INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL SCIENTIFIC AND CULTURAL ORGANIZATION

INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
34100 TRIESTE (ITALY) - P.O.B. 586 - MIRAMARE - STRADA COSTIERA 11 - TELEPHONES: 224281/2/3/4/5/6
CABLE: CENTRATOM - TELEX 460392-I

SMR/147- 40

COLLEGE ON SOIL PHYSICS
15 April - 3 May 1985

COLLOQUIUM ON ENERGY FLUX AT THE SOIL ATMOSPHERE INTERFACE
6 - 10 May 1985

RAINDROP IMPACT: SOIL PARTICLE DETACHMENT AND TRANSPORT

D. TORRI
CNR Centro Studio Genesi
Classificazione e Cartografia del Suolo
P.le Cascine 15
Firenze
Italy

COLLOQUIUM ON ENERGY FLUX AT THE SOIL ATMOSPHERE INTERFACE
May 6-10th, 1985
International Centre for Theoretical Physics
Miramare - Trieste, Italy.

Raindrop impact: soil particle detachment and transport

Dino TORRI

CNR Centro Studio Genesi, Classificazione e Cartografia del Suolo
P.le Cascine 15
Firenze (Italy).

Introduction.

Drop detachment of soil particles and aggregates has been recognised as the factor beginning soil erosion since the late 1940's (Ellison,1947). Since then many pieces of information have been collected by innumerable researchers (Mihara,1951; Mutchler,1967; Mazurak and Mosher,1968; Moss et al.,1979; Poesen, 1981; Poesen and Savat, 1981; Torri and Sfalanga, in press).

At present we know that drops detach particles (Ellison, 1947); runoff shields the soil and decreases detachment (Gadhiri and Payne, 1979); The amount of material splashed by a drop decreases exponentially as the distance from the impact point increases (Savat and Poesen,1981); detachment on a sloping surface is not simmetric around the vertical axis (De Ploey and Savat, 1968) usually considered coincident with the trajectory of an ideal drop; the angle of ejection of a particle is influenced by the depth of a water film standing over the soil surface (Mutchler,1967); soil shear strength is linked to the soil resistence to detachment (Al Durrah and Bradford,1982).

On the contrary the forces through which drops act in order to detach and splash soil particles are still scarcely investigated. Only Palmer (1963) and Gadhiri and Payne (1977) tried to measure the forces produced by the impact of a drop. Up to now drop kinetic energy is still used in order to estimate the drop detaching power - probably because of the successful equation proposed by Wischmeier and Smith (1958).

This paper will deal with a possible description of the whole process of detachment and transport trying to introduce forces as as direct causes of them.

Soil detachment.

The mechanics of the impact of a drop over a rigid surface has been described by Engel (1955) while a computer simulation based on the Navier-Stokes equation was carried out by Harlow and Shannon (1967).

Following their findings the collision of a drop on a rigid surface can be described as follows

The head of the impinging drop initially resists a change of shape because of its inertia or of its viscosity or of surface

tension, then a radial flow begins.

The radial flow is characterized by an initial high flow velocity followed by a strong decrease (Fig.1). The depth of the flow is variable, the higher values being reached at the periphery where a crown of droplets is splinkled upward and laterally.

The photograpies made by Mutchler (1967), De Ploey and Savat (1968), Gadhiri and Payne (1979) confirm that the behaviour is the same also when the drop impacts a soil surface.

The shear stress produced by the lateral flow at the solid-liquid contact area can detach soil particles and aggregates (Huang et al., 1983) if the force helding the soil particle to the soil mass is overcome:

$$(1) \qquad F = \tau_d S_t - \tau_s S_o$$

where:
- F = effective force;
- τ_d = average drop shear stress;
- S_t = average cross section opposed to the flow;
- τ_s = average soil shear strength;
- S_o = average surface over which τ_s acts.

The mass of the particles of diameter ranging between ϕ and $\phi + d\phi$, detached per unit of the drop mass, can be supposed directly proportional to the ratio between the effective force and the resistive force:

$$(2) \qquad \frac{dw(\phi)}{m} = k \left(\frac{S_t}{S_o} \frac{\tau_d}{\tau_s} - 1 \right) \psi(\phi)\, d\phi$$

where
- w = mass of the detached soil;
- m = mass of the drop;
- k = constant;
- $\psi(\phi)$ = grain size - stable aggregate distribution by weigth ($\int \psi(\phi)\, d\phi = 1$).

Integrating eqn(2) with respect to ϕ yields:

$$(3) \qquad \frac{w}{m} = \int_{\phi} k\left(\frac{\tau_d}{\tau_s}\,\frac{S_t}{S_o} - 1.\right)\psi(\phi)\,d\phi$$

Eqn(3) is not yet complete as other factors affect raindrop detachment. Actually when a water layer develops at the soil surface the raindrop has to pass trough it before hitting the soil; also the radial flow is going to meet a different resistence to its motion. Consequentely drop shear stresses are going to change.

Some authors (Palmer, 1963; Mutchler and Young, 1975) observed an initial increase in the detachment rate followed by a decrease as the depth (h) of the water film was increasing. Others (Gadhiri and Payne, 1979; Moss et al., 1979; De Ploey, 1980; Poesen, 1981; Poesen and Sawat, 1981) found out only a continuous decrease .

If we suppose that the rate of decrease of the force exerted over a soil particle is proportional to the force itself, an exponential decrease of the active force is obtained-in agreement with the findings by Ghadiri and Payne(1979):

$$(4) \qquad \tau_d\, S_t = \tau_{d_o}\, S_{t_o}\, e^{-bh}$$

where $\tau_{d_o} S_{t_o}$ = active force at $h = 0$.

Eqn(4) cannot be subsituted into eqn(3) without some additional consideration. The cross section S_t depends on the particle size and on the depth of the radial flow. In fact there are two possible situations: the particle partially emerges over the flow or it is completely submerged:

$$(5) \qquad S_t = \begin{cases} \left(\frac{\pi}{8} - \frac{\alpha}{4}\right)\phi^2 - \frac{\phi t}{2}\sin\frac{\alpha}{2}, & t < \phi/2 \\ \frac{\pi}{8}\phi^2, & t \geq \phi/2 \end{cases}$$

where t = average depth of the radial flow;
$\alpha = \cos^{-1}(2t/\phi)$.

As t can be affected by the depth of the flow the integral on ϕ should be splitted into two integrals:

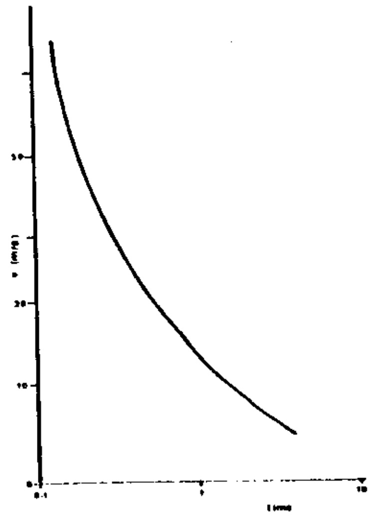

Fig1: Lateral flow velocity Vs time (millisecond) after Engel (1955).

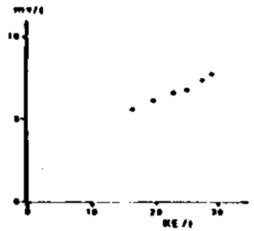

Fig2: Relationship between rain momentum and kinetic energy calculated on natural rain (Zanchi and Torri, 1980); both in S.I. units per unit of rain intensity (mm/h).

$$(6)\qquad \frac{w}{m} = \int_{\frac{\phi}{2} \le t(h)} \frac{dw}{d\phi}\frac{1}{m}\, d\phi + \int_{t < \frac{\phi}{2}} \frac{dw}{d\phi}\frac{1}{m}\, d\phi$$

This equation informs us that rain detachment power depends on the drop shear stress and mass. Superficial runoff intervenes through a shielding effect; as a consequence rain intensity, slope angle and slope length and all the soil characteristics affecting infiltration and superficial roughness influence soil detachment in the interrill areas. Moreover soil characteristics directly intervene through soil shear strength and grain-size/stable aggregate distribution.

Estimate of the drop shear stress

Engel (1955) showed that the initial velocity (v_{fi}) of the radial flow produced by an impinging drop is linked to the impact velocity (v) of the drop by the following relation:

$$(7)\qquad v_{fi} = (0.4\, C\, v)^{1/2}$$

where C = velocity of sound in water.

As the drag force exerted by a flow over a particle is proportional to the square of the flow velocity then it follows:

$$(8)\qquad \tau_d = c_o v$$

where c_o = constant.

Introducing (8) into (6) and rearranging it follows:

$$(9)\qquad w = c_o m v \left[\int_{\frac{\phi}{2} \le t(h)} e^{-bh} \frac{s_t}{s_o} \frac{1}{\tau_s} \psi(\phi)\, d\phi - \int_{\frac{\phi}{2} > t(h)} e^{-bh} \frac{s_t}{s_o} \psi(\phi)\, d\phi \right] - m$$

Adding all over the contributions of each drop composing a rain of a given intensity I eqn(9) can be rewritten as follows:

$$(10)\qquad w = I q c_o \left[\int_{\phi/2 \le t(h)} e^{-bh} \frac{s_t}{s_o} \frac{1}{\tau_s} \psi(\phi)\, d\phi + \int_{t(h) < \frac{\phi}{2}} e^{-bh} \frac{s_t}{s_o} \psi(\phi)\, d\phi \right] - I$$

where q = momentum per unit of rain intensity.

Looking through the literature momentum has not been used in order to forecast soil loss while rain kinetic energy has been widely used. This fact can be explained fairly easily if we consider that momentum and kinetic energy of rain are colinear over a wide range of rain intensity(Fig.2) and that statistics has been widely used in order to process experimental data, often misusing and abusing of it.

Displacement of the soil particles

Let us consider a horizontal soil surface. A drop falling vertically on it splashes particles at different distances from the impact area. Savat and Poesen (1981) proposed the following relationships:

$$(11)\qquad w = w_o\, e^{-\frac{r}{\bar{r}}}$$

where w_o = amount of material detached at $r = 0$;
r = distance from the impact area;
$\bar{r}$ = mean jump length by weight.

A possible explanation of the observed behavior will be proposed in the following part of this paragraph.

The distance at which a particle is splashed is linked to the initial speed at which the particle has been ejected and to the angle α of ejection (between the jump trajectory and a horizontal plan) by the following relation (derived from ballistics under the hypothesis of negligible air friction):

$$(12)\qquad r = \frac{v_o^2 \sin\alpha}{g}$$

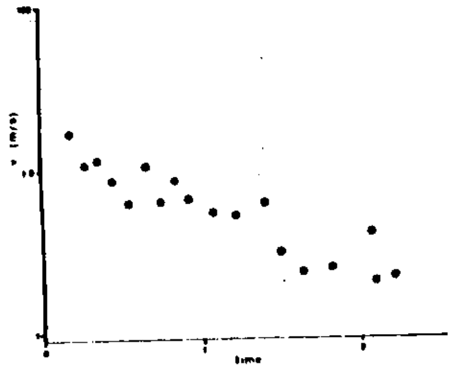

Fig3: Velocity at the periphery of the lateral flow Vs time (milli second) after Engel (1955).

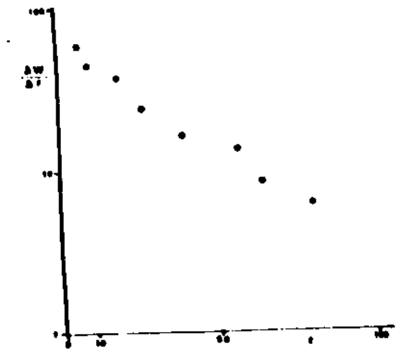

Fig4: Exponential decrease of the amount of splashed material (arbitrary units).

where v_0 = initial velocity;
g = acceleration of gravity.

In order to estimate the initial speed let us consider the equation of motion of a particle under the effect of the drag force exerted by the radial flow of the impinging drop:

$$(13) \qquad m\frac{dv_s}{dt} \doteq a\,(v_f - v_s)^2, \qquad a(v_f - v_s)^2 > S_0\,\tau_t$$

where v_s =soil particle velocity;
m =soil particle mass:
a =constant.

As the drag force works only during a very small interval of time v_s cannot reach a value near v_f so that

$$(14) \qquad v_f - v_s \sim v_s$$

Introducing eqn(14) into eqn(15) it yields:

$$(15) \qquad m\frac{dv_s}{dt} \simeq a\,v_f^2$$

In order to calculate v_f data collected by Engel (1955) can be used. In Table 1 of the quoted paper Engel reproduced the values of the radius of the radial flow versus time. It is then possible to calculate the velocity of advancement of the external perimeter of the flow. Plotting those velocities versus the time an exponential decrease is recognizable (Fig.3). Data by Ghadiri and Payne (1975) seem to confirm the trend.

Using an exponential for v_s , introducing it in eqn(15) and integrating with respect to time it follows:

$$(16) \qquad v_s = a_1 \int_{\Delta t} e^{-2kt}\,dt$$

where a_1, k = constants.

Substituting (16) into (12) it follows:

$$(17) \qquad r = \frac{a_i^2}{g}\left(\int_{\Delta t} e^{-kt}\, dt\right)^2 \sin\alpha$$

Eqn(17) enables us to compute distances following the velocity distribution during the impact.

In order to have an estimate of the amount of soil splashed at different distances the following procedure has been used: the amount of soil splashed with an initial speed between $v_s(t_1)$ and $v_s(t_2)$ has been considered proportional to the area of the corona of radii $d(t_1)$ and $d(t_2)$ which was explored by those velocities. Consequentely the amount of soil jumping between $r(t_1)$ and $r(t_2)$ can be estimated as follows:

$$(18) \qquad \frac{\Delta w}{\Delta r} \propto \frac{d^2(t_1) - d^2(t_2)}{r(t_1) - r(t_2)}$$

The data produced by Engel were used in order to calculate v_f, d, v_s, r and w. Plotting the data generated through eqn(18) versus the data generated through eqn(17) the exponential decrease shown in Fig.4 has been obtained in agreement with the observed behaviour.

Conclusion

The model that has been here proposed explains fairly well some experimental data which were not yet understood. Following this positive result the model can be considered a good approximation of the processes involved during drop impact.

The model obviously need further improvements in order to obtain a set of parameters to be used for interrill detachment and soil loss.

References

Al Durrah,M.M., Bradford J.M.(1982) The mechanics of rainsplash on soil surfaces. Soil Sci.Soc.Am.J. 46,1086-1090.

De Ploey,J. (1980) Crusting and time-dependent rainwash mechanisms on loamy soils. Proc. Conservation '80, Int.Conf. Soil Conservation, Bedford (Silsoe, U.K.),1980,139-152.

De Ploey,J. and Savat,J. (1968) Contribution à l'etude de l'erosion par le splash. Zeitschrift für Geomorfologie, 2,174-193.

Ellison,W.D. (1947) Soil erosion studies.Agricultural Engineering, 28.

Engel,O.G. (1955) Waterdrop collisions with solid surfaces. Journal of research of the National Bureau of Standards,54, 5,281-298,res.paper 2591.

Ghadiri,H. and Payne, D. (1977) Raindrop impact stress and the breakdown of soil crumbs. J. of Soil Science, 28, 247-258.

Ghadiri,H. and Payne, D. (1979) Raindrop impact and soil splash. Soil Physical Properties and Crop Production in the Tropics. Ed. Lal,R., Greenland, D.J., Wiley, 95-104.

Harlow,F.H. and Shannon, J.P. (1967) The splash of a liquid drop. J.of Appl.Phys.,38,10,3855-3866.

Huang,F.H.,Bradford,J.M.,Cushman,J.H. (1983) A numerical study of raindrop impact phoenomena: the elastic deformation case. Soil Sci. Soc. Am. J.,47,855-861.

Mazurak,A.P.and Mosher,P.N. (1968) Detachment of soil particles in simulated rainfall.Soil Sci.Soc.Am.Proc., 32,716-719.

Mihara,Y. (1951) Raindrop and soil erosion.Bulletin of the National Institute of Agricultural Sciences,A,1,1-51.

Moss,A.J.,Walker,P.H. and Hutka,J. (1979) Raindrop-stimulated transport in shallow water flow: an experimental study. Sedimentary Geology, 22,165-184.

Mutchler, C.K. (1975) Parameters for describing raindrop splash. Journal of Soil and Water Conservation, 22,91-94.

Mutchler,C.K. and Young,A. (1975) Soil detachment by raindrops. Present and prospective Technology for Predicting Sediment Yields and Sources, Proc. of the Sediment Yield Workshop,Oxford Mississippi, USDA-ARS-40,113-117.

Palmer, R.S. (1963) The influence of a thin water layer on waterdrop impact forces. I.A.H.S. publ.65, 141-148.

Poesen, J. (1981) Rainwash experiments on the erodibility of loose sediments. Earth Surface Processes, Poesen,J. and Savat, J. (1981) Detachment and transportation of loose sediments by raindrop splash: part II - Detachability and transportability measurements. Catena,8,19-41.

Savat,J. and Poesen,J. (1981) Detachment and transportation of loose sediments by raindrop splash: part I. Catena, 8,1-17.

Torri, D. and Sfalanga, M. (in press) Some aspects of soil erosion modelling. Workshop Prediction of Agricultural Non-point source pollution: model selection and application, Venezia (Italy),June 11-15th,1984.

Wischmeier, W.H. and Smith,D.D. (1958) Rainfall and its relationship to soil loss. Trans. Am. Geoph. Un.,39,2,285-291.

Zanchi, C. and Torri,D. (1980) Evaluation of rainfall energy in Central Italy. Assessment of Erosion, Ed. DeBoodt,M. Gabriels,D., Wiley,133-142.