Effects of Rock Fragment Covers on Erosion and Transport of Noncohesive Sediment by Shallow Overland Flow

KRISTIN BUNTE AND JEAN POESEN¹

Laboratory for Experimental Geomorphology, Catholic University of Leuven, Leuven, Belgium

Rock fragments on soil surfaces can have a variety of contrasting effects on the hydraulics of overland flow and soil erosion. This makes modeling soil erosion difficult. Systematic studies are needed to assess the effects of rock fragments on the hydraulics of overland flow and to specifically relate these hydraulics to sediment yield. Therefore flume experiments were conducted in which overland flow was applied to a highly erodible sediment surface covered by various percentages of rock fragments. High local turbulence was caused by horseshoe vortex erosion around individual rock fragments. For a given discharge and slope, the dimension of the scour was affected by the space between the rock fragments. For low cover percentages the scour can develop undisturbed, and sediment yield increases with percent of rock fragment cover up to about 20%. Sediment yield then declines as percent cover increases above 20%. Beyond a cover threshold value of 20%, the larger opportunity for scour hole development is counteracted by limited inter-rock fragment space that does not allow scour holes to develop to their full extent. As sediment yield varies nonmonotonically with rock fragment cover percent, sediment yield cannot be predicted by spatially averaged flow hydraulics.

1. INTRODUCTION

Soils commonly contain large numbers of rock fragments in their surface layer. In the Mediterranean region, soils rich in rock fragments cover more than 60% of the land [Poesen, 1990a], and among the variety of soil degradation processes, soil loss due to water erosion is the most important one. Rock fragments (including pebbles and cobbles) on soil surfaces have been reported to have various effects on runoff generation, overland flow hydraulics, and sediment yield [Poesen *et al.*, 1990; Poesen and Ingelmo-Sanchez, 1992; Abrahams and Parsons, 1993]. Poesen *et al.* [1993] showed experimentally and in their literature review that rock fragment covers can lead to an increase or to a decrease of soil erosion due to overland flow, depending on the type of soil porosity, the vertical position of the rock fragments in the soil top layer, the steepness of slope [De Ploey, 1981], and the size of the rock fragments [Poesen and Lavee, 1991].

New process-based soil erosion models like WEPP [Nearing *et al.*, 1989], EUROSEM [Morgan *et al.*, 1990], and RETIC [Kirkby *et al.*, 1991] intend to describe spatial and temporal variabilities in soil erosion intensities. The models route the overland flow downslope using two different concepts. Either the routing is based on a downslope variation of roughness which is assigned to a local variation of a friction factor, or the models vary the downslope soil surface topography, describing it by different distributions of flow depths. As rock fragments on the soil surface have effects on both flow depth and friction factor, modeling overland flow and soil erosion should not neglect the presence of rock fragments.

These two approaches lead to two different concepts of the effects of rock fragments on overland flow. According to the first concept, rock fragments are considered to increase

roughness and friction and therefore reduce the velocity of overland flow and decrease sediment yield [e.g., Foster *et al.*, 1989]; however, the exact influence of surface roughness elements on hydraulic friction is still unclear [Nearing *et al.*, 1990]. The other concept assumes that rock fragments reduce the cross-sectional flow area which leads to reticular flow [Thornes *et al.*, 1990] with increases in erosional capacity. In both cases, modeling is based on two assumptions: (1) for overland flow on stony soils, both the friction factor and the flow hydraulics are predictable for a given rock fragment cover, and (2) overland flow sediment yield is directly related to spatially averaged flow hydraulics that develop in the presence of a rock fragment cover. However, these assumptions have not been tested in combined studies that analyze the complex interactions between surface roughness, hydraulics of overland flow, and sediment detachment that develops in the presence of rock fragments on erodible soils.

In analyzing the relation between roughness and hydraulic friction (Darcy-Weisbach friction factor $f = 8gdS/v^2$ where g is acceleration due to gravity, d is mean flow depth, S is slope and v is mean flow velocity), roughness is expressed as relative roughness (ratio of flow depth d and roughness height k). A change in roughness is simulated by a change in flow intensity quantified by the Reynolds number ($Re = vd/\nu$ where ν is kinematic viscosity). Where flow depth d is greater than roughness height k , the effect of surface roughness on friction factor is usually presented by relative submergence leading to a decrease of friction with increasing flow intensity ("Moody diagram") as roughness elements become progressively submerged. On the other hand, when $d \leq k$, the friction factor becomes insensitive to relative roughness d/k and the effect of roughness on friction factor is usually represented by the wetted upstream projected area of the roughness elements [Abrahams and Parsons, 1993]. Testing the $f-Re$ relation for various rock fragment covers glued onto a plane surface and a given slope, Gilley *et al.* [1992] confirmed negative $f-Re$ relations where small gravels were submerged, but found positive $f-Re$ relations when

¹Also at National Fund for Scientific Research, Leuven, Belgium.

large cobbles protruded through flow. Friction generally increased with rock fragment cover percent. In addition to this, *Rauws* [1988] noted that the f - Re relation varied with slope angles: for hemispheres glued to a plane surface, convex upward f - Re relations turned into negative monotonic functions with increasing slope. This phenomenon was less pronounced with higher grain friction applied to the flume. The variations of all these factors, such as relative roughness, wetted upstream projected area of the rocks, rock fragment cover percent, slope angle, and percentage of grain friction, are combined on a natural gravel-covered hillslope. *Abrahams et al.* [1986, 1990] and *Abrahams and Parsons* [1991] found in their field experiments in semiarid southern Arizona that the f - Re relation can take various shapes as friction can either be increased by enlarging the wetted upstream projected area of a roughness element or the flow can smooth out roughness by increasing relative submergence. Hydraulic friction thus becomes solely a matter of protrusion or submergence. Depending on whether the relation d/k is larger or smaller than 1, relationships between Re and f will be positive, negative, or convex upward. These examples indicate the problems that arise in predicting friction factors.

None of the studies on friction exerted by pebbles and cobbles has included soil detachment and transport phenomena. *Abrahams et al.* [1986, 1990] and *Abrahams and Parsons* [1991] did not take into account the erosional component in their analyses of overland flow that developed on a gravel-covered natural hillslope, and *Gilley et al.* [1992] conducted laboratory experiments with gravel and cobble covers glued onto a fiberglass sheeting located within the flume. As these experiments were conducted in a nonerodible environment, their hydraulics do not reveal natural conditions, as flow energy is not allowed to be spent for soil detachment and transport processes.

Studies that identify threshold conditions and statistical relationships between spatially averaged overland flow hydraulics and soil erosion have not been carried out on slopes covered by rock fragments. For irregular, cultivated soil surfaces *Govers and Rauws* [1986] showed that transport capacity can be related to grain shear velocity. On the other hand, *Nearing et al.* [1989] predicted soil loss on rough surfaces by grain shear stress τ' which is calculated as total shear stress τ (equal to $\rho g d s$ where ρ is fluid density) multiplied by the ratio of f'/f where f' is the grain friction calculated for a soil surface without form roughness (or rock fragments). The question arises whether these findings also hold for soil surfaces covered by rock fragments. It seems to be questionable whether soil loss in the presence of rock fragments can be predicted from any spatially averaged flow hydraulics at all. Especially for high-power flows resulting from steep slopes [*De Ploey*, 1981] or large unit discharges, a strong local turbulence can develop close to a rock fragment. This observation suggests that the local erosional forces can deviate considerably from spatially averaged hydraulics.

The purpose of this study is a combined analysis of the effects which rock fragment covers on erodible soil may have on spatially averaged overland flow hydraulics as well as on a spatial variation of flow (e.g., rhombic flow structures [*Hodges*, 1982] or horseshoe vortices [e.g., *Boyer and Roy*, 1991]). The effects of local flow conditions will be observed, and their influence on local soil erosion and

sediment yield will be assessed. Although raindrop impact is widely recognized to contribute considerably to the amount of soil erosion [*Poesen and Savat*, 1981; *Iverson*, 1980], the effects of rainfall impact on sediment yield are not included in this study. The reasons for rainfall exclusion are twofold. First, the thorough description of the effects of raindrop impact on the hydraulics of overland flow and related soil erosion is very complicated. As the presence of the rock fragments leads already to a spatial variation of flow conditions and soil erosion processes, the experimental conditions are to be kept simple, in order to concentrate on the rock fragment effects. Therefore a simple erosive system was chosen, consisting of that part of an overland flow event that continues after the rainfall has ceased (afterflow). The second reason for rainfall exclusion is that raindrop impact is most effective for small cover percentages, when most of the soil surface is exposed. However, for larger rock fragment covers, the effect of raindrop impact must become negligible, as a high cover not only restricts the area available to raindrop impact, but also increases flow depth. Once flow depth exceeds the raindrop diameter, the drop impact does not further increase soil erosion [*Palmer*, 1963; *Schmidt*, 1991].

2. MATERIALS AND METHODS

As soils are commonly cohesive, the authors had considered using cohesive soil for the experiments as well. However, this would have posed serious problems in maintaining replicable soil conditions for all experiments. As the packing and therefore the structural porosity might vary in each experiment, the erodibility and the amount of water lost to infiltration is bound to vary as well. The second problem is to maintain replicable moisture conditions for all experiments. In addition to that, the erodibility not only depends on the actual moisture content, but is also very sensitive to whether a certain moisture content is reached during a drying or a wetting process [*Govers et al.*, 1990]. Therefore a silica flour with 1% clay, 31% silt, and 68% sand ($D_{50} = 0.09$ mm; U.S. Department of Agriculture classification, "sandy loam") was chosen in order to resemble a soil with mainly textural porosity. This fine but noncohesive material keeps infiltration at a reasonable level and, as similar soil moisture conditions can be established for each experiment, has negligible variation in erodibility. This noncohesive material also proved to be very responsive to variations of flow: The sedimentary patterns developing during an experiment nicely indicated local flow conditions. Before a new experiment started the former "active" top sediment layer in which erosion had occurred (about 1 cm) was replaced by a new dry layer of silica flour which was wetted by capillary rise and accurately planed before a rock fragment cover was applied. Experiments were conducted in a flume, 2 m long and 0.353 m wide.

Twelve different rock fragment cover percentages ($C\%$) between 0 and 99% were simulated using ellipsoidal flint pebbles with the mean diameters of the longest, intermediate, and shortest axes of 2.10, 1.45, and 0.86 cm respectively. The number of particles required for a certain rock fragment cover was calculated, and rock fragments were arranged in a diamond pattern in a random orientation flat on the flume bed (longest and intermediate axes parallel to soil surface). The cover percentage was later controlled by

placing a mesh wire grid (mesh width, 2.5 cm) over the flume and counting the number of grid points that had a pebble under them. Due to the random orientation, the average pebble width (b) exposed to flow is the mean between the longest and intermediate axes, $b = 1.78$ cm. Prior to each experiment the flume bed was presoaked by a nonerosive flow of $10 \text{ cm}^3/\text{s}$ for 30 min to provide replicable moisture conditions for each run. In this soaked state, the sandy loam lost its apparent cohesion, and pebbles sank 1–2 mm into the soft bed, leading to a better contact between pebbles and soil.

Inflow was controlled by a constant head tank and measured with a pressure flowmeter. An even distribution of flow over the entire flume width was achieved by dividing the flow into 17 evenly spaced outlet tubes from which the water flowed down a ramp. The junction between ramp and flume bed was smoothed by having the water percolate through some folded layers of geotextile. Nevertheless, some erosion at that junction could not be prevented.

The experiments were designed to simulate shallow overland flow in order to investigate the hydraulic conditions and the soil loss that develops in the presence of rock fragments. Rilling was intentionally avoided. *Rauws* [1987] has observed incipient rilling in plane beds of similar, highly erodible sandy loam ($0.09 \text{ mm} < D_{50} < 0.028 \text{ mm}$) for shear velocities $v_* = (gdS)^{0.5} > 3.4 \text{ cm/s}$. Therefore a combination of a constant discharge $Q = 83 \text{ cm}^3/\text{s}$ and a slope gradient $S = 1.4\%$ was chosen for all experiments, as this flow yielded shear velocities of only $1.4 \text{ cm/s} < v_* < 2.8 \text{ cm/s}$ for rock fragment cover percentages of 0–99%. This provided sheet flow conditions with only a small sediment yield (31 g in a 47-min experiment) for a plane, rock-free soil surface. Reynolds numbers around 200 indicated laminar flow for all experiments. Unit discharges $q = Q/w$ where w is flow width ranged from 2.4 to $2.6 \text{ cm}^3 \text{ cm}^{-1} \text{ s}^{-1}$, thus representing the upper limit of interrill flow on agricultural fields [Everaert, 1991]. Hydraulic conditions were below the threshold for entraining the pebbles [Poesen, 1987; Poesen and Torri, 1989; Poesen, 1990b]. At the flume outlet, timed volumetric samples were taken to measure outflow and sediment concentration. The amount of surface flow lost by infiltration was negligible. Each experimental run lasted for 45–50 min. Samples were taken at intervals of less than 1 min during the first few minutes and at 5-min intervals for the later periods of each run.

Flow velocity was measured each 5 min over a reach of 0.5 m situated in the central part of the flume. A line of dye was injected across the flume width about 10 cm upstream from the measuring section, and the time required for the center of the dye cloud to pass the 0.5 m distance was recorded. This travel time was taken as width- and depth-averaged mean flow velocity (v). Due to turbulence around rock fragments, local flow velocities can deviate considerably from the mean flow velocity. Each velocity value represents the mean of three individual consecutive measurements.

Calculating the effective flow width (w_{eff}) for various rock fragment covers requires an estimate of the width of the protruding parts of the rock fragments in a cross section (equaling those parts of the cross section with 0 depth), and subtraction of these values from the total flume width [Abraham and Parsons, 1990]. As the sandy loam bed became very soft when soaked, effective flow width and flow depth could not be measured with a manual profile meter

during the experiments. Instead, a photographic method was employed. The methodology is explained for the example of a 12% rock fragment cover. The percentage of protruding pebbles was calculated from close-up photos that cover a flume area of 20 cm by 12.5 cm. The sediment transported in suspension left a residue on the pebbles. This made it possible to identify those pebbles that had protruded above the flow. For a 12% rock fragment cover, 36% of the rock fragments were found to protrude through the flow. The total width of all the rock fragments in a cross section was also calculated, which for a 12% cover equals 12% of the 35.3 cm total flume width, or 4.24 cm. The width of the protruding pebbles (36% of 4.24 cm, or 1.53 cm) was calculated next. Due to the rounded pebble shape, on average only half of the pebble width protruded above the flow. Therefore the protrusion width was divided by 2 ($1.53 \text{ cm}/2 = 0.76 \text{ cm}$) and then subtracted from the total flume width to yield the effective flow width, $w_{\text{eff}} = 35.3 \text{ cm} - 0.76 \text{ cm} = 34.54 \text{ cm}$. Given Q , v , and w_{eff} , flow depth (d) and other hydraulic parameters such as Re and the Darcy-Weisbach friction factor could be calculated for bare (f') and pebble-covered surfaces (f). This allowed total shear stress τ and grain shear stress $\tau' = \tau(f'/f)$ to be calculated. For all rock fragment cover percentages, measured and calculated hydraulic parameters are listed in Table 1.

3. RESULTS AND DISCUSSION

Local Vorticity, Scour Development, and Soil Surface Morphology

As soon as the experiments started, flow created a high local turbulence close to the pebbles, all of which protruded into the flow. Local dye injections helped visualize the movement of the streamlines that formed horseshoe vortices around pebbles. The flow took a fast, spiraling motion from both sides to the frontal part of the scour, with a downward movement in front of the rock fragment and an upward movement along the steep face of the scour hole. In the wake of the rock fragments, flow slowed down considerably, and flow lines followed a circular pattern, curling inward from both sides of a rock fragment to the central part directly behind it. Considerable erosion was caused by the horseshoe vortices in the form of a local scour hole around the stoss and the lateral parts of each pebble, with some deposition in the wake. The form of the scour often resembled a hoofprint (Figure 1). These scour marks, also called current crescents, occur in fluvial, eolian, and marine environments [Karcz, 1968; Logie, 1982; Allen, 1985] whenever a current flows over erodible sediment and is obstructed by an obstacle. The morphology of these scour marks caused by horseshoe vortices is described in detail by Boyer and Roy [1991].

In our experiments, the morphology of the flume surface underwent some temporal and spatial variation. For rock fragment covers below 60%, vigorous scour took place in the horseshoe vortices in the initial stage of the experiments and eroded all sediment regardless of its size. Most of this sediment became suspended, but some of the finer material was deposited as tail berms in the wake vortices immediately behind the pebbles. For low cover percentages with a wide spacing between pebbles, part of the sediment was transported as bed load which moved in thin, fast threads in the upper part of the flume. In the downslope section of the

TABLE 1. Hydraulic Parameters for Shallow Overland Flow on Noncohesive Sediment Covered With Rock Fragments (0–99%)

C , %	w_{eff} , cm	v , cm/s	q , cm ² /s	d , cm	f	τ , Pa	f'/f , %	τ' , Pa
0	35.30	17.69	2.35	0.13	0.05	0.18	100.0	0.183
2	35.26	12.14	2.35	0.19	0.14	0.27	32.64	0.086
4	35.16	10.53	2.35	0.22	0.22	0.31	21.17	0.065
6	35.03	9.61	2.35	0.25	0.29	0.34	16.04	0.054
8	35.03	7.98	2.36	0.30	0.51	0.41	9.19	0.037
12	34.54	7.51	2.40	0.32	0.62	0.44	7.53	0.033
19	34.06	7.43	2.43	0.33	0.65	0.45	7.13	0.032
26	33.31	5.81	2.49	0.43	1.39	0.59	3.40	0.020
39	32.46	6.05	2.55	0.42	1.29	0.58	3.62	0.021
58	32.56	5.29	2.54	0.48	1.96	0.66	2.42	0.016
80	32.33	4.96	2.56	0.52	2.83	0.71	1.69	0.012
99	32.50	5.38	2.55	0.47	1.74	0.65	2.77	0.018

C is rock fragment cover; w_{eff} is effective flow width; v is mean flow velocity measured in the central part of the flume between 0.8 and 1.3 m from the upper end of the flume; q is unit discharge, equal to Q/w_{eff} where Q is total discharge; d is mean depth of flow, equal to q/v ; f is the Darcy-Weisbach friction factor, equal to $8gdS/v^2$; τ is total shear stress equal to $\rho g d S$ where ρ is fluid density, g is acceleration due to gravity, and S is slope; f'/f is the ratio of friction factor for bare surface and total friction factor; and τ' is grain shear stress, equal to $\tau(f'/f)$.

flume this material was deposited in lobes where the lateral parts of the scour holes began to fade out. These lobate deposits slowly migrated downslope. With narrowing space between the pebbles the sediment lobes vanished, and as space between the pebbles was further limited, the deposition of scoured material was confined to the wakes of the pebbles. After equilibrium scour depth had been reached, which took about 10 min, some of the flow concentrated in bowl-shaped channels about 2 cm wide, and individual scour holes were reshaped. This reshaping could either be an enlargement and a connection of a scour hole with its downstream neighbors or an infilling of those scour holes that had been abandoned by the mainstream of the flow. This subsequent adjustment of scour shape was less distinct when the interpebble space was limited by large rock fragment covers. Toward the downstream end of the flume, scour hole development was usually less pronounced and showed less temporal variation, and bed load motion was scarce. This raises the question of the influence of flume length on the

results of the experiments. The answer is necessarily speculative, but the less active scour and reduced sediment transport at the end of the 2-m-long flume suggests that if sediment concentration of the flow decreased below transport capacity further downstream in the flume, scour development would eventually set in again and sediment concentration would reach transport capacity. Thus a downslope repetitive pattern of zones with active scour followed by zones of less scour activity could be expected for a very long flume, comparable to the downslope alternation of headcuts and deposition in concentrated overland flow as observed by Bryan and Poesen [1989] in a 17-m flume. Sediment transport rates would also vary depending on whether samples were taken in active or less active zones of scour development.

Virtually all sediment that left the flume moved in suspension. This suspended load comprised only the finer part of the original sandy loam mixture. Grain size analyses carried out for sediment samples of experiments with 2, 6, 12, and 26% cover show that on average 90% of the sediment yield consisted of fine silt (2–37 μm), 5% medium silt (37–63 μm) and 5% sand (63–250 μm). The grain size distributions of the sediment transported out of the flume during a 47-min experiment showed no systematic variation with time, but grain sizes seemed to slightly coarsen with cover percentage.

Temporal Variation of Sediment Concentration

Due to this scour hole development and soil surface adjustment to the local shear stresses, sediment concentration (C_s) decreased with time in all experiments, following an exponential decay, even though discharge was kept constant. To better compare the effects of various rock fragment cover percentages ($C\%$) on the temporal variation of C_s , sediment concentrations obtained after given periods of time during the experiments were plotted versus rock fragment cover percent (Figure 2). The initial C_s , taken after the experiments had run for 1 min, increased for increasing rock fragment covers. Sediment concentrations at $t = 6$ min stopped increasing for $C\% > 20\%$. At later times during the

Fig. 1. Scour holes due to horseshoe vortex erosion around rock fragments at a 20% rock fragment cover percentage after a 47-min experiment, 1.10 m downslope from the flume inlet. At a 20% cover, scour holes do not interfere yet. Flow was from left to right. The scale bar at the bottom indicates centimeters and millimeters.

Fig. 2. Variation of sediment concentration with rock fragment cover for various times during the experiments.

experiments, C_s at $t = 15$ min as well as the final C_s at "steady state" ($t = 30-45$ min) even decreased as the cover percentage exceeds 20%. For low to medium rock fragment covers (0–20%), initial and final C_s maintain a difference of about 1 order of magnitude. For higher covers (>20%) the initially high erosion could not be sustained, and C_s strongly decreased with time, causing a difference between initial and final C_s of 2 orders of magnitude. The final sediment concentration therefore varied nonmonotonically with rock fragment cover. It reached a maximum at a cover of about 20% and decreased for higher covers.

Variation of Total Sediment Yield With Cover Percentage

To assess the effect of rock fragment covers on total sediment yield for a given discharge, slope, and time period, sediment discharge Q_s was integrated over time, and the mass of sediment that left the flume during an experimental run was calculated as

$$M_s = \int_{t=0}^{t=47 \text{ min}} Q_s dt \quad (1)$$

Total sediment yield (M_s) shows the same distinctive relation with cover percent as the midrun or final sediment concentration: The lowest M_s is observed for a 0% cover; M_s increases with increasing pebble cover to reach a maximum at a cover of about 20% and decreases for larger covers (Figure 3). Given the conditions of these experiments, a cover percentage of about 20% is ideal for "sediment har-

Fig. 3. Nonmonotonic variation of total sediment yield ($M_{s(\text{total})}$), initial sediment yield ($M_{s(\text{initial})}$), final sediment yield ($M_{s(\text{final})}$) and mass of scoured sediment (M_{scour}) with rock fragment cover percentage. Initial sediment yield consists of sediment transported out of the flume during the first 10 min of an experiment, while final sediment yield left the flume at "steady state" conditions during the last 17 min of an experiment.

vesting"; compared to a rock-free surface the identical discharge caused a nearly tenfold increase in soil loss.

Variation of Mean Overland Flow Velocity With Rock Fragment Cover

Throughout the literature, interrill and rill sediment detachment and transport by flow for bare soil surfaces is shown to be attributable to some velocity-related parameters of flow hydraulics [Rauws, 1987; Govers, 1990; Everaert, 1991]. However, mean flow velocity (v) of each experiment was found to steadily decrease with increasing rock fragment cover ($C\%$) (Figure 4) according to a power function. The equation for this function is given in Figure 4. This result is in contrast to statements made by Thornes *et al.* [1990], who

Fig. 4. Decrease of mean flow velocity (depth-, width-, and time-averaged) with rock fragment cover percentage.

Fig. 5. Monotonic relations of various hydraulic parameters with rock fragment cover percentage. The correlation coefficients r yielded values between 0.95 and 0.98 for all fitted regressions.

considered that for reticular flow of constant discharge Q , an increasing rock fragment cover would lead to an increase of unit discharge q which in turn would enhance mean flow velocity. However, our experiments with constant discharge Q show a drastic decrease of flow velocity as the cover percentage is raised from 0 to 20% and a slight reduction of mean flow velocity as the cover percentage is further increased. Especially, the strong reduction of mean flow velocity for covers between 0 and 20% indicates an increasing turbulence. Flow energy is spent in the fast, spiraling motion within the local vorticity around the roughness elements and in the subsequent scour, thus retarding the flow.

Predictability of Sediment Production by Hydraulic Parameters for Various Rock Fragment Covers

A combination of the results from Figures 3 and 4 yields a nonmonotonic relation between total sediment yield and mean flow velocity, indicating that sediment yield cannot be directly related to mean flow velocity. To assess the predictability of sediment yield by other hydraulic variables, their relations with rock fragment cover percent were analyzed first. Figure 5 shows the variation of some hydraulic parameters with rock fragment cover percentage. The regression equations are given as well. Correlation coefficients r yielded values of 0.95–0.98 for all regressions.

The mean depth of flow (d), calculated by the procedure explained above, steadily rises with increasing rock frag-

ment cover ($C\%$). Consequently, flow parameters having d in the numerator such as Reynolds number ($Re = vd/\nu$), Darcy-Weisbach friction factor ($f = 8gdS/v^2$) and total shear stress ($\tau = \rho g d S$) increase with cover percentage according to power functions (Figure 5). Because these variables are all monotonically related to $C\%$, none of them can be monotonically related to sediment yield.

As form roughness generally exceeds grain roughness on natural hillslope surfaces, it is of some interest to assess how the proportion of grain friction (f') to total friction (f) varies with rock fragment cover percentage and how these results compare to other measurements. *Rauws and Govers* [1988] found grain shear velocity in data by *Emmett* [1970] to be about 10% of total shear velocity. *Abrahams and Parsons* [1991] found on their gravel-covered hillslopes with a cover percentage of 50–80% that grain friction (f') would typically account for 5–3% of total friction. In our experiments the percentage of grain friction ($f'/f(100)$) was calculated for all rock fragment covers (Figure 5). After a very strong decrease for rock fragment covers between 0 and 20%, the percentage of grain friction ranged between 2 and 3% for covers of 50–80%. These results support the findings that grain friction represents only a small portion of total friction.

By analogy with river flow [*Einstein and Barbarossa*, 1952], *Rauws and Govers* [1988], *Nearing et al.* [1989, 1990] and *Abrahams and Parsons* [1991] emphasized that on rough soil surfaces grain shear velocity or grain shear stress τ' should be used to forecast sediment transport at transport capacity instead of the total shear stress τ , because only τ' is responsible for grain detachment and transport while τ largely overpredicts transport capacity. In the present study, τ' was calculated as $\tau' = \tau(f'/f)$ and found to decrease with rock fragment cover according to a power function (Figure 5), yielding only 2–3% of total τ for covers exceeding 50%. *Abrahams and Parsons* [1993] recently suggested that sediment transport capacity in overland flow on desert hillslope surfaces covered by rock fragments is probably larger than predicted by grain shear stress alone and presented laboratory results to support this contention. They found that a lot of turbulence was generated in the wake of roughness elements that were placed on a nonerodible flume surface. *Abrahams and Parsons* [1993] concluded that energy dissipated in the wakes of roughness elements in overland flow is transformed into turbulence and that this turbulence is sufficiently close to the bed to affect sediment transport.

All of the hydraulic variables measured or calculated (Figure 5) show monotonic relations with rock fragment cover percent. Therefore none of the spatially averaged flow parameters are able to predict the convex upward relationship between total sediment yield and cover percent with a maximum at a 20% pebble cover (Figure 3). This has important implications for sediment transport modeling: Contrary to results obtained by *Govers* [1990] and *Everaert* [1991] for bare interrill and rill soil surfaces, sediment yields are not directly related to spatially averaged hydraulic parameters such as shear velocity or unit stream power when important overland flow events occur on highly erodible soils covered with rock fragments.

The questions arise, What causes the differences in sediment output between various percentages of rock fragment cover and why is the relation between sediment yield and rock fragment cover nonmonotonic? The effects of rock fragments on local scour need to be described, and the mass

TABLE 2. Maximum Equilibrium Scour Depth (d_{sc}) Predicted for a 2% and a 20% Rock Fragment Cover by Selected Formulas

Author	Formula	d_{sc} , cm	
		2% Cover	20% Cover
Shen et al. (1969)*	$d_{sc} = 0.00073Re_p^{0.619}$	1.30	1.74
Inglis-Poona (1949)*	$h_{sc} = 2.32(q^{2/3}/b)^{0.78}b$	1.06	0.94
Laursen (1963)†	$d_{sc} = 1.11(d/b)^{1/2}b$	0.65	0.85
Blench (1966)‡	$h_{sc} = 2.43(b/a)^{1/4}a$	1.38	1.27
Breuser (1965)§	$d_{sc} = 1.4b$	2.49	2.49
Larras (1963)§	$d_{sc} = 1.42Kb^{0.75}$	2.19	2.19

Formulas were compiled and suggested by Raudkivi [1976] and Shen et al. [1969]. The Shen et al. formula gives d_{sc} in feet (1 foot equals 0.3048 m). Re_p (pier Reynolds number) equals vb/η where v is mean flow velocity, b is pier width or in our case mean pebble diameter exposed to flow, and η is kinematic viscosity; h_{sc} is scour depth below the water surface; $a = (q^2/1.9(D_{50})^{1/2})^{1/3}$ where q is unit discharge and D_{50} is mean particle diameter, all units in meters except D_{50} in millimeters; K is pier shape factor, equal to 1 for cylindrical piers.

*Formula for clear water scour.

†For scour during sediment transport other than bed load.

‡For scour with sediment transport.

§For scour with continuous sediment motion.

of scoured material needs to be quantified in order to answer these questions.

Calculation of Scour Dimensions

The development of local scour due to horseshoe vortices has received considerable attention as it can produce deep scour holes around bridge piers [Laursen, 1962, 1963; Shen et al., 1969; Jain and Fischer, 1980; Raudkivi and Ettema, 1983; Raudkivi, 1986; Melville and Sutherland, 1988; Boyer and Roy, 1991; Yanmaz and Altmbilek, 1991]. The Handbook edited by Vanoni [1977] and that written by Raudkivi [1976] summarize the basic findings. The three-dimensional nonuniform complex flow patterns of the vorticity that occurs during scour around an obstruction can still not be properly described, but empirical equations that are available for predicting maximum equilibrium scour depth (d_{sc}) relate d_{sc} to pier width (b) and its orientation and shape, and to the capacity of flow for scour from the scour hole (expressed by either unit discharge (q), flow depth (d), or mean flow velocity (v)). The maximum equilibrium scour depths predicted by these formulas for flow conditions observed for two cover percentages (2% and 20%) in our flume experiments are listed in Table 2.

Measured scour depth at the stoss side of pebbles ranged between 0.5 and 1.0 cm for rock fragment covers between 2 and 20% when scour holes could develop undisturbed. Among the formulas tested, the Inglis-Poona formula and the Laursen formula predict scour depth reasonably well, while the other formulas overpredict scour depth observed in our experiments, indicating that the hydraulic conditions around rock fragments resting on a soil surface are not totally comparable to an isolated bridge pier in their effects on scour. Length and width of fully developed scour holes were therefore smaller in our experiments than described by Yanmaz and Altmbilek [1991]. The scour hole morphology in our experiments is close to that described by Boyer and Roy

[1991] and in its mature state resembled a hoofprintlike depression with a triangular cross section (Figure 1).

Although dimensions of scour holes were subject to some temporal and spatial variation, for reasons of simplicity, a static distribution of "mature," semicircular scour holes around the stoss side of each pebble in the flume is assumed for rock fragment cover percentages between 0 and 20%. For a fully developed scour hole, the cross-sectional area (A_{sc}) is approximated by a regular-sided triangle. Based on visual observation, the width of the scour (w_{sc}) can be estimated as half the pebble diameter ($b/2$), and scour width equals scour depth (d_{sc}). The cross-sectional scour hole area (A_{sc}) is given by

$$A_{sc} = (d_{sc}w_{sc})/2 = (b/2)^2/2 \quad (= 0.40 \text{ cm}^2). \quad (2)$$

The length of a hoofprintlike scour hole was approximated by half the perimeter of a circle with a diameter $y = b + 2b/4 = b + b/2$. The scour hole length (U_{sc}) is then given by

$$U_{sc} = \pi(b + b/2)/2 \quad (= 4.19 \text{ cm}) \quad (3)$$

The volume scoured per fully developed scour hole is

$$V_{sc} = A_{sc}U_{sc} \quad (= 1.66 \text{ cm}^3). \quad (4)$$

The total scoured volume ($\sum V_{sc}$) per experimental run is

$$\sum V_{sc} = U_{sc}A_{sc} \sum n_p \quad (5)$$

where $\sum n_p$ is the number of pebbles required for a certain cover percentage (e.g., 56 for 2% cover). Multiplying by the dry bulk density of the soil mixture ($\rho_{bulk} = 1.3 \text{ g/cm}^3$) yields the scoured mass,

$$M_{sc} = \sum V_{sc}\rho_{bulk} \quad (= 121 \text{ g for a 2% cover}). \quad (6)$$

The previous calculations referred to scour holes that could develop undisturbed. The results of these calculations are listed in Table 3. For large rock fragment covers, however, the interpebble space is limited, and scour hole development is confined. The next step in the calculation of scoured mass is to define the critical distance between pebbles beyond which scour is confined and adjust the calculation of scoured mass accordingly.

For an even distribution of rock fragments over the flume area (A_{fl}), the distance (x_p) available for scour between two pebbles for a certain cover percentage is given by

$$x_p = (A_{fl}/\sum n_p)^{0.5} - b \quad (7)$$

where $\sum n_p$ is the number of pebbles required for a certain cover percentage. A semicircular scour hole surrounding the stoss side of a pebble has a total diameter of $2b$, when scour width on both sides of the pebble is $b/2$. If x_p , the distance between two neighboring pebbles, becomes smaller than one rock fragment diameter (b), the critical distance is reached beyond which the space between the rock fragments becomes too small and fully developed neighboring scour holes begin to interfere. For an effective pebble diameter $b = 1.78 \text{ cm}$ the critical distance is reached when the rock fragment cover density exceeds about 20% (see Table 3). Beyond this threshold, the largest possible scour width is $x_p/2$. Formulas employed for the calculation of mature scour holes need to be adjusted accordingly.

TABLE 3. Parameter Values for Various Cover Percentages ($C\%$) and the Number of Pebbles (Σn_p) Required for the Cover

$C, \%$	Σn_p	x_p, cm	V_{sc}, cm^3	M_s, g	$M_{s(0-3)}, \text{g}$	$M_{s(0-10)}, \text{g}$	$M_{s(30-47)}, \text{g}$	M_{sc}, g	M_s/M_{sc}
0	0	...	...	31	16	20	5	0	...
2	56	9.40	1.66	88	32	52	17	121	0.73
4	109	6.23	1.66	97	36	56	17	235	0.42
6	160	4.83	1.66	173	64	106	23	345	0.50
8	225	3.80	1.66	225	64	122	25	486	0.46
12	333	2.80	1.66	246	58	132	29	719	0.34
19	526	1.87	1.66	259	64	120	42	1136	0.23
26	735	1.31	0.82	294	93	168	42	784	0.38
39	1100	0.74	0.23	234	90	134	32	331	0.71
58	1626	0.29	0.032	207	70	126	14	67	3.09
80	2250	>0*	>0*	188	111	147	9	>0*	...
99	2770	>0*	>0*	166	79	132	12	>0*	...

Parameters are distance available for scour development (x_p), volume of scour around a pebble (V_{sc}), total sediment yield (M_s), initial sediment yield of the first 3 min ($M_{s(0-3)}$), initial sediment yield of the first 10 min ($M_{s(0-10)}$), final sediment yield for "steady state" conditions ($M_{s(30-47)}$), scoured mass (M_{sc}), and the relation between scoured and transported sediment (M_s/M_{sc}).

*Small value.

Based on visual observation, scour depth can also be assumed to equal scour width for restricted scour conditions. The cross-sectional scour area is then

$$A_{sc} = (d_{sc}w_{sc})/2 = (x_p/2)^2/2. \quad (8)$$

Consequently, the length of a scour hole is given by the circumference (U_{sc}) of a circle with a diameter of $b + x_p/2$,

$$U_{sc} = \pi(b + x_p/2)/2. \quad (9)$$

The calculation of total scoured volume and total scoured mass follows (4) and (5). The results are listed in Table 3.

Transport-Limited or Detachment-Limited Flow Conditions?

For low cover percentages (<20%) the soil mass scoured (M_{sc}) increases directly with the number of rock fragments present (Figure 3). Beyond a cover percentage of 20% the scoured mass decreases as the higher opportunity of local scour around a larger number of rock fragments is counteracted by decreasing interpebble space that does not allow the scour holes to develop to their fullest possible extent. For cover percentages between 2% and 40%, the mass of sediment scoured (M_{sc}) exceeded the mass of sediment transported out of the flume ($M_{s(\text{total})}$). This scour excess indicates transport-limited flow conditions, while detachment-limited flow conditions are prevalent for cover percentages larger than 40%, when limited interpebble space confines scour hole development.

The question arises whether these transport-limited conditions prevailed during the entire course of the experiments. To answer this question, initial sediment yield ($M_{s(0-10)}$) which left the flume when scour hole development was very active during the first 10 min of an experiment, and final sediment yield ($M_{s(30-47)}$) that occurred when "steady state" conditions were reached during the last 17 min of an experiment were compared with total sediment yield (M_s). Both initial and final sediment yield increase with rock fragment covers up to 20%, but for larger covers the initial sediment yield barely decreases, while final sediment yield decreases strongly. The reduction of total sediment yield for

covers >20% is mostly due to the small amount of sediment transported during the final phase.

During the first 10 min of an experiment, active scour hole formation provides ample sediment supply to the flow, and 50–60% of the total sediment yield is exported from the flume. During the last 35 min these transport-limited flow conditions turn into detachment-limited flow conditions after most of the scour has been completed and little sediment is contributed to the flow by scour hole reshaping.

For high rock fragment cover percentages, the different behavior of initial and final sediment yield has implications regarding the sediment yield of overland flow events of different duration. For short events (or during the initial phase of an event), total sediment yield is constant for rock fragment covers >20%. If the duration of an event becomes longer (or during the final part of an event), a rock fragment cover >20% shows a negative effect on total sediment yield and particularly on final sediment yield.

4. SUMMARY AND CONCLUSIONS

On highly erodible, noncohesive sandy to silty soils the erosivity of an overland flow event that has little erosive power on a bare, rock-free soil surface, can be greatly increased by introducing a rock fragment cover. The lack of cohesion of the sediment leads to the formation of horseshoe vortices associated with vigorous scour of hoofprintlike scour holes around individual rock fragments.

The intensity of the scour processes depends strongly on the rock fragment cover percentage. For a cover percentage between 0 and 20%, scour holes can develop to their fullest extent, and the volume of scoured material increases with the number of pebbles forming the cover. For cover percentages larger than 20% the areal extent of the scour exceeds the interpebble space available, and scour holes start to interfere with one another and only develop in a fragmentary way. Few local scour marks can be observed for rock fragment covers larger than 60%. But high roughness and turbulence still cause sediment entrainment and transport during the initial phase of an experiment. However, due to limited scour hole development and the shielding effect of high rock fragment covers, the final sediment yield decreases

for large cover percentages and causes total sediment yield to decrease with rock fragment cover, leading to a nonmonotonic relation between cover percentage and sediment yield. The nonmonotonic variation of sediment yield with cover percentage is not directly related to any spatially averaged hydraulic parameter such as mean flow velocity, mean flow depth, friction factor, or shear stress, which monotonically vary with cover percent. To explain the relation between rock fragment cover percent and sediment yield, the scour dimensions need to be quantified. Describing the volume of the hoofprintlike local scour by a simple geometrical form, the mass of scoured material (M_{sc}) can be calculated. It increases for covers between 2 and 20%. The critical distance between rock fragments at which individual scour holes start to hinder each other in their development is reached at a cover percentage of about 20%. Therefore M_{sc} decreases for larger covers, which agrees well with measured sediment discharges. For cover percentages between 2 and 40%, M_{sc} exceeds total sediment yield (M_s) exported from the flume, suggesting transport-limited flow conditions. Flow conditions are detachment-limited for cover percentages >40%. Within an experiment, flow conditions are transport-limited during the initial phase when vigorous scour development takes place. During the final phase of an experiment a low "final" sediment yield suggests detachment-limited flow conditions.

The shape of the nonmonotonic relation between cover percentage and sediment yield is not only affected by the unit discharge and the rock fragment size applied, but is especially dependent on the noncohesiveness of the soil. Hoofprintlike local scour can be observed in agricultural fields where sandy deposits cover the bottom of rills of concentrated flow. For cohesive soils, scour hole development is much less pronounced.

However, this study has implications for cohesive soils. First, the scour holes indicate the presence of a high local turbulence with an increased potential for soil erosion around rock fragments. Secondly, vorticity and scour development are nonmonotonically related to the spacing of the rock fragments, resulting in a nonmonotonic relation between cover percentage and sediment yield. In cohesive soils, neither the vorticity nor its nonmonotonic relation with cover percentage is easy to detect. But although vorticity and scour development are strongly interactive in noncohesive material, some of this turbulence must also act on cohesive soils. This has, so far, not been incorporated into soil erosion modeling.

The common approach in soil erosion modeling partitions total shear stress into grain and form shear stress and allows only grain shear stress (τ'), which typically accounts for only about 5% of total shear stress, to detach and transport sediment. Form shear stress (τ'') is entirely dissipated on surface irregularities and is assumed to not contribute to erosion. Our results suggest that for overland flow on erodible soils covered with rock fragments this assumption is not valid. Apparently, τ'' is not entirely dissipated on the rock fragments, but part of it seems to be converted into turbulence. Given an erodible soil surface, this turbulence produces local scour. Where flow intensities barely exceed the threshold of sediment motion on a smooth rock-free erodible surface, part of τ'' seems to produce the bulk of the sediment on the same surface covered by rock fragments. Consequently, models using the τ' concept to predict sedi-

ment yield on erodible soil surfaces covered by rock fragments are bound to underpredict sediment yield because of not taking into account horseshoe vortex erosion induced by turbulence. Moreover, as rock fragment cover increases, progressively more of the soil surface is shielded from τ' , calling into question the relevance of the concept of grain shear stress for rock-covered surfaces.

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K. Bunte and J. Poesen, Laboratory for Experimental Geomorphology, Catholic University of Leuven, Redingenstraat 16bis, B-3000 Leuven, Belgium.

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