Sand grain threshold, in relation to bed 'stress history': an experimental study

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ABSTRACT

Besides particle size, density and shape, the erodibility of a sediment bed depends also upon the exposure to prethreshold velocities in the overlying flow. Such flow effectively rearranges the grains (at and below the bed surface), causing them to become more resistant to subsequent erosion. The effects of the 'stress history', leading up to the critical condition for sediment movement, are investigated for unidirectional flows generated in a recirculating laboratory flume. The sediment beds investigated consisted of cohesionless quartz sand grains, with mean grain diameters of 0·194 mm (fine sand), 0·387 mm (medium sand) and 0·774 mm (coarse sand), with narrow particle-size distributions. The critical (threshold) shear velocity (target value) for the three beds was established, within 2·5 min of increasing the flow from zero velocity. The subsequent experiments were performed under prethreshold velocities at 70% (for 5, 10, 20, 40 and 80 min exposure duration), 80% (for 5, 10, 20, 40 and 80 min exposure duration), 90 and 95% (for 5, 10, 20, 40, 80 and 120 min exposure duration) of the target value. Following exposure to these different prethreshold conditions, the flow was increased then to reach actual critical conditions, within a period of 2·5 min. The critical condition for the initiation of sediment movement was established using visual observation (supplemented by video recordings), according to the Yalin criterion. The results show that if the exposure duration to prethreshold velocities remains constant, then the critical shear velocity increases with increasing prethreshold velocity. Likewise, if the prethreshold velocity remains constant, then the critical shear velocity increases with increasing exposure duration. In some circumstances, the critical shear velocity was found to increase by as much as 27%. An empirical formula is proposed to account for the exposure correction to be applied to the critical shear velocities of sand-sized sediment beds; this is prior to their inclusion into bedload transport formulae, for an improved prediction of the magnitude and nature of transport.

Keywords Critical shear velocity, exposure correction, stress history, threshold, unidirectional flow.

INTRODUCTION

Oceanographers, sedimentologists and coastal engineers have long considered the dynamics of sediment movement in riverine and marine (estuaries, beaches and continental shelves) environments, both within the establishment of understanding processes and in terms of practical interest. Quantification of sediment movement has always been (and will continue to be) of great interest; this is a requirement which explains the numerous predictive formulae proposed over the years, in relation to (for example) bedload transport. Bedload has been defined differently depending upon the context. However, within the context of numerical/physical modelling, it is more appropriate and more consistent with the concepts examined in the present investigation, to refer to the definition provided by Bagnold (1956). Bagnold (1956) defined bedload as the part of the total load which is supported by intergranular forces, as opposed to the remainder, i.e. suspended and wash load, supported by fluid drag. The majority of bedload transport formulae utilize a critical shear velocity (or stress), to define the onset of sediment transport; hence, to establish predictions in terms of sediment transport rates and directions (e.g. Du Boys, 1879; Shields, 1936; Kalinske, 1947; Meyer-Peter & Muller, 1948; Yalin, 1963, Bagnold, 1956, 1963; Ackers & White, 1973; Van Rijn, 1984; Hardisty, 1990; Nielsen, 1992).

The critical condition refers to the ‘threshold’ of sediment movement, which can be defined as the specific point, within the sequential process of transport, where a small (arbitrary) amount of sediment grains are entrained or set in motion. The concept of threshold is used widely, in qualitative and quantitative descriptions of sediment dynamics. The critical shear velocity (or stress) is estimated usually either by extrapolation of the measured transport rates to zero (or a low reference value), or by the gradual increase of the bed slope/water discharge until the critical condition is determined, on a visual basis (Paphitis, 2001). It can be argued that, with the amount of laboratory data produced over the years, in relation to the definition of threshold, the concept of sediment threshold should have been now reasonably well established. On the contrary, laboratory results on sediment threshold have demonstrated that a given grain size can be displaced by different critical (shear) velocities; this is evident from the experimental data scatter presented on empirical threshold curves, e.g. the Shields (Shields, 1936) and movability diagrams (Collins & Rigler, 1982). Although the Shields- and Yalin-type relationships have been accepted generally, large uncertainty and data scatter exist, as various investigators have adopted a wide range of methodologies (Buffington & Montgomery, 1997; Paphitis, 2001).

The difficulty in defining a ‘unique’ threshold can partially be attributed to the sensitivity of entrainment to turbulence; this produces stochastic shear stress fluctuations within the viscous sub-layer (Grass, 1970, 1971), making the determination of sediment threshold inherently subjective (Neill & Yalin, 1969; Buffington & Montgomery, 1997). Several investigators argued that grain motion can occur at any non-zero value of time-mean flow, through turbulent variations in the instantaneous stress exceeding (occasionally) the thresholds of individual sediment grains (Paintal, 1971; Taylor & Vanoni, 1972; Graf & Pazis, 1977; Lavelle & Mofjeld, 1987). Lavelle & Mofjeld (1987) presented an argument against the deterministic approach of defining a time-mean critical shear velocity (or stress), below which no sediment motion is assumed to occur, claiming that this is neither theoretically defensible, nor necessary. Lavelle & Mofjeld (1987) showed that a stochastic approach (Einstein, 1950), relating sediment transport rates to threshold stresses, does not require a threshold criterion. The aforementioned views challenge the applicability of the ‘threshold concept’, to a deterministic view of sediment motion; rather, they suggest that a brief observation of a sediment bed exposed to a turbulent flow may fail to reveal a small and variable (but non-zero) rate of erosion. In contrast, a longer observation of the same situation would result in evidence of sediment movement; this suggests a time dependence.

If it is accepted that there is a certain level of sediment motion occurring at prethreshold velocities, in situations where the flow is allowed to interact with the sediment bed, then it is only reasonable to assume that the most unstable grains would be provided with the opportunity of relocating themselves to more streamlined positions; these would offer improved protection from the overlying flow. Having accepted that comparatively short exposures to prethreshold velocities increase the resistance of a sediment bed, then a paradox arises in the interpretation of the results of experiments where the sediment bed is left exposed to near-threshold flow velocities; this is due to the extended periods of observation required to confirm the rate of grain motion, which qualifies as threshold. Natural environmental flows (riverine, tidal, etc.) experience changes over time (including increases), of increments ranging from a few minutes to several hours. Thus, if bedload transport formulae are to provide a reasonable description of the magnitude and composition of sediment transport, they require a prethreshold ‘exposure correction’ to be applied to the critical shear velocity (or stress) determinations.

The details of the exact procedure whereby the current is increased, until the selected threshold criterion for a particular grain size is satisfied, are provided only rarely in the literature. Such a history of events leading up to the flow velocity required to define threshold for any given sediment, herein referred to as the 'stress history', will be investigated now for fine, medium and coarse quartz sands, under unidirectional flows. Towards this objective, the selected sediment beds will be exposed to different prethreshold velocities for various durations, quantifiably assessing the extent to which this increases the resistance of the sediment bed to erosion.

METHODOLOGY

Sediment samples

For the purpose of the present investigation, subrounded quartz sand was sieved into narrow size ranges, through standard 1/4Φ interval screens with the methodology as described by Folk (1980). The sediment fractions selected for analysis, for threshold, were those retained by the 0·177, 0·354 and 0·707 mm sieves. The grain diameter (D) of the selected fractions was described as the arithmetic mean of the upper and lower sieve aperture limits, i.e. 0·194, 0·387 and 0·778 mm. The settling velocity tests carried out on each fraction revealed that the grain size distributions were both narrow in range and were symmetrical (Table 1). The settling analysis was undertaken in a settling tower, 2 m long, with an internal diameter of 0·2 m (for further general details; see Rigler *et al.*, 1981) and under a controlled temperature of 20 °C (±1 °C). The density of the sediment samples was confirmed as 2·65 g cm^{-3}, through the utilization of a Eureka can (a container with an overflow device). The shape of the sand grains was investigated visually, through photographs obtained with a scanning electron microscope (SEM) used in back-scatter mode. These photographs (Fig. 1) show that the sediment samples range from angular at 0·194 mm, to sub-rounded at 0·778 mm; all the fractions displayed low sphericity. These surficial characteristics are important, as the erodibility of individual grains depends upon the nature of the surrounding grains (Kirchner *et al.*, 1990).

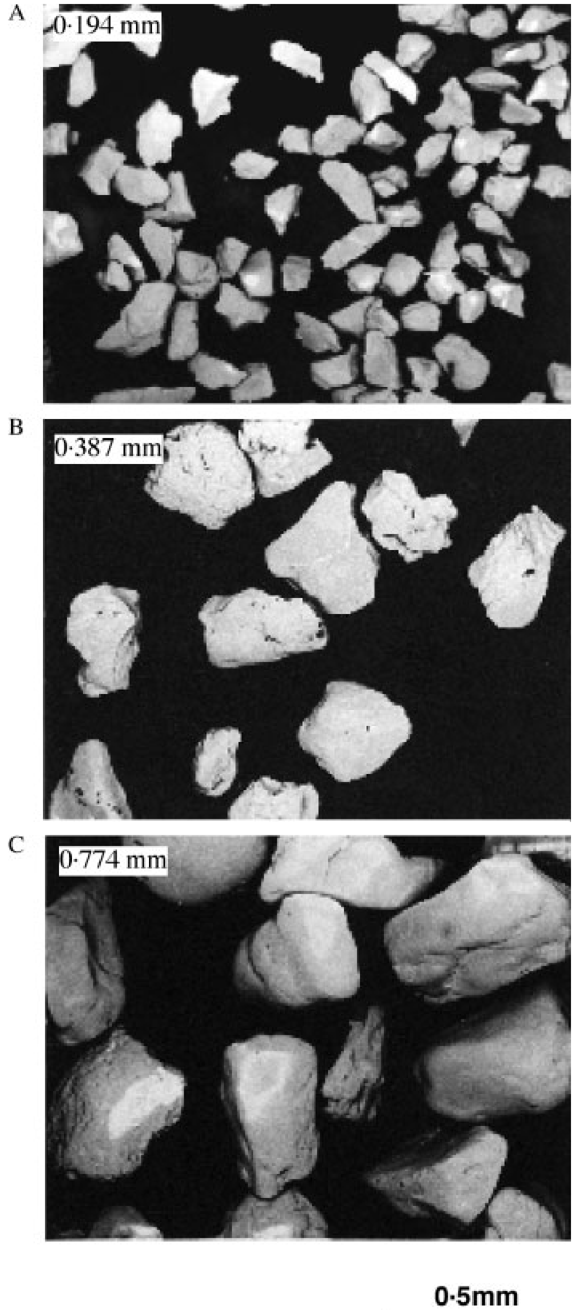

Fig. 1. Photographs of the three sediment beds, taken with a scanning electron microscope (SEM) used in back-scatter mode: (A) 0·194 mm bed; (B) 0·387 mm bed; and (C) 0·774 mm bed.

Table 1. Grain diameter, settling velocities and ranges, together with the number of grain detachments (Eq. 2) and the critical shear velocity 'target values' (as derived experimentally in the present investigation).

Grain diameter (mm)	Settling velocity (cm s^{-1})	Settling velocity ranges (cm s^{-1})	Grain detachments n s^{-1}	Target value u_* (SD) (cm s^{-1})
0·194	2·26	1·98–2·54	120	1·39 (0·009)
0·387	5·52	5·03–6·01	21	1·65 (0·011)
0·774	10·16	9·24–11·08	4	1·95 (0·012)

Experimental arrangement

The threshold experiments were undertaken in a steady flow recirculating flume, with a rectangular cross-section (0·30 m × 0·45 m × 5 m). Installed within the flume was a removable (aluminium) artificial bed, containing a sediment recess section of variable size (in relation to its extent along the flume); this had the possibility of being positioned at any distance from the leading edge of the working section (Paphitis & Collins, 2001a). The recessed area was 40 cm in length and occupied the whole width (30 cm) of the flume, with a 2·5 cm sediment depth (Fig. 2). Elsewhere, it has been demonstrated that the vertical structure of the flow is fully developed within about 45 water depths from the entrance to the working section, within this particular flume (Paphitis & Collins, 2001b). Therefore, with a working flow depth of *ca* 8 cm, the recessed section was positioned some 3·5 m downstream from the entrance. The area within the recessed section, which was used for threshold determinations, was selected to be square (*ca* 156 cm^2), 20 cm from the commencement of the recessed section and located in the middle of the flume, i.e. 9 cm away from the side glass panels (Fig. 2). The flow within this central portion of the flume was found to be undisturbed by the presence of the boundaries (Paphitis & Collins, 2001b). A fixed single layer of sand, consistent throughout in its composition and size in relation to the material under investigation, was attached to the surface of the artificial bed. In this way, the surface roughness of the artificial bed was made to correspond with the grain size of the sediment sample contained within the recessed section; this ensured the full development of the boundary layer. The water-saturated sand sediment sample was allowed to settle, from just below the water surface, through the water column (under still water conditions), into the recessed area. This approach to the introduction of the sediments was adopted, in an attempt to simulate the depositional process by which sand is settled onto the seabed, under no-flow conditions. The loosely consolidated sediment in the recessed area was then levelled carefully, using a straight-edge, in relation to the surrounding adhered sand layer.

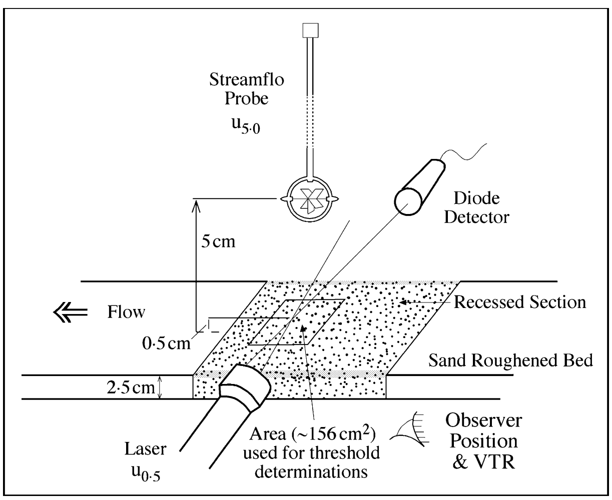

Fig. 2. The general arrangement of the flume, showing the recessed section and associated instrumentation.

Flow velocity (horizontal component) measurements were obtained simultaneously at two elevations, 0·5 cm and 5 cm ($u_{0\cdot5}$ and u_5, respectively) above the level of the loose sediment sample with a laser Doppler anemometer (LDA; with an accuracy of ±0·2 cm s^{-1}) and a Streamflo impeller current meter (with an accuracy of ±0·5 cm s^{-1}), respectively. Observations of grain motions were achieved using a video tape recording (VTR) system, overlooking the recessed section. The experimental arrangement used in all the threshold experiments is shown in Fig. 2. Before initiating each of the experiments, a low flow rate was established in the flume to check on the various instrumentation outputs and the digital display units of the flow meters. In each experimental run, the uniform and fully developed flow was increased incrementally, until the required number of grain detachments was reached (see below) and the flow velocity was recorded, from both meters. The mean and standard deviation of the flow velocity measurements ($u_{0\cdot5}$ and u_5) are listed in Table 2A–C.

Threshold criterion

The identification of the threshold condition can be achieved through the use of critical motion criteria. Various researchers have visually defined threshold, in a qualitative sense, such as: 'weak movement' (Kramer, 1935); 'when the first downstream movement of grains becomes perceptible' (Chepil, 1959); 'scattered particle movement' (Rathburn & Guy, 1967); 'weak sediment transport' (Graf & Pazis, 1977); and 'intermittent motion' (Collins & Rigler, 1982). Likewise, Graf & Pazis (1977) and Van Rijn (1989) identified that the critical shear stresses depend largely upon the frequency of grain displacements, selected as the

Table 2. Critical shear velocities (cm s^{-1}), derived using various different sources in the literature, together with the calculated mean and standard deviation.

Sediment bed	0·194 mm (A)	0·0387 mm (B)	0·0774 mm (C)
Experimentally derived target values	1·39	1·65	1·95
Miller *et al.* (1977)	1·25	1·57	1·98
Van Rijn (1993)	1·30	1·46	1·94
Soulsby & Whitehouse (1997)	1·27	1·47	1·94
Paphitis (in press) – 1 (movability no vs. Re_*)	1·34	1·53	2·00
Paphitis (in press) – 2 (u_* vs. D)	1·36	1·62	1·93
Mean critical shear velocity (SD)	1·32 (0·05)	1·55 (0·08)	1·96 (0·03)

visual criterion for sediment threshold. On this basis, in the present series of experiments, a qualitative visual criterion (the 'Yalin criterion') for the definition of threshold was used; this was developed originally by Yalin (1972) and used elsewhere successfully (e.g. Paphitis *et al.*, 2001). The Yalin criterion is given by:

$$\varepsilon = \frac{n}{At}\left(\frac{\rho D^5}{(\rho_s - \rho)g}\right)^{1/2} \qquad (1)$$

where ρ_s is the sediment density (taken as 2·65 g cm^{-3}), ρ is the water density (0·998 g cm^{-3}, for water of 20 °C) and g is the gravitational acceleration (981 cm s^{-2}). Essentially, the criterion requires that, at threshold, n number of grain detachments should occur in time t, over a given area of bed A (156 cm^2). The number of grain detachments (n) was calculated for the grain diameter (D) of the sediment samples under investigation, after establishing ε at 10^{-6}; this is the lower limit suggested by Yalin (Table 1).

A number of preliminary experimental tests were performed on each of the sediment beds, to determine the approximate critical flow conditions necessary to initiate (grain) motion. In spite of these precautions, the exact threshold velocities were difficult to establish, especially for the fine-grained sediment bed (0·194 mm); consequently, supplementary video recordings were used. Three experimental runs were adopted, following the careful examination of the video recordings (for each of the samples and the particular conditions investigated), where threshold was defined to within *ca* ±2% and ±5% of the required number of grain detachments, as defined by the 'Yalin criterion', for the medium- and fine-grained sediment beds respectively. The threshold conditions for the coarse-grained sediment bed were established in relation to the exact number of grain detachments (four grains), as defined by the 'Yalin criterion'.

Experimental design

The critical conditions for the selected sediment samples were established from 10 experimental runs, without significant exposure to prethreshold velocities. This approach was undertaken in such a way that threshold conditions were reached within 2·5 min of increasing the flow, from zero velocity. The resultant mean value (and standard deviation) of the critical shear velocity (u_{*c}) from the (10) experimental runs, for each size fraction, was termed the 'target value' (Table 1). An experiment was designed then to examine the effect, on the critical conditions, of exposing the bed to different prethreshold velocities (expressed as percentages of the identified target value), over different time-scales. The prethreshold velocities were selected to be at 70% (for 5, 10, 20, 40 and 80 min), 80% (for 5, 10, 20, 40 and 80 min), 90% and 95% (for 5, 10, 20, 40, 80 and 120 min) of the target value. Following exposure to these different prethreshold velocities, the flow was increased then to reach the critical condition, within the 2·5-min period. Three determinations of the resulting increase in the critical shear velocity were undertaken for each combination of the nominal prethreshold velocities and durations. Whilst the duration of exposure was controlled accurately, the actual prethreshold velocities differed slightly from the nominal percentage values (ranging between 68% and 98%); thus, the actual conditions representing each of the experimental runs were unique (Table 2A–C). Furthermore, it has to be noted that, within the 2·5 min period of defining threshold (in all the threshold experiments), the free stream flow velocity was increased in increments of *ca* 0·25 cm s^{-1}. Likewise, a 10 s period of observation was used, in deciding whether the critical condition had been reached or not. Any experiment where more than 2·5 min was required to reach threshold conditions was aborted; on such occasions the bed was re-formed, for another attempt.

Shear velocity determinations

Artificially roughened beds were prepared using quartz sand, similar in its composition and size to the samples which were to be examined in the threshold experiments. The different beds were examined in the flume under 'slow' ($u = 2$–10 cm s^{-1}), 'moderate' ($u = 8$–25 cm s^{-1}) and 'fast' ($u = 14$–37 cm s^{-1}) flow rates; these were established using the LDA, to measure the velocity at different elevations above the bed, in a vertical profile and within the middle section of the flume (Paphitis & Collins, 2001b). The results of these experiments confirmed that the velocity profile was logarithmic within the boundary layer, in relation to the various (three) flow settings. Likewise, that by measuring the flow velocity at two elevations, accurate estimates of the shear velocity (u_*) can be obtained using the differential form of the law-of-the-wall, such that:

$$u_* = \kappa y \frac{\mathrm{d}u}{\mathrm{d}y} \qquad (2)$$

where u is the time-average flow velocity, y is the height above the bed and κ is the von Karman constant (0·4). The use of the velocity gradient $\mathrm{d}u/\mathrm{d}y$ at any level in the flow (within the inner layer), can provide shear velocity determinations irrespective of whether the flow is smooth or rough. Using the chain rule (see Middleton & Southard, 1984),

$$\frac{\mathrm{d}u}{\mathrm{d}(\ln y)} = \frac{\mathrm{d}y}{\mathrm{d}(\ln y)}\frac{\mathrm{d}u}{\mathrm{d}y} = y\frac{\mathrm{d}u}{\mathrm{d}y}$$

Equation 2 can be written as:

$$u_* = \kappa \frac{\mathrm{d}u}{\mathrm{d}(\ln y)} \qquad (3)$$

where $\mathrm{d}u/\mathrm{d}(\ln y)$ is the slope of the straight-line part of the law-of-the-wall in the outer part of the inner layer, when plotting u against $\ln y$. In the present experiments, two synchronous velocity measurements were obtained at two different elevations above the bed (see above); therefore, Eq. 3 becomes:

$$u_* = \kappa\left(\frac{u_5 - u_{0\cdot5}}{\ln 5 - \ln 0\cdot5}\right) \qquad (4)$$

where u_5 and $u_{0\cdot5}$ are the flow velocity measurements at 5 cm (Streamflo) and 0·5 cm (LDA) above the bed, respectively. The mean and standard deviation of the flow velocity measurements ($u_{0\cdot5}$ and u_5), the exposure duration and the prethreshold velocities (expressed as nominal and actual percentages), the critical shear velocity calculations (see below) and the increase factors (derived from the target values; see Table 1) are listed in Table S1A, B and C, for the fine-, medium- and coarse-grained sediment beds respectively.

RESULTS

Evaluation of the experimentally derived target values

It is appropriate now to undertake a comparison of the critical shear velocity target values (Table 1) of the present investigation, with a selection of those which can be derived using selected empirical and semi-empirical threshold curves/expressions. The sources used to form the basis of the comparison include: (i) the curve of grain diameter plotted against critical shear velocity, as provided by Miller *et al.* (1977); (ii) the expressions of Van Rijn (1993), to represent different sections of the Shields curve, using the dimensionless grain number ($D_* = [(\rho_s - \rho)g/(\rho v^2)]^{1/3}D$, where v is the kinematic viscosity); (iii) the algebraic expression proposed by Soulsby & Whitehouse (1997) (also using D_*); and (iv) the empirical formulae proposed by Paphitis (2001), relating the movability number (u_*/w_s, where w_s is the particle settling velocity) to the grain Reynolds number ($\mathrm{Re}_* = u_* D/v$) and the critical shear velocity to the grain diameter. Table 2 lists the target values (derived experimentally within the present investigation) and the critical shear velocity values, derived using the aforementioned sources: the mean and standard deviation, calculated using all of the derived values, are also listed. The critical shear velocity target values compare well with those derived using a selection of empirical and semi-empirical threshold curves/expressions. This pattern suggests that the conclusions reached by the present series of experiments, which use the established target values as a basis, will apply to empirically derived values of critical shear velocity.

Results of stress history

The results of all of the threshold tests (Table 2A, B and C) for the three sediment beds are presented in Fig. 3A, B and C respectively. For the range of experimental conditions examined (5–120 min prethreshold exposures to 70–95% target velocities) the critical shear velocity was found to increase by 3·4–24·4%, 4·3–26·4% and 1·9–22·4% for the 194, 387 and 778 mm beds respectively. Essentially, the figures show that if the exposure duration to prethreshold velocities remains constant, then the critical shear velocity increases with an increase in the prethreshold velocity. Likewise, if the prethreshold velocity remains constant, then the critical shear velocity increases, with an increase in the duration of exposure.

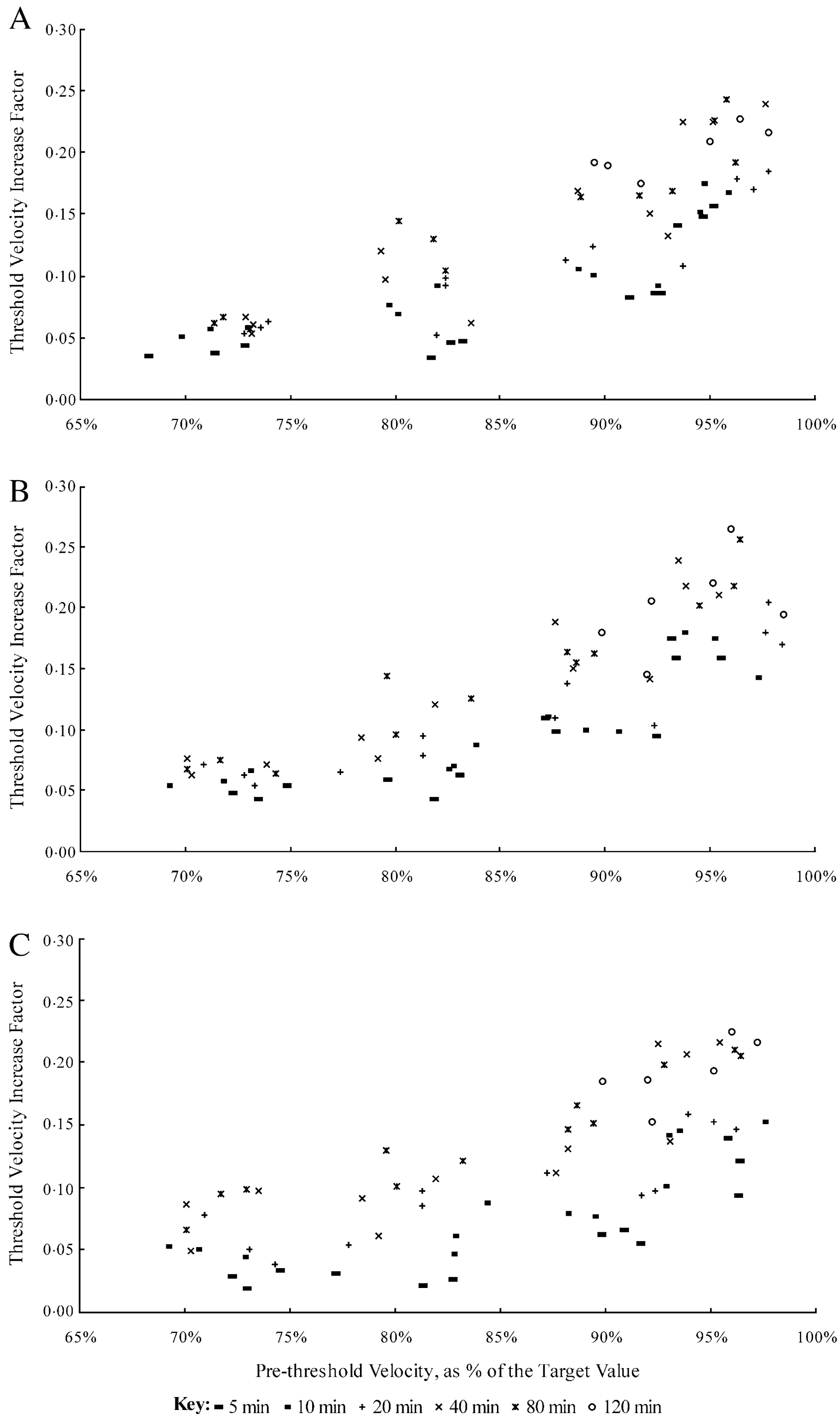

Fig. 3. The experimental results of the stress history of three sediment beds: (A) 0·194 mm; (B) 0·387 mm; and (C) 0·774 mm.

DISCUSSION

Causes of the stress history effects

Following confirmation that the experimentally derived target values compare well with some empirically and semi-empirically derived critical shear velocity values obtained from the literature, the effect of stress history in relation to the target values will be investigated now in more detail.

Sediment particles experience a sequence of motion events, with increasing flow velocity; in order of occurrence, these are sliding then rolling and, finally, saltating (Bagnold, 1956). Initially, non-cohesive particles undergo re-orientation in relation to their position within the bed, in such a way as to offer the minimum possible resistance to the flow; consequently, in effect, the maximum resistance to erosion. In response to increasing hydrodynamic forces, the particles pass through various stages of motion (as described above). As the particles experience such motion events, they collide with other neighbouring grains, dislodging and readjusting them in a more compact arrangement. As long as the number of grain motions is less than the number required for satisfying the preselected threshold criterion, the process of rearrangement will continue to take place; this is for all the grains undergoing any kind of movement, at a particular time. Following this particular argument, the longer the sediment grains are exposed to prethreshold velocities, the longer the sediment grains are allowed to re-position themselves, the more will be their resistance to flow; this, in effect, increases the threshold velocity that would otherwise be sufficient to mobilize the bed (Fig. 3). Likewise, the higher the prethreshold velocity, the more are the grains in motion; this, in turn, increases the opportunity for compaction to occur. The history of the events experienced by the sediment grains, prior to threshold, introduces the concept of different (sediment) behavioural characteristics, at threshold.

Few researchers have attempted to describe exactly the initial motion of sediment grains. In contrast to the earlier statements, Bagnold (1941), Chepil (1945) and Bisal & Nielsen (1962) reported that erodible particles ‘oscillate or vibrate unsteadily’ before leaving the bed. If the particles are allowed sufficient time to pass through this stage of vibration, then they will essentially be subjected to the repositioning process (as described previously). Madsen & Grant (1976), in a series of oscillatory flow threshold experiments, noted that the grains were rocking (in a ‘to and fro’ motion) about their position on the bed before the threshold criterion was satisfied. Hence, they have argued that such movement might cause the bed to become more compact and, in effect, more resistant to erosion.

The departure of oscillatory flow data obtained for threshold (plotting consistently higher than unidirectional flow data), from the Shields curve, has been attributed to an observation made for low wave periods; here, the grains were noticed to rock (in a ‘to and fro’ motion) about their position on the bed (Madsen & Grant, 1976). Although such grains were in motion, the threshold criterion on this occasion was not satisfied. Hence, these authors have argued that such movement might cause the bed to become more compact and, in effect, more resistant to erosion.

Consideration must be given also to the relative balance between the lift and drag forces, the magnitude of which will depend, amongst other factors, upon the friction angle (Eagleson & Dean, 1961; Li & Komar, 1986) and particle exposure (Sundborg, 1956; Fenton & Abbott, 1977). These key variables have been found to affect, apart from the critical shear velocity, the relative mobility and selective entrainment of different size fraction within a sediment bed (Komar & Li, 1986, 1988; Wiberg & Smith, 1987; Wallbridge *et al.*, 1999). Evidence from the aforementioned literature demonstrates that the friction angle and particle protrusion are affected by size, shape, orientation and the packing arrangement of the sediment bed.

In the present investigation, the samples were allowed to settle from a height just below the water surface, in an attempt to simulate (as closely as possible) the deposition of sand within the natural environment (see above). At this moment, the sediment beds were likely to have their highest porosity, than at any other stage during the experiments. Visual inspection of the surface confirmed that the sediment beds had a loose packing arrangement, with many pore spaces; this would result in low friction angles and relatively exposed particles. As soon as the flow velocity was increased, from zero, the beds were observed to respond immediately to all the changes in the ambient conditions. At very low velocities, the most unstable grains were observed to rock or pivot, in such a way as to establish a more stable position. When the flow became more turbulent, eddies present within the flow were able to penetrate the bed, consequently, to flow through the spaces between the various sediment grains. In smooth turbulent flow, above a permeable bed, the viscous forces in the laminar sublayer dampen the turbulent eddies as they approach the bed. However, unlike the case of a solid boundary (in which the vertical component of velocity in the immediate vicinity of the bed is zero and the eddies are forced to travel in a direction parallel to the solid bed), in the situation where the bed is no longer solid, the (flow) eddies are able to flow amongst the spaces within the bed surface.

Having adopted a recess section of some 25 mm in depth, extending to the glass side panels, flow penetration effects into the various beds were observed visually during the experiments. However, it should be noted that flow close to the side panels was affected by the presence of the boundary, causing an increase in turbulence. As such, the movement of grains lying immediately adjacent to the side panels should be treated with caution, when used as a representation of particle behaviour in the middle of the recessed section. The flow was observed to penetrate the bed by as much as 20 mm, at the threshold velocities; the depth of penetration was found also to increase, with increasing grain size. When the turbulent eddies started to penetrate into the beds and the velocity was increased gradually, the permeating flow was observed to cause the grains to shift and vibrate throughout the depth of penetration; this, in turn, caused the sediments to become more compact, creating a more resistant bed. The level of the transformation in the internal structure will depend upon size and shape variation within the sediment beds. In the course of the present experiments there was a slight, but nonetheless evident, variability both in size and shape of the individual particles (Fig. 1). Visual inspection of the sediment beds (following experiments undertaken with extended exposure duration) has confirmed that compaction (estimated on the basis of measuring the amount by which the surface of the bed was lowered, following an experiment) reached as much as 2 (±0·2) mm.

Implications of the stress history effects

The absence of any precise information regarding flow and sediment (bed) history from previous investigations, prior to the establishment of a critical condition, may explain partially the large amount of data scatter observed on empirical and semi-empirical threshold curves (e.g. the Shields and movability diagrams), when the sediment threshold values obtained from the various investigations are plotted together. In the various published laboratory threshold experiments, individual investigators specify their adopted threshold criterion, which they then utilize consistently; however, the flow history, prior to the establishment of threshold, is not documented. In the majority of such investigations, the flow velocity is increased from zero (at the initiation of the experiment), until a threshold condition is reached. This is a procedure which rarely exceeds a time period of some 5–10 min, within any particular experimental arrangement/approach.

Following a study of the effect of turbulent fluctuations on grain motion, Grass (1970) introduced the concept that each individual particle on a bed can be ascribed a certain critical shear stress value. With reference to the level of grain movement, Grass (1970) considered two distributions of variables: that of the available instantaneous shear stress (τ_i); and that of the threshold shear stress (τ_c) required to initiate movement. It was argued further that the level of movement could be represented by a measure of the overlap between the two distributions (Fig. 4).

On the basis of the Grass model, it is evident that experimental procedure has an impact on the stress history of grains lying within a sediment bed. Experiments during which the flow is either increased slowly, or the selected observational periods are relatively long, will produce a sample which is more compact (then the original bed) and is associated with strong particle interlocking; as such, it will be more resistant to erosion, resulting in the generation of higher critical shear velocities. However, in situations where the flow is either increased rapidly or the observational periods are short, turbulent eddies will be imposed upon the sediment bed; at such times, it will still be highly porous, with weak particle interlocking. Furthermore, the selection of a particular threshold criterion will have a considerable effect upon the stress history. Hence, a criterion which requires a significant degree of sediment movement, before it is satisfied, is subjected to the increased effect of the stress history. In an experiment where the threshold criterion is associated with a large number of grains set in motion then, as long as the number of moving grains is lower than that required, the time for satisfying the criterion is increased; in turn, this presents the bed with an enhanced opportunity for further compaction.

Exposure corrections

The results of the present investigation, where the 'increase factors' in the critical shear velocity

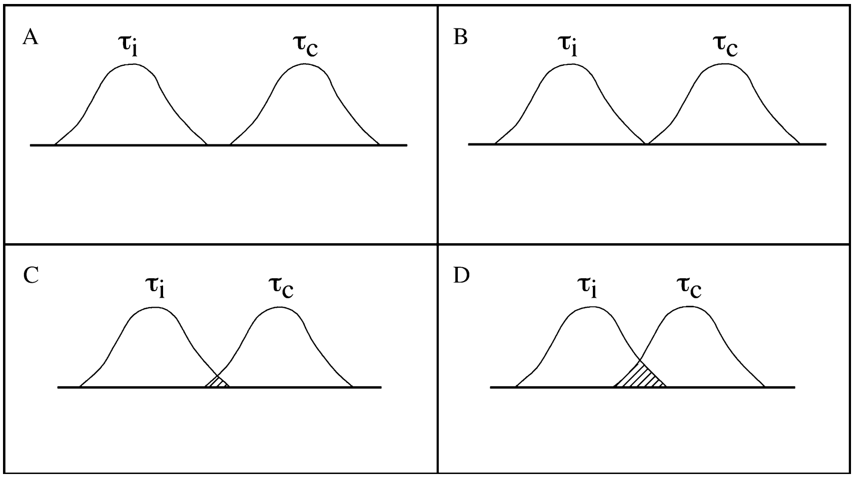

Fig. 4. Initiation of sediment movement for unidirectional currents over plane beds, according to the stochastic approach proposed by Grass (1970), where: (A) the surface grains are immobile; (B) there is a remote possibility that the most unstable grains will be mobilized; (C) there is an increased probability of a few grains moving; and (D) the required overlap to satisfy the selected threshold criterion.

are plotted against the duration under which the sediment bed was exposed to the investigated prethreshold velocities, are presented in Fig. 5. Utilizing all of the available data an empirical formula for the calculation of the exposure correction factor (u_{*cc}/u_{*c}, where u_{*cc} is the corrected critical shear velocity) in the critical shear velocity is derived; this includes, as explicit variables, the duration of exposure (E_D) and the percentage of prethreshold velocity (u_*/u_{*c}). Plotted on Fig. 5 are the empirical curves (calculated using Eq. 5) for the prethreshold velocity conditions investigated; the correlation coefficients of these curves were found to be over 0·83, with P-values of <0·001 at the 95% level of significance.

$$\begin{aligned}\frac{u_{*cc}}{u_{*c}} = {} & 1{\cdot}05\left(1 - 0{\cdot}01\mathrm{e}^{(-0{\cdot}005E_D)}\right) \\ & + \left(0{\cdot}005 + \left(\frac{u_*}{u_{*c}} - 0{\cdot}7\right)0{\cdot}1\right)\ln(E_D) \\ & + 0{\cdot}06\left(10^{-7(0{\cdot}97-(u_*/u_{*c}))}\right)\end{aligned} \qquad (5)$$

for

$$0{\cdot}70 \leq \frac{u_*}{u_{*c}} \leq 0{\cdot}95 \quad \text{and} \quad E_D \leq 120 \text{ min}$$

The derived formulae can be used readily in practical applications, where the sediment bed under investigation has been exposed (over a known duration) to prethreshold unidirectional currents. The application of the proposed formulae

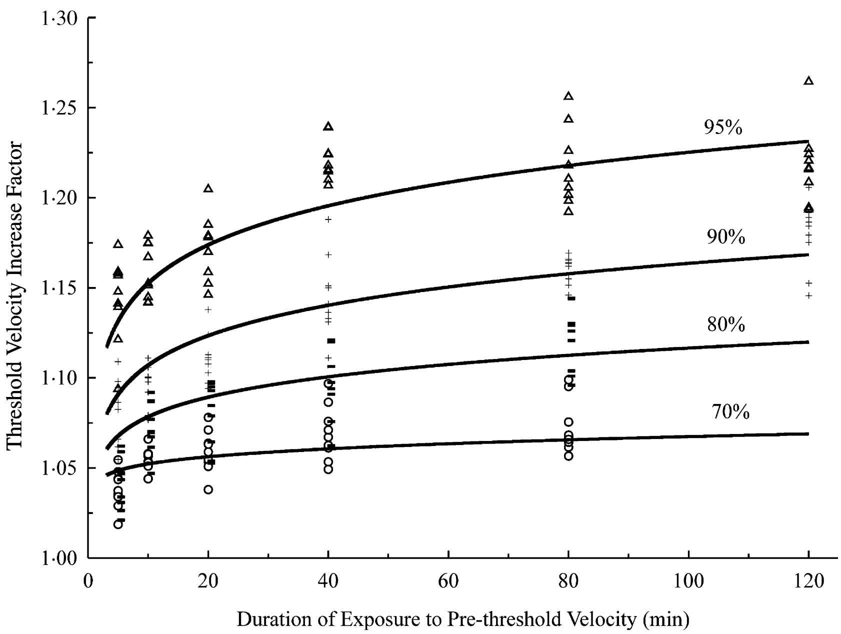

Fig. 5. Threshold velocity increase factors plotted against the exposure duration to prethreshold velocities. The series of curves were defined using Eq. 5; they represent the different prethreshold velocities investigated; key: ○; ▬, 80%; +, 90%; and △, 95%.

will provide practitioners with an exposure correction factor (i.e. the critical shear velocity 'increase factor'), which needs to be applied to the critical shear velocity. However, the formula is restricted to the conditions under which it has been derived, i.e. sand-sized sediments, prethreshold velocity ranging from 70% to 95% and for a duration of exposure of <120 min.

CONCLUSION

The effects on the critical (threshold) condition, of subjecting non-cohesive uniform sand beds to a prethreshold unidirectional current, have been found to be considerable. The stress history was found to increase the observed critical shear velocity by as much as 27%, under certain circumstances. If the ambient flow is increased to a level where the maximum instantaneous shear stress is equal to the threshold required by the most unstable grains on the bed (Fig. 4B), being allowed to flow over the sediment bed for a sufficient duration, it will undoubtedly increase the subsequent resistance of that particular bed to erosion. An empirical formula has been proposed here to account for the critical shear velocity correction factor, in cases where sand-size sediment beds are exposed (for a known duration) to prethreshold velocities. The application of this exposure correction factor, to the critical shear velocities prior to their inclusion into bedload transport formulae, should assist in the improved prediction of the magnitude and nature of the transport. This investigation does not claim to have resolved the problems associated with the required (temporal) exposure correction for sediment transport, given the restricted conditions under which the proposed formula has been derived. However, the experiments presented here provide a preliminary, quantitative, consideration of stress history events prior to the initiation of sediment movement.

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SUPPLEMENTARY MATERIAL

The following supplementary material is available for this article online

Table S1: The exposure duration and prethreshold velocities (expressed as 'nominal' and 'actual' percentages), the mean and standard deviation of the flow velocity ($u_{0\cdot5}$ and u_5), the critical shear velocity and increase factors (the percentage increase of the critical shear velocity following the exposure) for the investigated sediment beds: (i) 0·194 mm; (ii) 0·387 mm; and (iii) 0·774 mm.

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