the movement of material.

RESULTS

For each of the four beds, a graph featuring the τ_c versus D relationship was drawn, similar to that in

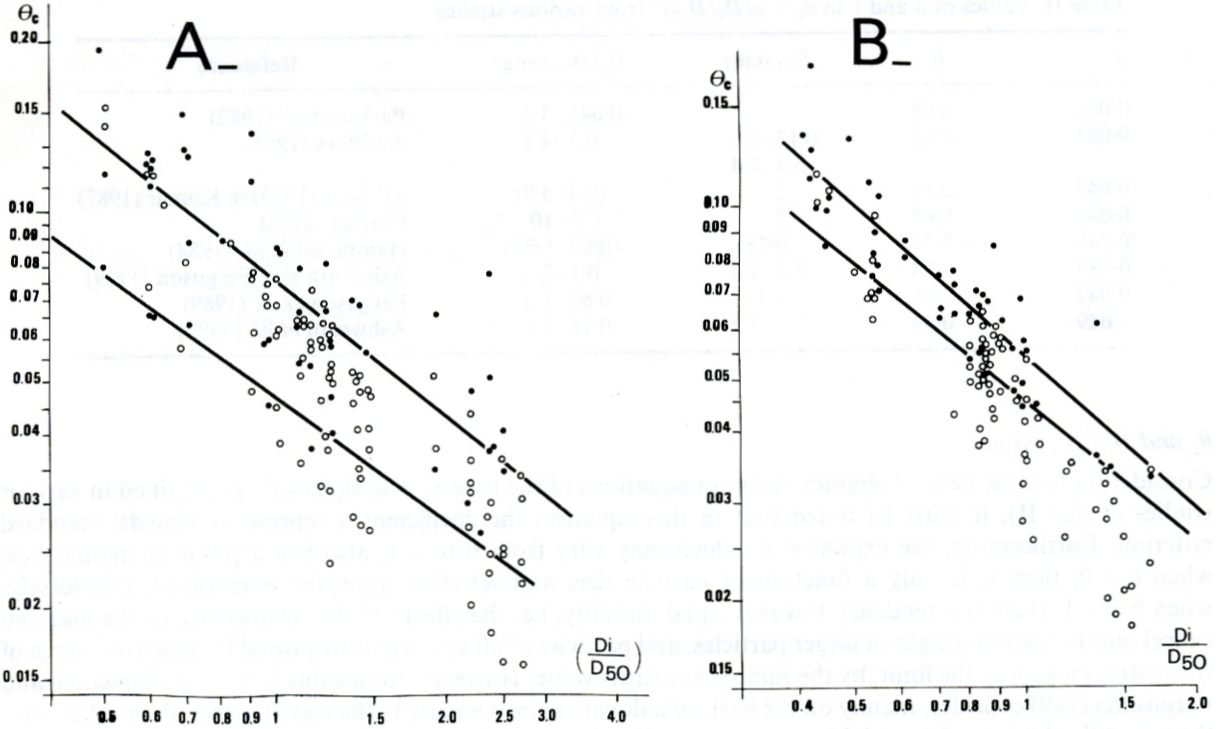

Figure 7. Relation between θ_c and D_i/D_{50} for (A) the bed with $D_{50} = 24{\cdot}2$ mm and (B) the bed with $D_{50} = 39{\cdot}2$ mm. Open circles represent no movement, while closed data points represent movement. For explanation of lines, see text

Figure 6. If one takes the example of experiments conducted with the bed composed of $D_{50} = 19{\cdot}5$ mm, one finds that the shear stress required to initiate movement of particles identical in diameter to the material forming the bed is relatively close to that calculated using a Shields' dimensionless shear stress (θ_c) equal to 0·06. For coarser elements this equation ceases to be applicable. Shear stresses on the order of 20 N m^{-2} allow initiation of movement for elements of 40 mm in diameter ($\theta_c = 0{\cdot}03$), and initiation of movement is generalized with shear stresses of 27 N m^{-2} ($\theta_c = 0{\cdot}04$). Conversely, elements of smaller diameter than the material forming the bed offer greater resistance and therefore require correspondingly higher values of θ_c. Thus, the onset of movement and general movement of particles of 15 mm diameter, for example, require θ_c values of 0·056 and 0·079, respectively.

One sees, therefore, the effect of relative grain exposure, as in the equations proposed by Andrews (1983), Ferguson *et al.* (1989) and Ashworth and Ferguson (1989). This effect, and the evolution of critical shear stresses that it implies, is also encountered in the other beds, give or take some slight differences, as will be seen later.

Graphs of θ_c against the ration D_i/D_{50} were plotted for each bed type, and equations for the lines of onset of movement and of generalized movement were calculated on the basis of these graphs. Relationships were also established between θ_c and the ratio D_i/y_0 in order to compare our results with the relationship proposed by Richards (1988) and Robert (1990). Finally, relationships between θ_c and the ratio D_i/D_{90} were also derived. In heterogeneous gravelly beds the phenomena of formation of pebbles into clusters and, to a lesser extent, imbrication require the presence of larger elements, and it seems likely that it is the stability of these larger elements which determines that of the bed material as a whole. This emerges clearly from research undertaken by Reid and Frostick (1984, 1986), which suggests that in a gravel-bed river, generalized transport of the bedload does not occur until shear stresses reach levels sufficient to ensure initial movement, or in any case destabilization, of the largest elements. In this instance, the D_{90} of the bed perhaps seems better than D_{50} in accounting for the microtopography of the bed and its roughness.

Table II. Values of a and b in $\theta_c = a(D_i/D_{50})^b$ from various studies

a	b	D_{50} (cm)	D_i/D_{50} range	Reference
0·088	−0·98		0·045–4·2	Parker *et al.* (1982)
0·083	−0·87	0·13–2·5 5·4–7·4	0·3–4·2	Andrews (1983)
0·045	−0·68	2	(0·4–5·9)	Milhous (1973) in Komar (1987)
0·045	−0·68	2	0·5–10	Carling (1983)
0·045	−0·71	0·75	(0·67–5·33)	Hammond *et al.* (1984)
0·089	−0·74	2·3–9·8	0·1–2	Ashworth and Ferguson (1989)
0·047	−0·88	7·3	0·04–1·2	Ferguson *et al.* (1989)
0·049	−0·69	1·8–3·2	0·15–3·2	Ashworth *et al.* (1992)

θ_c and D_i/D_{50} ratios

Considering first the general characteristics of equations of the type $\theta_c = a(D_i/D_{50})^b$, as obtained in various studies (Table II), it must be noted that in this equation the coefficient a represents Shields' standard criterion. Furthermore, the exponent b, which may vary from 0 to −1, also has a physical significance: when $b = 0$, then τ_c is only a function of particle size, and selective transport is involved. Conversely, when $b = -1$, there is a tendency towards equal mobility, i.e. the effects of the relative size of the material cancel out the greater weight of larger particles, and particles of all sizes are transported by a narrow range of shear stresses and, at the limit, by the same shear stress value. However, for a value $b = -0{\cdot}7$, Ashworth and Ferguson (1989) consider, mainly on the basis of a downstream decrease in the size of material on riffles, that there is still selection of material in entrainment. Furthermore, the value of b also depends on the method employed to determine θ_c (Wilcock, 1988).

Table II shows that the different equations may be grouped into two categories: the first with coefficient $a = 0{\cdot}045$ and an exponent $b = -0{\cdot}7$; the second with coefficient $a = 0{\cdot}085$ and $b = -0{\cdot}9$. This suggests two conclusions.

First, values of a equal to 0·08, as propounded by Andrews (1983) and other authorities, appear very high. This may reflect overestimates of the shear stress considered necessary to initiate movement, as a result of estimation from gradient and depth without subtraction of the bedform shear stress (τ'') and derivation of that part of the total shear stress (τ') available to initiate movement. Such high values for a thus become open to challenge. Experiments conducted on the Rhône with radioactively marked particles have shown that elements of 25 mm were transported for a θ_c value of 0·035, the bed having a D_{50} of 24 mm (Ramette and Heuzel, 1963). Andrews (1984) himself showed that θ_c varied from 0·029 to 0·063.

A second point concerns the evolution of θ_c when D_i/D_{50} is high. According to Andrews, there apparently exists a threshold (for $D_i/D_{50} > 4$) at which θ_c remains constant, with a value of the order of 0·020. However, this has been challenged by several authorities. Thus, according to observations by Carling (1983) and by Hammond *et al.* (1984), the minimum θ_c will reach 0·010, or even less for a D_i/D_{50} approaching 10. Likewise, Ferguson *et al.* (1989), studying a flow of gravel over sand, incline to extend this relationship to values D_i/D_{50} close to 100 with θ_c then equalling 0·010. Values as low as these have been obtained in a flume as well (Komar, 1987, p. 210). Furthermore, Fenton and Abbott (1977) have shown that a particle fully exposed on the bed can be transported when θ_c equals 0·010. Ramette and Heuzel (1963), still in respect of the Rhône, showed that particles of 75 mm ($D_i/D_{50} \approx 3.13$) could be set in motion when $\theta_c = 0{\cdot}016$.

When synthesizing an elaborate analysis of the various works on this subject, Komar (1987) put forward the following values for the first type of equation: $a = 0{\cdot}045$ and $b = -0{\cdot}7$. However, as Richards (1990) stresses, the parameters of such equations often reflect different methodologies, in terms of both the estimation of shear stresses and the way in which the material was collected. Furthermore, local conditions may intervene (the type and grading of sediments, development of bedforms) so that these parameters can in no way be transposed as they stand to other rivers without prior critical analysis.

The coefficients and exponents obtained from our experiments are summarized in Table III, with each bed

Table III. Values of a and b in $\theta_c = a(D_i/D_{50})^b$ from flume experiment (over beds with four different grain sizes)

D_{50} of the bed (mm)	Initiation of movement		Generalized movement		D_i range (mm)	D_i/D_{50} range
	a	b	a	b		
12·8	0·058	−0·66	0·076	−0·76	13–37	1·0–2·89
19·6	0·049	−0·68	0·068	−0·74	10–42	0·5–2·14
24·2	0·047	−0·73	0·074	−0·80	12–66	0·5–2·72
39·2	0·045	−0·81	0·054	−0·89	16–66	0·4–1·68

treated separately as advocated by Richards (1990), and with the equations for initiation of movement and generalized movement presented separately. In the case of equations for initiation of movement, it is found that the mean value of the coefficient (0·050) is close to the value 0·045 which emerged from Table II and which is recommended by Komar (1987). The same is true for the value of the exponent ($b = -0{\cdot}72$). Of course a few slight differences occur in the coefficients and exponents obtained in the four beds; such differences might be attributed to the fact that the grading of material is not identical and that the layout of the material forming the bed also shows slight differences, more especially in the case of the fixed bed ($D_{50} = 19{\cdot}6$ mm). But in these equations, the 95 per cent confidence intervals are ±0·015 for a and ±0·20 for b, which fit in with other results (Ashworth and Ferguson, 1989; Ferguson *et al.*, 1989).

On the other hand, the θ_c values could be lower in flume than for similar-sized particles within the natural bed structure, because the marked pebbles protrude slightly above the general bed level. However, with regard to equations relating to quasi-generalized movement, it was found, as expected, that the coefficient a has a higher value (0·070), whereas the exponent b is much the same ($b = -0{\cdot}78$). In other words, generalized movement of material in relation to the onset of motion requires a similar increase in shear stress whatever the D_i/D_{50} relationship.

θ_c and D_i/D_{90} ratio

When D_{90} of the bed is introduced as a reference value in place of D_{50}, it is noted that only the value of the coefficient a is altered; the exponents remain identical to those obtained in equations which feature the D_i/D_{50} ratio, because each bed is characterized by a single D_{50} and a single D_{90}. This will also be the case for the relationship D_i/y_0 considered subsequently, since each bed is characterized by a single value of y_0. Table IV shows that values of θ_c are, as expected, below those obtained in D_i/D_{50} relationships. However, they are not significantly lower: 0·043 as opposed to 0·050 for initiation of movement; 0·057 as opposed to 0·070 for generalized movement. This may be because in these experiments, D_{90} of each bed is not markedly higher than D_{50}.

Moreover, in studies conducted in a gravelly river in which transported material is related to shear stress, Reid and Frostick (1984) particularly take into account the D_{90} of the transported material (34 mm) which is very close to the D_{90} of the material forming the bed (35 mm). These authors find that the θ_c of initial motion, which destabilizes the bed, has a value of around 0·06. This is consistent with the values obtained in our

Table IV. Value of a in $\theta_c = a(D_i/D_{90})^b$ from flume experiments using four different beds

D_{50} of the bed (mm)	Initiation of movement a	Generalized movement a	D_{90}/D_{50}
12·8	0·054	0·068	1·15
19·6	0·038	0·051	1·45
24·2	0·039	0·061	1·27
39·6	0·041	0·049	1·11

Table V. Values of a in $\theta_c = a(D_i/y_0)^b$ from flume experiments using four different beds

D_{50} of the bed (mm)	Initiation of movement a	Generalized movement a
12·8	0·22	0·35
19·6	0·25	0·40
24·2	0·19	0·34
39·6	0·26	0·37

experiments for generalized movement ($\theta_c = 0.057$). However, we observe a threshold of initial motion for lower values ($a = 0{\cdot}043$). Two reasons for this can be adduced. First, the material constituting the different beds in the flume is significantly better graded than that of the river bed studied by Reid and Frostick (where the D_{90}/D_{50} ratio is 2·19). This implies that in the latter case, clusters are probably more fully developed than in the flume, and higher shear stresses are required to set this structured material in motion. Moreover, in evaluating critical shear stress, Reid and Frostick (1984) use the shear stress evaluated from the product of gradient and depth, and it is possible that this is overestimated, producing higher θ_c values, as a result of the presence of a bedform shear stress. On the other hand, as suggested by Clifford *et al.* (1992), these higher θ_c values might reflect form drag effects associated with pebble clusters.

θ_c *and* D_i/y_0 *ratios*

With regard to equations $\theta_c = a(D_i/y_0)^b$, results obtained for the different beds are very similar (Table V). Values of the exponents have mean values of −0·72 and −0·80 (for, respectively, initiation of movement and generalized movement), and these correspond well to the value −0·7 produced by Richards (1988) and Robert (1990). Conversely, values of the coefficients, respectively, 0·23 and 0·37, are significantly higher than the value of 0·07 obtained by these authors. It should be borne in mind in this connection that, in view of the well graded material, the roughness (y_0) of the different types of bed used in the flume is negligible and comes close to the equation $y_0 = 0{\cdot}15\,D_{50}$, whereas in a natural channel the values of y_0 are generally in excess of $y_0 = 0{\cdot}2\,D_{50}$, if not more (see Figure 1). In this regard, in the studies by Richards (1988) and by Robert (1988, 1990), the roughness of the bed would appear to be particularly high, with y_0 values in excess of 10 mm. Observations made in a river, where the conditions of roughness as defined by the ratio y_0/D_{50} are greater than those which characterize the flume (0·21 and 0·12, respectively), prove that the coefficient a decreases almost to the value proposed by Richards and by Robert.

CONCLUSION

Flume experiments were conducted using four different gravel beds (D_{50} varying from 12 to 39 mm) with relatively well graded material. Shear stresses were evaluated from friction velocities with a y_0 parameter defined by the law of the wall, in the knowledge that this method gives the closest approximation of the grain shear stress, the shear stress component which determines initial movement and transport of particles. Shear stresses were evaluated when initial movement occurred of marked particles of different diameters (10–65 mm) arranged in a sub-continuous layer on the bed, but evaluation also occurred when there was an absence of movement.

This procedure enabled us to obtain two types of equations: first, that for the threshold of initial motion (when about 20 per cent of particles are set in motion) and second, that for quasi-generalized movement. Whatever type of equation or bed, the phenomena of protection and imbrication occur when the particles are smaller than the D_{50} of the bed. On the other hand, protrusion also occurs when the diameter is significantly higher than that of the particles forming the bed. Consequently, an equation of the type $\theta_c = a(D_i/D_{50})^b$, as proposed by Andrews (1983), is also applicable here, even if the material is relatively homogeneous as compared with that encountered in studies undertaken involving natural rivers.

However, the values of coefficients a and b obtained for initial movement (0·050 and −0.70, respectively) are significantly lower than those proposed by Andrews (1983) and are closer to those established by Komar and Li (1988) in their synthesis of observations carried out on rivers. Generalized movement of bedload particles requires higher shear stress values ($a = 0{\cdot}068$) but selectivity of transport persists ($b = -0{\cdot}80$).

These results show that it is indeed the concept of initiation of movement (not that of generalized movement) which is closest to results obtained in natural rivers. Indeed, in such cases when the D_i was established from samples caught in sediment traps or with samplers, all the material of a given diameter was not necessarily in motion.

Furthermore, D_{90} of the bed material was also used as a reference value, working on the principle that it is the largest particles that determine the roughness of the bed and also its stability. It is therefore the destabilization of these larger elements that triggers generalized movement of material. Our results are consistent with the conclusions of Reid and Frostick, but with slightly lower values (0·043 and 0·057 as opposed to 0·060 for these authors), due to the fact that shear stresses were evaluated by different approaches and that the material used in the flume was better sorted.

Finally, equations were also established by using a ratio D_i/y_0 as defined by Richards and by Robert. Values of exponents are identical ($b = -0{\cdot}7$) but the coefficients a are significantly higher in the flume (0·22 and 0·37 as opposed to 0·07), owing to the fact that the roughness of the flume beds is considerably lower because their material is better sorted than that found in natural rivers.

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