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Effects of rock fragments incorporated in the soil matrix on concentrated flow hydraulics and erosion

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Abstract

Rock fragments can act as a controlling factor for erosional rates and patterns in the landscape. Thus, the objective of this study is to better understand the role that rock fragments incorporated into the soil matrix play in concentrated flow hydraulics and erosion. Laboratory flume experiments were conducted with soil material that was mixed with rock fragments. Rock fragment content ranged from 0 to 40 per cent by volume. Other treatments were slope (7 and 14%) and flow discharge (5·7 and 11·4 l min^{-1}). An increase in rock fragment content resulted in lower sediment yield, and broader width of flow. Rock fragment cover at the soil surface, i.e. surface armour, increased with time in experiments with rock fragments. Flow energy was largely dissipated by rock fragment cover. For more turbulent flow conditions, when roughness elements were submerged in the flow, hydraulic roughness was similar for different rock fragment contents. In experiments with few or no rock fragments a narrow rill incised. Flow energy was dissipated by headcuts. Total sediment yield was much larger than for experiments with rock fragments in the soil. Adding just a small number of rock fragments in the soil matrix resulted in a significant reduction of sediment yield. Copyright © 2007 John Wiley & Sons, Ltd.

Keywords: **soil erosion; rock fragments; surface armouring; headcutting; flow hydraulics**

Introduction

Rock fragments play an important role in soil erosion. However, past research efforts have been primarily directed towards the soil particles, which are easily washed or blown away, and less to rock fragments, which are less easily eroded and whose presence can greatly influence erosional behaviour (Poesen *et al*., 1994). Erosion pavements are widespread in semi-arid and arid regions (Mensching, 1990). In the Mediterranean more than 60 per cent of the soils contain a considerable number of rock fragments (Poesen and Lavee, 1994). A review on the general impact of rock fragments on soils, soil moisture, plant growth, fertility and overland flow hydraulics, as well as rill and interrill erosion, was compiled by Poesen and Lavee (1994) as well as Brakensiek and Rawls (1994).

The effects of rock fragments in an eroding environment are threefold (Poesen *et al*., 1994): (i) protection against raindrop impact and flow detachment, (ii) the reduction of the physical degradation of the eroding surface and (iii) the retardation of overland flow velocity. These effects can be further differentiated for different flow regimes. Savat (1980) showed for different soil surfaces that log f (where f is the Darcy–Weisbach coefficient) decreases with log N_r (where N_r is the Reynolds number). In field experiments on desert pavements the f–N_r relationship has been shown to vary with the nature of experiments (Abrahams and Parsons, 1994). Gilley *et al*. (1992) tested the f–N_r relation for different rock fragment covers glued to a plane surface at varying slopes. They found a negative relation for f–N_r when rock fragments were submerged and a positive f–N_r relationship when rock fragments protruded above the flow. The frictional resistance of a rock fragment covered surface decreases rapidly with depth of flow when rock fragments are submerged, because as flow depth increases a greater fraction of the water flux takes place above the roughness elements. Lawrence (1997) therefore differentiated the influence of rock fragments for three flow regimes: partially, marginally and well inundated.

All the experiments discussed above were conducted on non-erodible or fairly stable surfaces, so that findings from this research do not reflect natural conditions, i.e. after tillage, as flow is not allowed to erode the soil surface by spending energy for detachment and transport processes. Bunte and Poesen (1993) conducted flume experiments with rock fragments embedded in the soil surface. In these experiments they observed local turbulences causing scour even when N_r (Reynolds number) was of the order of 250. In flume experiments that lasted up to 60 s, a 30 mm thick soil layer containing rock fragments was exposed to concentrated flow (Poesen *et al*., 1999). Rock fragment cover reduced concentrated flow erosion rates exponentially. The exponential relationship depended on the initial moisture conditions of the soil. The influence of rock fragments in reducing erosion rates was less efficient for initially air-dry soils, which are common in Mediterranean and other arid or semi-arid environments.

Erosion pavement can also affect the spatial patterns of flow velocities and erosion in the landscape. Studies of flow induced erosion in south-eastern Arizona, USA, have indicated that the hydraulic roughness of slopes of different gradients may evolve in such a way that a slope–velocity equilibrium is established through differences in rock cover on different slope steepnesses. Measurements have shown that overland flow velocities may become independent of slope gradient because of differential rock cover, which evolves as a result of previous, preferential erosion of fine material (Nearing *et al*., 1999). Thus, steeper slopes tend to have greater rock cover in semi-arid environments (Simanton *et al*., 1994; Poesen *et al*., 1998). Nearing *et al*. (2005) used ^{137}Cs measurements in two small semi-arid watersheds in south-eastern Arizona, USA, to show that variation in hillslope erosion and deposition rates appeared to be dominated by variation in rock covers. Areas of steeper slopes had greater rock cover, which induced the slope–velocity equilibrium discussed by Nearing *et al*. (1999), which tended to equalize flow velocities across the landscape. The additional rock cover on steeper slopes reduced the flow energy (and hydraulic shear) available for erosion as a function of the increased hydraulic roughness of soil surface cover because of the energy lost on the roughness elements. The overall result in the study of Nearing *et al*. (2005) was that the erosional patterns within the small, rocky, semi-arid watersheds did not show any consistent pattern of erosion as a function of hillslope position, slope steepness or slope curvature.

Rock fragments can act as a controlling factor for erosional rates and patterns in the landscape. Thus, the objective of this study is to better understand the role that rock fragments incorporated into the soil matrix have on concentrated flow hydraulics and erosion by concentrated flow as simulated in laboratory experiments. Slope steepness and flow discharge were also considered as treatments. Qualitative and quantitative measures describing the effect of rock fragment on soil loss are presented.

Material and Methods

The soil for this study was taken from the Ap horizon of an agricultural corn field approximately 20 km southwest of West Lafayette, Indiana, USA. The silt loam of the Miami series contained 25 per cent sand, 52 per cent silt and 23 per cent clay by mass. Soil organic matter content was 1 per cent by mass. Soil bulk density was 1·27 g cm^{-3}. The original soil contained only a marginal number of rock fragments larger than 2 mm. The soil was passed through an 8 mm sieve and air-dried for 2 days before mixing with two different classes of rock fragments of mixed lithology that were taken from fluvial deposits from the Wabash River, 5 km west of West Lafayette, IN, USA. The D_{50} (median diameter of the intermediate axis of the rock fragment) values of the finer and coarser rock fragment material were 8 mm and 30 mm, respectively. The density of rock fragments was 2·6 g cm^{-3}. The rock fragments were well rounded, having a flatness index of 1·75 and 2·0 for the coarser and finer material, respectively. The flatness index was calculated as described by Leser (1977, p. 203) as follows:

$$F = (l + i) \cdot (2s) - i \tag{1}$$

where F is the flatness index and l, i and s are the lengths of the longest, intermediate and shortest mutually perpendicular axes of the rock fragment, respectively.

Rock fragments were mixed with soil to yield a rock fragment content of 0, 5, 10, 20 and 40 per cent by volume (Table I). For experiments that contained rock fragments, three parts of the smaller and one part of the larger rock fragments was mixed with the soil. The material was packed loosely in the flume over a geotextile covering a silica sand tension table bed to a V-shaped surface, the depth of the V being 5 mm and the total width being 400 mm. The material was pre-wetted through a tension table for 24 hours and then brought to 15 cm tension for 12 hours. This procedure allowed reproducible results with the soil–rock fragment mixture close to field capacity. During the experiments water tension was clamped off, except for the end drainage hole, which was allowed to drain freely to prevent re-emergent flows at the bottom end of the soil bed during the experiments. The flume was then tilted to the appropriate slope.

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Table I. Experimental data

Slope (%)	Discharge (L min^{-1})	Experimental time (min)	Rock fragment content (vol.%)	Rock fragment content (mass%)	Intermediate diameter of largest transported rock fragment particle (mm)[a]	Rock fragment surface cover before/after experiment (%)
7	5·7	60	0	0	n.a.	n.a.
			5	14	7·9	6/15
			10	20	None[b]	9/16
			20	31	None[b]	14/15
			40	50	None[b]	28/28
	11·4	40	0	0	n.a.	n.a.
			5	14	9·2	10/37
			10	17	8·7	8/46
			20	29	7·9	23/40
			40	50	4·0	27/52
14	5·7	35	0	0	n.a.	n.a.
			5	–	–	–
			10	18	7·5	8/31
			20	31	4·6	17/35
			40	–	–	–
	11·4	20	0	0	n.a.	n.a.
			5	18	–	11/37[c]
			10	20	9·4	13/46
			20	30	10·4	13/42
			40	53	4·6	23/55

[a] Particles retained by a sieve with 2 mm grid size were collected at the flume outlet.
[b] No particle of >2 mm was retained in the sieve.
[c] Stopped after 5 minutes.

Laboratory experiments were carried out (Table I) in a 3 m flume that was described earlier by Nearing *et al.* (1997). A concentrated flow of deionized water was added at the top of the flume at nominal flow rates of 5·7 and 11·4 l min^{-1}. Two slopes of 7 and 14 per cent were used. During the experiment, mean flow velocities were determined measuring the velocity of the leading edge of a fluorescent dye and multiplying by a correction factor (Gilley *et al.*, 1990). Flow discharge and sediment yield samples were taken at the bottom end of the flume during 1–3 min intervals. The flume outflow was directed through a 2 mm sieve to collect eroded rock fragments. The diameter of the medium axis of the largest eroded rock fragment was measured after the experiment. Rill and flow width were measured with a ruler during the experiments every 30 cm along the flume. The occurrence of headcuts in the rill was recorded; width and height of headcuts were measured with a ruler. Experiments were run in two stages and were stopped after each stage to take photographs for rock fragment cover calculation. Photographs were scanned and a point count method using a grid of 100 evenly distributed points in the flow path of the water was used to make the calculation. In addition scanning of cross sections (Eltz, 1993) was conducted in order to develop digital elevation models (DEMs) of the soil surface. The laser scanner was too small by design to cover the entire flume in one scan. Therefore, three 100×400 mm^2 cross sections were scanned at the top, middle and bottom parts of the flume. After each experimental stage the scanner was brought to the same three positions as for the previous stage.

After each run the rock fragment content by mass (Table I) in the flume was determined by sampling an undisturbed area of the soil surface over a depth of approximately 100 mm, oven drying the sample and calculating the ratio of rock fragment mass, i.e. material with a particle size larger than 2 mm, to total mass.

Results and Discussion

The range of data in this experiment represented all four conditions of subcritical laminar, supercritical laminar, subcritical turbulent and supercritical turbulent flow regimes (Figure 1). Froude number (Fr) was calculated as

$$Fr = v \cdot (g \cdot d)^{-0{\cdot}5} \qquad (2)$$

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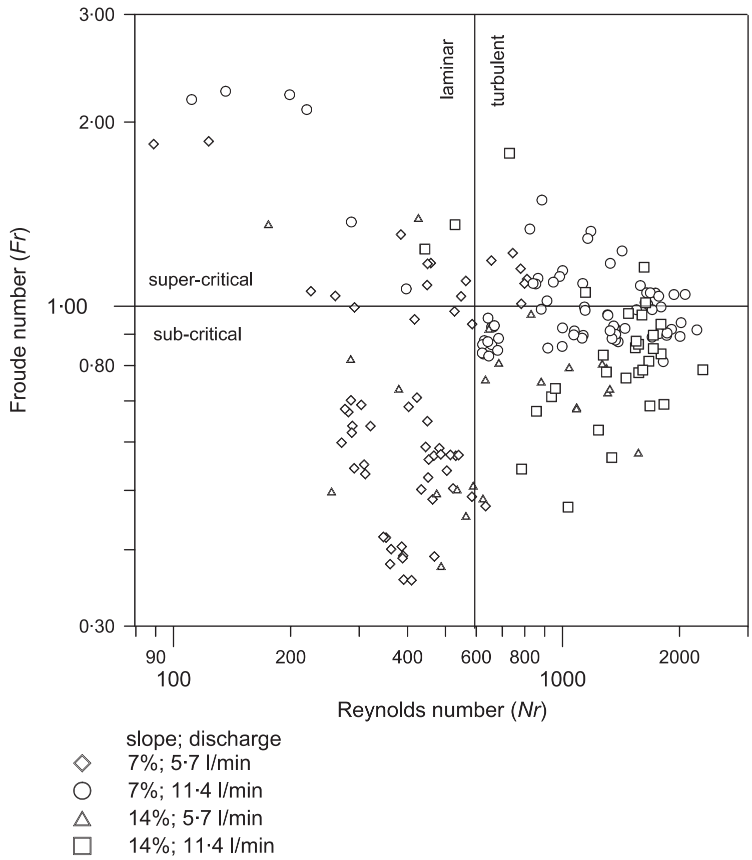

Figure 1. Flow conditions of experiments. The break line between laminar and turbulent conditions at $N_r = 600$ was set arbitrarily based on the observation of different flow behaviour.

where v represents the average flow velocity ($m^3 s^{-1}$), g the acceleration due to gravity ($m s^{-2}$) and d the flow depth (m). The Reynolds number (N_r) was calculated as

$$N_r = v \cdot U \cdot \upsilon^{-1} \tag{3}$$

where U is the hydraulic radius and υ the kinematic viscosity of water ($m^2 s^{-1}$). The break line between laminar and turbulent flow conditions in Figure 1 was chosen at $N_r = 600$. Ahnert (1996) places the threshold between laminar and turbulent flow at $N_r \leq 500$ in open channels. Here, a change in behaviour can be observed at a somewhat larger value of $N_r = 600$ when plotting the hydraulic roughness – Darcy–Weisbach coefficient (f) – versus Reynolds number (Figure 2). The Darcy–Weisbach coefficient (f) was calculated as

$$f = 8g \cdot U \cdot I \cdot v^{-2} \tag{4}$$

where I represents slope and all other factors are as defined before.

When N_r was less than 600, hydraulic roughness (f) varied with flow rate and rock fragment content. For N_r greater than 600, hydraulic roughness (f) was also affected by headcutting as well as surface armouring over time. Both effects indicate turbulent flow conditions.

Total sediment yield within each series of experiments varied with rock fragment content (Figure 3). The largest amount of sediment was collected when no rock fragments were incorporated in the soil. Minimum sediment was collected when rock fragment content was at a maximum. By far the most sediment was collected for the experimental series with maximum slope (14%) and discharge ($11{\cdot}4\ l\ min^{-1}$). This observation is even more meaningful considering that experiments of this series lasted for only 20 minutes while the other series were run for up to 60 minutes

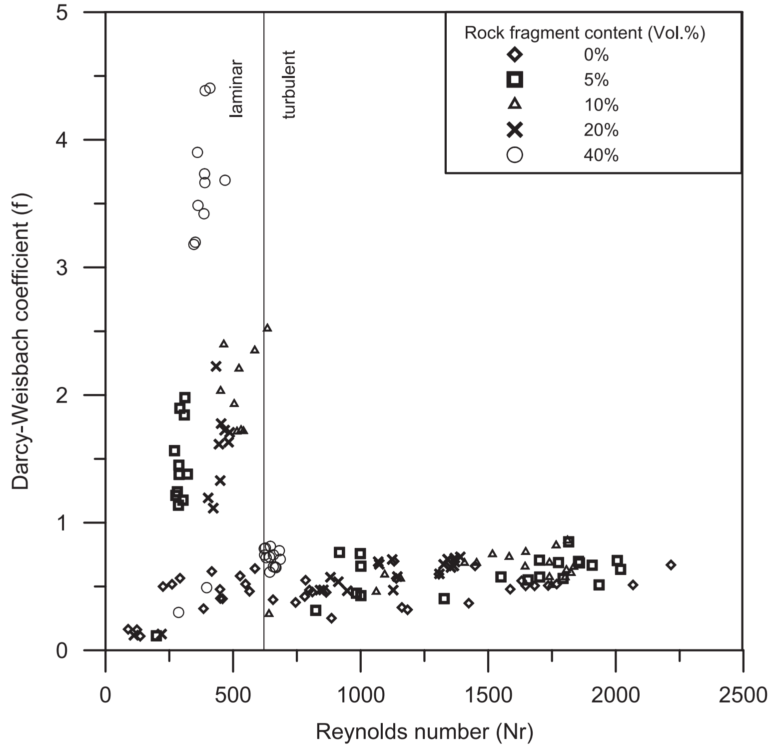

Figure 2. Plotting Darcy–Weisbach coefficient against Reynolds number for all experiments with 7 per cent slope reveals a difference in behaviour around a Reynolds number of 600. The break line between laminar and turbulent flow in the box was therefore placed at $N_r = 600$.

(Table I). In general, all four experimental series exhibit a linear reduction of sediment yield with increase of rock fragment content. At a certain rock fragment content sediment yield was negligible. The differences were so extreme that only negligible sediment yield was collected for all experiments with maximum rock fragment content in the soil (0·07–0·37 kg), while experiments without rock fragments exceeded this value in all series approximately by an order of magnitude. The experiment with no rock fragments and maximum slope and discharge had to be stopped after just 5 minutes, because the eroding rill had cut through the soil bed while the experiment with 53 per cent (by mass) rock fragments yielded just 0·37 kg of sediment over 20 minutes. For the series with 7 per cent slope and 5·7 l min^{-1} discharge sediment yield without rock fragments was 63 times greater than for the same experiment, but with a rock fragment content of 51 per cent by mass. Adding rock fragments to the soil severely reduced sediment yield. The effect depended on slope and discharge conditions. At 7 per cent slope and 5·7 l min^{-1} discharge 14 per cent (by mass) of rock fragments already reduced total sediment yield by a factor of 28 to a negligible amount of 0·16 kg. For larger discharge rates and steeper slopes, more rock fragments are needed to reduce total sediment yield to a negligible amount.

The total sediment yield graphs (Figure 3) do not reflect the change of the soil surface with time. The change of the rock fragment surface cover with time is shown in Table I. For all experiments with rock fragments, removal of fine particles results in exhumation of rock fragments that will stay in place. This effect increases the rock fragment cover with time and is referred to as surface armouring.

The intermediate diameter of the largest rock fragment transported to the flume outlet was recorded (Table I). All rock fragments larger than this were added to the surface armouring in the flow path of the water. The sizes of the rock fragments reflect the flow energy in the rill. The more rock fragments were mixed with the soil, the smaller were the transported rock fragments for a series of experiments. Rock fragments dissipate energy in the flow path and thus protect the fine material from erosion. For the experimental series with 7 per cent slope and 5.7 l min^{-1} discharge surface cover for the experiment with 40 per cent rock fragments did not change during the experiment. All the other experiments of this series with rock fragments in the soil approached a similar value of surface cover at the end of the experiment, which was between 15 and 16 per cent. This indicates that exhumation of the rock fragments continues

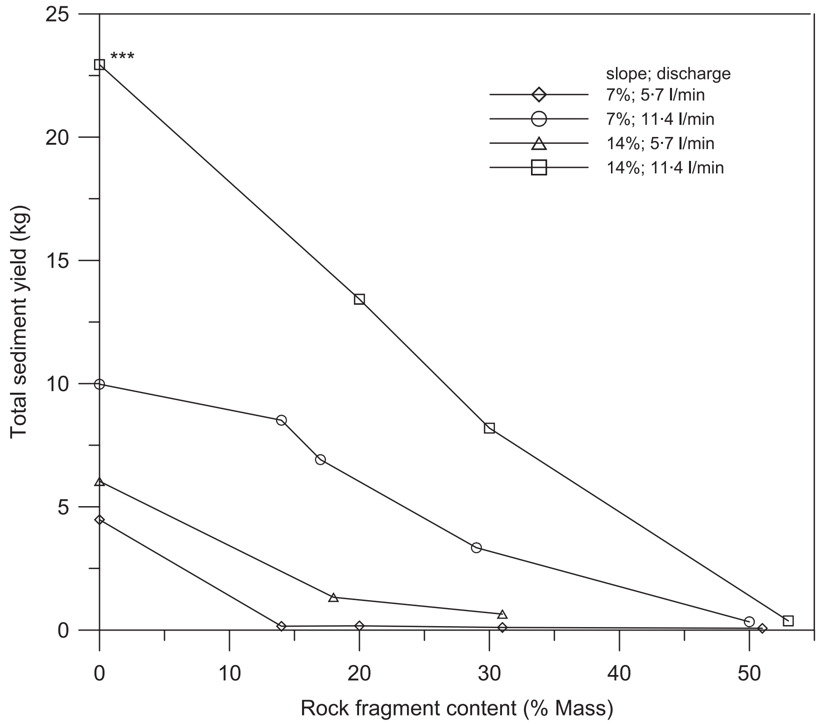

Figure 3. Total sediment yield decreased when rock fragment content was increased. *** Extrapolated data point; experiment stopped after 5 minutes.

until a stable surface cover is established that inhibits further rill incision. When flow energy was increased by raising slope or discharge, final rock fragment cover in the flow path did not converge to a similar value. This is probably due to the fact that rill incision is more significant at the beginning of experiments when rock fragment cover is low. When rock fragment cover increases with time, a rill has already formed and the flow energy is more concentrated, requiring an increased surface cover for effective armouring of the flow path. Therefore, not only rock surface cover, but also average width of flow (Figure 4), is an important factor for surface armouring.

For experiments with an intermediate rock surface cover at the beginning of the experiment, concentrated flow will start rill incision until the exhumation of rock fragments is sufficient for effective surface armouring in the flow path. Therefore, flow width as well as rock surface cover are important parameters when judging the effectiveness of surface armouring. Width of flow 167 cm down slope from the inflow was widest for experiments with the largest number of rock fragments for all series. The best protection from flow energy is provided when shallow water flow over a wide area with protruding roughness elements is present. Concentrated flow will incise a narrow rill as long as flow energy is not sufficiently dissipated by rock fragments or other means. Therefore, surfaces with initially fewer rock fragments will experience rill incision, i.e. narrow width of flow, until flow energy is dissipated by excavated rock fragments in this rill. Since rill incision also implies concentration of flow energy, rock fragment cover in this rill needs to be larger than for a surface with initially large surfaces cover to allow for efficient surface armouring. The less rock fragments cover the initial soil surface, the more time is required to reach effective armouring. The more time has elapsed before effective surface armouring is reached, the more significant will be the changes of the surface during that period of time.

The narrowest width of flow was obtained in experiments with no rock fragments added to the soil. Elevation profiles from laser scanning taken 167 cm down slope of the inflow illustrate this (Figure 5). Comparing the profile of the run with 40 per cent (by volume) rock fragments with the profile of the run from the same series, but with no rock fragments added, shows the change in the surface. In the first case the surface is eroded to a depth of approximately 30 mm; the entire width of the profile serves as the flow path. In the latter case rill incision after 20 minutes reaches 40 mm depth and the width of the rill is approximately 50 mm. After 40 minutes the rill has cut to a depth of 70 mm and width of flow is further reduced to approximately 30 mm. Images of the same cross sections (Figure 6) illustrate that the surface with 40 per cent (by volume) rock fragments does not undergo much change over the whole

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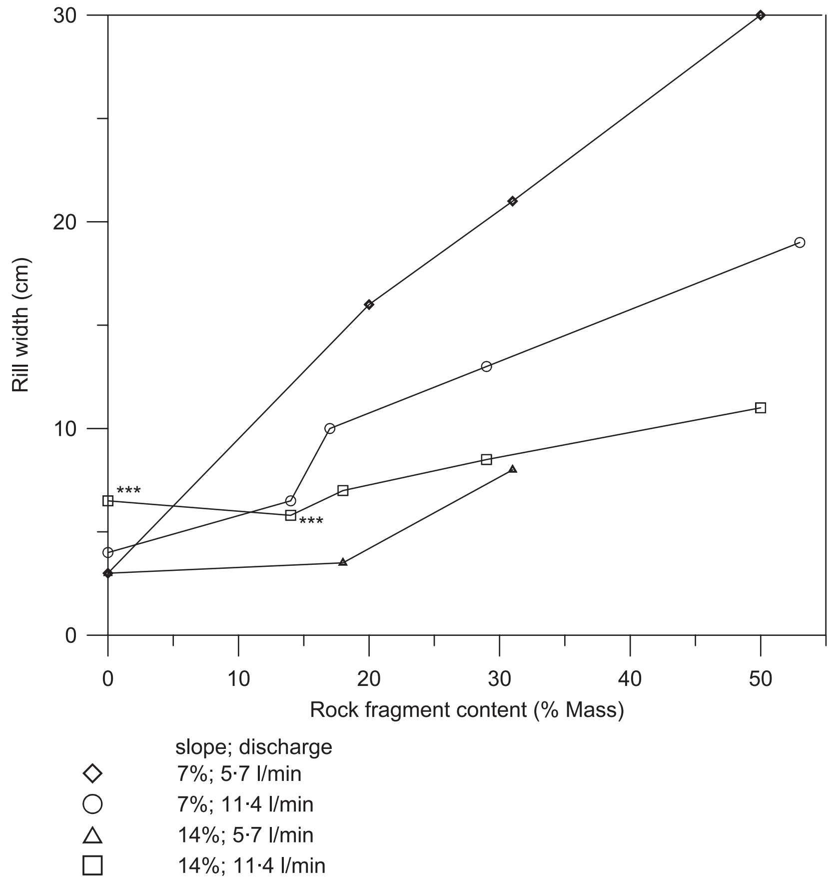

Figure 4. Average width of flow was wider for experiments with larger rock fragment content. *** Runs were stopped after 5 min.

experiment and appears almost unaffected in the last 20 minutes (Figures 5 and 6). When no fragments are present, the surface response is different. A deep rill is cut into the soil, while its depth increases continuously with time.

Plotting the hydraulic roughness– Darcy–Weisbach coefficient (f) –versus Reynolds number, one would assume that hydraulic roughness would increase with increasing rock surface cover and that Reynolds number should decrease with increasing surface cover. This is the case for the series with 7 per cent slope and 5·7 l min^{-1} discharge (Figure 7(a)). Hydraulic roughness for the experiment without rock fragments in this series remains fairly constant for the whole range of Reynolds numbers covered. Hydraulic roughness is less than for experiments with rock fragments. The largest hydraulic roughness is found for the experiment with the largest rock fragment content. The experiments with 5, 10 and 20 per cent of rock fragments reveal similar hydraulic roughness at different Reynolds numbers. Hydraulic roughness is similar for all three experiments, as is final rock fragment cover in the flow direction of these experiments (Table I), both indicating that surface armouring for these experiments at the end of the experiment was similar.

Reynolds number varied most for the run with no rock fragments ranging from approximately 200 to 800. It was the only experiment in this series where Reynolds number increased with time. Hydraulic roughness of the surface remained approximately constant at $f = 0·5$. In this experiment several 5–10 mm tall headcuts formed in the rill. Some small headcuts also formed in the run with 5 per cent rock fragments. They reached a height of up to 5 mm and became less abundant and less tall with experimental time, i.e. while rock fragments were excavated and surface armouring dissipated flow energy. Hydraulic roughness of the 5 per cent rock fragment experiment was larger than for the 0 per cent run and similar to the runs with 10–20 per cent rock fragments. No headcuts developed in runs with rock fragment content larger than 5 per cent in this series.

Increasing the slope to 14 per cent and keeping the inflow rate at 5·7 l min^{-1}, Reynolds numbers became larger. Hydraulic roughness increased for all experiments compared with the series with 7 per cent slope (Figure 7(b)). Hydraulic

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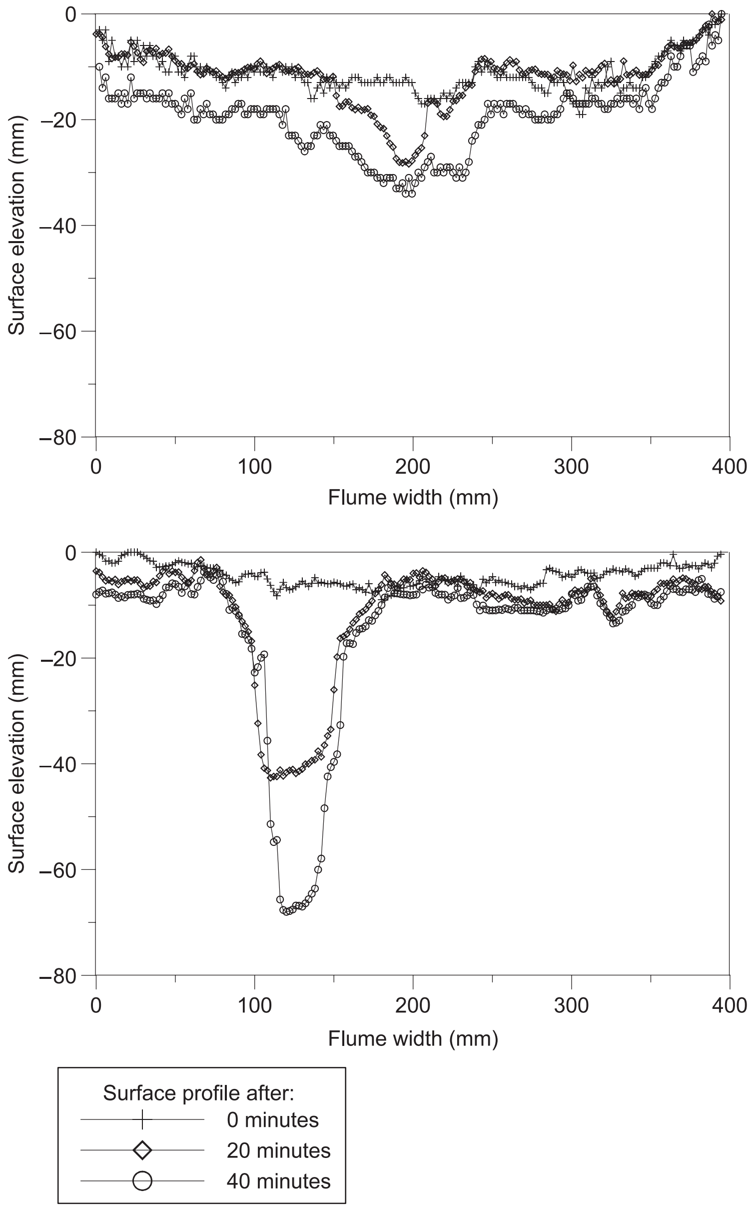

Figure 5. Change of the soil surface cross section 167 cm down slope from the inflow. The laser scanner profiles show surfaces with 40 per cent rock fragments by mass (above), and 0 per cent rock fragments by mass (below) at three different experimental stages.

roughness for the run with 20 per cent (by volume) was almost three times greater than before. Headcuts developed in all experiments (0, 10, 20% rock fragments). Their height and abundance increased with time for the run with 0 per cent rock fragments and reached in this case up to 80 mm by the end of the experiment. Mass wasting at the sides of the channel and severe headcutting resulted in pulses of sediment in the rill for the experiment with 0 per cent rock fragments. These pulses boosted the value for hydraulic roughness above 3, not indicating a rough and stable surface, but the response of an eroding surface to concentrated flow. In the other experiments of this series headcutting was important only in the beginning of the experiment. Headcut height became smaller with time. Maximum headcut height at the beginning and end of the experiments was between 50 and 15, as well as 30 to 10 mm for the experiments with 10 and 20 per cent (by volume) rock fragments, respectively. Rills cut less deep and less wide for experiments with rock fragments. Therefore, mass wasting at the sides of the channel was not a significant source of sediment.

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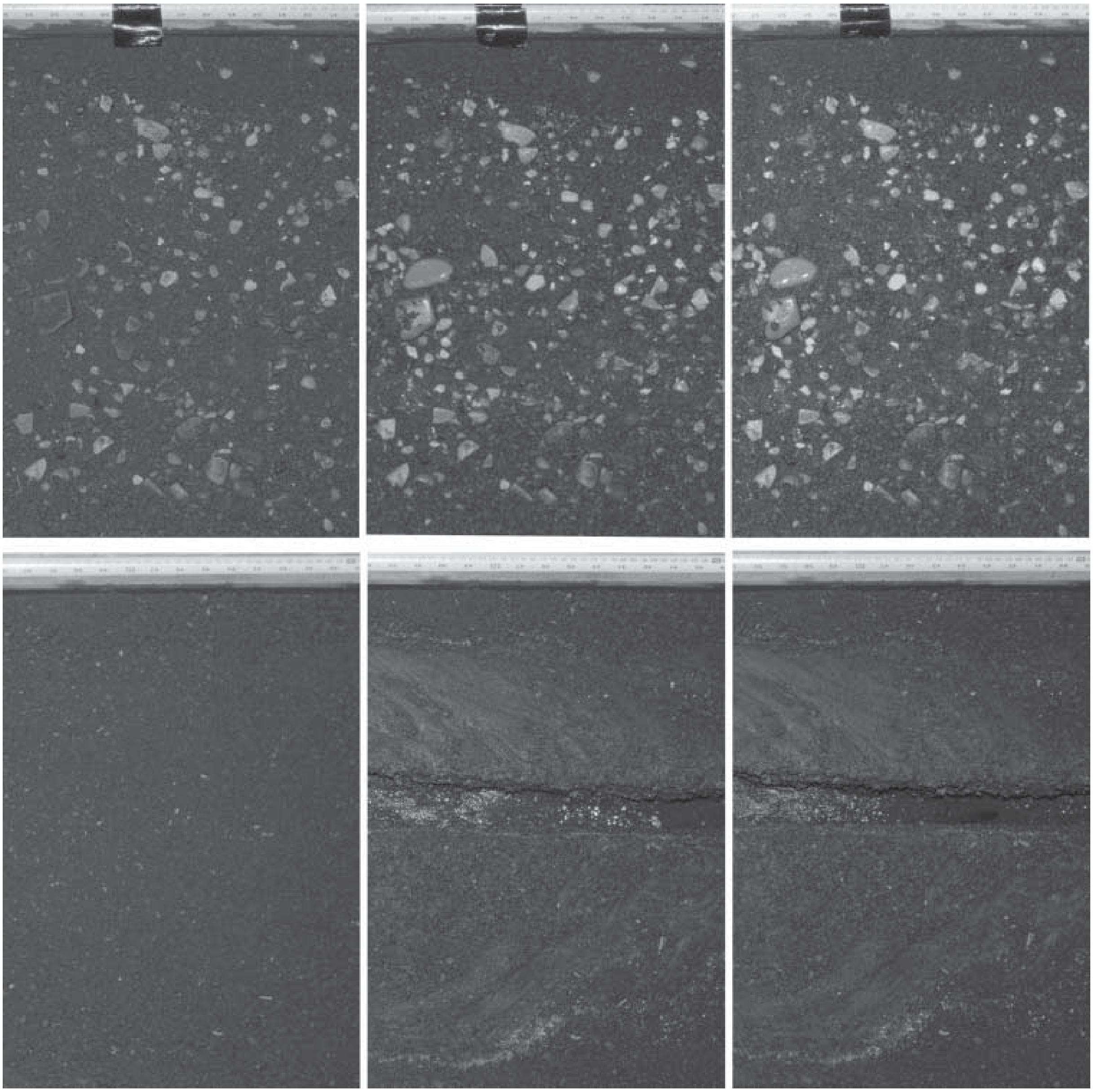

Figure 6. The images show the flume surface 167 cm down slope from the inflow. While the surface with 40 per cent rock fragment content (above) did not change much with time, a deep and narrow rill cut quickly in the experiment with no rock fragments (below). Flow direction is from left to right. Corresponding cross sections from laser scans are shown in Figure 5.

Reynolds number indicates more laminar flow conditions for the experiment with 20 per cent rock fragments, while almost all Reynolds numbers for the runs with 0 and 10 per cent indicate turbulent flow conditions in the flume. Rock fragment cover (Table I) at the end of the experiment was similar for the experiment with 10 and 20 per cent rock fragments, indicating that in both cases surface armour was developed over time.

Plotting hydraulic roughness against Reynolds number for the series of experiments with 7 per cent slope and 11·4 l min^{-1} discharge shows mixed results (Figure 7(c)). Reynolds number indicates turbulent flow conditions for all data points. Hydraulic roughness was less than unity for all experiments, which is less than for the runs with 5·7 l min^{-1} discharge. In the aforementioned experiments, large hydraulic friction was recorded only when Reynolds number

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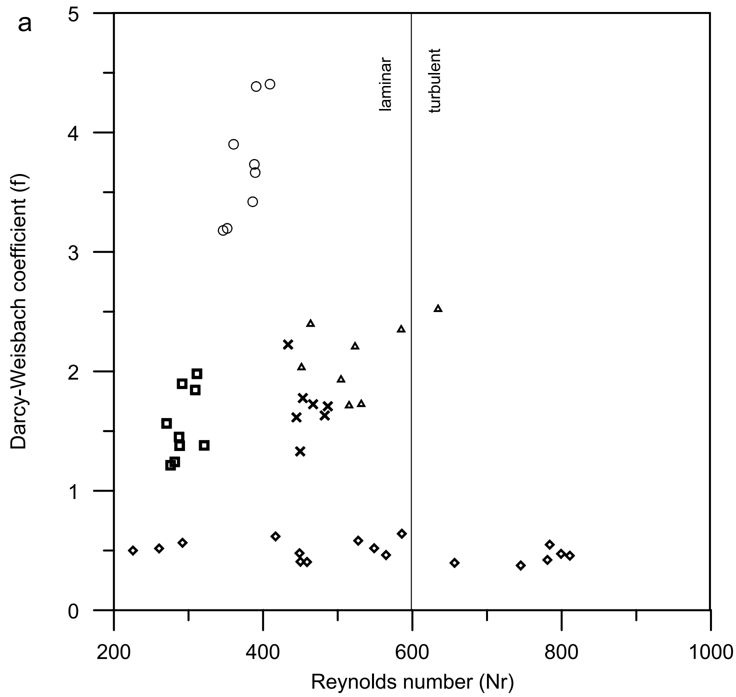

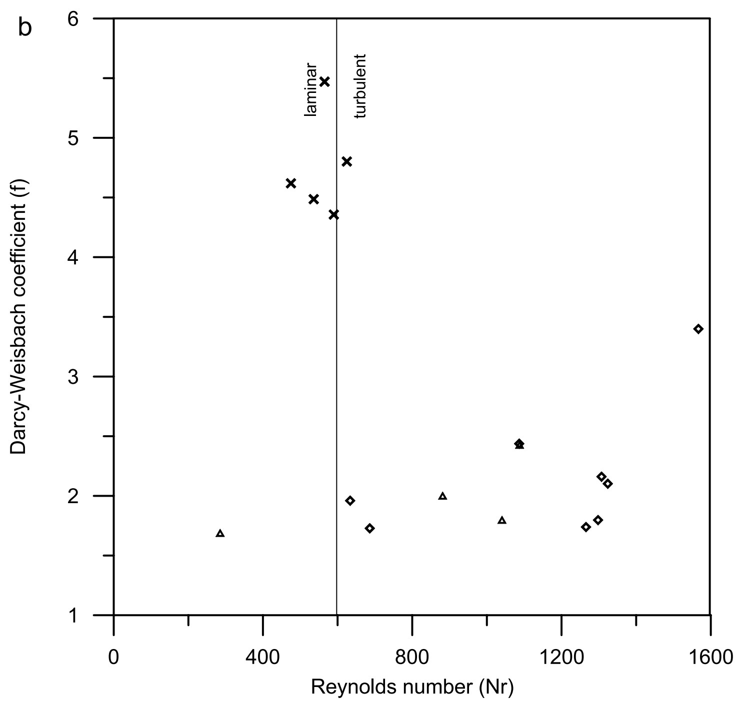

Figure 7. Hydraulic roughness versus Reynolds number for different treatment combinations. Slope, discharge: a) 7%, 5·7 l min^{-1}; b) 14%, 5·7 l min^{-1}; c) 7%, 11·4 l min^{-1}; d) 14%, 11·4 l min^{-1}.

indicated laminar or close to laminar flow conditions or when severe headcutting took place in the rill. In this series 30 and 5 mm tall headcuts developed in the experiment with 0 and 5 per cent rock fragments, respectively. Both experiments formed a fairly narrow rill, less than 70 mm wide. This might explain the wide scatter for data points of these series. In all the other experiments flow width was wider and headcutting was not a significant factor. Rock

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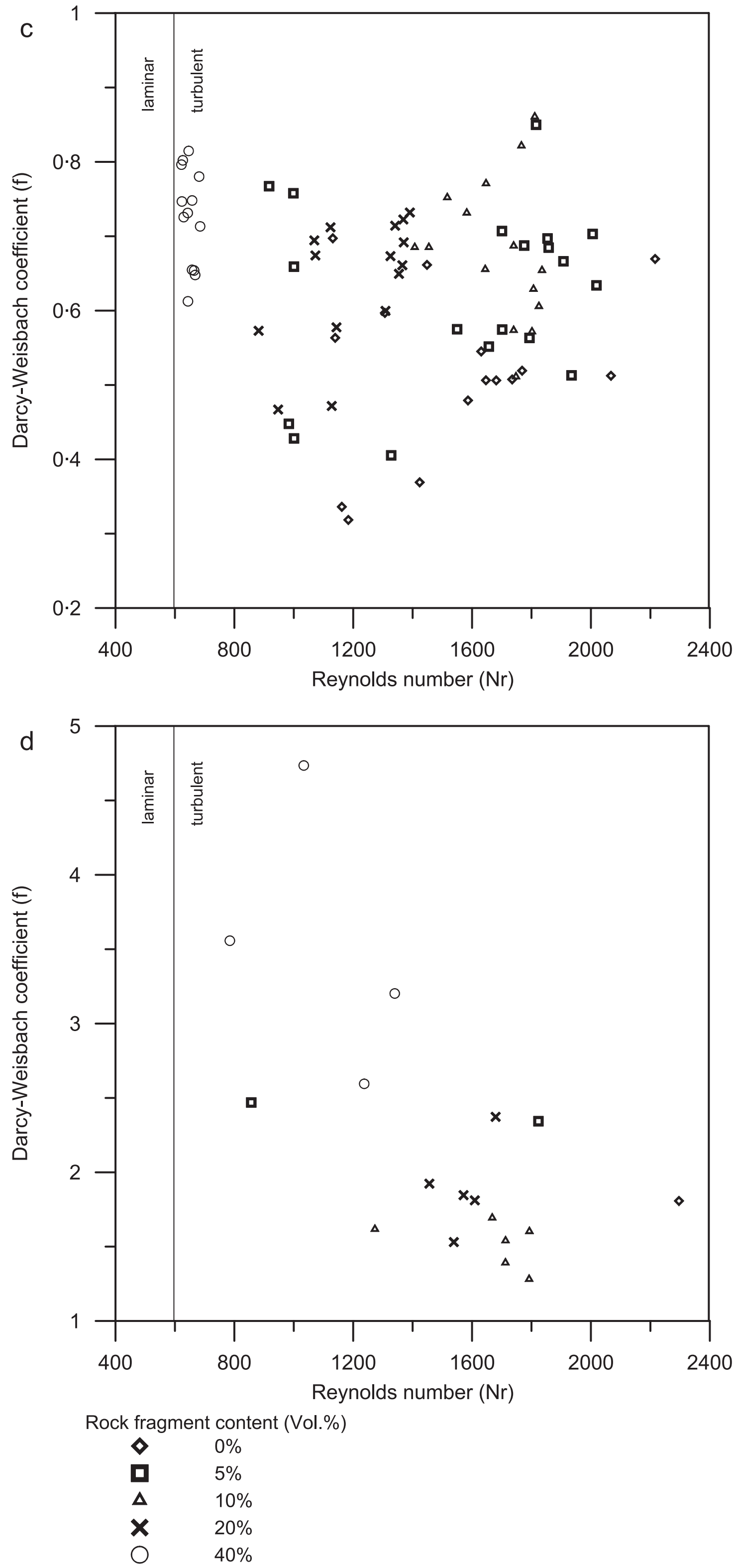

Figure 7. (*Continued*)

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fragment cover in the flow path reached values larger than for the series with 5·7 l min^{-1} discharge. These changes are not prominent, plotting hydraulic roughness against Reynolds number. This can be explained with surface inundation by water as described by Lawrence (1997). Increasing runoff may result in inundation of roughness elements. When roughness elements are submerged by the flow, hydraulic roughness will decrease and flow conditions become similar for different rock fragment contents. Nevertheless, the change of rock surface cover with time (Table I) and total sediment yield (Figure 3) as well as width of flow for this series indicate that the experimental surfaces underwent significant changes and surface armouring occurred.

Flow was concentrated in 40–100 mm wide rills in the experimental series with 14 per cent slope and 11·4 l min^{-1} discharge. This series produced the most sediment yield for a given rock fragment content, suggesting the most extreme changes of the surface. The experiments with 0 and 5 per cent rock fragments had to be stopped prematurely, because headcutting was so intense, close to the inflow, that the soil layer was eroded down to the geotextile. The experiments had to be stopped after just 5 minutes with the rill cutting up to 200 mm deep. The three data points resulting from the two experiments (Figure 7(d)) indicate a large hydraulic roughness due to severe erosion and not due to a type of armouring. The remaining experiments in this series produced much less sediment yield. Significant headcutting was recorded for the run with 10 per cent rock fragments only. The maximum height of headcuts reached 30 mm and was much less than for the two experiments with 0 and 5 per cent of rock fragments. Surface armouring allowed continuation of the experiments with 10–40 per cent rock fragment content for 20 minutes with no risk of the rill cutting to the bottom of the soil layer. After discarding the data points from the two experiments that had to be stopped, the data indicated that increased rock fragment content led to large hydraulic friction and lower Reynolds numbers. Hydraulic friction was increased by a factor of two compared to experiments with 7 per cent slope and the same discharge (Figure 7(c)). While the magnitude of Reynolds number was similar to the magnitude observed in the series with 7 per cent rock fragment content and the same discharge, flow width was narrower (Figure 4). Rock fragment cover in the series with 14 per cent and 11·4 l min^{-1} after 20 min reached similar values as in the series with 7 per cent slope and the same discharge after 40 min. The intermediate diameter of the largest rock fragment removed from the flume (Table I) was also larger than in the series with 7 per cent slope, or any other series. Narrower width of flow and faster excavation of rock fragments also resulted in the largest sediment yields for this series.

Conducting experiments with actively eroding surfaces allowed us to study surface armouring with time under different treatment combinations of discharge, slope, and rock fragment content. Surface response, i.e. surface armouring, and headcutting, was quicker and more significant when flow energy was greater because of increased slope or discharge. While sediment yield is reduced when rock fragment content is increased, the response of the soil surface to concentrated flow depends on several factors. Flow energy is dissipated by surface roughness. Rock fragments served as roughness elements, and the more rock fragments covered the active flow area, the larger was the Darcy–Weisbach roughness coefficient. Rock fragments reduced sediment yield, and width of flow. With time, more rock fragments were excavated and served as permanent roughness elements. When roughness elements were submerged by the flow, hydraulic friction was less than for experiments with less rock fragment cover.

In experiments with few or no rock fragments mixed with the soil, armouring by rock fragments was less effective and headcuts developed in the flow path. Headcutting was more severe when flow was more concentrated. Headcuts retreated with time and are not permanent roughness elements. While they can increase surface roughness, leading to Darcy–Weisbach hydraulic roughness coefficients even greater than for surfaces armoured with rock fragments, sediment yield is not significantly reduced and rill incision is not stopped. Rill incision will ultimately reduce slope in the rill bed, and it can be assumed that this adjustment will, over longer periods of time, also result in reduction of flow energy and in a more stable surface.

In experiments with 5–20 per cent (by volume) rock fragments, the effects of headcutting and armouring by rock fragments were both active. The more rock fragments were mixed in the soil, the faster the surface was stabilized by rock fragments. In most cases rock fragments stabilized the surface with time; only the most concentrated flow conditions resulted in severe headcutting and no effective surface armouring with time. Headcutting for experiments with no rock fragments added to the soil was more severe under more concentrated flow conditions. At 40 per cent (by volume) rock fragment content, sediment yield was negligible under the simulated conditions and the surfaces changed only little with time (Figures 5 and 6).

The experimental results presented here indicate that several processes are superimposed when soil surfaces are subjected to concentrated flow and the process of surface transition takes place. Surface roughness may increase with time, lead to surface armouring and reduce sediment yield. Headcutting can also result in an increase of surface roughness, but sediment yield will be much larger than for armoured conditions. Increasing the discharge changes flow depth and inundation of roughness elements. Therefore, a simple relationship between rock fragment content and Reynolds number was not visible when comparing all experimental data.

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Surface response with time may be split in three different groups. (i) *Continuous rill incision*. With no rock fragments added to the soil, total sediment yield is the largest and the surface responds to concentrated flow by rill incision. Headcuts serve as temporary roughness elements that retreat with time. This results in larger sediment yield. Headcut retreat and mass wasting at the banks of channels can result in sediment pulses at the flume outlet. Slope in the rill may adjust over time to reduce flow energy and therefore stabilize the surface; this response is rather slow. (ii) *Transitional surface*. With some rock fragments mixed in the soil matrix, sediment yield is significant under initial conditions and is reduced by surface armouring with time. When this process is efficient, the soil surface will be stabilized with time. Surface armouring will inhibit rill incision and sediment yield will be minimized with time. (iii) *Surface armour.* The soil surface is protected by a rock fragment cover and does not change with time. Sediment yield is negligible and the surface does not change significantly with time.

Previous research was concentrated almost exclusively on relatively stable surfaces, representing groups (i) and (iii). Soil surfaces in nature are typically adjusted to local flow conditions. Even on very steep slopes, soil surfaces are stable under normal weather conditions. Surface armouring on steep slopes of European vineyards, for instance, resulted in negligible sediment yield for average rainstorm events, and significant sediment yield for extreme rainstorms (personal observations).

The case of a transient surface (ii) may be observed in nature on freshly prepared surfaces, i.e. after tillage, or when flow conditions have changed due to changes in climate or land use or as a response to base level change or to human impact. From global climate change scenarios, we can expect a change in rainfall pattern and intensity of rainfall events. In cases where surface runoff becomes more concentrated, we can expect the surface to adjust to the new flow conditions, similarly as observed in the presented experiments.

Conclusions

The influence of rock fragment content on surface armouring and rill erosion rates was measured and described. The response of the soil surface was different than for previous experiments where the soil surface was fairly stable or non-erodible. In general, exhumation of rock fragments by concentrated flow increased hydraulic roughness of the soil surface with time and reduced sediment yield. Without rock fragments in the soil, rill incision continued over time. Width of flow and total sediment yield was less when rock fragment content of the soil was greater. Headcutting increased hydraulic surface roughness for experiments with few or no rock fragments in the soil. Headcuts were not stable roughness elements, but eroded with time and therefore retreated in the rill. At large inflow rates and turbulent flow conditions, when roughness elements were submerged by flow, hydraulic roughness was less than for more laminar conditions.

Exposing soil surfaces to different flow conditions revealed that several parameters influenced the direction in which the soil surface may develop. Research will be needed to separate the influence of these different parameters to judge whether a surface tends towards continuous rill incision or surface armouring over time for a given inflow. This question is becoming increasingly important, considering global climate change scenarios where rainfall patterns and therefore inflow rates for large areas of the world may change in the future.

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