Erosion, Transport and Deposition Processes (Proceedings of the Jerusalem Workshop, March-April 1987). IAHS Publ. no. 189, 1990.

Conditions for the evacuation of rock fragments from cultivated upland areas during rainstorms

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Abstract Most studies dealing with erosion of stony soils have treated rock fragments at the soil surface as mulch elements. This study considers rock fragments on upland areas as erodible particles and addresses the following questions: (a) which erosion processes are capable of moving rock fragments? (b) under what hydraulic conditions do rock fragments start moving on slopes? (c) what factors determine displacement distances of rock fragments? The monitoring of coloured rock fragment movement revealed that during a moderate rainfall event, rock fragments up to 9.0 cm in diameter travelled downslope by rill flow. The competence of interrill flow was about one order of magnitude smaller. Incipient motion conditions for rock fragments lying on a rill bed coincide with a critical Shields entrainment parameter (θ_c) of 0.012 rather than with θ_c = 0.06. Rock fragment transport distance was controlled more by fragment size than by fragment shape and it correlated better with rill bed slope than with peak rill flow discharge.

INTRODUCTION

In literature dealing with soil erosion on cultivated lands the presence of rock fragments, i.e. particles 2 mm or larger in diameter and including all sizes that have horizontal dimensions less than the size of a pedon (Miller & Guthrie, 1984), on the soil surface or in the plough layer is usually considered to be beneficial insofar as the rock fragments reduce the intensity of soil degradation processes such as surface sealing, compaction, interrill as well as rill erosion. In fact rock fragments lying on the soil surface are regarded as mulch elements, reducing or even eliminating raindrop impact energy - which leads to a retardation of surface sealing and, hence, to an increase of water intake into the soil surface - and reducing runoff velocities. Due to the latter, the detaching and transporting capacity of overland flow will also be reduced.

These aspects are well documented by several studies (Seginer *et al.*, 1962; Adams, 1966; Epstein *et al.*, 1966; Deffontaines & De Montard, 1968; Meeuwig, 1970; Meyer *et al.*, 1972; Collinet & Valentin, 1984). Very few studies, however, exist in which rock fragments are considered as erodible particles. Field observations on agricultural lands in central Belgium reveal that considerable amounts of rock fragments can be eroded from cultivated upland areas and, in part, be deposited at the foot slopes (Fig. 1). A field study and a laboratory experiment were thus set up to answer the following questions:

(a) Which erosion processes are capable of moving rock fragments at the surface of stony soils?
(b) Under what conditions do rock fragments start moving on slopes?
(c) What factors determine displacement distances of rock fragments?

Fig. 1 Recent colluvial deposits containing considerable amounts of rock fragments (Huldenberg, central Belgium). Length of stick equals 60 cm.

MATERIALS AND METHODS

Field study

The field study was conducted on a 0.75 ha field plot, located in Huldenberg (central Belgium) and is described in detail in Govers & Poesen (1986). Soils on the plot can be described as gravelly/cobbly loam or gravelly/cobbly sandy loam. Rock fragments in the plough layer or at the soil surface originate from gravel-rich fluviatile deposits (mainly flint pebbles and cobbles), probably of early Quaternary age, at shallow depth. They are brought to the surface either by surface lowering due to soil erosion, by ploughing, or by freezing and thawing.

After the field plot was tilled and placed in a conventional seed bed on 15 November 1983, the soil surface was kept bare by the application of herbicides, replicating to some extent semi-arid conditions. As a consequence, surface sealing, compaction of the plough layer and inter-rill as well as rill erosion occurred the following year (Poesen & Govers, 1986; Fig. 2). Due to the selective removal of fines, an erosion pavement developed on the inter-rill areas while, at the bottom of the rills, a discontinuous layer of rock fragments was deposited after hydraulic erosion of the rill bed and/or mass movement processes on the rill banks took place. On 7 November 1984, four rills were selected on the basis of catchment size and the dimensions of the rill cross section and, in addition, five seeding transects were chosen on the basis of surface slope gradient (Fig. 3). Each seeding transect was named after the colour of the painted rock fragment used. Following this, 687 coloured and numbered flint pebbles and cobbles, with intermediate diameters ranging from 0.35 to 9.8 cm and having both variable roundness and shape (flatness index (FI) varied between 1.1 and 3.9; $FI = (L + I)/(2S)$ with L denoting the longest, I the intermediate and S the shortest dimension of the fragment along three perpendicular axes), were placed on the rill beds at selected sites. Each rill site was located close to each crossing of a seeding transect on one of the four selected rills. At each rill site, three places, about

Fig. 2 The 170 m long and 45 m wide rilled field plot in Huldenberg (central Belgium).

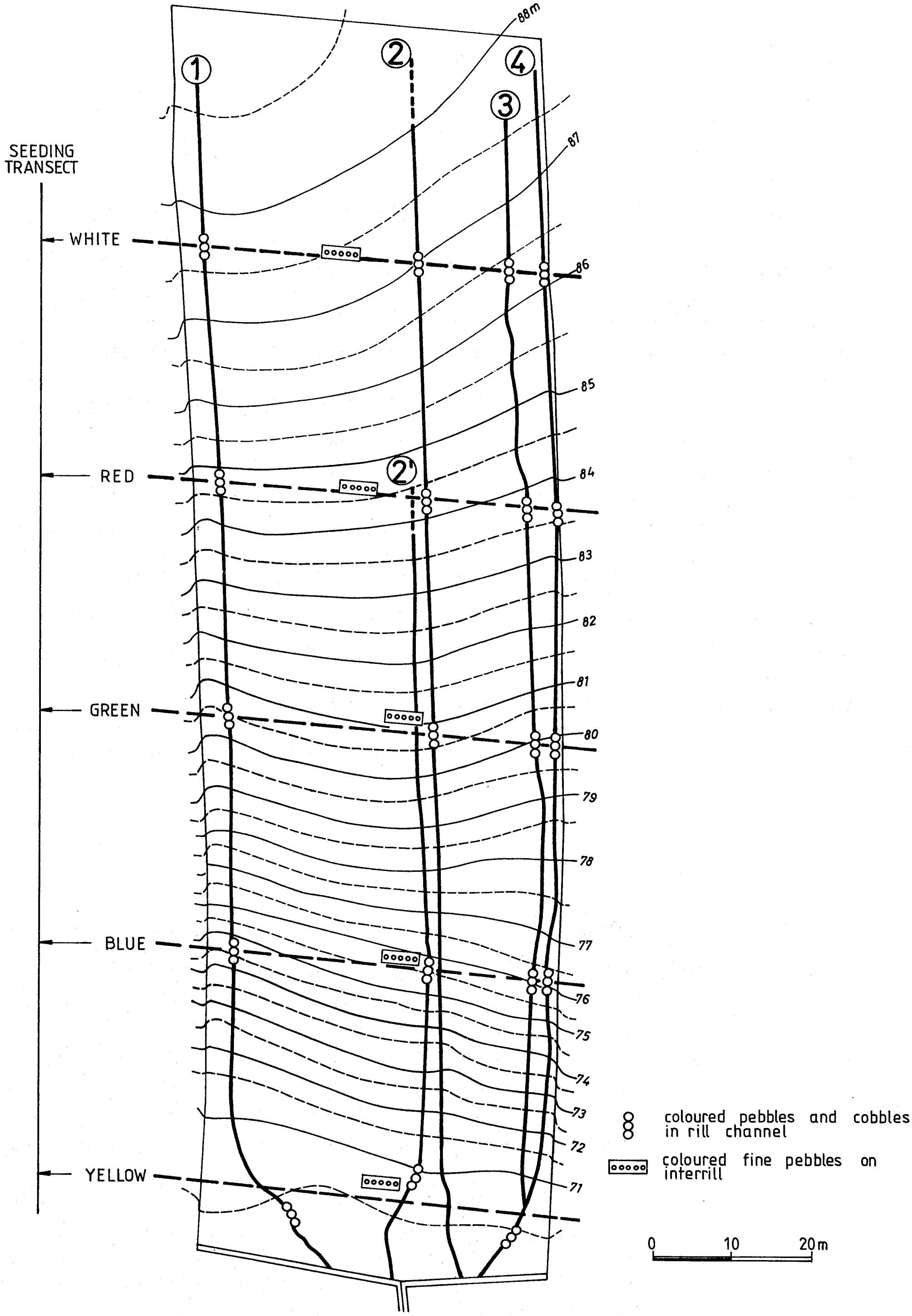

Fig. 3 Topographic map of the Huldenberg field plot and location of the selected inter-rill and rill sites.

1 m apart, were selected and a set of 5 to 35 coloured fragments was randomly placed in a cluster on the rill bed. Care was taken to ensure that rock fragments were oriented in a manner commonly adopted by undisturbed rock fragments of the same type.

The drainage area (A) of each rill upslope of a selected rill site was calculated after mapping flowlines, visible on the inter-rills, on a topographic map of scale 1:200. Area A varied between 2.4 and 159.2 m^2. Rill bed width ranged from 3 to 52 cm and the slope gradient of the rill beds varied between 0.049 and 0.268. In addition, coloured fine pebbles with intermediate diameters ranging from 0.2 to 0.8 cm, and with variable flatness, were placed on the inter-rill area along 1 m long seeding lines, close to the transects. A recording rain gauge, installed at a distance of 650 m from the field plot, provided the necessary rainfall data. On 26 November 1984, following a rainy period, the coloured rock fragments in the rills and on the inter-rills were recovered. Some 71% of the fragments used as tracers were found again.

Laboratory experiments

Threshold conditions for incipient motion of rock fragments by rill flow were determined in the laboratory using a tilting flume which consisted of a 12 m long PVC roof gutter with a trapezoidal cross section (Fig. 4). The bottom width of the flume was 11.8 cm, typical for rills in the field, while the walls were inclined at 0.176. The flume slope gradient could be varied from 0 to 0.50.

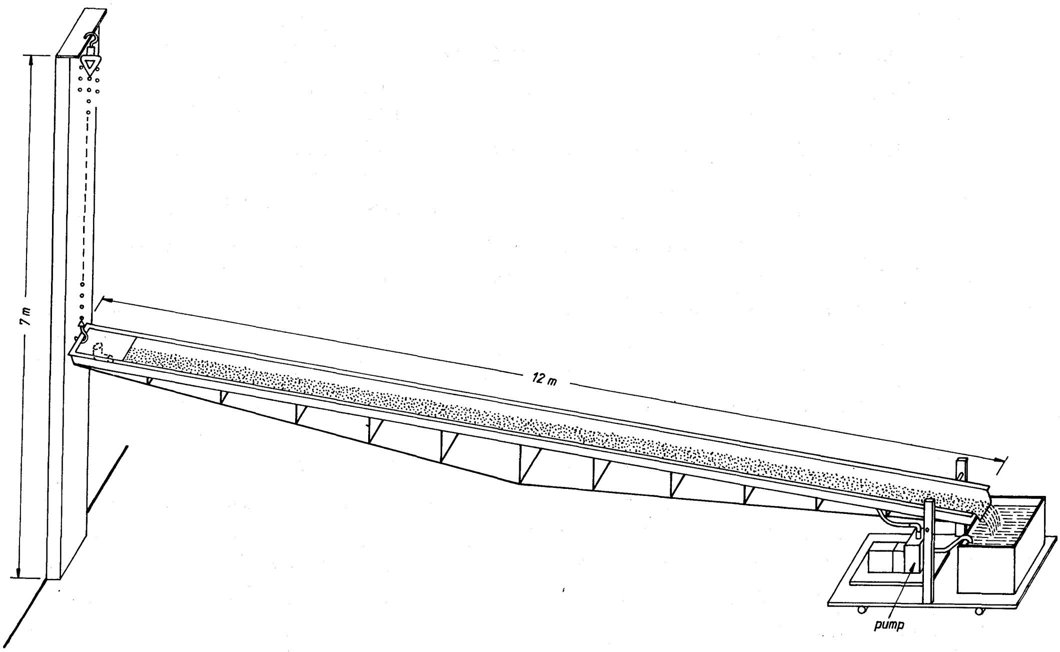

***Fig. 4** Experimental setup in the laboratory.*

To simulate different rill bed roughnesses, very fine sand (D_{50} = 0.010 cm, i.e. a smooth bed) and medium gravel (D_{50} = 0.6 cm, i.e. a rough bed) were fixed with a hard water-repellent glue to the bottom of two flumes. Rill flow was simulated by recirculating tap water with a temperature varying between 15 and 22°C. Maximum unit discharge (q) equalled 135 $cm^2\ s^{-1}$. Rollwave-trains were eliminated by means of a net suspended in the flow at about 5.5 m upstream from the bottom end of the rill channel.

Twenty-four flint (ρ_s = 2.65 g cm^{-3}) pebbles and cobbles ranging in intermediate diameter from 0.3 cm to 6.6 cm and having different FI values were used (De Wilde, 1986). After establishing uniform flow close to the threshold condition for a given fragment size, the individual fragment was gently placed on the rill bed in its most stable position. For a given unit discharge, the slope was adjusted while making simultaneous observations for any movement of the fragment. Each fragment was tested for at least 10 points along the last 4 m of the rill channel. When the ratio between the number of unstable spots to the total number of tested spots fell between 0.75 and 0.85, these values being arbitrarily chosen, incipient motion was considered to be reached. At that moment flow discharge, mean flow velocity (using coloured dye), water temperature and rill bed gradient were measured.

RESULTS AND DISCUSSIONS

Inter-rill and rill flow competence

During the period of observation (7 November to 26 November 1984) total rainfall equalled 63 mm with a maximum rainfall intensity occurring on 22 November of 6.0 mm in 12 min (or 30.0 mm h^{-1}). Such a rainfall event has a return period of 6 months in central Belgium (Laurant, 1976). It was assumed that the main movement of the traced rock fragments on the field plot could be attributed to the peak flow occurring during the rainfall event.

During the period of observation, movement of the largest pebbles on the inter-rills, i.e. fragments with an intermediate diameter of 0.8 cm, occurred over a maximum downslope distance of 5 cm. In the rills, however, considerably larger rock fragments moved downslope. Table 1 lists for each rill site the mean maximum intermediate diameter of rock fragments moved by rill flow. This value was calculated as the mean intermediate axis of the five largest fragments which were moved by the flow and the five smallest rock fragments which did not move. Hence, each value represents an intermediate diameter of a rock fragment which has only just become mobile at the peak stress value exerted by the flow on the rill bed.

From the observations it can be concluded that the competence of the rill flow, i.e. the ability of the flow to transport rock fragments as measured by the size of the largest fragment it can move, exceeds by almost a factor of 10 the competence of the inter-rill flow. Processes responsible for the slight downslope displacement of fine pebbles on the inter-rill soil surfaces are thought to be splash-creep (Moeyersons & De Ploey, 1976) and runoff-creep (De Ploey & Moeyersons, 1975). Assuming a uniformly distributed sheet flow

Table 1 Mean maximum intermediate diameter (cm) of rock fragments, moved by rill flow during the period of observation

Transect	*Rill no.* 1	2	3	4
white	*1.2*	*6.2*	*2.6*	*5.7*
red	*4.3*	*7.8*	*5.4*	*9.0*
green	*4.2*	*6.1*	*6.0*	*6.3*
blue	*5.7*	*5.8*	*7.5*	*5.8*
yellow	*4.6*	*5.4*		*7.0*

on the inter-rill areas of the field plot, one will find that during peak runoff sheet flow unit discharge never exceeded 10 cm^2s^{-1}. Such flow discharges are usually not competent to transport rock fragments with diameters ranging between 1 and 8 cm, as shown by the experimental results of De Ploey & Moeyersons (1975). On the other hand, rill flow caused by a moderate rainfall event is capable of moving rock fragments which have mean intermediate diameters of up to 9 cm (Table 1). Hence, rill flow and other forms of concentrated overland flow (e.g. ephemeral gully flow) can be held responsible as the most important processes evacuating pebbles and cobbles from upland areas.

Threshold conditions for incipient motion of rock fragments by rill flow

Data on the hydraulic threshold conditions for the incipient motion of sediment particles in turbulent flow are usually expressed in terms of Shields' model (Vanoni, 1977):

$$\theta = \frac{\tau_0}{(\rho_s - \rho)gd} = f(u_* d/\nu) = f(Re_*) \qquad (1)$$

in which:

θ = Shields entrainment parameter;
ρ_s, ρ = density of sediment, density of fluid (kg m^{-3});
g = acceleration due to gravity (m s^{-2});
d = effective diameter of a bed particle in a state of incipient motion (m);
τ_0 = boundary shear stress (N m^{-2}); (= ρgRS with R = hydraulic radius (m) and S = rill bed slope gradient);
f = function of;
u_* = shear velocity (= $(\tau_0/\rho)^{1/2}$);
ν = kinematic fluid viscosity (m^2 s^{-1}); and
Re_* = grain Reynolds number.

θ must be assigned a critical value (θ_c) in order to solve the left hand term of equation (1) for a given grain diameter (*d*) or stress value (τ_c). Hence, *d* is a measure of theoretical flow competence.

In order to compare our field data on rock fragment movement initiation by rill flow to existing theory, θ_c and Re_* were calculated for the different rill sites. Since the time of concentration for each rill catchment was well below the duration of the rainfall event causing peak runoff (i.e. 12 min), rill flow discharge was calculated by the rational formula:

$$Q = C\,I\,A \qquad (2)$$

with: Q = rill flow discharge ($m^3\ s^{-1}$);
C = runoff coefficient;
I = rainfall intensity ($m^3\ s^{-1}\ m^{-2}$); and
A = rill catchment area (m^2).

On compacted and sealed soils of the field plot, having a moisture content exceeding field capacity, Govers (1986) obtained *C* values approaching 1.00 when rainfall intensity equalled several tens of mm per hour. Hence, for our calculations, *C* was set equal to 1.0. Next, unit peak rill flow discharge was calculated as $Q(b_s)^{-1}$, where b_s represents the smallest rill bottom width for each rill site. The b_s value was chosen in order to obtain the maximum possible peak unit rill flow discharge. Calculated *q* values varied between 2.4 and 99.7 $cm^2\ s^{-1}$. Hydraulic radius (expressed in m) was then calculated using a modified Manning formula:

$$R = (q\ n\ S^{-0.5})^{0.6} \qquad (3)$$

with *q* expressed in $m^2\ s^{-1}$ and n = Manning roughness coefficient.

The value of *n* was estimated on the basis of photographs of the rill beds and published *n* values (Foster *et al.*, 1984) as well as measured *n* values for different rill beds in the laboratory (De Wilde, 1986). For the rill beds at the field plot, *n* varied between 0.015 for a flat sandy bed and 0.05 for an irregular gravelly bed.

Using ρ, ρ_s, q, R, S, ν and d (taken from Table 1) as input data, θ_c and Re_* were calculated using equation (1). Fig. 5 shows the field rill data plot well below $\theta_c = 0.06$ for rough turbulent flow conditions ($Re_* \geqslant 400$); i.e. on average $\theta_c = 0.012$. In addition, these data show a significant positive relation between θ_c and Re_* which can be well described by a power relation with exponent 0.41. A graphed representation of the laboratory data, using for *d* the rock fragment diameter parallel to the flow instead of the intermediate diameter, is shown in Fig. 6.

Laboratory data corresponding to the rough rill bed plot close to the Shields curve, but data corresponding to the smooth rill bed plot well below $\theta_c = 0.06$ and can be represented by an equation very similar to that found for the field data.

From the laboratory data it can be concluded that incipient motion conditions for rock fragments are determined, to a large extent, by the roughness of the rill bed. For a rough rill bed the data almost coincide with the Shields curve, while for a smooth rill bed incipient motion conditions are

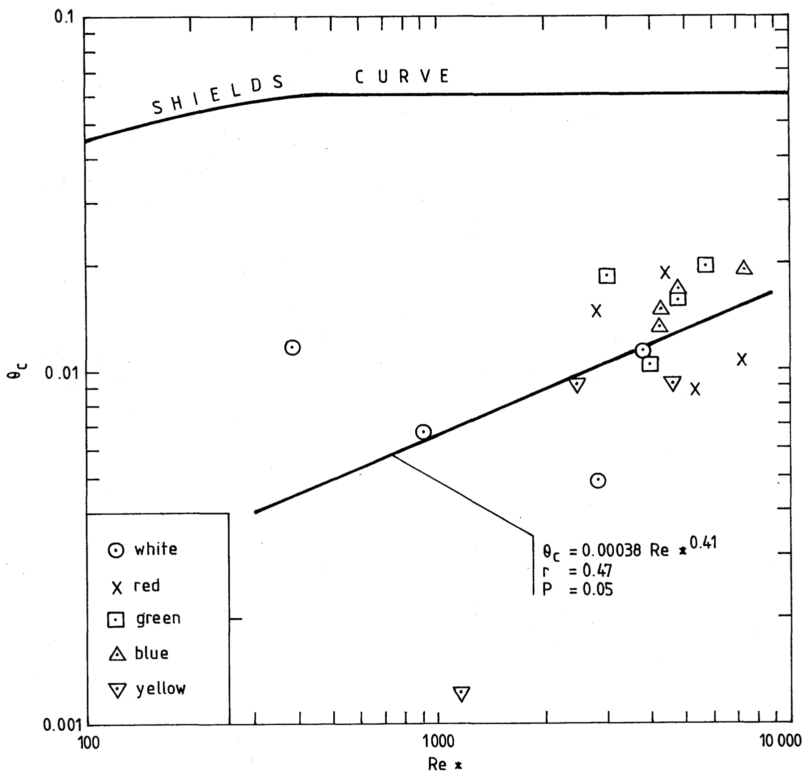

Fig. 5 Shields' entrainment parameter (θ_c) versus grain Reynolds number (Re_*) for the field rills. Different symbols refer to different seeding transects.

reached at θ_c values which, on average, equal one-fifth of the θ_c value given by Shields. In order to develop his model, Shields used results from almost equi-dimensional grains laid in flat beds. This was clearly not the case in our field measurements given that rock fragments were laid on a relatively smooth rill bed. Accordingly, these fragments protruded considerably above the mean bed elevation. Experiments by Fenton & Abbott (1977) and field data compiled by Andrews (1983) clearly show that the entrainment parameter decreases with an increasing degree of exposure of individual grains to the fluid flow.

On the basis of the laboratory findings, it can be stated that the field data are not well represented by a classical Shields entrainment parameter of 0.06 because the traced rock fragments were placed *on* a relatively *smooth* rill bed. Consequently, the angle of repose was much lower than for a situation in which the fragments would have been placed *in between* fragments of the same size. This analysis clearly shows that the threshold relation for the transport of rock fragments by overland flow on uplands is different from those developed for rivers. Similar findings were recently reported by Abrahams *et al.* (1988) for the transport of sediment by overland flow on desert hillslopes.

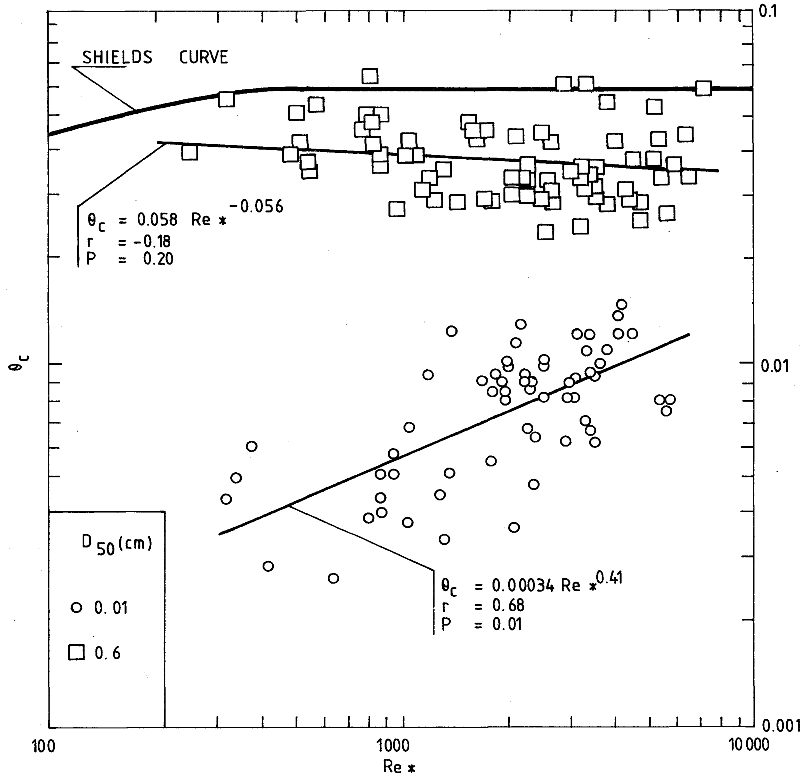

***Fig. 6** Shields' entrainment parameter (θ_c) versus grain Reynolds number (Re_*) for the laboratory rills with a smooth (D_{50} = 0.01 cm) and a rough (D_{50} = 0.6 cm) bed.*

Factors controlling displacement distances of rock fragments in rills

The factors investigated controlling displacement distances were divided into two groups; rock fragment properties and rill site characteristics.

Properties of rock fragments investigated were size (intermediate diameter) and shape (flatness index). Figure 7 illustrates the relationship between fragment size, fragment shape and transport distance for two selected rill sites. In general, fragment size and distance moved tend to be inversely related (e.g. Fig. 7, blue transect, rill 3). For a given fragment diameter, however, a large variation in transport distances exists. This variation decreases as size increases.

A visual inspection of all scatter diagrams leads to the conclusion that there is little dependency of travel distance on shape. Thus it can be concluded that fragment size plays a more important role with respect to the displacement of rock fragments than does fragment shape. However, there is no defined relationship between rock fragment size and transport distance. This is in accord with findings of Leopold *et al.* (1966) and Schick *et al.* (1987) for ephemeral streams. The relatively aselective nature of rill flow can partly be explained by the stochastic nature of gravel entrainment and by rill

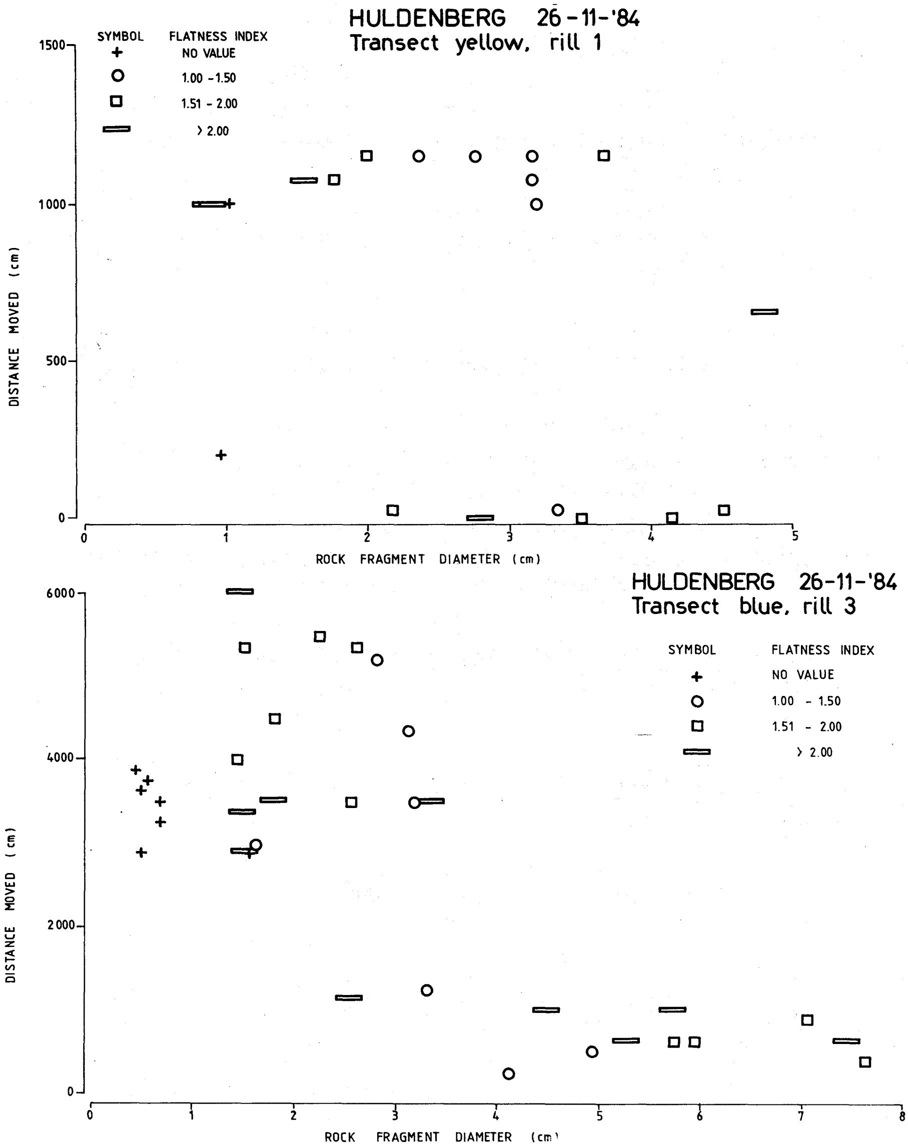

Fig. 7 Relationship between rock fragment diameter and displacement distance in rills for two selected sites.

bed roughness; pools formed in the rill beds often trapped considerable amounts of rock fragments. This is illustrated in Fig. 7 (yellow transect, rill 1) where a set of different sized particles (1 to 3.5 cm) were trapped in a rill bed depression occurring at a distance of 10 to 12 m downslope of the seeding transect.

In order to explain the variation in observed rock fragment transport distances between the different rill sites, we deduced for each rill site the mean displacement distances, corresponding to a 1 cm (Y1) and a 4 cm (Y2) diameter rock fragment from the scatter diagrams using linear regression equations. Hence, part of the variance in displacement distance due to rock fragment diameter was removed. Next, both displacement distances were related to peak rill flow unit discharge (q was calculated with the rational formula) and mean slope gradient of the rill bed (S). From the analysis it could be concluded that rock fragment displacement distances always correlate better with S (r = 0.43 to 0.44) than with q (r = 0.27 to 0.33). In addition, critical bed slope angle (S_{cr}), for rill flow transport of rock fragments with diameters between 1 and 4 cm, varied in our study between 2° 20' and 3° 30'.

These S_{cr} values were obtained by extrapolating the curve, fitting data points in a (S)–($Y1$,$Y2$) diagram for each of the four selected rills (e.g., Fig. 8). This observation indicates that incision of rills in stony soils can commence during moderate rainfall events on hillslopes having gradients above these S_{cr} values. These critical slopes are in agreement with reported S_{cr} values for initiating rill and gully formation on fine colluvial gravels (i.e. 2°, Newson, 1980) as well as on loamy soils (2–3°, Savat & De Ploey, 1982). In addition, these observations indicate that complete surface armouring, due to selective erosion of fines and the concentration of rock fragments at the surface, will essentially occur on slopes less than the S_{cr} values mentioned. For values exceeding critical slopes, the probability of complete surface armouring decreases.

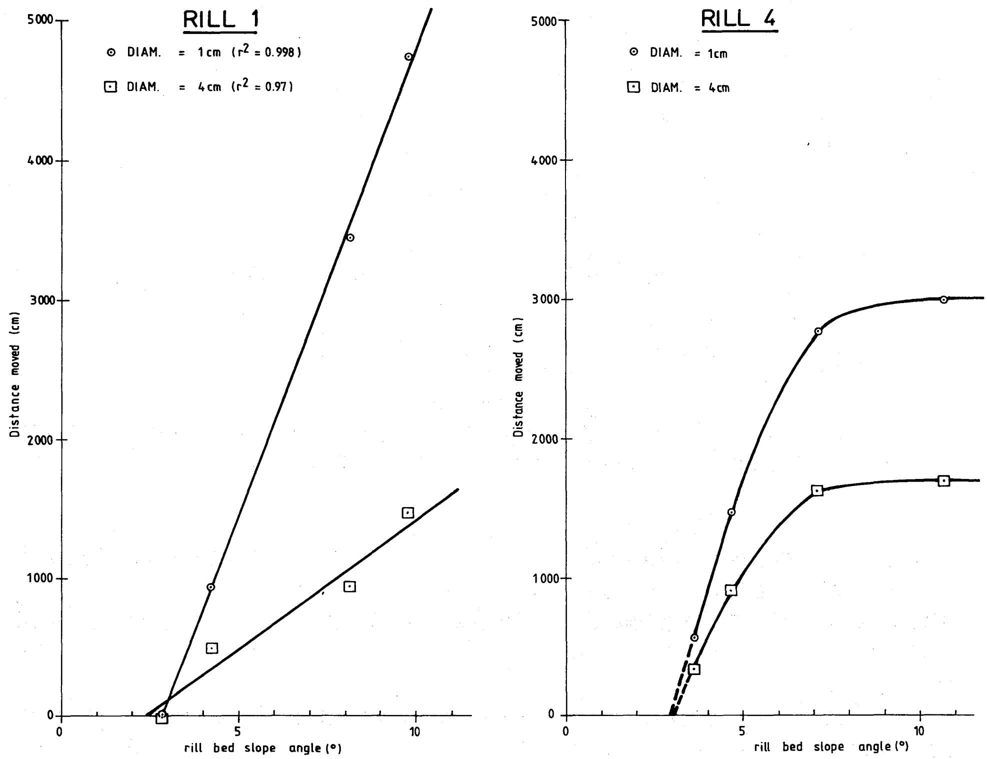

Fig. 8 Relationships between slope angle of rill bed and mean transport distance for two selected pebble diameters.

Implications of results

(a) Rock fragment content is a soil property. In addition, rock fragments themselves can be eroded by rill flow during moderate rainfall events, as shown in this study. Hence, it would be scientifically more accurate to include the effects of rock fragments on soil loss in a "universal soil loss equation soil erodibility factor" (K) rather than in a "cover and management factor" (C) (Wischmeier & Smith, 1978; Box & Meyer, 1984).

(b) This study clearly demonstrates that under moderate rainfall conditions rock fragments, having intermediate diameters up to 9 cm, can be transported downslope over considerable distances by rill flow. Hence, when applying stones as a mulch for erosion control on rillable soils (e.g. Adams, 1966; Meyer *et al.*, 1972; Jennings & Jarrett, 1985; Kochenderfer & Helvey, 1987), attention should be paid to selecting rock fragment sizes large enough to prevent erosion of the stone mulch itself.

(c) From a review of the literature, Tharp (1984) concluded that for natural river channels a bed is stable if D_{85} is immobile. If we apply this principle to the rill channels on the experimental plot, which have a D_{85} of 4 cm, we can conclude from Table 1 that most of the rill beds were unstable during the recorded moderate rainfall event. Thus it can be stated that rill channel armouring will be overcome several times per year on the experimental plot. The formation of an armour layer in rills formed in a highly gravelled soil, as described by Foster (1982, p. 338), may therefore be limited to low-magnitude rainfall events.

(d) Our field results also have some implications for archaeology. Vermeersch (1989) states that in the Belgian loam region, mesolithic sites are virtually unknown. Furthermore, this author assumes that if mesolithic sites were located on loam slopes, they have by now disappeared due to soil erosion. Our findings give more insight into the processes which are responsible for the evacuation of artifacts from loam-covered slopes; i.e. rill flow can easily transport flint artifacts with intermediate diameters up to 9 cm (Table 1) during moderate rainfall events, while the competence of inter-rill flow during such events is almost one order of magnitude smaller. Since rilling is very likely to occur on bare loam covered slopes having slope angles greater than 2 to 3° (Savat & De Ploey, 1982), and since forest clearance and cultivation of the soils in the Belgian loam belt was initiated at least since medieval times, the probability of downslope transport of artifacts by rill flow in the loam region is very high.

(e) From the field observations it can safely be said that rill and/or gully flows are the main processes responsible for the evacuation of rock fragments from cultivated upland areas in the Belgian loam region. Hence, the presence of rock fragments in colluvial deposits (Fig. 9) is an important indicator of the type of processes acting on the upland areas during colluviation. From Fig. 9, it can be concluded that recent colluvial deposits contain more rock fragments than older, historical colluvial deposits. This can be attributed either to the fact that more and more rock fragments have become available at the upland soil surface for subsequent evacuation, or to an increased frequency of rilling. The latter could then be an indication of accelerated soil erosion in the area.

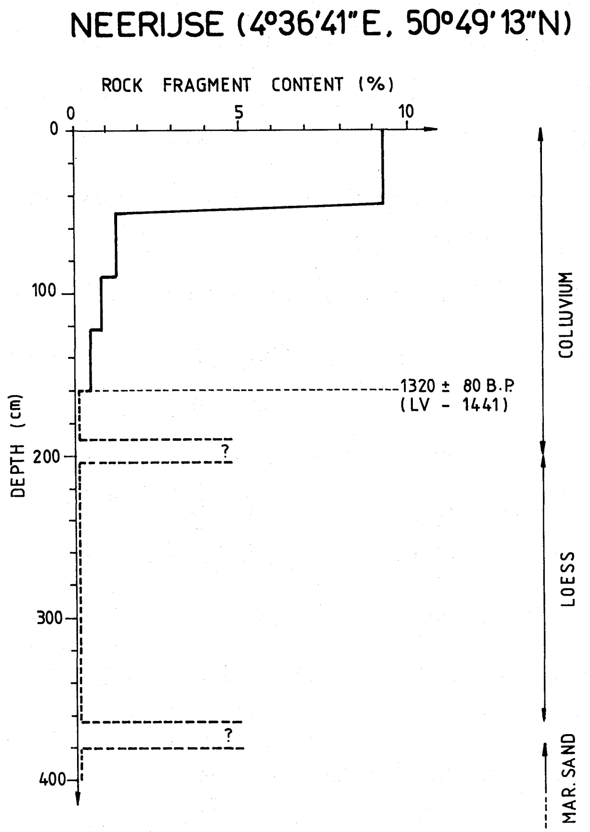

Fig. 9 Rock fragment content in historical and recent colluvial deposits in the valley bottom of a first order catchment (Neerijse, central Belgium).

CONCLUSIONS

The main conclusions of this study can be summarized as follows:

(a) Rill flow, generated during moderate rainfall events, can be identified as the most important process leading to the downslope movement of rock fragments on upland areas in the Belgian loam region. The competence of rill flow during such events exceeds by almost a factor 10 the competence of inter-rill flow. Obviously, during extreme rainfall events, rill flow will be even more effective in moving rock fragments.

(b) Incipient motion conditions, for single or clustered rock fragments lying on a relatively smooth field rill bed, coincide with a mean critical

Shields entrainment parameter (θ_c) of 0.012. This θ_c value is smaller than the generally accepted θ_c value for conventional open channel flows having gentle slopes, large ratios of flow depth to sediment size, and fine bed materials (i.e. $\theta_c = 0.06$). Laboratory data suggest that the low θ_c values corresponding to the field rills can be explained by the low rill bed roughness and, hence, a corresponding low angle of repose for the rock fragments lying on such a bed.

(c) With respect to the influence of rock fragment properties upon the distance over which rock fragments were moved by rill flow, it can be stated that fragment size plays a more important role than fragment shape. Nevertheless, for a given fragment diameter a large variation in transport distance is observed. Furthermore, it was shown that rock fragment displacement distances always correlate better with rill bed slope than with peak rill flow unit discharge and, hence also with rill catchment area. The critical slope gradient for rill flow transport, of 1 and 4 cm diameter rock fragments, varied between 2° 20' and 3° 30'.

Acknowledgements Dr G. Govers, Dr G. Rauws and Mr L. Cleeren are thanked for their assistance in the field. I also wish to thank Dr G. Wyseure who placed the rainfall records at my disposal. Mr R. Geeraerts is thanked for drawing the illustrations.

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