Front. For. China 2007, 2(3): 305–309
DOI 10.1007/s11461-007-0049-5

RESEARCH ARTICLE

ZHANG Xiaoming, WANG Yujie, WANG Yunqi, XIA Yiping, WU Yun, CHEN Lin

Shear strengths of undisturbed and remolded soil under typical forests in Jinyun Mountain, Chongqing City, southwest China

Abstract To find the controlling measures in preventing soil and water loss from soil mechanics, according to the prescribed methods of soil engineering test regulations, shear strengths of undisturbed and remolded soils under five typical forests in Jinyun Mountain, Chongqing City were measured using the direct shear apparatus. Shear difference of both undisturbed and remolded soils was compared at the same vertical loading, under the condition of the same dry density and water content from the same forest land. The effect of roots (the finest roots) in soil-root composites (undisturbed soils) was analyzed. The results indicate that undisturbed soils have higher shear resistance and less shear displacement than remolded soils at the same vertical loading, when both soils have the same dry density and water content under the same vegetations. It has been shown that shear failure of undisturbed soils approximately indicate plastic failure, while shear failure of remolded soils is of the elastic nature. Shear strength of undisturbed soils has a positive correlation with root content, and relevant regression models about undisturbed soil were established from this.

Keywords root content, shear strength, shear displacement, undisturbed soils, remolded soils

1 Introduction

Water erosion is a complicated process in soil mechanics during rain splash-shear by raindrop and wash-shear by runoff (Zhang and Yang, 2001); therefore, shear strength of soil is an important index for soil mechanical properties and water loss estimation.

The anti-erodibility of soil could be enhanced by the soil root system. Zhang (2002) showed that because of the interposition and snarling of fibers, aggregation of soil can be improved, then the ability of soil against scattering and suspension can be strengthened. Wang (2001) found that the effects of plant roots on anti-erodibility of soil shows that roots less than 1 mm in length make the most important contribution to hydraulic effect, and this was also proved by Chen et al. (2000). Liu and Li (2003) suggested that an undisturbed soil and a remolded soil of the same water content and dry density have different mechanics. Wu and Wang (1997) reported that soil is pressed and twined by plant roots in undisturbed soil, especially if the length of the root is less than 1 mm, and this can increase the number of soil aggregate, improve stability of soil mechanics and contributes to an increase in both infiltration capacity and soil anti-erodibility.

Shear strength parameters of soil are not easily obtained from direct shear test. This study concentrated on the shear differences between undisturbed soil and remolded soil in the same dry density and water content beneath the same forest type under identical vertical loadings. After that, the relationship between roots (the finest roots) and shear strength was analyzed, which could supply the scientific basis to slope stability analysis by using plant roots against soil and water loss.

2 Materials and methods

The Jinyun Mountain National Nature Reserve (the research area) (29°45′ N, 106°22′ E) is located on the west bank of the Wentang gorge of the Jialing gorges in Beibei, district of Chongqing City. Jinyun Mountain has an elevation peak of 951.5 m, with a relative height of 600 m, where acid yellow soil and paddy soil with pH 4.0–4.5 are dominant. The horizontal zone is typical central Asia tropical evergreen

Translated from *Transactions of the Chinese Society of Agricultural Engineering*, 2006, 22(11): 6–9 [译自: 农业工程学报]

ZHANG Xiaoming, WANG Yujie (✉), WANG Yunqi
College of Soil and Water Conservation, Beijing Forestry University, Beijing 100083, China
E-mail: wyujie@bjfu.edu.cn

XIA Yiping, WU Yun, CHEN Lin
Management Bureau of Jinyun Mountain National Nature Reserve, Chongqing 400700, China

broad-leaved forest, with an average annual temperature of 13.6°C and an annual rainfall of 1,611.8 mm and an annual evaporation of 777.1 mm.

Research on the shear strength has been carried out on the undisturbed soils and the remolded soils beneath five typical vegetations which were as follows: mixed forest, broadleaf forest, shrub forest, needle-leaved forest and farmland, accordingly marked from 1 to 5.

Ten soil samples were obtained according to the characteristics of soil profiles (soil horizon A and B) and four undisturbed soil samples were collected at each soil horizon using the cutting rings measuring 61.8 × 20 mm. Immediately after that, root fresh weight was measured (Bohm, 1985) and root content was calculated (Hao et al., 2000).

$$m_r = R/60 \quad (1)$$

where m_r is the root content of an undisturbed soil (g/cm^3), R is the root fresh weight (g).

The quick shear test was performed using SDJ-1 electromotive direct shear apparatus under three constant rates of shear. Then, c (cohesion) and φ (angle of friction) were obtained through shear strengths and vertical loadings (100, 200, 300, 400 kPa) curve (GBJ10-89, 1991). Soil unit weight and natural density were measured by the cutting ring method; soil natural water content was measured by dry oven method.

The soil samples separated from roots and big stones were air-dried and triturated. Quick shear test was done on the remolded soils, and their water contents and dry density were identical to the undisturbed soils. Each soil sample was named by the following rules: vegetations (from 1 to 5) plus soil layers (letters A or B; the remolded soil with peculiar form "′") plus loadings in sequence. For example, A soil horizon beneath mixed forest under loading of 100 kPa was marked by 1-A100 kPa for the undisturbed soil, and 1-A′100 kPa for the remolded soil.

Root diameter was measured with vernier calipers after the undisturbed soil quick shear test. Then, the roots were classified as follows: the finest root (< 1 mm); radicel (1–2 mm); medium-sized root (2–5 mm); large root (> 5 mm). Because the smallest roots (also named as hair root) experimented in the test were dominant, a simplified apparatus that can measure the stain value obtained with the range of 0.25–10 N was created to determine the strain of the smallest roots.

3 Results and discussion

3.1 Behavior of root mechanics

It is observed that an increase in the cross-sectional area of the finest root produces the same increase in tensile strength. The equation for tensile stress is

$$F_r = A_r \times f_r \quad (2)$$

where F_r is the tensile stress of the smallest root (N); A_r is the cross sectional area of the smallest root (mm^2); f_r is the tensile strength of the smallest root (kPa).

The average tensile strength of the smallest roots beneath the five typical forests was obtained from the test in the following sequence:

$$f_{r1} = 7{,}195 \text{ kPa}; f_{r2} = 8{,}429 \text{ kPa}; f_{r3} = 7{,}925 \text{ kPa};$$
$$f_{r4} = 7{,}086 \text{ kPa}; f_{r5} = 7{,}722 \text{ kPa}$$

The average value of the above-mentioned tensile strengths was used as the tensile strength of the smallest root, i.e. $f_r = 7{,}671$ kPa.

3.2 Contrast between the undisturbed soil and the remolded soil

3.2.1 Soil behavior differences between the undisturbed soils and the remolded soils on shear test

The quick shear test of the undisturbed soils due to their close-grained skeleton and snarling of roots behaves like an undrained shear test during which volume is kept unchanged and water is undrained from soil samples. However, it is essentially characteristic of volume change in shear test (Chen et al., 1992). Soil is gradually getting rid of interposition and snarling of roots and extension happens to roots in the course of shear, therefore, soil tends to swell. Correspondingly, negative pore water pressure produced in soil to prevent the expansion trend of soil samples contribute to the increase, because soil skeleton causes the rise in shear stress of soil samples. Whereas, complete shear failure occurred to soil samples along with thorough failure in the close-grained structure of soil-root complex at high loadings. It shows that there has been a peak value, on the left of which the curve is upward, similar to a line until the failure. In contrast, the curve on the right is almost parallel to the horizontal shaft or a little downward (Figs. 1 and 2).

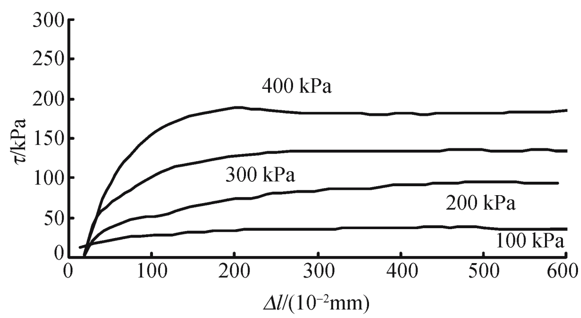

Fig. 1 Shrub forest A: curve about shear stress and shear displacement

Quick shear on the remolded soil behaves like drained shear test; volume starts to be reduced because water is drained from soil samples. Consequently, an increase in shear stress due to reduced volume causes a rise in density.

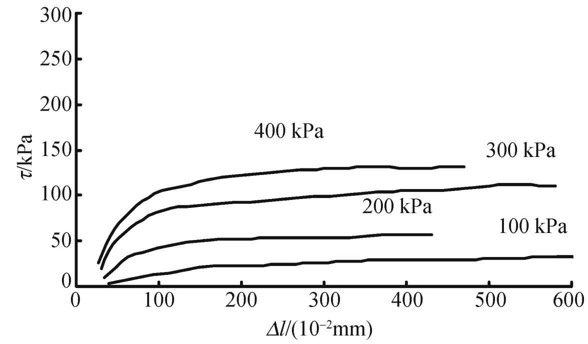

Fig. 2 Shrub forest A′: curve about shear stress and shear displacement

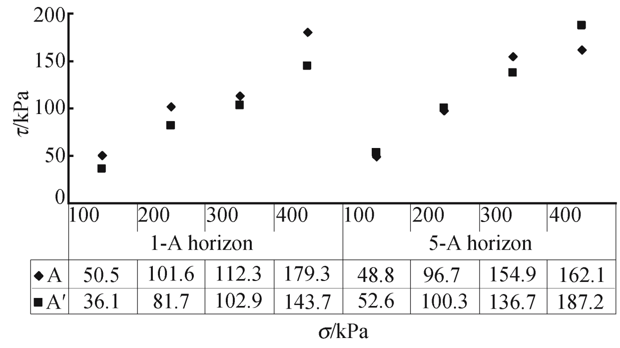

Fig. 3 Two vegetations A layer soil: shear stress and vertical load

As shown in Figs. 1 and 2, the curve is smooth, and the shear strength increased with the rise in shear displacement. Therefore, the failure of the undisturbed soils is plastic failure, while the failure of the remolded soil is elastic in nature.

Table 1 shows that shear strength displacement of an undisturbed soil is less than that of a remolded soil under the same vertical loading except in soil sample 2-A.

Table 1 Comparison of shear displacement between the undisturbed soil and the remolded soil at the same vertical load (unit: mm)

Samples	Shear displacement (undisturbed soil/remolded soil)			
	100 kPa	200 kPa	300 kPa	400 kPa
1-A	3.93/6.00	4.06/6.10	4.00/6.01	4.06/5.97
1-B	3.99/4.10	3.31/4.72	3.98/5.97	3.80/6.00
2-A	4.06/5.42	3.98/5.19	4.09/4.92	4.04/3.81
2-B	3.81/3.73	3.85/4.28	4.01/4.81	3.96/4.09
3-A	3.52/6.09	4.00/6.09	3.94/5.84	4.01/5.24
3-B	3.97/6.37	3.33/4.94	4.03/4.19	3.86/5.04
4-A	4.00/6.22	3.92/4.30	2.89/5.41	2.00/4.70
4-B	3.98/6.04	3.97/5.92	4.05/6.10	3.91/5.97
5-A	3.94/5.30	4.09/4.66	3.98/5.25	3.94/5.37
5-B	3.23/4.14	4.09/5.57	4.06/5.15	4.06/6.03

3.2.2 Shear strength contrast between undisturbed soil and remolded soil

An undisturbed soil enjoys a high level of strength due to its close-grained skeleton and snarling of roots. However, in contrast, shear strength increased rapidly under vertical loading inducing a quick volume reduction, a rise in density, and close-grained particles (Fig. 3).

The shear strength disciplines of the undisturbed soil and the remolded soil are as follows: shear strength of the undisturbed soil is higher than that of the remolded soil except for soil samples on the A horizon of farmland (space is lacking for a detailed description of it, and only mixed forest for example). The main reason lies in the fact that the shear strength of the undisturbed soil obviously rises because of its close-grained skeleton and snarling of roots. However, the reasons why the strength of the undisturbed soil is higher than that of the remolded soil in the beginning, but lower since then, may be as follows. 1) Because the farmland soil A horizon is used for cultivation, roots become less than others due to scarification, hoeing, etc., and close-grained skeleton is destroyed. 2) Because of fertilization in the farmland, the soil A horizon enjoys a high level of organic matter but lower density. However, the structure of the remolded soil had less organic matter owing to crushing, stirring and storing, therefore, the remolded soil increases in shear strength. 3) Shear stress on the undisturbed soil under low loadings is too small to destroy its original structure. Whereas, the soil skeleton is destroyed and complete failure happens to soil when shear displacement occurs at high vertical loadings, then this leads to relatively small shear strength; the shear strength of the remolded soil is higher than that of the undisturbed soil under vertical loading inducing reduced volume, a rise in density, and an increase in shear strength. However, because of disturbance, soil in farmlands does not belong to undisturbed soil essentially. The strength of the farmland soil A layer will be discussed further in detail.

3.3 Shear strength constitution of undisturbed soil

The shear strength of undisturbed soil is subjected to Mohr-coulomb Criterion.

$$\tau = c + \sigma \cdot \mathrm{tg}\varphi \tag{3}$$

Shear strength of soil is comprised of friction strength ($\sigma \cdot \mathrm{tg}\varphi$) and cohesion ($c$). An increase in the strength due to the snarling of roots occurs in undisturbed soil.

The main differences between an undisturbed soil and a remolded soil lie in the fact that the former has a closer structure and roots. The test result shows that shear strength of an undisturbed soil basically has a positive correlation with root content and the strength of a remolded soil (Figs. 4 and 5).

The strength can be decomposed into three parts: 1) the strength with respect to soil properties themselves such as organic matter content, grain size, density and water content, etc., which are totally identical to that of remolded soil of the

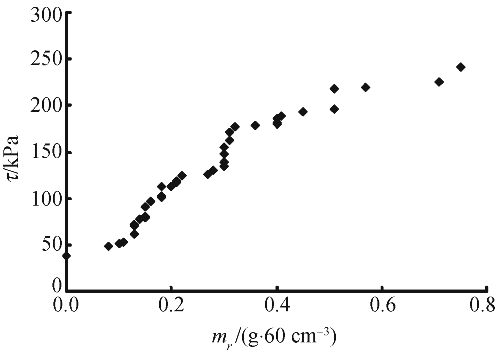

Fig. 4 Shear strength of undisturbed soils and root content

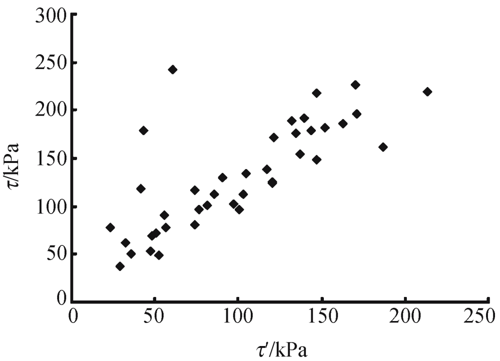

Fig. 5 Shear strength of undisturbed soils and remolded soils

same water content and density; 2) the strength arising from the roots; 3) the strength due to the close structure formed under field conditions.

Regression analysis was made for shear strength of an undisturbed soil (τ) as the dependent variable, with root content of undisturbed soil (m_r), the average shear strength of the finest root (f_r), and the shear strength of a remolded soil (τ_0) as independent variables using MatLab 6.1 software. There were 40 samples in total and 35 of them, in which exceptional data points have been eliminated, are used for regression analysis, while the other samples were used for testing forecast (Chen et al., 2002).

$$\tau = 27.712,5 + 0.276,3\tau_0 + 0.035,5m_r \cdot f_r \qquad (4)$$

The confidence interval of regression coefficients b were as follows: $b_0 = (18.432,9, 36.992,2)$; $b_1 = (0.159,0, 0.393,6)$; $b_2 = (0.031,0,\ 0.040,0)$. Multiple correlation coefficient $R^2 = 0.961,3$; test statistics $F = 372.472$; significance probability $P = 0$; $R^2 > 0.95$, $P \approx 0$. Therefore, regression effect is significant from the data above. Regression coefficients are made for significance test, and test statistics are as follows: $T = 2.042,3$; $T_1 = 4.811,2$; $T_2 = 16.163,6$. Apparently, both values of T_1 or T_2 are bigger than that of T, therefore, the influences of the strength of a remolded soil and the root content on shear strength of undisturbed soil are significant. Eq. (4) is tested for precision of prediction with the other five samples (Table 2).

Table 2 Observation value, estimation value and interval estimation of anti-shear strength of undisturbed soils

Sample name	Observation value	Estimation value	Interval estimation	
5-A400 kPa	162.1	163.9	151.5	176.3
5-B100 kPa	69.9	76.4	64.8	88.0
5-B200 kPa	96.5	92.3	80.8	103.8
5-B300 kPa	139	141.8	130.3	153.3
5-B400 kPa	176.3	152.0	140.4	175.6

Almost all estimate values within the interval estimation are approximately near the measured values except sample 5-B 400 kPa, so, Eq. (4) enjoys a high level of precision of prediction. It is noteworthy that all the soil samples are tested at loading values less than 400 kPa. Aside from this, the strength of an undisturbed soil made up of soil and roots, which is like armored concrete according to reports, would decrease along with a rise in vertical loading when loading value is beyond the peculiar scope. Therefore, the equation is only applicable when it is used to calculate shear strength of an undisturbed soil under vertical loadings less than 400 kPa in the Jinyun Mountain in Chongqing.

4 Conclusions

From the results of this study, we can conclude that tensile strength of the smallest root has a positive correlation with its diameter, and it contributes to the rise in shear strength of soil within 400 kPa. The contrast between undisturbed soils and remolded soils of the same water content and dry density are as follows: failure of undisturbed soils may approximately be classified as plastic failure, while shear failure of remolded soils is elastic in nature. In addition, the displacement of the former is less than that of the latter, while strength of undisturbed soils is higher than that of remolded soils, with the soil of farmland A layer being the exception. The shear strength of an undisturbed soil increases along with a rise in root content, and its shear depends on three factors: 1) close structure formed under field conditions; 2) soil properties; and 3) the smallest root content. Eq. (4) can be applied to calculate shear strength of an undisturbed soil under vertical loadings less than 400 kPa in the Jinyun Mountain in Chongqing.

Acknowledgements This study was supported by the National Natural Science Foundation of China (Grant No. 30671661), the 11th Five National Science and Technology Program (No. 2006BAD03A1802), "948" Project of State Forestry Administration, China (No. 2007-4-14) and Chinese Forest Ecosystem Research Network (CFERN) Three Gorges Reservoir Areas (Chongqing) Forestry Ecosystem Position Station.

References

Bohm W (1985). Methods of Studing Root Systems (in Chinese, trans. Xue D R, Tan X L). Beijing: Science Press, 88

Chen S Y, Huang Y Q, Wu X B (2000). Study on the effect of soil's antierosion capacity by *Pinus elliottii* Engelm root systems. J Southwest Agric Univ, 22(5): 468–471 (in Chinese)

Chen G M, Qi H Y, Pan W (2002). MATLAB Statistics (6.x). Beijing: Science Press, 135–175 (in Chinese)

Chen Z Y, Zhou J X, Wang H J (1992). Soil Mechanics. Beijing: Tsinghua University Press, 178–180 (in Chinese)

Hao T Q, Xie X Y, Hong T S (2000). Experiment study on the shear strength of soil root composite. J South China Agric Univ, 21(4): 78–80 (in Chinese)

Liu G B, Jiang D S, Zhu X M (1996). Study on grasses root bio-mechanics in Loess Plateau. J Soil Water Conserv, 2(3): 21–28 (in Chinese)

Liu D H, Li Y (2003). Mechanism of plant roots improving resistance of soil to concentrated flow erosion. J Soil Water Conserv, 17(3): 34–37 (in Chinese)

Ministry of Construction of the People Republic of China (1991). Code for Design of Concrete Structures. GBJ10-89. Beijing: China Architecture & Building Press, 3–72 (in Chinese)

Ministry of Construction of the People Republic of China (1999) Standard for Soil Test Method. GB/T 50123-1999. Beijing: China Architecture & Building Press, 89–96 (in Chinese)

Wang K (2001). Effects of plant roots on soil anti-erosion. Soil Environ Sci, 10(3): 250–252 (in Chinese)

Wu Y, Liu S Q, Wang J X (1997). Effect of plant root system on soil anti-erosion. Chin J Appl Environ Biol, 3(2): 119–124 (in Chinese)

Zhang A G, Li R, Yang Q K (2001). Study on soil anti-shearing intensity of water erosion in China. Bull Soil Water Conserv, 21(3): 5–9 (in Chinese)

Zhang R Z (2002). Study on improving soil's antiwash by botanic roots. J Western Chongqing Univ (Nat Sci Ed), 15(1): 31–35 (in Chinese)