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Sediment transport by dry ravel

Emmanuel J. Gabet

Department of Geological Sciences, University of California, Santa Barbara, California, USA

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[1] Dry ravel is a general term that describes the rolling, bouncing, and sliding of individual particles down a slope and is a dominant hillslope sediment transport process in steep arid and semiarid landscapes. During fires, particles can be mobilized by the collapse of sediment wedges that have accumulated behind vegetation. On a daily basis, particles may be mobilized by bioturbation and by small landslides. Experiments on a dry ravel flume indicate that a basic expression of the momentum equation predicts the distance traveled by particles propelled down a rough surface. This equation is further elaborated to produce a nonlinear slope-dependent transport equation for dry ravel that represents the rate at which sediment crosses a contour width of slope. Sediment traps installed on two hillslope transects near Santa Barbara, California, measured the flux from dry ravel initiated by bioturbation, and the data support the form of the equation. Additionally, a physical model, based on the infinite slope stability analysis, is proposed for the initiation of dry ravel by landsliding. The analytical result from this model is supported by experiments and field data reported by others. *INDEX TERMS:* 1815 Hydrology: Erosion and sedimentation; 1824 Hydrology: Geomorphology (1625); 5120 Physical Properties of Rocks: Plasticity, diffusion, and creep; 5415 Planetology: Solid Surface Planets: Erosion and weathering

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1. Introduction

1.1. Hillslope Sediment Transport

[2] Since the early days of geomorphology, there has been an effort to link the magnitude of soil creep processes to hillslope gradient. *Gilbert* [1909] studied hillslope profiles and hypothesized that sediment flux on soil-mantled hillslopes was proportional to the distance from the divide. From this insight, *Gilbert* [1909] reasoned that gradients must increase downslope on steady state hillslopes. *Gilbert*'s [1909] work led to studies by *Culling* [1960, 1963, 1965], who perceived that the movement of individual soil particles was analogous to Brownian motion and determined that sediment flux was proportional to the hillslope gradient. *Kirkby* [1967] derived an expression for soil creep by cyclic wetting and drying and found that flux rates should be proportional to the sine of the slope angle. Laboratory experiments by *Kirkby* [1967] with a soil monolith supported the form of his equation. *DePloey and Savat* [1968] made a detailed analysis of the trajectory of soil particles during raindrop impact to develop a transport equation for rain splash and found a complex relationship between sediment flux and slope angle. *Andrews and Bucknam* [1987] and *Roering et al.* [1999, 2001a] derived similar generalized transport equations that suggest that sediment flux increases nonlinearly as slopes approach a threshold gradient. Both *McKean et al.* [1993] and *Small et al.* [1999] estimated flux rates with cosmogenic radionuclides and found a linear relationship between gradient and sediment flux on gentle slopes (<13°). On the basis of field measurements, *Gabet* [2000] found that soil transport by pocket gophers was nonlinearly dependent on hillslope gradient. *Gabet et al.* [2003] have developed slope-dependent flux equations for tree throw and for the dilation and contraction of soil by root growth and decay.

[3] Landscape evolution modeling provides an important motivation for determining the functional relationship between topographic attributes and sediment transport, and the transport of sediment on hillslopes by slope-dependent processes is commonly referred to as "diffusion" [e.g., *Culling*, 1963; *Gabet*, 2000; *Roering et al.*, 1999]. *Culling* [1960] first introduced Fickian diffusion as an analogy for soil creep and explored the idea more thoroughly in later contributions [*Culling*, 1963, 1965]. Since then, hillslope diffusion has entered the geomorphological vernacular to represent the sediment flux by a specific process [e.g., *Gabet*, 2000] or the aggregate effect of all slope-dependent processes [e.g., *Roering et al.*, 1999]. However, diffusion is not a geomorphological process. In reality, sediment is transported by various individual processes that are identifiable and, in many cases, measurable.

[4] There is considerable value in developing specific sediment transport equations for individual processes. The form of hillslopes and the processes that transport sediment along hillslopes reflect conditions such as vegetation and climate [*Strahler*, 1950]. By developing suites of specific flux equations for various environmental conditions, geomorphologists will be able to fine-tune hillslope evolution models [e.g., *Willgoose et al.*, 1991] and sediment delivery models [*Benda and Dunne*, 1997] to render them sensitive

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to climate. In this contribution I examine sediment transport by dry ravel.

1.2. Dry Ravel

[5] Dry ravel is a general term that describes the downslope movement of individual particles by rolling, sliding, and bouncing [*Rice*, 1982]. Dry ravel may be the dominant form of chronic sediment transport in steep, arid, and semiarid environments where there is little ground cover to impede the movement of particles [*Anderson et al.*, 1959; *Krammes*, 1965]. Dry ravel may also be the primary creep-like transport process on other planets, where other abiotic creep processes such as freeze-thaw may not be important.

[6] Raveling particles may be initially mobilized by various processes. For example, during and immediately after a fire, the burning of vegetation releases wedges of sediment that have accumulated behind it [*Rice*, 1982], causing large pulses of sediment to be delivered to stream channels [*Florsheim et al.*, 1991; *Wells*, 1985]. In noncohesive coarse skeletal soils, raveling particles may also be initially mobilized as a small landslide. In this case a reduction in cohesion among soil particles on steep slopes puts them near a stability threshold such that even vibrations from a plane flying overhead may be sufficient to trigger a minor slope failure [*Anderson et al.*, 1959]. The reduction in cohesion may be due, for example, to evaporation of soil moisture [*Anderson et al.*, 1959]. In soils that are cohesive and not prone to the landslide form of dry ravel, individual particles may be initially mobilized by small animals moving through the brush [*Krammes*, 1965; *Rice*, 1982]. In arid and semiarid landscapes these last two forms of dry ravel may grade into each other, the relative importance of each dependent on soil type and texture. In this study, fieldwork was carried out on cohesive soils where the third form of dry ravel appears to be dominant.

[7] A physical model of dry ravel can be derived by considering the forces on a particle moving down a plane inclined at an angle θ. The downslope distance, s_d, traveled by a decelerating particle can be calculated with

$$s_d = \frac{v_i^2}{2(-dv/dt)}, \tag{1}$$

where v_i is initial velocity ($L\ T^{-1}$) in the downslope direction and dv/dt is acceleration ($L\ T^{-2}$). Note that s_d and v_i are defined as slope-parallel quantities. Combining equation (1) with the momentum equation

$$\frac{dv}{dt} = g\sin\theta - \mu g\cos\theta \tag{2}$$

yields

$$s_d = \frac{v_i^2}{2g(\mu\cos\theta - \sin\theta)}, \tag{3}$$

where g is gravitational acceleration and μ is a coefficient of kinetic friction that encompasses friction from rolling, bouncing, and collisions with other grains. On hillslopes with gradients steeper than μ, the particles accelerate (i.e., $dv/dt > 0$), rendering equation (3) invalid for determining transport distance. On these steeper slopes the transport distance depends on hillslope length and may be determined by explicitly routing the particles down a hillslope profile [*Howard and Selby*, 1994].

[8] *Kirkby and Statham* [1974] derived an equation identical to equation (3) in a study of the formation of talus slopes. In the case of the talus slopes studied by *Kirkby and Statham* [1974], the stones acquired an initial velocity from falling vertically from a cliff and landing at the top of the talus pile. With the form of dry ravel examined here, the initial velocity comes from sources such as animals walking along the slopes [*Anderson et al.*, 1959; *Krammes*, 1965; *Rice*, 1982].

[9] The distance, s_d, can be incorporated into the following general equation for the mass flux, q ($ML^{-1}T^{-1}$), from discrete events, across a unit contour width of slope

$$q = \left(\frac{\text{distance}}{\text{event}}\right) \times \left(\frac{\text{mass}}{\text{event}}\right) \times \left(\frac{\text{events}}{\text{area}}\right) \times \left(\frac{\text{events}}{\text{time}}\right). \tag{4}$$

Combining equations (3) and (4) and assuming that the last three terms on the right-hand side of equation (4) and the initial velocity are not slope-dependent yields

$$q_d = \frac{\kappa}{\mu\cos\theta - \sin\theta}, \tag{5}$$

where q_d is the downslope mass flux and κ ($M\,L^{-1}T^{-1}$) is a constant that incorporates the distribution of initial velocities, gravitational acceleration, the frequency and spatial density of events, and the average mass of displaced sediment. There are three caveats to note in the formulation of equation (5). First, the assumption that the last three terms in equation (4) are not slope-dependent implies that the process that initially mobilizes the sediment, such as small animals [*Anderson et al.*, 1959; *Krammes*, 1965; *Rice*, 1982], acts equally over slopes of different gradients. *Reichman and Aitchinson* [1981] have shown that small mammals are relatively indifferent to slope steepness, suggesting that this assumption may be valid. Second, specific values for κ would be difficult to estimate directly with equation (4) because the terms in equation (4) are described by frequency distributions, and simply using average values for these quantities may not yield the correct average sediment flux. Finally, at this point I am only considering the case where particles are mobilized downslope; the case where particles may also be initially propelled upslope will be considered in section 4.1.

2. Material and Methods

2.1. Flume Experiments

[10] An adjustable hillslope flume (Figure 1a) was constructed to evaluate whether equation (3) correctly predicts the average distance traveled by raveling particles. The surface of the flume (2 m long and 0.8 m wide) was roughened with a thin layer of concrete imbedded with randomly arranged gravel ranging from 1 to 5 cm in diameter (Figure 1b).

[11] A hopper at the top of the flume dropped 1-cm gravel from a known height, h, onto a wooden ramp that formed an 11° angle with the surface of the flume (Figure 2). The wooden ramp helped provide a consistent initial velocity.

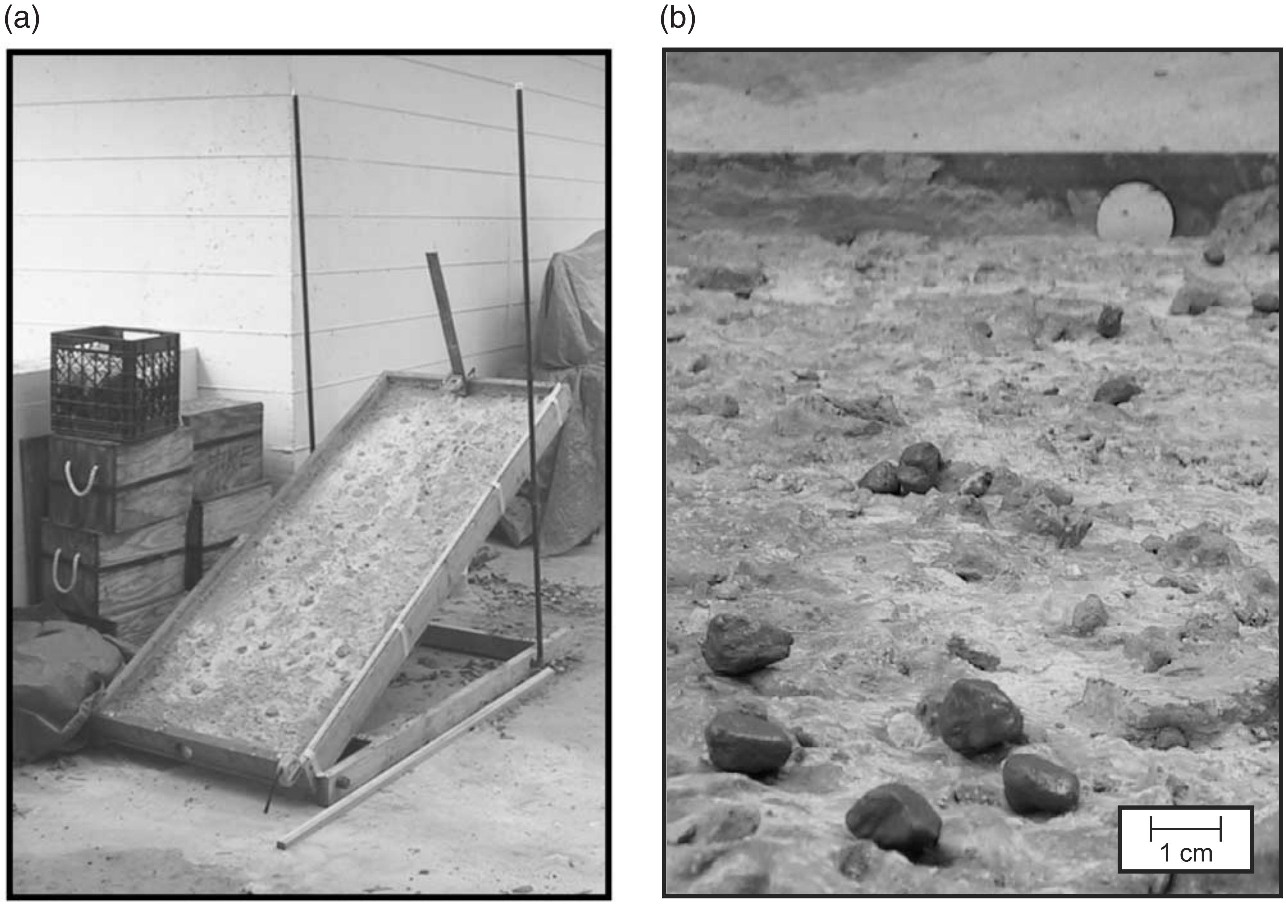

Figure 1. (a) Dry ravel flume. (b) Surface of the flume. Dark particles are those that were dropped from the hopper. The scale only applies to objects in the immediate foreground.

The particles, upon hitting the ramp, were propelled downslope with an initial velocity determined by

$$v_i = \sqrt{2gh}\sin(\theta + 11). \tag{6}$$

Each run consisted of dropping a group of 10 stones and then measuring the distance that each stone traveled. This was repeated 10 times at each slope setting. Also, at each slope setting the height of the hopper was adjusted so that the initial velocity was constant for all of the runs (0.7 m s^{-1}). An average distance was calculated for each run and was used to determine a value for μ with equation (3). Similar values of μ at different slopes would indicate that equation (3) captures the physical process of particles raveling down a rough surface. At slopes >20°, a particle would occasionally travel the entire flume length, its progress interrupted only by the end of the flume. Because of this experimental limitation, results from settings >20° are not reported.

2.2. Field Measurements

[12] Sediment traps were used to determine whether sediment flux by dry ravel may be represented by equation (5). The field site is located in the Santa Ynez Valley in the tectonically active Transverse Ranges near Santa Barbara, California. The climate is semiarid Mediterranean, and the lithology is weakly consolidated Plio-Pliestocene fanglom-

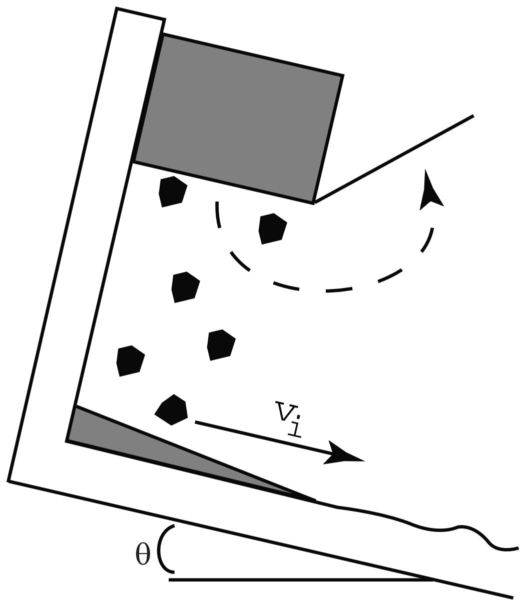

Figure 2. Illustration of the hopper and ramp (shaded) that propelled the particles down the flume with an initial velocity (v_i). The height of the hopper was adjusted for each flume setting (θ) so that the initial velocity was constant throughout the experiments. A spring quickly opened the trapdoor of the hopper, releasing the particles.

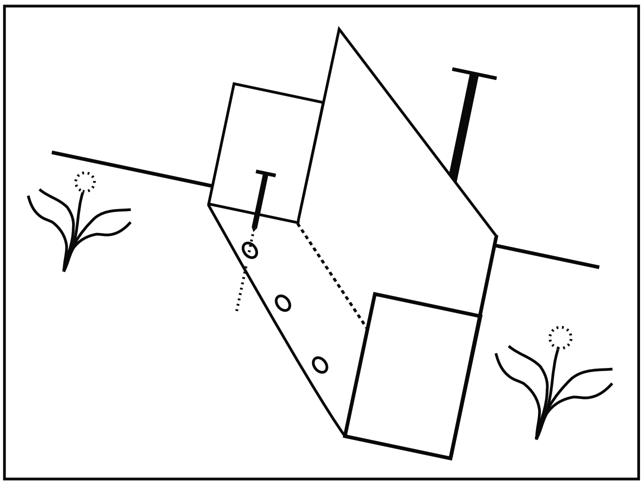

Figure 3. Illustration of a sediment trap constructed from a length of roof gutter. The trap width is 0.67 m, and the height is 0.25 m. The lip was installed flush to the ground surface and affixed with three large nails. A metal spike was driven into the ground behind the trap for added stability.

erate of the Paso Robles Formation [*Dibblee*, 1993]. The fanglomerate has been incised into a series of unpaired, step-like strath terraces to create soil-mantled hillslopes with slopes up to 40°. Soil depths range from 0.1 to 0.3 m on the planar hillslope sections and up to 0.7 m in the colluvial hollows [*Gabet and Dunne*, 2002]. The soil is a cohesive sandy loam [*Gabet and Dunne*, 2002], and the surface is covered by loose particles and plant litter. The vegetation community is coastal sage dominated by California sagebrush (*Artemisia californica*) and purple sage (*Salvia leucophylla*).

[13] The 0.67-m-wide sediment traps, constructed from lengths of roof gutter, were set flush to the ground surface on planar sections of hillslope (Figure 3). Two sets of nine traps were installed parallel to the contour lines along two hillslope transects at Sedgwick Reserve, a reserve in the University of California Natural Reserve System. The traps were set out at the beginning of the dry season in order to isolate dry ravel as the sole transport process. The traps were left in place for 5 months and were recovered before the onset of rain.

[14] The material caught in the traps consisted primarily of rock fragments with some soil aggregates. In the laboratory the sediment was dried and weighed. Organic material was removed from the samples by combustion in a muffle furnace [*Buol et al.*, 1997]. A downslope sediment transport rate was calculated from the mass of each sample with

$$q_d = \frac{\text{mass}}{wt}, \tag{7}$$

where w is the width of the trap and t is the length of time that they were installed.

3. Results

3.1. Flume Experiments

[15] The results from the flume experiments are presented in Table 1. The similar values of μ for a range of slopes (analysis of variance test) indicate that the average particle travel distance is adequately predicted by equation (3). Further, the average distance traveled by a particle for each set of runs clearly demonstrates the nonlinearity of this transport process (Figure 4). At lower slopes (<15°) the particles quickly decelerate and stop; however, as slopes approach 23° ($\tan^{-1}$ 0.42), the particles roll some distance before stopping. Similar observations were made by *Mosley* [1973], who found that particles mobilized by rain splash rolled downhill on slopes >25°.

Table 1. Values for μ Determined From the Dry Ravel Experiments

Slope, deg	Coefficient of Kinetic Friction, μ	1 Standard Deviation
6	0.41	0.08
9	0.39	0.06
12	0.39	0.04
14	0.44	0.07
16	0.42	0.02
18	0.42	0.02
20	0.43	0.01

[16] Although equation (3) describes reasonably well the process of particles raveling down a rough surface, there are simplifications inherent in its formulation that should be addressed. First, the derivation of equation (3) assumes that dv/dt is constant, which is unlikely given the bumpy and irregular paths taken by raveling particles. In experiments similar to those reported here, *Kirkby and Statham* [1974] noted that the moving particles were slowed by impacts with the large roughness elements and did not exhibit a constant deceleration. They concluded, nonetheless, that the simple frictional model derived from the momentum equation captured the essential behavior of the process. The general decrease in the variance of the average travel distances with increasing slope (Figure 4) suggests, perhaps, that the frictional model becomes progressively more valid as slopes steepen. Second, the calculation of v_i with equation (6) is only strictly correct for a sphere dropped onto a smooth planar surface in a perfectly elastic collision.

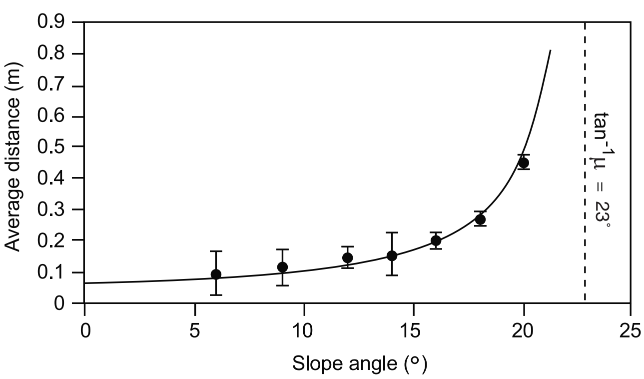

Figure 4. Results from flume experiments showing average transport distance as a function of slope. The line represents equation (3) parameterized with the average value for μ, 0.41. The close fit of the line to the data indicates that the distance traveled by raveling particles can be predicted with equation (3). The line predicts a nonzero transport distance at zero slope because the particles were imparted an initial velocity by the 11° ramp. The error bars represent 1σ.

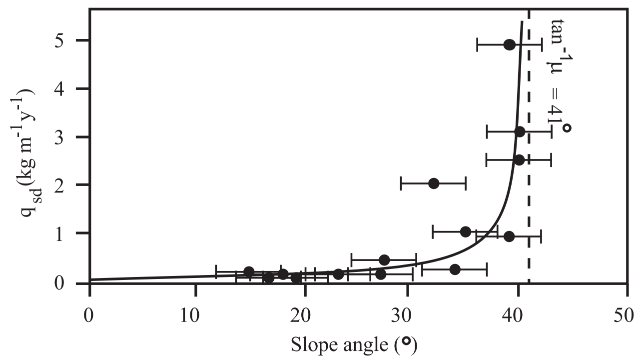

Figure 5. Dry ravel sediment flux measurements from the sediment traps. The error bars represent the range of slope angles directly upslope of each trap. The line represents equation (5) parameterized with values of 0.1 kg m^{-1} yr^{-1} for κ and 0.87 for μ.

Because the collisions between the ramp and the gravel were likely inelastic, a coefficient of restitution should be included in equation (6). The actual initial velocity, then, was less than the one reported here; however, the general principle demonstrated by the experiments remains valid. Finally, because the gravel is irregularly shaped, the initial velocity imparted to each particle would have varied depending on how it struck the ramp.

3.2. Field Measurements

[17] Of the 18 traps installed on the hillslopes, the lips of 4 of the traps were no longer flush with the soil surface; thus only 14 traps provided reliable data. The downslope sediment flux determined for each trap is presented as a function of hillslope angle in Figure 5. Because the ground surface was not smooth, the hillslope angles shown in Figure 5 represent an average angle over a distance of 0.6 m, the minimum distance needed to characterize the average local slope. Within this distance, slope angles varied approximately ±3°. Equation (5) was visually fit to the field data to produce values of 0.1 kg m^{-1} yr^{-1} for κ and 0.87 for μ. The values for μ determined from the flume experiments are lower than the one determined from the sediment traps primarily because of the hardness and immobility of the flume surface. On hillslopes, collisions with the soil, vegetation, and other particles are more inelastic, resulting in a higher coefficient of kinetic friction.

4. Discussion

4.1. Net Sediment Flux

[18] The results indicate that equation (5) adequately describes the downslope flux of sediment by dry ravel. However, for the purposes of modeling hillslope evolution the net flux must be determined. In their study on talus slopes, *Kirkby and Statham* [1974] were able to assume that all the particles falling from a cliff had an initial velocity in the downslope direction. In the case of the form of dry ravel investigated here, the initial mobilizing events may not impart an initial velocity preferential to any direction; therefore the flux equation must account for particles mobilized in all directions over time. Equation (3) is modified such that the transport distance of particles mobilized upslope, s_u, is calculated by

$$s_u = \frac{(-v_i)^2}{-2g(\mu\cos\theta + \sin\theta)}. \tag{8}$$

The net transport distance, s_n, averaged over an infinite number of randomly oriented mobilizing events is the sum of the upslope and downslope components, $s_u + s_d$, or

$$s_n = \frac{(v_i)^2\tan\theta}{g\cos\theta(\mu^2 - \tan^2\theta)}. \tag{9}$$

Net transport distance, s_n, incorporated into the general sediment flux equation (4) yields the following:

$$q_n = \frac{\kappa'\sin\theta}{\mu^2\cos^2 - \sin^2\theta}, \tag{10}$$

where q_n is the net flux and κ' is similar to κ except that it also incorporates the uphill flux of sediment. Although the sediment traps only recorded the downhill flux of sediment, the field data may be used to estimate κ'. On slopes steeper than 33°, the upslope particle travel distance is negligible relative to the downslope distance (Figure 6). Therefore, by considering only the measured fluxes on the steeper slopes, a value of 0.2 kg m^{-1} yr^{-1} for κ' can be estimated (Figure 7).

[19] Whereas equation (10) represents the total flux of sediment, an equation for the horizontal flux is required for hillslope evolution models based on the continuity equation. Adjusting equation (10) to account only for the horizontal transport of sediment, the net horizontal flux, q_{nx}, is

$$q_{nx} = \frac{\kappa'\tan\theta}{\mu^2 - \tan^2\theta}. \tag{11}$$

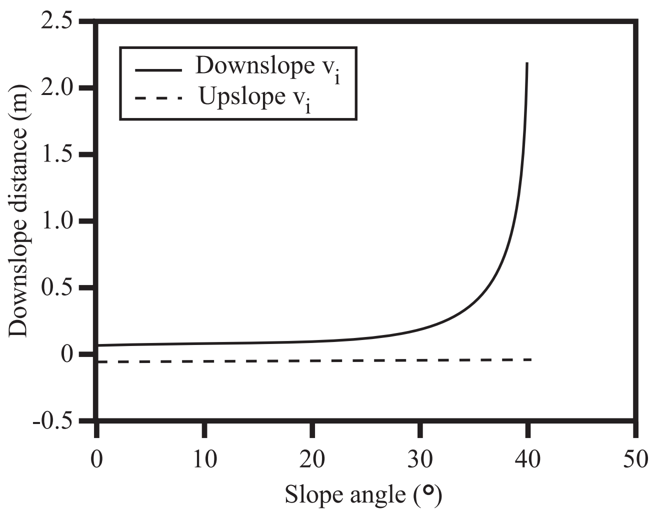

Figure 6. On slopes steeper than 33°, the absolute distance traveled by a particle that is initially mobilized upslope is negligible relative to the distance traveled by a particle initially mobilized downslope. For Figure 6, the assumed initial velocity is 1 m s^{-1}; the relative difference between upslope and downslope distances changes very little with initial velocity.

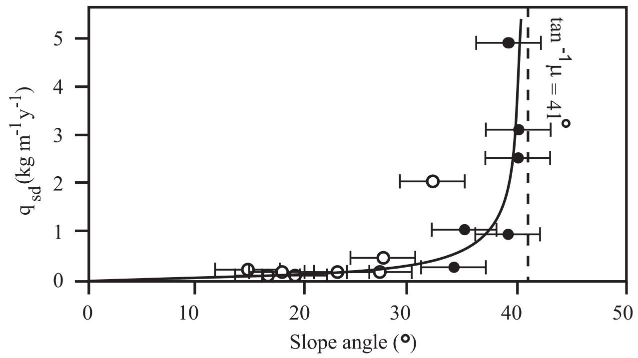

Figure 7. A value for κ' is estimated from the sediment trap data by only considering fluxes on slopes >33°. Visually fitting equation (10) through the trimmed data (solid circles) yields a value of 0.2 kg m^{-1} yr^{-1} for κ'.

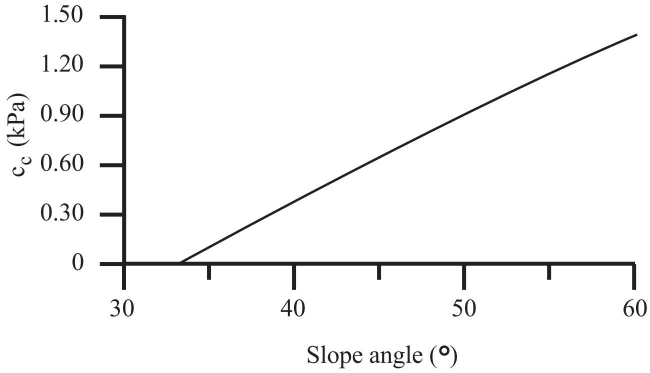

Figure 8. Critical values of cohesion (F = 1) determined as a function of hillslope angle with the stability analysis. There are no failures on slopes <33°.

Andrews and Bucknam [1987] and *Roering et al.* [1999, 2001a] derived an equation nearly identical to (11) but assumed that moving particles have an initial energy, whereas I assume that the particles have an initial velocity. Additionally, *Andrews and Bucknam* [1987] and *Roering et al.* [1999] found values for the two constants by topographic analysis rather than by direct measurements of sediment flux.

4.2. Landslide-Initiated Dry Ravel

[20] Because the soils at Sedgwick Reserve are cohesive, the dry ravel was likely initiated by external events, such as animals walking along the slope, rather than by small landslides. Landslide-initiated dry ravel, however, is an important process in arid and semiarid regions where the bedrock weathers into coarse-grained, noncohesive fragments. For example, *Anderson et al.* [1959] and *Krammes* [1965] measured high rates of dry ravel in the San Gabriel Mountains from hillslopes underlain by diorite. *Anderson et al.* [1959] found that the rate of sediment production from these "summer slides" was low during the wet season and high during the dry season, and they attributed this seasonality to changes in the moisture among the particles. During the winter, moisture contributes to interparticle cohesion, but as the seasons progress into summer, the cohesion declines as the moisture evaporates. With the decline in cohesion, small failures on steep slopes may be triggered by disturbances from the wind or from animals walking along the slope [*Anderson et al.*, 1959; *Krammes*, 1965; *Rice*, 1982].

[21] A model for the initiation of these small failures can be derived from the infinite slope stability analysis [e.g., *Selby*, 1993]. In this stability analysis the ratio of resisting forces to shear forces defines the factor of safety F such that

$$F = \frac{c + \gamma z \cos\theta \tan\phi}{\gamma z \sin\theta}, \tag{12}$$

where

c cohesion (kPa);
γ unit weight of failing mass (26 kN m^{-3});
z thickness of failing mass (m);
ϕ internal angle of friction (deg).

The failing mass is assumed to be a solid layer of 1-cm gravel on the surface of the hillslope. Because failure occurs when $F < 1$, critical values for cohesion at the threshold of failure (F = 1) can be determined as a function of hillslope angle. Assuming a value of 33° for ϕ [*Selby*, 1993], critical cohesion, c_c, is shown for a range of slopes in Figure 8. Figure 8 also suggests that landslide-initiated dry ravel is not an important process at slopes <ϕ.

[22] Specifically addressing the case where the cohesion comes from soil moisture, hypothetical annual changes in cohesion from cyclic wetting and drying are shown in Figure 9. As the soil moisture begins to decrease from the wet season high, interparticle cohesion will first approach critical values on the steepest slopes, and as soils continue to dry, cohesion will approach c_c on gentler slopes. Of course, when cohesion from moisture drops below the c_c values shown in Figure 8, hillslopes do not become instantly denuded by dry ravel because cohesion from other sources may help to prevent failures. Furthermore, equation (12) assumes a failure plane that is infinitely long and wide and thus only considers the forces on the basal slip surface. Because the failures are small, forces along their edges may be significant, and the infinite slope assumption may not be strictly valid, so that in addition to cohesion from other sources, these forces may provide additional resistance not accounted for in equation (12). Therefore, as values of F approach and fall below unity, this should be interpreted as an increase in the potential for failure.

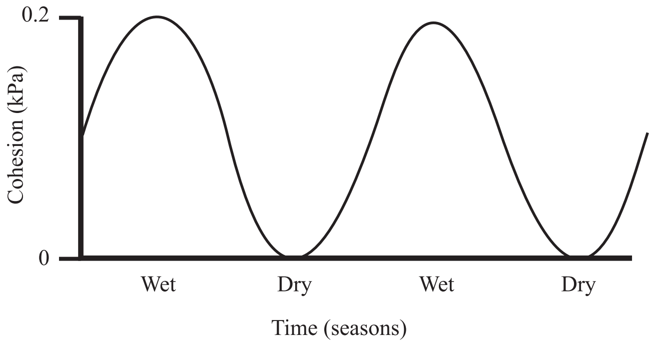

Figure 9. Hypothetical seasonal changes in interparticle cohesion from soil moisture.

[23] Because random events such as the wind, small animals, or slight tremors [*Anderson et al.*, 1959; *Krammes*, 1965] may instantaneously increase the shear stress or decrease the normal load sufficiently enough to trigger a failure when the cohesion is close to critical, it may be reasonable to assume that the number of failures on a hillslope is proportional to the amount of time spent near the critical cohesion. With equation (12) the cumulative time that slopes of angle θ are below the threshold cohesion may be calculated according to the seasonal changes in moisture presented in Figure 9. Figure 10 indicates that, annually, there will be a greater number of failures on the steeper slopes than on the gentler slopes and suggests that the total volume of sediment mobilized increases with slope such that κ' in equation (10) is dependent on slope for landslide-initiated dry ravel. This analytical result is supported by experiments and field data presented by others. In an experimental study, *Roering et al.* [2001b] found that the frequency of landslides on a vibrating sand pile increased with slope. Additionally, sediment yields (ML^{-2}) reported by *Anderson et al.* [1959] and *Krammes* [1965] support a nonlinear dependence of sediment transport on hillslope angle for dry ravel that is dominantly landslide-initiated (Figure 11). The nonzero yields at slopes <33° suggest that bioturbation may have contributed to the dry ravel activity (Figure 11).

[24] Unfortunately, for the data shown in Figure 11, it is not possible to determine what proportion of the nonlinearity is attributable to a rapid increase in the frequency of dry ravel events and what proportion is due to a rapid increase in transport distance. Nevertheless, the analysis of the two forms of dry ravel investigated here emphasizes the point that the magnitude of sediment flux from soil creep processes is dependent on the frequency of transport events (or volume per time) and the distance that the sediment is transported. Thus nonlinear increases in flux may be due to nonlinear increases in event frequency, transport distance, or both.

5. Conclusion

[25] Dry ravel is a dominant hillslope transport process in steep, arid, and semiarid landscapes. Dry ravel is a general term that describes the downslope movement of individual particles by rolling, bouncing, and sliding. The particles may be initially mobilized by the release of sediment trapped behind vegetation, by small landslides, or by bioturbation. In this contribution I investigate the motion of particles down a rough surface with experiments on a hillslope flume. Furthermore, I derive a sediment flux equation for bioturbation-initiated dry ravel and calibrate it with data from sediment traps installed on hillslopes near Santa Barbara, California. Finally, I present an analytical approach for understanding the effect of seasonal changes in soil moisture on the triggering of landslide-initiated dry ravel.

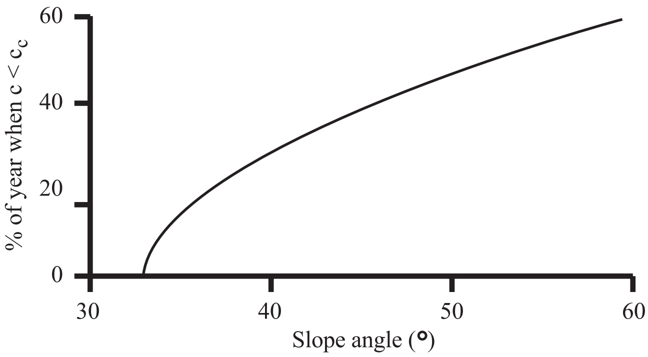

Figure 10. The steeper slopes are below a critical cohesion a greater percentage of the year than the gentler slopes. If the number of failures on a slope is proportional to the cumulative time spent near the critical cohesion, there will be more dry ravel events on the steeper slopes.

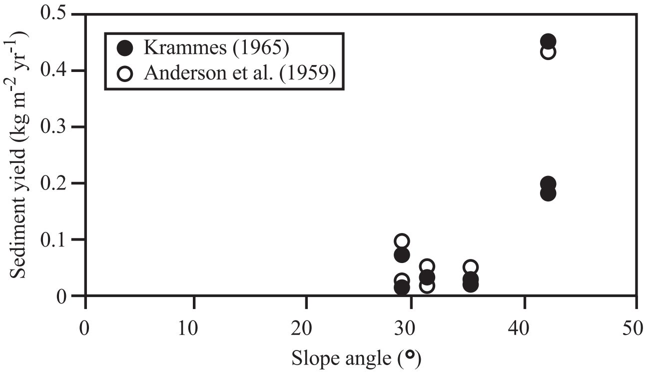

Figure 11. Sediment yield by dry ravel from *Anderson et al.* [1959] and *Krammes* [1965]. These data are reported as mass per area and therefore cannot be directly compared to the rates measured in this study; however, sediment yield appears to increase nonlinearly with slope.

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E. J. Gabet, Department of Geological Sciences, University of California, Santa Barbara, Santa Barbara, CA 93106, USA. (egabet@bren.ucsb.edu)