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"Soil Erosion Mechanics and Models"

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SOIL EROSION MECHANICS AND MODELS

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SUMMARY

Recent achievements in soil erosion mechanics indicate that soil detachability is mainly linked to soil shear strength. This is a dynamic soil property and changes in space and time. These variations must be considered for soil loss forecasting during critical erosive events. It must be noticed that chemical reactions between colloid fraction of the soil and ions dispersed in runoff and infiltration water can change soil shear strength even during the same event.

The aggressivness of raindrop impact can be estimated using drop momentum while runoff shear stress seems to be the leading force determining soil detachment.

Transport capacity due to raindrop impact can be described using Poesen's model (1985) as a first approximation. Wright's approach should be improved in order to calculate the contribution of splashed sediment to rills.

Runoff transport capacity can be approached using the methodology proposed by Govers and Rauws (1986) which is based on Einstein-Barbarossa procedure for dividing bed form shear stress from grain shear stress. Following this approach, transport capacity can be estimated using the unit stream power dispersed against soil grains. This methodology can also be used for estimating the amount of runoff shear stress and unit stream power dispersed against vegetation. This allows a logical introduction of a crop factor in soil loss control.

De Ploey's stem flow equation (1984) can be useful

for evaluating local concentration of water due to plants. It can improve the evaluation of the probability of rill formation.

INTRODUCTION

Soil erosion hac been modelled for many decades using a mixture of statistics and some hints of physical interpretation of the processes. The universal soil loss equation (Wischmeier and Smith, 1965) and the modification of erosivity introduced by Oltan and Foster (1975) represent some of the best achievements in this line of research. Despite their names those equations are not universal. They can be properly used only for describing average trends inside the pool of data used in assessing them. Extrapolations may fit new observations but often do not.

Only equations based on understanding of the processes have a fairly good probability of matching reality also when applied in areas not used during calibration. Nevertheless, a model completely based on the physics of the processes has never been attempted. The general framework described by Chisci and Morgan (1986) is already physically oriented. In this paper some aspects will be presented and discussed in order to outline a model based on soil erosion mechanics.

SOIL EROSION MECHANICS

A physically based model requires its overall formulation is coherent and different aspects are treated in a homogeneous way. Consequently every process will be described in terms of force and energy.

A first subdivision of soil erosion can be as follows:

1- soil particle detachment;

2- transport of detached soil.

In those two statements, as well as in the following, the term particle means both primary and aggregated particles.

Those two aspects of soil erosion can be summarized in detachment rate (DR) and potential transport rate (PTR). When PTR is larger than DR the actual transport rate (ATR) equals DR; otherwise ATR equals PTR. Deposition occurs at the passage from the former to the latter situation.

A European model must consider both conditions because of the large variety of pedo-climatic zones characterizing Europe. For example, critical erosive events in the Spanish Mediterranean zone are probably characterized by PTR=ATR. On the contrary, in the Italian clay slopes ATR=DR because of soil cohesiveness.

DETACHMENT RATE

Let us now consider DR and PTR in more details. Agents of detachment are raindrops and surface runoff. Other agents also exists (slaking of aggregates, water outburst from a saturated subsurface layer, etc.) but they can be neglected during this first stage of model development.

The situation to be described is like that: a particle is at rest on the soil surface to which it is linked by some bonds. Detachment takes place when the particle is removed from its initial position by a detaching agent. It is well known that all the time a particle change its status of motion a force is at work. Consequently detachment is ruled by a balance between detaching and resisting forces.

Splash detachment rate

During drop impact a crown of lateral jets is produced. The flow velocity of those jets can be very high (Engel, 1955; Ghadiri and Payne, 1979). Shear stresses, able to detach particles, can be produced (Harlow and Shannon, 1967; Torri, Sfalanga and Del Sette, in press). This hypothesis is reflected in nature by the fact that the amount of detached particles is inversely proportional to soil shear strength (Al Durrah and Bradford, 1982). The following relationship can be proposed for detachment rate (Torri, Sfalanga and Del Sette, in press):

$$(1) \quad DR_s = f_1(\varphi) \frac{(\tau_d - \tau_s)}{\tau_s}$$

where DR_s = mass of soil detached per unit of mass of rain;

f_1 = function;

φ = particle size distribution;

τ_s = soil shear strength;

τ_d = shear stress of a representative raindrop.

Function f_1 has not yet sufficiently been studied. Nevertheless clay fraction seems to play a major role.

Drop total shear stress seems to be linked to drop momentum (Torri, 1985) also if drop kinetic energy shows a better correlation with the splashed amount (Reizebos and Epema, 1985).

The partially elastic behaviour of soil determines the partial restitution of the drop momentum. Upward ejected droplets can entrain soil particles (Wright, 1986). Also in this case drop detaching power can be estimated through drop momentum while soil resistence is still soil shear strength. Consequentely an equation similar to eqn.(1) still holds.

RUNOFF DETACHMENT

When a particle is immersed into a fluid in motion tractive and lift forces are acting on it. Usually only tractive forces (F) are considered. They are usually estimated with the following equation:

(2) $F = A_r \tau_r$

where τ_r = runoff shear stress;

A_r = surface on which τ_r acts.

In its turn, τ_r is calculated as follows:

(3) $\tau_r = g \rho R \tan \Gamma = \rho u_*^2$

where g = acceleration of gravity;

ρ = fluid density;

R = hydraulic radius;

Γ = slope angle;

u_* = shear velocity

Even in this case the force keeping the soil particle at rest can be estimated using soil shear strength. Consequently the following condition for detachment of a single particle can be given:

(4) $A_r \tau_r > A_s \tau_s$

where A_s = surface on which τ_s acts.

Inequality (4) obviously holds if and only if the tractive force is a good approximation of the total detaching force acting on the soil particle. In more general terms the following equation for detachment rate can be proposed:

(5) $Dl_r = \psi(\varphi) \dfrac{(\tau_r A_r - \tau_s A_s)}{\tau_s A_s}$

where Dl_r = runoff detachment power;

ψ = function.

For incipient rilling condition an empirical equation (Torri, Sfalanga and Chisci, in press), which resembles inequality (4), has been proposed:

(6) $\tau_r / \tau_s > 10^{-4}$

Splash transport

Once a drop has detached soil particles these are ejected around. Their trajectories are described by the usual laws ruling balistic. The dispersion of the splashed sediment follows an exponential distribution around the drop impact area (Poesen and Savat, 1981). The dispersion shows a circular symmetry only on a flat surface with vertical trajectory of the impacting drop. On sloping surfaces or with inclined raindrops the circular symmetry is lost. This gives rise to a net particle movement. These aspects are considered in a model proposed by Poesen (1985). It can be used, with minor changes, in order to estimate the contribution of splashed sediment to rills.

Runoff transport capacity

A promising approach to transport capacity estimation is based on some concepts developed by Govers and Rauws (1986). Following them runoff transport capacity is due to that part of unit stream power that is available for moving soil particles. More precisely, stream power is partially dispersed against form roughness, vegetation and all the other obstacles to fluid motion that cannot be removed. The remaining part of stream power can be used for carrying detached sediment. The calculation of this part of stream power can be made following the Einstein-Barbarossa procedure for subdividing shear stress in its grain and form components. The former can be calculated using a computer programme prosed by Savat (1980).

Govers and Rauws (1986) also observed that the soil transport modality affects transport. This agrees with the observations made by Gerits and De Boer (1986) on the fact that chemical reactions between soil colloids and solute influence both detachment and transport. Actually when deflocculation occurs soil shear strength becomes almost zero and detachment rate increases. In this situation suspended sediment transport becomes more important for two reasons: increased detachment and deflocculation of already detached particles. An increase in total transport rate is consequently observed.

This modelization is homogeneous with detachment description because it is based on parameters (energy) directly derived from hydraulic forces.

This approach can be used in computing transport capacity of both diffuse overland flow and rill flow.

Runoff transport capacity is strongly affected by the number and size of rills. Actually rill flow is characterized by a higher transport capacity than interril flow. Consequently an estimator of rill frequency is needed. As already proposed by Chisci and Morgan (1986) soil shear strength can be used as an indicator of soil rillability (from disequation 6). Unluckily this one alone is not enough because all the factors facilitating overland flow concentration must be taken into account. In order to exemplify it let us consider a vineyard with rows oriented up and down. Every interrow is a small catchment in which 2 or 3 lines of concentration can be detected: 2 along the tractor wheel tracks and, sometime, a third one in the middle. Consequently the small catchment, usually 4 m wide, can be subdivided in 2 or 3 sub-catchments. Overland flow concentrates from 2 or 1.3 m of width to 0.2 m increasing its unit stream power of a factor in between 10 and 100.

Also stem flow can concetrate runoff. Corn is an effective plant in doing it. De Ploey's stem flow model (1984) can be used for estimating such contributions.

SOIL SHEAR STRENGTH

Soil shear strength has been here presented as an important factor for both detachability and transport estimates. Consequently it can be useful to discuss some problems that can arise in measuring it as well as some parameters that can make it vary in time.

Soil shear strength, which we are interested in, is the one relative to the very first layer of soil particles. This means that those measurement apparatuses such as Casagrande shear box or triaxial test are inadequate. They measure soil shear strength for a thick soil sample not representative of suface conditions. Swedish falling cone and vane apparatus can measure soil surface shear strength. Only measurements made with the latter present a fairly high ripetibility (Brunori, Penzo and Torri, unpublished data).

Here a list of source of variations is given, some of which inherent to the measure, other to soil shear strength itself:

1- soil moisture content influences almost exponentially soil shear strength;
2- only the first few millimeters of soil should be interested by the vane - this means that the resisting torque is very low and the spring deflection angles are near the lower end of the calibration curve; it is here that the inertia of the whole apparatus can false the measure;
3- soil shear strength is not constant during the year also at the same moisture content; weathering and management practices make it vary;
4- soil shear strength varies in space for the same soil at the same moisture content because of induced and inherent variability;
5- interactions between soil colloids and solute transported in surface runoff and in infiltration water, can change soil shear strength during one event (Gerits and De Boer, 1986). Also sealing can produce rapid variations lasting for long period (Poesen, 1986).

While the first 2 items can be easily controlled, items 3 and 4 depend on soil dynamics and must be considered for modelling purposes . Actually item 3 implies that the combination of rain aggressivness and soil resistence combine in order to define how critic an event is. Item 4 implies that two soil with equal average value of shear strength can differ in rillability: the more rillable will be the one with the larger variability. The main implication of item 5 is that chemistry and mineralogy cannot be neglected in a soil erosion model.

CONCLUSION

Soil erosion mechanics is already sufficiently developed for modelling purposes. A model can be proposed based on the following parts:

1- determination of detachment rate;
2- dermination of potential transport capacity;
3- determination of actual transport rate and soil loss.

Detachment rate is primarily based on soil surface shear strength. Its variations in time and space must be considered in order to evaluate critical condition.

Drop momentum and runoff shear stress can estimate rainstorm detachment power while particle unit stream power estimates runoff potential transport rate.

Chemical reactions between soil colloids and solute influences both detachment and transport; they must consequently be considered for modelling soil loss.

This general approach introduces phoenomena (such as sealing and soil compaction) and factors (such as vegetation and management practices) in a logical and natural way. This does not mean that a simple 'collage' of present knowledge can produce a reliable computer programme. On the contrary, a great effort is needed in order to prepare it. Moreover additional research is needed in order to investigate some aspects (e.g., soil shear strength variations) and to parametrize the influence of some factors (e.g., vegetation and tillage practices).

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