https://doi.org/10.17221/87/2018-SWR

Identifying the soil structure of the piedmont–plains by the fractal dimension of particle size

*Yujiang He, Guiling Wang**

Institute of Hydrogeology and Environmental Geology, CAGS, Shijiazhuang, Hebei Province, P.R. China
**Corresponding author: ihegwh@163.com*

Citation: He Y., Wang G. (2019): Identifying the soil structure of the piedmont–plains by the fractal dimension of particle size. Soil & Water Res., 14: 212–220.

Abstract: Soil structure fundamentally determines the hydrodynamic characteristics of the saturated–unsaturated zone, solute transport characteristics, and thermodynamic properties of the soil. Additionally, it regulates the process of transfer and conversion of matter and energy in the saturated–unsaturated zone. However, the quantification of soil structure is difficult because it depends on a combination of factors including soil particle sizes and types and spatial distribution of pores. In this study, the structural characteristics of the vadose zone are examined based on self-similarity in the soil and the fractal theory of non-linear science. This approach describes the soil particle sizes and spatial distribution of pores in the interior layers of the soil. The study area stretches across 165 km of the piedmont–plains of the Taihang Mountains. The particle sizes and volume percentages of particle sizes in 57 soil samples were measured using the Mastersizer 2000 laser diffraction particle size analyser (Malvern Instruments, UK). This information is then combined with the volume-based fractal dimension (D), calculated using the fractal theory, of the various samples. The results obtained indicate that: (*i*) the fractal theory can be used to effectively identify the characteristics of three-dimensional structural changes within the soil profiles. The average soil particle size decreases from the piedmont of the Taihang Mountains towards the plains. Similarly, the volume percentage of particle size and the maximum volume percentage of a single particle size decreases. Moreover, the D values show an overall declining trend; (*ii*) the D values of the soils of the piedmont–plains of the Taihang Mountains show significant spatial variations in the range of 1.037–1.925. Although there is no correlation between the D value and soil particle size, the D value is very sensitive to the soil structure uniformity. The higher the uniformity, the greater is the D value; and (*iii*) D values cannot be used as the sole basis for determining the soil hydraulic properties. The D values and soil hydraulic properties are correlated only for a particular range of soil particle sizes.

Keywords: Daqing River basin; fractal features; soil hydraulic properties; soil particle-size distribution; spatial variation

Soil structure determines the fundamental nature of the vadose zone (Botula *et al.* 2013), which is jointly characterised by soil particle sizes and types and the spatial distribution of particle sizes (Gargiulo *et al.* 2014). Generally, traditional particle analysis methods (such as screening or specific gravity methods) are used to determine the soil particle-size distribution (PSD). These methods are not only time-consuming and laborious, but also they are unable to describe the soil structure fully (the spatial distribution of different particle sizes cannot be quantified).

Since the soil properties of the North China Plain change drastically, it is practically impossible to carry out large-scale testing and analyses of soil particles. This is especially the case of the piedmont–plains of the Taihang Mountains, which have a thick vadose zone, thereby resulting in an extremely complicated soil structure of shallow aquifers (He *et al.* 2013).

Supported by the National Natural Science Foundation of China, Projects No. 41672249 and No. 41877201.

https://doi.org/10.17221/87/2018-SWR

Groundwater recharge in this region is highly non-linear, which hinders quantitative studies of the transport mechanism of moisture and solutes and thermal vapours in groundwater. Hence, a more scientific method for the quantification of the distribution of soil particle sizes must be developed (Gao *et al.* 2014). This will allow a thorough understanding of the structure of the vadose zone and the laws governing the transfer and conversion of matter and energy in a thick vadose zone.

The fractal theory is an important component of non-linear science that can be used to examine strictly or statistically self-similar phenomena at the global and local scales. No specific scale is imposed on the study subject and either recursive or iterative algorithms can be used for calculations. This theory has been widely applied to the study of particle size characteristics of soil (Yu *et al.* 2017). The fractal dimension of the soil particle size distribution characterises the composition of soil particle sizes and reflects soil structural characteristics including the degree of uniformity, arrangement of particles, and combination of different textures (Chandra *et al.* 2011; Hu *et al.* 2011).

The detailed soil structure hidden within a chaotic phenomenon can be clearly observed through the application of the fractal theory and identification of self-similarity within the interior of the soil (Sedaghat *et al.* 2016). When the fractal theory is used for quantitative studies of soil particle-size distribution, new approaches to studying the physicochemical properties (Ghanbarian & Daigle 2015) and hydrodynamic characteristics of regional soil can be identified (Ahmadi *et al.* 2011). Hence, this study aims to directly quantify the soil structure through calculating a volume-based fractal dimension by means of fractal theory. The study area stretches across 165 km of the piedmon–plains of the Taihang Mountains. Particle sizes and volume percentages of particle sizes in 57 soil samples were measured using the Mastersizer 2000 laser diffraction particle size analyser (Malvern Instruments, UK).

MATERIAL AND METHODS

Overview of the study area. The study area is mainly located in the Daqing River basin (DRB) as shown in Figure 1. The Daqing River is formed by the confluence of the Baigou and the South Juma River in the town of Baigou. Its main tributaries are the Pu, Cao, Fu, Tang, and Zhulong Rivers, all of which flow into the Baiyang Lake. The DRB has the typical climatic conditions and topographic features of the North China Plain. The piedmont alluvial fan system and the central palaeochannel tributary system comprise the piedmont–plains of the DRB. The main features of the shallow aquifers in this region include thick vadose zones and significant spatial variabilities in the soil structure. Five typical soil profiles in the study area were selected. The two piedmont profiles were from Shijiazhuang City and Luancheng District, both located at the DRB's southern edge. The three plains profiles were from Wangdu County, Laohetou Town, and Baiyang Lake, which are typical river confluence zones of the DRB.

Experimental setup and testing methods. The soil layers to be sampled were determined based on the results of previous studies (He *et al.* 2013). Subsequently, the sampling points in the piedmont and plains were identified based on past analytical data of the lithology and soil particles of the respective areas (Min *et al.* 2015). Five typical soil profiles were selected in the work. And all the five profiles were bare soil. The vadose zones of the Shijiazhuang and Luancheng profiles, which are both typical piedmont profiles, were thick, with the groundwater table located at depths of 28–45 m. In total, 38 samples were extracted from the 0.3–24.6 m layer of both these

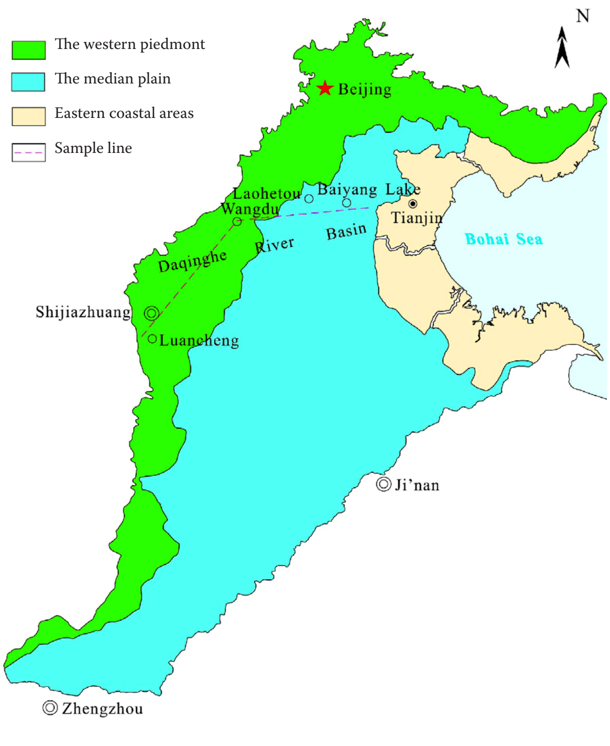

Figure 1. Map of the study area

Table 1. Geographic characteristics of the sampling sites

Sample No.	Depth (m)	Location	Geographical coordinates		Elevation (m)
			ψ (N)	λ (E)	
SJZ01-13	4.4–24.6	Shijiazhuang city, Hebei province	114°28'33''	38°04'59''	85
LC01-26	0.3–3.5	Luancheng county, Shijiazhuang city	114°40'58''	37°53'16''	55
WD01-04	0.9–1.3	Wangdu county, Baoding city	115°09'18''	38°41'40''	46
LHT01-06	0.4–1.2	Laohetou town, Anxin county	115°41'55''	38°49'24''	13
BYL01-09	0.4–1.6	Baiyang Lake, Anxin county	116°03'10''	38°51'52''	5

profiles (Table 1). Wangdu, Laohetou, and Baiyang Lake are located at the confluence zones of the DRB. These three profiles show significant lithological differences and are typical plains profiles, with the groundwater table located at depths of 1.2–1.6 m. A total of 19 samples were collected from the 0.4–1.6 m layer of these three profiles. According to soil taxonomy (International soil grading standards), the basic soil types of the five typical soil profiles are listed in Figure 2. The horizontal distances, from west to east, between the Luancheng, Wangdu, Laohetou, and Baiyang Lake profiles and the Shijiazhuang profile were 15, 60, 133, and 165 km, respectively.

The Mastersizer 2000 laser diffraction particle size analyser (Malvern Instruments, U.K.) was used to determine the volume percentage of particle sizes in 57 soil samples. The volume and cumulative volume percentages of 130 particle size ranges between 0 and 2000 μm were measured. The analytical results of the measured particle sizes were used to obtain the fractal dimension D of these 57 samples.

Calculation of fractal dimension. At the regional scale, the calculation of fractal dimension for soil particle sizes in the various layers is usually based on the fractal dimensional model for the distribution of particle sizes. This can be expressed as:

$$\left[\frac{d_i}{d_{\max}}\right]^{(3-D)} = \frac{V(\delta < d_i)}{V_0} \quad (1)$$

where:

d_i – diameter of soil particles, with $i = 1, 2, 3, ..., n$

$d_{\max}$ – maximum diameter of soil particles

D – fractal dimension

δ – particle-size variable of soil particles

$V(\delta < d_i)$ – volume of soil for which the particle size is smaller than d_i

V_0 – volume of the soil sample (Peng *et al.* 2015)

The first step for calculating the fractal dimension of a sample uses the measured particle sizes and their volume data to calculate:

$$\lg \frac{V(\delta < d_i)}{V_0} \text{ and } \lg \frac{d_i}{d_{\max}}$$

The next step applies a linear least squares fitting method with:

$$\lg \frac{V(\delta < d_i)}{V_0} \text{ and } \lg \frac{d_i}{d_{\max}}$$

as the vertical and horizontal coordinates, respectively. Subsequently, the slope of the fitted line is used to calculate fractal dimension D of the corresponding sample.

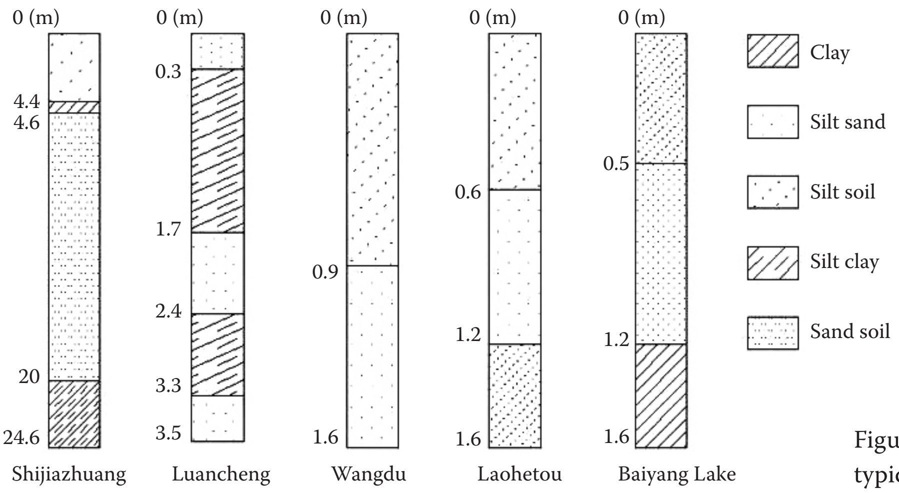

Figure 2. Basic soil types of the five typical profiles

https://doi.org/10.17221/87/2018-SWR

RESULTS

Characteristics of particle-size distribution (PSD) in typical vertical profiles. The Luancheng vertical profile is a typical piedmont profile with a thick vadose zone and the water table was at a depth of 28–45 m. Since there are great lithological differences within the Luancheng vertical profile, 26 samples were extracted from the 0.3–3.5 m layer. The minimum value of:

$$\frac{d_i}{d_{max}}\left(\text{Min}\,\frac{d_i}{d_{max}}\right)$$

for the samples from this profile was 0.084, which represented the maximum difference between all the samples occurring at a depth of 4.4 m. The average value of:

$$\frac{d_i}{d_{max}}\left(\text{Adv}\,\frac{d_i}{d_{max}}\right)$$

for all the samples from this profile at various depths was 0.294.

The Baiyang Lake profile is a typical plains profile. There was a significant decrease in the thickness of the vadose zone and the degree of lithological differences in the central plains. Taking the Baiyang Lake profile as a typical example, its water table was at a depth of approximately 1.6 m. A total of nine samples were extracted from the 0.4–1.6 m layer. The Min (d_i/d_{max}) for the samples from this profile was 0.010, which occurred at a depth of 0.4 m. The Adv (d_i/d_{max}) for all the samples at various depths was 0.237.

It can be seen from Figure 3 that the Min (d_i/d_{max}) and Adv (d_i/d_{max}) trends of the samples are similar; both values decrease with depth. This indicates that for shallow soil layers (within a depth of 5 m), variabilities in particle sizes increase with depth. This could be related to the impact of human activities on the shallow soil layer. Generated from various agricultural activities, soil particle sizes tended to be uniform in the shallow soil layer (especially within a depth of 1 m). At depths of 0.5–1 m, the Min (d_i/d_{max}) and Adv (d_i/d_{max}) of the typical piedmont and plains profiles reached the respective maximum values.

Characteristics of particle size distribution in the piedmont–plains. The particle sizes in 38 samples from the piedmont profile ranged from 0.429 to 697.168 μm. The minimum particle size was found at a depth of 2.7 m in the Luancheng profile, while the maximum particle size occurred at a depth of 14.9 m in the Shijiazhuang profile. Among all the samples from this region, the maximum volume percentage of a single particle size was 15.15%, which corresponded to the particle size of 215.915 μm and the sample at a depth of 14.9 m in the Shijiazhuang profile.

The depths of the five profiles were normalised, meaning that the ratios between the various depths and the total profile depth were used as the Y-coordinates for the distribution map of the samples. Additionally, the horizontal distances between each profile and the Shijiazhuang profile as stated in experimental setup and testing methods were normalised; the ratios between the various distances and 165 km were used as the X-coordinates (the x-coordinates of the Shijiazhuang and Baiyang Lake profiles were 0 and 1, respectively). Subsequently, the coordinates were used to plot the distribution maps of the Min (d_i/d_{max}) and Adv (d_i/d_{max}) (Figures 3 and 4) for samples from the piedmont–plains.

The ranges of both Min (d_i/d_{max}) and Adv (d_i/d_{max}) were larger for the piedmont samples than for the plains samples, indicating that the piedmont had more significant variabilities in particle sizes. As can be seen from Figures 4 and 5, both the Min (d_i/d_{max}) and Adv (d_i/d_{max}) of the samples gradually decreased from the piedmont towards the plains. This means that the difference between the minimum and the maximum particle size gradually diminishes from the piedmont towards the plains.

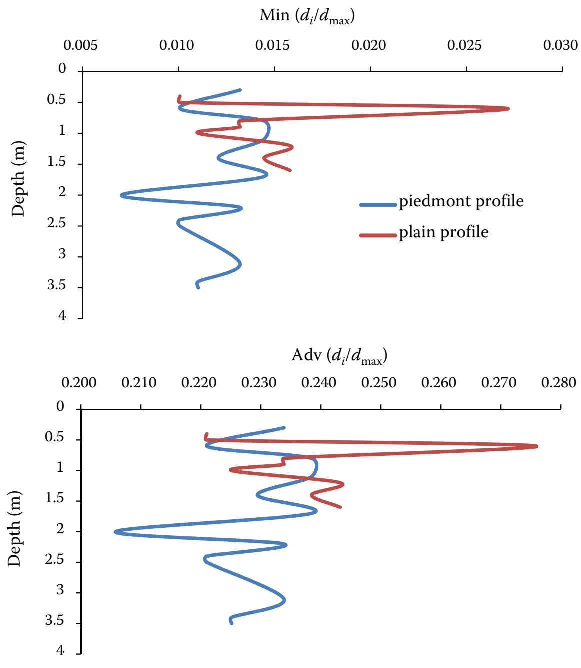

Figure 3. Minimum (Min (d_i/d_{max}) and average (Adv (d_i/d_{max}) scatter plot of the typical piedmont–plains profiles
d – soil particle diameter

https://doi.org/10.17221/87/2018-SWR

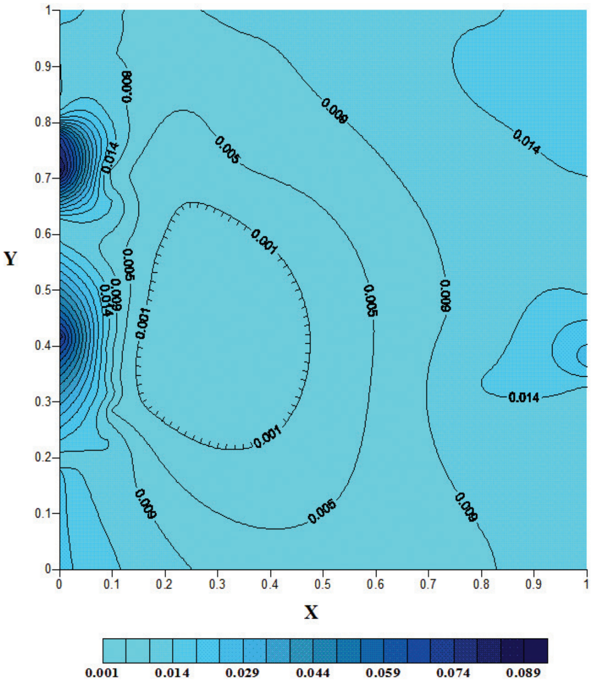

Figure 4. Distribution map of the Min (d_i/d_{max}) in the piedmont–plains samples
d – soil particle diameter

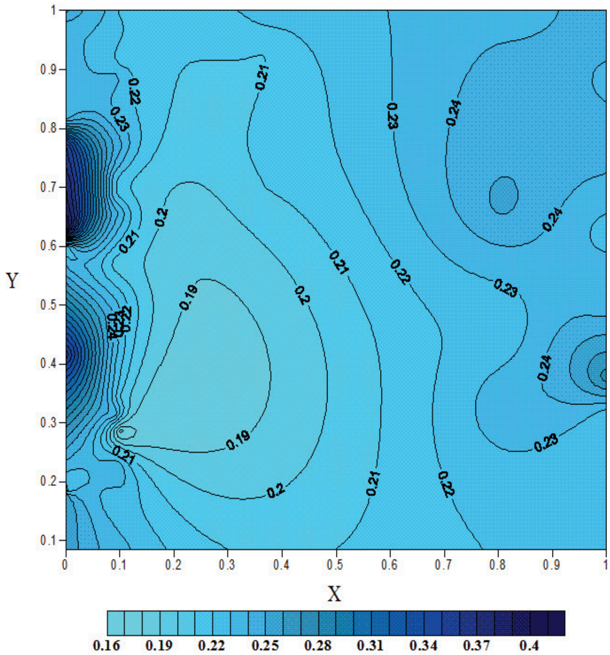

Figure 5. Distribution map of the Adv (d_i/d_{max}) in the piedmont–plains samples
d – soil particle diameter

Theoretically, the smaller the Min (d_i/d_{max}), the more significant will be the difference in particle sizes and the larger the Adv (d_i/d_{max}), the more uniform will be the particle sizes. However, the phenomenon of Adv (d_i/d_{max}) becoming larger as Min (d_i/d_{max}) becomes smaller was also common. In the Shijiazhuang profile, for example, the Min (d_i/d_{max}) was only 0.013 but the Adv (d_i/d_{max}) was as high as 0.407 for the sample from a depth of 15 m. This illustrates that the degree of soil structure uniformity cannot be determined based solely on the minimum and average soil particle sizes.

An understanding of particle size distribution alone is insufficient to correctly identify the soil structure. The volume percentage of the different particle sizes must be ascertained and the degree of variabilities in particle sizes and the corresponding volume percentages must be extensively considered. Thus, quantitative studies of soil structure require the fractal dimensions of particle sizes.

Identifying soil structure using fractal dimension of PSD

Sample LC17, located at a depth of 2.9 m in the Luancheng profile, was selected as a representative sample for the calculation of fractal dimension as described in calculation of fractal dimension. First, the soil particles in LC17 were subdivided according to the particle size intervals stated in experimental setup and testing methods. Based on the volume percentages of soil particles smaller than a certain size listed in Table 2, LC17 contains 51 different particle sizes. This table also shows that the volume percentages of soil particles smaller than 3.118 and 282.981 μm accounted for 1% and 100% of the total volume, respectively. This means that all the particles in the LC17 soil sample were smaller than 282.981 μm.

Figure 5 shows that the soil particle sizes in LC17 increased from 3.118 μm, leading to a gradual increase in the corresponding volume percentage. After attaining the peak value of 61.104 μm, the particle sizes were reduced rapidly. This sample from the piedmont region and sample BYL02 from the plains region were compared. The distribution of soil particle sizes in LC17 was concentrated within a smaller range (40–80 μm) and the peak was obvious. In contrast, the volume percentage of particle sizes in BYL02 continued to increase by two orders of magnitude after attaining the peak value. This difference is clearly shown by the two cumulative volume percentage curves in Figure 6.

The second step in the calculation of fractal dimension was to calculate:

https://doi.org/10.17221/87/2018-SWR

Table 2. Summary of the volume percentages of soil particle sizes (sample LC17)

Particle-size (μm)	Volume percentage (%)	Particle-size (μm)	Volume percentage (%)	Particle-size (μm)	Volume percentage (%)
3.118	0.01	14.439	0.59	66.869	8.36
3.412	0.01	15.801	0.69	73.179	7.37
3.734	0.04	17.292	0.79	80.084	6.14
4.086	0.06	18.924	0.89	87.640	4.83
4.472	0.10	20.710	0.97	95.909	3.59
4.894	0.16	22.664	1.06	104.959	2.54
5.356	0.20	24.802	1.19	114.862	1.70
5.861	0.24	27.142	1.42	125.700	1.09
6.414	0.27	29.703	1.81	137.560	0.69
7.019	0.30	32.506	2.43	150.539	0.42
7.681	0.32	35.573	3.32	164.744	0.26
8.406	0.34	38.93	4.47	180.288	0.16
9.199	0.36	42.603	5.78	197.299	0.10
10.067	0.39	46.622	7.10	215.915	0.05
11.017	0.41	51.022	8.20	236.288	0.04
12.057	0.46	55.836	8.84	258.582	0.01
13.194	0.52	61.104	8.89	282.981	0.02

$$\lg\frac{V(\delta < d_i)}{V_0} \text{ and } \lg\frac{d_i}{d_{max}}$$

using the least squares method as described in calculation of fractal dimension After plotting the correlation diagram for:

$$\lg\frac{V(\delta < d_i)}{V_0} \text{ and } \lg\frac{d_i}{d_{max}}$$

the slope and correlation coefficient were determined to be 1.6899 and 0.8776 (Figure 7), respectively. The D value of LC17 was then found to be 1.3101.

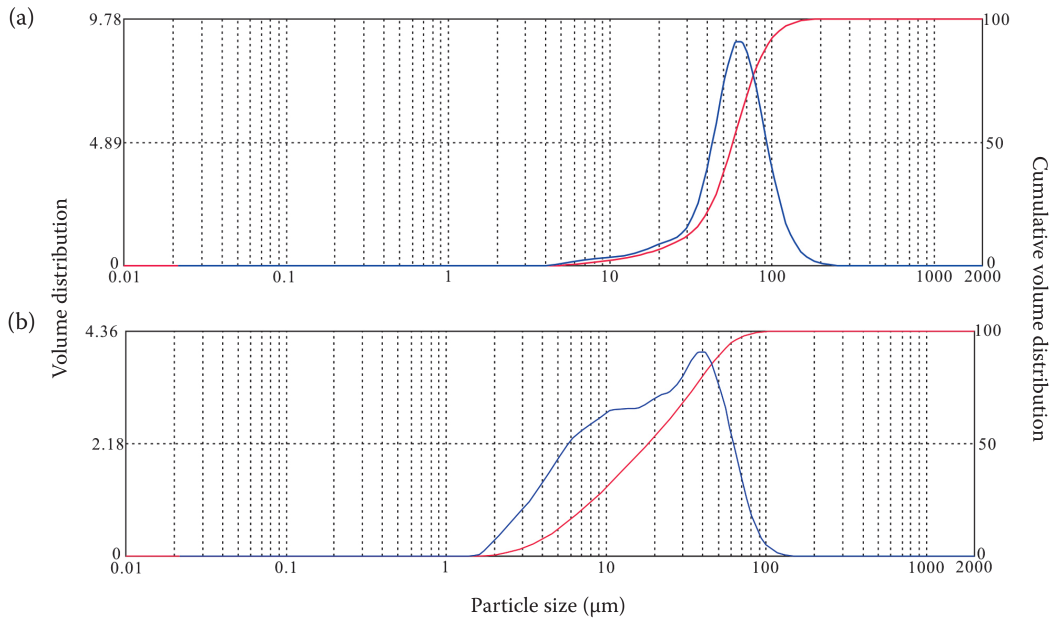

Figure 6. Volume and cumulative volume distributions of the representative soil particle sizes in the piedmont–plains: sample LC17 (a) and BYL02 (b)
blue – volume distribution; red – cumulative volume distribution

https://doi.org/10.17221/87/2018-SWR

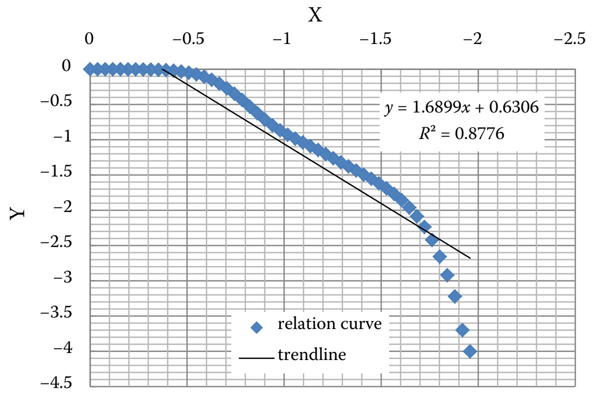

Figure 7. Correlation diagram between $\lg \frac{d_i}{d_{max}}$ and $\lg \frac{V(\delta < d_i)}{V_0}$

X-coordinate: $\lg \frac{d_i}{d_{max}}$ and Y-coordinate: $\lg \frac{V(\delta < d_i)}{V_0}$

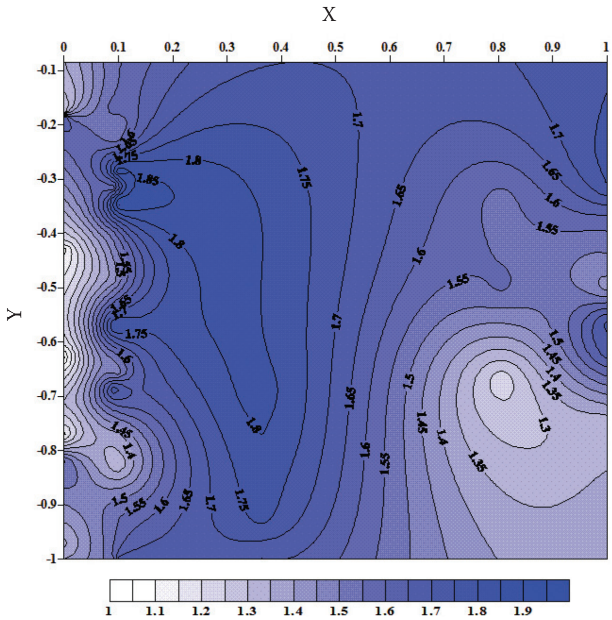

Figure 8. Distribution map of the fractal dimension values for the piedmont–plains samples

In the last step, the D values of all 57 samples from the piedmont–plains were calculated according to the aforementioned method. Prior to plotting the distribution map of the D values for the piedmont–plains (Figure 8), the vertical and horizontal directions of the five piedmont–plains profiles were normalised according to the methods explained in characteristics of particle size distribution in the piedmont–plains.

The fractal dimensions of soil volumes and particle sizes in the piedmont–plains of the Taihang Mountains were mainly in the range of 1–2 (Figure 7). The minimum and maximum values were 1.039 and 1.925, respectively. The minimum value occurred at a depth of 15 m in the Shijiazhuang profile, while the maximum value occurred at a depth of 1.2 m in the Luancheng profile.

According to Figure 8, spatial variability in D values was significant along the X direction from the piedmont towards the plains, exhibiting an overall increasing trend. The D value was smaller in the 0–0.1 interval along the X direction, with 1.2 being the average; this value was larger in the 0.2–0.35 and 0.92–1.0 intervals, with the average being 1.8. However, the D value decreased in the 0.7–0.8 interval along the X direction, which was not consistent with the general trend. This might be related to the shallower sampling depth (only 1.2 m) for the Laohetou profile. Therefore, samples for further testing must be extracted from soil layers with greater densities and at greater depths. The D values along the X direction of all the profiles were larger in the 0.3–1.0 interval. And the D values of the profiles decreased at a slow rate with depth. This phenomenon became more apparent with increasing proximity to the plains, representing the typical characteristics of the plains profiles.

Similarly, spatial variability in D values along the Y direction (from the ground surface downward) was also significant and presented an overall decreasing trend. The D value was larger in the 0–0.4 interval but declined rapidly in the 0.4–1.0 interval. The average D values for the two intervals were 1.65 and 1.35, respectively. The D value along the Y direction changed significantly in the 0–0.8 interval for the Shijiazhuang profile (0 on the X-coordinate in Figure 7). The samples from this profile had the smallest D value among all the samples tested in this study, and it represents the typical characteristics of the piedmont profiles.

DISCUSSION

Relationship between particle size and D value. Previous studies have accepted that the fractal dimension of soil pores is generally smaller than that of their volume and the fractal dimensions are distributed over a wide range. The fractal dimensions of soil volumes measured by various researchers ranged from 1.22 to 1.85 (Ozhovan *et al.* 1993; Peyton *et al.* 1994; Anderson *et al.* 1996; Gimenez *et al.* 1997). The fractal dimensions of soil volumes measured by Peyton *et al.* (1994) for particle sizes in the range of 1000–10 000 μm were the smallest at

https://doi.org/10.17221/87/2018-SWR

1.22–1.44 and those measured by Anderson *et al.* (1996) for particle sizes in the range of 50–250 μm were the largest at 1.85.

In this study, the range of particle sizes considered for the soil samples from the typical profiles of the piedmont–plains of the Taihang Mountains was 0.02–2 000 μm. The particle sizes of the samples were mostly in the range of 0.429–697.168 μm. To calculate the fractal dimensions of soil volumes, this range of particle sizes was converted to D values in the range of 1.037–1.925. Overall, the findings of this study were similar to those of previous studies, although the range of D values was wider. This might have resulted from the wide sampling range adopted, stretching 165 km from the piedmont of the Taihang Mountains to the plains. Consequently, there were high spatial variabilities in the D values, with the difference in values amounting to 0.888.

Among the 57 samples, the highest volume percentage of a single particle size was 15.15% (the corresponding particle size was 215.915 μm). Additionally, the D value of this particular sample was the smallest. However, it should be noted that a small D value does not imply that the particle size is large. A small D value implies that there was less uniformity in the distribution of particle sizes. This phenomenon is more likely to occur in coarse-grained soil samples, thus creating the false impression that "large particle sizes lead to small D values".

Relationship between D value and soil permeability. Particles in the piedmont soil were coarser and had poorer uniformity, leading to good permeability but poor water accumulation ability (He *et al.* 2013). The D values were generally smaller than 1.5, although the D values of some sampling points were 1.8 or higher (for example, the D value of LC428 was 1.812).

Further analyses of the samples revealed that samples with coarse particles had a silty texture and good permeability. However, the distribution of particle sizes was more uniform, thereby leading to larger D values. Variabilities in the D values of the plains profiles were more substantial than those of the piedmont profiles, with the values being generally greater than 1.5. However, some exceptions were observed; the D values of BYD90 and BYD788 were only 1.311 and 1.375, respectively. In these cases, the particles were fine and the texture was clayey and non-uniform. The pores in the soil were filled with particles of various sizes, leading to poor permeability.

The aforementioned cases illustrate that a large D value does not necessarily indicate poor permeability; poor permeability can also be observed in soils with small D values. In soils where the particle size is large and uniformly distributed, the pores between the particles are relatively large. As such, permeability remains good even if the D value is large. Therefore, the relationship between the D value of an atypical soil and its hydraulic properties must be examined for different ranges of particle sizes. The task is to identify the range of particle sizes for which the corresponding D values can be used as indicators of soil permeability.

CONCLUSION

(*i*) The fractal theory was used to identify the soil structure of the piedmont–plains of the Taihang Mountains. A clear, accurate, and effective illustration of the characteristics of the three-dimensional structural changes in the soil profiles was obtained. The average particle sizes, volume percentages of particle sizes, and the maximum volume of a single particle size were reduced from the piedmont towards the plains. Additionally, the D values exhibited an overall diminishing trend.

(*ii*) There was no correlation between the D values and soil particle sizes. However, the D value is very sensitive to uniformity in the soil structure; the more uniform the soil, the larger is the D value. As such, soils with coarse particles but high uniformity can still have large D values.

(*iii*) The D value cannot be used as the sole basis for determining the hydraulic properties of soils. Soil particle sizes must also be considered simultaneously. The relationship between the D values and the soil hydraulic properties should be determined using a specific range of particle sizes. Further study is required to establish this specific range of particle sizes.

Acknowledgements. We gratefully acknowledge the key laboratory of Geothermal Survey and Research Center, Chinese Academy of Geological Sciences, and its fruitful cooperation on experiments in both the field and laboratory.

References

Ahmadi A., Neyshabouri M.R., Rouhipour H., Asadi H. (2011): Fractal dimension of soil aggregates as an index of soil erodibility. Journal of Hydrology, 400: 305–311.

Anderson A.N., McBratney A.B., Fitzpatrick E.A. (1996): Soil mass, surface, and spectral fractal dimensions estimated from thin section photographs. Soil Science Society of America Journal, 60: 962–969.

https://doi.org/10.17221/87/2018-SWR

Botula Y.D., Cornelis W.M., Baert G., Mafuka P., Ranst E.V. (2013): Particle size distribution models for soils of the humid tropics. Journal of Soils and Sediments, 13: 686–698.

Chandra S., Ahmed S., Rangarajan R. (2011): Lithologically constrained rainfall (LCR) method for estimating spatio-temporal recharge distribution in crystalline rocks. Journal of Hydrology, 402: 250–260.

Gao P., Niu X., Lv S.Q., Zhang G.C. (2014): Fractal characterization of soil particle-size distribution under different land-use patterns in the Yellow River Delta Wetland in China. Journal of Soils and Sediments, 14: 1116–1122.

Gargiulo L., Mele G., Terribile F. (2014): Effects of iron-based amendments on soil structure: a lab experiment using soil micromorphology and image analysis of pores. Journal of Soils and Sediments, 14: 1370–1377.

Ghanbarian B., Daigle H. (2015): Fractal dimension of soil fragment mass-size distribution: A critical analysis. Geoderma, 245–246: 98–103.

Gimenez D., Perfect E., Rawls W.J., Pachepsky Y. (1997): Fractal models for predicting soil hydraulic properties: a review. Engineering Geology, 48: 161–183.

He Y.J., Lin W.J., Wang G.L. (2013): In-situ monitoring on the soil sater-heat movement of deep vadose zone by TDR100 system. Journal of Jilin University (Earth Science Edition), 43: 1972–1979.

Hu H.C., Tian F.Q., Hu H.P. (2011): Soil particle size distribution and its relationship with soil water and salt under mulched drip irrigation in Xinjiang of China. Science China: Technological Sciences, 54: 1568–1574.

Min L.L., Shen Y.J., Pei H.W. (2015) Estimating groundwater recharge using deep vadose zone data under typical irrigated cropland in the piedmont region of the North China Plain. Journal of Hydrology, 527: 305–315.

Ozhovan M.I., Dmitriev I.E., Batyukhnova O.G. (1993): Fractal structure of pores in clay soil. Atomic Energy, 74: 241–243.

Peng H.T., Horton R., Lei T.W., Dai Z.C., Wang X.P. (2015): A modified method for estimating fine and coarse fractal dimensions of soil particle size distributions based on laser diffraction analysis. Journal of Soils and Sediments, 15: 937–948.

Peyton R.L., Gantzer C.J., Anderson S.H., Haeffner B.A., Pfeifer P. (1994): Fractal dimension to describe soil macropore structure using X ray computed tomography. Water Resources Research, 30: 691–700.

Sedaghat A., Bayat H., Safari S.A.A. (2016): Estimation of soil saturated hydraulic conductivity by artificial neural networks ensemble in smectitic soils. Eurasian Soil Science, 49: 347–357.

Yu Y., Wei W., Chen L.D., Feng T.J., Daryanto S., Wang L.X. (2017): Land preparation and vegetation type jointly determine soil conditions after long-term land stabilization measures in a typical hilly catchment, Loess Plateau of China. Journal of Soils and Sediments, 17: 144–156.

Received for publication April 29, 2018
Accepted after corrections January 21, 2019
Published online March 29, 2019