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Full Length Research Paper

Multifractal analysais of particle-size distributions of alluvial soils in the dam farmland on the Loess Plateau of China

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Multifractal techniques have been widely used in soil science to explore more intrinsic information, such as characterizing a distribution for the entire range of particle-size. A soil particle-size distribution (PSD) constitutes an important soil property correlated to soil properties and processes. For the alluvial soil, however, the study on its PSD information using multifractal techniques is important for soil conservation, agricultural productivity, and riverway safety. The multifractal spectra of 35 typical alluvial soil PSDs covering four soil textural classes were analyzed. The results showed that the *f*(*α*)-spectrums of alluvial soil was more symmetric than the primary soil's. The result indicates that there is a wide range of variability in the heterogeneity of the alluvial soil samples which resulted from erosion and deposition processes. The alluvial soil samples exhibited two distinctively different slopes showing their multifractal characteristics. In this study, multifractal parameters did not show any trend with sand content for the analyzed samples. It could be explained by that multifractal analysis is related to the existence of scaling inside the structure of the measure. Consequently, the multifractal tool is invalid to predicate and evaluate the soil degradation or soil desertification for alluvial soils. Further studies about alluvial soils or sediment should be more concerned with the applicability of multifractal techniques on this kind of psoil to avoid exaggerating its efficiency.

Key words: Alluvial soils, dam farmland, multifractal characterization, particle-size distribution, soil conservation.

INTRODUCTION

As one of the basic soil physic attributes of soils, soil particle-size distribution (PSD) takes a very important role in exploring soil science. Soil PSD can influence soil hydraulic characteristics, and in turn, soil moisture movement, contaminant transport, and soil erosion (Giménez et al., 1997; Oyedele et al., 2009; Aydinalp, 2010). Depending on particle-size, different fractions of soils can be mobilized, deposited, and redistributed during the soil erosion process. Therefore, soil PSD is an important factor for estimating the erosion rate and for characterizing alluvial soils (or fluvisol). On the Loess Plateau of China with exceptional high erosion rates in the world (Tang et al., 1993), alluvial soils are widely formed where fertile farmlands can be formed. The newly formed farmlands provide important income revenue for local farmers, as the crop yield is normally 4 to 6 times higher in the check-dam farmlands than in sloping farmlands and 2 to 3 times than in terraces. By 2002, there were about 3,340 km^2 dam farmlands, which held 2.1×10^{10} m^3 of alluvial soils transported from a 9,247

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Abbreviations: ***α*,** Singularity of strength; ***f(α)*,** Hausdorff dimension; ***D_0*,** capacity dimension; ***D_1*,** entropy dimension; ***D_q*,** the generalized fractal dimension; **PSD,** particle-size distribution; ***τ(q)*,** correlation exponent of the q^{th} order; ***q*,** moment order of a distribution.

km^2 drainage area in the Loess Plateau of China. The areas of dam farmland, the amount of alluvial soils, and the area of the controlled drainage regions are expected to double by 2020 (Gao and Zhang, 2007). Consequently, knowledge about the alluvial soil in dam farmland became very important concern with crop yield and soil conservation.

As a robust rule, a number of complicated natural phenomena have been found to obey the power-law distribution depending on either spatial or temporal scales, such as coastline (Mandelbrot, 1967), earthquake (Gutenberg and Richter, 1954), forest fire (Malamud et al., 1998), and asteroid impact (Chapman and Morrison, 1994). As a very useful tool, fractal models have also been widely used to quantify and characterize soil texture for the past several decades, most of which are based on the power law dependence of particle mass on particle diameter (Turcotte, 1986). Earlier studies have shown that the exponent of the power law depends only on a single fractal dimension, *D* (Matsushita, 1985; Turcotte, 1986; Tyler and Wheatcraft, 1992; Li et al., 2008; Zhao et al., 2009; Jia et al., 2009). However, recent studies have suggested that a single fractal dimension might be insufficient to characterize the full range of soil PSD (Wu et al., 1993; Grout et al., 1998). A multifractal analysis has been employed to capture the inner variations in a system by resolving local densities and expressing them by a distributional spectrum. This approach is well suited to soil analysis because soil properties are determined by several soil-forming factors and processes operating at different temporal and spatial scales. Consequently, multifractal methods were applied in soil science abundantly by many researchers. Grout et al. (1998) applied multifractal techniques to study the PSDs of clayey soils and the research of Posadas et al. (2001) covered a wide range of soil textural classes. To characterize soil using Rényi dimension spectra was applicable for modeling empirical data and generating synthetic data was proved by Montero (2005). Miranda et al. (2006) characterized intrinsic PSD variability of the saprolite material using multifractal techniques. In addition, multifractal analyses in soils from different land-use styles were conducted and compared by Wang et al. (2008). As far as we know, however, there were very few affords to study the PSDs of alluvial soils using multifractal methods.

The objective of this study was to apply multifractal methods to characterize alluvial soil PSDs obtained by laser diffractometry, and to identify trends in the multifractal parameters related to textural separates.

MATERIALS AND METHODS

Soil samples

The study area is located at the Liudaogou catchment in the Loess Plateau of China. The catchment falls in the center of the water-wind erosion crisscross region, where serious soil erosions occur. The mean soil erosion modulus is 150 Mg ha^{-1} $year^{-1}$ for this catchment (Tang et al., 1993). A total of 35 soil samples were selected randomly from 1208 alluvial soil samples listed by sand content (USDA) in the present analysis. The selected samples included four soil classes following the USDA classification of soils (Figure 1). This was because that there were only four texture classes for the total database. All the soil samples were air-dried, gently ground with a mortar and pestle, and finally homogenized and sieved to pass through a 2-mm mesh for the analysis of particle size distribution. After soil organic matter was removed using hydrogen peroxide, soil samples were dispersed by sodium hexametaphosphate (NaHMP) and the particle fractions were determined with two duplicates by using Longbench Mastersizer 2000 (Malvern Instruments, Malvern, England) based on the laser diffraction technique, as follows. The soil samples were disaggregated with an ultrasonic mixer for 30 s. According to the analysis results, particle-size distribution ranges from 0.3 to 1500 µm in this study were applied. The size interval is partitioned into 64 subintervals $I_i = [\gamma_i, \gamma_{i+1}]$, I = 1, 2,…, 64. Length of subintervals follows a logarithmic scale such that $log(\gamma_{i+1}/\gamma_i)$ is constant. A transformation can be made creating a new dimensionless interval partitioned into 64 subintervals of equal length (Montero, 2005; Wang et al., 2008). Table 1 listed the percentages of clay, silt, and sand of the alluvial soil samples.

Determination of multifractal parameters

The method developed by Chhabra and Jensen (1989) was followed to calculate the $f(\alpha)$-spectrum because of its simplicity and accuracy when using experimental data. The distribution of a measure was evaluated within intervals of size ε for different moment's q of the distribution. The normalized measure $\mu_i(q, \varepsilon)$ can be expressed as:

$$\mu_i(q,\varepsilon) = \frac{p_i^q(\varepsilon)}{\sum_{i=1}^{N(\varepsilon)} p_i^q(\varepsilon)} \quad (1)$$

where $p_i(\varepsilon)$ is the occurrence probability of a class-i measure in the interval ε.

In our case, a PSD was partitioned in intervals of size ε, and μ_i was constituted by the percentage of mass contained in each i^{th} interval. The multifractal spectrum, $f(q)$ vs. $\alpha(q)$, was calculated as in (Chhabra et al. 1989; Chhabra and Jensen 1989):

$$f(q) = -\lim_{N\to\infty} \frac{1}{\log(N)} \sum_{i=1}^{N(\varepsilon)} \mu_i(q,\varepsilon)\log[\mu_i(q,\varepsilon)] \quad (2)$$

$$\alpha(q) = -\lim_{N\to\infty} \frac{1}{\log(N)} \sum_{i=1}^{N(\varepsilon)} \mu_i(q,\varepsilon)\log[p_i(\varepsilon)] \quad (3)$$

Cumulative mass size distribution curves were interpolated using a spline technique, and the amount of mass determined for each interval of size ε. The maximum value of ε that can be used in Equations (2) and (3) and the range of q values was assessed by the linear behavior of the function $\sum_{i=1}^{N(\varepsilon)} \mu_i(q,\varepsilon)\log[\mu_i(q,\varepsilon)]$ vs.

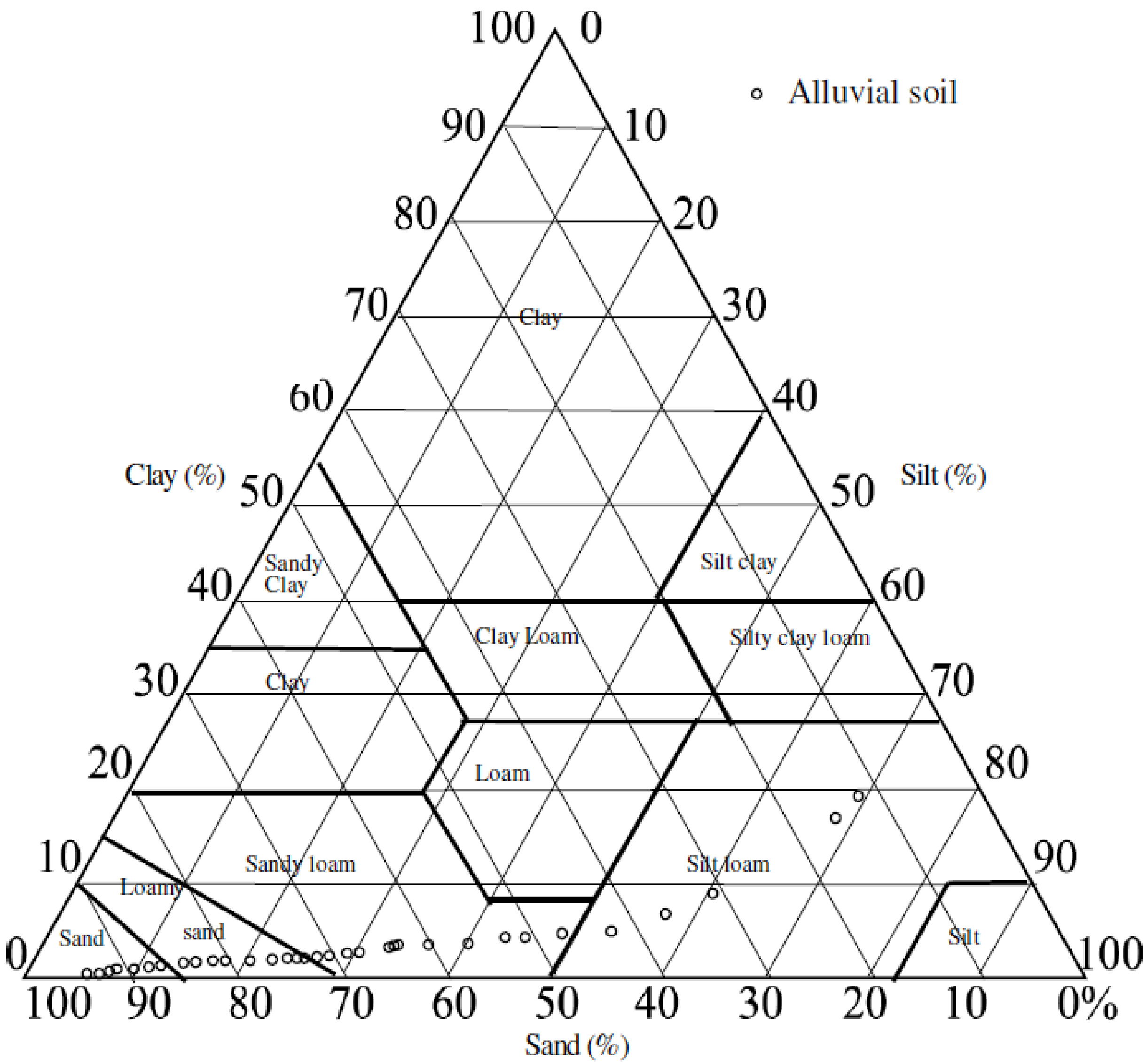

Figure 1. Texture of analyzed soil samples.

$\log(\varepsilon)$ for all the values of q used (Chhabra et al. 1989). The values of q considered were between -10 and +10 taken at 0.5 lag increments. In addition, we tested the validity of the results by verifying that the tangent of the graph $f(\alpha)$ vs. α at $\alpha = 1$ is the bisector defined by $df(\alpha)/d\alpha = q$. The point of intersection corresponds to $f[\alpha(1)] = \alpha(1) = D_1$. The D_q and $\tau(q)$ were obtained with methods from paper of Chhabra et al. (1989).

RESULTS AND DISCUSSION

The characteristics of alluvial soil

The PSD of one sample selected from the 35 alluvial soils with the same soil texture of primary soil is shown in Figure 2. Compared with the primary soil, the percentage of fine particles content (1 to 80 µm) of the alluvial soils are relatively higher and the percentage content of coarse particles content (300 to 1500 µm) are lower. In general, the curves of the PSD against diameter are consecutive and limited between 0.3 and 1500 µm. Compared with the primary soil, the content of fine particles (1 to 80 µm) of the alluvial soils are relatively higher and the content of coarse particles (300 to 1500 µm) are lower. In addition, the curve of alluvial soil PSD has more convexities than the primary soil. The PSD of deposited soil is wider than the primary soil. The coupled effect of erosion and deposition redistributed the distribution more even. Generally, the PSD of alluvial soil is different from the primary soil with the same soil texture due to the processes of soil erosion and deposition.

The shape and symmetry of the $f(\alpha)$-spectrum allow the assessment of the variation in the PSDs of the alluvial

Table 1. Soil number, soil classification, and soil textural composition of the studied 35 soils.

Soil sample	Soil textural	Sand (%)	Silt (%)	Clay (%)
1	Silt loam	11.24	69.92	18.84
2	Slit loam	15.31	67.38	17.31
3	Slit loam	31.86	58.98	9.16
4	Slit loam	37.71	55.30	6.99
5	Slit loam	42.99	51.41	5.60
6	Slit loam	46.65	48.15	5.21
7	Sandy loam	50.87	44.64	4.49
8	Sandy loam	53.26	42.48	4.26
9	Sandy loam	57.94	37.97	4.09
10	Sandy loam	60.31	35.71	3.98
11	Sandy loam	62.63	34.10	3.27
12	Sandy loam	63.55	33.32	3.13
13	Sandy loam	63.95	33.11	2.95
14	Sandy loam	64.80	32.32	2.88
15	Sandy loam	66.48	30.74	2.78
16	Sandy loam	68.01	29.30	2.69
17	Sandy loam	69.45	28.03	2.53
18	Loamy sand	70.20	27.47	2.33
19	Loamy sand	71.08	26.69	2.23
20	Loamy sand	73.13	24.77	2.10
21	Loamy sand	74.30	23.61	2.09
22	Loamy sand	75.11	22.87	2.01
23	Loamy sand	76.04	21.98	1.98
24	Loamy sand	78.30	19.91	1.79
25	Loamy sand	80.37	17.97	1.67
26	Loamy sand	81.45	17.11	1.45
27	Loamy sand	82.92	15.79	1.29
28	Loamy sand	84.68	14.33	1.00
29	Sand	85.94	13.25	0.81
30	Sand	87.16	12.06	0.78
31	Sand	88.42	11.06	0.51
32	Sand	89.47	10.18	0.35
33	Sand	90.90	8.79	0.30
34	Sand	92.44	7.33	0.23
35	Sand	95.40	4.50	0.10

soils. The typical $f(\alpha)$-spectrums of the samples of Figure 2 are illustrated in Figure 3. The plots of the samples are both characterized by a typical convex parabolic shape, but exhibit different symmetry features. A homogeneous multifractal is characterized by a narrow range of $f(\alpha)$-spectrum. The PSD of alluvial soil is more homogeneous than primary soil for its $f(\alpha)$-spectrum is narrower than the primary one's. It means that the interaction of erosion and deposition processes widens the soil particle distribution. From Figure 3, the curve of the selected alluvial sample shows better symmetric characteristics than that of the primary soil. The strong symmetry of the $f(\alpha)$-spectrum is the result of the high sand content for this fraction dominates the deposited soil (Figure 2). From the database, the spectrum does not show any correlations with the contents of sand, silt, or clay. This result was differed with the study of Posadas et al. (2001) who stated that the distribution heterogeneity increased with clay content. This is can be explained that the coupled erosion and deposition process disordered the intrinsic information of alluvial soils. The soil particles were transported by the runoff with different speed and amount due to the different gravity of the particles. Once the particles came into the check-dams, the heavy ones were deposited first then the light ones. Consequently, the intrinsic information of alluvial soils differed significantly

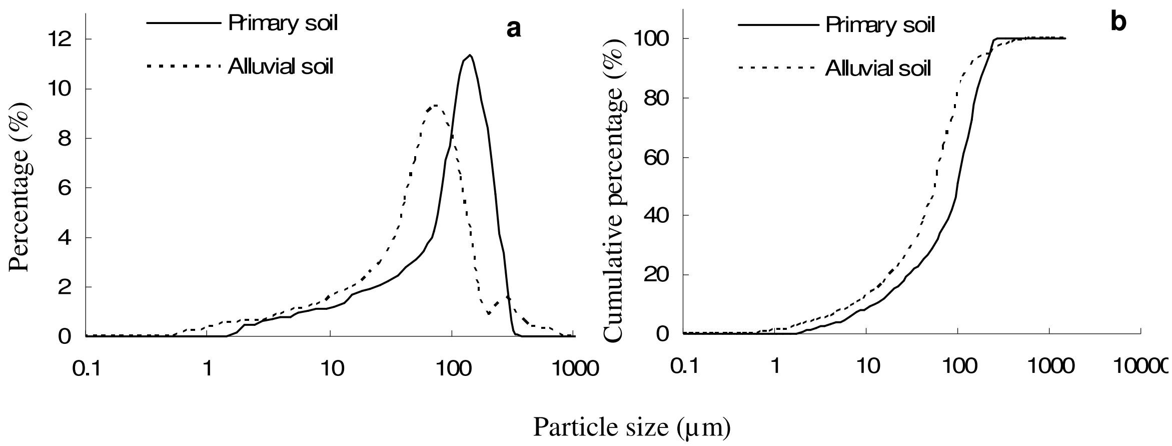

Figure 2. Particle- size distribution (a) and cumulative distribution (b) of one alluvial soil sample and one primary soil sample within the same soil texture.

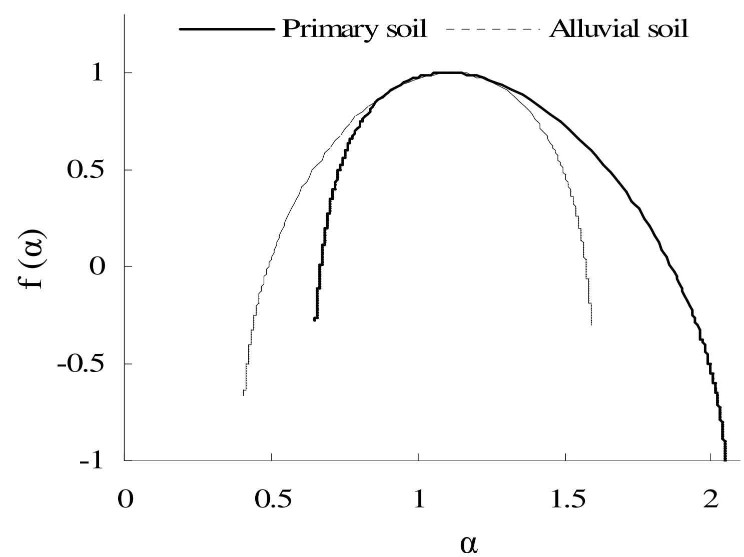

Figure 3. Example of f (α)-spectra for soil samples in Figure 2.

with the natural formed soils.

Multifractal parameter and sand content

The relative proportions of sand, silt, and clay fraction can impact the scaling properties of $\tau(q)$. A linear relationship between $\tau(q)$ and q implies a single fractal system characterized by one scaling exponent (homogeneous fractal). On the other hand, variable slopes in a $\tau(q)$ vs. q relationship are indicative of a multifractal (heterogeneous) system (Machs et al., 1995). All the deposited soil samples within the four textured soils exhibit two distinctively different slopes for $q < 0$ and $q > 0$ (Figure 4). The shape of the $\tau(q)$ vs. q plot suggests that the alluvial soils at the study site exhibit a bifractal behavior with two groups of distinct particle sizes, which lead to the scaling properties of PSD. In order to explore the relationship between soil texture and the scaling properties of $\tau(q)$, $\tau(q_{-10})$ and $\tau(q_{10})$ are both plotted vs. sand content as shown in Figure 5. From the results, the values of $\tau(q)$ do not show significant trend with the sand content. This result showed that the multifractal tool was invalid to predict the sandy degree or soil degradation of alluvial soils.

Rényi dimensions spectra, $D(q)$ for $-10 \le q \le 10$, are plotted in Figure 6a for the 35 soil samples. $D(q_{-10})$ vs. sand content is also plotted in Figure 6b. Soil PSDs exhibit different scaling properties as demonstrated by various $D(q)$ values. From the data, there is little correlation between $D(q)$ and soil texture for alluvial soils. For the samples with low sand fraction, the value of $D(q_{-10})$ is high. Following the increase of sand content, the

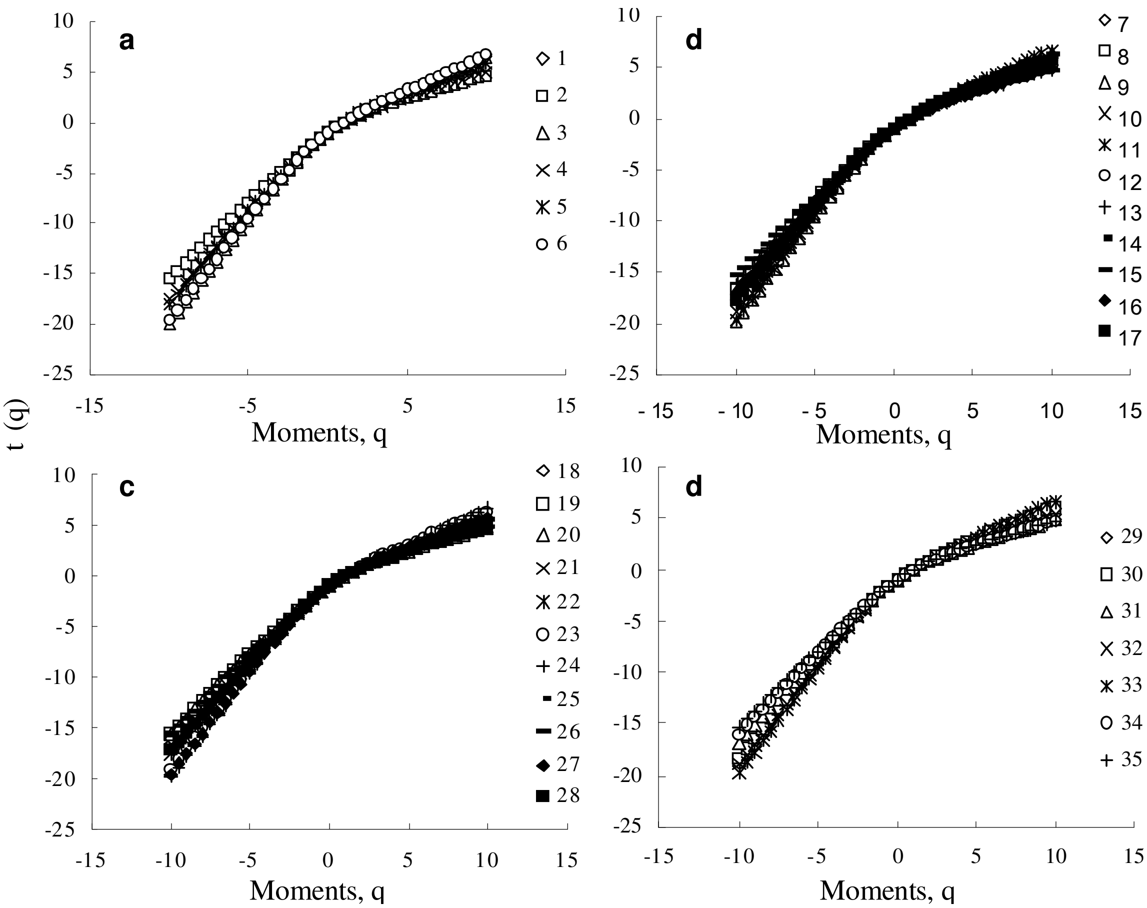

Figure 4. Plots of τ(q) vs. q for soil textures of alluvial soils shown in Figure 1, (a) silt loam, (b) sandy loam, (c) loamy sand, and (d) Sand.

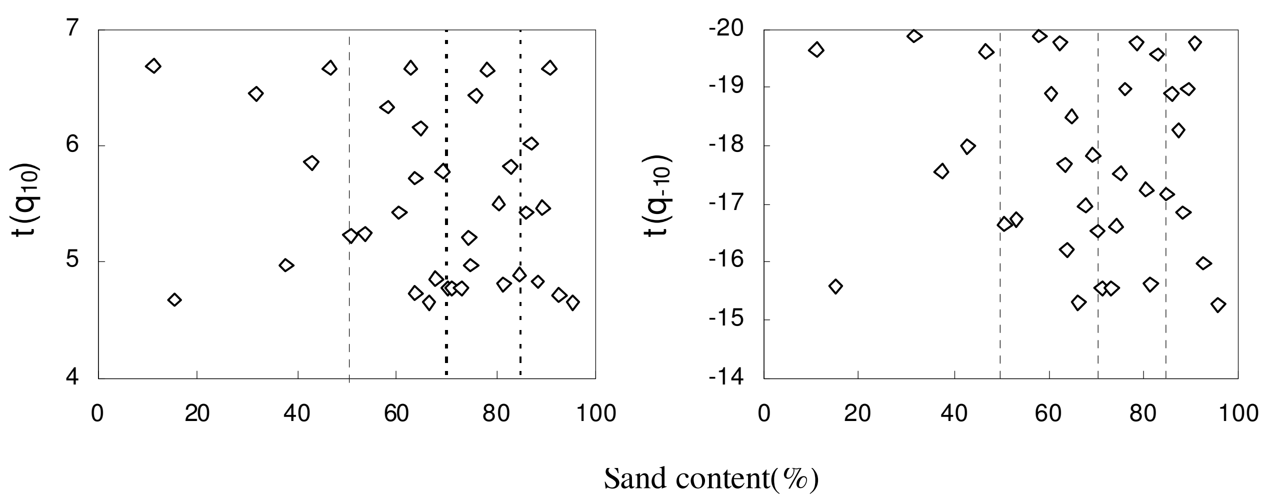

Figure 5. The values of t (q_{10}) and τ (q_{-10}) following the increasing of sand content (the dotted line differentiate the different soil textures which are silt loam, sandy loam, loamy sand and sand soil from left to right).

values of D (q_{-10}) fluctuate between 1.4 and 1.8. This result was same with the report of Montero (2005) who stated the same phenomenon by 20 soil samples. It should be recalled that multifractal analysis is concerned about the existence of scaling inside the structure of the measure.

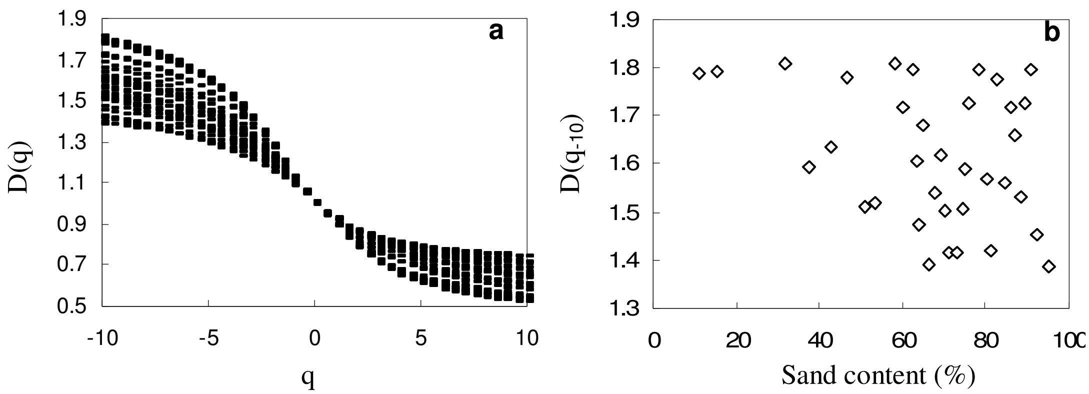

Figure 6. Rényi dimensions spectra curves for total 35 samples analyzed (a) and the plot of D (q_{-10}) versus sand content (b).

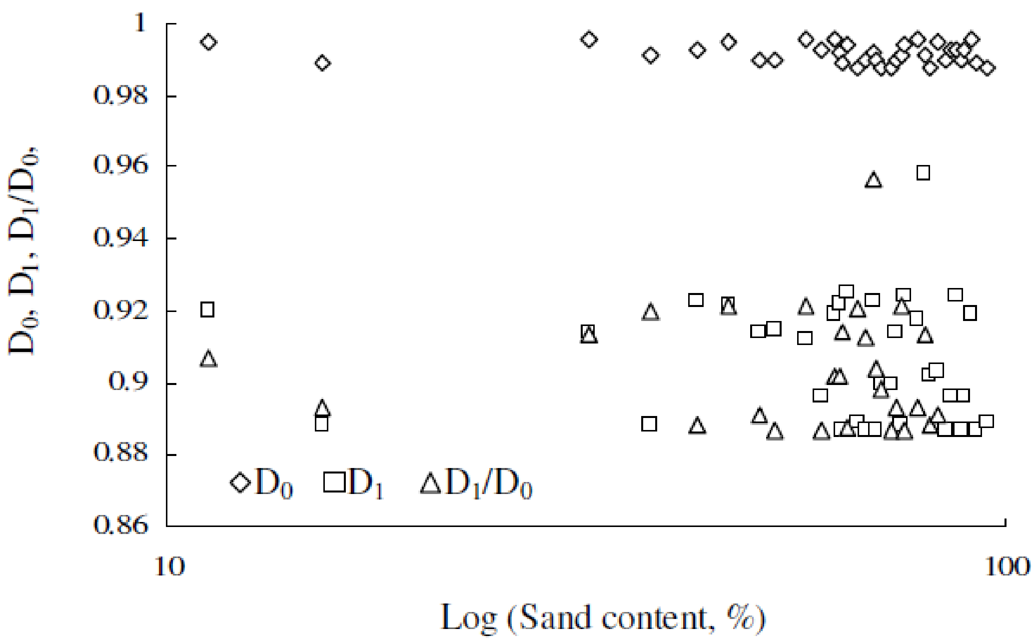

Figure 7. Plot of the capacity dimension, D_0, the entropy dimension, D_1, and the ratio of D_1/D_0 as a function of sand content for all sampled soils.

When q = 0, D_0 is the capacity dimension which is known as box-counting dimension and provides average information of a system. When q = 1, D_1 is related to Shannon entropy, and quantifies the degree of disorder present in a distribution (Wang et al., 2008). The data show that D_0 is not the accurate equality of D_1 for all the samples (Figure 7). However, the values are close within a scope of 0.89 to 1 to show the alluvial soil could be characterized by a single fractal some extent. For all the samples with different sand content, D_0 from 0.988 to 0.996 remains statically not different from 1.0 ($P<0.01$), whereas D_1 ranges from 0.89 to 0.96 become unstable with increasing sand content, they does not show any trend with sand content by correlation analysis. D_0 = 1 means that the interval of particle-size from 0.3 to 1500 µm were all occupied at all scales. Therefore alluvial soils' PSDs took a relatively wide range. That means the alluvial process widens the range of redistribution of particle size. This result agrees with the finding observed from Figure 2. In multifractal systems, the dimension D_1 is directly associated with the entropy of the system. From Figure 7, D_1 values were found to stabilized at a high level within the PSDs. The high value of D_1 means that the soil's PSD are heterogeneous. This is consistent with the interpretation of entropy in an open system. The result is same with the explanation of the relative symmetric *f(α)*-spectrum of alluvial soil PSD. A way of quantifying the dispersion of the measure over the set of sizes is to obtain the relation between these two parameters: D_1/D_0. As D_0 takes values very close to 1, the values range from 0.98 to 0.95, the quotient D_1/D_0 is almost the same with D_1. Values of D_1/D_0 close to 1 indicate the measures dispersed over the set of sizes. Consequently, the particle of alluvial soils dispersed over the set of sizes for the relative high values of D_1/D_0.

The results presented in this paper suggest that multifractal techniques provide additional information on characterizing the redistribution of alluvial soil particle size. The results may be more authoritatively for the study alluvial soils because of the homogeneous background of loess soil (Tang et al., 1993; Wang et al., 2008). That means the alluvial soils is derived from the same or very similar materials. Further studies including samples representing all regions of the textural triangle may develop the applicability of multifractal analysis in alluvial soils.

Conclusions

Multifractal analysis revealed the intrinsic information of the alluvial soil particle size distributions (PSDs) by showing suitable scaling properties in general. The samples showed great variability of in their mutilfractal behaviors. The asymmetry of the *f(α)*-spectrum showed that particle-size dispersed over the set of size. The shape of the *τ(q)* vs. *q* plot suggests that alluvial soils exhibit obvious multifractal behavior without relationship with the texture class. Rényi dimensions spectra followed the typical sigmoidal non-increasing shape obtained for the PSDs. A wide variety of spectra was found for the alluvial soil samples.

From the results of this work, high values of D_1 characterized the PSDs of alluvial soils were relatively uniform throughout all scales. However, D_1 was derived from alluvial soil PSD data and show no relationship with soil texture. In general, multifractal parameters did not significantly relate to sand content in this study. The alluvial soils not only suffer soil erosion process, but also the samples experienced deposition process. The superposition of the two processes weakened the relationship between soil texture and multifractal parameters. Therefore, it is invalid to reflect the coupled effects of soil erosion and deposition on alluvial soil PSDs information. Future research should be devoted to study the PSDs of alluvial soils using multifractal techniques widely and abundantly. More effort should be devote to link these diferences with erosion and deposition processes to fully interpret the significance and potential of muitifractal parameters as a representation of an alluvial soil PSD.

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