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Soil aggregate stability in a Tunisian semi-arid environment with reference to fractal analysis

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Soils from semi-arid environments have traditionally been considered to have poorly stable aggregates. The use of aggregate stability methods for erosion research seems of particular interest. However, its use to predict crusting and erosion have yielded conflicting results. In this study, we investigate the possible relations between aggregate stability and soil physical properties, and soil water erosion parameters using the mean weight diameter concept, based on dry and wet sieving method. We introduced also a new aggregate stability parameter based on the stability quotient which takes into account the percentage of soil fraction larger than 2 mm. Twenty soil sites were sampled from a Mediterranean semi-arid watershed for aggregate stability test. This study is part of a research work about erosion processes in semi-arid regions of Tunisia conducted during the period 1999 to 2013. Results indicate a correlation between aggregate stability indices and quotients with organic matter content (r = 0.70), a positive correlation with clay content (r = 0.30), but a negative correlation with the amount of soil loss and splash (r = -0.49 and r = -0.40 respectively) as collected in a laboratory rainfall simulation experiment. The stability quotient is the best soil parameter that explains soil erosion. It shows that more than 80% of the soil samples have poor structure stability. The fractal dimension, a characteristic property of the number-size distribution of fragments as a mass of material is broken down, was calculated for all soil samples. After wet sieving all samples follow the law of fractal dimensions.

Key words: Aggregate stability, erosion, rainfall simulation, stability quotient, fractal analysis.

INTRODUCTION

In Tunisia, land degradation is one of the most severe and widespread environmental problems (Jebari et al., 2010). The most common land degradation mechanism is erosion caused by water. Most of agricultural land is threatened by erosive degradation and desertification. In Tunisia no study that has directly or indirectly investigated the relationship between soil erosion and soil structural stability was found.

Aggregate stability is an important physical indicator of soil quality, and so methods are required to measure it rapidly and cost-effectively so that sufficient data can be collected to detect change with adequate statistical power (Rawlins et al., 2013).

Bronick and Lal (2005) consider that soil aggregation is

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a fundamental property of soils and is a primary control of aeration, hydrological properties such as water-holding capacity and the storage of organic carbon. The stability of soil aggregates is also important because it influences how these properties change with time, and the susceptibility of soils to erosion by both wind and water.

A wide range of methods for measuring water-stable aggregates (WSA) has been developed and applied (Le Bissonnais, 1996; Amezketa, 1999; Le Bissonnais, 2007). A framework for assessing AS was presented by Le Bissonnais (1996) incorporating both fast and slow-wetting of aggregates, the latter typically reducing the effects of slaking relative to the other aggregate breakdown mechanisms. In most of these methods, aggregates are passed through a set of sieves of particular mesh size. New methods include the use laser granulometer (LG) instrument.

The breakdown of unstable aggregates results in pore collapse that reduces infiltration, resulting in runoff and erosion from the soil surface increase, which subsequently leads to plant drought (Levy and Miller, 1997). To determine the aggregate stability, a known amount of some size fraction of aggregates is subjected to a disintegrating force designed to simulate the field situation. The disintegration is measured by the proportion (by weight) of aggregates that are broken down into smaller aggregates and primary particles (Kemper and Roseneau, 1986).

Attempts to use aggregate stability to predict soil susceptibility to crusting and erosion have yielded conflicting results (Amezketa et al., 1996). Aggregate stability has been reported to correlate with soil erodibility either positively (Bryan, 1968; Elwell, 1986; Miller and Bahruddin, 1987; Coote et al., 1988), or negatively (Bajracharya et al., 1992; Bajracharya and Lal, 1992; Kemper and Roseneau, 1986), or non_significant (Miller and Bahruddin, 1987; Levy and Miller, 1997). These reported incongruities could be attributed, at least in part, to the large variety of methods used to determine aggregate stability (Levy and Miller, 1997). Kemper and Roseneau (1986) consider that the continued existence of large pores, that favor good infiltration, depends on the stability of aggregates; they concluded also that erodibility of soils decreases as aggregate stability increases.

Mhiri (1981) studied the effect of irrigation on aggregate stability on fine texture soils in Tunisia; he found that irrigation increase the structural degradation specially on surface horizons. Le Bissonnais et al. (2007) discussed the relevance of the aggregate stability methods and the significant soil variables to the prediction of erodibility of Mediterranean vineyard soils. They concluded that the aggregate stability index resulting from the slaking test by the method suggested by Le Bissonnais (1996) was a good indicator of the risk of runoff and erosion for soils subjected to intense rain in dry conditions of the Mediterranean climate. They proposed a pedotransfer function to estimate such index from SOC and other soil characteristics. Attou et al. (1998) studied the effect of clay content and silt-clay fabric on stability of artificial aggregates. The study showed that even if aggregate stability is related to clay content, it is also related to thesilt-clay fabric. In relation with splash detachment,Gumiere et al. (2009) reported that one of the methods used for the determination of interrill soil erodibility is based on the measurement of soil aggregate stability and that the Limburg Soil Erosion Model (LISEM) (De Roo et al., 1996) used this parameter to determine splash detachment. Antecedent soil moisture and landuse can also have an influence on soil aggregate stability, in that Vermang et al. (2009) tested aggregate stability and erosion response to antecedent water content of loess soil in Belgium and, they found that erodibility decreases with increasing soil moisture. Saha et al. (2010) studied the landuse impacts on SOC fractions and aggregate stability in typic ustochrepts of Northwest India. They found that among the SOC fractions, the aggregate stability under simulated raindrop impact method could be better explained by hot water soluble carbon. Whereas, the one under water aggregate stability method could better be explained by particulate organic carbon. New development in the field was discussed by Rawlins et al. (2013) where they applied a novel method for soil aggregate stability measurement based on the use of the laser granulometry with sonication. Their aggregate stability measure was the difference between two measurements of mean weight diameter (MWD) for a soil specimen. The first MWD measurement is made after the soil has been subject to circulation in water and the resulting mild disruptive forces (water-stable aggregates). The second measurement is made after applying a sonication treatment which subjects soil aggregates to strong disruptive forces. They concluded that the iron oxyhydroxide content of the soils used was currently the dominant control on aggregate stability.

The objective of this study is to investigate the influence of some soil properties and erosion parameters on aggregate stability indices under a semi-arid environment of northern Tunisia with reference to a fractal analysis.

MATERIALS AND METHODS

Twenty sites were sampled from the Sbaihia watershed located in northern Tunisia characterized by a mediterranean semi-arid climate (Figure 1). The main soil types according to the soil FAO classification are « Entisols», « Regosols », « cambisols », « Xerosols », and « Vertisols ». This diversity of soils is the result of a complex topography, a variety of parent material and a mediterranean climate (FAO, 1995; 1996).

The wet sieving method was used for this study. The method is based on the fact that the initial aggregate size distribution is compared to the final distribution of the material being subjected to well defined and reproducible forces (Ouessar et al., 1993).

The method was preferred on other methods, in that the recent one of Le Bissonnais (1996) because of its simplicity and efficiency.

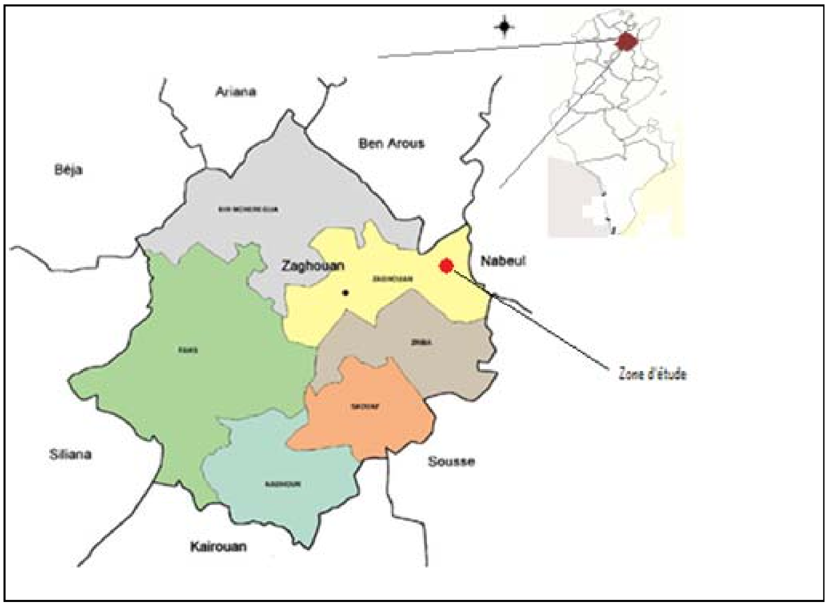

Figure 1. The study area as located in northern Tunisia.

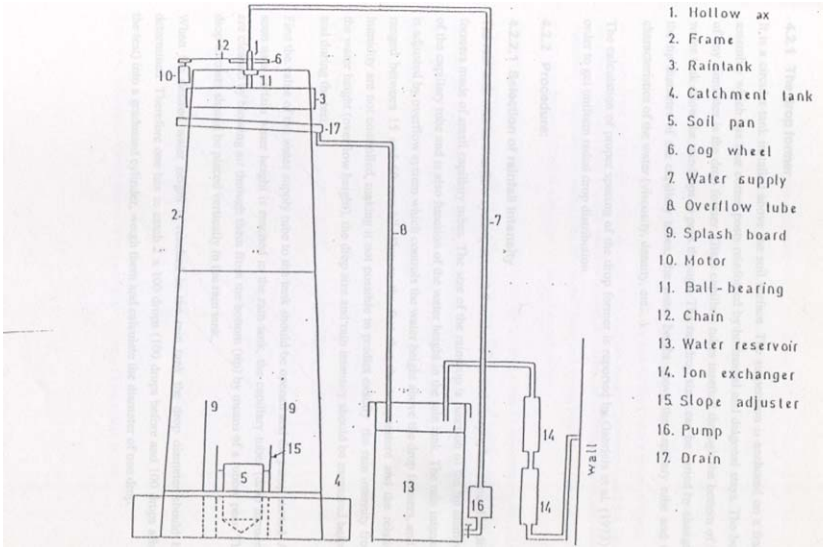

Figure 2. General scheme of the rainfall simulator (after Cornelis et al., 1999).

This method uses the concept of the mean weight diameter (MWD):

$$MWD = \frac{\sum_{i=1}^{n} m_i . d_i}{\sum_{i=1}^{n} m_i} \quad (1)$$

Where, m_i = mass of the fraction (g); d_i = mean diameter of the fraction (mm), and n = total number of the fractions. The aggregate instability index (IS_w) is then calculated as:

$$IS_w = (MWD)_d - (MWD)_w \quad (2)$$

Where, d and w stand for dry and wet sieving respectively. Instead of an instability index a stability index (SI_w) was introduced as:

$$SI_w = \frac{1}{(MWD)_d - (MWD)_w} \quad (3)$$

In parallel to the aggregate stability test, each soil sample was subjected to a rainfall simulation experiment. The objective was to estimate the splash and soil loss, the duration was 90 min, and the rainfall intensity was constant equals 40 mm/h. The rainfall simulator is of a rotating drum type with stationary nozzles as described by Gabriels et al. (1973) (Figure 2). Drop diameters ranged from 4.88 to 4.94 mm and were dropped from a constant height of 2.8 m. The terminal drop velocity of 6.7 ms^{-1} was computed according to Laws and Parsons (1941). The slope has two parameters to be fixed on the runoff plot; these were slope

Table 1. Some properties of the twenty soils under investigation.

Soil sample	Texture Clay (< 2 µ)	 Silt (2- 50 µ)	 Sand (50 µ- 2 mm)	Organic matter (%)	$CaCO_3$ (%)
SB49s	63.6	24.9	11.5	3	49
SB78s	72.7	25.5	1.8	1.79	51
SB29s	29.7	9.3	61	2.39	18
SB36s	44.9	40.8	14.3	1.35	61
SB27s	61.5	19.9	18.6	2.54	46
SB64s	62.1	31.7	6.3	0.9	34
SB13s	17.4	4.8	77.8	1.94	8
SB70s	68	31	0.9	2.21	27
SB05s	13.5	6.1	80.4	1.04	8
SB104s	64.6	26.2	9.3	4.64	59
SB62s	40.5	47	12.4	4.79	32
SB35s	58.1	38.1	3.9	1.35	33
SB04s	8.1	3.5	88.4	1.27	2
SB16s	67.8	16.4	15.8	2.54	36
SB50s	69.7	19	11.3	3.25	62
SB95s	65.3	30.2	4.5	7.55	57
SB24s	14.8	28.3	56.9	0.82	34
SB101s	68.3	22.3	9.4	5.76	62
SB10s	37.6	12.5	49.9	1.79	34
SB82s	77.2	19.6	3.2	3.51	50

gradient and slope length. The slope gradient was fixed to 20% and was selected in accordance with the dominant terrain slope encountered on the various soil groups in the study area. Slope length was standardized at 55 cm on runoff plots for all simulation runs. Each run consisted of 9 observations (every 10 min) of runoff volume, percolation of soil water, soil detachment by rainsplash and sediment transport by runoff. Splash detachment was measured by a set of collecting side panels installed parallel to the runoff plots.

Sediment entrainment was measured gravimetrically as sediment load in the runoff waters.

A soil texture analysis, organic matter and calcium carbonate content were determined on each soil sample used in this investigation. Table 1 shows the characteristics of these twenty soils. A detailed soil texture analysis was also done, but not presented here, in which the following texture classes being 2-10, 10-20, 20-50, 50-100, 100-200, 200-500 and 500-2000 µm. These classes are of a particular interest in soil erosion studies.

The Law of fractal dimension D as shown in Equation (4) first proposed by Turcotte (1986) was finally used in this study. It is a characteristic property of the number size distribution of fragments as a mass of material (in this case soil) is broken down. It characterizes the size distribution of aggregates subsequent to fragmentation (Rasiah et al., 1992, 1993).

$$N_i = c\bar{x_i}^{-D} \tag{4}$$

Where N_i, is the cumulative number of fragments in the number-size distribution, obtained subsequent to fragmentation, $\bar{x_i}$ is the mean size of the objects in the respective class, c is a constant, and *D* is the fractal dimension.

For determining the fractal dimension D, we used Perfect et al. (1992) equation (5) as estimation from mass size distribution data.

$$\sum_{x=\bar{x}_{max}}^{x=\bar{x}_i}[{m_i}/{x_i^3}] = kx_i^{-D} \tag{5}$$

Where *D* and *k* are the fractal dimensions, m_i is the oven dry mass of aggregates on the *i*th sieve, and $\bar{x}_i$ is the average size. The nonlinear fitting procedure was used for the estimation of values of the fractal parameters D and k.

RESULTS AND DISCUSSION

Soil properties and MWD

The soil texture analysis shows that most of the soil samples contain a large amount of clay, reaching in some cases more than 77%. The organic matter content is in general lower than 3% and is less than 1% for SB24s and SB64s. The calcium carbonate content is relatively high since that these soils are mostly calcareous and the geologic mother rock is limestone (Table 1).

The method suggests that of each fraction (8 - 4.76, 4.76 - 2.83 and 2.83 - 2 mm) the same fixed amount should be used being 40, 32 and 28 g, respectively. Consequently, the MWDd used to determine soil stability indices was calculated, it reached 4.45 mm. Using these amounts, the wet sieving resulted on a mean weight diameter (MWDw) ranging from 1.86 mm for SB64s soil to 4.27 mm for SB101s soil.

Table 2. Descriptive statistics of the stability index (SIw).

Mean	Standard deviation	Coefficient of variation
1.32	1.27	96%

Table 3. Modified Structure classification according to the stability quotient (SQ).

PSIw (%)	Appreciation
> 50	Excellent
40 - 50	Very good
33 - 40	Good
25 -33	Unsatisfactory
< 25	Bad

Table 4. Correlation coefficients at $\alpha_{0.05}$ between the stablity index (SIw) or the stability quotient (SQ) and some soil properties.

Index	Clay	Silt	Sand	OM	$CaCO_3$
SI_w	0.18	0.16	-0.20	0.62	0.44
SQ	0.30	0.23	-0.32	0.72	0.52

Table 5. Correlation coefficients at $\alpha_{0.05}$ between stability indices and erosion parameters.

Index	Splash (kg m^{-2})	Loss (kg m^{-2})	Total erosion (kg m^{-2})	K(SI)
SI_w	-0.35	-0.50	-0.53	-0.51
Qs	-0.40	-0.49	-0.55	-0.49

Stability indices and quotients

The stability index (SIw) as explained in (3) varied from 0.39 for SB64s soil to 5.74 for SB101s soil. Table 2 shows the mean, standard deviation and the coefficient of variation for the stability index. A nearly perfect' crumb stability showed a change in mean weight diameter of 0.5 mm (Mhiri and De Waele, 1975). Thus, the percentage stability index (PSIw) is:

$$PSIw = (0.5\times100) / ISw \qquad (6)$$

Based on that percentage stability (PSIw) De Leenheer and De Boodt classified the soil structure into five classes which are excellent, very good, good, unsatisfactory and bad (Mhiri and De Waelle, 1975).

In order to improve that index we introduced a stability quotient (SQ) which takes into account, after dry sieving, the percentage of soil fraction larger than 2 mm (Table 3):

$$SQ = SI_w . Q \qquad (7)$$

where Q, is the percentage of the fraction larger than 2 mm.

If we apply the stability quotient (SQ) as a criterion of evaluation we conclude that around 55% of the samples present a bad structure and 30% an unsatisfactory one, which means a total of 85% of all the samples having a bad structure.

The main physical property that shows the best correlation with stability index (SIw) and the stability quotient (SQ) is organic matter content, followed by the calcium carbonate content (Table 4). Hartmann and De Boodt (1974) consider that organic matter plays an important role in the aggregation process, but has no influence on the critical capillary depression. Le Bissonnais et al. (2007) consider that in general, the stability of soil aggregates is positively correlated with organic carbon content, which commonly decline under arable cropping.

Erosion and stability of aggregates

It is clear (Table 5) that all the erosion parameters are negatively correlated with the stability quotient. Total soil erosion, in fact gives better correlation with the stability index.

Table 6. Influence of soil stability quotient (SQ), $CaCO_3$, OM and silt content on soil erosion of the Sbaihia watershed (northern Tunisia).

	Coefficients	Standard error	P-value	Multiple R	Significance F
Intercept	0.755	0.101	2.10^{-06}	0.697	0.032*
SQ	-0.188	0.105	0.093		
$CaCO_3$ (%)	-0.004	0.003	0.209		
OM (%)	0.028	0.033	0.404		
Silt (%)	-0.004	0.004	0.309		

*Significant at $\alpha_{0.05.}$

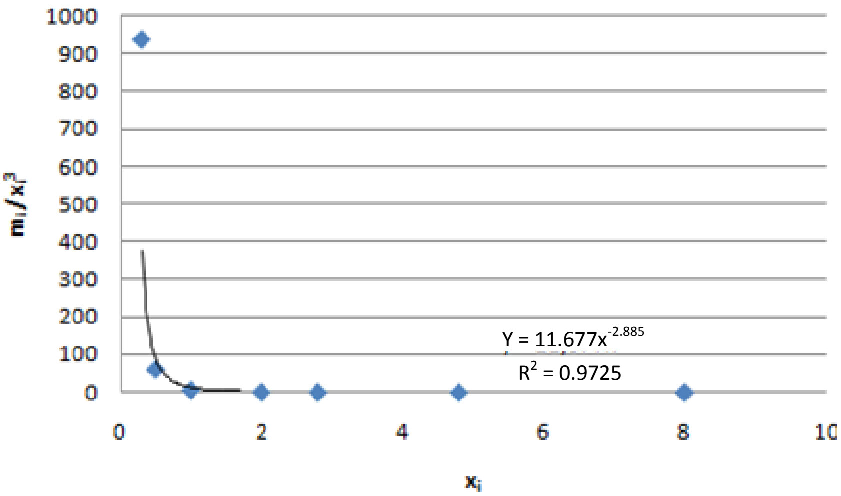

Figure 3. Fractal dimension determination for SB50s soil.

A model based on a multiple regression analysis taking into account some major soil parameters including the stability quotient was established to relate them to soil erosion. The analysis shows that silt content, organic matter content, calcium carbonate content and the stability quotient are the soil factors best related to soil erosion (Table 6). The model significant at $\alpha_{0.05}$, is represented as:

$$E = 0.76 - 0.19\ SQ - 0.004\ (\%)\ CaCO_3 + 0.028\ (\%)\ OM - 0.004\%\ Silt\ (R^2 \qquad (8)$$

Where, E represents total erosion (kg m^{-2}). The stability quotient explained better soil erosion than the other indices because it includes the percentage of the fraction larger than 2 mm.

For organic matter, it is well known that this parameter plays an important role in structuring soils in semi-arid conditions (Le Bissonnais et al., 2007), however, their structure stability is the key factor for the resistance of these soils to water erosion. Measurements of organic carbon content and aggregate stability should enable us to assess the risk of structural degradation. Including silt in the model is also justified because it is an essential element for erosion dynamics, mainly its role in the silt-clay fabric (Attou et al., 1998).

The concentration of SOC across the watershed is likely to have been reduced during the last years by long-term arable production under conventional tillage. Given that SOC content is one of the dominant controls on AS (Haynes and Swift, 1990), it is likely that the latter has also declined over this period.

The model proposed was applied for the sbaihia dam, it gave encouraging results and very close to the reality. In fact the observed erosion during the period 1996 – 2005 was 15 t ha^{-1} or 1.5 kg m^{-2} (Makhlouf, 2013). Though, such model can help in predicting erosion in small catchments of small hill reservoirs that are threatened by siltation in very few years (Jebari et al., 2010). Such reservoirs were initially expected to have an effective life period of around 20 to 30 years were, in some cases, silted completely after seven or even five years.

Fractal dimension analysis

The wet sieving used in this study showed that all samples follow the law of fractal dimensions discussed by Perfect et al. (1992) and Rasiah et al. (1995). It is useless to present results for all soils, but as an example, Figures 3 and 4 show the fractal dimensions determination for soils SB50s and SB10s respectively following a perfect

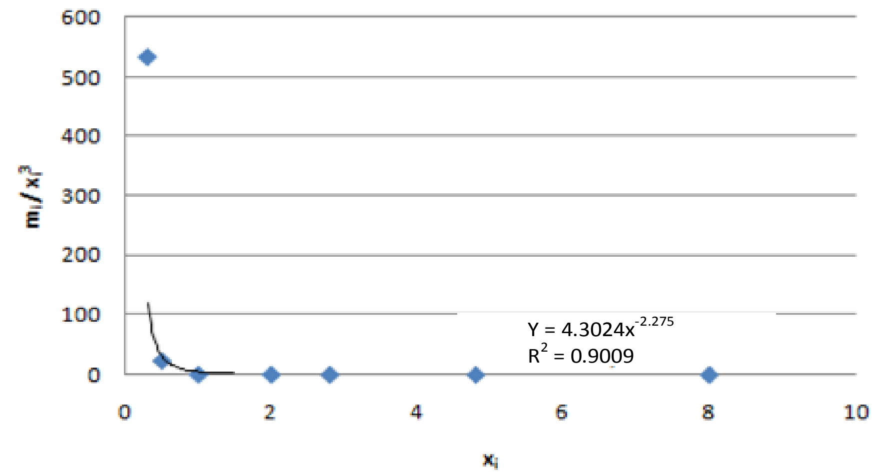

Figure 4. Fractal dimension determination for SB10s soil.

fit, as the residual sum of squares of the best fit or R^2 is around 1Values of D are lower than 3.00 for all soils, this confirm the hypothesis of Tyler and Wheatcraft (1992) which consider that values of D cannot exceed 3.00. D values are 2.89 and 2.75, respectively. We note that k is a function of the shape and the bulk density of aggregates (Rasiah et al., 1995).

Conclusion

Soils from semi-arid environments have traditionally been considered to have a poorly stable structure. The aim of this study was to investigate the influence of some soil properties and erosion parameters on aggregate stability indices. The results indicated a strong positive correlation between the aggregate stability indices or the stability quotients versus the organic matter content, a weaker positive correlation with clay content, and a negative correlation with the amount of soil loss by runoff and by splash as collected under the laboratory rainfall simulation experiment. Soil erosion was better explained by the stability quotient then the different soil properties. It showed that more than 80% of the soil samples have poor structure stability. A model based on a multiple regression analysis taking into account major soil parameters including the stability quotient was established to relate them to soil erosion. Such model can help in predicting erosion in small catchments of small hill reservoirs. The fractal dimension which is a characteristic property of the number-size distribution of fragments as a mass of material is broken down was analyzed for all soil samples. The wet sieving showed that all samples follow the law of fractal dimensions. Finally, we can say that there is a need for the future to investigate erosion sub processes in relation to soil aggregate stability.

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