KSCE Journal of Civil Engineering (2016) 20(2):639-646

DOI 10.1007/s12205-015-0408-y

Geotechnical Engineering

pISSN 1226-7988, eISSN 1976-3808
www.springer.com/12205

Micro-characteristics of Strength Reduction of Tuff Residual Soil with Different Moisture

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Received July 23, 2014/Revised January 8, 2015/Accepted May 4, 2015/Published Online July 7, 2015

Abstract

The weathered residual soil slope formed by the long term weathering of large igneous rock mass under the impact of abundant rainfall in southern China is prone to instability and deformation, causing wreak havoc. Therefore, it is very important to study the internal mechanisms of its instability and deformation induced by rainfall based on its special structural properties. In this paper, we 1) analyzed its mineral compositions using X-ray diffraction method, 2) obtained its shear strength parameters through quadruplet direct shear tests in the conditions of different moisture contents and dry-wet cycles, 3) studied its microstructure using Scanning Electron Microscopy (SEM), 4) quantitatively studied its porous distribution with the help of MATLAB image processing toolbox, and 5) established the fitting curve of fractal dimension and soil shear strength parameters of the tuff residual soil of Qishan landslide zone in Yongtai County, Fujian Province, China. The results indicated that 1) tuff residual soils are rich in clay minerals with lamination as the dominant microstructure, 2) moisture content and dry-wet cycle significantly affect soil microstructures as characterized with decreased pore size and increased pore number, and 3) soil mass has obvious fractal characteristics, the shear strength decreases gradually with the fractal dimension increasing and the fractal dimension has greater impact on soil cohesiveness than the angle of internal friction.

Keywords: *tuff residual soil, microstructure, moisture content, fractal dimension, shear strength*

1. Introduction

Igneous weathered residual soil slopes, as an important slope project type in the current field of engineering, are mainly distributed on mountain areas of South China where granite and other igneous rocks outcrop, develop. Under the influence of typhoons and rainfalls, these kinds of slopes often wreak landslide disasters. Compared with rock slope and other silt soil or sandy soil slopes, igneous residual soils are macroscopically characterized by a series of complex properties such as discontinuity, heterogeneity, anisotropy, indeterminacy, and significant structures. Therefore, the properties and failure mechanisms of this kind of special soil have not been discussed in depth.

Currently, most researches on the stability and instability mechanisms of igneous residual soil focus on the macroscopic characteristics of soil mass such as particles' size, density, moisture content, shear strength parameters and their changes (Wu *et al.*, 2008; Hu *et al.*, 2009; Liao *et al.*, 2003), only few studies on media structures, especially on analysis of their microstructures. With macroscopically analysis techniques and interdisciplinary researches developing, the applications of static, qualitative, and quantitative microscopic soil testing technology in landslide studies have made some achievements. The microstructure features and mechanical parameters of the typical landslide and slip zone soils of Zhaoshuling in Badong County, Hubei Province, the expansive soil of Nanyang, Henan Province, the collapsible loess, and the slip zone soil in Shanxi Province, has also been investigated in detail respectively (Liu *et al.*, 2009; Chen *et al.*, 2009; Fang *et al.*, 2013; Wen *et al.*, 2004, 2005). However, the current studies all consider the particle-composed simplex clay and loess as their main objects. Studies on this type of soil, which has not only specific, complex characteristics of structure and composition, but also strong regional distribution, are still in the primary stage, especially those on the relationship between its macroscopic strength and microstructure under the influence of rainfall or different water content remains unclear.

As is known, the soil strength is sensitive to moisture content, and it is the main reason of the strength changes. Lots of researchers have established the relationship between moisture and strength parameters in their articles. However, all these results are located at the macro level. "How and why the increase of water content can cause the strength reduction?" was still no clear resolution, especially at the micro level. And that was the main purpose of this studies.

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The macroscopic complexity exhibited by some soil mass lies essentially on the discontinuity and uncertainty of its microstructure. Soil's complex physical properties reveal the nonlinearity of its microstructural compositions (Chen *et al.*, 2007). Thus, it is of significance analyzing the microstructural features of igneous residual soil mass and their effects on the shear strength parameters in the rainfall condition to reveal the landslide's deformation and failure mechanism. With the typical tuff residual soil developed in Fujian Province, South China, as an example, we chose the fractural dimension to describe the microstructure morphology in different moistue, and analyzed the microstructural characteristics of tuff slip zone soil mass subject to moisture content and their relationship to the shear strength parameters.

2. Research Scheme

The slip zone of Qishan landslide, Yongtai County, Fujian Province, belongs to the tectonic, erosive, hilly topography. Its overlying layer is formed by the Quaternary residual slope sediments and its underlying layer is crystal tuff. The slope rock and soil mass is representative of the tuff of Fujian Province, China. The tuff weathered residual soil was chosen as our object of study.

2.1 Testing Scheme

The testing scheme was list as below:

1. The mineral components soil powder samples were identified by conducting an in situ X-ray diffraction experiment using a Bruker AXS D8-Focus X-ray diffractometer (Jia *et al.*, 2013).
2. The shear strength parameters of soil samples were obtained using quadruplet direct shear tests in conditions of different moisture contents and dry and wet cycle conditions with the vertical load of 100, 200, 300 kPa (Table 1).

Table 1. Experiment Scheme of Quadruplet Direct Shear Test

Sample number	Sample state	Moisture content (%)	Vertical load (kPa)
D-1	Saturation	37	100
D-2			200
D-3			300
E-1	Sub-dry	25.3	100
E-2			200
E-3			300
F-1	Nature dry	9.8	100
F-2			200
F-3			300
G-1	Three cycles of wet-dry	34.6	100
G-2			200
G-3			300
H-1	One cycle of wet-dry	34.6	100
H-2			200
H-3			300

Fig. 1. The Gilt Soil Sample

3. Microstructures of the tested soil samples were observed using a Hitachi SU8010 field emission Scanning Electron Microscope (SEM) (Chao *et al.*, 2014). To ensure the degree of vacuum in the SEM vacuum system, dry soil samples were used. In addition, samples were polished by removing disturbed particles on the surface and coated with gold before subject to image scanning (Fig. 1).

2.2 Qualitative and Quantitative Analysis Methods of Soil Sample Microstructure

Soil microstructure images scanned by the SEM at different magnifications and different angles intuitively show the disposition of soil's microstructure units and the size of pores in it. In order to acquire the physical parameters of these microstructures, particles and pores in the images were separated first using both image preprocessing and binary threshold segmentation techniques supported by MATLAB (Mao *et al.*, 2004; Liu *et al.*, 2003), and their microstructure parameters such as area, circumference, orientation degree were obtained using both bwlabel and regionprops functions supported by MATLAB (Miao *et al.*, 2014). In this study, the manually set threshold and the images of 7,000 magnification were used for analysis. The definition and calculation of those quantitative parameters need to be extracted from the soil samples are shown as follows (Fang *et al.*, 2013; Xu, 2008; Song, 2012).

2.2.1 Area S and Circumference L

After binary image processing, what we obtained is a monochrome image of only two gray values 0 and 1, where the value 0 represents pores and the value 1 denotes particles. In order to distinguish inter-connected graphs and separately calculate their areas and circumferences, it is necessary to mark the images and statistically calculate the number of pores or particles. The areas and circumferences were calculated by counting the pixels they occupied.

2.2.2 Circularity R

The circularity R $(= 4\pi S/L^2)$ denotes the extent of a particle close to a circle. S is the region area the particle occupies, L is the circumference of the region. The larger R is, the closer the particle is to a circle.

2.2.3 Degree of Orientation *H*

In the quantitative analysis of the soil microstructure, the directionality of a region is often measured using the probability of entropy. The directionality of pores is determined by the azimuth of its longest chord and correspondingly represented using the parameter of azimuthal angle. Assuming that the azimuthal angle of the pore is α with its value domain $[0, \pi]$, and equally dividing α*'s* increment into n parts*,* the probability of the pore oriented at certain domain $[i, i+1]$ is $p_i(\alpha)$, thus, the degree of orientation is:

$$H = -\sum_{i=1}^{n} p_i(\alpha)\log_n p_i(\alpha) \tag{1}$$

It is clear from Eq. (1) that the smaller the *H* is, the better the order of soil structure unit body disposition, vice versa.

2.2.4 Fractional Dimension D_p

Fractal theory can be used to deal with very unsmooth and irregular geometries produced in nature and nonlinear systems (Ma *et al.*, 2009; Liang *et al.*, 2012). In this paper, the plane fractal dimension D_p is used as an indicator to study the soil microstructure fractal and estimated by a box-counting dimension (Fig. 2).

$$D_p = -\lim_{\varepsilon \to 0} \frac{\lg N(\varepsilon)}{\lg(\varepsilon)} = -k \tag{2}$$

where ε is the side length of a cubic box, $N(\varepsilon)$ is the total number of grids occupied by the target, and *k* is the slope of the straight line.

The larger plane fractal dimension is, the larger the proportion shared by pores in the soil mass, and the lower the degree of agglomeration of soil particles.

3. Qualitative Analysis of Microstructure of Soil with Different Moisture Contents

3.1 Analysis of Soil Sample Mineral Compositions

The typical diffraction patterns of tuff residual soil were obtained through X-ray diffraction experiments (Fig. 3). It is known from the figure that the main components of tuff residual soil are quartz, montmorillonite, illite, and hematite, with contents

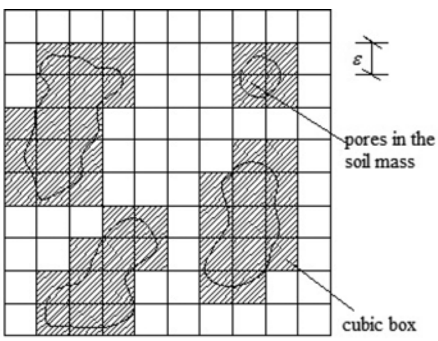

Fig. 2. The Box-counting Dimension Diagram

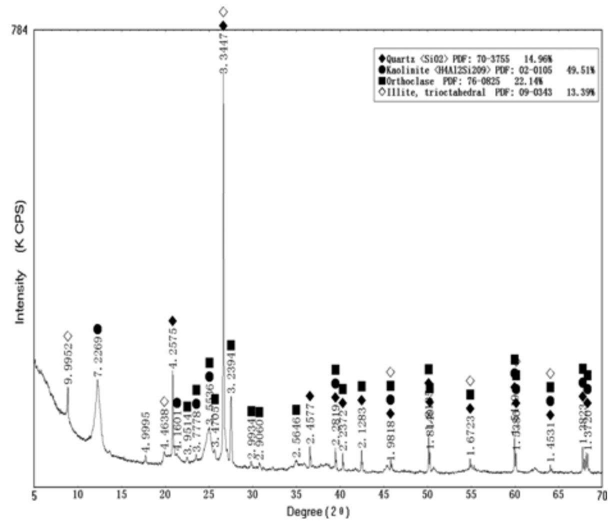

Fig. 3 Tuff Residual Soil Undisturbed Sample X-ray Diffraction Pattern

of 65%, 15%, 12%, and 8%, respectively. The tuff residual soil contains 15% montmorillonite, which has strong water absorption ability, thus, once interacting with water, it is prone to softening and expansion due to the formation of electric double layer, leading to increased thickness of diffusion layer or weak water bound layer, enlarged spacing of interparticles, weakened coupling force, and eventually resulting in easier slip among soil particles.

3.2 Qualitative Analysis of Soil Microstructure

The microstructure images of slip zone soil in the different conditions were obtained through SEM experiments. Some researches confirms that rainfall is the main culprit causing the area to slide (Tang, 1999; Jin, 2005). In this study, the micro-structure images of the in-situ soil sample, water saturated soil samples and soil samples underwent wet and dry cycles were taken for comparative and qualitative analysis (Fig. 4):

1) In the in-situ soils, granular quartz and flaky clay minerals fill in the intergranular pores; during long-term leaching and erosion, the collocation of particles of the in-situ soil is relative loose, therefore, its surface distributes a large number of micro-ores and rare pores

2) In saturated samples and samples underwent dry and wet cycles, particles under certain pressure tend to aggregation. Because flaky clay minerals are adsorbed onto the surface of particles or filled into pores and the fast leaching of relative small tuff residual soil particles under the action of the capillary force, under the expansive force of clay minerals after their water absorption, interconnected pores appears. Under the same pressures, the more the cycles of wet and dry, the looser the collocation of soil particles. Particles in H-1 sample are generally interacted through surface to surface contacts, and show obvious orientation, and interparticle microcracks, and particles in G-1 sample are flaky, loose, and disorderly arranged, interacted prevalently through surface–edge and

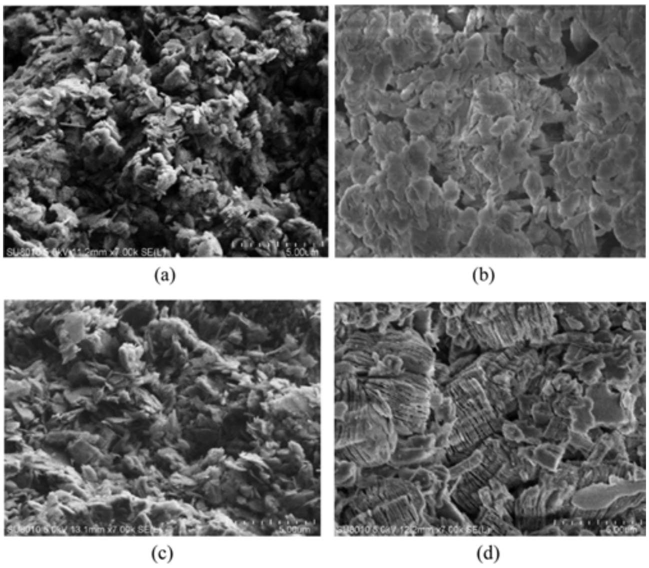

Fig. 4. Typical Microstructure Images of Tuff Residual Soil Samples Taken by SEM: (a) In-situ Soil Sample F-1; (b) Saturated Soil Sample D-1; (c) Soil Sample After 3 Cycles of Wet and Dry (G-1); (d) Soil Sample After 1 Cycle of Wet and Dry (H-1)

corner-edge contact, and have plentiful, easily disturbed interparticle pores. The reason for these phenomena is the presence of hydrophilic minerals in the soil, therefore, development of intergranular pores or presence of Fe^{3+} in water could accelerate soil disintegration, form flaky or granular stripping of soil units and eventually resulting in the destruction of soil microstructure.

The above-mentioned soil microstructure images indicate that soil has laminated microstructure that is often found in the surface–surface and surface-side contacting clay minerals and small amount of internal granular particles and its pores often propagate along the long axis direction of clay flakes.

4. Quantitative Analysis of Soil Microstructure with Different Moisture Contents

4.1 Quantitative Analysis of Soil Microstructure

Table 2 lists their quantitative analyses parameters of pore microstructures in soil samples and Fig. 5 shows the characteristic varying curves of pore microstructures under different moisture contents and wet-dry cycle conditions. Because the moisture contents of soil samples were same in the wet-dry cycle condition, the mean values of the characteristic parameters of soil microstructures were used for comparison.

From Table 2 and Fig. 5, we could conclude as follows:

4.1.1 Effects of Vertical Load

By comparison among three specimens in group D, in the same water content condition, with the vertical load increasing, the pores become smaller in size, greater in number, and more directionally arranged. The soil structure changes from the honeycombed into the flaky one and the planar porosity and the fractal dimension all have decreasing trends. When the vertical load reaches 300 kPa, the soil structure fails and the interparticles collocation becomes disorderly. The samples of Groups E and F obey the same rule. Sstatistical analysis shows that the fractal dimension has a good linear relationship to the plane porosity, as shown in Fig. 6. The larger the fractal dimension D_p of the soil, the higher the pore content.

4.1.2 Effect of Moisture Content

In the same vertical load condition, comparison of samples with different moisture contents in D, E and F groups finds that the higher the moisture content, the more significant the changes in soil structure, the weaker the stability of soil. This phenomenon is mainly because these samples contain water-sensitive minerals such as illite and smectite. Their flaky microcrystallines separate pores into many micropores, thus increasing the tortuosity of

Table 2. Characteristic Parameters of Soil Pore Microstructures

Sample No.	Plane porosity	Mean area	Mean perimeter	Number	Circularity	Orientation	Fractal dimension
In-situ soil	45.33	200.77	55.36	164	0.82	0.93	1.9616
D-1	41.94	180.21	50.65	405	0.88	0.95	1.9475
D-2	39.23	132.43	42.81	338	0.91	0.92	1.9372
D-3	39.48	124.81	40.6	258	0.95	0.87	1.9315
E-1	40.86	219.32	57.93	464	0.82	0.93	1.9411
E-2	38.01	127.8	39.39	230	1.03	0.94	1.9225
E-3	37.53	76.67	29.33	126	1.12	0.91	1.8906
F-1	41.27	174.01	50.46	430	0.86	0.93	1.9356
F-2	39.96	89.53	32.71	211	1.05	0.9	1.9321
F-3	38.39	77.34	30.47	211	1.05	0.89	1.9065
G-1	43.16	243.3	55.59	326	0.99	0.97	1.9653
G-2	41.37	207.31	47.82	217	1.14	0.92	1.9422
G-3	38.55	113.68	34.77	186	1.18	0.92	1.9337
H-1	42.24	187.22	48.12	364	1.02	0.94	1.9581
H-2	41.83	146.93	43.44	255	0.98	0.94	1.9433
H-3	39.61	128.57	38.37	262	1.1	0.89	1.9276

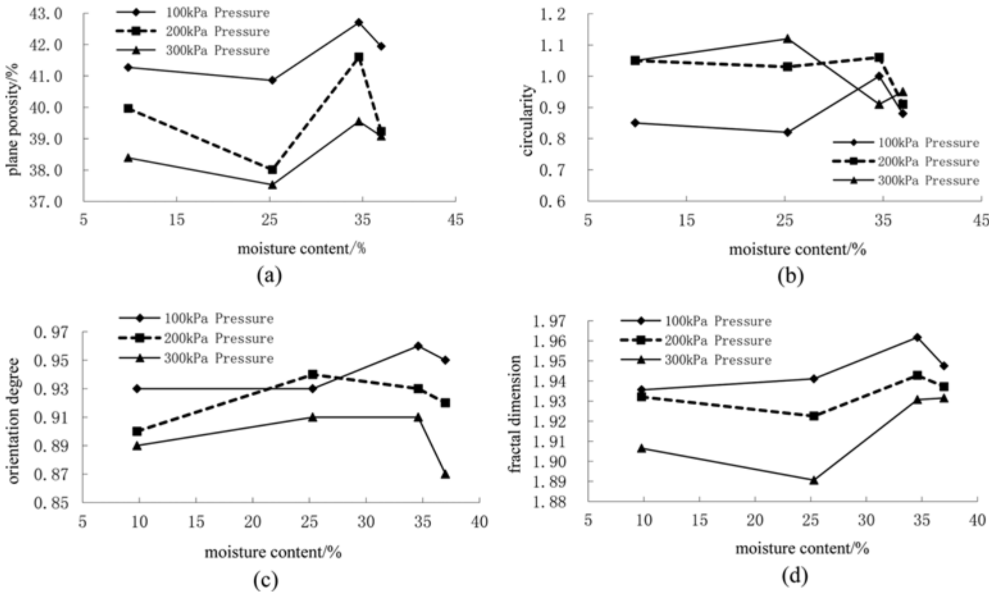

Fig. 5. Relationships of Quantitative Characteristic Parameters of Pores to Moisture Content: (a) Plane Porosity vs. Moisture Content; (b) Circularity vs Moisture Content; (c) Orientation Degree vs Moisture Content; (d) Fractal Dimension vs Moisture Content.

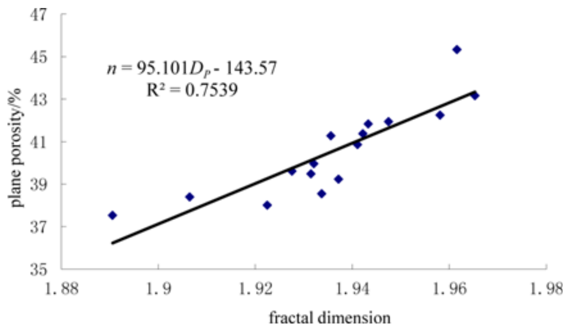

Fig. 6. Fitted Relationship Between Plane Porosity and Fractal Dimension D_p

water flowing in the soil. However, wirelike minerals are easy to be washed away, blocking pores and damaging soil structure.

4.1.3 Effects of Water Content on Microstructural Parameter

The effect of water content on microstructural parameters of soil samples fluctuates possibly due to the following reasons. On the one hand, significant effect of wet and dry cycles on soil micro-structure leads to obvious fluctuation, demonstrated as significantly increased pore numbers, poor directional arrangement, increased pore fractal dimension, and reduced soil particle aggregation. On the other hand, the microscopic characteristics of soil samples do not show a change of unidirectional trend with water content increasing. It can be seen from Fig. 5 that soil samples have lest pore number and fractal dimension when their water content is 25.3%, lower than that, pore directional collocation decreases and higher than that, pore directional collocation increases. By contrast, the circularity is barely affected. In general, when soil moisture content is 25.3%, pore orientation degree is relatively poor, the pore number is relatively small, and the sliding friction and occlusive friction among particles are relatively large, indicating that at moisture content of about 25.3%, soil strength is relatively large, in consistence the result of shear strength test.

4.1.4 Effect of Rainfall (wet) and Transpiration (dry)

Soil mass was affected by cycles of rainfall (wet) and transpiration (dry). After one cycle of wet-dry, the structure of soil (sample G) rarely changed, showing slightly increased interparticle gaps, uniformly distributed pores and obviously orientated particle collocation. After three cycles of wet-dry, the structure of soil (sample H) changed significantly, showing significantly increased pore gaps among particles, increased pore ratio, weakened particle orientation, irregular collocation, severely damaged flaky particles, and decreased particle size (from 4~5 mm to 0.5~2.5 mm), changes of soil structure from originally laminated structure to flocculent one, and attenuated stability. It is clear that with aggregation and rearrangement of soil particles, changes of soil microstructure significantly alter soil physical and mechanical properties.

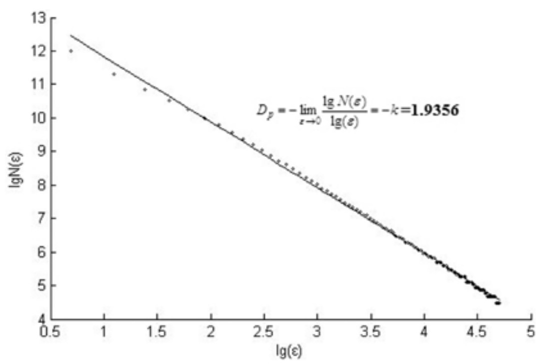

Fig. 7. Fitting Curve of Fractal Dimension D_p of Undisturbed Samples (F-1)

Table 3. Shear Strength Parameters and Fractal Dimension D_p

Sample Number	Shear force (kPa)	Cohesion (kPa)	Internal friction angle (°)	Fractal dimension D_p	Mean fractal dimension
D-1	69.68			1.9475	
D-2	110.69	28.67	22.31	1.9372	1.9387
D-3	151.7			1.9315	
E-1	94.38			1.9411	
E-2	137.05	51.71	23.12	1.9225	1.9181
E-3	179.72			1.8906	
F-1	82.79			1.9356	
F-2	124.94	40.63	22.87	1.9321	1.9247
F-3	167.1			1.9065	
G-1	63.47			1.9653	
G-2	102.17	24.76	21.17	1.9422	1.9471
G-3	140.88			1.9337	
H-1	72.38			1.9581	
H-2	112.6	32.16	21.92	1.9433	1.943
H-3	152.81			1.9276	

4.2 Relationship Between Soil Microstructural Characteristics and Soil Shear Strength Parameters

Microstructure image analysis found that soil samples had good fractal characteristics and established calculated curve of fractal dimension D_p (Fig. 7). Table 3 shows the results of direct shear test of soil samples. Figs. 8 and 9 show the established relationship between shear strength parameters and fractal dimension D_p.

Their quantitative relationship can be expressed as:

$$\left.\begin{array}{l}\varphi = -2658.3D_p^2 + 10214D_p - 9788.9 \\ R^2 = 0.9735\end{array}\right\} \quad (3)$$

$$\left.\begin{array}{l}c = -23201D_p^2 - 90497D_p + 88274 \\ R^2 = 0.9434\end{array}\right\} \quad (4)$$

Where φ is internal friction angle, c is cohesion, D_p is fractal dimension.

As can be seen from the above figures, the internal friction

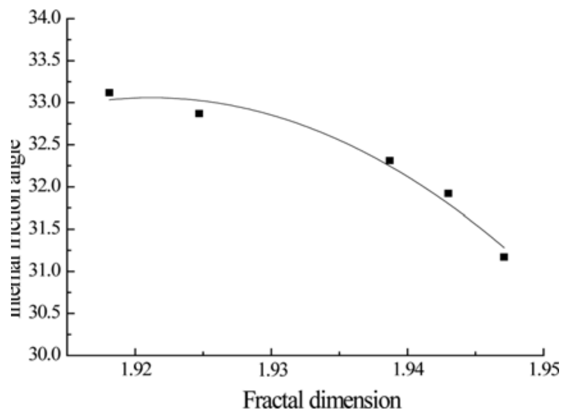

Fig. 8. Fitting Curve of Internal Friction Angle and Fractal Dimension D_p

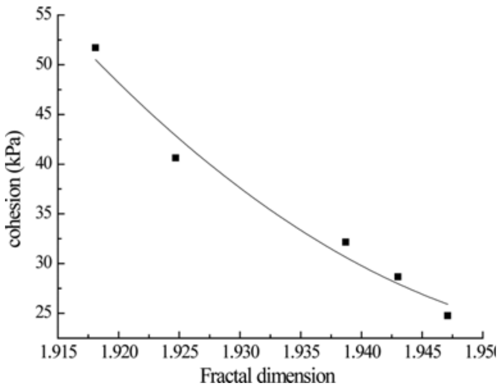

Fig. 9. Fitting Curve of Cohesion and Fractal Dimension D_p

angle and cohesion decrease with fractal dimension increases and have a good quadratic function relationship. Internal friction angle increases with fractal dimension and demonstrates an increased reduction rate; Cohesion increases with the fractal dimension and has a progressively decreased reduction rate. Relatively speaking, the effect of fractal dimension on cohesion is greater than that on internal fiction angle, indicating that at different fractal dimension, soil samples with different porosity have different internal structure and different contact and arrangement among particles. The greater the fractal dimension, the greater the porosity among particles, the more the soil particles tend to disperse and the smaller the friction between soil particles. Cohesion of soil with fine particles is mainly composed of connection force of water gel formed by bound water between soil particles or connection force coproduced by soil cementation connection and capillary water connection. Due to the presence of bound water surrounding soil particles, the cohesion of soil with fine particle is smaller. At rainfall condition, with water content increases, the shear strength of soil particles is reduced.

4.3 Microscopic Mechanism of Rainfall-induced Landslides Soil Instability

As can be seen from the above analysis, for residual soil formed by igneous rock weathering, because its rock medium contains pyroxene, hornblende and other minerals, it is easily weathered and hydrolyzed, forming a large number of clay minerals. These minerals' micro-structure could be damaged in rainfall condition, thus its porosity gradually increases, resulting in reduced soil shear strength parameters and subsequent slope instability.

5. Conclusions

For tuff weathered residual soil, soil-water interaction affects the physicochemical environments of soil particles as well as the soil micro-structural properties such as pore size and arrangement patterns. Porosity changes are the internal factor affecting soil deformation and the major determinants of soil physical and mechanical properties. Both soil deformation characteristics and strength properties are affected to varying degrees by changes in soil microstructure.

The main mineral components of tuff residual soil found by X-ray diffraction experiments are montmorillonite and illite with loose structure, larger porosity, honeycomb structure. This soil has high sensitivity, low strength, high compressibility and characteristics of water softening and disintegration and is the major source affecting soil slope engineering geology and the material basis for rainfall-induced landslides.

FESEM image shows that microscopic particles of tuff residual soil is composed of massive single columnar and bulk particles and flaky mineral polymers. Most massive particles are covered with high levels of single particles (quartz particles). Clay mineral particles inside the massive particles are mostly contacted side by face and face by face.

At the same water content, with the vertical load increasing, the plane porosity and mean pore area show a decreasing trend. Thus, the sample particles are more densely arranged and have more obvious orientation and increased circularity, thus leading to more serious damage to soil structure.

At moisture changing and wet-dry cycle conditions, experiencing a cycle of wet-drying process, soil structure change is not obvious, showing increased number of pores, and oblivious particle orientation. However, after 3 cycles of wet-dry process, pores between sample particles increases greatly, become disorientated and disorderly arranged, breakage of flaky particles become severe, particles are smaller in size and soil structure becomes flocculation rather than a stack of sheet-like.

Tuff residual soil has fractal characteristics obviously. With increased cycles of wet-dry process, the fractal dimension is also increasing, indicating that soil particles after wet-dry cycle become loose, and their density decreases, thereby reducing soil shear strength, which is consistent with soil disintegration characteristics.

The fractal dimension of pore distribution D_p have a good quadratic function relationship with unsaturated shear strength, indicating that with the fractal dimension of soil increasing, soil internal friction angle and cohesion decrease. Among them, the cohesion is affected to a larger degree by fractal dimension.

Overall, the study from the microscopic structure point of view studied the internal characteristics of worsened soil shear strength parameters at rainfall condition using tuff residual soil as an example, with the hope to provide a basis for analysis of sliding slope deformation mechanisms.

Acknowledgements

This study was supported by grant from the Special Fund for the scientific research in the Public Interest of Ministry of Land and Resources (No. 201211039), the National Natural Science Foundation of China (Grant No. 41202201, 41102196, 51379194) and the Special Fund for Basic Scientific Research of Central Colleges (Grant No. CUGL110215).

References

Chao, Y., Zhou, J., and Yan, J. J. (2014). "Study of microstructures of soft clay under dynamic loading considering effect of cyclic stress ratio and frequency." *Rock and Soil Mechanics*, Vol. 35, No. 3, pp. 735-743.

Chen, H. Y., Yu, G. J., and Zhang, G. P. (2007). "The microstructure and physical mechanics of the typical sliding belt of the Badong-type landslide in the Three-Gorge reservoir." *Resources Environment & Engineering*, Vol. 21, No. 2, pp. 147-151, DOI: 10.3969/j.issn.1671-1211.2007.02.013.

Chen, Z. H., Fang, X. W., Zhu, Y. Q., Qin, B., Wei, X. W., and Zhao, Z. H. (2009). "Research on meso-structures and their evolution laws of expansive soil and loess." *Rock and Soil Mechanics*, Vol. 30, No. 1, pp. 1-11, DOI: 10.3969/j.issn.1000-7598.2009.01.001.

Fang, X. W., Shen, C. N., Wang, L., Chen, Z. H., and Cheng, P. J. (2013). "Research on microstructure of Q-2 loess before and after wetting." *Rock and Soil Mechanics*, Vol. 34, No. 5, pp. 1319-1324.

Hu, H. T., Wang, A. F., Liu, Y. J., and Zhao, X. Y. (2009). "Stability of granite soil high slopes." *Chinese Journal of Geotechnical Engineering*, Vol. 31, No. 6, pp. 824-828.

Jia, C. G., Chen, J. H., Guo, Y. T., Yang, C. H., Xu, J. B., and Wang, L. (2013). "Research on mechanical behaviors and failure modes of layer shale." *Rock and Soil Mechanics*, Vol. 34, Supp. 2, pp. 51-57.

Jin, K. S. (2005). *Study on consolidation traits and characteristic coefficients of microstructure pictures to literate of kunming*, MSc Thesis, Kunming University of Science and Technology, Kunming, China.

Liao, X. P. (2003). "Failure mechanism and stability analysis of cutting soil slopes." *Chinese Journal of Rock Mechanics and Engineering*, 22(suppl. 2), 2765-2772, DOI: 10.3321/j.issn:1000-6915.2003.z2.049.

Liang, W., Li K. G., Hou, K. P., and Du, J. (2012). "Fractal characteristics of granularity of loose micaschist and its relation to shear strength parameters." *Rock and Soil Mechanics*, Vol. 33, No. 3, pp. 767-772, DOI: 10.3969/j.issn.1000-7598.2012.03.018.

Liu, X. Y. (2003). *Experimental and numerical simulation of excavation process and microstructure study*, MSc Thesis, Tianjin University, Tianjing, China.

Liu, Z., Tang, Z. H., Peng, L., Liang, H. C., and Shan, H. M. (2009). "SEM test analysis on loose rock-soil Mini-structure in Zhao shuling slope under the condition of water-rock interaction." *Safety and Environmental Engineering*, Vol. 16, No. 2, pp. 1-4, DOI: 10.3969/j.issn.1671-1556.2009.02.001.

Ma, X., Guo, Z. Y., and Yang, Q. (2009). "Shear performance of asphalt mixtures based on fractal method." *Journal of Chong Qin Jiao Tong University (Natural Science)*, Vol. 28, No. 5, pp. 873-876.

Mao, L. T., Xue, R., and An, L. Q. (2004). "Quantitative analysis on SEM image of microstructure with MATLAB." *Journal of Chinese Electron Microscopy Society*, Vol. 23, No. 5, pp. 579-583, 10.3969/j.issn.1000-6281.2004.05.014.

Miao, D. Y. and Bai, X. H. (2014). "Microstructure of soil using SEM images based on Matlab." *Hydrogeology & Engineering Geology*, Vol. 41, No. 6, pp. 141-146.

Song, B. H. (2012). *Experimental study on engineering properties of sliding zone soils in landslides*, MSc Thesis, Lanzhou University, Lanzhou, China.

Tang, D. X. (1999). *Engineering Geotechnical*, Geological Publishing House, Beijing, China.

Wen, B. P. and Aydin, A. (2005). "Mechanism of a rainfall-induced slide-debris flow: Constraints from microstructure of its slip zone."

Engineering Geology, Vol. 78, Nos. 1-2, pp. 69-88, DOI: 10.1016/j.enggeo.2004.10.007.

Wen, B. P., Duzgoren-Aydin, N. S., and Aydin, A. (2004). "Geochemical characteristics of the slip zones of a landslide in granitic coprolite Hong Kong: implications for their development and microenvironments." *Environmental Geology*, Vol. 47, No. 1, pp. 140-154, DOI: 10.1007/s00254-004-1145-6.

Wu, S. C., Zhang, X. P., and Liu, Y. (2008). "Analysis of failure process of similar soil slope with weak intercalated layer based on particle flow simulation." *Rock and Soil Mechanics*, Vol. 29, No. 11, pp. 2899-2904, DOI: 0.3969/j.issn.1000-7598.2008.11.003.

Xu, Q. H. (2008). *Application of image analysis technology on soil microstructure study and data analysis*, MSc Thesis, Taiyuan University of Technology, Taiyuan, China.