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FARKLI ŞEKİLSEL ÖZELLİKLERE SAHİP KIRINTILI SEDİMANLARIN HİDRODİNAMİK ÖZELLİKLERİNİN GÖRÜNTÜLENMESİ: KABA ÇAKIL AĞIRLIKLI NEHİRLERDE YATAK YÜKÜ TAŞINMA MEKANİZMALARI BAKIMINDAN YORUMLANMASI

Visualisation of the solitary grain sediment dynamics of paerticles of varying shape: Implications for sediment transport over coarse-gravel bed rivers

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ÖZET

Akarsu yataklarında taşınan yatak yükünün şekil, boyut ve yoğunluk özellikleri onların hidrodinamik davranışını kontrol eden temel özelliklerdir. Yatakta taşınan tanelerin şekil özellikleri, onların su içerisindeki çökelme ve yatak üzerinde hareket mekanizmasını kontrol etmeleri bakımından oldukça önemli rol oynamaktadır. Bu çalışmanın amacı akarsu yataklarında bulunan çakılların şekil özelliklerinin onların harekete geçmesi ve yatak içerisindeki taşınması üzerine olan etkilerinin araştırılmasına dayanmaktadır.

Çalışma kapsamında tane hareketini fotoğraflama deneyleri yoluyla farklı şekil, boyut ve ağırlıklara sahip doğal ve yapay olarak üretilmiş çakılların hareket mekanizmaları tespit edilmeye çalışılmıştır. Bu amaçla, etrafı saydam camla kaplı dolayısı ile içerisi kolaylıkla görülebilen ve 10 litre su ile doldurulmuş dikdörtgen şeklindeki bir tank ile bu tankın tam karşısına sabit bir konumda durabilecek bir fotoğraf makinesi monte edilmiştir. İlk olarak değişik boyut ve şekle sahip taneler su ile dolu tankın içerisine yukarıdan bırakılmış ve onların su içerisinde batma hareketi, batma hızı ile eğimli cam yüzey üzerindeki hareketleri sürekli fotoğraflama metodu ile tespit edildi. Aynı deney düzeneği kullanılarak bu sefer değişik yüzey pürüzlülüklerine (7 ve 14 mm) sahip cam levhalar üzerinde farklı şekil, boyut ve ağırlıklara sahip taneler yerleştirilmiş ve bunların ilk hareket açıları tespit edilmiştir. Bu amaçla üzerine değişik boyut ve şekle sahip taneler yerleştirilen levhaların yatak eğimleri, üzerine konulan tane hareket edinceye kadar, sürekli olarak artırılmış ve bu tanelerin ilk harekete geçtiği yatak eğimi açısı ile söz konusu pürüzlü yüzey üzerinde tanenin hareket mekanizması tespit edilmiştir.

Bulgular, tane şekli özelliklerinin onların su içerisindeki çökelme oranı ile yatak üzerindeki hidrodinamik hareketleri üzerine önemli etkileri olduğunu ortaya koymuştur. Bu etkiler tane boyunun artması oranında daha da belirgin olarak ortaya çıkmaktadır. Tane şeklinin küresellikten uzaklaşma oranı onun su içerisindeki batma hızının da azalmasına sebep olmaktadır. Yapılan bütün deneyler göstermiştir ki, test edilen bütün tane boyutlarında, aynı boyut ve ağırlıktaki taneler içerisinde kübik/küresel ve silindirmsi/kalemsi şekilde olanlar su içerisinde daha yüksek batma oranına sahipler ve yatak üzerinde yuvarlanarak hareket etme eğilimi gösterirler. Buna karşılık disk ve bıçağımsı şekilde olan tanelerin su içerisindeki batma oranları daha yavaş ve büyük bir çoğunlukla yatak üzerinde kayma şeklinde hareket etme eğilimi gösterirler. Düzensiz şekle sahip doğal çakıllarla yapılan deneyler oldukça değişebilir çökelme oranları ile yatak üzerinde düzensiz hareket örnekleri göstermişlerdir. Hemen her tane boyutu sınıfında, küresel/kübik ve silindirimsi taneler disk ve bıçağımsı şekle sahip tanelere göre hareket etmeleri için daha düşük kritik yatak eğimine ihtiyaç duyarlar. Hemen her şekil gurubu için tanenin üzerinde bulunduğu yatağın pürüzlülük oranı arttıkça onların harekete geçmeleri için daha yüksek kritik yatak eğimi açısı gerektirir. Tanenin hareketi bakımından, genellikle tane boyutu ile tanenin üzerinde bulunduğu yatağın pürüzlülük oranı arasında ters bir ilişkinin olduğu ortaya çıkmıştır. Yüksek pürüzlülük oranına sahip yüzeyler üzerinde küçük boyuttaki tanelerin hareket etmeleri için daha yüksek yatak eğimine ihtiyaç duyarlar. Bu deneyler sonucunda tespit edilen bulgular akarsu yataklarındaki yatak yükü taşınma süreçlerinin yorumlanması bakımından önemi tartışılmıştır.

ABSTRACT

Shape, size, and density are fundamental properties controlling the hydrodynamic behaviour of sediment particles. Particle shape can play a significant role in bedload transport processes by controlling the nature of particle settling and near-bed motion. The aim of the experiments reported here is to investigate the influence of shape on the settling initial motion and transport of gravel-size particles.

Experiments, using strobe-light photography, were carried out with natural and artificial gravel-size particles of differing shape (sphere, rod, disc and blade), size and weight. Two types of experiment were undertaken in a 10 litre, water-filled rectangular tank. Firstly, particles were dropped, through water, onto a 30° inclined, smooth glass plate. A camera mounted outside the tanlq normal to the sloping glass, recorded the fall and movement of each particle. Particle velocities and trajectory paths were measured from the photographs by plotting successive centres of mass of the particle. A second set of experiments, using the same set-up as the first, but this time investigating the initial motion of particles of varying shape and size was also tested on two beds of differing roughness (7 and 14 mm). The bed was tilted until the test particle moved from its pocket of origin and strobe-light photographs were taken at the initiation of motion.

Results indicate that shape is an important particle characteristic that has a significant effect on settling rates and also the mode of transport. These effects increase with larger particle sizes. Departure from a spherical form leads to a decrease in its settling velocity. Experiments show, across the range of sizes tested that, when compared to a sphere of approximate equivalent weight and density, sphere and rod shaped particles tend to settle the fastest and move by rolling. Discs and blades showed slower settling rates and, in most instances, moved by sliding. Experiments carried out with irregularly shaped, natural particles show greater variability in settling behaviour and irregular patterns of motion. For every size group, sphere and rod shaped particles have lower critical angles of initial motion than blade and discshapes. Regardless of shape, greater bed roughness, or decreasing particle size results in an increase in the critical angle for motion. The implications of these results for bedload transport in river channels is briefly discussed.

INTRODUCTION and BACKROUND

Shape, size and density are fundamental properties controlling the hydrodynamic behaviour of sediment particles. Grain shape can play a significant role in bedloadtransport processes by controlling the nature of particle settling and near-bed motion. This paper presents results of a series of visualisation experiments designed toinvestigate the influence of grain shape on settling, initial motion and transport ofgravel-size particles. Several studies have shown that particle shape, size and weight are important properties affecting the hydraulic behaviour of sediment durine transporr and deposition (e.g. Lane, 1938; McNown and Malaika, 1950; Allen, 1969; Carrigy, 1970; Goldbery and Richardson, 1989;Komar and Reimers, 1978; Hallermeier, 1981; Willetts and Rice, 1983; Li and Komar, 1992a,b). Particles entrained from a bed are transported by the flow in a variety of ways, depending on their shape, size and density, as well as the viscosity and velocity of the fluid. Generally three modes of transport have been described for coarse gravel particles in water. These are sliding, rolling and saltation. During sliding, particles remain in continuous contact with the bed, although they may tip-up or down slightly during travel. A rolling particle turns continuously about a flow-transverse axis, while remaining essentially in contact with the bed. Saltation involves the progressive forward movement of a particle in a series of short intermittent jumps along the channel bed. Saltation continues as long as the flow is turbulent enough to lift particles and carry them downstream. A decrease in lift and turbulence will result in particle settling.

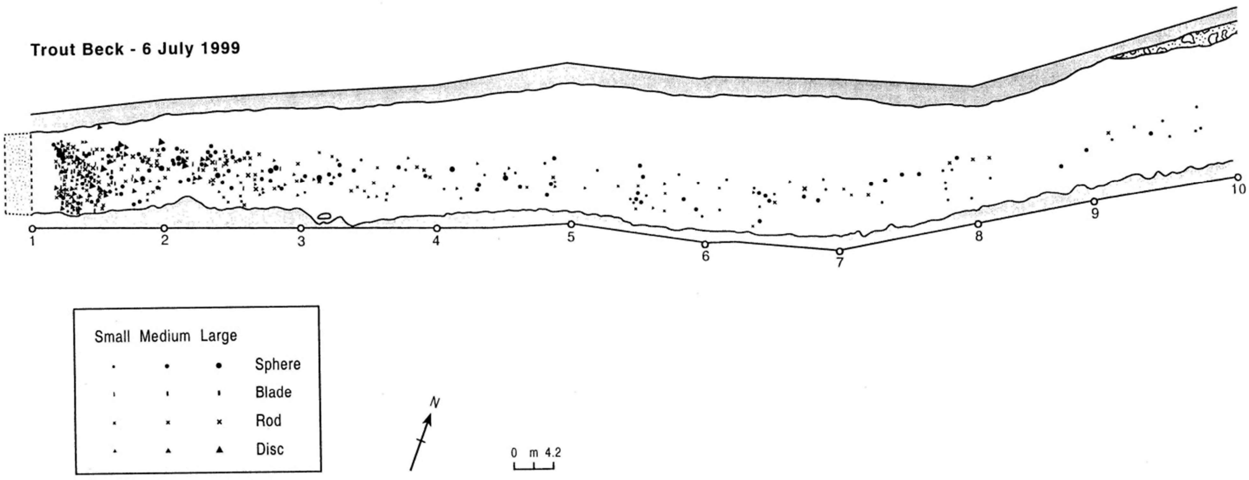


Figure 1

The purpose of this paper is to examine the influence of shape on settling and motion of gravel-size particles. Although particle shape has been considered an important variable in the transport of coarse bedload transport, empirical investigations of the phenomena in both the laboratory and field have been rather few. Figure 1. shows the results of a field tracer experiment designed to investigate the significance of particle shape on bedload transport in an upland, coarse-gravel river channel (Warburton and Demir, 2000). The field site is on the Upper Rivers Tees, Northern England. Figure 1 shows the spatial distribution of 900 magnetic tracers (size range 32 to 256 mm) on Trout Beck after the experiment had run for 20 months. Result are plotted in terms of the shape class of the tracer particles and size. Only particles which have moved greater than 3 meters beyond the start line are shown. This corresponds to approximately 48% of the tracers at Trout Beck. Originally 900 tracers were introduced at each site. The dispersion of the tracers at the Trout Beck is clearly concentrated in the deeper channel sections. In terms of size, it is clear that there is preferential movement of the small and medium size classes. Although some large particles moved, the majority of the transport is confined to the first 30 metres downstream (Figure 1). The general pattern, shows a decrease in the frequency of movement with distance down the channel. In terms of shape sphere and rod shaped particles are transported by far the greatest distance. Discs show a lesser degree oftransport compared to spheres and rods and blade-shaped particles appear to have moved the shortest distances and in the least numbers. Figure 1 demonstrates that there is a significant decrease in the number of disc and blade-shaped tracers with distance downstream at the sites. An important question that arisese from such empiurical evidence is what are the particle processes that produce size and shape sorting in coarse river gravels?

Direct observations of individual particle motions in the field are extremely difficult becase of the multitude of particles in transport and poor visibility of transport pathways (Drake, 1972). In addition particle motion on a natural river bed is dependent on many factors which include size, shape and to some extent surface characteristics of particles, as well as size, shape and roughness characteristics of the channel bed. Therefore the complex nature of the field phenomenon does not easily lend itself to direct investigation. However, laboratory experiments often involving simpliftying conditions and sometimes abstract physical settings have proved very useful in providing empirical data of particle dynamics. For example, these factors have been shown to have significant effects on particle friction or pivoting angles measured in tilting table experiments. Indeed, the friction angle of a particle depends on its size, median bed grain size, and the degree of bed sorting. Earlier studies (eg. Komar and Li, 1986; Buffington et al., 1992) have shown that friction angles decrease with increasing grain size relative to the median bed grain size, and are a systematic function of sorting with lower friction angles associated with poorer sorting. Pivoting angle, on the other hand, is related to the contact point of a particle with an underlying grain, which is also dependent on the shape and size oftest particles and also size. shape and imbrication of underlying bed material. Particle pivoting angles have an important effect on the threshold of movement. Particle roundness has also been found to be significant in controlling entrainment and transport. For example, a single perfectly rounded sphere on a flat surface is much more easily entrained and kept in motion by a fluid than a highly angular particle of equivalent weight. Li and Komar (1986) and Komar and Li (1988) clearly showed (for uniform-sized particles) that angular particles of crushed gravel have larger pivoting angles than either spherical particles or ellipsoids of the same size. The difference in pivoting angle between the angular and more rounded particles was found to greater with increasing grain size (Pye, 1994b).

Laboratory studies have shıwn that, for particles of equal density and size, shape is an important secondary factor, in controlling the settling (Pye, 1994a). In generali the greater the departure of a particle from a spherical shape, the greater is the reduction in its settling velocity and the more irregular its motion during settling (Wadell, 1934; Garnett, 1966; Komar and Reimers, 1978; Baba and Komar, 1981a, 1981b; Hallermeier, 1981; Cui et al., 1983; Pye, 1994b; Wilson and Huang, 1979). Although settling is not a highky significant aspect of transport of coarse size particles in gravel-bed rivers, since most of the time, movement occurs by sliding or rolling, such material may intermittently lose contact with the bed and may be temporarily suspended. In high flow events sliding and rolling are disturbed by vertical particle movements. Under these circumstances, flat-shaped particles may easily be lifted up as a result of increasing velocity and turbulence, and may spend a longer time away from the bed (saltation) and,as a result, be transported further downstream. Spherical particles would (if lifted) settle more easily and move downstream in a rolling mode. Therefore for coarse-size material differences in the settling velocities of individual particles may be controlled by shape. Experimental studies have shown that the effect of shape on settling velocities diminishes with decreasing particle size. Pye (1994b) attributed this relationship to the fact that at large Reynolds numbers (equation 1), the greater relative magnitude of surface irregularities causes the particles to spin, tumble, and rock to a greater degree, shedding turbulent eddies, that deflect the trajectory of the grain and reduce its overall terminal settling velocity.

$$Rp = \frac{v_f\, \mathrm{d}\, p}{\mu} \qquad (1)$$

Where Rp is particle Reynolds number v_f: fall velocity, d: diameter of the particle, p:density of the water, μ: dynamic viscosity.

Of particular significance appears to be the degree of particle flatness. Flatness is an important shape characterictics that has an influence across a wide particle-size range, although the effect is greater for larger grains (Wilde, 1952; Alger, 1964; Romanovskij, 1966; Komar and Reimers, 1978; Baba and Komar, 1981; Hallermeier, 1981; Hottovy and Sylvester, 1979). These studies demonstrate that, when compared with a sphere of the same volume and density, the flatter the particle, the slower the seftling. This can be explained partly by the large cross sectional area (measured perpendicular to the flow direction) of a strongly flattened particle to its volume, and hence higher flow resistance. Another reason is that the highly curved edges of such particles result in flow separation at much lower Reynolds numbers than in the case of more spherical particles. As a result, strong flattening may induceinstabilities in the settling of a particle, which will cause rotation, tumbling andoscillation so that the settling velocity of the particle will decrease (Stringham and Guy, 1969; Allen 1985). Middleton and Southard (1978) pointed out that the same kinds of flow regimes as developed around spheres, can be developed around many shapeg but the details of motion and the exact values of drag coefficients and of the Reynolds numbers for the transition from one regime to another differ between shapes. At high Reynolds numbers, values for drag coefficients vary from less than 0.1 for well streamlined shapes to more than 1.0 for flat discs transverse to the flow. They also noted that settling of non-spherical particles is quite complicated and therefore it cannot be represented by a single diagram of the drag coefficient and Reynolds number. In other words, for particles of irregular shapg there is no simple relationship between the laws of resistance and laws of settling (Middleton and Southard, 1978).

METHODOLOGY: VISUALISATION EXPERIMENTS

A series of visualisation experiments were deigned to examine collision and hydraulic behavior of particles of various shape and size in water. Visualisation experiments, using strobe-light photography, were carried out with natural and artificially moulded gravel-size particles of differing shape, density and weight. Settling and transport velocities of particles of varying size and shape (sphere, blade, rod, disc) were measured for artificially-moulded and natural particles. The density of the artificial particles was approximately 1.48. Experiments were undertaken in a 10 litre, water-filled rectangular tank. Particles were dropped, through water,onto a 30° inclined, smooth glass plate. A camera mounted outside the tank, normal to the sloping glass, recorded the fall and movement of each particle. A strobe light (strobe rate 25 flashes / second) was mounted at right angle to the camera. By keeping the camera shutteropen for the duration of the experiment multiple images of the particle could berecorded on the same frame of film. A mirror was placed opposite the strobe with the subject in between. This configuration meant the particles received strobe lighting from two directions. The camera shutter was kept open for the duration of each particle drop and collision in order to observe multiple images of the particle before and after impact on a single frame of film. The pattern of each particle were caught on a single frame of film. The film was used was 400 ISO black and white negative film which was up-rated to 3200 ISO. Settling velocities and trajectory paths were measured from the photographs by plotting successive centres of mass of the particle. A second set of experiments, using the same set-up as the first, but this timeinvestigating initial motion of particles of varying shape and size was undertaken on two beds of differing roughness 7 and 14 mm. This involved the same set of ‘drop’ experiment used in the first experiments but particlews were also placed on the bed and the bed was tilted until the test particle moved from its pocket of origin. Strobe light photographs were taken at the initiation of motion. In all experiments the distinction is made between settling (motion of the particle in the water column) and transport (movement of a particle at the bed). The method follows Schmeeckle (1998) and Schmeeckle et al. (2001).

RESULTS

Settling and transport velocities of artificial particles of similar b-axis size but varying shape (sphere, blade, rod, disc) were measured. For each shape 10 measurements of settling velocity and transport velocities were taken to determine a mean and standard deviation. Figures 2 and 3 summarise the settling and transport paths of four artificial grain shapes (sphere, rod, disc and blade). The experiment was repeated 10 times for each grain shape and the paths overlaid. The point of impact of the particles with the glass plate was used as a common reference position for overlaying the traces (Figure 3).

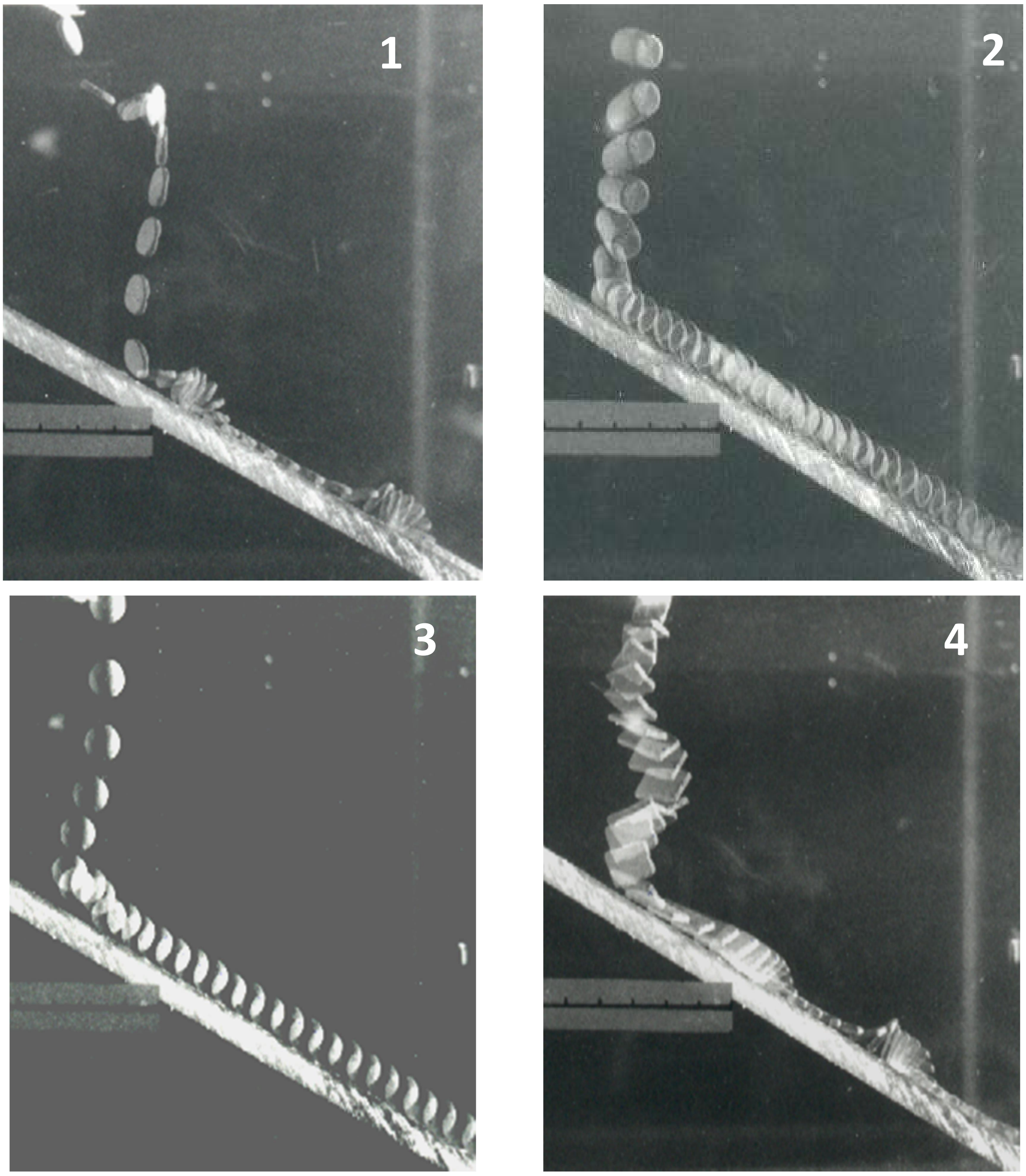


Figure 2: Strobe-light photographs of sphere particle striking a glass surface inclined at 30^0 degrees in water. The same experiment was replicated 10 times. These photographs show four examples of a sphere (1), rod (2), disc (3) and blade (4). The strobe rate was set at 25 flashes per second.

The particle motions observed in the experiments can be divided into three modes: settling, impact and transpoft (rolling or sliding). Characteristic movement patterns can be observed. Spheres fall steadily during settling and because ofthe high speed ofimpact show a large rebound followed by a smooth rolling motion. Rods show asteady fall with some rotation. Rebound is minimal and transport is by relativelysmooth rolling with the long axis transverse to the slope. Spheres and rod-shapedparticles generally settle in a more uniform fashion, despite a slight initial increase inrate of settling.

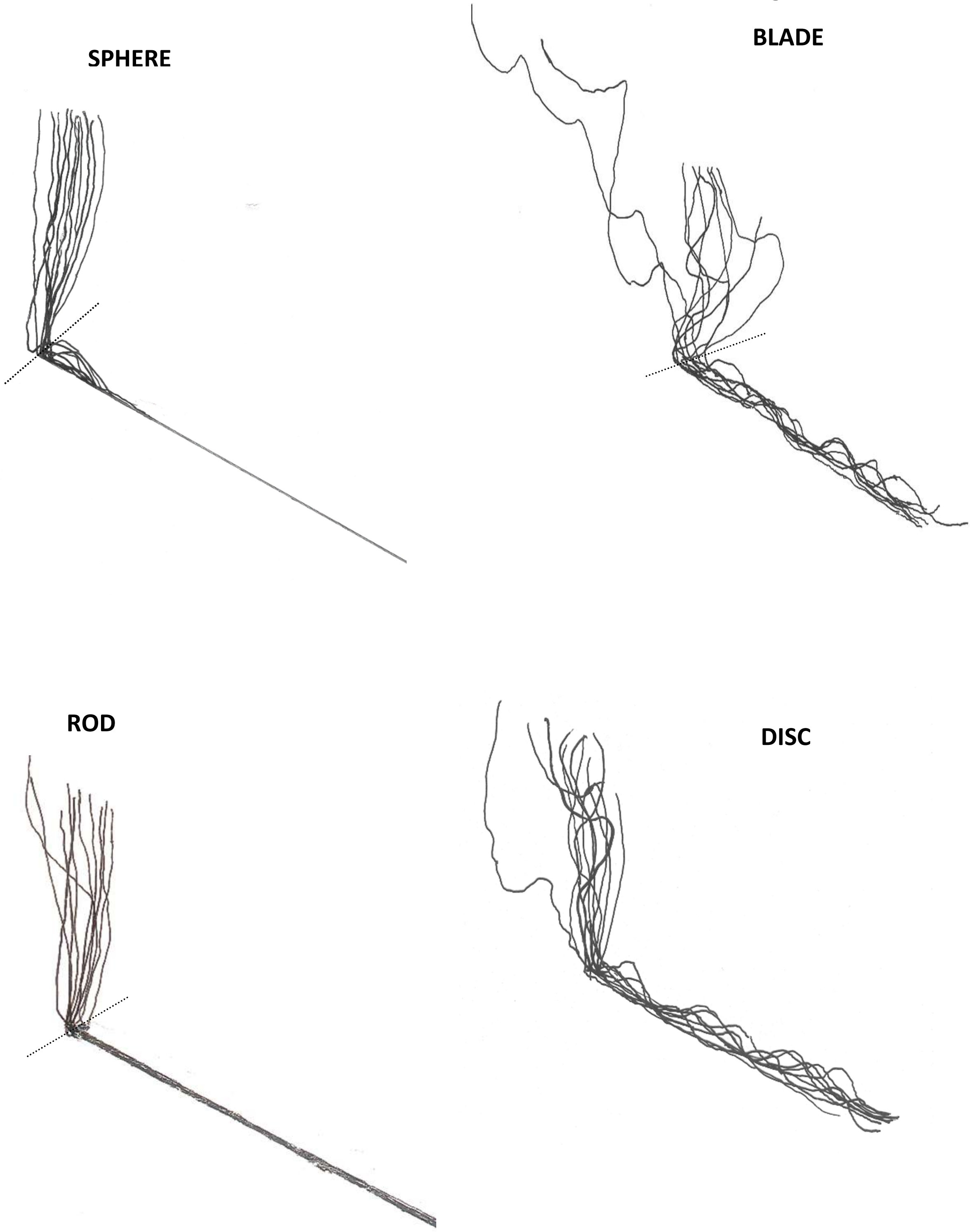


Figure 3: Summary of particle settling and transport paths for four particle shapes in water striking a glass surface inclined at 30º degrees. The same experiment was replicated ten times for each particle. The dotted line shows the division between settling and transport modes.

After the initial impact on the base plate the sphere tends to reboundslightly and then rolls downslope (Figure 3.1). The velocity of rolling slightly increase as the particle rolls further.

Figure 3.2 shows the rod also showed very uniform settling. The rod tends to settle with its a axis transverse to the slope and to roll with the same orientation. There is little rebound after the initial impact and the rod tends to accelerate with downslope distance. Blade settling paths are highly variable, often showing a glide and tumble motion. Although impact angles are highly variable rebound is negligible. Transport is variable but usually follows an oscillatory sequence of 'collapse-slide-lift-stall-collapse-slide' with the long axis transverse to the slope. Discs tend to follou either a regular oscillatory settling path or a glide and tumble motion. There is little rebound on impact and transport follows a similar pattern to the blade with occasional 'on edge' rolling (Figures 2 and 3). Blade and disc shapes, however, showed a more complex and irregular hydraulic behaviour depending on their orientation ln general, for disc and blade-shaped particles (Figure 3.3 and 3.4) the settling paths tended to be much longer and irregular than for the rod and sphere shapes. Settling velocities are greatest when the test particle falls in a vertical orientation, whereas in a horizontal orientation, particles tend to move laterally, leading to a slower settling velocity. Blades show some degree of irregular settling. For example, the blade tends to fall in a horizontal plane and then stall. After the initial impact with the glass plate it tends to accelerate in a sliding mode and then stall by standing on its vertical plane with its long axis transverse to the slope. Following a short movement in a vertical plane the particle collapsed on its horizontal plane and accelerated again, which result in a second vertical motion in the lower part of slope, after which it collapses again. Discs show similar hydraulic settling behaviour to blades. Discs tend to change orientation from a vertical position to horizontal or from horizontal to vertical, which results in differential settling rates (Figure 3.3). As the larger surface area of a particle tums to a horizontal position, the contact area oft he water column with the particle surface increases and this leads to a greater resistance which results in lower settling velocity. In terms of the settling trajectories, Figures 3.3 and 3.4 also show that sinuous settling paths occur if a particle is in a horizontal position, whereas in a venical downward movement, particle-settling paths seem to be relatively straight.

Artificially moulded grains are geometrically perfect but natural river gravel is far less uniform. Figures 2 and 4 show settling and transport paths for both artificial and natural particles. The artificial particles are slightly larger than the natural ones and significantly less dense. General pattems of motion are similar to those described above. There is little difference between the movement of spheres and rods. Blades and discs show greater differences, particularly in settling. The motion of natural grains is often more complex and less hydrodynamically predictable. Small differences in shape produce fairly large differences in hydrodynamic behaviour. In Figure 4 discs and blades show rotation rather than the glide and tumble settling of the artificial particles.

Settling velocities of four natural sandstone particles (sphere, blade, rod, disc, density 2.41) were measured. The same set of experiments as those carried out on the artificial particles were repeated for the natural particles. Behaviour between the two sets of experiments cannot be compared directly due to difference in particle density. In general, sphere-and rod-shaped particles produced a similar pattern of settling and transport velocities (rolling) to the artificial particles. Blade-and disc-shaped particles, on the other hand, exhibited more uniform and relatively shorter senling paths as compared to those measured with artificially formed particle shapes. Figure 4 shows typical strobe-light photographs of natural gravel sphere, blade, rod, and disc-shaped particles. Figure 4.1 shows that sphere-shaped particles have a relatively consistent pattern of settling. After the initial impact with the glass plate both the rebound heightand also damping distances ofthe natural sphere tended to be greater than for artificialones due to the greater density of natural the particles. The rod showed a similarpattem of settling to the sphere but for the rod there was little rebound and a shorterdamping distance (Figure 4.2).

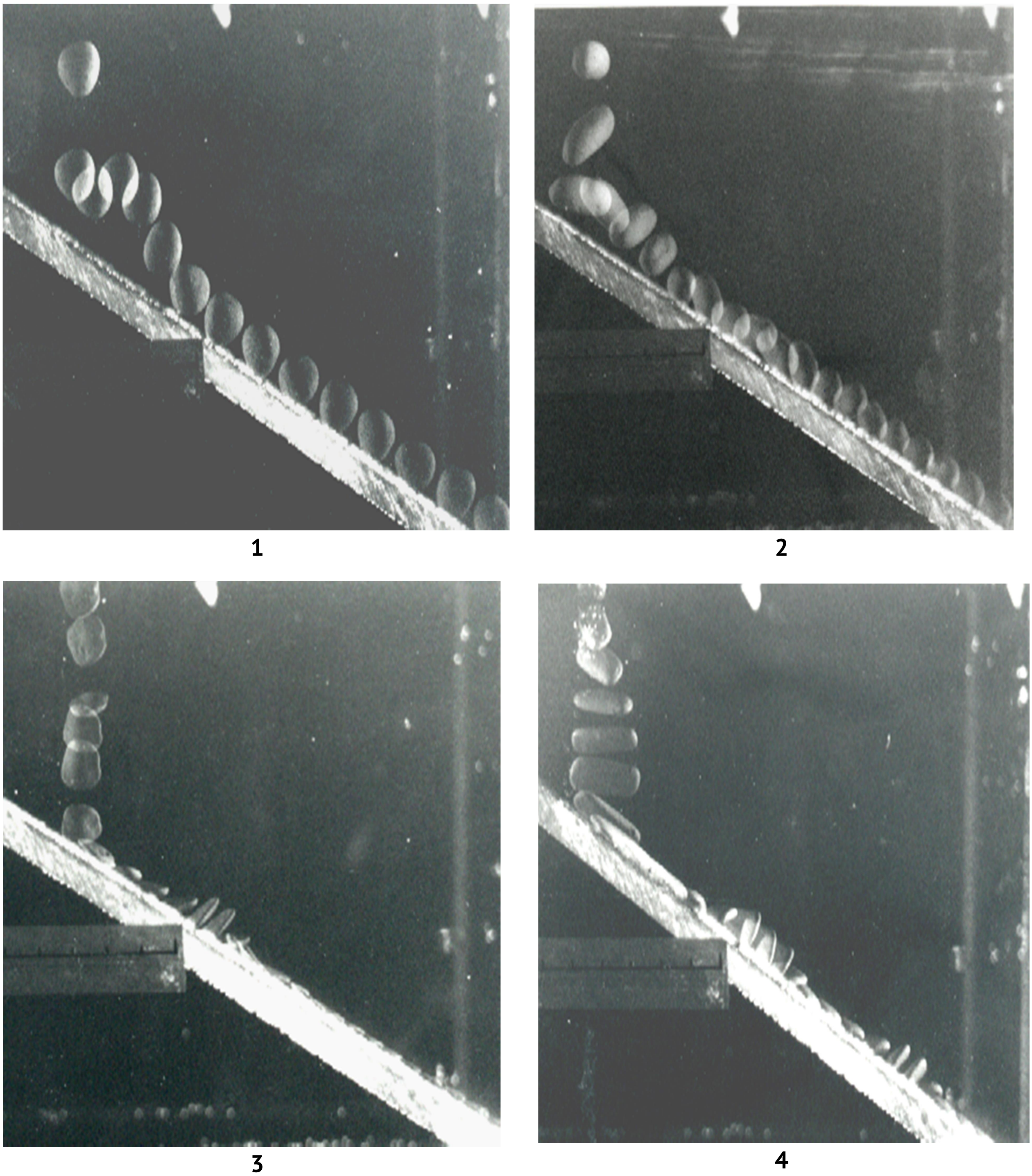


Figure 4. Strobe-light photographs of a natural sphere striking a glass surface inclined at 30^0 degrees. The same experiment was replicated 10 times in water. These photographs show four examples as sphere (1), rod (2), disc (3) and blade (4). The strobe rate was set at 25 flashes per second.

The rod hit the base plate with its long axis in avertical plane which caused a small rebound, and then it re-oriented itself with the long axis transverse to the slope. In each experiment, the rolling velocity ofthe rod tended to increase slightly downslope. The natural blade and disc-shaped particles settle inrelatively straight, vertical paths that are more constant than with the artificialparticles. However, in relation to transport velocity, similar patterns of motionbetween artificial and natural particles were observed. The blade in Figure 4.4, shows a straight vertical line of fall with its long axis in a vertical plane. Following initialimpact the blade with its long axis transverse to the slope, accelerates with a slidingmode, which then leads to an elevation ofthe particle in a vertical plane (which resultin a decrease in transport velocity). It then collapses onto a horizontal plane and slidesagain. This irregular pattern of movement with varying sequence of orientation is repeated downslope. In other replicate drops the blade slid at an almost constant velocity with its long axis parallel to the slope. This indicates that blades slidingdownslope with long axes transverse to slope tend to accelerate. This accelerationforces the blade to elevate and changes its orientation from the horizontal to the vertical plane or from'vertical to a horizontal plane which leads to irregularity intransport. On the other hand, a blade moving downslope with its long axis parallel toslope shows a relatively consistent sliding mode ofmovement along the slope.

The natural disc in Figure 4.3 shows an initial increase in settling velocity ofthe disc falling in a vertical plane. It then turned in a horizontal plane, which caused a decrease in settling velocity. Finally it began its vertical fall again with an increase in settling velocity. After the first impact on the glass plate, it accelerated with a sliding motion until it lifted and then collapsed again in a horizontal plane. It then accelerated again in a sliding mode and a second elevation took place. Observations ofreplicate drops showed that ifthe particle impacted on the base plate in the vertical plane it tended to jump or accelerate immediately after the landing, which then led to elevation in the upper slope. On the other hand, if the landing took place in a horizontal plane, the particle tended to slide along most of the slope and accelerate towards the bottom of the slope.

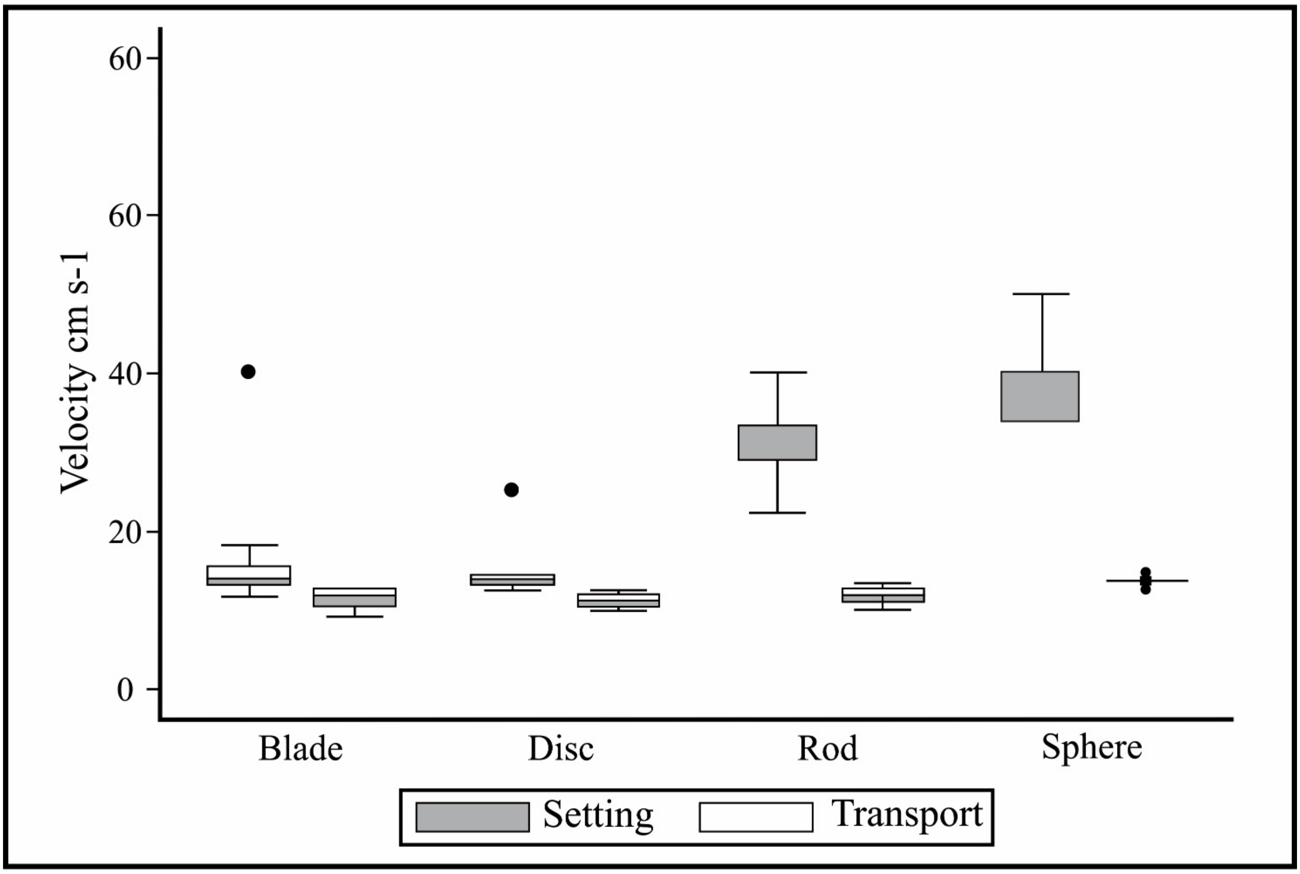


Figure 5 shows the mean settling and transportvelocities of artificial particles of different shapes. This demonstrates thal particle flatness has an important influence on the settling velocity. The more the particles are flattened, the slower they will settle compared with spheres and rods of the same size and density. Indeed, sphere-and rod-shaped particles tend to have greater mean settling velocities than blades and discs, which have relatively similar mean values. The increasing order of the rank is 14.6 cm s^{-1} for discs, 16.8 cm s^{-1} for blades, 29.4 cm s^{-1} for rods, and 37.0 cm s^{-1} for spheres. Bladesand

discs settle more slowly and show relatively large scatter around their mean values in terms of particle transport velocity. Figure 5 also showsthat, despite faster meansettling velocity for spheres and rods than for blade- and disc-shaped test particles, asimilar pattem in the mean transport velocities does not emerge. Mean transportingvelocities are much lower than the settling velocities ofspheres, blades, and rods(Figure 5). For sphere-shaped particles, transport velocities vary between 12.5 cm $s^{-1}$and 14.3 cm $s^{-1}$with a standard deviation value of 0.6. For rods the velocity variesbetween 10 cm $s^{-1}$and 13.3 cm $s^{-1}$with a standard deviation value of 0.9. Differencesbetween the individual transport velocities varied between 9.1 and 12.5 for blade anddisc with a standard deviation value of0.9. After the collision with the base plate,blade-shaped particles did not move for two measurements. For the disc shapes in two out of the 10 experiments test particles did not move after impact.

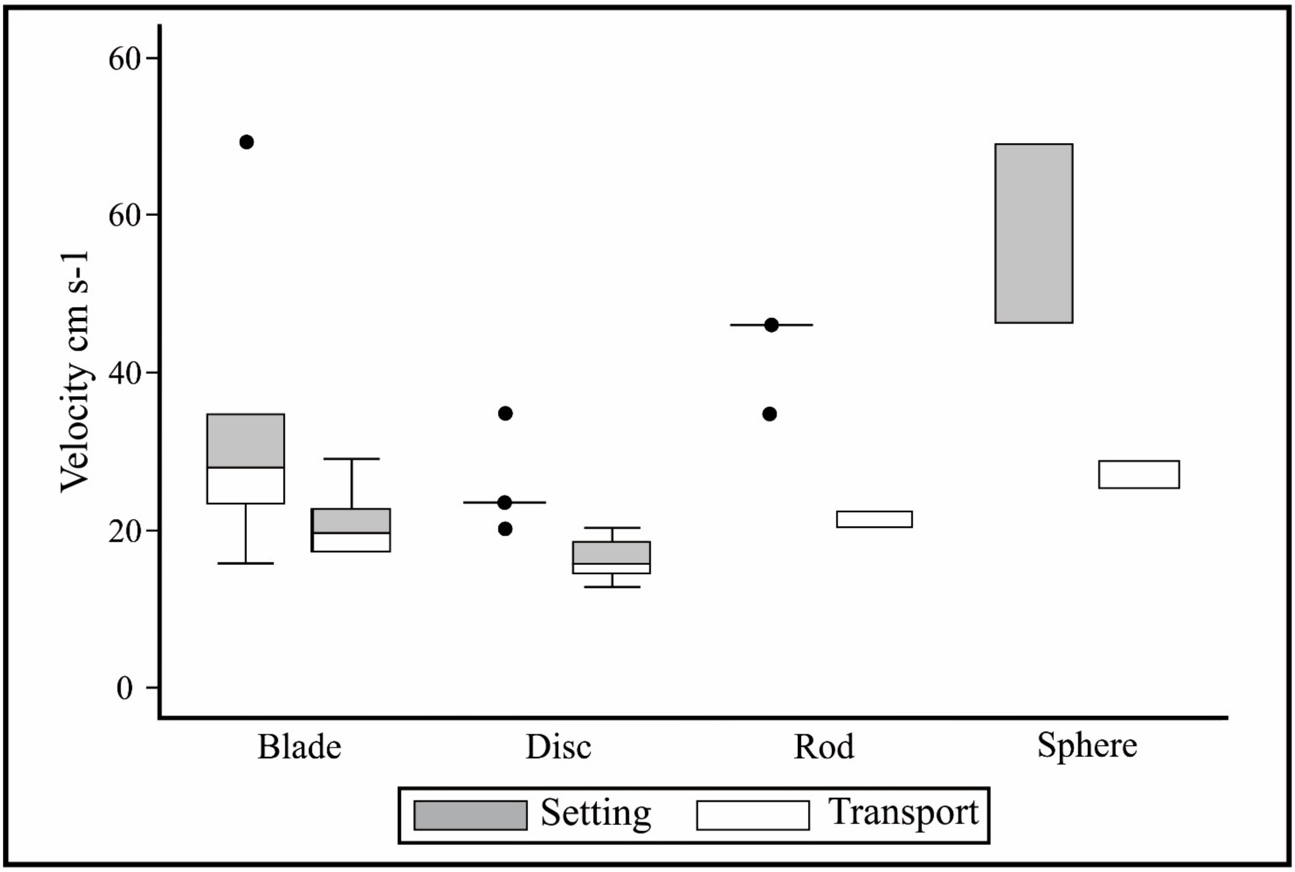


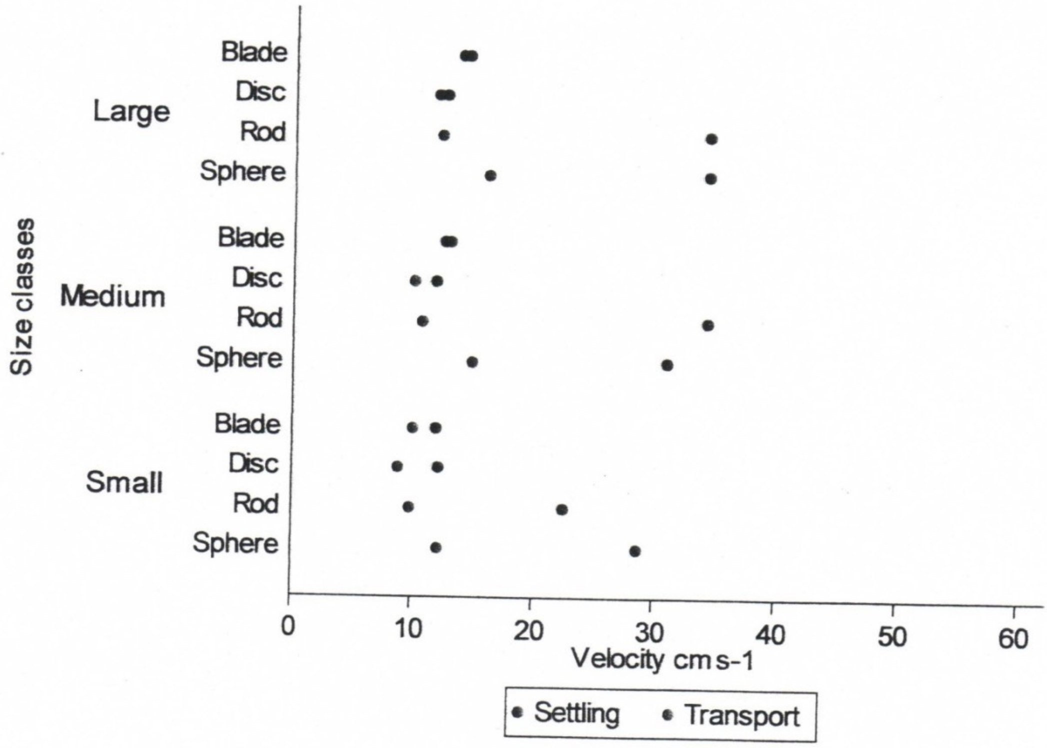
Figure 6 summarises the settling and transport velocities of the natural test particles. Although standard deviations are quite large a clear pattem emerges: spheres settle fastest, followed by rods, blades and discs. The transport velocity of a particular grain is always less than its settling velocity often by a factor of two or three. This pattern is similar to the artificial test particles except that settling and transport velocities are greater on account of the greater density of the material.

In general, patterns of settling velocities of natural particles is similar to those measured for artificial ones, e.g. higher settling velocities for sphere-and rod-shaped particles, lower values for disc-and blade-shaped particles. However, natural particles tend to settle much faster due to their greater density (2.41) than the artificial particles used (1.48). Mean settling velocities vary between 68.8 cm s^{-1} (sphere) and 23.4 cm s^{-1} (disc). Again, sphere- and rod-shaped particles show greater settling velocities. The increasing order, the mean velocities are 23.4,31.4,48.1 and 68.8 cm $s^{-1}$for disc-blade-rod-and sphere-shaped particles respectively (Figure 6). The settling andtransport velocities ofindividual particles within each shape class and their mean and standard deviation values indicate that settling velocities, for individual sphere-and rod-shaped particles tend to be greater, and more consistent than for blade-and disc-shaped particles. For sphere-shaped particles, settling velocity is very uniform (68.8cm s^{-1}) with a standard deviation of 11. It changes between 34.4 cm $s^{-1}$and 68.8 cm $s^{-1}$for rod-shaped particles wirh a standard deviationof 48.1. For blades, however, settling velocities are much greater and vary between 15.3 cm s^{-1} and 68.6 cm s^{-1} with a standard deviations of 14.6. Discs, on the other hand, shows less variation between the individual measurement (19.6-22 9 cm s^{-1}; with a small standard deviation of 4.1. In terms of particle transport velocity the pattern is again similar to the artificial deviation value of 1.1. On the other hand, as with artificial particles, the differences between the individual measurements tend to increase for the blade (16.7-28.6 cm s^{-1}) and disc, 12.5-20.0 cm s^{-1}). Greater standard deviation in transport velocities of blade and disc-shaped particles result because variations in particle orientation have a significant effect on settling rate and the nature of the particle transport velocity. Comparison of artificial and natural particles within the same size range particles, with is no great variation between different shapes. Figure 6 shows that, on a 30°inclined smooth base plate, mean transport velocities tend to decrease from sphere (27.5 cm s^{-1}) to rod (20.9 cm s^{-1}), blade (20.2 cm s^{-1}) and disc (16.1 cm s^{-1}) respectively. However, for a given distance, mean transporting velocities are much lower than that of settling velocities for all shape classes and the difference becomes greatest for sphere-shaped particles, while it is smallest for discs. For spheres, rolling velocities vary between 25.0 cm $s^{-1}$and 28.6 cm s^{-1} (standard deviation 1.7), while for rods it varies between 20.0 cm s^{-1} and 22.2 cm s^{-1} with a standard and same shape class showed that density has an imponant influence on particle settling velocity and hence Reynolds number. Natural particles are greater in density than artificial particles. This leads to higher settling rates and hence greater Reynolds number values for natural particles. Mean Reynolds number for the settling velocity of natural particles is almost twice (6188) that ofthe artificial particles (3700).

Settling and transport velocilies of arrificial particles of differing shape and size

In order to investigate the combined influence of particle shape and size on settling velocity, form of movement (rolling or sliding) and trajectory paths a series of experiments were carried out with artificially-moulded gravel-size particles. The test particles were arranged in three size groups in terms of their intermediate axes (b-axis): 5 mm small, 10 mm medium and 15 mm. Individual particles were dropped through water onto an 30° inclined smooth glass plate and each drop was replicated to ensure consistency.

Figure 7 shows that, in common with previous experiments, in each size group, sphere-and rod-shaped particles tend to have faster settling velocities than discs andblades. In the small size group, the settling velocities are 28.6 cm s^{-1}, 22.5 cm s^{-1}, 12.2cm s^{-1} and 11.9 cm s^{-1} for sphere rod, disc, and blade respectively. In the medium sizegroup again rods and spheres show faster mean settling velocites; 30.6 cm s^{-1} forspheres, 34.3 cm s^{-1} for rods, 12.6 cm s^{-1} for blades, and 11.8 cm s^{-1} for discs, while inthe large size group the rank is also 34.3 cm s^{-1} for both spheres and rods, 14.4 cm $s^{-1}$for blades and 12.6 cm s^{-1} for discs. For almost all shape classes there is an increase inthe settling velocity with particle size. The increasing rate of mean settling velocity for sphere-shaped particles is greater than blade and disc. In the small, medium and large size groups it varies between 28.6, 30.6 and 34.3 respectively for spheres, while for rods the variation is between 22.5 (small size) and 34.3 (large size). There is a similar trend for blades, 11.9-14.4, and discs, 12.2-12.6. In tenns of transport velocities, it appears that, regardless of shape, velocities tend to increase slightly with size. Figure 7 shows small differences between settling and transport velocities of blade-and disc-shaped particles, with greater differences for rod-and sphere-shaped particles in each size group. The ratio of settling velocities to transport velocities indicates the importance of settling to transport. In every size group settling velocities for sphere and rod-shaped particles are noticeable greater than that of blades and discs. The reason is that sphere-and rod-shaped in each size group tend to be of greater weight, which leads to laster settling, and have smaller projection areas compared to discs and blades.



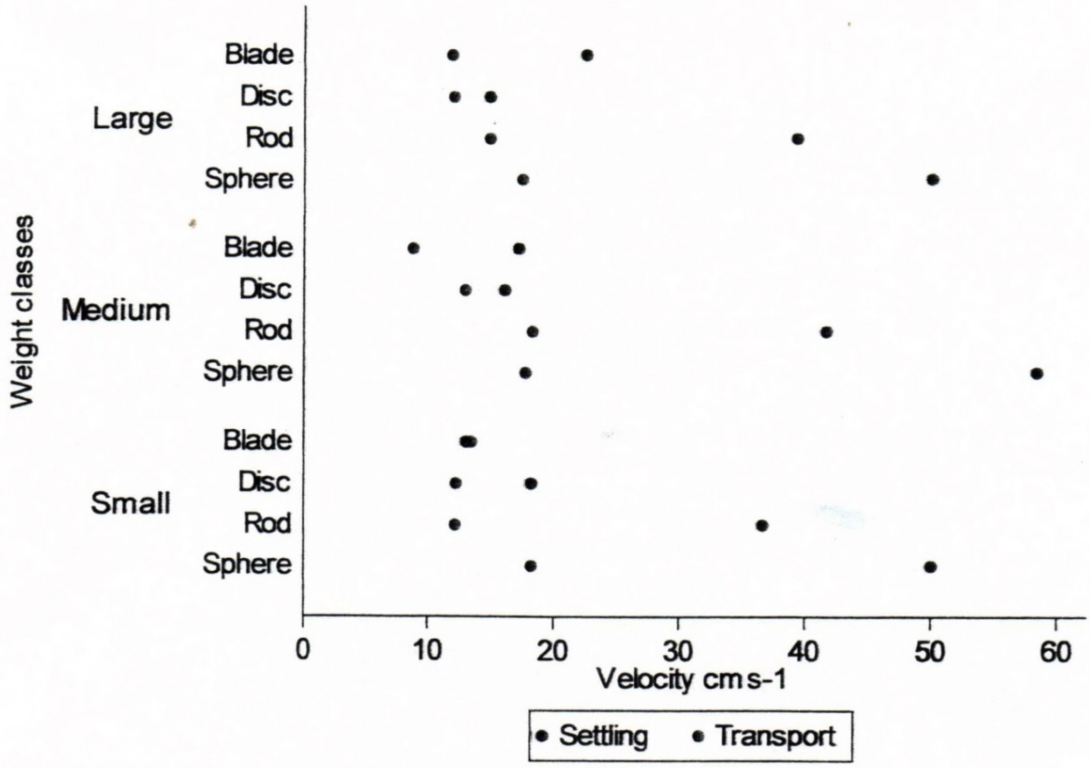


Figure 7

A series of experiments were carried out with artificially-moulded gravel-size particles in order to determine changes in settling and transport velocities of different particle shapes in relation to weight (Figure 8). The dependence of settling velocity is clearly demonstrated in settling equations such as Stokes Low. Particles were classified into three weight classes. In each class particles were prepared using wet clay of equal weight. However, on drying resultant weights showed some slight differences.Therefore, in each class test particles were of approximately equal weight but differed in shape. Sphere-and rod-shaped particles tend to be heavier than blades and discs due to their greater c axes. Figure 8 shows that, despite their similar weights, mean settling velocities of the sphere-and rod-shaped particles are noticeable greater than discs and blades in almost each weight group. Within each weight group, spheres tend to show the fastest settling velocities, while discs, except in the small group, show the slowest rates. The decreasing order of settling velocities in the small group is sphere, rod, disc and blade, while for the medium and large size groups the ranks are sphere, rod, blade and disc. Within each weight group spheres have relatively uniform vertical settling trajectories, while rods show similar settling velocities but with slightly more rotation about their long axis, Discs and blades on the other hand exhibit slower, more irregular modes of settling depending on their orientation.

Settling and transport velocities of irregular shaped natural particles

Although it is well known that the settling velocity ofa particle is strongly dependent on its shape (Allen, 1969,Corey, 1949;McNown and Malaika, 1950; Graft, 1971; Komar and Remiers, 1978; Baba and Komar, 1981; Dietrich, 1982) there have been few studies investigating the settling velocities of natural particles with irregular shapes. These are appreciably different from ideal shapes such as spheres, ellipsoids and cubes (Goossens, 1987). The purpose of this section is to examine the settling and transport velocity of irregular shape natural particles. Natural (irregularly shaped) particles were selected in two size ranges 4-8 mm and 8-16 mm. The test particles were taken from Trout Beck (Figure 1). In each size group 10 particles were randomly selected from a total sample of 100. The reasons for choosing these size ranges were for ease of measurement and also these ranges were most commonly transported in floods at the experimental sites. It was assumed that smaller sized particles would reduce the effect of particle shape on settling and transport velocities. Sandstone particles with an average density of 2.41 were used. Each particle within the two size groups was dropped twice through water, onto a 30° inclined, smooth glass plate. Settling velocity, form of movement (rolling or sliding) and trajectory paths were measured from the photographs.

In terms of settling velocities (Figures 9A and 10) the experiments show that there is no simple pattern of settling and transport velocities between the particles of various shapes and size. However, in common with the earlier experiments Figures 9A and 10 show that sphere and rod-like particles tend to settle slightly faster than blade-like and disc-like particles. Mean settling velocity of the large particles (42.2 cm s^{-1}) is noticeable greater than the small size group (30.7 cm s^{-1}). High standard deviation values for the large size particles indicate that differences between the settling velocities of various shapes is greater than in the small size group. This demonstrates a positive relation between the particle size and the influence of shape on settling velocity. In other words, as particle size increases, differences between the settling velocity of various shapes tends to be greater. In the small size group, mean settling velocities vary between 40.1 and 34.0 cm s^{-1} for rods and spheres respectively, while for disc-like and blade-like particles it is 26.9 and 27.8 cm s^{-1}. In the large size group, there tends to be an increase in mean settling velocities for almost all shapes. Mean settling velocities are 57.3 for sphere and rod-like, 43.3 for blade-tike and 28.8 cm s^{-1} for disc-like particles. Particles falling in a vertical plane have relatively greater settling velocities than those falling in a horizontal plane. Differences in the mean settling velocities between spheres, blades and discs, tend to be smaller in the 4-8 mm size than the 8-16 mm size.

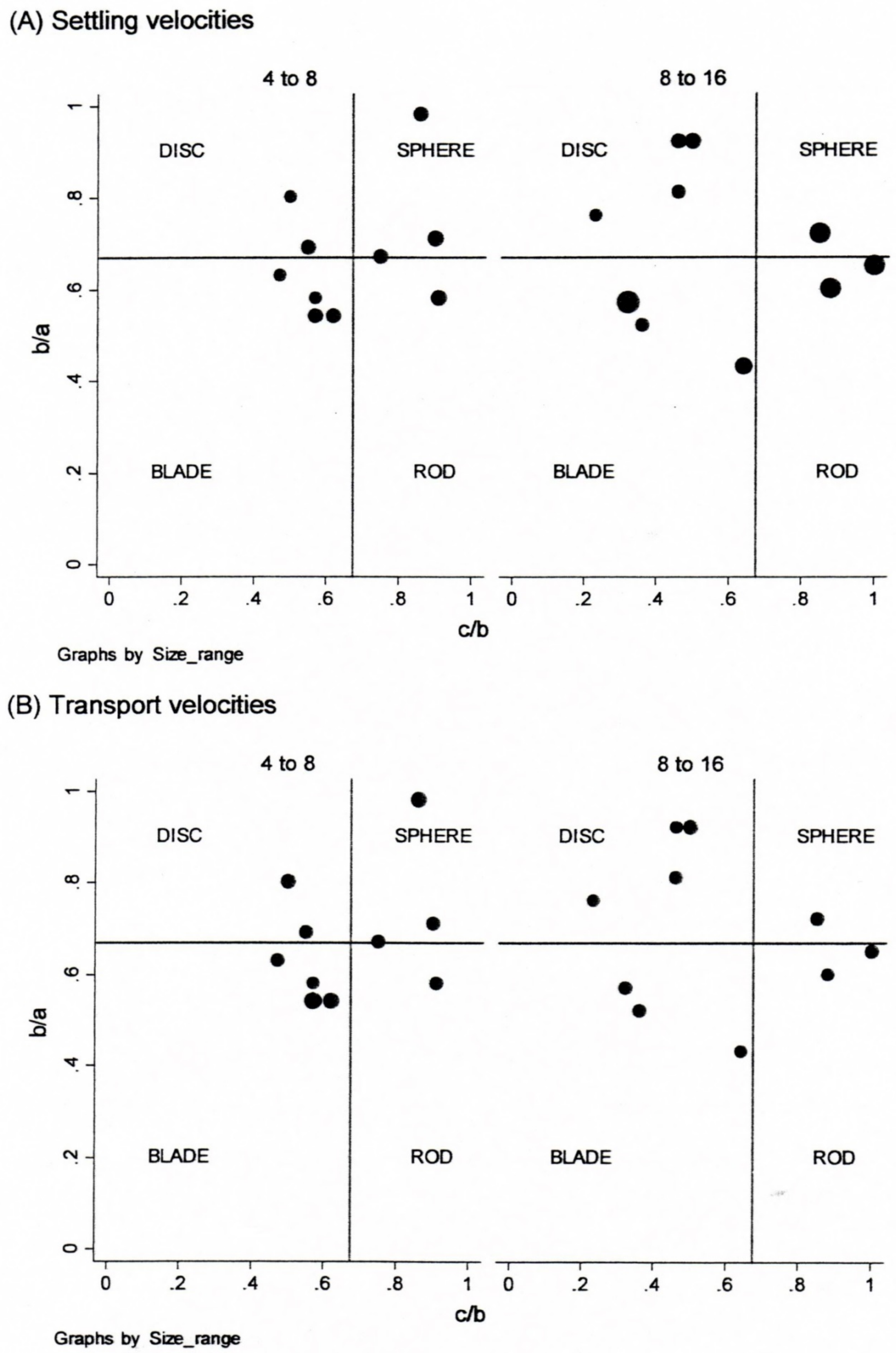


Figure 8

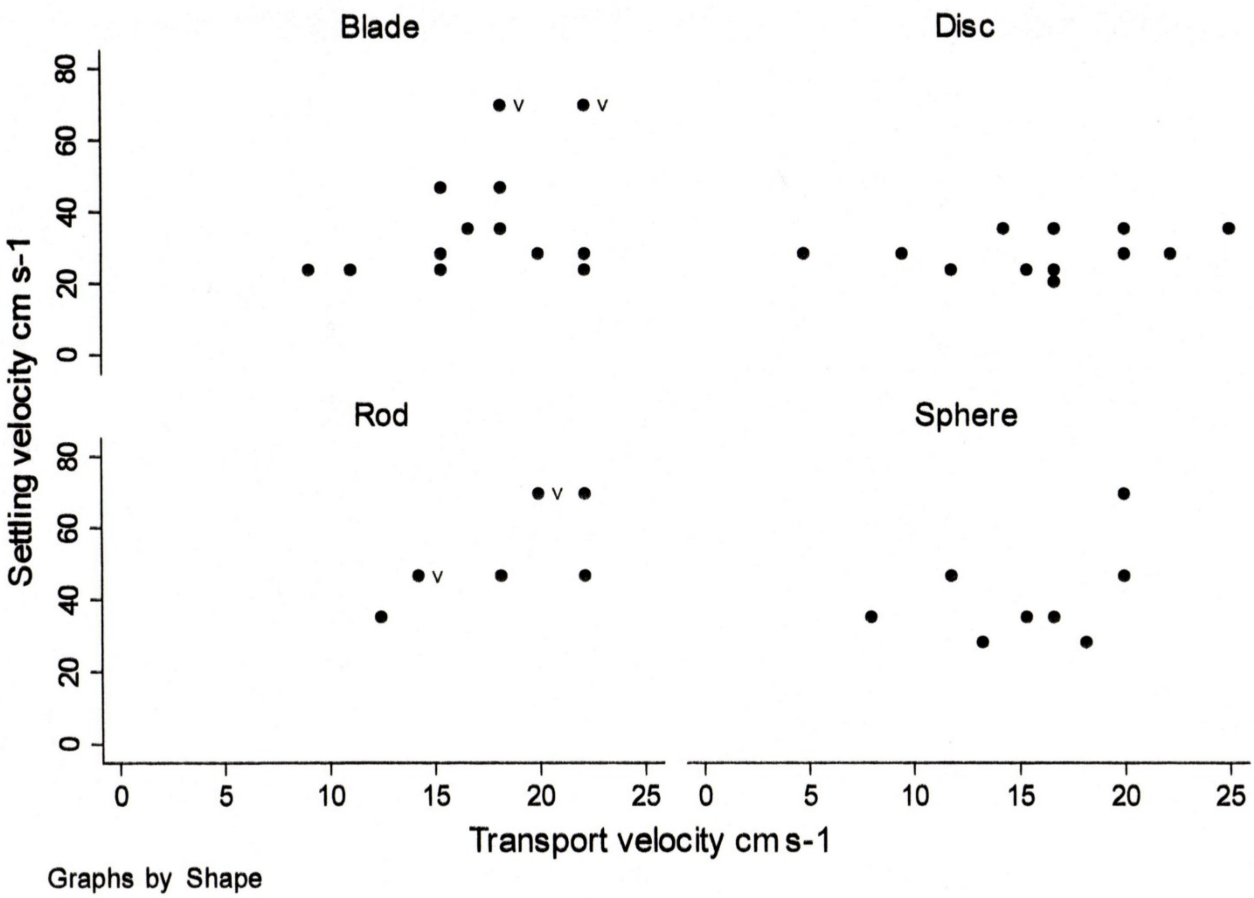


Figure 9

In terms of the mode of movement and the transport velocities, Figures 9B and 10 show that mean transport velocity for large size particles (regardless of shape) is much greater than the mean small size group (13.9 cm s^{-1} small and 19.1 cm s^{-1} large size groups). However, lower standard deviations in each size group indicate that there is no greater variation between the transport velocities of different shapes. ln contrast to the previous experiments carried out with uniform-shaped particles, in which rod-and sphere-shaped particles moved in rolling modes, most of the irregularly-shaped natural test particles exhibited a sliding mode of movement rather that rolling. For example, although they are expected to roll, some sphere-and rod-like particles moved in a sliding mode. The reason might be attributed to their rather lower sphericty and roundness values. For example some spheres moved in a rolling mode because of their greater roundness and sphericity degrees and hence lower flatness. This highlights the fact that apaft fiom particle form (eg. sphere, rod, blade and disc), other shape properties (eg. degree of sphericity, roundness, flatness etc) have also significant influence on the hydraulic behaviour of particles. Even small variations in these shape parameters result in significant differences in transport mechanisms.

Initial motion and movement of particless of various shape on bed of varying roughness-Friction (Pivot) Angle Measarements

A series of experiments were undertaken using four test grain shapes to investigate (a) how critical friction angle depends on grain shape and the relative size of the pivoting grain relative to the underlying roughness and (b) the mode of movement of artificial particles of various shape on two different bed roughnesses. Four artificial particles with different shapes but the same size range (b-axis) were placed on beds with different forms of roughness elements. Two bed roughnesses were formed by attaching glass rods of different diameters (7 and 14 mm) across the sloping glass plate. With the test particle in place, the beds were tilted until the test particle moved from its pocket of origin. For each of the test particles five measurements were taken. For blade-and rod-shaped test particles, five measurements with transverse orientation and five with parallel orientation were collected.

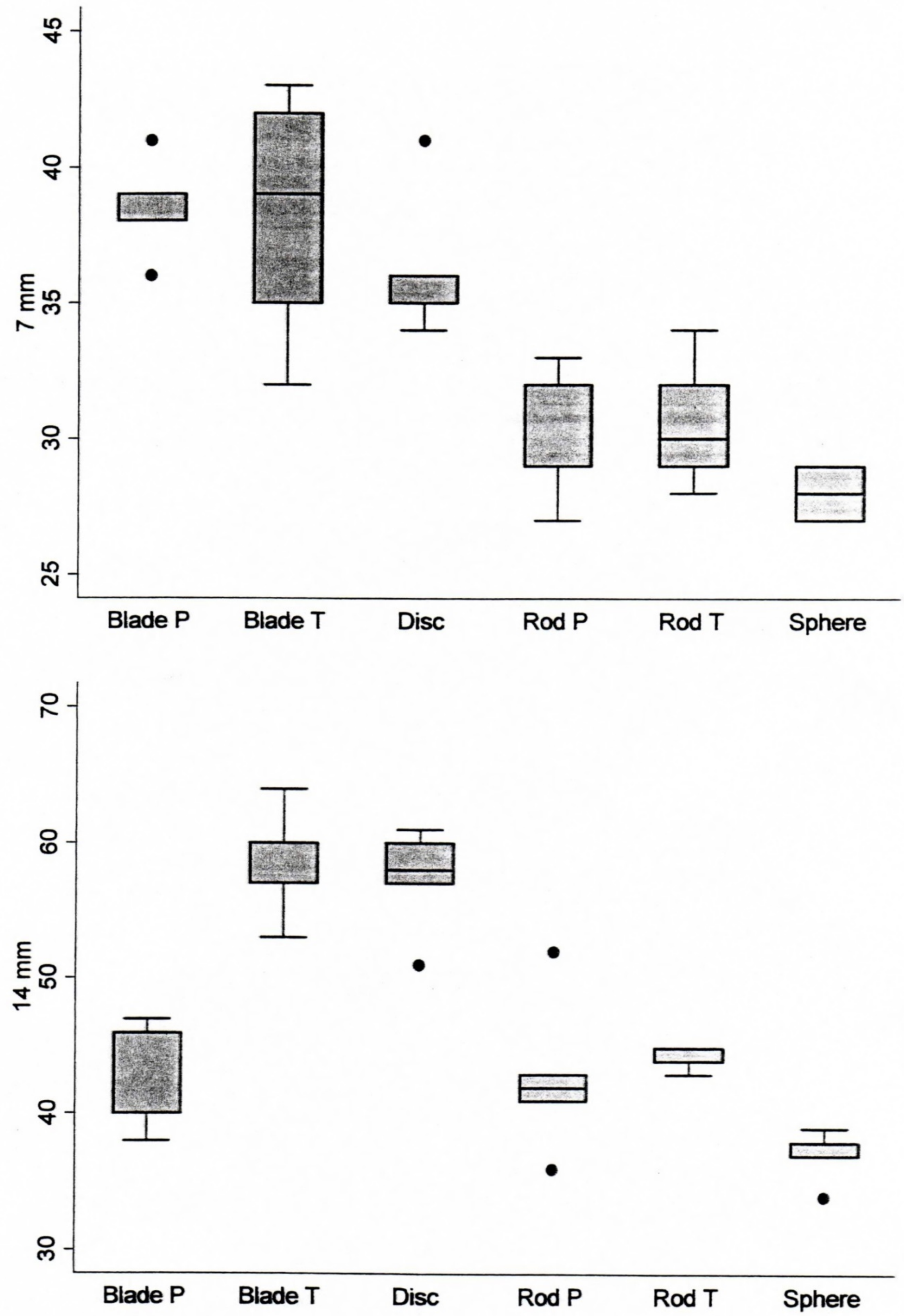
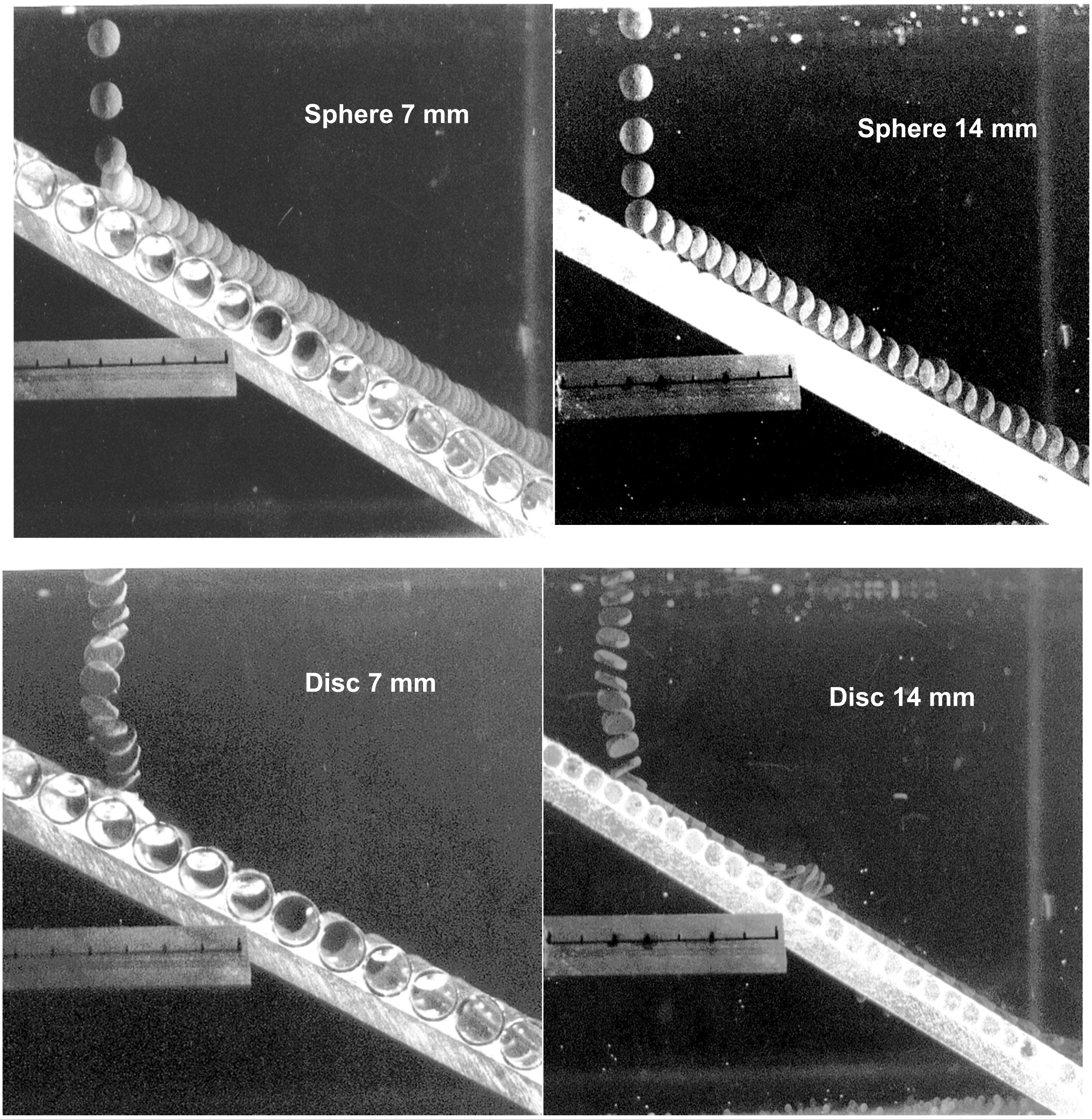


Figure 10

Results are shown in Figure 11. Generally, sphere and rod-shaped particles have lower friction angles than blade and disc shapes. The orientation ofelongate particles has a bearing on the friction angle. As bed roughness increases the critical frictionangle also increases. Discrepancies in friction angles between the two roughness types are greatest fort he blade (transverse arientation) and disc. This is because the intermediate axes(10mm) of these grains tends to lodge in the pockets of the 14 mm roughness elements and the small axis inhibits pivoting out of the pocket. However, the blade in parallel orientation (long axis 20mm) 'bridges' the roughness elements and has a friction angle similar to the 7 mm roughness type. In both cases movement is by sliding. Overall particle dimensions, relative grain-size and the mechanism of movement (pivoting or sliding), therefore control initial motion.



Detailed examination ofthe strobe photogaphs for the two roughness types (Figure l2) clearly shows that the spherical particle has a more irregular movement pattern on the coarser bed. On the 14 mm roughness' after initial movement the grain tends to 'pivot and drop' from pocket to pocket Comparison ofthe behaviour ofan artificial sphere and disc on two roughnesses (7 and l4 mm) is shown in Figure l2 For the sphere, settling and transport paths are very similar. The mode of movement for the bed roughnesses (7 and 14 mm) artificial particles of various shapes on two different is shown in Figures 12. Settling and transport pathsfor the sphere and rod were very similar on both roughnesses. Rebound after initial impact was negligible and the particles moved by Rolling. However, on the 14 mm roughness surface, movement was a little more irregular with fluctuations in velocity as the particles passed over the underlying pockets. The disc and blade, on the other hand, showed a very different pattern of movement. They settled along a regular oscillatory path. On the 7 mm roughness surface the disc and blade impacted at an angle approximately 45°, then they collapsed and began to slide. The particles accelerated until there was sufficient lift to allow them to climb from the bed. The particles then ‘stalled’, collapsed and began sliding again. On the 14 mm roughness, these particles impacted on their edges rotated and began to slide. However, the first pocket the disc encountered immediately stopped it. The leading edge of the grain abutted against the upstream face of the roughness element and motion ceased (Figure 12.) At 30° the slope is well below the critical friction angle for this particle and roughness (57°). The blades exhibited a similar movement pattern to that on the 7 mm roughness surface. It accelerated in a sliding mode, stalled, collapsed and began sliding again.

SUMMARY and DISCUSSION

Shape is an important particle characteristic that has a significant effect on settling rates and the mode of near-bed transport. Characteristic movement pattems can be observed. These effects increase with larger particle sizes. During settling, grains always orientate themselves with their maximum projection are normal to the flow. However, on the bed, due to grain-grain interactions, this is not always the case. This investigation has focussed on the influence of the particle shape, size and orientation on the mode of motion and threshold entrainment conditions. Based on visualisation experiments. Results show, across the range of particle sizes tested, that sphere and rod-shaped particles tend to settle faster and move by rolling. Discs and blades Show slower settling rates and, in most instances, move by sliding. Experiments carried out with inegularly shaped, natural particles show greater variability in settling behaviour and irregular pattems of motion.

The nature of settling is a function of particle mass, size, shape and orientation. Experiments have shown that there are some fundamental differences in settling velocities and the pattern of settling trajectories between particles of various shape classes (Figures 2, 3 and 4). First of all, spheres and rods exhibited more uniform seftling patterns and modes of movement. Spheres settled vertically in a very uniform fashion whereas rods also showed similar settling with slightly more rotation about their axes (Figure 4). Blade and disc shapes, however, showed a more complex and irregular hydraulic behaviour. For blade- and disc-shaped particles the settling paths are much longer and irregular (sinuous) than for the rod and sphere shapes (Figures 2 and 3).

An important control upon settling behaviour is particle settling orientation (Figures 2 and 10). A particle with its maximum projection area horizontal to the water tends to settle more slowly than a particle with its long axis inclined at a 90° to the flow. This differential settling velocity reflects differences in resistance to settling. Discs showed similar hydraulic settling behaviour to blades. For most ofthe observations, blade-and disc-shaped test particles tended to change their orientation from a vertical position to horizontal or from horizontal to vertical, which resulted in different settling rates. As the larger surface area of a particle turns to a horizontal position, the contact area of the water column with the particle surlace increase and this leads to a greater resistance which results in lower settling velocity. Whereas a downward movement with a venical orientation was found to minimise resistance, leading to an increase in settling velocity. Settling tended to be slower when disc and blade particle were in a horizontal orientation whereas in a vertical downward movement, particle settling paths seemed to be relatively straight and settling velocity greater. It has been shown that as a particle settles and changes orientation, the rate of settling will also vary.

Settling in a vertical orientation tended to be faster than settling with the maximum projection area parallel to the base. Spheres and rods settle along more uniform paths. In terms of the settling paths, it has been demonstrated that, in common with the findings of Willmarth et al (1964) some disc- and blade shaped panicles showed an irregular oscillation during settling. Disc and blade-shaped particles exhibited a glide-tumbleJike settling pattern in which they swung from side to side as they settled (Figure 3). Tumble settling was also observed as flat-shaped particles continuously tumbled end over end, and moved along a path that was straightbut oblique to the vertical.

Transport velocities are much lower than the settling velocities ofspheres, blades, and rods. Despite faster mean settling velocity for spheres and rods than for blade-and disc-shaped test particles, a simiiar difference in the mean transport velocities between various shapes does not exist. In relation to the mode of transport, it was observed that the initial impact of a particle with the sloping plate (inclined at 30°from horizontal) produces two distinct sets of behaviours. First spheres impact the plate and bounce off, whereas, discs and blades hit the slope plate in a more gentle wal'and then begin to slide down the slope. Spheres always rebound and rods somerimes rebound, but blades and discs do not. This might be attributed to the fact that spheres and rods offer less resistance during settling because of their smaller surface areas therefore impact the plate at a greater velocity. Following the initial impact the velocity of movement along the sloping plate was almost constant for rods and spheres, whereas discs and blades tended to accelerate. The mode of movement down the slope is again a function of panicle shape. For most of the experiments, spheres exhibited a uniform rolling mode with close contact with the bed. Similarly rods rolled down the slope with their long axes transverse to the slope. Discs andblades moved mostly in a sliding but more complex movement during their transport.

It has been found that general pattems of motion ficr natural particles are similar to those of artificial particles. There is little difference between the movement ofspheres and rods, while blades and discs show greater differences, particularly in settling. The motion of natural grains appeared to be more complex and less hydrodynamically predictable. Small differences in shape produce fairly large differences in hydrodynamic behaviour. Comparison of the settling and transport velocities of natural particles indicated that spheres settle faster, followed by rods, blades and discs (Figure 4). Ajthough there are much smaller differences, transport velocities follow a similar pattern. It was found that the transport velocity ofa particular grain is always less than its settling velocity, often by a factor of two or three. The implications for sediment transport are interesting. Lower transport velocities mean slower movement at the bed. Rolling is faster than sliding. However, slower settling velocities do not equate directly with lower transport rate as a particle once entrained may remain in the upper flow profile longer and as a consequence step length may be greater.

In terms of settling and transport velocities of irregular-shaped natural particles, experiments have shom some significant differences between artificial and natural panicies with ideal shapes. In general, no simple patrern of settling and transport velocities was found between particles of irregular shapes and to some exlent size (Figure 10). Particles with angular shapes are observed to show a greater variability in settling behaviour and irregular patterns of motion. This is an important factor in bedload transport studies because, in gravel bed rivers, natural bed material shape deviates considerably from the ideal shape type and hence may not conform to models established for sphere, blade, rod and disc settling and transport (Figure 10). This suggests that, despite some indications about the settling and transport mechanisms of particles of various shape and size, the experiments carried out here with artificial and natural panicles of ideal shapes do not directly represent acrual particle motion in a natural channel. However, some general trends appear to be valid. The more spherical the shape the faster it settles. Departure fiom a sphericalform leads to a decrease in settling velocity. The sphere and rod-like particles tend to settle faster and move by rolling, while disc and bladelike particles tend to Show slower settling rates and, in most instances, move by sliding mode.

Generally, sphere-and rod-shaped particles were found to have noticeably lower friction angles than blade and disc shapes. The orientation ofelongate particles (rods and blades) has an influence on the friction angle. As bed roughness increases the critical friction angle also increases. Differences in friction angles between the two roughness types are greatest for blades (transverse orientation) and discs. This is because the intermediate axes (10 mm) of these grains tends to lodge in the pockets of the 14 mm roughness elements and the small a axis inhibits pivoting out of the pocket. However, a blade moving in parallel orientation (long axis 20 mm) ‘bridges’ the roughness elements and has a friction angle similar to the 7 mm roughness type. In both cases movement is by sliding. Thus, it was found that, overall, the initial motionofa particle is controlled by its dimensions relative grain-size and the mechanism ofmovement (pivoting or sliding). Spherical particles have a more irregular movement pattern on the coarser bed. On the 14 mm roughness, after initial movement, the graintends to ‘pivot and drop’ from pocket to pocket (Figure 12).

In terms of settling and transpon on different bed roughnesses, comparisons of the behaviour of the particles of various shapes showed some distinct differences. Spheres and rods showed very similar settling and transport paths on both roughnesses (7 and 14 mm), although on the 14 mm roughness transport was a little more irreeular with fluctuations in velocity as the particle passed over the underlying pockets. The discs and blades showed a very different pattern of movement by settling along a regular oscillatory path. Subsequent to the initial impact on the 7 and 14 mm roughnesses, discs and blades tended to collapse and begin to slide. The particles accelerated until there was suflicient lift to allow them to climb from the bed (Figure l2).

These experiments have clarified some aspects of the hydraulic behaviour of particles (in different shape and size characteristics) that cannot be observed directly in the field. However, these observations cannot directly be related to bedload transport mechanisms in a stream for the following reasons. Firstly, in a coarse-gravel channel, flow resistance is more complex and generally controlled by large-scale roughness elements and the local characteristics ofthe bed material. Even under a steady flow there is a wide scatter in the relationship between hydraulic variables and bedload transport. The roughness elements also have very complex arrangements depending on the size and shape characteristics of bed material, local bed gradient and flow conditions. Thus particles moving over these beds may have relatively complex hydraulic behaviour compared with those on a relatively smooth bed with constant gradient. The present experiments was carried out on a relatively constant slope (30°)with no roughness. Although two settling and transpon experiments were also carriedout on rough beds, they cannot directly represent natural gravel bed roughnesses, since they were made up with uniform sized (7 mm and 14 mm) roughness elements. When the test particles were released onto inclined plates (either smooth or with roughened slopes) they tended to roll or slide continuously depending on particle shape, due to the constant and high gradient ofslope. Spheres and rods generally tended to move in a smooth rolling motion, while transport for the blades and discs usually varied with an oscillatory sequence of collapse-slide-lift-stall-collapse-slide with long axis transverse to the slope. As earlies studies (e.g. Hassan and Church, 1992) have demostrated, the movement of coarse particles in a gravel bed is not continuous, but instead consists of a series of step and rest periods due to complex bed roughness elements, local flow condition and variation in channel gradient. The experimental set-up used here was to create a simple model to investigate particle shape effects. The gravity settling experiment in a static fluid on to an inclined planes cannot be seen as a direct surrogate for natural stream flow conditions where dynamic turbulenceand shear and lift forces are operating in a complex multidimensional space. Under such condirions coarse bedload will be in contact with bed for most of time and would be continually colliding with other particles therefore the influence of settling and shape dependent transpon would be greatly diminished.

Secondly, in terms of shape and size characteristics of test particles, it was clear there were some clear differences between the test particles used for the present experiments and natural particles moving in a natural river channel. Most of the test particles used (both artificial and natural) for the present experiments were geometrically 'ideal' shapes, whereas in a gravel-bed river, bed material (in most cases) will not include 'true' spheres, blades, rods and discs (which would plot in the extreme corners of the Zingg diagram). In other words, in a natural gravel bed river many of the spheres and rods are very blocky with rather lower roundness values, while blades and discs are rather thicker with high c/b axis ratios and tending towards equant diameters. Thus, as it was shown in the experiments carried out with irregular shaped natural particles, particles with irregular shapes (typical of a natural stream channel) probably do not have similar hvdraulic behaviour to those demonstrated here with ideal shapes.

Finally, a major control on the settling behaviour is particle density. The experiments carried out with artificial test particles may not truly represent actual settling rates.This is because, as shown with natural particles, natural particles tend to settle much faster than the artificial particles due to their greater density.

The implications for sediment transport are interesting. Lower transport velocities mean slower movement at the bed. Rolling is faster than sliding. However, slower settling velocities do not equate directly with lower transport rates as particles once entrained may remain in the upper flow profile for longer and as a consequence step length may be greater. Although the results of these experiments cannot be directly related to the actual stream channels, they may shed light into some problems encountered in sediment transport mechanisms in gravel bed rivers. One of the findings of the present study is that particle shape has an important influence on its hydraulic behaviour. Experiments have proved that settling and transport velocities are predominantly controlled by particle shape, orientation, size and to some extent density. Sphere-and rod-shaped particles tend to settle faster than the other shapes. It was also found that, apart from shape, the velocity of settling increases with size and density. Within the same size-and shape-ranges particles with greater density tend to settle much faster than those of with lower density.

In a gravel-bed river channel the majority ofparticles are irregular in shape rather than geometrically ideal shapes. The present study clearly showed that particles with irregular shape have very complicated hydraulic behaviour. In other words they do not settle or move in a way in which an ideal shaped particle of natural or artificial form behaves. However, although irregular shaped particles in a natural channel do not have similar hydraulic behaves to those with ideal shape, their proximity to any ideal shape (either spherical or flat) indicates their type of hydraulic behaviour. In other word, a sphere-like particle tends to have a hydraulic motion similar to a well-formed sphere. Along with the high roundness degree, the more spherical the panicles the faster it settles or rolls on a surface. Similarly, depending on its proximity to perfect flat-shaped particles, blade and disclike particles tend to settle rather more slowly and move in a sliding mode.

The present study also showed that increased irregularity of particle shape, such as blocky sphere and rod-like particles with low roundness, or disc and blade-like particles with greater c/b ratio, may diminish the influence of shape on hydraulic behaviour. In this case the effect of size becomes the dominant factor on particle transport phenomena. It was also found that the influence ofparticle shape on both settling and transport mode increases with increasing size.

The experiments here demonstrated that the degree of bed roughness and channel gradient has a significant influence on the initial motion of a particle and also its hydraulic behaviour. For a given size, shape and density, the entrainment of a particle sitting on a bed depends on the degree of bed roughness and also local channel bed gradient. In the light of the present experiments it is likely that, on a rougher river bed, the initial motion of all particle and also their movement will be retarded by the bed roughness elements. It has been shown that as the bed is roughened, particles begin to move at relatively greater friction angles.

Finally, the proportion of time a particle spends in settling or transport mode is critical in determining the transporf rate. Size and shape are crucial in governing this. In the field natural particles will tend (dependent in size) to spend a greater proportion of their transport history in “transport mode” rather than in “settling” or indeed “lift” modes. Therefore, differences in transport velocities are probably more important than settling velocities. Furthermore, in natural bedload transport, when multiple particles are in motion, the whole process is completed by inter-particle collisions and local near-bed turbulence (Schmeeckle, 1998). However, following the dispersion of particles in the channel, the shape and size selectivity (sorting) becomes importancefactors.

Assuming that bedload transport is a function of entrainment potential, efficiency of transport (in the fluid and in contact with the bed) the results presented here provide a physical basis for observed patterns of shape sorting observed in natural river channels (Figure 1).

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