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MATHEMATICAL SIMULATION OF SOIL CLODDINESS

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A b s t r a c t. A theoretical model was developed to predict soil clod size distribution attained after tillage so that it can be taken as initial state of soil for following erosion processes. The model was developed previously for rocks. The model predicts soil fragmentation resulting from multiple crack formation due to statistically uniform stresses. Peculiarities inherent to soils in view of their plastic properties are discussed. Comparison between calculated results and published experimental data demonstrates a satisfactory agreement.

K e y w o r d s: soil mechanics, clods, cracking, size distribution, mathematical simulation

INTRODUCTION

Soil cloddiness evolution is an important process in controlling a number of processes such as infiltration, soil crusting, particles detachment, and erosion as a whole. Initial state is determined by cloddiness attained after tillage. There are empirical expressions for quantifying cloddiness (see e.g. [4]). However, theoretical description of cloddiness attained after tillage, or a model to forecast it, is absent.

Chertkov [1-3] proposed a model of multiple crack formation under the action of statistically uniform stresses, which described fragmentation of rock both in its natural state, and by blasting. The purpose of the present work is to generalize the model to describe soil clod distribution attained after tillage, as well as applying it to soil fragmentation, and comparing the results with published data [5].

THEORY (MAIN NOTIONS)

The main characteristics of the basic model [1-3], and its generalization are:

A probabilistic approach, which means that fragments are the result of crack space distribution variations;

Multiple crack formation, which has two meanings. a) the formation of a crack preferably by merge of smaller cracks and not as growth of main crack; and b) independence of cracks, which means that a Poisson's distribution of distances exists between them along a profile; and

Kinetic concepts of accumulation and coalescence of microcracks. These mean existence of: (i) characteristic microcrack size, (ii) characteristic time of microcrack formation and (iii) characteristic average concentration of microcracks, above which they coalesces and form macrocracks.

Assuming average cracking $I(x)$ as the average number of cracks of a size x in a volume of the same size, and $f(x)$ to be the crack coalescence probability (simultaneously this is fragment formation probability for fragments with size less than x), it follows that $I(x)$ and $f(x)$ are given by Eqs. (1) and (2), respectively [1,2]:

$$I(x) = \ln(K^* + 1)\, c\, (x/d)^4 \exp(-x/d) \quad (1)$$

and

$$f(x) = 1 - \exp(-I(x)) \quad (2)$$

where K* is critical value of mean distance between microcracks (in units of their characteristic size). For rocks and soils $K^* \sim 5$ [7]; c is a dimensionless factor, describing the extent of crack coalescence in crack net [2] (in the case after the tillage event; in general $c \leq 1$, for natural rock mass $c=1$ [1]); d is average distance between cracks after the tillage event, which are chaotically disposed in the volume under consideration.

It can be shown that $I(x)$ and $f(x)$ as given in Eqs. (1) and (2) have maxima at $x_m = 4d$ and the value $x = x_m$ exactly matches the maximum fragment size [1]. Fragment size distribution determined by means of volume share of fragments with sizes less than x are given as:

$$F(x) = f(x)/f_m$$

$$0 \leq x \leq x_m = 4d \quad (3)$$

where $f_m = f(x_m)$ (f_m is volume share occupied by fragments and is for natural rock mass $f_m = 1$) [1].

RESULTS AND DISCUSSION

Cracks at rupture in soil

In an elastoplastic material, such as soil, multiple crack formation differs from the model given above, in that during deformation (in particular by tillage) sets of slip lines develop. By sliding a soil volume along the slip lines of a given set, there appear normal tensile stresses to the slip lines of the other sets. When the tensile stresses equal the tensile strength of the soil, open rupture cracks develop on slip lines of the other sets. The sliding process takes place along all slip line sets. Therefore, the considerations as described above apply to each of the slip line sets, explaining the development of crack net (which is not necessarily continuous) or soil crack structure. The resultant separation causes the soil volume to fragment into clods of different sizes.

Another peculiarity of cracking and fragmentation of an elastoplastic material, such as soil, is that there always occur very large clods (huge-clods) which are conglomerates of uncompleted division of clods to smaller sizes. It means that factor c in Eq. (1) determining extent of crack coalescence (or connectedness of crack net) must be less than 1. Such values of c for soils necessitate or suggest a difference of scale dependence of test results of compressive strength of soil clods for different soils and their states [6]. For rocks the power index of the dependence of strength on natural block size does not especially depend on their natural mass blokiness, or mean block size and, approximately equals 0.5 [3]. At the same time the power index differs for different soils [6]. Mean clod size d entering average cracking Eq. (1) as scaling factor cannot influence the above mentioned power index. Therefore, only the factor c must determine the trend of the 'strength-soil clod size' dependence. Thus, in contrast with natural rock mass, where c is 1, c for soils varies, and is less than 1. It is obvious that for soils c may be estimated from a scale effect of strength. This problem is beyond the scope of this presentation.

Comparison between simulation results and experimental data

The comparison between simulated and experimentally measured data was based on using laboratory clod size distribution for a two-dimensional case [5]. The data concern clod size distribution in artificially dried thin soil samples of Italian Fluvisol clay soil (Fig. 1, after [5]). The clod size distribution measurement method [5] is based on electro-optical determinations.

One ought to note some differences between the two-dimensional case, when compared with a three-dimensional one. As it follows from the general approach [1] the power of the argument x/d in formula (1) should be changed from 4 to 3 as given in Eq. (4):

$$I(x) = ln\,(K^{*}+ 1)\, c\, (x/d)^{3} \exp\,(-x/d)\,. \quad (4)$$

Equations (2) and (3) remain unchanged. However, according to Eq. (4) being distinct from the case of Eq. (1), the maximum is attained at $x_m = 3d$. Moreover, as one can see in Fig. 1 for the soil under consideration, almost all clods are delineated by cracks. It means that in this soil and two-dimensional case $c=1$. Then according to (4) and (2) $f_m = 0.91$ or $f_m<1$. This means that there always existed huge-clods which were in fact conglomerates of incompletely separated parts.

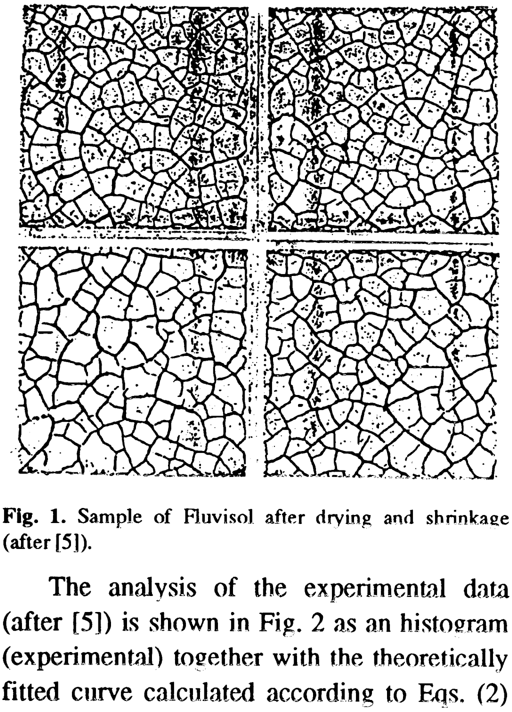

Fig. 1. Sample of Fluvisol after drying and shrinkage (after [5]).

The analysis of the experimental data (after [5]) is shown in Fig. 2 as an histogram (experimental) together with the theoretically fitted curve calculated according to Eqs. (2) and (4) for $K* = 5$ and d = 6.62 mm. Here, value d was found as mean clod size according to histogram in Fig. 2 (note the possibility of the estimation of a d-value with help of the relation $d = x_m / 3$). It can be seen that the agreement between the fitted theoretical curve and the experimental data is quite satisfactory except for 0-3 mm size range. This discrepancy can be attributed to the fact that the soil samples were formed by stacking aggregates of the 1-2 mm fraction of the original soil [5].

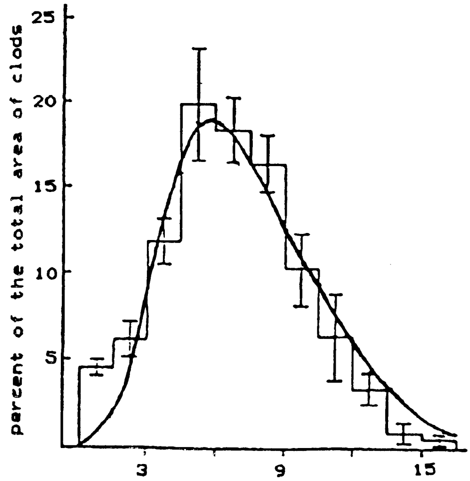

Fig. 2. Frequency histogram of percentage area distribution of the clods in the Fluvisol samples. The error bars represent the mean deviation from the mean of four replicates (after [5]). Solid curve is theoretical relationship.

CONCLUSION

It has been shown that the model of cracking and fragmentation for rocks can be extended to soil.

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