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Effects of particle shape and mobility on stable armor development

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Abstract. The relative size and roughness of a stable armor varies with particle shape. For a given imposed shear stress the order of increasing nominal particle diameter is flat, angular, and rounded gravel. The order of increasing surface roughness is flat, rounded, and angular gravel. The mobility of fine flat gravel particles is enhanced by the lower surface roughness of armors which exhibit an imbricated structure. However, the generally lower mobility of ellipsoids means that, for a given stream power, bed load discharge associated with armor development on flat gravel is less than that for rounded gravel (at greater depth to grain size ratios). The larger projected area of angular gravel enhances the mobility of coarse grains at high flows, offsetting interlocking effects which restrict the mobility of angular gravel at low flows. Relative and absolute size effects contribute to the departure from equal mobility of coarse and fine particles that is a ubiquitous feature of stable armor development below the limit for the formation of a threshold armor when all particles are equally mobile. The transport of fine sediment as throughput load may mask the effect due to hiding in the field and give the erroneous appearance that stable armors develop solely through winnowing. All particle sizes in the underlying bed material are present in the armor and in the bed load, and coarsening is but one of several adjustments to the surficial bed material that occur as a stable armor evolves. It likely involves the wholesale rearrangement of surficial particles and may entail minimization of shear due to drag on background roughness.

Introduction

Stable armored surfaces develop on degrading beds in the absence of significant sediment input from upstream, under conditions where the imposed boundary shear stress is less than the critical boundary shear stress required to initiate motion of all particles on the bed surface [*Parker and Klingeman*, 1982; *Parker and Sutherland*, 1990]. A stable armor is essentially one grain diameter thick and, although all size fractions contained in the subsurface bed material are present on the bed surface, is coarser than the underlying sediment [*Harrison*, 1950; *Lane and Carlson*, 1953; *Gessler*, 1965; *Günter*, 1971; *Davies*, 1974; *Proffitt*, 1980]. The term stable armor [*Raudkivi and Ettema*, 1982; *Gomez*, 1984] is analogous to the term static armor used by *Sutherland* [1987] and *Parker and Sutherland* [1990].

The process of stable armor formation is conventionally attributed to the selective erosion (winnowing) of fine, mobile particles from the bed surface which slowly concentrates coarse, immobile particles at the bed surface and isolates the underlying bed material from the flow [*Sutherland*, 1987]. For a given initial bed material the resulting stable armor coarsens as boundary shear stress increases [*Gessler*, 1965; *Günter*, 1971; *Davies*, 1974; *Day*, 1976; *Proffitt*, 1980; *Lamberti and Paris*, 1992], to the point where the bed load and substrate size distributions are identical (i.e., all particle sizes on the bed are equally mobile). Thereafter, at low transport rates a mobile armor may form that will gradually disappear as transport rates increase in response to greater imposed shear stresses [*Parker*, 1980; *Parker and Klingeman*, 1982; *Andrews and Parker*, 1987; *Parker*, 1990]. Thus stable armors evolve as a consequence of a marked imbalance between sediment supply and transport and may be considered to constitute a limiting state of mobile armor that is reached as sediment transport diminishes locally or over the entire bed surface [*Dietrich et al.*, 1989; *Parker and Sutherland*, 1990; *Lisle et al.*, 1993]. The time taken for a stable armor to develop decreases as the proportion of immobile particles in the bed material increases [*Harrison*, 1950; *Garde et al.*, 1977], but because of the progressive decline in transport rates the adjustment time is correspondingly lengthy [*Andrews and Parker*, 1987].

Laboratory studies of stable armor development have a long history [*Harrison*, 1950; *Gessler*, 1965]. However, attention has increasingly been directed toward mobile armor development [*Parker*, 1980; *Kuhnle*, 1989; *Wilcock and Southard*, 1989; *Wilcock*, 1992] because of its affiliation with the concept of equal mobility [*Parker and Klingeman*, 1982; *Parker et al.*, 1982]. Field investigations undertaken in unregulated channels have largely been concerned with measurements of transport rates and analysis of size distributions of bed load [*Milhous*, 1973; *Kuhnle*, 1992]. An exception is the study of stable armor development undertaken by *Gomez* [1983a], who monitored temporal changes in the particle size distribution of surficial bed material.

Recognition that, under a wide range of flow conditions, the transport of heterogeneous sediment leads to the development of a bed surface that is coarser than the subsurface bed material has led to renewed interest in the evolution of

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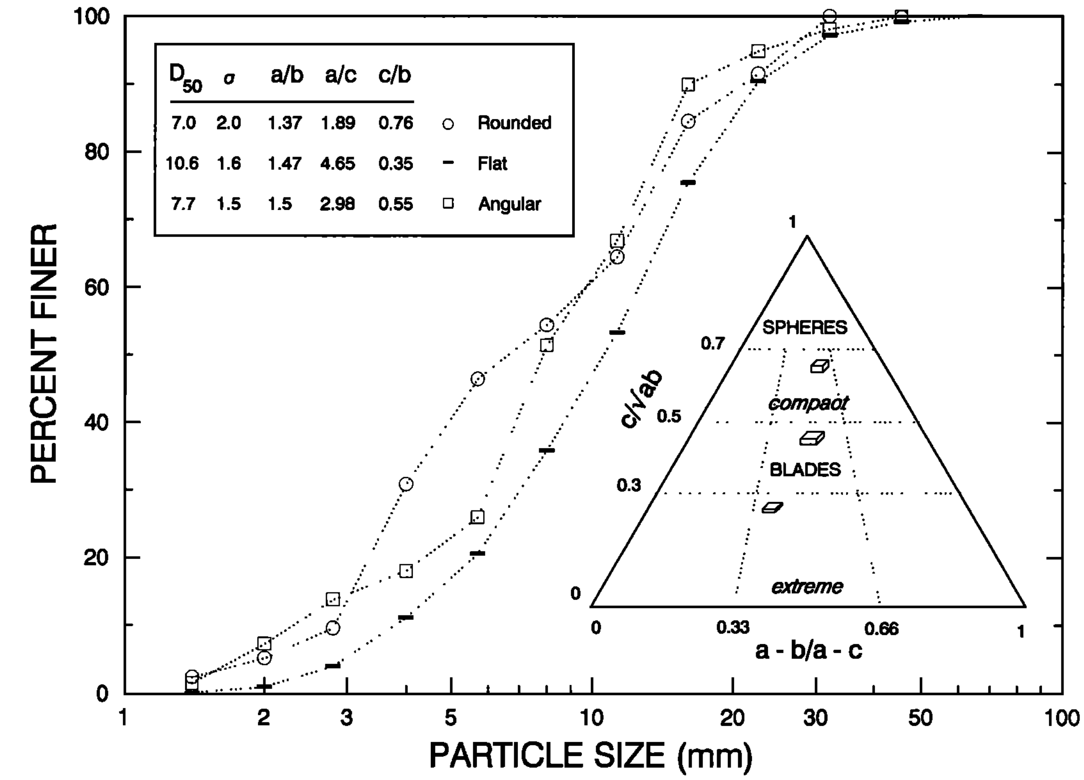

Figure 1. Particle size and shape of gravel mixtures. Scaled symbols indicate where gravel mixtures plot on shape diagram. Axial ratios are means for 100 randomly selected particles of all sizes, and D_{50} is in millimeters.

stable armors and to the description of the armoring mechanism under conditions of partial bed load transport [*Parker and Sutherland*, 1990]. The process is often viewed as an incipient motion problem [*Sutherland*, 1987] where the critical shear stress for movement of an individual particle depends on both its relative and absolute size [*Parker*, 1990]. *Lane and Carlson* [1954] and *Li and Komar* [1986] observed that the threshold of motion is also sensitive to particle geometry. Surprisingly, the effect of variations in particle shape on stable armor formation has not been investigated.

The effect that variations in particle shape have on the development of stable armored surfaces is examined in this paper. The armors developed on unimodal sediment mixtures composed of differently shaped particles in a laboratory flume, in which the imposed shear stress was always below that required to generate a threshold or late stage armor (i.e., the coarsest possible armor [*Günter*, 1971; *Parker and Sutherland*, 1990]). Differences in the particle size distribution and topography (roughness) of the resultant armored surfaces are examined. Fractional bed load transport rates are used to elucidate differences in the mobility of individual size fractions. The armoring process is inextricably linked with particle mobility, and these data permit an integrated investigation of the characteristics of stable armors that couples observations of surface structure and transport over a range of flow conditions and on differently shaped sediments. Comparisons with data derived from other studies of stable armor development [*Gomez*, 1981, 1983b] provide additional insight into the armoring mechanism via the changes that occur in the mobility of different size fractions during armor formation.

Experiment Design

The experiments were conceived with the object of developing plane, stable armored surfaces under steady flows and conditions of parallel degradation (i.e., where bed degradation and slope reduction were constant along the length of the channel). They were conducted in the 6-m-long by 0.5-m-wide and 0.5-m-deep tilting flume in the Geomorphology Laboratory, Department of Physical Geography, University of Uppsala [*Hjulström and Sundborg*, 1962]. No sediment was fed into the flume or recirculated during a run, and all material leaving the flume was retained in a stilling basin.

Three sediment mixtures with similar particle size distributions were used (see Figure 1, D_0 = 1 mm, D_{50} = 7–10.6 mm, and $D_{100} \leq 64$ mm, where D_x is the size for which x% of the distribution is finer). The particles comprising each mixture exhibited different bladed forms. In the first mixture the particles were compact, subrounded; in the second very bladed, subrounded; and in the third bladed, subangular (Figure 1). The sediments are qualitatively referred to as rounded, flat, and angular gravel. The rounded and angular gravel had a specific gravity (s) of 2.68. For the flat gravel, s = 2.78.

A fresh, smooth bed was created for each run, and water was gradually introduced into the flume to prevent unintentional segregation of the surficial bed material. The range of applied flows was constrained by the conditions required to initiate particle motion and by the depth of scour required to stabilize the bed surface and ensure that the largest particles were free to adjust vertically within the 0.12-m-deep bed. A run was terminated once the bed load transport rate had declined to <1% of that recorded at the start of the run and typically lasted about 24 hours.

Average total bed load transport rates and bed load size distributions were determined for a run by weighing all the sediment retained in the stilling basin and sieving a 5-kg bulk sample. Using a grid-by-number technique [*Kellerhals and Bray*, 1971], the particle size of the armored surface was determined at two locations (2.25 and 3.75 m from the flume entrance) by measuring the intermediate axis of 100 particles located beneath the intersections of 30 × 30 mm grid squares.

Armor topography was characterized using the location and elevation of the highest point on and the contact points between particles. Elevations were recorded (to ±0.25 mm in the vertical and ±0.5 mm in the horizontal) along a 1-m transect running down the centerline of the flume, located between the two bed material sampling points. Vertical photographs were taken of a 250-mm-wide strip centered along the length of the profile. Full details of the experiments and the methods utilized to describe armor roughness are provided by *Gomez* [1993] along with the unabridged data set. The stream power and average bed load discharge for each run, and an index of surface coarsening, are given in Table 1.

Table 1. Sediment Transport During Armor Development

Run	Stream Power,* kg s^{-1} m^{-1}	Bed Load† Discharge, kg s^{-1} m^{-1} × 10^{-4}	D_{50a}/D_{50m}
		Rounded Gravel	
1A	0.770	2.72	1.73
1B	0.864	2.37	1.86
1C	0.667	1.27	1.74
1D	1.648	8.07	1.91
1E	1.493	15.14	1.96
1F	1.595	13.94	1.96
1G	2.853	32.18	2.17
1H	3.043	26.14	1.99
1I	2.772	30.19	1.93
1J	4.436	54.24	2.14
1K	4.049	50.96	2.14
1L	3.571	53.77	2.10
1M	5.875	70.28	2.56
1N	5.093	63.81	2.20
1O	5.765	63.30	2.10
		Flat Gravel	
2D	1.443	1.14	1.21
2E	1.230	1.98	1.25
2F	1.247	3.61	1.38
2G	2.313	11.44	1.39
2H	2.607	14.14	1.55
2I	2.789	10.52	1.54
2J	3.761	24.25	1.57
2K	3.905	25.38	1.75
2L	3.514	24.41	1.74
		Angular Gravel	
3D	1.294	4.51	1.34
3E	1.570	4.55	1.31
3F	1.359	5.69	1.27
3G	2.848	25.03	1.43
3H	2.634	22.67	1.48
3I	2.904	27.76	1.58
3J	3.882	42.16	1.58
3K	4.248	44.45	1.64
3L	3.847	45.87	1.64
3M	6.472	60.86	1.94
3N	5.513	58.65	1.81
3O	6.116	61.49	1.66

See *Gomez* [1993] for complete hydraulic and roughness data.
*Corrected for sidewall effects.
†Average for complete run, adjusted to mean depth to grain size ratio.

Armor Characteristics and Particle Mobility

The stable armors that evolved in these experiments contained all particle sizes present in the original mixture (subsurface bed material). The D_{50} of the armor was consistently coarser than the D_{50} of the original mixture and, as in other studies [*Gessler*, 1965; *Günter*, 1971; *Davies*, 1974; *Day*, 1976; *Proffitt*, 1980], increased with increasing shear stress (Table 1). For a given bed shear stress the order of increasing median nominal particle diameter (D_n, the diameter of an equivalent spherical particle having the same volume) of a stable armor composed of differently shaped particles is flat, angular, and rounded gravel (Figure 2). *Lane and Carlson*'s [1953] observations of stable armors formed in unlined irrigation canals, Komar and Li's [*Li and Komar*, 1986; *Komar and Li*, 1986] analysis of the threshold of motion for differently shaped particles, and *James et al.*'s [1990] experiments on the entrainment of different shaped sediments from rough beds also demonstrate there is a strong dependence of entrainment on particle size and shape (following *Li and Komar* [1986], D_n is employed in Figure 2). The regression lines in Figure 2 are not parallel because (1) D_n was estimated from ratios, not measured axial lengths, (2) the degree of geometric similarity between natural gravel particles and regular triaxial ellipsoids varies with particle shape [*Koster et al.*, 1980; *Cui and Komar*, 1984], and (3) the larger projected area of angular particles likely contributes to their increased susceptibility to movement as armors form at progressively higher flows [cf. *Komar and Li*, 1986].

The relative coarseness of an armor (D_{50a}/D_{50m}, where subscripts a and m refer to the armor and mixture, respectively) is related to sorting ($\sigma = (D_{75}/D_{25})^{1/2}$). Well-sorted sediments exhibit smaller values of D_{50a}/D_{50m} for a given boundary shear stress than do poorly sorted sediments [*Proffitt*, 1980]. This is because, given the constraints of a fixed D_0 and D_{100} and the appearance in the armor of all particle sizes present in the original bed, the particle size distribution of the surficial bed material becomes more positively skewed as the surface coarsens, reflecting a tendency for the upper part of the grading curve to steepen and the lower part to flatten relative to the original curve. That is, the relative percentage of coarse particles on the bed increases solely at the expense of the finer fractions [*Gessler*, 1965]. The effect is accentuated in well-sorted sediments, in which a large proportion of the distribution occupies a relatively narrow size range. It also, as *Proffitt* [1980] noted, allows σ_a to approach σ_m if all particle sizes are in motion. This was the case in these experiments [*Gomez*, 1993].

D_{50a}/D_{50m} is plotted against the Shields stress $\tau_* = \tau/(s-1)\rho g D_{50m}$ in Figure 3 (where $\tau = \rho g S_e Y$, ρ is the density of water, g is the acceleration due to gravity, S_e is the energy slope, and Y is the flow depth). The comparatively small increase in D_{50a}/D_{50m} observed over the range of flow conditions is commensurate with the well-sorted sediment mixtures used in these experiments. Nevertheless,

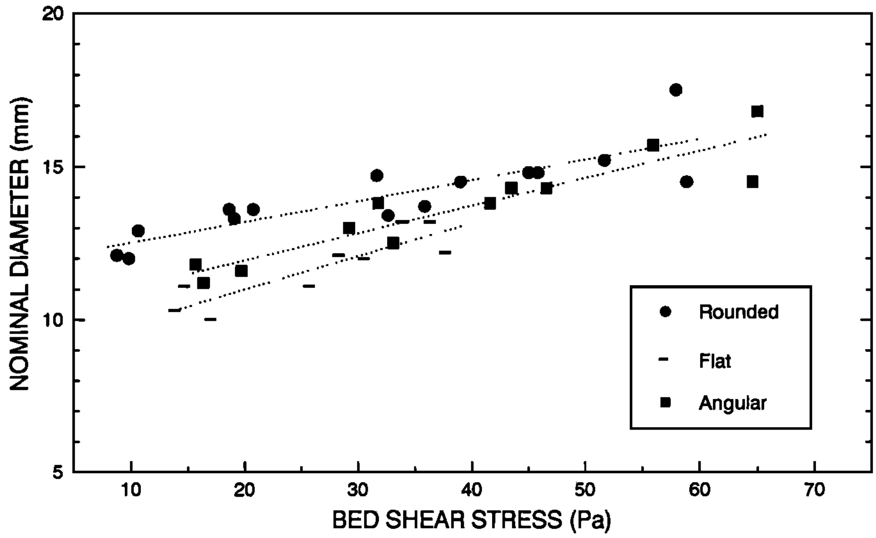

Figure 2. Variation of nominal diameter of stable armor with shear stress for rounded, flat, and angular gravel. Dotted lines indicate least squares regression relations.

variations in the relative coarseness of the stable armors due to sorting are apparent. For a given shear stress, D_{50a}/D_{50m} for the flat and angular gravel is less than that for the somewhat more poorly sorted rounded gravel. Regression lines are used in Figure 3 to accentuate the trend of the relations between D_{50a}/D_{50m} and τ_*. The slopes of the regression lines for the rounded and angular gravels are similar, suggesting that, in spite of differences in sorting and particle shape, these sediments elicit the same response in terms of the amount of coarsening that accompanies a given increase in the flow conditions. However, in the case of the stable armors developed on flat gravel, D_{50a}/D_{50m} increases more rapidly with τ_*. This is a product of the stability of the finer size fractions on an armored bed with an imbricated structure. For given flow conditions the order of increasing armor roughness is flat, rounded, and angular gravel [*Gomez*, 1993]. The fine flat gravel size fractions are more mobile than their rounded and angular counterparts because the relatively subdued topography (roughness) of an imbricated bed surface affords less opportunity for fine grains to shelter behind coarse particles as the armor matures.

Armor roughness increases with increasing flow. Changes in the distribution of effective roughness height (h, the difference in height between the highest point on a particle and the average elevation of points of contact with adjacent upstream and downstream particles) reflect the contrasting ability of armors composed of differently shaped particles to retain fines on the surface as the bed coarsens. Large particles account for the bulk of surface roughness, and regardless of particle shape, distributions of effective roughness height are leptokurtic (Figure 4). For armored surfaces developed on rounded and angular gravel (Figures 4a and 4c), variations in the distribution of effective roughness height with increasing flow reflect the increase in the proportion of coarse grains on the bed and are most pronounced within the upper 50th percentile. There is little change within

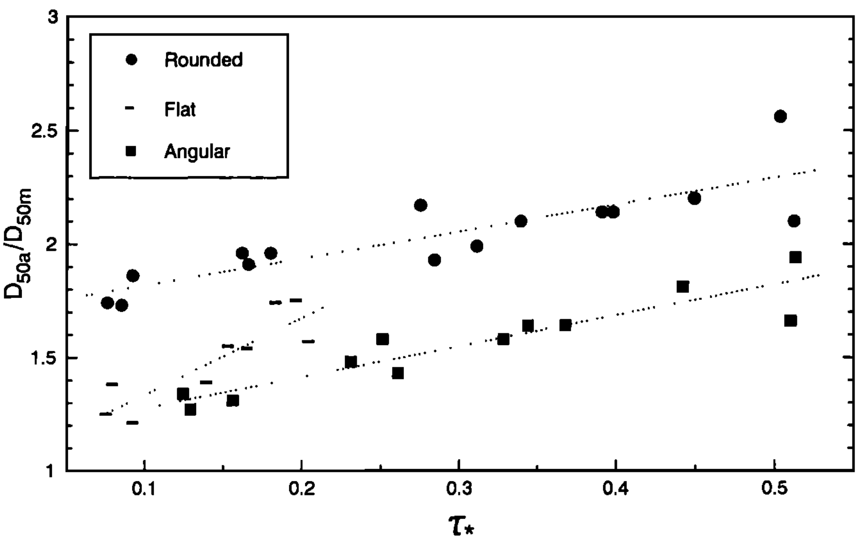

Figure 3. Variation of relative coarseness of stable armor with Shields stress for rounded, flat, and angular gravel. Dotted lines indicate least squares regression relations.

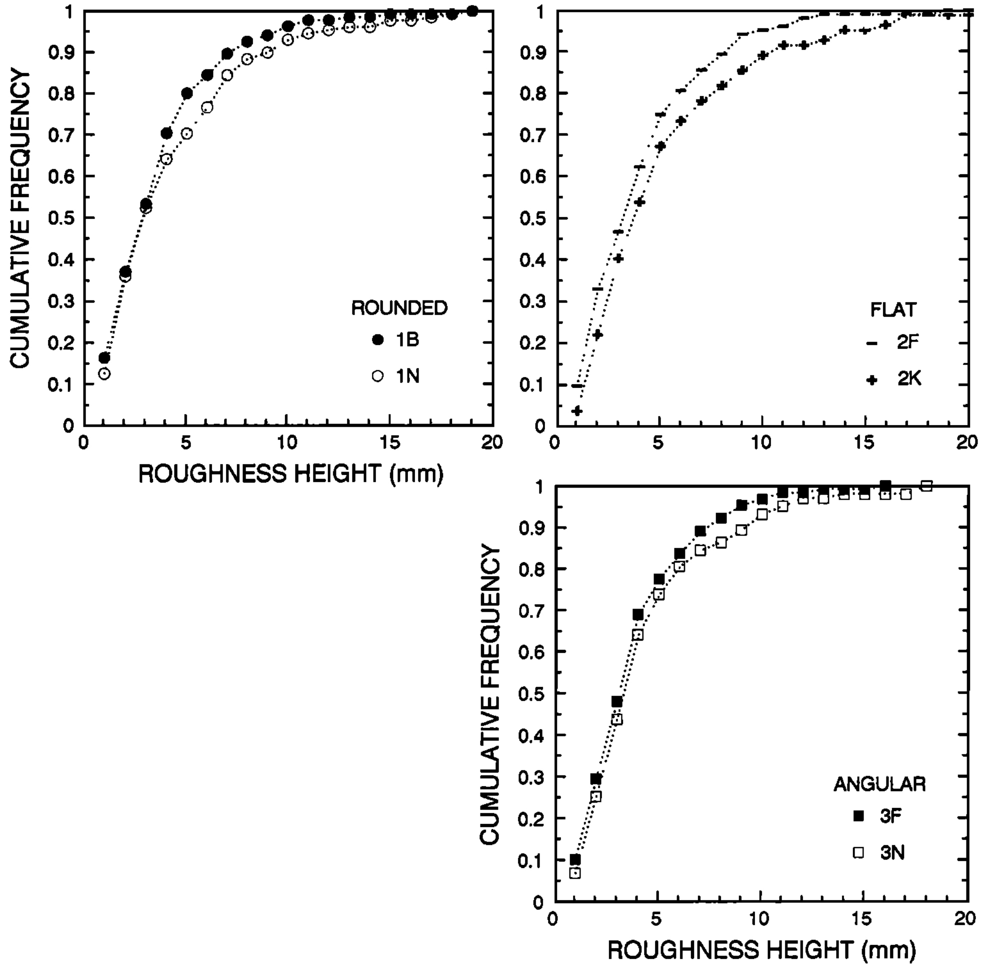

Figure 4. Typical distributions of effective roughness height on stable armors for two runs with rounded, flat, and angular gravel.

the lower 50th percentile. These small (<3 mm in height) effective roughness elements, which constitute background roughness [*Gomez*, 1993], are equated primarily with particles in the 1- to 8-mm size range clustered behind or trapped within interstices between larger roughness elements (particles). In the case of the flat gravel the increase in effective roughness height is equally pronounced in both halves of the distribution, implying that fewer fine particles are retained on the bed surface as the armor coarsens with increasing flow. This suggests that, for imbricated particles, the reduction in hiding may be commensurate with the degree of surface coarsening.

Spatially averaged roughness is a product of element height and concentration (i.e., the size and concentration of particles larger than the limiting size for movement on the bed surface). Despite the overall coarsening (Table 1) and the persistent increase in net surface roughness (indexed in Figures 5a–5c by h_{AV}, the average height of all effective roughness elements), representative roughness height (k, the average height of effective roughness elements $\geq h_{95}$ in height, where h_{95} is the height for which 95% of the effective roughness was smaller) may exhibit a tendency initially to increase and subsequently to decrease with increasing flow (Figures 5a and 5c). This is because roughness height is constrained by the size of the coarsest particles on the bed. It is also regulated by particle protrusion and increasing roughness concentration, which eventually act to smooth the bed [*Morris*, 1955; *Koloseus and Davidian*, 1966; *Wooding et al.*, 1973]. Roughness concentration is relatively free to adjust within the limits imposed by the threshold for particle motion, when only a few particles are in motion, and the threshold for the sediment mixture, when all particles are in motion [*Gessler*, 1971]. Thus representative roughness concentration (the number of roughness elements $\geq k$ in height exposed on the bed surface multiplied by their projected area) increases as the proportion of coarse, stable particles on the bed surface increases with increasing flow (Figure 5d, *Garde and Hassan* [1967], *Williman* [1975], and *Day* [1981]). That is, as the large particles occupy more of the surface area, bed relief is reduced. Each of the different gravel shapes plots in its own field. The regression lines are not parallel because *Gomez* [1993] employed simple geometric arguments to characterize a representative element and its equivalent dimensions. For example, k represents the exposure of a particle to the flow, but it is not an exact measure of c axis length, and for individual nonspherical particles, typically $c > k$. For given flow conditions, roughness concentration is highest for armors composed of flat gravel, which occupies a disproportionately large area of the bed and is compensated for by the relatively small representative

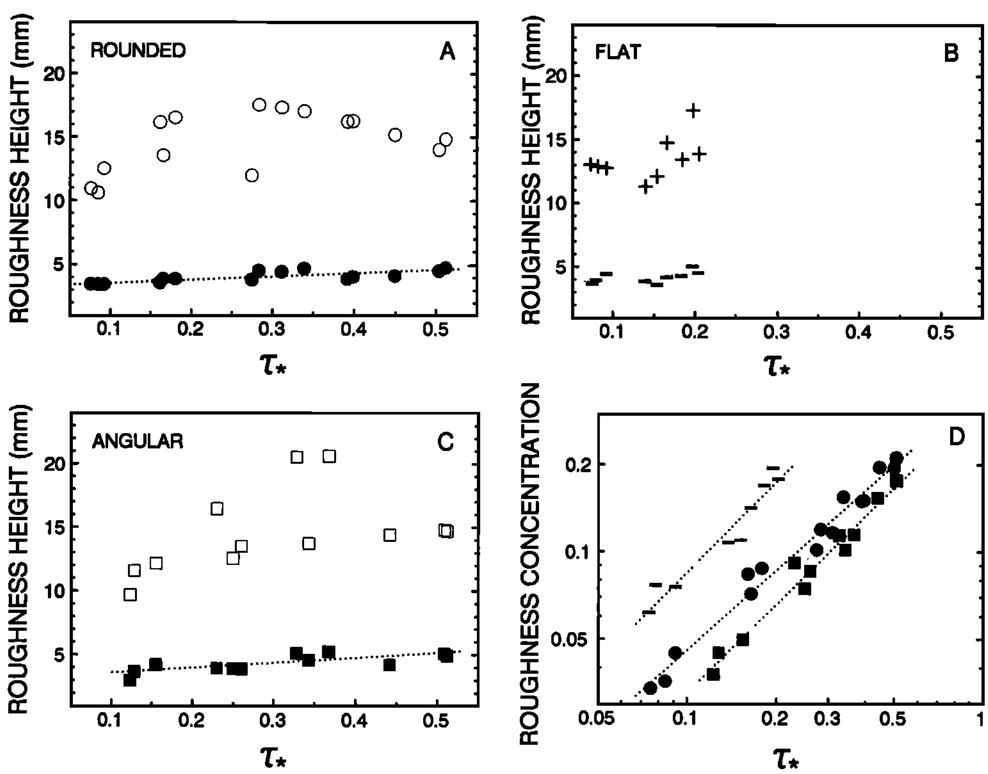

Figure 5. (a)–(c) Variation of average effective roughness height (h_{AV}, solid symbols) and representative roughness height (k, open symbols and crosses) with Shields stress for stable armors developed on rounded, flat, and angular gravel. Dotted lines indicate least squares regression relations. (d) Variation of representative roughness concentration with Shields stress for stable armors developed on rounded, flat, and angular gravel. Dotted lines indicate least squares regression relations.

roughness height of imbricated particles. Conversely, the low roughness concentration of angular gravel is compensated for by a relatively large representative roughness height.

Transport Rates of Total Bed Load

The changes in particle mobility discussed above are seen in fractional transport rates of total bed load (q_{bi}/f_i, where q_{bi} is the bed load transport rate of grain size fraction i, and f_i is the proportion of grain size fraction i in the subsurface bed material). Data points in Figure 6 represent averages for all runs with the specified sediment at a given flume slope-water discharge combination (and D_i is the geometric mean size of fraction i in the subsurface bed material). Averages are employed to define trends because, with the exception of the presence or absence of the coarsest particles in the bed load samples, the data for runs with similar flow conditions were remarkably consistent. Data for the coarsest size fraction were omitted if the bed load in all three runs in each group did not contain particles in these size classes. Although isolated clasts were consistently observed on the bed surface and in the total bed load, particles in the 45.3–65 mm size class were rarely present in the bed load samples from the runs with flat gravel.

Parker and Sutherland [1990] hypothesized that for equilibrium conditions the fraction by weight of each size range in the bed load approximates that in the substrate, as the limit of vanishing sediment transport is approached in late stage, static armor development. Although, as observed by *Wilcock* [1992], there remains a tendency for size-selective transport to persist, with the finer fractions being transported at a perceptibly greater rate than coarser particles. In the runs with angular gravel there was a tendency toward fully mobilized transport during the runs at higher flows [cf. *Harrison*, 1950; *Parker*, 1980; *Proffitt*, 1980]. This is a consequence of the comparatively large projected area of angular particles, which renders them more susceptible to movement as armors develop at higher flows and grain projection effects begin to influence armor stability. By contrast, at high flows the subdued topography of armors formed of flat gravel enhances the mobility of the finer size fractions. In most runs the departure of both the coarsest and finest size fractions from full mobility is the most pronounced trend in these experiments (Figure 6).

The persistent departure from equal mobility exhibited by the coarser size fractions (Figure 6) has been attributed to the likelihood that a proportion of these grains is rarely, if ever, in motion [*Wilcock and McArdell*, 1993]. Partial transport is a prerequisite for stable armor formation. Hiding exerts a similar effect on the mobility of the finer size fractions during stable armor formation (Figure 6). Although differences in the percentage of fine particles present in the three sediment mixtures (Figure 1) make it difficult to make precise comparisons, the increase in the mobility of the fine flat gravel size fractions at low to intermediate transport rates as compared to the rounded and angular gravels is also conspicuous. Angular particles are rarely preserved in the fluvial environment. However, the contrasting mobility of

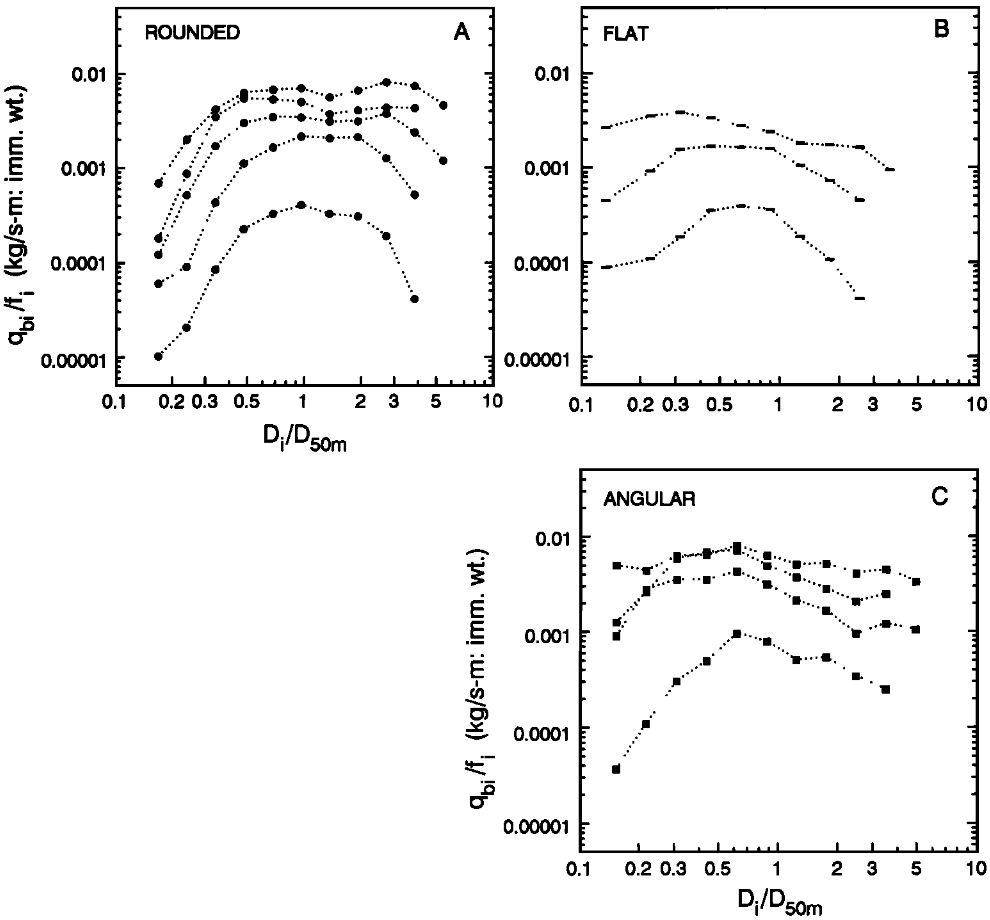

Figure 6. Average fractional transport rate during stable armor formation as a function of relative size for groups of three runs with similar flow conditions (see Table 1) with rounded, flat, and angular gravel. The closeness of the dotted lines to the horizontal indicates how near the size distribution of the bed load is to that of the bed material.

the two forms of fine subrounded gravel particles suggests that hiding functions [e.g., *Diplas*, 1987; *Proffitt and Sutherland*, 1983; *Parker et al.*, 1982] are not necessarily consistent between particles with different shape (axial) ratios [cf. *James et al.*, 1990].

For given flow conditions, average bed load discharge also varies with particle shape (Figure 7). Regression lines are used to emphasize the relations for rounded and flat gravel. The data have been adjusted to minimize variations in flow depth in the manner suggested by *Bagnold* [1977]. For a given stream power ($\omega = \tau u$, where u is the flow velocity), *Williams* [1970] and *Bagnold* [1977] demonstrated that bed load transport decreases with increasing depth to grain size ratio (Y/D_{50}). The relation is influenced by the contrasting mobility of gravels with different shape ratios inasmuch as the lower bed load discharge of the flat gravel at a smaller Y/D_{50} than the rounded gravel is consistent with the observation that it is more difficult to entrain flat particles than rounded grains. The rounded and angular gravel exhibit similar shape ratios (Figure 1). However, the reduced mobility of angular particles due to interlocking effects [*Li and Komar*, 1986] probably accounts for the discrepancy between transport of rounded and angular gravel at low to intermediate flows. The effect appears to be offset by particle projection at higher flows. In other respects, for a given stream power, the decline in bed load discharge between runs with the rounded and angular gravel ($\bar{Y}/\bar{D}_{50}$ = 21.3 and 22.5, respectively; where $\bar{Y}$ and $\bar{D}_{50}$ are means for all runs with a given particle shape) is consistent with theory. This suggests that for some transport relations the influence of particle form and roundness, respectively, may vary with the flow conditions.

Comparisons With Other Studies

Wilcock and McArdell [1993] argued that the particle size distribution of bed load should be related to the size distribution of the surficial bed material from which it is entrained rather than to the size distribution of the substrate. *Gomez* [1981] undertook experiments using a "rounded" gravel (D_{50} = 3.25 mm, σ = 2.0) in a 0.385-m-wide flume with a 2.5-m-long active bed. The experimental format was similar to that described above, except that the size distribution of the evolving armor was determined by stopping the flow, draining the flume, and sampling the bed surface using a 0.01 m^2 adhesive pad [*Gomez*, 1979]. Surficial (area-by-weight) size distributions were converted to volume-by-weight equivalents using the conversion factor of $1/D_i$ [*Kellerhals and Bray*, 1971]. The bed load size distribution and transport rate were determined concurrently during one run, in which

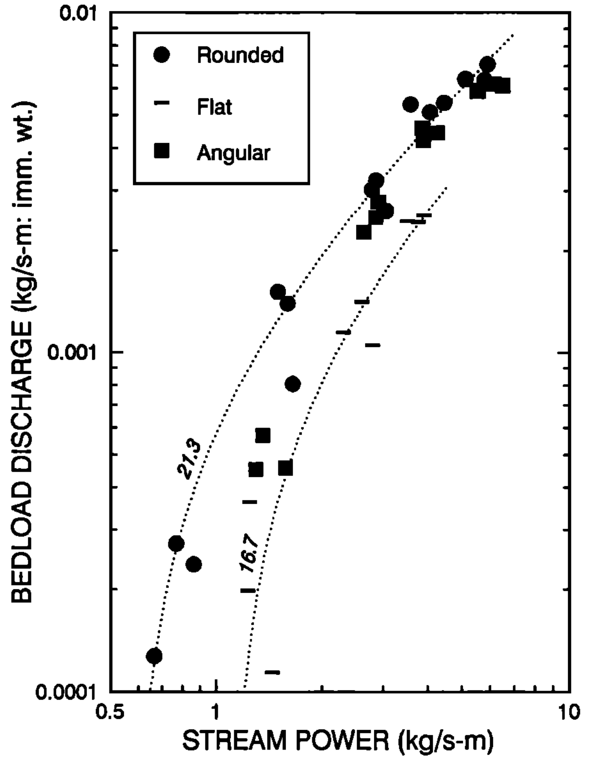

Figure 7. Variation of average bed load discharge (adjusted to the mean depth to grain size ratio for runs with rounded, flat, and angular gravel) during stable armor formation with stream power (data from Table 1). Dotted lines indicate least squares regression relations and the numbers the mean depth to grain size ratio for the rounded and flat gravel.

flow conditions were only slightly below those required to initiate a threshold armor (run 11; $Q = 33\ \mathrm{s}^{-1}$, water surface slope (S) = 0.0127, Y = 0.13 m). Surface-based fractional transport rates for this run are plotted in Figure 8a. The data are averages for successive 2, 6, 25, and 67% increments of the run, in which time 44, 37, 13, and 6% of the bed load was discharged. D_{50a}/D_{50m} provides an index of the degree of armor formation accomplished in each period.

The data are directly comparable to *Wilcock and McArdell*'s [1993] data for steady state recirculating transport of a bimodal sediment mixture. They lend equivocal support to *Parker and Sutherland*'s [1990] hypothesis of equal mobility. All grain sizes exhibit a tendency toward full mobility with respect to their availability on the bed surface, at least for the intermediate portion of the run when equilibrium transport was most likely attained (Figure 8a). The instability of large particles as they are exhumed from the bed probably accounts for the initially high transport rate of the coarse size fractions [cf. *Johansson*, 1976; *Tait et al.*, 1992]. During the latter stages of the run the relative immobility of both coarse and fine particles restricts their availability for transport, preventing the wholesale departure from fully mobilized transport.

Gomez [1983b] presented field data that are broadly comparable to the experimental data for rounded gravel (Figures 6a and 8a). Intensive bed load and bed material sampling revealed that the material in transport exhibited a similar particle size distribution to the subsurface bed material (D_{50} = 2.4 mm, σ = 2.8). Flow conditions remained virtually constant throughout the sampling period (ω = 2.95 ks s^{-1} m^{-1}, $\bar{Y}/\bar{D}$ = 60). Fractional transport rates (based on the subsurface bed material) are plotted in Figure 8b. The data are cross-sectional averages (including zero values) derived from two consecutive, nine-sample traverses of the central (1.2 to 2.8 m) portion of the active bed. On August 19, 1979, all transport ceased shortly after 1400, and subsequent bed material sampling demonstrated the presence of a stable armor (D_{50} = 16.9 mm, σ = 1.6). Transport efficiency $[q_b \tan \alpha]/\omega$, where q_b is the average bed load transport rate for each pair of traverses, and $\tan \alpha$ is the solid to solid friction coefficient ($\approx$ 0.6 [*Bagnold*, 1977]) provides an index of the reduction in bed load transport associated with armor development.

The departure from fully mobilized transport due to the relative immobility of both coarse and fine particles persists (Figure 8b). However, it is also clear that as transport rates decline during armor formation, the mobility of coarse particles decreases more rapidly than that of the fine size fractions, which tend toward size-invariant transport. That is, as the armor develops, the transport rate of the finer grain sizes is increasingly determined by their proportion on the bed surface whereas, in spite of their relative abundance, the transport rate of the coarse grain sizes declines in response to their comparative immobility. This is precisely the effect observed by *Wilcock and McArdell* [1993, Figure 6a].

The field situation is analogous to *Wilcock and McArdell*'s [1993] conditions of steady state recirculating transport inasmuch as the sampling section is one of a series of interconnected reaches, with the sediment discharge from one providing the upstream sediment input to the next. In the case of the field data (and in Wilcock and McArdell's experiments), once the bed surface becomes saturated with small particles, excess fines overpass the bed, and the size-independent transport of fine fractions thus represents throughput load [cf. *Lisle and Madej*, 1992]. No sediment was recirculated in these laboratory experiments, and the hiding effect observed during the latter stages of armor formation reflects the decreased mobility of the finer fractions in the absence of any sediment input from upstream.

Observations on Armor Development

The development of a stable armor is conventionally associated with the winnowing of fine grain sizes from the bed, as is most obviously manifest by the well-documented phenomenon of surface coarsening. However, all size fractions in the subsurface sediment mixture are apparent on the bed surface and in the bed load, and coarsening appears as but one of several adjustments that occur as the surficial bed material evolves into a stable armor. Stable armor development may entail a change in sorting [*Proffitt*, 1980] and must involve a change in bed roughness. Representative roughness concentration increases as the armor coarsens with increasing flow, but representative roughness height first increases, then decreases, as the stability of large particles becomes progressively more dependent on the degree to which the grains protrude into the flow (Figure 5).

Gomez [1993] postulated that formation of a stable armor likely involves minimization of shear due to drag on background roughness (approximated as the average height of all

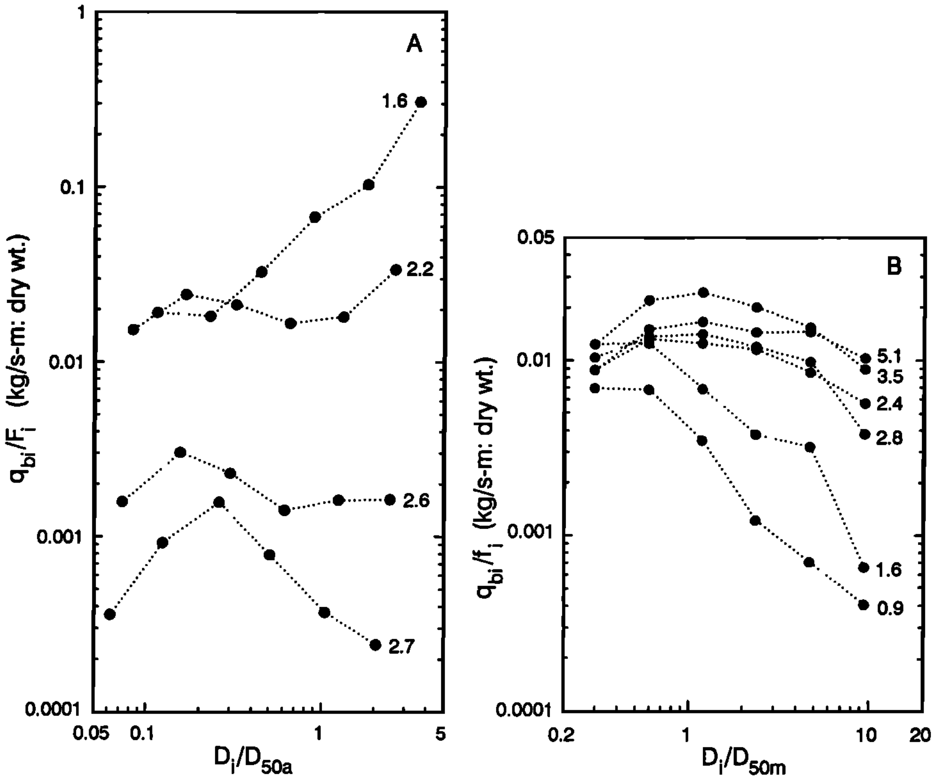

Figure 8. (a) Change in average surface-based fractional transport rate (q_{bi}/F_i), as a function of relative size (calculated with reference to surface samples, D_{50a}) during stable armor formation (experiments described by *Gomez* [1981]). Numbers indicate relative coarseness of armor (D_{50a}/D_{50m}). (b) Change in fractional transport rate as a function of relative size during stable armor formation, Borgne d'Arolla, Switzerland, 0949 to 1359, August 19, 1979 (field data described by *Gomez* [1983b]). Numbers indicate transport efficiency ($[q_b \tan \alpha]/\omega$). See text for notation.

effective roughness elements $\leq h_{AV}$ in height). Total bed shear stress (τ) is composed of the shear stress due to drag on the background roughness (t) plus the shear stress due to drag on discrete roughness elements (T), such that $(T/\tau) + (t/\tau) = 1$, and the ratio $T/\tau \approx 1 - (t/\tau)$ indicates the relative magnitudes of the shear stress due to drag on representative roughness elements and the total shear stress. Values of T/τ exhibited a tendency toward some maximum value for a given particle shape that was attained once the flow became large enough to initiate wholesale rearrangement of the surficial bed material. If this is the case, it may provide a quantitative solution to the vexed question of how to define the criteria necessary for a completely effective armor. The implication is that not all beds on which the surficial bed material is coarser than the underlying bed material should be considered armored sensu stricto: the complete development of a stable armor involves wholesale rearrangement of the surficial bed material. This is consistent with observations that armor formation involves the erosion and deposition of surficial particles [*Harrison*, 1950; *Davies*, 1974; *Proffitt*, 1980; *Sutherland*, 1987; *Wolcott*, 1990] and with the changes in bed roughness that occurred as stable armors formed at progressively higher flows.

Only in field data during the latter stages of stable armor formation was the systematic decrease in transport with grain size indicative of winnowing manifest, as bed load transport rates became vanishingly small (Figure 8b). This size-selective transport (to the point where the fine fractions appear fully mobile) is likely an artifact of the pervasive mobility of the finer grain sizes which persist in transport as throughput load [cf. *Schiller and Rowney*, 1984; *Ashworth and Ferguson*, 1989]. It may dominate in the field during the latter stages of stable armor formation but is not observed in flumes where there is no sediment input from upstream (Figures 6 and 8a) and effects due to hiding predominate. During the initial stages of armor formation the mobility of both coarse and fine particles appears limited by absolute and relative particle size (Figure 8b). Both of the above mentioned effects, in turn, become less pronounced as the flow conditions increase to the point where all grain sizes on the bed are equally mobile and a threshold armor develops (cf. Figure 8a; *Wilcock and McArdell* [1993, Figure 6a].

Conclusions

The effect of particle shape on the development of a stable armor is manifest in the size of particles present on the bed surface. The relative size of particles present on the bed is as expected from theory [e.g., *Li and Komar*, 1986]. For a given bed shear stress the order of increasing nominal particle diameter is flat, angular, and rounded gravel. The order of increasing surface roughness (flat, rounded, and angular gravel) is also as expected [cf. *Koloseus and Davidian*, 1966].

Effects due to differences in particle form exert a pervasive influence on particle mobility. The mobility of fine, flat gravel particles is enhanced by the lower roughness of armors that exhibit an imbricated structure. In consequence, hiding functions likely vary with particle shape. The larger projected area of angular gravel particles also enhances the mobility of coarse grains at high flows, offsetting interlocking effects that restrict the mobility of angular gravel at lower flows. Commensurate with the generally lower mobility of ellipsoids, for a given stream power, bed load discharge during armor development on flat gravel is less than that for rounded gravel (at a greater $\bar{Y}/\bar{D}$).

Although equal mobility may conceivably be approached during late stage armor development, relative and absolute size effects contribute to the departure from equal mobility exhibited by the finest and coarsest size fractions. This is a ubiquitous feature of stable armor development below the threshold condition (when all particle sizes are equally mobile). The influence of both effects on fractional transport rates appears to be preserved in the field during the initial stages of stable armor development, but as transport rates become vanishingly small during the latter stages of armor formation, relative size effects are likely suppressed (as they are in recirculating flumes) by the transport of the finer size fractions as throughput load. At this stage, fractional transport rates may exhibit the well-known systematic decrease with grain size that is conventionally assumed to be indicative of armor formation by the winnowing of fines from the bed surface. However, the development of a stable armor must involve wholesale rearrangement of the surficial bed material, because all particle sizes are consistently present on the bed surface and in the bed load. Thus stable armor development cannot be viewed as a product of winnowing alone.

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