Detachment of Undisturbed Soil by Shallow Flow

Guang-hui Zhang,* Bao-yuan Liu, Guo-bin Liu, Xiao-wu He, and M. A. Nearing

ABSTRACT

Quantification of soil detachment rates is necessary to establish a basic understanding of soil erosion processes and to develop fundamental-based erosion models. Many studies have been conducted on the detachment rates of disturbed soils, but very little has been done to quantify the rates of detachment for natural soil conditions. This study was conducted to evaluate the influence of flow discharge, slope gradient, flow velocity, shear stress, stream power, and unit stream power on detachment rates of natural, undisturbed, mixed mesic typical Udorthent soil. Flow rates ranged from 0.25 to 2.0 L s^{-1} and slope gradient ranged from 8.8 to 46.6%. This study was compared with a previous study that used disturbed soil prepared by static compression. The results indicated that the detachment rates of disturbed soil were 1 to 23 times greater than the ones of natural undisturbed soil. It was necessary to use natural undisturbed soil samples to simulate the detachment process and to evaluate the influence of hydraulic parameter on detachment rate. Along with flow rate increasing, detachment rate increased as a linear function. Detachment rate also increased with slope gradient, but the functional relationship between the two variables depended on flow rate. Stepwise regression analysis indicated that detachment rate could be well predicted by a power function of flow rate and slope gradient ($R^2 = 0.96$). Mean flow velocity was closely correlated to detachment rate ($r^2 = 0.91$). Flow detachment rate was better correlated to a power function of stream power ($r^2 = 0.95$) than to functions of either shear stress or unit stream power.

SOIL EROSION has been defined as the process of detachment and transportation of soil material by erosive agents (Ellison, 1947). Soil detachment is the subprocess of dislodgment of soil particles from the soil mass at a particular location on the soil surface. The dislodgment is caused by the forces applied on the soil particles by the erosive agents, which are mainly raindrops and overland flow (Owoputi and Stolte, 1995). In process-based soil erosion models, the sediment source is conceptually separated into that from interrill and rill areas. In interrill areas, dominant processes are detachment by raindrop impact and transport by raindrop-impacted shallow flow. In rills, dominant processes are detachment and transport by concentrated flow (Huang et al., 1996). Therefore, understanding of the detachment mechanisms for both interrill and rill areas is necessary for the development of process-based erosion model.

Detachment by raindrop impact has been studied in detail during the past several decades. The relative importance of the roles played by raindrop impact and overland flow (Gilley and Finkner, 1985; Bradford et al., 1987), the effect of flow depth and sediment load on splash (Hirschi and Barfield, 1988; Kemper et al., 1985), and transport capacity (Guy et al., 1987; Kinnell, 1993) have been simulated and analyzed. The relationship between soil detachment by raindrop impact, raindrop size and mass, drop velocity, kinetic energy, soil strength, water drop impact angle, and surface sealing have also been investigated (Nearing and Bradford, 1985; Bradford et al., 1987; Sharma et al., 1991; Sharma et al., 1993; Cruse et al., 2000). These experiments have contributed to the better understanding of the mechanism of soil detachment by raindrop impact and provided a basis for models for interrill areas (Gilley and Finkner, 1985; Sharma et al., 1991; Sharma et al., 1995).

Detachment of cohesive soils by shallow clear-water flow under laboratory conditions has received less attention (Nearing et al., 1991). Detachment by overland flow occurs when the stress or energy applied by the overland flow is great enough to pull the soil particles away from the bulk material. Shear stress (τ), stream power (ω), and unit stream power (P) are normally used hydraulic parameters to simulate detachment rate in rills, which given the functions as follow:

$$\tau = \rho g h S \qquad [1]$$

where τ(Pa) is shear stress, ρ(kg m^{-3}) is water mass density, g (m s^{-2}) is the gravity constant, h (m) is the depth of flow, and S (fraction) is the tangent value of bed slope degree.

$$\omega = \tau V = \rho g h S V \qquad [2]$$

where ω(kg m^{-3}) is stream power, V (m s^{-1}) is mean flow velocity.

$$P = VS \qquad [3]$$

where P (m s^{-1}) is unit stream power. It is clear that shear stress, stream power, and unit stream power are functions of flow depth, velocity, and slope gradient. Therefore, through combinations of different slope gradients, flow rates, and flow depths, the relationship between soil detachment rate and these hydraulic parameters can be derived based on the data from hydraulic flume studies. Lyle and Smerdon (1965) were among the first to use a hydraulic flume to investigate the relationship between soil erosion and flow shear stress under constant slope. The results revealed a unique relationship for a given soil type.

Nearing et al. (1991) conducted a series of experiments in a hydraulic flume with varying bed slope to investigate the relationship between soil detachment by shallow flow, flow depth, bed slope, and mean weight diameter of the aggregates with small, statically com-

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pressed samples of two soil types. The results indicated that the logarithm of detachment rate was correlated to flow depth, slope, and mean weight diameter. Soil detachment was not a unique function of either shear stress or stream power. However, because of the disturbance of the soil samples prepared by static compression, the difference of detachment rate was not great between the Russell and Paulding soils, though the bulk densities and textures were very different for the two soils. In a field study, Elliot and Laflen (1993) found that stream power was the best variable to predict detachment capacity for rills.

Nearing et al. (1997, 1999) conducted a series of field experiments to investigate the relationship between soil detachment rate, shear stress, stream power, and hydraulic friction. The results demonstrated that rill detachment rates were best correlated to a power function of either shear stress or stream power. Zhang et al. (2002) conducted controlled laboratory experiments to evaluate the influence of flow discharge, slope gradient, and flow depth on soil detachment rate by shallow flow and to investigate the relationship between soil detachment rate, flow velocity, shear stress, unit stream power, and stream power in a hydraulic flume with small, compressed soil samples. The results illustrated that detachment rates were more sensitive to discharge than to slope gradient, and that detachment rate could be well predicted by a power function of discharge and slope gradient. The results also indicated that stream power was the best hydraulic parameter to describe the detachment by shallow flow.

Shear stress (Nearing et al., 1989), stream power (Rose at al., 1983; Hairsine and Rose, 1992; Nearing et al., 1997), and unit stream power (Morgan et al., 1998; De Roo et al., 1996) have all been related to detachment rate in rills. The lack of consistency or agreement on what parameter actually controls detachment rates implies that the fundamental mechanism of detachment in rills was still not fully understood. Further studies and new concepts are needed to establish a full understanding of the mechanism of detachment in rills (Zhang, 2000).

In addition to the capability of rill flow to detach soil particles, rills are also the main, down-slope transporting agent for detached sediment from both rill and interrill areas. It is known that the detachment rate by overland flow will decrease as sediment load increase, since the portion of the energy of the flow expended to transport sediment reduces the energy level that remains available to detach new soil particles (Moore and Burch, 1986; Merten et al., 2001). This interaction between sediment load in the flow and associated reduction in detachment capacity for the flowing water has made it difficult to identify true detachment rates of flow in long rills, because the processes of detachment and transport are more strongly interactive as the rill length is increased. This explains the great difference between the data set of Laflen et al. (1991) taken on long rills, and those of Nearing et al. (1991, 1999), Nearing and Parker (1994), and Zhang et al. (2002). Soil samples of small size and the use of clear water is necessary to simulate the detachment process without the serious complication of needing to account for the interaction of sediment laden flow on detachment rates.

In addition to the hydraulic characteristics of flow, detachment rate is also strongly influenced by soil properties such as soil type, bulk density, texture, cohesion, soil strength, organic content, water content, infiltration, seepage, and so forth (Khanbilvardi and Rogowski, 1986; Nearing et al., 1988; Owoputi, 1994; Morgan et al., 1998). In the studies of Nearing et al. (1991), Nearing and Parker (1994), and Zhang et al. (2002), soil samples were disturbed. Though the samples were reconstituted by static compression to a desired bulk density, it is reasonable to assume that the resulting soil structure was different from that of the natural undisturbed soil. We hypothesize that the use of natural, undisturbed soil samples will result in lesser rates of detachment relative to disturbed soil.

The objectives of this study were: (i) to assess the difference of using natural, undisturbed soil samples, compared with the use of disturbed samples in previous studies to quantify the mechanism of soil detachment by overland flow; and (ii) to evaluate the influence of flow discharge and slope gradient on detachment rate of natural undisturbed loess soil and to investigate the relationships between detachment rate and commonly used hydraulic parameters. Undisturbed soil samples obtained in the field were placed in a flume located in a laboratory to obtain the desired soil loss and hydraulic measurements.

MATERIALS AND METHODS

Soil Sample Collection

Experiments were performed at the Ansai field station, which is located near the center of the Loess Plateau of China and has an annual average precipitation of 549 mm. More than 70% of precipitation falls during the months of June through September. The soil properties of current study and previous study (Zhang et al., 2002) are given in Table 1. Although a Haplustalf soil was used in previous study (Zhang et al., 2002), the soil texture is the same. The soil sample preparation is the principal difference between the current study and the previous (Zhang et al., 2002). In the current study, natural undisturbed loess soil sample was taken directly from field, whereas the soil was sieved and reconstructed by static compression in the previous study (Zhang et al., 2002).

The samples were taken from the top layer of soil planted

Table 1. Soil properties, land use, and sampling methods of current and previous studies.

Studies	Sand	Silt	Clay	Organic matter content	Texture	Bulk density	Location	Land use	Sample preparation
		—— % ——				g cm^{-3}			
Current	**7.9**	**66.7**	**25.4**	**0.9**	**Silt loam**	**1.15**	**Beijing**	**Rangeland**	**Static compression**
Previous	**16.8**	**56.9**	**23.6**	**0.4**	**Silt loam**	**1.20**	**Loess Plateau**	**Cropland**	**Original**

with soybean [*Glycine max* (L.) Merr.] using iron rings with a diameter of 9.8 cm and depth of 5.0 cm. Soybean was planted 10 Apr. 2002, and had no other management measure except one weeding with a hoe. One rainfall occurred before soil sampling, resulting in a thin crust on the soil surface. To fill the sample ring fully and to maintain the elevation of sample surface evenly within the rings, the flat area of the soil surface between the soybeans was used. The iron ring was pressed carefully into the ground, and the surrounding soil was cut with a knife as the ring went down to make sure the soil was loose enough around the edges to remove the sample. Before taking the sample out from the soil, it was necessary to check whether the ring was filled fully. After removal, the soil sample was turned over and the surplus soil was cut carefully from the bottom end of ring. When the soil was level with the bottom of the ring, lids for both the top and bottom of the sample were put in place and held onto the metal sample ring with rubber rings. A cushion of cotton cloth was covered over the soil surface to prevent the disturbance of the sample as much as possible.

Soil moisture was measured with a Delta–T (ML2x) probe (Delta-T Devices, UK), which was calibrated by oven method, at ten random points near where the ring sample was taken. The average soil moisture was used to calculate the water weight for each ring sample. The weight of the soil samples was measured as soon as possible to decrease the influence of evaporation.

Measurement of Hydraulic Parameters

Detachment rates were measured in a 4-m-long, 0.35-m-wide hydraulic flume. The elevation of the top end of flume could be adjusted, allowing bed gradients of the flume up to 60%. Loess soil was glued on the surface of flume bed so that the hydraulic roughness of the flume was similar to that of the samples. The roughness of the flume bed was kept constant during the experiment.

The flow rate was controlled by a series of valves and measured directly by a calibrated flow meter. Velocity of flow was assessed using a fluorescent dye technique in which the velocity of the leading edge of dye was multiplied by a reduction factor of 0.8 to obtain a measure of mean velocity (Luk and Merz, 1992; King and Norton, 1992). The flow depth was measured by a level-probe with an accuracy of 0.01mm. Both flow velocity and flow depth measurements were replicated ten times. The average value was used to determine the shear stress, stream power, and unit stream power of flow for the different treatments of flow discharge and slope gradient.

Measurements of Detachment

The surface of soil sample was wetted by light spraying. The flume bed gradient and flow rate were adjusted to the desired values. Immediately before the start of the experiment, the soil sample was removed from the container, and placed in a hole (with the diameter of 10 cm) in the bed of flume, located at a distance of 0.5 m from the lower end of flume, keeping the elevation of the sample surface even with the flume bed. Then the detachment experiment was conducted.

Soil detachment rate (mass per unit area per unit time) was calculated as the total soil loss (original weight of wet soil sample minus the weight of water within sample, and then minus the final oven-dry mass) divided by the time of duration of test and the cross-section area of soil sample. To decrease the influence of uneven detachment within the sample ring, the test duration was adjusted to maintain a similar scouring depth of the soil samples (Nearing et al., 1991; Zhang, 2002). A series of 25 combinations of flow discharge (0.25, 0.50, 1.0, 1.5, and 2.0 L s^{-1}) and flume bed slope (8.8, 17.6, 26.8, 36.4, and 46.6%) were used. Each treatment was replicated five times.

Flow Reynolds number of the present study ranged from 902 to 7054. Thus, the flow fell within turbulent flow regimes. The mean velocity and flow depth ranged from 0.306 to 0.898 m s^{-1} and 1.62 to 8.48 mm respectively. The Darcy-Weisbach friction factor ranged from 0.145 to 0.334. The hydraulic conditions used in present study were almost the same as hydraulic conditions of a previous study conducted for disturbed soil (Zhang et al., 2002). Therefore, the data set of these two studies can be used to analyze the difference of detachment rates between disturbed soil and natural, undisturbed soil.

RESULTS AND DISCUSSION

The flow rate and slope gradient for the current experiment was the same as that used in the study of Zhang et al. (2002), except for the lowest slope (3.5%). The comparison of detachment rate for the two studies indicated that detachment rates are significant different between natural, undisturbed soil and disturbed soil, though the hydraulic conditions were almost the same. Detachment rates of disturbed soil were 1 to 23 times greater than detachment rates of natural undisturbed loess soil. Comparing ratios of the detachment rates from the previous experiment to the current one showed that three fourths of the ratios were greater than four. The hypothesis that the use of natural, undisturbed soil samples would result in lesser rates of detachment relative to disturbed soil was supported by this result. It is apparent that when the soil is reconstructed during the sample preparation, detachment rates are much greater than for undisturbed samples. The effect of disturbance on detachment rate was significant and may not be ignored. Even though detachment rates were different, there was a linear correlation between these two data sets (Fig. 1).

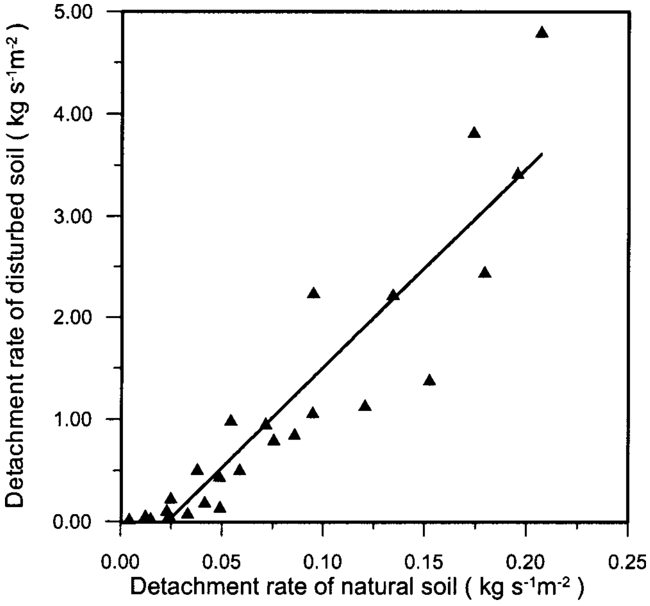

Fig. 1. Relationship between detachment rate of natural undisturbed sample and disturbed sample.

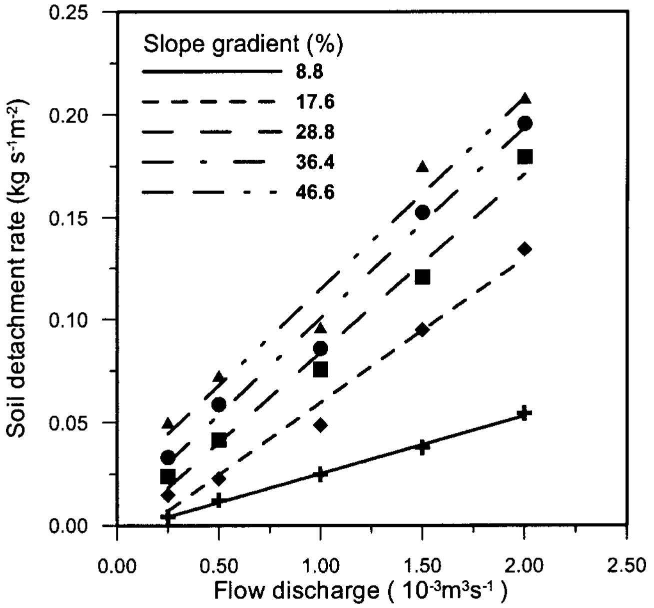

Fig. 2. Measured detachment rate as a function of flow discharge.

$$D_{\mathrm{rd}} = 19.583D_{\mathrm{rn}} - 0.450 \quad r^2 = 0.85 \qquad [4]$$

where D_{rd} (kg s^{-1} m^{-2}) is the detachment rate of the disturbed soil sample of previous study, and D_{rn} (kg s^{-1} m^{-2}) is the detachment rate of natural soil samples of the current study.

Detachment rates increased with both increased flow discharge and increased slope gradient (Fig. 2 and 3). Detachment rates increased as a linear function of flow discharge for all slope gradients, with high coefficients of determination ($r^2 \geq 0.98$). However, the relationship between detachment rates and slope gradients was dependent on the flow discharge (Fig. 3). The relationship changed from a power function at the two lower flow discharges (0.25 and 0.5 L s^{-1}) to a logarithmic function for the three greatest flow discharges (1.0, 1.5, and 2.0 L s^{-1}).

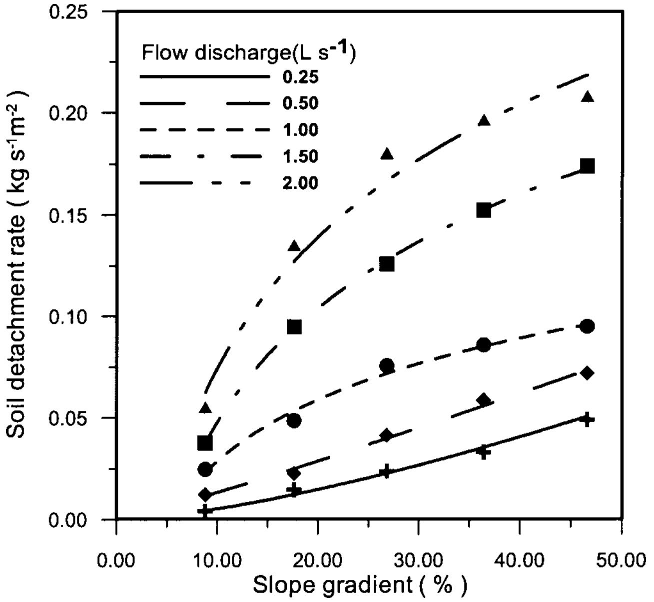

Fig. 3. Measured detachment rate as a function of slope gradient.

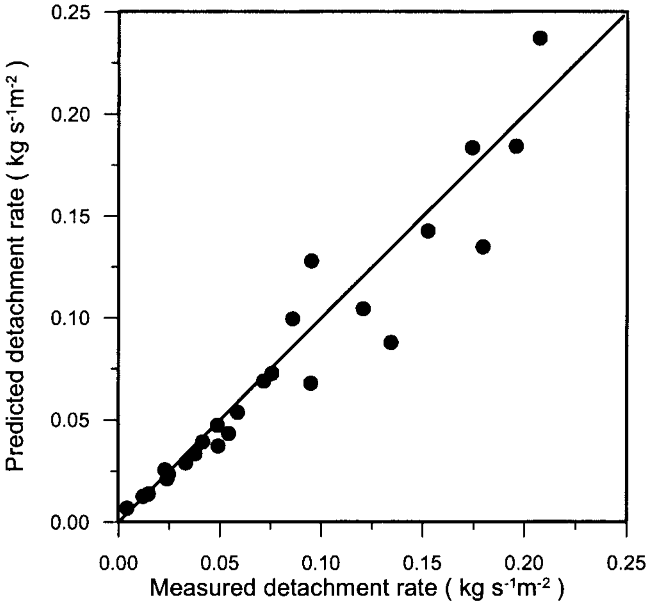

Fig. 4. Measured detachment rate vs. predicted detachment rate using Eq. [5]

Analysis indicated that soil detachment rates were well simulated by the power function of flow rates and slope gradients (Fig. 4).

$$D_{\mathrm{c}} = 130.41q^{0.89}S^{1.02} \quad r^2 = 0.96 \qquad [5]$$

where D_{c} (kg s^{-1} m^{-2}) is detachment rate, q (m^3 s^{-1}) is flow rate, and S is the tangent value of slope degree. When the detachment rate was low, the predicted detachment rate was very close to measured detachment rate (Fig. 4). However, when the detachment rate was greater than 0.8 kg s^{-1} m^{-2}, the points were scattered, and the predicted result was not ideal. The best predicting equation between detachment rates and mean velocities was a power function (Fig. 5).

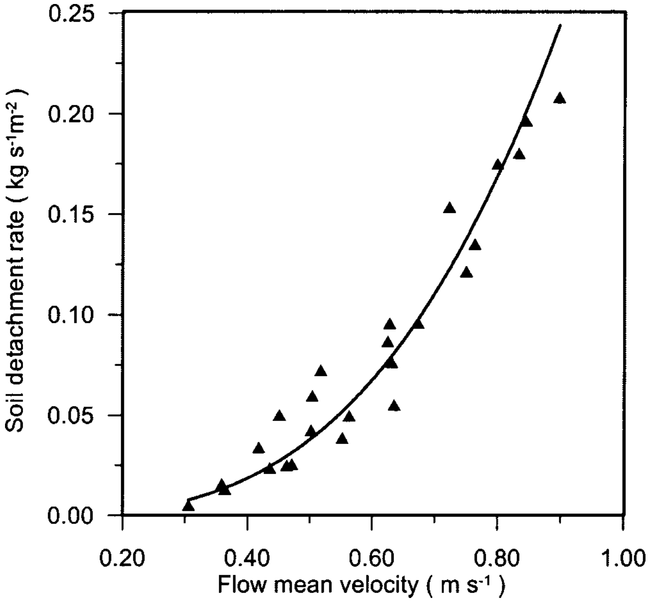

Fig. 5. Measured detachment rate as a function of mean flow velocity.

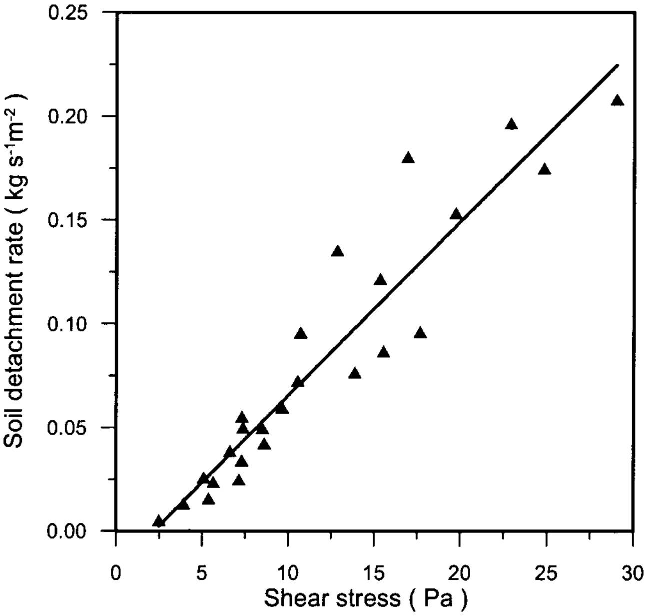

Fig. 6. Measured detachment rate as a function of shear stress.

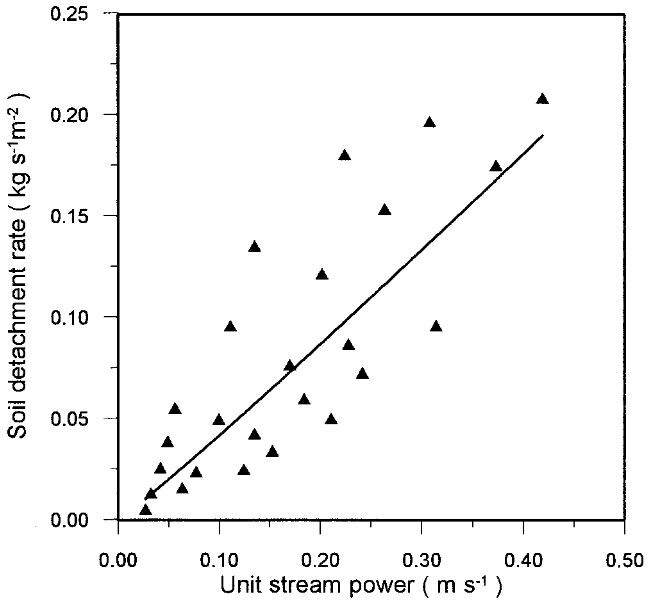

Fig. 7. Measured detachment rate as a function of unit stream power.

$$D_c = 0.344V^{3.18}\ r^2 = 0.91 \qquad [6]$$

where V (m s^{-1}) is mean flow velocity.

As mentioned earlier, there remains a gap between the study of mechanisms of erosion and erosion model development. Results of many studies have indicated that stream power is the best hydraulic parameter to describe the process of detachment and transport in rills (Elliot and Laflen, 1993; Nearing et al., 1997; Nearing et al., 1999; Li and Abrahams, 1999; Zhang et al., 2002). Nevertheless, in many process-based soil erosion models, detachment rate is defined as the function of either shear stress (Nearing et al., 1989) or unit stream power (Morgan et al., 1998; De Roo et al., 1996). It is useful for the development of soil erosion science to analyze the relationship between detachment rate and those hydraulic parameters. No such analysis has been performed for natural soil cores. Therefore, detachment rates were plotted against shear stress, unit stream power, and stream power (Fig. 6, 7, and 8, respectively).

The linear relationship between detachment rate and shear stress was analyzed first to compare the current study with the results reported by Laflen et al. (1991), Nearing et al. (1999), and Zhang et al. (2002). Using simple linear regression between detachment rates and shear stress produced a value of 0.0084 s m^{-1} and 2.19 Pa for erodibility (K_r) and critical shear stress (τ_c), respectively. Hence

$$D_c = 0.0084\tau - 0.0184\ r^2 = 0.89 \qquad [7]$$

where D_c (kg s^{-1}m^{-2}) is detachment rate, and τ(Pa) is shear stress. The critical shear stress was within the range of the values reported in other studies (Laflen et al., 1991; Nearing et al., 1999; and Zhang et al., 2002). The erodibility parameter, however, was 16 times greater than those found in the WEPP rill erosion study (Laflen et al., 1991), but only 4% of that reported by Zhang et al. (2002). The value found in this study was quite close to the erodibility value of 0.00795 s m^{-1} that was reported by Nearing et al. (1999). The large difference between erodibilities found in Laflen et al. (1991) study and the current study was probably because of the sediment feedback phenomenon discussed above and by Cochrane and Flanagan (1997) and Merten et al. (2001). The reason for the difference between the current study and the previous research by Zhang et al. (2002) is hypothesized to be because of the fact that the soil samples in the previous study were completely reconstituted and not undisturbed as in this study.

The correlation between detachment rate and shear stress was improved when a power relationship was used instead of the linear function. Compared with linear function, the coefficient of determination (r^2 = 0.92) improves with 3%. This result corroborates the results of Nearing et al. (1999) and Zhang et al. (2002).

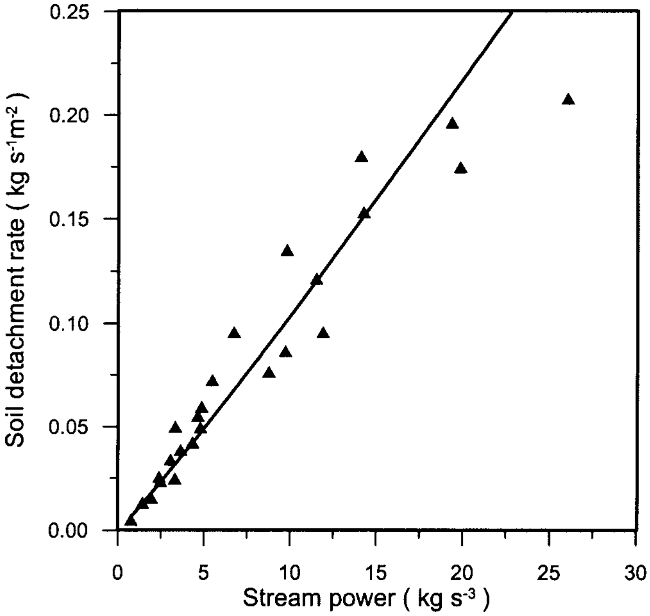

Fig. 8. Measured detachment rate as a function of stream power.

$$D_c = 0.0017\tau^{1.53}\ r^2 = 0.92 \qquad [8]$$

As in the previous study (Zhang et al., 2002), the correlation between detachment rates and unit stream power was not as good as for the other variables (Fig. 7). The coefficient of determination was only 0.71. Detachment rate was well correlated to stream power with a power function (Fig. 8). The coefficient of determination (r^2 = 0.95) was greater than for either shear stress or unit stream power. The regression equation was

$$D_c = 0.0088\omega^{1.07}\ r^2 = 0.95 \qquad [9]$$

where ω (kg m^{-3}) is the stream power.

CONCLUSIONS

We observed a great difference between the detachment rates of disturbed soil samples prepared by static compression (Zhang et al., 2002) and the natural, undisturbed soil samples of the current study. The detachment rates of disturbed soil samples were 1 to 23 times greater than the detachment rates of natural, undisturbed soil samples. Therefore, it is necessary to use natural undisturbed soil samples to simulate the detachment process and to evaluate the influence of hydraulic parameter on detachment rate if the desire is to understand erosion rates on undisturbed soil material.

Detachment rate increased with both increased flow rate and slope gradient. Detachment rate increased as a linear function of flow rate, however, the relationship between detachment rate and slope gradient was dependent on flow discharge. The relationship was a power function at low flow rates, and logarithmic at higher flow rates. The detachment rate was well represented by a power function of flow rate and slope gradient (R^2 = 0.96). There was close correlation (r^2 = 0.91) between detachment rate and mean velocity. Detachment rate increased as a power function of mean velocity.

The linear relationship between detachment rate and shear stress gave a poorer prediction (r^2 = 0.89) than did a power function of shear stress (r^2 = 0.92). Among shear stress, stream power, and unit stream power, stream power was the best hydraulic parameter to predict detachment rate (r^2 = 0.95). This result also corroborates the results of previous studies that showed that stream power was a better parameter to predict detachment than was shear stress (Elliot and Laflen, 1993; Nearing et al., 1997; Nearing et al., 1999; Zhang et al., 2002).

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