Research Article

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Fractal expression of soil particle-size distribution at the basin scale

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Abstract: Soil structure at the basin scale affects the superficial moisture content, heat, salinity balance, and ecological balance of groundwater system. To study the soil particle size fractal characteristics at the basin scale, 188 groups of soil samples were collected over a distance of 258 km in the Ziya River basin of the North China Plain. Particle volume percent was measured using a laser particle size analyzer, and then analyzed by applying the fractal theory to reveal the spatial distribution of soil particle size and soil voids. The results showed that: (1) From the Taihang Mountain piedmont to the coastal area, soil particle-size volume percentages varied in a small range, with the fractal dimension D showing an overall decreasing trend; (2) D showed a significant spatial variation, ranging from 0.13 to 2.188. It was jointly determined by particle uniformity and particle size range; (3) When $D \leq 1$, the characteristic fractal size was $30 \mu\text{m}$ in the basin. When $1 < D \leq 1.5$, the characteristic fractal size was $20 \mu\text{m}$ and D_a was 1.37, and when $D > 1.5$, the two parameters were $10 \mu\text{m}$ and 1.77, respectively. The research results indicated that D can effectively quantify the characteristics of soil structure at a large scale.

Keywords: soil structure, particle-size distribution, fractal dimension, basin scale, characteristic fractal size

1 Introduction

Soil properties and terrain characteristics influence spatiotemporal patterns of soil moisture across a watershed [1]. Soil hydraulic properties are important to the understanding and modeling of hydrological processes at the watershed scale [2]. These properties are presumed to be correlated with associated topographic attributes and other soil factors [3,4] operating at different intensities and scales [5]. To improve the predictive power of landscape hydrologic models [6], it is essential to consider both soil and terrain attributes when stratifying a catchment into similar hydrologic functional units [7]. The basin is an important part of the ecosystem and its abundant water resources are important for human life, irrigation of farmland, and environmental purification [8,9]. As an important food production area in North China, the Ziya River basin has the ecological disadvantage of low water and thin soil [10], which is vulnerable to mountain torrents and heavy rainfall floods that bring great danger to human safety and social economy in the region. It is of great importance to know the distribution characteristics and uniformity of soil structure and particle size for the hydrological resource management of the basin.

Soil structure refers to the pattern [11] in which soil particles are arranged and the bulk properties resulting from the pattern [12]. And many processes in soil are highly sensitive to soil structure [13]. It is jointly characterized by the size, type, and spatial distribution [14] characteristics of soil particles, which should be considered while determining the fundamental properties of the vadose zone [15]. Traditionally, soil particle-size distribution is determined using particle analysis methods such as the sieving and gravimetric methods [16]. These methods are time-consuming and laborious, and fail to fully characterize soil structure, including the spatial distribution characteristics of different sized particles. Therefore, to reveal the transport and transformation mechanisms of material and energy [17] in shallow aquifers at the basin scale [18], soil particle-size distribution must be quantified in a more scientific manner to reveal the structure of the vadose zone.

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The fractal theory is an important field of nonlinear science. It can be used to study rigorous or statistically significant self-similarity of objects. In recent years, the fractal theory model approach has been widely used to reflect the structural characteristics of soils, as well as to calculate the fractal dimension of soil particle composition and pore structure, to characterize the structural composition of soils and their textural homogeneity [19,20]. The fractal dimension of soil particle-size distribution can not only characterize soil particle-size compositions, but also reflect the uniformity, arrangement, and combination of soil texture, that is, the structural characteristics of soils [21]. Based on the fractal theory, self-similarity of soils can be used to reveal the fine structure underlying the seemingly random bulk properties in order to characterize the distribution of soil particle sizes and soil voids. Moreover, it can be used to explore the mechanisms underlying other physiochemical properties of soils and its implication to geo-environmental evolution. Quantitative analysis of soil particle-size distribution based on the fractal theory serves as a novel method to study the physiochemical properties and hydrodynamic characteristics of basin soils. Therefore, in this study, we applied the fractal theory to assess the fractal dimension of 188 sets of soil samples within 258 km of the Ziya River basin in the North China Plain, while revealing the spatial distribution of soil particle size and soil voids, and exploring the applicability of soil particle fractal characteristics in the basin.

2 Materials and methods

2.1 General condition of the study region

The Ziya River basin (Figure 1), in the North China Plain, has typical climatic and topographical features. It is located in the central and southern parts of the Haihe River basin, consisting of two major river systems, namely the Fuyang and Hutuo Rivers. The two rivers merge in Xian county, and then flow through the New Ziya River into the Bohai Sea. The Ziya River basin spans from the Taihang Mountain in the west to the Bohai Sea in the east, bordered by the Zhangwei River in the south and Daqing River in the north; it spans across two provinces, namely, Shanxi and Hebei, and one city, namely, Tianjin. The average annual rainfall in the entire basin is approximately 540 mm per a. The piedmont alluvial fan, central paleochannel belt, and eastern coastal area, as three subsystems, constitute a piedmont-plain-coast region of the Ziya River basin. The shallow aquifer of the basin is primarily characterized by thick vadose zones with significant spatial variation in soil structure.

Figure 1: Map of the study area.

2.2 Experimental layout and test method

Sampling layers were determined according to previous study results [22]. Based on the lithology and particle analysis data of a typical area [4], sampling sites in the basin were chosen in the piedmont, plain, and coastal areas. Seven typical profiles were chosen in the study region, namely two piedmont profiles in Shijiazhuang and Luancheng cities in the upper reaches of the Ziya River basin, three plain profiles in Shenzhou city, Xian county, and Hejian city near the confluence of Fuyang and Hutuo Rivers in the Ziya River basin, and two coastal profiles in Dacheng and Tianjin cities along the flow path towards the sea (Table 1). Each area was sampled within a depth of 3.0 m from the surface. In each sampling area, two sites were drilled and soil samples at the same depth were uniformly mixed and passed through sieves of void size 2 cm. Then, the coning and quartering method was employed to prepare samples for the particle size analysis, with a total of 188 groups of samples.

Thirty-eight groups of soil samples were collected from Shijiazhuang and Luancheng cities in the piedmont, where there are thick vadose zones with groundwater table at the depth of 28–45 m. Ninety groups of soil samples were collected from Shenzhou city, Xianxian county, and Hejian city in the plain area, with the sampling areas located at river confluences in the Ziya River basin, they

Table 1: Geographic characteristic of the sampling sites

Sample num.	Depth (m)	Location	District	Geographical coordinates		Elevation (m)
				ψ (N)	λ (E)	
SJZ01-12	0–3.0	Shijiazhuang city, Hebei province	The western piedmont	114°28'33"	38°04'59"	85
LC01-26	0–3.0	Luancheng county, Shijiazhuang city		114°40'58"	37°53'16"	55
SZ01-30	0–3.0	Shenzhou county, Hengshui city	The median plain	115°30'58"	37°59'14"	30
XX01-30	0–3.0	Xianxian county, Cangzhou city		116°10'11"	38°12'29"	15
HJ01-30	0–3.0	Hejian county, Cangzhou city		116°07'55"	38°23'53"	14
DC01-30	0–3.0	Dacheng county, Langfang city	Eastern coastal areas	116°38'20"	38°39'37"	8
BH01-30	0–3.0	Binhai new region, Tianjin city		117°32'24"	39°00'48"	4

have significantly different lithology. In the coastal area, the sampling area in Dacheng city was located at the confluence of Ziya and Daqing Rivers, while that of Tianjin Binhai New Area was located at the estuary, both are representative of the coastal area. Sixty groups of samples were collected from the coastal areas. The horizontal distances from the profiles of Luancheng, Shenzhou, Xianxian, Hejian, Dacheng, and Tianjin Binhai New Area, in the order of west to east, to the profile of Shijiazhuang were 15, 94, 145, 178, 202, and 258 km, respectively.

Soil samples were pre-treated as follows. They were air-dried and passed through a sieve of mesh size 2 mm. Organic matter was removed using 6% H_2O_2 , carbonate was removed using 0.12 mol L^{-1} HCl, and Ca^{2+} and Cl^- were removed using 0.05 mol L^{-1} diluted HCl and distilled water. Next 0.5 mol L^{-1} NaOH was added to the mixture with stirring, and then the mixture was allowed to stand undisturbed overnight [23], followed by dispersion using a sonicator (160 W, 10–15 min). A QT-2002 laser particle size analyzer (Qudao Technology Company, Beijing, China) was used to measure particle volume percent of the 188 groups of soil samples. Particle-size volume and cumulative particle-size volume percentages were measured for 130 particle-size intervals in the range of 0–2,000 μm , and the data were analyzed to determine fractal dimension (D) of the 188 groups of samples.

2.3 Fractal dimension calculation

Fractal dimension of soil particle-size distribution at different soil profile depths in the basin was calculated using a fractal model of particle volume distribution as shown below.

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

where, d_i ($i = 1, 2, 3, \dots, n$) is the soil particle diameter, $d_{\max}$ is the maximum value of soil particle diameter, D is the

fractal dimension, δ is the soil particle-size variable, $V(\delta < d_i)$ refers to the cumulative volume of particles of size less than d_i , and V_0 denotes the volume of a soil sample.

When determining D , the first step is to calculate $\lg \frac{V(\delta < d_i)}{V_0}$ and $\lg \frac{d_i}{d_{\max}}$ using the measured particle-size data and volume data, and then to generate a y vs x plot of $\lg \frac{V(\delta < d_i)}{V_0}$ vs $\lg \frac{d_i}{d_{\max}}$ and fit the plot using the least-squares method to derive the slope, which was considered as D .

To effectively determine the spatial variation characteristics of D of soil particle-size distribution in the basin, three relevant parameters were defined according to the fractal theory and statistical calculation as follows. First, for a given soil profile, the particle size leading to the highest linear correlation coefficient in the above log–log linear fitting was identified (by plotting the cumulative volume percentages of particle sizes smaller than a given particle size as the x -axis values vs D values as the y -axis values) and defined as the characteristic fractal size δ for a given soil profile. Second, the volume percentage of particle size δ was allowed to vary within a certain range on the x -axis where the linear correlation was still maintained, and such a range was defined as the characteristic fractal interval. Finally, the average fractal dimension, that is, the average of the upper and lower limits of the corresponding D value range on the y -axis was denoted as D_a .

3 Results

3.1 Soil particle-size distribution characteristics of the basin

3.1.1 Particle size range

The 38 groups of samples from the western piedmont ranged in size from 0.429 to 697.168 μm . The minimum

Figure 2: $\text{Min} \frac{d_i}{d_{\max}}$ scatter plot of the typical piedmont-plains-coastal areas profiles.

particle size of $0.429 \mu\text{m}$ appeared at the depth of 2.7 m in the Luancheng profile (LC27), while the maximum particle size of $697.168 \mu\text{m}$ appeared at the depth of 1.1 m in the Shijiazhuang profile (SJZ11). Among the 38 samples collected from the piedmont, the maximum volume percentage of single particle size was 15.15% , corresponding to a particle size of $215.915 \mu\text{m}$ in the sample of SJZ11.

The 90 groups of samples from the central plain area ranged in size from 0.327 to $405.872 \mu\text{m}$. The minimum particle size of $0.327 \mu\text{m}$ appeared at $0.8\text{--}0.9 \text{ m}$ in the Xianxian profile (XX08 and XX09), while the maximum particle size of $405.872 \mu\text{m}$ appeared at 0.7 m in the Shenzhou profile (SZ07). Among the 90 samples, the maximum volume percentage of single particle size was 10.95% , corresponding to a particle size of $51.022 \mu\text{m}$ in the sample collected at the depth of 0.9 m in the Shenzhou profile (SZ09).

The 60 groups of samples from the eastern coastal area ranged in size from 0.327 to $338.901 \mu\text{m}$. The minimum particle size appeared at 1.5 m in the Tianjin Binhai New Area profile (BH15), while the maximum particle size appeared at 1.5 m in the Dacheng profile (DC15). Among the 60 samples, the maximum volume percentage of single particle size was 8.61% , corresponding to a particle size of $66.869 \mu\text{m}$ in the sample collected at the depth of 1.7 m in the Dacheng profile (DC17).

Figure 3: $\text{Aver} \frac{d_i}{d_{\max}}$ scatter plot of the typical piedmont-plains-coastal areas profiles.

The minimum particle size of soil samples was similar across the whole region from the piedmont to the coastal area, while the maximum particle size showed an obvious decreasing trend, that is, the particle size range of the samples gradually decreased. Furthermore, the single particle size and maximum volume percentage gradually decreased. Therefore, soil particle-size distribution tended to be more uniform from the piedmont to the coastal area and the particle size tended to decrease.

3.1.2 $\text{Min} \frac{d_i}{d_{\max}}$ and $\text{Aver} \frac{d_i}{d_{\max}}$

$\text{Min} \frac{d_i}{d_{\max}}$ is the ratio of the minimum particle size to the maximum particle size of a soil sample; the smaller the ratio, the larger the particle size range and the more significant the difference in particle composition. $\text{Aver} \frac{d_i}{d_{\max}}$ is the ratio of the average particle size to the maximum particle size; the larger the ratio, the closer the particle size of the sample to the maximum particle size and the higher the overall uniformity of particle size.

The horizontal distances between the profiles presented in Section 2.2 and the Shijiazhuang profile were normalized; that is, the distance between each profile and the Shijiazhuang profile was divided by a distance

of 258 km (the distance between the Tianjin Binhai New Area and Shijiazhuang profiles). With the results as the x -axis values (the x -axis value was set to 0 for the Shijiazhuang profile and 1 for the Tianjin Binhai New Area profile), $\text{Min} \frac{d_i}{d_{\max}}$ and $\text{Aver} \frac{d_i}{d_{\max}}$ were plotted as y -axis values, to draw the distribution graph of the Ziya basin (Figures 2 and 3).

As shown in Figures 2 and 3, both $\text{Min} \frac{d_i}{d_{\max}}$ and $\text{Aver} \frac{d_i}{d_{\max}}$ in the basin showed an overall decreasing trend from the west to the east. Both $\text{Min} \frac{d_i}{d_{\max}}$ and $\text{Aver} \frac{d_i}{d_{\max}}$ presented significant changes at low depths of the soil profile in the piedmont, especially within a depth of 1 m where the maximum $\text{Aver} \frac{d_i}{d_{\max}}$ reached 0.407, while the minimum value was only 0.004. A significant amount of large soil particles were present in the piedmont, while small particles were present at lower depths of the soil profile due to natural and anthropogenic processes. This led to a large difference in the particle size within 1 m below the surface and consequently a significant change in both $\text{Min} \frac{d_i}{d_{\max}}$ and $\text{Aver} \frac{d_i}{d_{\max}}$. However, in the central and coastal areas, both $\text{Min} \frac{d_i}{d_{\max}}$ and $\text{Aver} \frac{d_i}{d_{\max}}$ presented relatively significant changes only at depths greater than 1.5 m. This can be attributed to the fact that soil particle sizes in the central and coastal areas were small. Furthermore, the surface particles tended to have the same size due to precipitation and weathering, with a small number of large particles existing only in the deeper layers below 1.5 m.

At the whole-basin scale, $\text{Min} \frac{d_i}{d_{\max}}$ and $\text{Aver} \frac{d_i}{d_{\max}}$ were not always high at each depth in the western piedmont profiles. Moreover, significant differences in particle size were also observed at depths of 1.5–2.0 m in the coastal profiles. However, there were large differences between the two areas in soil structure, with the soils of the piedmont dominated by sandy soils and those of the coastal area dominated by clay. This indicated that it is necessary to obtain deeper insight into the particle-size volume percentages and consider both particle size differences and particle size percentages. Therefore, it is necessary to introduce D of particle-size distribution for quantitative characterization of soil structure.

3.2 Soil structure identification of the basin based on D of particle-size distribution

3.2.1 Calculation of D of particle-size distribution

Fractal dimension of particle size was calculated as described in Section 2.3, as exemplified with sample XX01, which referred to the first sample (No. 01) at a depth of 0.1 m in the Xianxian profile.

First, particle size grouping was performed according to the particle size intervals mentioned in Section 2.2. Table 2 presents the cumulative volume percentages of all the particle sizes that were below a given particle size. Sample XX01 consisted of 52 size fractions, in which the minimum particle size was $0.806 \mu\text{m}$, with the

Table 2: Summary of the volume percentages of soil particle sizes (XX01)

Particle-size (μm)	Volume percentage (%)	Particle-size (μm)	Volume percentage (%)	Particle-size (μm)	Volume percentage (%)
0.882	0.02	4.472	3.07	22.664	2.6
0.966	0.06	4.894	3.3	24.802	2.27
1.057	0.13	5.356	3.51	27.142	1.97
1.156	0.2	5.861	3.68	29.703	1.69
1.266	0.28	6.414	3.79	32.506	1.42
1.385	0.39	7.019	3.88	35.573	1.12
1.516	0.52	7.681	3.93	38.93	0.84
1.659	0.71	8.406	4.02	42.603	0.58
1.815	0.92	9.199	4.09	46.622	0.36
1.986	1.14	10.067	4.1	51.022	0.22
2.174	1.33	11.017	4.04	55.836	0.12
2.379	1.51	12.057	3.94	61.104	0.06
2.603	1.68	13.194	3.83	66.869	0.03
2.849	1.88	14.439	3.71	73.179	0.02
3.118	2.1	15.801	3.57	80.084	0.01
3.412	2.35	17.292	3.43	—	—
3.734	2.59	18.924	3.21	—	—

Figure 4: Volume and cumulative volume distributions of the representative soil particle sizes in the piedmont-plain-coastal samples (LC17, XX01, and BH10). (Black bar chart: volume distribution and Red line: cumulative volume distribution).

cumulative volume of particles larger than $0 \mu\text{m}$ but smaller than $0.806 \mu\text{m}$, accounting for 0.01% of the total particle volume of the sample. The maximum particle size was $80.084 \mu\text{m}$ and the cumulative volume of particles was larger than $73.179 \mu\text{m}$ but smaller than $80.084 \mu\text{m}$, which also accounted for 0.01% of the total particle volume of the sample.

Second, particle-size distribution curves were plotted for the representative soil samples of the basin based on particle-size volume percentages (Figure 4). As shown in Figure 4, soil particle sizes in the basin tended to be normally distributed, with the distribution being relatively

steep for the piedmont samples (a certain particle size accounted for more than 9%) and being relatively flat for the plain and coastal samples. From the piedmont to the coastal area, the highest particle-size volume percentage decreased in the order of the particle sizes 60–70, 10–15, and 2–4 μm .

Next $\lg \frac{V(\delta < d_i)}{V_0}$ and $\lg \frac{d_i}{d_{\max}}$ were calculated as described in Section 2.3. The y vs x plot of $\lg \frac{V(\delta < d_i)}{V_0}$ vs $\lg \frac{d_i}{d_{\max}}$ was fitted using the least-squares method, deriving a D value of 1.5827 for sample group XX01.

Finally, the D values of the 188 groups of samples from the 7 profiles in the basin were calculated following the above steps, and a D -value distribution map (Figure 5) was generated based on the aforementioned normalization method for horizontal distances of the 7 profiles mentioned in Section 2.2.

Figure 5 shows the D values of the basin between 0 and 3; they were subjected to significant spatial variation, with the minimum of 0.130 at the depth of 1.5 m in the Shijiazhuang profile and the maximum of 2.188 at the depth of 1.0 m in the Tianjin Binhai New Area profile. The D values presented the most significant changes at the depth of 1.5 m, making this a dividing depth. The D values above the dividing depth showed an overall increasing trend along the river flow direction from the

Figure 5: Distribution map of the D values of the basin.

piedmont to the coastal area, while the D values below the dividing depth tended to decrease along the river flow direction. Along the x -direction, the D values of the piedmont were generally small in the range of 0.3–0.6 with an average of 1.202, in contrast to the average of 1.757 in the coastal area. However, as clearly depicted in the figure, the soil samples at the normalized distance of 0.8–0.9 in the coastal area showed relatively small D values, and there were significant differences in soil particle-size distribution, indicative of typical spatial variation. The above D -value analysis revealed that soil particle sizes did not monotonically decrease from the piedmont to the coastal area, nor tended to have a uniform distribution, but it was the spatial variation that showed a decreasing trend.

To further determine the spatial variation in D , it is necessary to identify a particle-size fraction that had the greatest effect on D , and the corresponding particle size was defined as the characteristic fractal size. The content of such particle-size fraction can affect the D of particle-size distribution and ultimately lead to spatial variation in D at the basin scale.

3.2.2 The average fractal dimension (D_a) of the basin

As shown by Figure 6 and the previous analysis, the D values in the basin varied greatly, and therefore, the average D value was calculated in different segments of D , that is, $D \leq 1$, $1 < D \leq 1.5$, and $D > 1.5$. In each segment, by taking the cumulative volume percentages of particle sizes smaller than 2, 5, 10, 30, 50, 100, 200, and 300 μm as the x -axis values and the corresponding D values as the y -axis values, a scatter plot was generated in which the particle size leading to the largest linear correlation coefficient was defined as the characteristic fractal size. The results showed that when $D \leq 1$, the characteristic fractal size was 30 μm in the basin (Figure 6). As shown in Figure 6,

Figure 6: The correlation between the particle size cumulative percentage ($d_i \leq 30 \mu\text{m}$) and the fractal value ($D \leq 1$).

the characteristic feature interval was 3–22%, and the D values corresponding to the lower and upper limits of the interval were 0.18 and 0.68, respectively, indicating an average of 0.43, which was taken as D_a of the basin. Similarly, when $1 < D \leq 1.5$, the characteristic fractal size was determined to be 20 μm and D_a was 1.37, and when $D > 1.5$ the two parameters were 10 μm and 1.77, respectively.

4 Discussion

- (1) It has been widely accepted that the larger the particle size, the smaller the D value. The results of this study revealed that D might be small in the case of small particle size with a uniform distribution, depending on the particle-size range of the samples, namely $\text{Min} \frac{d_i}{d_{\max}}$. In the case of large $\text{Min} \frac{d_i}{d_{\max}}$, namely a small particle-size range, D was small, which suggests that cohesive soils having small particle sizes may also have a small D value (the particle sizes of sample LC24 were in the range of 0.429–27.142 μm and the D value was 1.383). Furthermore, we observed that even in the case of large particle sizes, D could be large if the particle sizes are uniformly distributed within a small particle-size range. In summary, in the case of small particle-size range, with uniform particle-size distribution, the sample would show an abnormal D value – the larger (or smaller) the particle size, the greater (or smaller) the D value.
- (2) At the basin scale, the particles in the piedmont were coarse with non-uniform distribution; the particles in the central plain were still relatively coarse, but tended to gradually have a uniform distribution. The particles in the coastal area were small with a more uniform distribution. However, soil particle sizes in the deeper regions (below 1.5 m) of the piedmont were smaller, whereas the counterparts of the coastal area were larger, which was inconsistent with the widely accepted view. This may be related to the spatial variation in soil particle size, and to better understand this aspect, it is necessary to include more sampling sites in studies dedicated to spatial variation in typical areas.
- (3) The average fractal dimension of the basin was conducted using a three-segment method to identify the representative particle size in the basin, as the volume percentage of such particle size would determine the differences in soil structure of the basin. This approach is consistent with a recent proposal to construct a “soil structure library” based on different types of soils [13].

Rabot suggested using this technique to build up an open access “soil structure library” for a large range of soil types, which could form the basis to relate more easily available measures to pore structural attributes in a site-specific way.

A soil structure library based on the fractal methods would make it much easier to quantify the differences in soil voids and to predict the corresponding hydraulic properties, solute transport properties, and thermodynamic properties of the quantified soil structures.

5 Conclusion

- (1) By studying the fractal dimension of 188 sets of soil samples within 258 km of the Ziya River basin in the North China Plain, it was found that the fractal dimension D was not correlated with soil grain size, but was highly sensitive to the uniformity of the soil structure.
- (2) At the basin scale, the fractal theory can effectively quantify the characteristics of soil structure, and can accurately and effectively describe three-dimensional structural changes in soil. The average particle size, range of particle-size volume percentage, and maximum volume percentage of a single particle size decreased from the piedmont to the coastal area, with D showing an overall decreasing trend.
- (3) The potential of using characteristic fractal size and average fractal dimension to quantitatively characterize representative soil structure at a large scale to construct a “soil structure library” provides a new direction for the calculation and inversion of hydraulic properties, solute transport properties, and thermodynamic properties.

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