Landmarks in Earth Reinforcement, Ochiai et al. (eds),
© 2001 Swets & Zeitlinger, ISBN 90 2651 863 3

Study on the critical height of fiber-reinforced slope by centrifuge test

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ABSTRACT: Centrifuge model tests were carried out to study the behavior of fiber-reinforced cohesive steep slope. It has been found that unlike unreinforced one, reinforced soil still retains a certain tensile strength in the crack zones, which increases greatly the critical height of the steep slope. A simple method to estimate the critical height of the steep slope is also presented in this paper.

1 INTRODUCTION

Fiber-reinforced soil (Texsol) is a promising geotechnical material. It can be considered to be a composite made of soil and continuous threads of synthetic fibers. To obtain such a material, a number of threads are penumatically or hydraulically projected on soil in a movement at the extremity of a conveyor belt or at the vent of a pipe used to build a hydraulic fill(Leflaive 1998). It has excellent mechanical, hydraulic and environmental performance in civil engineering. The soil used to produce texsol is mostly natural sand. However, cohesive soil should also be paid enough attention to, especially in places where there is short of sand.

Tsinghua University has conducted a series of tests on the static, dynamic and hydraulic behavior of fiber-reinforced cohesive soil (Zheng 1992, Li et al. 1993, Li et al. 1995, Zhang 1995). It has shown by the tests that fiber-reinforcing increases greatly the shear resistance of the cohesive soil, and improves its plasticity under tensile stress. The fiber-reinforced cohesive soil has excellent performance in resistance against hydraulic fracture, too.

In this paper, centrifuge model tests are carried out to study the fiber-reinforced and the unreinforced cohesive soil slope. A cohesive soil with two dry densities ρ_d=1.65g/cm^3 and ρ_d=1.55g/cm^3 was used in the tests. Failure process was observed on CCTV camera. It was found that the reinforced slopes have different failure pattern in comparison with unreinforced ones, and they still retain a certain tensile strength in the crack zones, which increases greatly their critical heights. A simple method is also proposed in the paper to estimate the critical height of fiber-reinforced steep slope.

2 TEST MATERIALS

The physic properties of the soil used in the tests are listed in Table 1.

The thread used is polypropylene fiber. The average tensile strength is 0.06N/d, and the average Yang's modulus is 0.8N/d.

Triaxial compression tests were performed to determine the cohesion and friction angle of the soil and fibers. The samples, 100mm in diameter and 200mm in height, were prepared with two density, ρ_d=1.65g/cm^3 and ρ_d=1.55g/cm^3, respectively. The content of polypropylene fibers used in the soil is 0.2% by weight. The test results are shown in Table 2.

Table 1. Physic properties of the soil.

Physic property	Value
Specific gravity (G_s)	2.71
Plasticity index (I_p)	14.9
Optimum water content (ω_{opt})	17%
Maximum dry density (ρ_{dmax})	1.7g/cm^3

Table 2. Index properties of shear strength.

Dry density		Adhesion strength c	Friction angle φ
g/cm^3		kPa	°
1.55	(Unreinforced slope)	51	27.1
	(Reinforced slope)	78	27.1
1.65	(Unreinforced slope)	68	27.6
	(Reinforced slope)	100	27.6

3 CENTRIFUGE MODEL TEST

The geotechnical centrifuge at the University of Tsinghua used in this study has a capacity of 50 gtons. All model slopes were 303×200 mm in area, and 350mm in height. They were constructed in a rigid aluminum container with inside dimensions of 600mm by 200mm in area, by 300mm in depth. The inside vertical side boundaries of the container were sprayed with silicon and overlaid with a thin plastic film to reduce boundary friction effect. One side of the container is fixed with plexiglass, so that the behavior of the model slope can be observed through CCTV camera.

Each test involved loading the model by gradually increasing its self-weight till failure occurred. The increment of each step of loading the acceleration was 5g or 10g (g is the acceleration of gravity). The next loading step was conducted after the slope displacement almost ceased. The test results are shown in Table 3 and in Figure 1.

Table 3. Results of centrifuge model tests.

	Reinforced slope		Unreinforced slope	
Dry density (g/cm^3)	1.55	1.65	1.55	1.65
Acceleration when failure occurred	100g*	120g*	45g*	60g*
Critical height H_{cr} (m)	35.0	42.0	15.7	21.0
Depth of tension Zone Z_0** (m)	14.4	17.5	9.4	11.9

* g is the acceleration of gravity, which equals to appromately 9.81 meters (32 feet) per second per second.
** How to obtain the depth of tension zone Z_0 is described below.

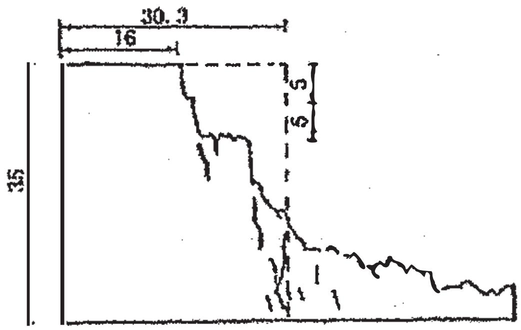
It showed from the model tests that unlike the unreinforced ones, fiber-reinforced cohesive steep slopes fail gradually. There are a family of failure surfaces in the reinforced cohesive slope. The failure surfaces developed progressively. Cracks appeared initially at places near the front side of the slope, then they developed gradually further into the slope. Most of the cracks are vertical. The two parts separated by cracks were still connected with each other by fibers. However, unreinforced slopes collapsed abruptly at certain acceleration (see Figure 1).

4 A SIMPLE METHOD FOR THE CALCULATION OF REINFORCED SLOPE

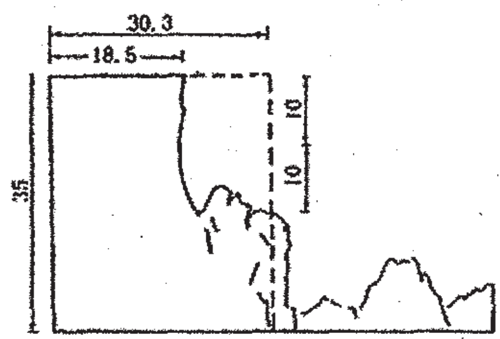
The apparent cohesion and friction angle of reinforced soil can be determined through triaxial compression tests, as shown in Table 2. The depth of tension zone Z_0 can then be obtained:

$$Z_0 = \frac{2c}{\gamma\sqrt{K_a}} \quad (1)$$

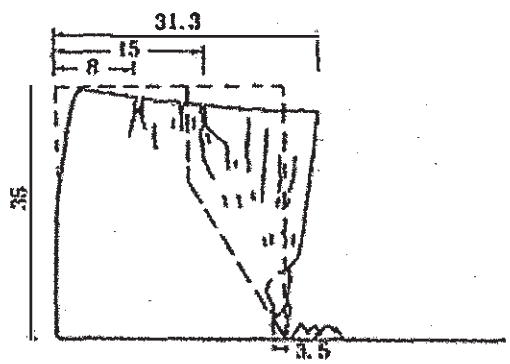
The results are presented in Table 3. For unreinforced slopes, Z_0 is 60 percent of the critical height H_{cr} tested, while for reinforced ones, it is only 40 percent.



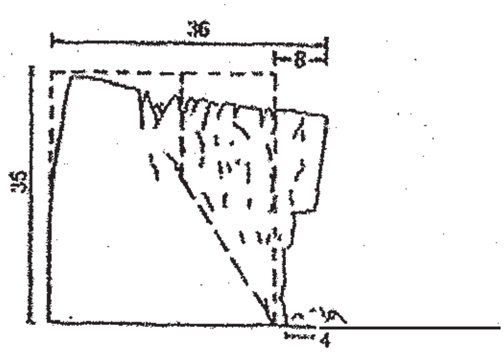
Unreinforced soil slope (ρ_d =1.55g/cm^3)



Unreinforced soil slope (ρ_d =1.65g/cm^3)



Fiber-reinforced soil slope (ρ_d =1.55g/cm^3)



Fiber-reinforced soil slope (ρ_d =1.65g/cm^3)

Figure 1. Failure patterns of the reinforced and unreinforced cohesive steep slopes (-------- indicates the slide surface used in the calculation).

If cracks develop in the unreinforced cohesive soil slope, it usually means that tensile resistance reduces to zero. However, fiber-reinforced slope is not the case. The separated parts at each side of the

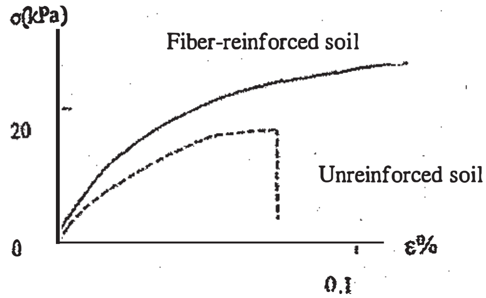


Figure 2. Uniaxial tension test of the reinforced and unreinforced cohesive soil.

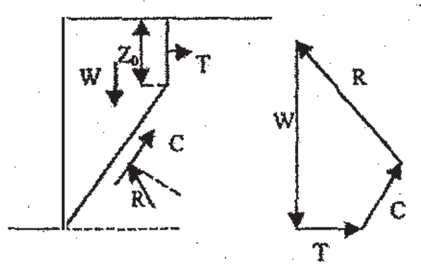


Figure 3. Forces acting on the potential slide wedge.

cracks are connected with each other by fibers. Fibers can sustain tensile stress, so that the reinforced soil can still retain a certain tensile strength when cracks develop in the soil. The tensile strength increases when tensile strain increases. The uniaxial tension test results of fiber-reinforced and unreinforced cohesive soil are shown in Figure 2. The potential slide wedge of the Texsol slope is shown in Figure 3.

The depth of the tension zone (or crack zone) Z_0 can be achieved by Equation 1. The vertical crack zone constitutes one of the slide surfaces. The other slide surface intersects with the crack zone and passes through the toe of the slope, and it makes an angle of $(45^\circ+\varphi/2)$ with the horizontal plane, see Figure 3.

The tension force T acts on the wedge at the crack zone, it can be obtained by:

$$T = Z_0 \sigma_t \quad (2)$$

in which σ_t is the tensile strength of fiber-reinforced soil,

$$\sigma_t = \frac{\Delta c}{tg\varphi} \quad (3)$$

where Δc is the cohesion difference between the reinforced and the unreinforced soil, and φ is the friction angle of the Texsol.

The force polygon is shown in Figure 3. Following Coulumb's theory, the critical height of reinforced soil slope can be calculated, the results of which are presented in Table 4.

Table 4. Calculation results of the critical height of reinforced steep slope.

	Slope 1	Slope 2
ρ_d (g/cm^3)	1.55	1.65
c (kPa)	78	100
Z_0 (m)	14.4	17.5
σ_t (kPa)	52.7	61.2
T (kN)	759	1071
W (kN)	4092	5250
C (kN)	1518	2046
H_{cr}, calculated (m)	31	35
H_{cr}, tested (m)	35	42

5 CONCLUSION

Fiber-reinforced is a promising material. Fiber-reinforced slope hardly collapses when failure occurs, except that cracks develop progressively in the soil. However, unreinforced slope collapses abruptly when fails.

In crack zones, fiber-reinforced soil has still a certain tensile strength resulting from the tensile strength of fibers. It is the reason that the reinforced slope has a much higher critical height in comparison with the unreinforced one.

6 ACKNOWLEDGEMENT

The support of China National Science Foundation under award No.50099620 is greatly acknowledged.

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