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Using Digital Elevation Models and Image Processing to Follow Clod Evolution under Rainfall

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Abstract

Soil surface roughness plays an important role in determining how the soil will interact with its environment. Analysis of soil roughness at small scale matters both for preparation of soil in order to allow for plant emergence, and for decisions to favor soil conservation. Indeed, soil roughness may be shaped by tillage operations and then changes with time, under rainfall impact. Soil surface roughness is usually estimated by various indices, computed on measured profiles or images of elevations. Another approach is focusing on soil cloddiness, either by sieving or by image segmentation. The objective of this study is to monitor the evolution of clods under rainfall with Digital Elevation Model (DEM) recording and image processing.

We prepared two trays of artificial soil surfaces in the laboratory with silt loam soil topped by pre-sieved clods. They were designed to look like a seedbed. Soil surface evolution was achieved by subjecting the trays to controlled artificial rainfalls, and DEM were recorded at each stage. We performed automatic clod segmentation and measurement of the volume of individual clods. Under rainfall impact, we could see smoothing and leveling of clods until disappearance of the smaller ones. We focused on the larger clods greater than 12 mm in diameter that remained till the last rainfall. They showed swelling (volume increase) followed by erosion (volume decrease), these two phenomena being size dependent. Clod volume decrease was modeled by an exponential function. Now, the slope and the amplitude parameters decreased according to a power law, as a function of mean volume of clods.

Monitoring of clod volume with cumulated precipitation with the help of DEM measurements is able to differentiate the dynamics of clod depending on their size. This technique improves the usual roughness description and allows for a better understanding of the processes.

Keywords: Soil surface roughness; Digital elevation model; Monitoring; Cloddiness; Modeling; Rainfall impact; Erosion

Introduction

The role of surface roughness for soil interactions with its environment, and soil properties is commonly acknowledged. Indeed, soil surface has a large impact on geomorphologic processes, especially at millimeter scale. The soil surface roughness is a result of soil and water mechanisms interaction and feedback. It is also created by tillage practices. Indeed, soil roughness may be shaped by tillage operations and then changes with time, under rainfall impact [1,2]. Analysis of soil roughness matters both for preparation of soil in order to allow for plant emergence [3], and for decisions to favor soil conservation. Some studies have focused on soil water storage [4-6], soil crust formation [7,8], soil detachment by rain splash [9] or soil erosion [10-14].

Soil surface roughness is usually estimated by various indices, such as the standard deviation of elevations. These indices are computed on measured profiles or images of elevations [13-17]. In this approach, the soil surface roughness is characterized on the whole. Another approach is focusing on soil cloddiness, either by sieving or by image segmentation [5,6,18-22]. The recent development of photogrammetry and laser scanners affords to retrieve the digital elevation model (DEM) of the soil surface at millimeter accuracy [13,16]. With image processing, DEMs allow for the monitoring and modeling of soil surface local irregularities such as clods. They are suitable to survey the soil roughness both on the whole and more locally [17,19-21,23].

The objective of this study is to monitor the evolution of clods under rainfall with DEM recording and image processing. Controlled soil surfaces made in the laboratory will be subjected to rainfall events performed by a rainfall simulator. The dynamics of clod will be differentiated depending on their size. In particular, the parameters of exponential decrease of volume as a function of cumulated precipitation will be modelled according to the initial volume of clods. Then the laws followed by these parameters will be included in the exponential model so as to propose an estimation of the clod volume at a given cumulated precipitation as a function of the volume occupied by the clod at an earlier stage.

Material and Methods

We prepared two trays of 50 cm by 50 cm with loose soil of silt loam (11% clay, 60% silt, 29% sand) topped by pre-sieved clods collected in the field. The clods were air-dried and of different sizes, to represent a wide range of diameters (Table 1). They were set upon a nearly horizontal surface of soil, by hand, randomly, in order to look like a seedbed except for the rows (Figure 1). The resulting soil surfaces show an isotropic property. The first tray and the second tray have a density

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of 530 and 800 clods per m^2 respectively and standard deviations of elevations of 10.5 mm and 9 mm respectively. Let us notice that the clods stand out well from the soil support and are isolated on tray 1 and more gathered on tray 2. The clods of tray 2 are also generally smaller than those of tray 1.

Diameters	Min (mm)	Max (mm)	Median (mm)
Tray 1	4	76	18
Tray 2	5	40	14

Table 1: Range of clods on soil surfaces.

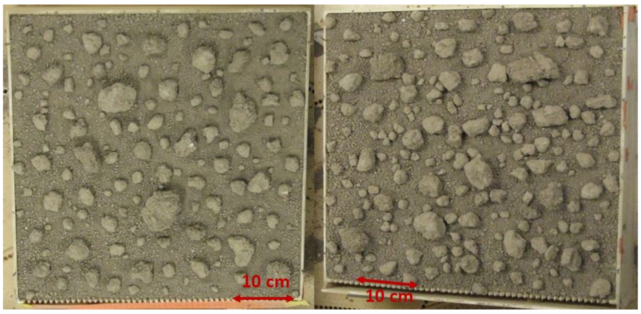

Figure 1: Controlled soil surfaces made in the laboratory, a) tray 1 b) tray 2.

Soil surface evolution was achieved by subjecting the trays to five controlled rainfalls, using a laboratory rainfall simulator equipped with oscillating nozzles (Figure 2). The experiment was done at INRA laboratory of soil science, in Orleans (France). The rainfall simulator was placed 6 m above the trays and produced raindrops of 1.5 mm median diameter. The rainfall intensity was adjusted by the number of sweeps per minute. The first set of rainfalls had an intensity of 33 mm h^{-1} and duration of 60 minutes. Then, in order to speed up clod erosion, the intensity was set to a higher value of 42 mm h^{-1}.

The three last rainfalls had a variable duration from 38 minutes to 90 minutes. They were stopped when the soil surfaces seemed to have evolved visually. The rainfall impact made the clods smoothed and flattened, and the smaller ones disappeared. Where the clods were close together on tray 2, we also observed the formation of blocks of clods. We shall consider only the isolated clods in this study. It is done to perform a clod by clod volume variation study, which requires stable clods and not varying blocks of clods according to merging and splitting. The total amount of cumulated rainfall was near 200 mm. The trays had a permeable bottom to allow for water percolation. They were also set at a 5% slope for water runoff.

The DEM of each stage of the soil surfaces was recorded by laser scanner with accuracies of 0.5 mm in x and y axes, and 1 mm in z axis. The surface geometry was measured along a profile in the x-z plane, with the help of lasers producing a line on the soil surface and a CCD camera set at an angle. Then, a stepper motor allowed to move the lasers and camera assembly along the x-axis to retrieve the whole surface geometry (Figure 3). More details on this process can be found in [23].

Figure 2: Rainfall simulator.

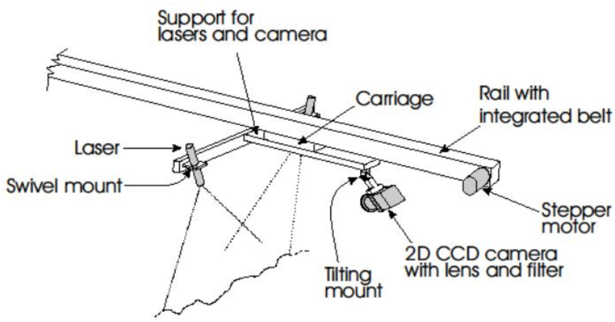

Figure 3: Schematic of laser scanner used to measure DEMs of soil surfaces.

The clod contours were automatically segmented by thresholding the elevations above 1 mm. The reference level of elevations is the soil support of the clods. A program was written in Matlab software for this purpose [23]. Then the volume of each clod was computed from the DEM, for the selected data points belonging to the clod. It was normalized by the volume occupied by the clod at initial stage. Let us denote $V_i(j)$ the volume occupied by clod i at the end of rainfall n°j, denoted stage j, where $j \in \{1;2;3;4;5\}$ for the 5 rainfall events. The initial stage is referenced as j=0. We then consider the average of the normalized clod volumes among a subset of N clods: $\overline{V_n}(j) = \frac{1}{N}\sum_i \frac{V_i(j)}{V_i(0)}$

The average of the normalized volumes is then studied as a function of cumulated precipitation P. The decreasing part of V_n from the end of rainfall n°2 to the end of rainfall n°5 is modelled by: $\overline{V_n}(j) = ae^{-bP(j)}$

with $j \in \{2;3;4;5\}$. Let us notice that modeling of $\overline{V_n}$ is performed at constant rainfall intensity equal to 42 mm.h-1.In order to prevent bias when averaging the clod volumes and modeling the decreasing part of $\overline{V_n}$, only the clods remaining after rainfall n°4 were taken into account to present the findings of this study. As an example, the Figure 4 shows the evolution of the clod contours from initial to final stage. We can see that a few clods have disappeared among the smallest and that a big clod have broken up. The clods have swelled during the first rainfall event and still have an enlarged perimeter at final stage. Let us notice that the swelling phenomenon is not isotropic. This was due to the inclination of the trays at 5% slope in order to allow for water outflow. The DEMs were detrended before segmentation of clods. The dynamic of elevations is represented by the colormap on this top view of the soil surface. The dimensions of the surface were reduced in the x and y axis, in order to allow for a clod by clod survey.

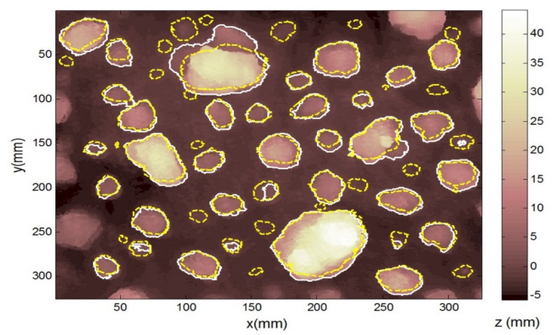

Figure 4: Clod contours on tray 1 at initial stage (in yellow dotted line) and at final stage (in white and solid line). The DEM is that of the final stage.

There remained a total of 58 single isolated clods from both trays. They were all greater than 1.2 cm in diameter. We gathered them evenly into five subsets of increasing initial clod volume to study a clod size influence upon the erosion of clods by rainfall impact. Each subset contained 11 or 12 clods. The characteristics of the clod equivalent diameters (for a half-sphere approximation) among the subsets are shown in Figure 5. The standard deviation among the subset of the largest clods is more elevated than the others because the large clods are scarce on both trays.

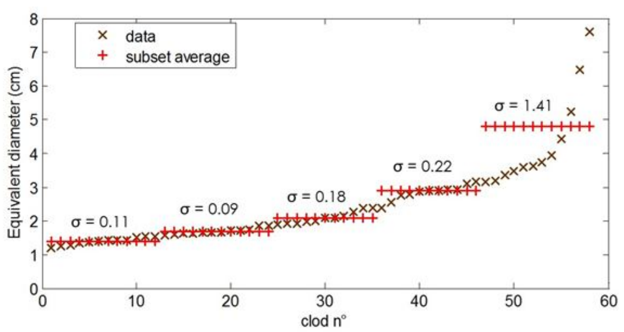

Figure 5: Equivalent diameters of the clods among the 5 subsets of the study. The standard deviation of diameters among each subset is written above the subset average and denoted .

In order to check the goodness of fits, we used the reliability factor introduced in [23]. This reliability factor corresponds to a normalized error and is defined as:

$$\varepsilon = \sqrt{\frac{\sum\left(s_i - \hat{s}_i\right)^2}{s_i^{\,2}}}$$

where s_i denote the ith data and the estimate of the ith data. The goodness of fit is even better when ε is small.

Results and Discussion

Figure 6 illustrates the average of the normalized clod volumes among the five subsets of clod size, as a function of cumulated precipitation. The smallest clods are represented in green, the next subsets respectively in cyan, blue, magenta and the largest clods in red. The clod initial volume ranges, in average, from 0.7 cm^3 to 28.3 cm^3. The reliability factors of the exponential modeling are less than 2% among all subsets.

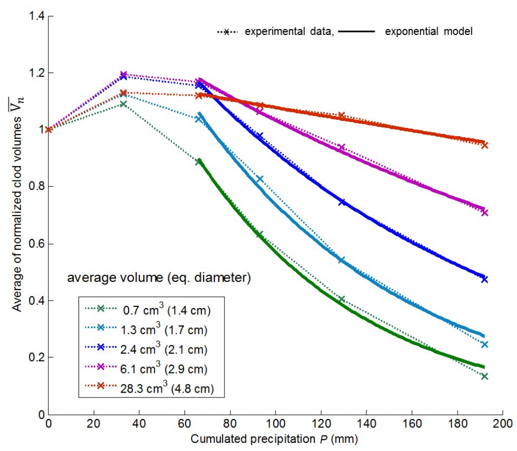

Figure 6: Evolution of clod volumes, in average, under rainfall impact and according to clod size. The average volume of clods among each subset is indicated at initial stage, with equivalent diameter in parenthesis.

We can see an increase of $\overline{V_n}$ during the first rainfall, which reflects a swelling phenomenon.

This swelling is increasing with clod size until 2.1 cm in diameter and is then saturating. For the largest clods, greater than 4.8 cm in diameter, the swelling is reduced and comparable to that of the clods around 1.7 cm in diameter.

Therefore, the largest clods might be more compact and less subjected to volume variations than the other clods.

This can be seen also on the decreasing part of $\overline{V_n}$, which is nearly linear for this category of clods. The decrease in volume is faster and faster as the size of clods decreases. It goes together with the value of b in the exponential model (Equation 2). Indeed, b is very small for large clods (0.0013) and increases as the size of clods decreases, with a maximum of 0.0134 for the smallest clods (Table 2). This shows that the small clods are more sensitive to breakdown by raindrop impact than the larger clods. Other authors [24] have already noticed that clod size is a major factor influencing soil detachment under rainfall. A possible explanation for this might be the earlier clod saturation for small clods. They are also more friable as the soil was tilled finer to produce them.

$\bar{V}(0)$ cm	a	b
0.73	2.175	0.0134
1.254	2.151	0.0107
2.396	1.852	0.0070
6.125	1.525	0.0039
28.274	1.227	0.0013

Table 2: Parameters of exponential model among the subsets, according to clod subset average volume at initial stage.

The parameter b of exponential decrease of clod volume under rainfall was further studied as a function of the average volume of clod subset at initial stage. Figure 7 represents the logarithm of b as a function of the logarithm of clod subset average volume at initial stage $\bar{V}(0)$. The linear fit has a reliability factor of 1%. It leads us to model b as:$b = k\bar{V}(0)^{-\gamma}$

With k=0.012 and γ=0.65. Thus parameter b clearly shows a size dependency of the erosion of clods under rainfall impact. With a lower value of b, the large clods resist better than the smaller ones. The power law shows that this resistance increases with clod size but tends to steady as the size of clods increases.

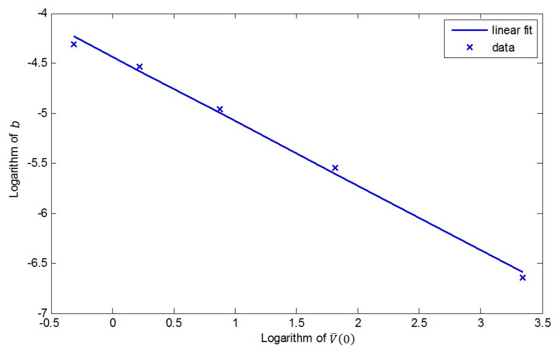

Figure 7: Size dependency of parameter b.

The parameter a of equation 2 was also studied as a function of $\bar{V}(0)$. Its evolution shows a discrepancy for the small values of $\bar{V}(0)$ (Table 2). Therefore, this was circumvented by representing $a\bar{V}(0)$as a function of $\bar{V}(0)$ in logarithmic scale (Figure 8). The reliability factor of the linear fit is 1% again. We thus model a as:$a = k\bar{V}(0)^{\gamma - 1}$

with k=2.13 and γ=0.83. This confirms the size dependency of the erosion of clods under rainfall impact. Whereas parameter b is a slope parameter, parameter a is an amplitude parameter. It enables us to introduce a parameterization of the individual volume of clods $V_i(j)$as a function of $V_i(0)$ by combining equations 4 and 5 with equation 2, written for individual volumes instead of average volume:

$$V_i(j) = 2.13V_i(0)^{0.83}e^{-0.012V_i(0)^{-0.65}P(j)}$$

This equation is valid from the end of rainfall n°2, i.e. for j≥2, where $V_i(j)$is maximum. It can be normalized as:

$$\frac{V_i(j)}{V_i(2)} = e^{-0.012V_i(0)^{-0.65}(P(j) - P(2))}$$

It was applied to estimate $V_i(5)$as a function of $V_i(2)$for the whole set of 58 clods. Let us denote $\widehat{V_i}(5)$ the estimate of $V_i(5)$according to eq. 7. The linear regression of $\widehat{V_i}(5)$as a function of $V_i(5)$has a slope of 0.96, an intercept of 0.026 and a coefficient of determination R2=99%. That is to say that $\widehat{V_i}(5)$is highly correlated to $V_i(5)$the slope is close to the expected value of 1 and the intercept is close to expected value of 0. However, the reliability factor of estimation is 9.3%, which shows that the model giving $V_i(j)$as a function of an earlier stage undergoes over- and under-estimations. It will need further deepening.

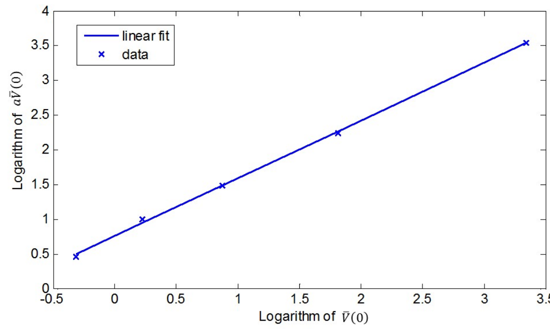

Figure 8: Size dependency of parameter $a\bar{V}(0)$.

Conclusion

DEM recording and image processing enabled to monitor the erosion of clods under rainfall, with a quantified clod by clod survey. The clods were automatically segmented and the volume occupied by each clod was computed for the different stages of the soil surface. This study highlights the size dependency of the clod volume variation as a function of cumulated precipitation. This might be due to clod saturation occurring earlier for the smaller clods, allowing for a faster soil detachment as was already noticed by other authors. A parameterization of the clod volume decrease under rainfall, as a function of clod size at an earlier stage could be introduced. It gives satisfactory results on average but undergoes individual errors. Therefore, this parameterization will need further deepening before being implemented in surface generation and evolution programs. Future work will have to make the link with weathering models and will tackle a more in-depth analysis of the roughness of natural soil surfaces.

The better resistance of large clods under rainfall impact raises again the compromise between tillage requirements for plant emergence and decisions for soil conservation. This study shows the behavior of individual and isolated clods under controlled rainfall impact. It would need to be completed by a study of the behavior of clustered clods under rainfall impact and also by studies in natural field conditions. It then could be used to estimate the expected surface roughness evolution as a function of expected cumulated precipitation and clod initial volumes. This knowledge could then enlighten the decisions for agriculture and soil management.

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