EARTH SURFACE PROCESSES AND LANDFORMS, VOL. 15, 135–148 (1990)

EVALUATION OF GRAIN SHEAR STRESSES REQUIRED TO INITIATE MOVEMENT OF PARTICLES IN NATURAL RIVERS

F. PETIT

Laboratoire de Géographie physique, Laboratoire de Géomorphologie et de Géologie du Quaternaire, Université de Liège, Place du 20 Août, 7-B-4000 Liege, Belgium

Received 21 September 1988
Revised 9 May 1989

ABSTRACT

Shear stresses were evaluated at different sites on two rivers. The first (the Rulles) is characterized by a pebbly bedload and a meandering bed with riffles and pools. The second (the Rouge Eau) has mainly a sandy rippled bed where meandering is well developed but also flat gravelly sectors without meandering system.

Shear stresses calculated from friction velocities (τ^*) using a redefined y_1 roughness height parameter were compared with total shear stresses calculated from the energy grade line and the hydraulic radius (τ). Divergence between these shear stresses seems to increase in the presence of bedforms and large-scale irregularities of the channel. The τ^*/τ ratio is close to 0·5 in the gravelly sector of the Rouge Eau and reaches 0·65 in the riffles of the Rulles (generally located at the inflexion point of the meanders), while it is less than 0·3 in the pools of the same river (located in the loops) and only 0·2 in the sandy rippled sector of the Rouge Eau.

Grain and bedform shear stresses were evaluated at these same sites by different methods. The grain shear stress (τ') represents on average 30 per cent of the total shear stress in the riffles of the Rulles and the gravelly sector of the Rouge Eau, but less than 15 per cent in the pools in the Rulles and the sandy sectors of the Rouge Eau. However, it emerges from experiments conducted with marked pebbles and *in situ* observations of erosion and transport of sandy and gravelly particles, that the grain shear stresses are underestimated and cannot explain the movements and modifications actually observed.

Conversely, shear stresses calculated from friction velocities at the sites where erosion actually occurred (or failed to occur despite very high velocities) provide a better explanation of the observed movements.

KEY WORDS Gravel bed Sand ripples Roughness height Manning coefficient Grain and form shear stress Critical shear stress

INTRODUCTION

It is becoming increasingly apparent that shear stress must be considered as the predominant criterion for transport of bedload (Bagnold, 1977) and, more generally, in explaining the fashioning of river beds in meander systems (Dietrich *et al.*, 1979; Lisle, 1979; Bridge and Jarvis, 1982; Petit, 1987). However, in the evaluation and application of this parameter, three types of problem arise.

The first is bound up with the fact that, for the most part, it is total shear stress which is evaluated. However, the tractive stress based on depth and slope is a poor predictor of bedload transport, especially in narrow channels (Carson, 1987). This represents a combination of shear stress linked with grain resistance and shear stress due to the resistance of bedforms. However, present-day thinking seems to accept that only the shear stress due to grain resistance should be taken into account in the transport of the particles. It is not always easy however—as will be subsequently shown—to determine the exact proportion of each of these shear stresses in the total shear stress.

Secondly, in determining the shear stress using one of the two standard methods—that involving friction velocity—there arises the problem of determining the parameter of roughness which must be taken into

0197–9337/90/020135–14$07.00

consideration. This depends on the granulometry of the material forming the bed (Kamphuis, 1974; Petit, 1988b).

Finally, a third problem involves the calculation of critical shear stress in the case of pebbly particles, especially in natural rivers. Several relationships have been proposed, notably the Shields' curve. However, appreciable discrepancies have been observed, particularly in the case of pebble-loaded rivers (Baker and Ritter, 1975; Carling, 1983). As will be seen later, these discrepancies arise partly from the fact that it was the total shear stress which was used and not solely the grain shear stress. However differences in the arrangement and mix of particles also play a significant role (Laronne and Carson, 1976; Leopold and Emmett, 1981). These factors confer greater stability on the particles enabling them to withstand a significantly higher shear stress than would be required to initiate movement if these same particles had been in isolation on the surface of the bed (Reid and Frostick, 1984).

Other naturally-occurring features of the environment influence the movement of particles, in particular, the increased resistance due to the formation of pavement, the protection of particles by aquatic vegetation, and the removal of the fine matrix by winnowing which facilitates displacement of larger particles (Petit, 1988a). Moreover, as shown by experiments conducted in flumes (Johansson, 1976; Petit, 1989b), the shape of elements also plays a considerable part; flattened elements offering much better resistance than rounded ones (Komar and Li, 1986).

It is with a view to offering answers to some of these questions that the results obtained from two modestly-sized natural rivers are presented below. Experimental work is also proceeding in a pebble-bed flume which the Department of Physical Geography at the University of Uppsala has graciously placed at our disposal.

CHARACTERISTICS OF THE RIVERS

Observations were made in two small rivers (the Rulles and the Rouge Eau) differentiated both by the nature of their load and their discharge regime (Petit, 1986). The former river cuts into the southerly-facing slopes of the Ardenne with its hydrographic basin (16 km^2) overlying the quartzophyllades and quartzites of the lower Devonian. The river load is pebbly and it has a discharge regime in which bankfull stage (1·3 $m^3 s^{-1}$) is reached or exceeded on average 2·5 times per annum. The river flows in a channel forming a series of meanders (sinuosity index close to 2·0) with associated pools and riffles made up of pebbly accumulations (Petit, 1984).

The second river flows on the dip slope of the first cuesta of Belgian Lorraine with its hydrographic basin (10 km^2) lying on calcareous sandstone of Jurassic age. In view of the permeable nature of the substratum, discharge is almost constant and, over five years, bankfull discharge has never been recorded. The river load is almost exclusively sandy resulting in the formation on the bed of small ripples reaching 1 cm in height. Despite the absence of significant variations in discharge, an almost continuous flow of bedload is observed which it was possible to quantify by means of sediment traps. However small tributaries on steep slopes may transport a gravelly load to the màin river which totally alters its morphology and dynamics (Petit, 1986).

EVALUATION OF SHEAR STRESS

General equations

Shear stress was evaluated by the two standard approaches. The first method based on the following equation provides the mean shear stress

$$\tau = \gamma RS \tag{1}$$

where τ is the mean shear stress, γ the specific weight of the fluid, R the hydraulic radius, and S the energy line gradient.

The last (S) is calculated from the longitudinal slope of the water surface and the longitudinal variation of the term

$$\alpha v^2/2g$$

where v represents the mean velocity of the current, g acceleration due to gravity, and α a coefficient generally equal to 1 (Carlier; 1972).

Shear stress was also determined by the method which relies on friction velocities.

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

where ρ is the density of the fluid, and u_* the friction velocity. This can be determined from the distribution of the velocities as a function of the depth which obeys a logarithmic law:

$$\frac{u}{u_*} = \frac{1}{\kappa} \operatorname{Ln} \frac{y}{y_1} \tag{3}$$

where y is the distance from the bottom at which the velocity u is measured, κ is the Von Karman constant, and y_1 is a parameter of roughness.

Von Karman's constant is generally considered to be equal to 0·4 although it may have distinctly lower values (as low as 0·2) when the concentration of material in suspension is very high (Vanoni in Briggs and Middleton, 1965). However, currently, such variations in the value of κ appear to be under challenge (Bridge and Dominic, 1984), and in any case, according to the diagrams produced by Vanoni the load in suspension would have to reach very high values never recorded in the rivers studied even at times of greatest flood (maximum recorded 160 mg l^{-1}). However, it does seem that κ may vary and reach values between 0·5 and 0·8, inclusive, as a fuction of channel curvature and the presence of helicoidal movements in the heart of the current in the meanders (Hooke, 1975).

The roughness height y_1 is, according to Nikuradse's experiments, equal to $k_s/30$ (where k_s is the 'sand roughness size') in the case of immobile, flat, rough beds. The equation $k_s = D$ (where D represents the diameter of the grain forming the bed) has generally been retained, so that, by transposition of Equation 3, one obtains the Prandtl–Von Karman equation in its best known formulation (Larras, 1972). But the equation $k_s = D$ has been questioned by different authors. Thus, on the basis of experiments conducted in a flume, Kamphuis (1974) proposed the relationship $k_s = 2D_{90}$ which is consistent with the results of O'Loughlin and MacDonald (1964); while Meland and Norrman (1966), also using flume evidence, have proposed a relationship which links the logarithm of y_1 with the logarithm of k_s (assuming $k_s = D$). The relationship they propose is

$$\log y_1 = 1{\cdot}95 \log k_s - 0{\cdot}94$$

for spheres with a diameter between 0·21 cm and 0·78 cm.

From measures in a gravelly tidal channel, Hammond *et al.* (1984) suggest the relation $y_1 = 0{\cdot}2D$, which produces values very close to those obtained using the relation recommended by Hey (1979) for gravels, in which $k_s = 6{\cdot}8 D_{50}$.

It appears that all these values are much larger than the one obtained from the more generally accepted equation $k_s = D$. On the other hand, the use of this last equation, in connection with the two rivers studied, resulted in a serious underestimation of the shear stress in comparison with that which was obtained using Equation 1 (Petit, 1986, 1987). This clearly shows that there is a problem in using $k_s = D$ as a roughness parameter, and that is why, as will be seen below, we have sought to evaluate the latter in relation to the different types of material which constitute the bed.

Separation into grain and form shear stress

From the initial work of Einstein and Barbarosa (1952), it is apparent that the total shear stress evaluated by Equation 1 in fact represents the sum of of the shear stress due to the resistance of the particles (τ') and a supplementary shear stress τ'' due to irregularities in the channel and the banks, i.e. to the bedforms (Bogardi, 1974). The latter is frequently referred to as the form drag (Graf, 1971), so that one can write:

$$\tau = \tau' + \tau'' \tag{4}$$

However, it is only the shear stress due to the grains (τ') which ought to be taken into consideration for the transport of sediments (Laursen, 1958). Moreover, by extension of Equation 4 and substitution of Equation 1, one can write (Bogardi, 1974):

$$\tau=\gamma RS=\gamma S(R'+R'') \tag{5}$$

where R' and R'' are the hydraulic radii due respectively to the resistance of the grain and the resistance of bedforms, or alternatively

$$\tau'=\gamma S'R \quad \text{and} \quad \tau''=\gamma S''R$$

where S' is the gradient due to the resistance of grains, and S'' the excess slope necessary to overcome shape resistance (Bogardi, 1974). This is fundamental to the different methods proposed for determining apportionment between shear stresses. The distinction between shear stresses now seems to be fully accepted, not only in the case of flume or natural rivers (Singhal *et al.*, 1980; Carling, 1983) but also in respect of overland flow on irregular surfaces (Govers and Rauws, 1986).

The distinction between these two shear stresses is a difficult issue. An early approach focused on the differences in roughness in Manning's formula (Richards, 1982, p. 113). The primary objective is to ascertain the solid transport and to achieve this a correction factor K is attributed to the total shear stress which thus enables the shear stress operative at grain level alone (τ') to be defined according to the following equation:

$$\tau\cdot K^{3/2}=\tau' \tag{6}$$

where K in fact represents the relation n'/n_0 where n_0 is the total Manning roughness and n' is the Manning coefficient due solely to grain resistance, which can be obtained from the following equation proposed by Richards (1982) as the summary of Strickler's data on gravel-bed streams:

$$n'=0{\cdot}0151\,D_{50}^{1/6} \tag{7}$$

where D_{50} represents the median diameter of the material forming the bed expressed in mm. According to Richards (1982), the value of the coefficient K fluctuates between 0·5 and 1.

This approach is founded on the same principle as that used by Laursen (1958) which also brings into play the Manning and Strickler equations with a view to determining the value of the hydraulic radius R' which is due solely to grain resistance.

$$V=21{\cdot}1\,\frac{R'^{2/3}\,S^{1/2}}{k_s^{1/6}} \tag{8}$$

where V is the mean velocity, S the energy gradient, and k_s the roughness parameter considered equal to the diameter of the constituent material of the bed. Knowning R', τ' can be calculated from Equation 1.

Elsewhere, in the approach of Meyer-Peter and Müller used by Singhal *et al.* (1980), separation of the total shear stress is effected by dividing the slope (S) into two parts and S' can be found from the equation:

$$\frac{V}{\sqrt{gRS'}}=5{\cdot}75\log\frac{12{\cdot}27Rx}{k_s} \tag{9}$$

where V is the mean velocity, R the hydraulic radius, k_s the parameter of roughness and x a correction factor for flat beds. Once S' is determined in this way, it is then possible to evaluate the shear stress (τ') due solely to grain resistance. Singhal *et al.* compared the results obtained by this method with those calculated using Equation 8, for a mobile sand-bed flume with well-developed bedforms. They also compared these values of τ' with the grain shear stresses obtained in identical conditions with the same sediment discharge but with a fixed flat bed i.e. where the 'grain shear stresses' represents the total shear stress. In this way, these authors were able to test the validity of the equations employed and they conclude that the values of τ' calculated by Laursen's method were closest to the experimental data.

Carling (1983) also applied a method perfected by Hey (1979) from readings taken in gravel-loaded rivers. Again this is a method based on Keulegan's equation in which:

$$\frac{1}{\sqrt{f}}=2{\cdot}03\log\left(\frac{aR'}{3{\cdot}5D_{84}}\right) \tag{10}$$

where f = Darcy–Weisbach coefficient of friction, and a = coefficient varying as function of width/depth ratio. R' can be evaluated only by iteration (when f and d are known); and the divergences between R' and a field measure of R give an estimation of R''. But in Equation 10 R' is the adjusted hydraulic radius term used to standardize the roughness element in a compositely roughened gravel channel; indeed Hey (1979) considered form roughness to be of little importance, this author studying wide and straight channels. However, Carling's results show that τ' is clearly overestimated and that some losses must be attributed to τ'', due to spill resistance and form resistance.

Thus in order to evaluate the grain shear stress in our meandering rivers, the Laursen method (Equation 8) and Meyer-Peter method (Equation 9) were used, together with the method where the Strickler n' coefficient is compared with the Manning total roughness n_0.

Study methods

In each of the rivers studied, total shear stress was evaluated by the two approaches (Equations 1 and 2). The longitudinal slopes of the water surface and longitudinal variations in the mean current velocity were measured so as to calculate the grade line, as well as the other parameters necessary for the calculation of the shear stress using Equation 1. Thus, it was possible to calculate shear stresses for thirty seven cross-sections of a pebble-bedded river spread over five types of site (Petit, 1987). This was effected for discharges ranging from particularly low water ($0{\cdot}006\ m^3\ s^{-1}$) to a discharge almost equivalent to the 5 year flood ($4{\cdot}5\ m^3\ s^{-1}$). In the sand-load river, the readings—fewer in number, in view of the absence of variations in discharge—were taken for seven cross-sections located in a sector where the load is predominantly sandy, and at three sites in a sector where the load is gravelly owing to confluence with a small tributary. For each of these rivers, the hydraulic radius, energy gradient, and mean velocity were introduced into Manning's formula so as to determine the coefficient of total roughness n_0 and to define its variations as a function of discharge. This coefficient can be determined by reference to tables (Chow, 1959), but this involves a certain degree of subjectivity and inaccuracy.

In order to determine shear stress using Equation 2, current velocities were measured with an OTT meter (OTT–C2) fitted with 3 cm and 5 cm diameter propellers. The coefficient of roughness y_1 was determined by the method based on the logarithmic distribution of velocities as a function of the depth, y_1 then representing the distance above the reference surface where the velocity curve intersects the y axis (Briggs and Middleton, 1965). This height can be determined graphically and this has been done by Meland and Norrman (1966) in a flume, and by Dietrich *et al.* (1979) and Bridge and Jarvis (1982) in natural rivers. The validity of the logarithmic distribution law occurs only just close to the bottom, for less than 0·2 depth (Lyles and Woodruff, 1972; Bridge and Jarvis, 1982; Bathurst, 1982).

This method was applied by measuring velocities at 1·5 cm from the bottom, 3 cm, 5 cm, and thereafter in steps of 5 cm when water levels were high, but in steps of 2·5 cm at low water levels. It was thus possible to evaluate the roughness height y_1 corresponding to a bed of determined granulometry.

RESULTS

Evaluation of the roughness height

Values of the roughness height y_1 are given in Figure 1. In this graph, each point is the average of several values of y_1 deduced from profiles measured at the same site (usually ten measures for the Rulles river and the sandy sector of the Rouge Eau, but only three points for the gravelly sector of this river). They are markedly higher than those obtained by applying the equation $y_1 = k_s/30$ (with $k_s = D$).

For the pebbly river, the values of y_1 are fitted by a line obtained by regression ($r = 0{\cdot}923$) for which the equation is

$$y_1 = 0{\cdot}39\,D_{50}^{0{\cdot}80}$$

(where y_1 and D_{50} are both expressed in mm). For material more than 10 mm in diameter, the y_1 values are not very far from those deduced from the relationship purposed by Hey (1979). But for the flume and the flat bed with little differentiation in depth (the gravelly sector of the Rouge Eau), the y_1 values are lower than those

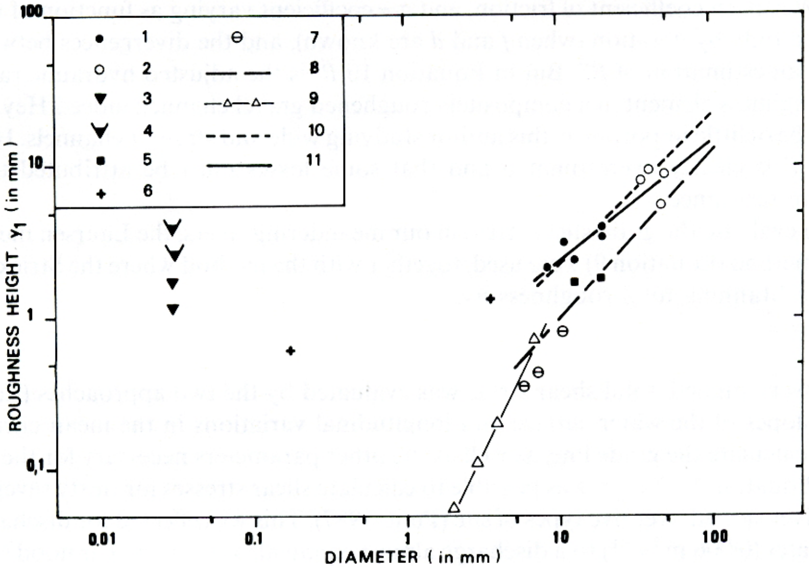

Figure 1. Relation between the roughness parameter (y_1) and the diameter of the particles (D_{50}): (1) Riffles of the Rulles River; (2) Pools of the Rulles River; (3) Compacted silt (Rulles); (4) Vegetation covering compacted silt; (5) Flume experiments (Petit, 1988b); (6) Sandy reach of the Rouge Eau River; (7) Gravelly reach of the Rouge Eau River; (8) Relation from Kamphuis (1974) experiments; (9) Relation from Meland and Norrman (1966); (10) Relation from Hey (1979); (11) Relation from data on the Rulles River (1) and (2)

obtained for the Rulles and are closer to those deduced from the relationship put forward by Meland and Norrman (1966).

Comparison with the Kamphuis relation which uses D_{90} has been possible. For each site, the D_{90} of the bed material was inserted in the relation of Kamphuis in order to calculate the y_1 roughness height (Table I). These values of y_1 are then plotted against the D_{50} bed material of the same site and the line produced by regression between y_1 and D_{50} ($r=0{\cdot}981$) is drawn on the graph. These values are not far from those measured for the largest particles in the pebbly river but diverge as far as finer material is concerned.

On the other hand, the y_1 value for the sandy bed is very high ($y_1=0{\cdot}6$ mm for a D_{50} of 0·17 mm). On this type of bed, the presence of numerous ripples is indeed observed. This can cause some inaccuracy because of the difficulty of determining a reference level on the bed. But the velocity profiles usually were measured at the crests (as in Dietrich *et al.*, 1979). On the other hand, it is not out of the question that a part of the roughness due to the form of the bed is taken into account in the evaluation of the y_1 parameter. Following Richards (1982), in the case of a dune bed, the bed roughness is controlled by dune size rather than grain dimensions. The high y_1 values for rippled beds could be explained in the same way. Thus, Bridge and Jarvis found for this kind of bed, a range of values between 0·1 mm to 1 mm for 0·5 mm–1 mm diameter particles. On the other hand, Jonsson (1967) has suggested the relation $k_s=4\eta$ (where η is the ripple height) while Swart (in Davies, 1985) derived the following equation $k_s=(25\eta/\lambda)\eta$ (where λ is the ripple wavelength). Assuming that in the Rouge Eau, the ripple height is 10 mm and the wavelength is about 100 mm, the application of these two relationships gives y_1 values respectively equal to 1·33 mm and 0·83 mm, values still larger than those calculated from the velocity profiles.

It is probably a phenomenon of the same type which would explain the high values of y_1 recorded in the Rulles for compacted silt ($y_1=1{\cdot}0$–$2{\cdot}0$ mm), but in this case, it may be the small cavities and irregularities present on the surface of the silt which contribute towards a kind of form roughness. These measurement also show clearly that the presence of aquatic vegetation, on the compacted silt, very significantly increases the roughness of the bed.

Comparison between shear stresses

The mean shear stress calculated using the energy gradient τ (Equation 1) is compared with the shear stress deduced from friction velocities τ^* (Equation 2). The latter is, each time, given by the average of four or five

Table I. Particle size distribution of bed material in study streams, and roughness height (all values are expressed in mm)

	D_{50}	D_{90}	y_1*	y_1†
Rulles River				
1. Riffles	8·50	13·9	2·15	0·93
	19·0	26·0	3·73	1·73
	12·8	23·7	2·33	1·58
	19·2	27·1	3·72	1·81
	10·8	15·2	3·04	1·01
2. Pools	38·0	80·0	9·3	5·3
	50·0	100·5	8·8	7·0
	35·0	72·5	8·3	4·1
	47·0	70·0	5·6	4·7
3. Sandy deposit (along a convex bank)	0·67	1·30	0·46	0·09
4. Compact silt	0·030	—	1·7	—
	0·030	—	1.1	—
5. Compact silt	0·030	—	2·5	—
Covered by vegetation	0·030	—	4·0	—
Rouge Eau River				
6. Sandy sector (Gravels in pools)	3·60	6·40	1·28	0·43
7. Sandy sector with ripples	0·17	—	0·59	—
8. Gravel sector	5·80	9·0	0·36	0·60
	10·9	16·6	0·80	1·11
	7·70	12·5	0·45	0·83
Flume				
	19·6	28·5	1·8	1·90
	12·8	14·7	1·7	0·98

* Roughness height from velocity profiles
† Roughness height from Kamphuis relation using D_{90}

points measured across the channel bed. Figure 2 shows that the shear stresses from friction velocities are systematically lower than those calculated using the energy gradient but a breakdown of the data reveals two different tendencies:

1. A mean τ^*/τ ratio of 0·64 for the riffles of the Rulles, which are generally located at the inflection points of meanders (although some divergences can be noted as a function of the kind of riffles or the localization of profiles along the ripples); this ratio is 0·51 in the gravelly sector of the Rouge Eau where differentiation of depth and meandering are not very pronounced.
2. τ^*/τ values are only of 0·27 in the pools of the Rulles, located in the loops of meanders and where there is an appreciable differentiation in current velocities, and of 0·19 in the sandy sector of the Rouge Eau where there are ripples present on the bottom and closely alternating riffles and pools going hand in hand with pronounced meandering.

The better agreement between τ^* and τ in the riffles of the Rulles could be expected since the side wall effects are less important. On the contrary, in pool sections where the flow is deeper, the side wall shear stress could increase relative to the bed, and therefore shear stress deduced from Equation 2 and from Equation 1 could be expected to diverge. Lateral variations of shear stresses on the bottom and the banks can be determined by tracing the orthogonals to the isotachs, following the method suggested by Leliavsky (1954) and used

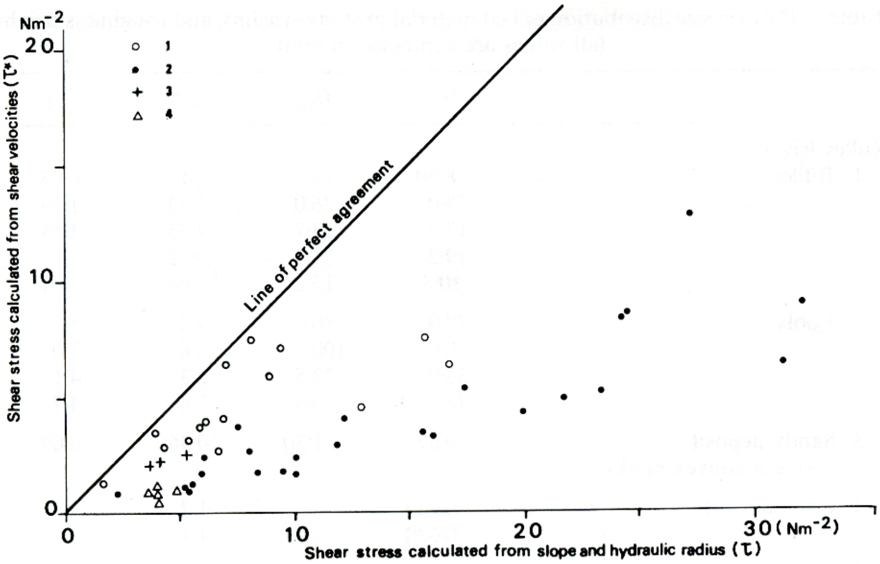

Figure 2. Relation between shear stress calculated from Equation 1 τ and from Equation 2 τ^*: (1) Riffles of the Rulles River; (2) Pools of the Rulles River; (3) Gravelly reach of the Rouge Eau; (4) Sandy reach of the Rouge Eau

particularly by Bhowmik (1982). In fact application of this method showed that the shear stress applied on the banks is very low in the case of riffles. It seems somewhat more important for pools, but, because of the arrangement of the isotachs in the pools, this method is not very easy to apply in these cases and produces unsatisfactory results. On the other hand, internal flow friction seems to be more important in the pools (because of the differentiation of velocities or the presence of countercurrent cells), and this form a more significant part of the total stress (τ).

Evaluation of the grain shear stress

The apportionment between shear stress due to grain resistance (τ') and that due to bedform resistance (τ'') was determined for the different types of site on the two rivers by the three approaches set out in the section *General equations.*

With respect to the application of Equation 6, clarification is required regarding the value of the coefficient of roughness (n_0) which occurs in Manning's formula. A synthesis of results is set out in Table II below.

As far as the Rulles is concerned, values are significantly higher than those deduced from tables ($n=0{\cdot}060$) and they reach, at least at times of low discharge, very high values which, however, are not exceptional in small rivers (Dingman, 1984). Furthermore, it is well proven that there is a decrease of n_0 as discharge increases and a tendency towards a constant for flows close to bankfull stage.

For the Rouge Eau, values of n_0 are higher in the sandy sector where there are meanders than in the gravelly sector. The effect of bedforms comes into play here as well. The application of Equations 6 and 7 with a D_{50} of 14 mm and 45 mm respectively for the riffles and pools of the Rulles on the one hand and of 0·17 mm and 8·5 mm respectively for the sandy and gravelly sectors of the Rouge Eau on the other hand, gives the τ'/τ ratio in Table III. The τ'/τ ratio was also calculated for nine sites on the Rulles and in both types of sector on the Rouge Eau, using the Laursen method (Equation 8), and the Meyer–Peter method (Equation 9) (Table IV). Laursen's method, as expected, produces values close to those obtained using Equations 6 and 7 (Table III), but gives higher values—by nearly double—than those obtained by the Meyer–Peter method. This tallies with the conclusions of Singhal *et al.* (1980) and Petit (1989a).

Furthermore, there remain comparisons between riffles in the Rulles and gravelly sectors in the Rouge Eau on the one hand, and between pools and sandy sectors on the other. At low water and when discharges are close to the mean discharge, values of τ' are very low in the pools, probably owing to the internal friction of the

Table II. Determination of Manning's coefficient of total roughness (n_0) by means of Manning's formula

	Low water	Mean discharge	Bankfull stage	Flood (> annual flood)
Rulles riffle	0·088	0·058	0·055	0·042
Rulles pool	0·432	0·113	0·103	0·073
Rouge Eau (Sandy sector)	—	0·074	—	—
Rouge Eau (Gravelly sector)	—	0·051	—	—

Table III. The ratios of grain shear stress to total shear stress (based on Equations 6 and 7)

	Low water	Mean discharge	Bankfull stage	Flood (> annual flood)
Rulles riffle	0·14	0·26	0·28	0·42
Rulles pool	0·02	0·13	0·15	0·24
Rouge Eau (Sandy sector)	—	0·06	—	—
Rouge Eau (Gravelly sector)	—	0·28	—	—

Table IV. The ratios of grain shear stress to total shear stress, based on (a) the Laursen method, and (b) the Meyer–Peter method. Figures in brackets represent the number of observations

	Low water	Mean discharge	Bankfull stage	Flood (annual flood)
Rulles riffle	a) 0·34) b) 0·18)(29)	a) 0·38) b) 0·10)(19)	a) 0·33) b) 0·15)(13)	a) 0·46) b) 0·21)(21)
Rulles pool	a) 0·06) b) 0·03)(24)	a) 0·13) b) 0·06)(25)	a) 0·15) b) 0·06)(17)	a) 0·29) b) 0·12)(15)
Rouge Eau) (Sandy sector)	—	a) 0·06) b) 0·02)(6)		
Rouge Eau (Gravelly sector)	—	a) 0·28) b) 0·12)(3)		

current associated with the presence of backwater zones or countercurrents. But when discharges are near or above bankfull stage, values of τ' are highest in the pools—even if the τ'/τ ratio is only about 0·3—because the total shear stress is then much higher in the pools than at the riffles (Petit, 1987).

The τ' values of the rippled bed are very low in comparison with the results produced by Singhal *et al.* (1980) from experiments conducted in a flume where bedforms are developed and where there is also transport of material (i.e. in conditions analogous to those of the sandy sector of the Rouge Eau). Indeed, these authors discover a τ'/τ ratio equal on average to 0·39 using the Meyer–Peter method and 0·62 using Laursen's method while we find in our investigation a τ'/τ ratio equal to 0·02 using the first method and 0·06 using the second. However, the results of Kapdasli and Dyer (1986) also in a rippled-bed flume, show a form drag component (τ'') of between 5 and 12 times the skin friction, which fits with our observations.

On the other hand, applying Hey's method to two rivers in the Pennines, both of which have a pebble-load but which differ in respect of the morphology of their beds, Carling (1983) was able to determine that τ' represented 45 per cent of the total shear stress in the case of a very narrow river and could even attain 80 per cent when discharge approached bankfull stage. These values are much higher than in the Rulles, although as emphasized by Carling (1983), τ' of his rivers seems to be overestimated, probably because of the method used.

However, it is not out of the question that in the case presently under investigation, τ' is underestimated. We shall attempt to assess this below.

Evaluation of shear stresses in relation on particle motion

Shear stress determined by friction velocities and grain shear stress calculated by the different approaches were related to morphological modifications and tested by means of experiments conducted with *in situ* marked pebbles (pebbles constituting the bed layer).

An early approach employing only current velocities measured at different levels has appeared elsewhere (Petit, 1988a) and enabled the influence of certain features peculiar to the natural environment (imbrication of material, protection by vegetation, effects of removal of fine matrix by washing) to be delimited.

By using these velocity values on the one hand and the roughness parameters as defined in Figure 1 on the other, it was possible to determine shear stress from friction velocities (Equations 2 and 3) (Figure 3). In the case of the sandy and gravelly reaches—found mainly in the two sections of the Rouge Eau—as well as for the small pebbles (<20 mm) which are more specific to the Rulles riffles—the points observed plot relatively closely to the $\tau_c = D$ relationship deduced from Shields' curve, (where, from Baker and Ritter (1975) τ_c represents the critical shear stress expressed in kg m^{-2}, and D the diameter of particles expressed in centimetres). Of course the influence of certain features detailed elsewhere is encountered. Thus the effect of

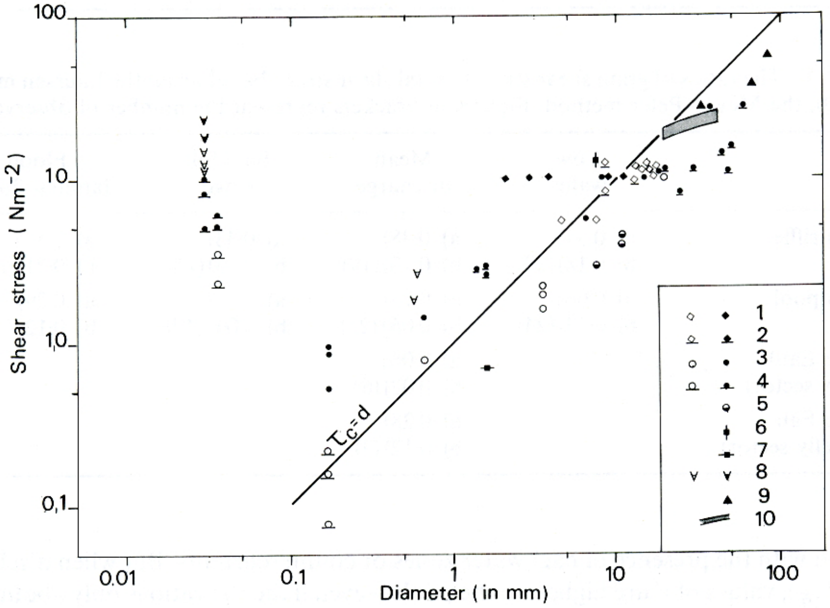

Figure 3. Shear stress calculated from Equation 2 with y_1 from the relation of Figure 1 in the sites where erosion or transport occurs (black points), where no erosion or deposition occurs (white points): (1) Riffles of the Rulles River: Deposition (in white) or non-deposition (in black) of particles coming from upstream; (2) Riffles of the Rulles River: No motion (in white) or motion (in black) of particles in place; (3) Pools of the Rulles River (for pebbles) sandy reach of Rouge Eau River, and cut-off channels of Rulles River (for silt material) Arrest (in white) or non-deposition (in black) of particles coming from upstream; (4) Pools of the Rulles River (for pebbles), sandy reach of Rouge Eau River and cut-off channels of Rulles River (for silt material). No motion (in white) or motion (in black) of particles in place; (5) Episodic motion of the particles because of the erosion of the fine matrix (gravelly reach of the Rouge Eau River); (6) Erosion of heterogeneous material (Rulles River); (7) Erosion in a countercurrent cell (agitation and turbulence) (Rulles River); (8) Protection by aquatic vegetation: erosion of particles in place (black points), no motion of particles in place (white points); (9) Data of Mercenier (1973); (10) Critical shear stress from flume experiments (Petit, 1988b)

imbrication in the pavement is very apparent: a shear stress of 10 Nm^{-2} guarantees transport on the riffles of particles with a diameter of 8 mm, whereas at these same sites, this same shear stress is not sufficient to cause erosion of elements of the same diameter where they form part of settled pavement.

In the case of larger pebbles which are generally present in the pools of the Rulles, the points deviate appreciably from Shields' relationship. Thus, a shear stress of the order of 20 Nm^{-2} allows erosion of particles of 40 to 50 mm diameter in the bottom of pools, whereas, the transport of elements 20 mm in diameter is effected by a shear stress barely exceeding 10 Nm^{-2}. A similar phenomenon is encountered, but to a lesser extent, in the case of values of shear stress calculated from observations by Mercenier (1973) in a small river in the Central Ardennes, lacking appreciable distinction between riffle and pool. Here, initiation of movement of marked pebbles of 60 to 80 mm diameter occurred at shear stresses of the order of 40 Nm^{-2}.

The validity of the relationship $\tau_c = D$ for coarse elements has been brought into question by different authors. Thus Baker and Ritter (1975), find that for elements in excess of 50 mm in diameter, the critical shear stress deduced from Shields' curves is significantly overestimated. Carling (1983) reaches the same conclusion, at least in a relatively shallow-banked river, for in a narrow river he notes that the **total** shear stress necessary for transport of particles is higher than that deduced from Shields' diagram. However it is very probable that this is tied up with the fact that form shear stress is very considerable here. Conversely, Reid and Frostick (1984) observe that values deduced from Shields' curve may be significantly underestimated as a result of the phenomenon of imbrication.

An early series of experiments conducted in a pebble-bedded flume (Petit, 1988b) showed that the shear stress necessary to erode particles of the same size as those forming the bed of the flume is very close to that derived from Shields' curve. On the other hand, particles coarser than those forming the bed (respectively 40 mm and 20 mm) can be moved by shear stress significantly lower than that derived from Shields (of the order of 25 Nm^{-2}). This is connected with the facts that these particles receive less protection from the bed, and that a protrusion effect as described by Fenton and Abbott (1977) also plays a part. This is also what emerges from the relationship proposed by Andrews (1983) in which there is little difference between the shear stress necessary for the erosion of pebbles ranging from 0·3 to 4·2 times the median diameter of the bed material particles. However, in the case of coarse material present in the bottom of the pools in the Rulles, this effect does not seem to have a role to play since the material eroded is generally intercalated between coarser material and should be protected, requiring higher critical shear stresses to effect erosion.

From measures made in a meltwater stream in Norway where bed material was collected in a Helley-Smith sampler and velocity profiles were measured at the same spot, Robert and Richards (1989), produce the relationship

$$\theta_c = 0{\cdot}07\ (D_i/y_1)^{-0{\cdot}7}$$

where θ_c = critical dimensionless shear stress (as in Shields relation), and D_i/y_1 = a bed of roughness index where D_i is the diameter of given particles and y_1 the roughness height. This ratio seems somewhat similar to the D_i/D_{50} index in Andrew's relation (with D_{50} the size of the underlying material). However, as emphasized by Robert and Richards, the use of y_1 gives 'a measure of boundary roughness which incorporates the effect of skin friction (. . .) and form resistance associated with small-scale bed irregularities'. Thus, variation of θ_c values as a function of D_i and y_1 variations, takes into consideration the change in the form drag proportion. When the bed roughness increases and D_i/y_1 tends to 30—as is the case for uniform beds where only grain friction occurs and where the shear stress due to microscale form effects decreases and reaches nil—θ_c values becomes much smaller (0·01), while, for example, the θ_c value is about 0·045 for a bed roughness index close to 2.

Robert and Richards relation was applied to the Rulles data of Table I, in order to calculate θ_c and evaluate the observations of Figure 3 with these critical shear stresses. For pools and riffles of Rulles River (a pebble range of 10–50 mm in Figure 3), the D_{50}/y_1 index is more or less constant and produces $\theta_c = 0{\cdot}025$, although this seems to decrease with increasing diameter. This produces a critical shear stress of about 18 Nm^{-2} for particles of 50 mm in diameter, and this fits well with our observations. In the gravelly sector of the Rouge Eau River, the bed roughness index is high (about 25), producing a θ_c of about 0·01 and critical shear stresses of only 0·7 Nm^{-2}, but these pebbles are not really in motion until 4 Nm^{-2}. Except for this case, evidence confirms Robert and Richards' interpretation. Elimination of part of the form stress due to the particle arrangement on the bed improves results, mainly for the coarsest material present in the pools of the Rulles River. Thus, the shear stress calculated using friction velocities could be considered as a rather good predictor of the grain shear stress.

With regard to grain shear stresses evaluated by the Equations 8 and 9, it should first be remembered that in the bottom of pools, pebbles measuring 20 to 30 mm in diameter are eroded by a discharge close to bankfull stage and that, furthermore, marked elements measuring 60 mm in diameter are dislodged from the bed during discharges slightly in excess of those experienced in the mean annual flood. The value of τ' reaches only 5 Nm^{-2} at bankfull discharge and 15 Nm^{-2} at the time of the near annual flood. The same is true for the riffles in which particles of 15 mm in diameter can pass through in a flood at slightly in excess of bankfull stage, and this at a time when τ' allegedly reaches only 5 Nm^{-2}.

Therefore it does seem that values of τ' calculated in the pools, and to a lesser extent at the riffles, fail to provide an explanation for the erosion and transport actually observed to take place. Of course the total shear stress—and therefore the grain shear stresses—are only mean values which, for a given discharge, apply to the cross-section taken as a whole. Also there exist lateral variations in shear stress, particularly in the pools, which could offset differences between τ' and the shear stress required to cause the observed erosion. However this must play only a partial role since, on the riffles, lateral differentiation in shear stress is insignificant and yet discrepancies between τ' and the shear stress required for erosion are observed.

On the other hand, it is not out of the question that, as noted by Carson (1987), side wall effects could act somewhat. The evaluation of R_b (the hydraulic radius related to the bed alone) following the procedure described by Vanoni (1975), and the use of this in the calculation of the bed tractive stress, could improve τ' values. However, in the case of the gravelly sector of Rouge Eau where side wall effects are not significant (width/depth ratio being about 15), underestimates of τ' values also seem to occur.

CONCLUSION

The roughness parameter y_1 which is involved in determining friction velocities has been redefined in different sites of a pebble-bedded river according to the equation $y_1 = 0{\cdot}39\,D_{50}^{0{\cdot}80}$ (where D_{50} is the median diameter of the material). The values obtained are significantly closer to those deduced from the relationship put forward by Meland and Norrman (1966), Kamphuis (1974), and Hey (1979) than to the values in general use which lead finally to Prandlt–Von Karman's equation in its most formulation. In the case of sandy beds and compacted silty material, the values are proportionally higher, as a result of the influence of microforms at river-bed level (ripples in the case of sands, cavities in the case of silt).

There is not really close agreement between the shear stress calculated from firction velocities and that calculated using the energy grade line and the hydraulic radius. The τ^*/τ ratio is about 0·6 for the riffles of the pebble-bedded river and 0·5 for the gravelly sector of the Rouge Eau. The shear stresses which initiate movement in gravelly and pebble material (less than 20 mm), correspond relatively well with Shields' relationship. Moreover, evaluation at the same sites of the bed shear stress (τ'') and the grain shear stress (τ') shows that the latter represents less than 50 per cent of the total shear stress, so that the values obtained appear too low to account for erosion and movement of material.

In the pools of the pebble-bedded river, the shear stress calculated using friction velocities is distinctly lower than that evaluated using the energy grade line and causes erosion of large-sized elements at values distinctly lower than the critical shear stress deduced from Shields' relationship. However, motion of this material can be explained when critical shear stress deduced from Robert and Richards' relation, is used. The grain shear stresses here represent only 20 per cent of the total shear stress and corresponds even less to the modifications observed.

Thus, without denying the existence of a τ'', it nevertheless seems as if τ' is underestimated. Shear stress calculated using friction velocities, with y_1 redefined as set out in Figure 1, provide a better evaluation of the shear stress required to initiate movement in particles.

ACKNOWLEDGEMENT

I wish to extend my deep gratitude to Professor J. Alexandre who directed my research. My warmest thanks go to Professor A. Sundborg and Professor J. O. Norrman for the welcome they extended to me in their Department in Uppsala and for their advice during the writing of this manuscript.

Many thanks are also expressed to Professor A. Pissart and to Professor J. De Ploey and his team (University of Leuven) for the discussion they made during the preparation of this paper and to Dr K. Richards (University of Cambridge) for his suggestions and corrections to my paper.

The comments of two anonymous referees led to considerable improvements in the manuscript.

REFERENCES

Andrews, E. D. 1983. 'Entrainment of gravel from naturally sorted riverbed material', *Geol. Soc. Am. Bull.*, **94,** 1225–1231.

Bagnold, R. A. 1977. 'Bedload transport by natural rivers', *Water Resources. Res.*, **13–2,** 303–312.

Baker, V. R. and Ritter, D. F. 1975. 'Competence of rivers to transport coarse bedload material', *Geol. Soc. Am. Bull.*, **86,** 975–978.

Bathurst, J. C. 1982. 'Theorical aspects of flow resistance', in Hey, R. D., Bathurst, J. C., and Thorne, C. R. (Eds), *Gravel-bed rivers.* Wiley and Sons, 83–105.

Bhowmik, N. G. 1982. 'Shear stress distribution and secondary currents in straight open channels', in Hey, R. D., Bathurst, J. C., and Thorne, C. R., (Eds), *Gravel-bed rivers.* Wiley and Sons, 31–61.

Bogardi, J. 1974. *Sediment Transport in Alluvial Streams*, Akademiai Kiado, Budapest.

Bridge, J. S. and Dominic, D. F. 1984. 'Bedload grain velocities and sediment transport rates', *Water Resour. Res.*, **20–4,** 476–490.

Bridge, J. S. and Jarvis, J. 1977. 'Velocities profiles and bed shear stress over various bed configurations in a river bend', *Earth Surface Processes*, **2,** 281–294.

Bridge, J. S. and Jarvis, J. 1982. 'The dynamic of a river bend: a study in flow and sedimentary processes', *Sedimentol*, **29–2,** 499–541.

Briggs, L. L. and Middleton, G. V. 1965. 'Hydromechanical principles of sediments structure formation', in *Symposium Primary Sedimentary Structures and their Hydrodynamic Interpretation*, Society of Economic Paleontologists and Mineralogists Special Publication, Tulsa Oklahoma, 1965, 6–16.

Carlier, M. 1972. *Hydraulique Générale et Appliquée*, Eyrolles, Paris, 565 pp.

Carling, P. A. 1983. 'Threshold of coarse sediment transport in broad and narrow natural streams', *Earth Surf. Process and Landform*, **8,** 1–18.

Carson, M. A. 1987. 'Measures of flow intensity as predictors of bed load', *Am. Soc. Civ Eng J. Hydr. Div.*, **113–II,** 1402–1421.

Chow, V. T. 1959. *Open Channel Hydraulics*, McGraw Hill, 630 pp.

Davies, A. G. 1985. 'Field observations of the threshold of sediment motion by wave action', *Sedimentol.*, **32,** 685–704.

Dietrich, W. E., Smith, J. D., and Dunne, T. 1979. 'Flow and sediment transport in a sand bedded meander', *J. Geol.*, **87,** 305–315.

Dingman, S. L. 1984. *Fluvial Hydrology*, Freeman and Cie, New York, 383 pp.

Einstein, H. A. and Barbarossa, N. L. 1952. 'Channel roughness', *Am. Soc. Civil Eng.* **117,** 1121–1132.

Fenton, J. D. and Abbot, J. E. 1977. 'Initial movement of grains on a stream bed: the effect of relative protrusion', *Proc. R. Soc. London*, **A352,** 523–537.

Govers, G. and Rauws, G. 1986. 'Transporting capacity of overland flow on plane and irregular beds', *Earth Surf. Process. and Landforms*, **11,** 515–524.

Graf, W. H. 1971. *Hydraulics of Sediment Transport*, McGraw Hill, 513 pp.

Hammond, F. D. C., Heathershaw, A. D., and Langhorne, D. N. 1984. 'A comparison between Shields' threshold and the movement of loosely packed gravel in a tidal channel', *Sedimentol.*, **31,** 51–62.

Hey, R. D. 1979. 'Flow resistance in gravel bed rivers', *Am. Soc. Civ. Eng. J. Hydr. Div.*, **105,** 365–379.

Hooke, R. L. 1975. 'Distribution of sediment transport and shear stress in curved trapezoidal channels', *J. Geol.*, **83,** 543–565.

Johansson, C. E. 1976. 'Structural studies of frictional sediments', *Geog. Ann.*, **58a,** 201–302.

Jonsson, I. G. 1967. 'Wave boundary layers and friction factors', Proc. 10th Int. Conf. Costal Engineering, 1966. *Am. Soc. Civil Eng.*, 127–148.

Kamphuis, J. W. 1974. 'Determination of sand roughness for fixed beds', *J. Hydraul. Res.*, **12–2,** 193–203.

Kapdasli, M. S. and Dyer, K. R. 1986. 'Threshold conditions for sand movement on a rippled bed', *Geo Marine Letters*, **6,** 161–164.

Komar, P. P. and Li, Z. 1986. 'Pivoting analyses of the selective entrainment of sediments by shape and size with application to gravel threshold', *Sedimentol*, **323,** 425–436.

Laronne, J. B. and Carson, M. A. 1976. 'Interrelationship between bed morphology and bed material transport for a small, gravel-bed channel', *Sedimentol.*, **23,** 67–85.

Larras, J. 1972. *Hydraulique et Granulats*, Eyrolles Paris, 254 pp.

Laursen, E. M. 1958. 'The total sediment load of streams', *J. Hydrol. Div., Paper*, **1530,** 36 pp.

Leliavsky, S. 1954. *Précis d'hydraulique fluviale* (trans. An introduction to fluvial hydraulics), Dunod Paris, 1961, 256 pp.

Leopold, L. B. and Emmett, W. W. 1981. 'Some observations on the movement of cobbles on a streambed', Proc. Florence Symp. *Erosion and Sediment transport measurement*, 49–59.

Lisle, T. 1979. 'A sorting mechanism for a riffle–pool sequence', *Geol. Soc. Am. Bull.*, Part II, **90,** 1142–1157.

Lyles, L. and Woodruff, N. P. 1972. 'Boundary-layer flow structures; effects on detachment of noncohesive particles', in Shen, H. W., (Ed.) *Sedimentation.* **2,** 1–17.

Meland, N. and Norrman, J. O. 1966. 'Transport velocities of single particles in bedload motion', *Geog. Ann.*, **48A,** 165–182.

Mercenier, J. 1973. *Dynamique fluviale dans un petit bassin du rebord méridionol du plateau des Tailles*, Mém. de licence en Sc. Géog., inédit, conservé à l'Univ. de Liège, 148 pp.

O'Loughlin, E. M. and MacDonald, E. G. 1964. 'Some roughness concentration effects on boundary resistance', *La Houille Blanche*, **7,** 773–783.

Petit, F. 1984. 'Les processus contrôlant l'évolution d'une rivière ardennaise', *Z. Geomorphol., N.F. Suppl. Bd.* **49,** 95–109.

Petit, F. 1986. 'Channel development in two streams of contrasting bedload and regime', *Int. Geomorphol.*, 1986–1, Gardiner (Ed.), Wiley and Sons, 611–622.

Petit, F. 1987. 'The relationships between shear stress and the shaping of the bed of a pebble-loaded river', *Catena*, **14–5,** 453–468.

Petit, F. 1988a. 'Phénomènes influencant la mise en mouvement et le transport des particules en rivières naturelles', *Z. Geomorphol.*, **32–3,** 299–310.

Petit, F. 1988b. 'Critical shear stress from experiments conducted in a pebble-bedded flume', *Geog. Ann.* (Submitted for publication)

Petit, F. 1989a. 'The evaluation of grain shear stress from experiments in a pebble-bedded flume', 4th Benelux Colloquium Proceedings, *Earth Surf. Process and Landforms* **14–6–7,** 499–508.

Petit, F. 1989b. 'Evaluation de l'influence de la forme des cailloux sur la résistance à l'érosion. Expériences en flume et observations en rivière naturelle—Revue de géographie de Lyon' (in press).

Reid, J. and Frostick, L. E. 1984. 'Particle interaction and its effect on the thresholds of initial and final bedload motion in coarse alluvial channel', in Kosher, E. H. and Steel, R. J. (Eds), *Sedimentology of Gravel and Conglomerates. Canadian Society of Petroleum Geologists Memoir*, **10,** 61–68.

Richards, K. 1982. *Rivers, Form and Process in alluvial Channels*, Methuen, London, 358 pp.

Robert, A. and Richards, K. S. 1989. *Bedload Transport and Bed Roughness Properties in Coarse-grained Alluvial Channels*, unpublished manuscript.

Singhal, M. K., Mohan, J., and Agrawal, A. K. 1980. 'Role of grain shear stress in sediment transport', *Irrigation and Power*, **37**, 105–108.

Vanoni, V. A. 1975. 'Sedimentation engineering', *Manuals and Report on Engineering Practice*, **54,** ASCE.