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Experimental study and development of empirical model for assessing the risk of water erosion of bare soil, using measurable influence parameters

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Abstract

This work concerns the development of an empirical model for rapid assessment of the risk of erosion caused by rain or adverse weather, on bare ground. This model is built on influencing parameters such as rain intensity, slope, and cohesion of soil particles. To develop this model, the mini rain simulator produced by [1] was used. This simulator made it possible to multiply rain events by simulation, to assess the corresponding soil losses, and to draw up a table of the influencing parameters of erosion. A controlled compaction press was also used to materialize soil cohesion during data collection. The data collected were used to plot curves of average erosion evolution according to each parameter and to establish a correlation between the eroded soil masses and the different factors. The results obtained from the new MFEPE model (Exponential Erosion Potential Function Model) show that it is 78% compatible with the experimental results. The MFEPE model built here from sandy clay soils, then presents itself as a rapid means of assessing the risk of erosion of bare soils and gives the possiblilty to make extrapolations in situ. An application can be made in the dimensioning of earthen structures in the field of civil engineering, when we want to assess the risks of soil loss before investments.

Keywords: Compaction, Mini rain simulator, Soil cohesion, Slope, Water erosion

Introduction

Water erosion is the cause of a lot of damage observable worldwide [2], [3]. In Africa, in particular in Algeria [4]–[7], in Ivory Coast [8]–[11] and particularly in Cameroon [12]–[14], research is very extensive on the study of erosion, due to the multiple consequences of the phenomenon. This tearing phenomenon of particles is sometimes responsible for the destruction of earth structures, the destruction of roads [3], [15], [16], bridges and other constructions. The silting up of dams is also a consequence of erosion according to the studies of [17]. The foundations of certain habitats are sometimes exposed by the simultaneous effect of the drop of rainwater drops and the runoff of accumulated water, which develop a kinetic energy favoring the removal of particles from the soil in the passage. These uprooted particles are then deposited in the bottom, thus contributing to sedimentation due to insufficient mobilization energy. The Wouri basin is the seat of a cycle which goes from the erosion of the banks and the slopes, then the transport of particles, passing by the sedimentation and the remobilization of sediments in the river, one of the consequences of which is l 'increased flooding due to the raising of the river bed and the clogging of pipes. These floods in turn weaken the cohesion of soil particles, which promotes erosion by runoff and the cycle begins again. In view of the consequences caused by erosion, the study and evaluation of the parameters influencing this phenomenon is the subject of general interest [18]–[24]. Several study methods can be used. According to the procedures, a distinction is made between experimental studies, following the example of the work of Lague et al. [25] and Leguedois [26]; in particular those Mbiakouo [1], [27] and also modeling methods, like the empirical model USLE [28] and its derivatives [29]–[31] which are better adapted to agricultural soils, or to well-defined regions defined. There are also numerical models for assessing erosion [32]–[36]. All of these models use a very large amount of measurable data in the field, which causes a real problem when a data is not accessible. We are interested in this work in a simple application modeling that will be used to assess the risk of erosion by extrapolation, from 03 essential parameters which are the intensity of the rain, the compaction of the soil and the slope of the soil.

Materials and Method

Materials

The experimental setup mainly includes two pieces of equipment: a mini rain simulator shown in Figure 1 and a laboratory press (Figure 2).

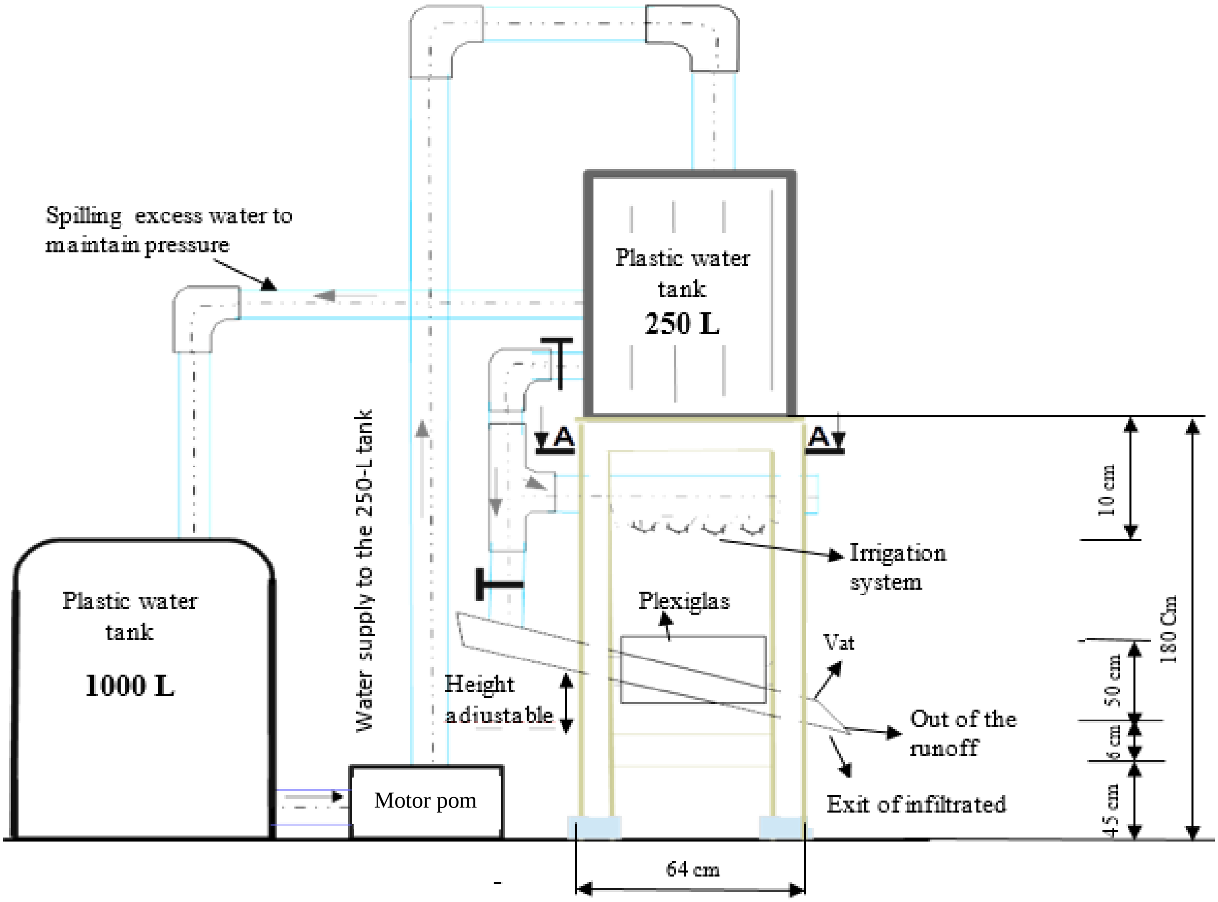


Fig. 1: diagram of the mini-rain simulator initially produced by [1], and improved here by adding a plexiglass fence to recover the erosion of the splash.

The mini rain simulator includes a soil sample holder, whose slope is adjustable. A 1000 liter tank constitutes the source of the water used. A 250 liter tank placed at 1.5 meters above the tank, it allows to adjust the pressure at the sprinkler system, it is a pressurization tank. A motor pump takes the water from the tank of 1000 liter and delivers it to the tank of 250 liter. The simulator itself is a set of pipes and valves as shown in Figure 1 and allows us to vary the rainfall intensity.

The second material used is a variable compression press whose pressure varies from 0 to 20N /mm^2. The soil sample submitted to this press is compacted at the desired pressure using a mold.

The main material is sandy clay soil composed of 30 to 40 percent clay and fine sand. The compaction of a sample of this soil makes it possible to study in the laboratory the influence of the cohesion of the soil particles.

Compaction on the press is done using a wooden mold in the shape of a parallelepiped. This makes it possible to obtain briquettes with a thickness of 0.15 m. constituting the soil sample see Figure 3.

The soil used in the experiment was collected from the Tongo Bassa Basin in Douala V. This soil taken from depths ranging from 1.00m to 2.75m has the following geotechnical characteristics: Water content (W%) ranges from 17.6 to 20.8 with an average of 20.8; Specific weight (KN /m^3) ranges from 25.3 to 27.3 with an average of 26.3; The pre-consolidation constraint (KPa) ranges from 34 to 81 with an average of 50; The empty index e (%) ranges from 0.824 to 1.04 with an average value of 0.958.

Several soil samples are obtained by compaction at different pressures (0.5 N/mm^2 - 0.7 N/ mm^2 - 0.9 N / mm^2 - 1 N/mm^2). For each series of tests, 4 blocks of the soil sample compressed at the same intensity, are placed in the tank, thus corresponding to the surface of the tank. Between the contact surfaces of the blocks, the floor has a scratched appearance. To ensure the continuity of the ground, a tiny amount of moistened earth is inserted into it, then the whole groomed and dried. The discontinuity is therefore neglected by this procedure. We can only consider the presence of micro-accidents certain of real ground.

Method

The mini rain simulator allows us to take into account: the rainfall of a given region and the support of the sample whose position varies according to the desired inclination, allows us to assess the influence of the slope. The press allows to take into account the influence of the cohesion of soil particles to the shear resistance by water. The influence of each parameter is measured experimentally, by varying it, while keeping the others constant. Following this experiment, a graphical analysis allows us to model the erosion potential in the experimental plots by a method of adjustment to the mean of evolution.

The working method is divided into two stages :

- Firstly, an experiment using the rain simulator and blocks of earth taken from the field. The experimental procedures are described in detail in the previous publications of [1], [12]. This step collects a set of information used to develop the MFEPE extrapolation model.
- Secondly, the analysis of the results obtained by simulation will be used as input data in a computer calculation code, for the development of the extrapolation model itself.

Development of MFEPE model

To determine the model function of the erosion potential, the first part consists in taking input data from the experimental results in the form of a table.

The model that we propose to better understand the phenomenon of erosion in our environmental context, is a global empirical model, obtained from graphical and statistical analysis of the average evolution of the results of experimental measurements. The method used is a phenomenological analysis, assisted by linear regression techniques with the help of computerized data analysis tools. The analysis of the graphical representations makes it possible to develop a correlation function between the eroded masses and the parameters of influence of erosion, which are: the slope, the compaction and the intensity of the rain. This model is therefore defined by two procedures:

- An interpolation calculation managed by a digital linear interpolation algorithm.
- A linear extrapolation calculation managed by the MFEPE function.

The MFEPE function will be used to detect areas with high erosion potential using field data representing the variables. It is then a question of determining a function with 3 variables :

$$M = f(p, C_0, I) \tag{1}$$

Where f is the erosion distribution function in Kg/m^2/s, p is the slope in %, C_0 is the cohesion of the soil evaluated by the compaction pressure in N/m^2 and I, the rainfall intensity, in mm/m^2 /year.

The determination of the function f is framed by the following assumptions:

1- For a very large cohesion, tending towards infinity as is the case for plastics, well calibrated beams, water erosion is nonexistent. This is translated by:

$$\lim_{C_0 \to +\infty} f(p, C_0, I) = 0 \tag{2}$$

2- In the absence of precipitation, water erosion is zero. This is explained by :

$$f(p, C_0, 0) = 0 \tag{3}$$

3- The differential of f is total and we can write:

$$df = \frac{\partial f}{\partial p} dp + \frac{\partial f}{\partial C_0} dC_0 + \frac{\partial f}{\partial I} dI \tag{4}$$

According to the experimental measurements we have Table 1 below, grouping experimental measurements on blocks of surface 0.32m2 for a duration of precipitation of 120s.

Graphical analysis of the results and development of the model

We have plotted the curve of the measured masses by varying each parameter in turn, using the function of linear regression techniques.

The observations made are as follows:

• For a sample of soil of given stress, the losses in soil evolve in an increasing way for the values of the slopes increasing; the curves in Figures 4 and 5 below shows the evolution of soil losses as a function of the slopes

These average curves make it possible to conjecture the influence of the slope in the form of an exponential function. Schumm and Hadley [37] in their erosion research also made this observation. According to some researcher for slopes greater than 45% there should be a regression of the curve in the direction of a decrease in mass loss. This is not entirely verified because everything also depends on the length of the slope. This assertion will be verified in our next work. We will limit ourselves in the context of this article to the small slopes which are unanimous. In this case the function of contribution of the slope on the loss of mass can be sought in the exponential form as follows:

$$M = j(C_0, I)(A + B \cdot Exp(b \cdot p)) \tag{5}$$

$j(C_0, I)$ is a function which depends on the rainfall intensity and also the mechanical properties of the soil, here like cohesion. So it takes into account the climate of the basin studied and the topography. The function j has the same dimension as *M*. *A* and *B* are constants.

By keeping the slope and intensity variables constant, we also represented the shape of the curve of evolution of soil losses as a function of the cohesion of the particles.

• For a given slope, the eroded soil losses tend rather to decrease towards the samples of greatest stress; the curve in **Figure 6** and **7** below shows the influence of soil cohesion on the evaluation of water erosion.

By observing the evolution of the average curves which present the influence of the cohesion of particles of the ground, we can notices that for the small slopes, we have an evolution of Gaussian function, but for the big slopes the evolution can be modeled by a function of exponential decay having a small coefficient of relaxation. This correspond well to the behavior of the function exp (-x) when x is very large. The contribution of this cohesion is evolving in the direction of reducing soil losses and by assumption when the cohesion is infinite, there are no losses of soil. We obtain the following form of the model function:

$$M = k(I)(A + B \cdot Exp(b \cdot p)) \cdot Exp(-c \cdot C_0) \tag{6}$$

The constants b and c are necessarily positive. The function k (I) is related to climate, space and time.

For the purpose of this article we have a fixed duration of precipitation per test and also a fixed watering surface.

- For a soil constraint and a given slope, soil losses increase towards the greatest rainfall intensities. Figure 8 and 9 below shows the evolution of the losses of a soil subjected to variable rainfall intensities.

With regard to the average curves of the evolution of eroded masses according to the rainfall intensity parameter, it should be noted that, they have a linear evolution. The physics of the phenomenon requires a shift from function to origin in 0 for *I*=0, which corresponds well to the absence of water erosion due to rains. This function can then be modeled by:

$$M = a \cdot I \cdot (A + B \cdot Exp(b \cdot p)) \cdot Exp(-c \cdot C_0) \quad (7)$$

In this last expression *M* represents the mass lost per unit of surface and per unit of time.

- The constant a allows adjustments to be made in terms of scale. For our calculations we found a = 14.72. It has the dimension of the reverse of length.
- The constant b translates the frequency of the evolution of the slope. Its experimental value is between 0 to 6 for sandy clay soils. We evaluated it at b = 1.57.
- The constant c has the pressure inverse dimension, it makes the term adimensional on exponential, its experimental value for sandy clay soils is between 0.67 and 1.29. We got c = 0.9832
- - A is a constant so the value is between -3.68x106 and 3.68x106. For our calculations A = -0.3312
- B is a dimensionless constant between 0 and 7.9x106. We took B = 0.713.
- The MFEPE erosion risk assessment model is therefore translated by the formula :

Results and Discussions

In this part, we present the overall results of the exponential function of 3D erosion risk model to verify the simultaneous influence of all components**.** Figures 10, 11 and 12 present the comparison between the average evolution of the experimental measurements and the forecasts of the MFEPE model.

function and experimental measurements. We note that the MFEPE model reflects the influence of particle cohesion on erosion reduction. An effective way to control erosion would then be to increase the cohesion of the soil, this is possible by covering it with a cohesive layer, or by strengthening cohesion with plants. The model can then assess the risk of soil loss due to the effect of water erosion, when slope and soil cohesion are known.

The **Figure 11** shows that the MFEPE model and the experimental measurements also agree for the evaluation of the influence of slopes and rainfall intensities. We can see in this figure, the simultaneous influence of the intensity of the rain and the slope of the ground. Water erosion increases as the slope increases and also increases with the intensity of the rain. This model then makes it possible to assess erosion if we know the slope and intensity of rain..

In view of the Figure 12, there is the same overall evolution for the function of the MFEPE model in the sense of experimental measures, i.e. growth according to the increase in intensity and simultaneously, a decrease according to the compacting pressure. Based on the results of the MFEPE model, it is clear that the influences of bare soil erosion are taken into account. The model highlights this influence and can therefore be adapted to the estimation of soil loss and thus to the assessment of the risks of instability of the earth structures.

Conclusion

In this article, we have proposed an empirical model for the rapid assessment of the risk of water erosion of a bare earth surface, using linear regression techniques of the measurements obtained on the rain simulator and by conjecture of the evolution of the phenomenon assisted by software. Indeed, the MFEPE model is a first test, the development of a simple tool for civil engineers, which can be used in the dimensioning of earthen structures. It use requier only the evaluation of the slope by a simple calculation, the evaluation of the compaction by determining the lift index and the evaluation of the intensity of the rain, using the rain gauge. The proposed model is simple and practical because, it allows to calculate the erosion potential using a function with several variables, depending on some topographic, climatic, and time parameters. The model developed is valid for bare soils. It takes into account the slope, the cohesion of soil particles, the rainfall intensity and the duration of the rains. This Model of the exponential function of erosion potential is presented as one of the simplest means of prediction. It can also be adjusted according to the regions, especially when the soil has remarkable heterogeneity.

An assessment of the potential risk of soil loss would allow us to situate ourselves in the possibility of reducing it by modifying the appropriate parameters on the ground, either by applying ingenious techniques, such as leveling, adding a particular soil, compaction and all another practice to reduce the risk of erosion.

Fig. 2: Compacting press

Fig. 2: Soil compressed and left to dry

Table 1: Summary of eroded soil masses (kg) as a function of constraints, rain intensities and slopes for t = 120s and A = 0.32m^2

Slope (%)	compaction pressure (bar)	intensity of rain (mm/s)	experimental masse (kg)
8,75	0,5	0,046875	0,45386
8,75	0,5	0,09375	0,48068
8,75	0,5	0,140625	0,53259
8,75	0,5	0,1875	0,55863
8,75	0,7	0,046875	0,40429
8,75	0,7	0,09375	0,45783
8,75	0,7	0,140625	0,48268
8,75	1	0,046875	0,21209
8,75	1	0,09375	0,27258
8,75	1	0,140625	0,30316
8,75	1	0,1875	0,34963
14,41	0,5	0,046875	0,47807
14,41	0,5	0,09375	0,49056
14,41	0,5	0,140625	0,58515
14,41	0,5	0,1875	0,61129
14,41	0,7	0,046875	0,43094
14,41	0,7	0,09375	0,482
14,41	0,7	0,140625	0,50613
14,41	0,7	0,1875	0,52898
14,41	1	0,046875	0,21334
14,41	1	0,09375	0,27784
14,41	1	0,140625	0,34195
14,41	1	0,1875	0,39402
28,49	0,5	0,046875	0,63142
28,49	0,5	0,09375	0,67379
28,49	0,5	0,140625	0,68945
28,49	0,5	0,1875	0,71586
28,49	0,7	0,046875	0,48987
28,49	0,7	0,09375	0,57651
28,49	0,7	0,140625	0,61242
28,49	0,7	0,1875	0,69068
28,49	1	0,046875	0,26624
28,49	1	0,09375	0,36168
28,49	1	0,140625	0,39721
28,49	1	0,1875	0,45587
36,4	0,5	0,046875	0,81653
36,4	0,5	0,1875	0,93887
36,4	0,5	0,09375	0,87598
36,4	0,5	0,140625	0,89543
36,4	0,7	0,046875	0,58118
36,4	0,7	0,1875	0,79786
36,4	0,7	0,09375	0,67005
36,4	0,7	0,140625	0,71667
36,4	1	0,046875	0,39832
36,4	1	0,1875	0,50613
36,4	1	0,09375	0,4013
36,4	1	0,140625	0,45892

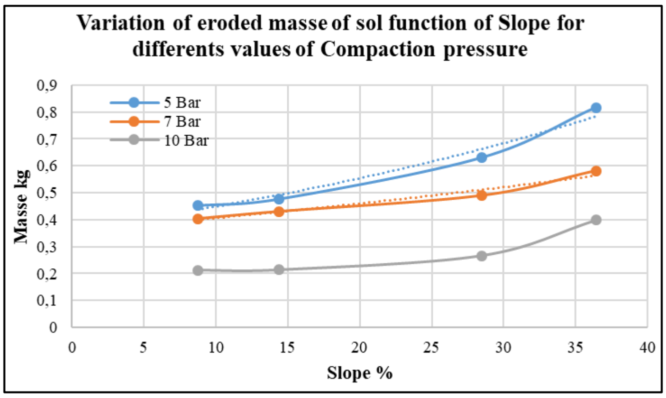
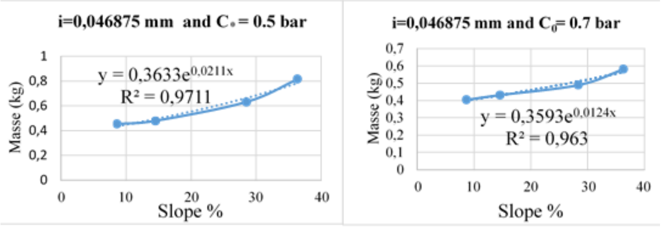


Fig. 3: Influence of slope on soil loss

A detailed analysis of individual curves leads to the curves below



(a) (b)

Fig. 5: Slope correlation function and soil loss

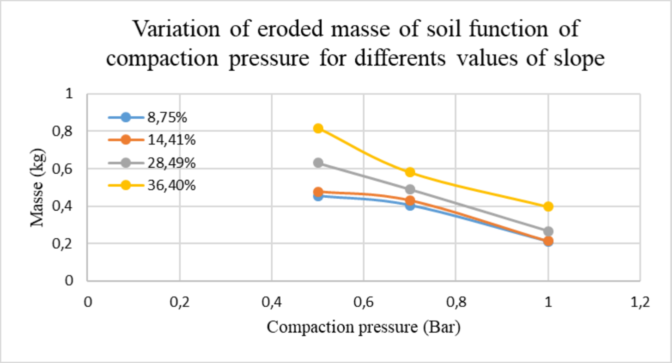
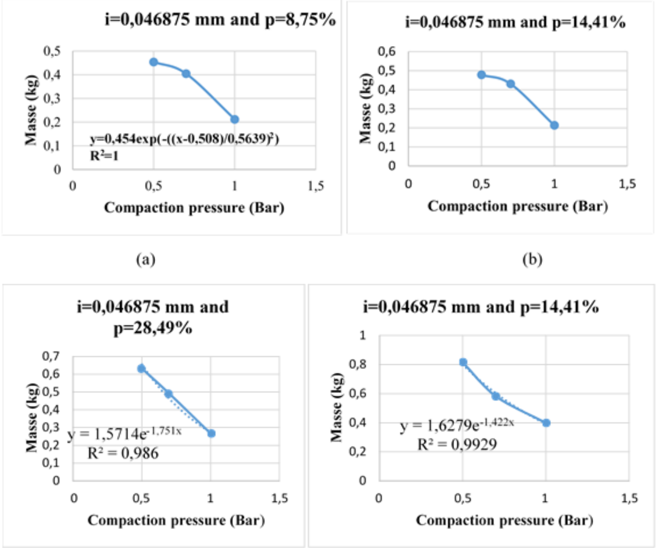


Fig. 6: Average evolution curve of eroded masses based on soil cohesion



(a) (b)

(c) (d)

Fig. 7: Correlation function of compaction and soil loss

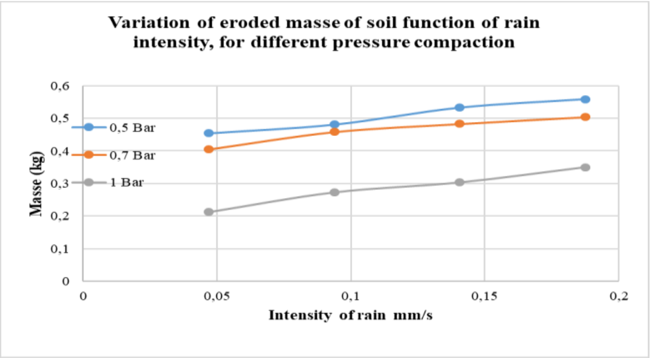
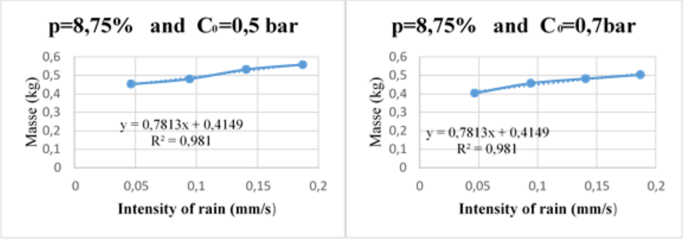


Fig. 8: Average evolution curve of eroded masses based on rainfall intensities.



(a) (b)

Fig. 9: Correlation function of rainfall intensity and soil loss.

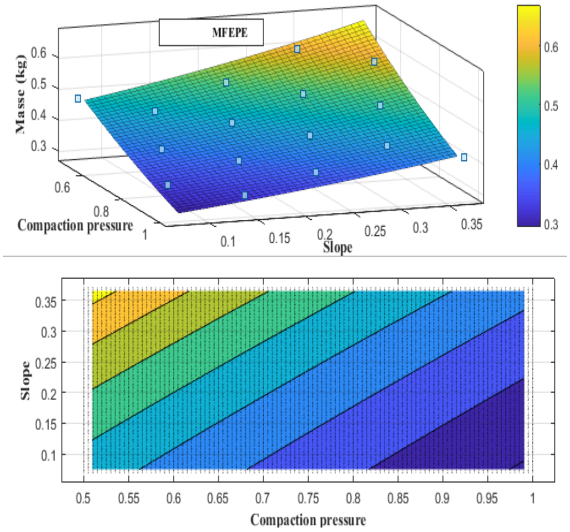


Fig. 10: Surfaces and contours of average evolution of the eroded masses of the MFEPE model at constant rain intensity.

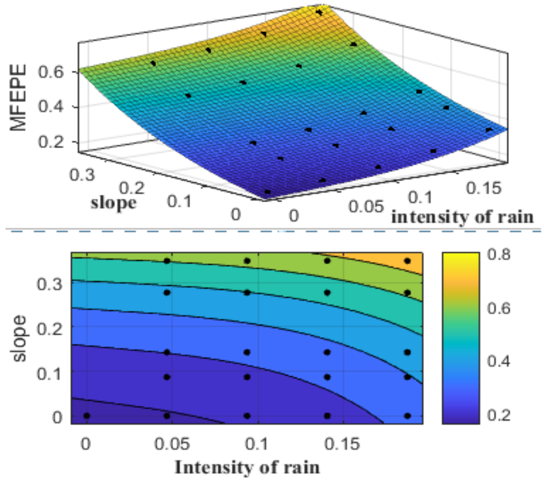


Fig. 11 : Surfaces and contours of the average evolution of the eroded masses of the uniformly cohesive MFEPE model.

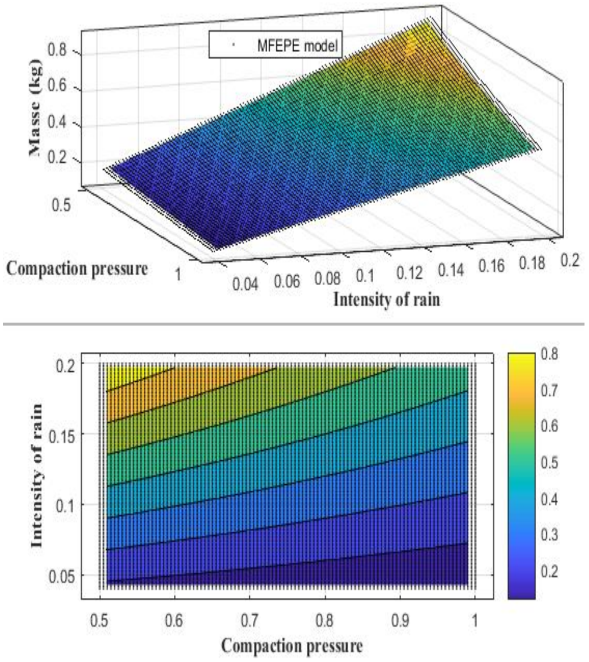


Fig. 12: Surfaces and contours of the average evolution of the eroded masses of the uniformly sloping MFEPE model.

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