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Ultimate pullout forces of orthogonally horizontal-vertical geosynthetic reinforcement

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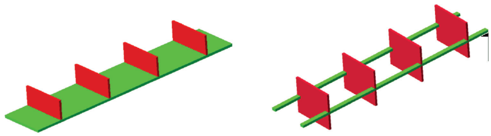
ABSTRACT: The geosynthetic reinforced soil, as a new reinforcement technique, has come to play a rapidly increasing role in a variety of civil and geotechnical engineering applications. In conventional reinforced soils, the reinforcements are often laid horizontally in the soil. A new concept of soil reinforced with orthogonally horizontal-vertical (H-V) geosynthetics was proposed. In the proposed H-V reinforced soil, besides conventional horizontal reinforcements, some vertical reinforcing elements are also placed upon the horizontal ones. The remarkable function is that the vertical elements can not only restrict the lateral deformation of soil, but also form strengthened zones and provide passive resistances to soil enclosed within the H-V reinforcing elements. Moreover, it can change the stress distribution and deformation of reinforced soil effectively, that will increase the strength and stability of soil. The interface behaviour would be significant to reinforcing mechanism, bearing capability and stability of the soil retaining structure reinforced with orthogonal H-V inclusions. In this paper, a series of pullout tests of orthogonal H-V geosynthetics were carried out to study the interface behaviour between sand and orthogonal H-V inclusions in terms of load-displacement relationship and pullout resistances. Comparison was made between load-displacement relationship and pullout resistances of the soil reinforced with horizontal inclusions and with orthogonal H-V ones. The influences of the height, horizontal space of vertical reinforcing elements, and kind of reinforcement material on the interface behaviour between sand and orthogonal H-V inclusions were discussed. From the test results, the coefficient of apparent pullout friction was evaluated. The interaction mechanism between sand and orthogonal H-V inclusions was analyzed and a new theoretical model was proposed to determine the pullout resistance. The comparison between theoretical values and experimental results was in good agreement.

1 INTRODUCTION

The behavior of interface between soil and reinforcements are the main influential factors in the safety and stability of reinforced structure. Due to its importance, many investigations have been carried out to study the pullout mechanism experimentally and theoretically. Jewell et al. (1984) & Rowe et al. (1985) investigated the pullout mechanism. Irsyam & Hryciw (1991) analyzed the friction and passive resistance in soil reinforced by plane ribbed inclusions. Raju & Fannin (1997) studied pull-out resistance of geogrids under monotonic and cyclic load. Racana et al. (2003) studied the pull-out response of corrugated geotextile strips. Hong et al. (2003) analyzed the pullout resistance of single and double nails. The concept of three-dimension inclusions was studied (Zhang et al. 2006), and a series of triaxial tests were carried out to investigate the behaviour and strength of the soil reinforced with three-dimension inclusions (Zhang & Min 2006). The contributions related to new reinforcing styles have played an active role in development of reinforced soil technology.

A new concept of soil reinforced with H-V geosynthetics was proposed. In H-V reinforced soil, besides conventional horizontal elements, some vertical reinforcements were also placed upon the horizontal ones. In this paper, the interaction mechanism between sand and H-V inclusions was analyzed and a new theoretical model was proposed to determine the pullout resistance. A series of pullout tests of H-V geosynthetics were carried out to prove the model.



(a) (b)

Figure 1. The typical H-V reinforcing elements: (a) horizontal-vertical reinforcing elements with the different width; (b) horizontal-vertical reinforcing elements with the different width.

2 TYPE OF SOIL REINFORCED WITH DENTI-STRIP REINFORCEMENTS

In 3D reinforcements, some kinds of reinforcing structure schemes have been established. The H-V reinforcement is one specific example of 3D reinforcements. A typical H-V reinforcing element with the same width is shown in Fig. 1(a), while H-V reinforcement with the different width is shown in Fig. 1(b). For the former, the horizontal reinforcements provide a friction force to the soil, and the vertical inclusions also provide a resistance force, but, for the latter the soil restricted mainly by the vertical reinforcements.

3 PULLOUT RESISTANCE MODEL FOR THE H-V REINFORCEMENT

3.1 *Mechanism analysis*

In conventional reinforced soil, the reinforcements are laid horizontally. The soil is restricted only by the frictional stress between soil and the reinforcement. In H-V reinforced soil, the vertical inclusions block the soil to a whole system. Besides the τ_{h1} and τ_{h2}, the vertical reinforcements block a part of soil, and provide stress ($\sigma_P - \sigma_a$) to restrict the soil. The top of the vertical reinforcements also provide a frictional stress τ_v to the soil (see Fig. 2).

3.2 *Analysis of pullout resistance model*

A conventional reinforcement (such as strip inclusions) of width B and length L is embedded in soil. A pullout force T is applied at the end of the strip. According to Mohr-Coulomb theory, at limiting equilibrium, the ultimate pullout resistance can be calculated as follows:

$$T_0 = 2A_0(c_0 + \sigma_0 f) \tag{1}$$

where, T_0 is pullout resistance (kN), A_0 is contact area between soil and reinforcement (m^2), c_0 is cohesion, σ_0 is normal stress (kPa), f is the coefficient of friction and $f = \tan\delta$, where δ is friction angle between soil and inclusion (°).

According to the above analysis, the pullout resistance is equal to the sum of passive resistance

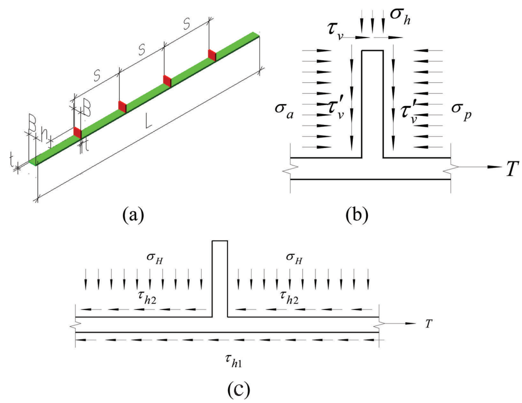


Figure 2. Mechanism analysis of H-V reinforced soil.

component of vertical reinforcements, frictional components of horizontal and vertical elements. So the following relationship can be given:

$$T = T_h + T_v + E_v \tag{2}$$

where T is ultimate pullout resistance; T_h is ultimate frictional resistance of horizontal reinforcements; T_v is ultimate frictional resistance of vertical reinforcements; E_v is passive resistance of vertical reinforcements.

(1) The friction resistance of horizontal reinforcements

If f_1^* is the coefficient of interface friction determined by horizontal reinforcements and sand, A_{h1} is the top contact area of horizontal reinforcements and $A_{h1} = B(L - nt)$, A_{h2} is the bottom contact area of horizontal reinforcements and $A_{h2} = BL$, σ_H is the normal stress of the interface of horizontal inclusions; γ is unit weight of sand (kN/m^3); H is the distance from the top of sand to the top of horizontal reinforcements (m). Then,

$$T_h = A_h \sigma_H f_1^* = (A_{h1} + A_{h2})\sigma_H f_1^* \tag{3}$$

(2) The friction resistance of single vertical element

It can be assumed that the two sides of vertical reinforcements arrive at active limiting equilibrium and passive limiting equilibrium at the same time. In comparison with the thickness of sand laid on the horizontal reinforcements, the height of vertical reinforcements is small. The following relations are given.

$$E_v = E_p - E_a \tag{4}$$

$$E_p = \left(\sigma_H K_p + 2c\sqrt{K_p}\right) A_1 \tag{5}$$

$$E_a = \left(\sigma_H K_a - 2c\sqrt{K_a}\right) A_1 \tag{6}$$

$$E_v = \left(\sigma_H \left(K_p - K_a\right) + 2c\left(\sqrt{K_p} + \sqrt{K_a}\right)\right) A_1 \quad (7)$$

where, A_1 is the profile area of vertical reinforcements and $A_1 = Bh$.

The friction resistance of the vertical reinforcements developed by top contact can be expressed as

$$T_v = A_v \sigma_h f_2^* \quad (8)$$

where, A_v is the top area of vertical reinforcements and $A_v = Bt$; f_2^* is the coefficient of interface friction determined by vertical reinforcements and sand.

Finally, integrating equations (3), (7), (8) and (1), gives the theoretical pullout model, *i.e.*

$$T = (2BL - nBt)\sigma_H f_1^* + nBt\sigma_h f_2^*$$

$$+ nBh\left(\sigma_H \left(K_p - K_a\right) + 2c\left(\sqrt{K_p} + \sqrt{K_a}\right)\right) \quad (9)$$

If the distribution of earth pressure is assumed as the area of rectangle, i.e.

$$\sigma_H = q + \gamma H \quad (10)$$

$$\sigma_h = q + \gamma(H - h) \quad (11)$$

where, q is surcharge (kN/m^2).

Similarly, if the distribution of earth pressure is assumed as the area of trapeziform, i.e.

$$\sigma_H = q + \frac{1}{2}\gamma H \quad (12)$$

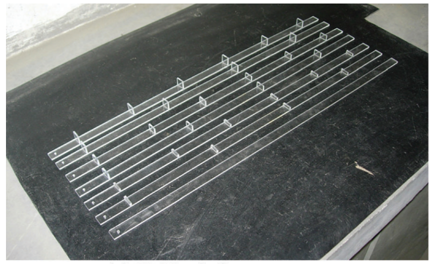
$$\sigma_h = q + \frac{1}{2}\gamma(H - h) \quad (13)$$

4 EXPERIMENTAL RESULTS AND COMPARISON

Twenty-four series of pullout tests (6 horizontal reinforcements and 18 H-V reinforcements) were performed to investigate the effects of test parameters on the behavior of sand reinforced with H-V inclusions. Uniform, clean, beach sand was used. The physical properties of the sand are presented in Table 1. The reinforcements used in the tests were geosynthetics (e.g., plexiglass) with a thickness of 3 mm shown in Fig. 3(a). The configurations of vertical elements included 5, 10, 15 mm. The thickness and width of the vertical inclusion were 3 and 15 mm.The width and length of the horizontal elements were 15 and 550 mm. The distance from the top of sand to the top of horizontal reinforcements was 150 mm. The dimension of pullout box was 650 mm (length) × 800 mm (width) × 1100 mm (height), as shown in Fig. 3(b), various reinforced inclusions were installed in the central location.

Table 1. Physical properties of sand.

Unit weight γ (kN/m^3)	Moisture content w (%)	Specific gravity Gs	Void ratio e
15.99	0.15	2.643	0.5855



(a) H-V reinforcements

(b) pullout box

Figure 3. Layout of pullout test.

A layout of pullout test was used for testing specimens of sand reinforced with H-V reinforcements. The data collected in these tests include displacement of reinforcement and pullout force.

The aim of these tests was to verify the interface behavior theory of reinforced sand with different configuration of H-V reinforcements. The H-V reinforcements used in this study were composed of vertical reinforcing elements with different height and space. The typical pullout load-displacement curves of H-V reinforced sand are presented in Fig. 4.

Figure 4 indicated that the reinforced sand with H-V elements increases the pullout resistance considerably, compared with horizontally reinforced soil. Compared with sand reinforced with shorter vertical inclusions, the sand reinforced with higher vertical inclusions provides greater ultimate pullout resistance.

The results calculated from equation (9) were compared with the force corresponding to mutational displacement of the H-V reinforcement during tests, as shown in Table 2 and Fig. 5. It can be found that theoretical values are in good agreement with the experimental ones. The percentage error was mostly smaller than 10%.

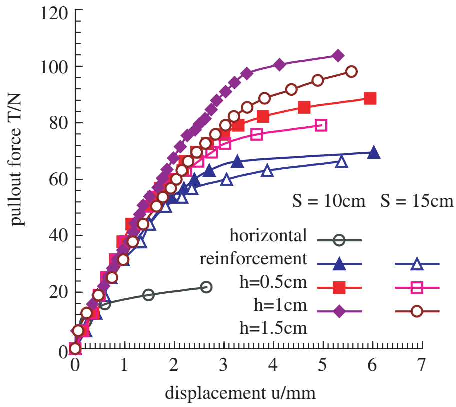


Figure 4. The curves of pullout force versus displacement under different height of vertical elements. Note: S is the spacing of the adjacent vertical elements.

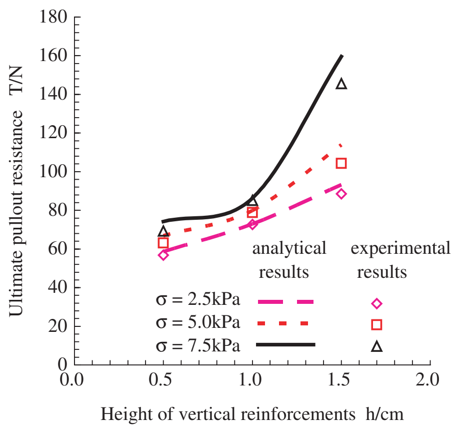


Figure 5. Comparison of the experimental results and analytical ones.

5 CONCLUSIONS

In this paper, a new concept of soil reinforced with H-V reinforcements was proposed, to change conventional reinforcing types. The interaction mechanism between sand and H-V inclusions was analyzed and a new theoretical model was proposed to determine the pullout resistance. In order to study the interface behavior of the reinforced sand under different configurations of H-V reinforcements, a series of pullout tests on dry sand reinforced with H-V reinforcements were carried out. The following conclusions can be drawn from the results:

(1) The ultimate pullout resistance of sand reinforced with H-V reinforcements increases with the increment of height of the vertical reinforcement.

Table 2. Comparison of experimental results and analytical ones.

σ_H (kPa)	S (cm)	h (cm)	T proposed model (N)	T test results (N)	*Error* (%)
2.5	10	0.5	66.86	63.12	4.16
		1.0	84.68	79.02	6.68
		1.5	105.6	97.38	7.78
	15	0.5	58.57	56.76	3.09
		1.0	72.93	72.66	0.37
		1.5	93.21	88.56	4.98
5.0	10	0.5	71.48	66.3	7.25
		1.0	95.93	85.26	11.1
		1.5	123.7	107.52	13.1
	15	0.5	66.81	63.12	5.52
		1.0	79.86	78.9	1.20
		1.5	113.8	104.34	8.31
7.5	10	0.5	87.42	78.90	9.75
		1.0	114.2	97.86	14.3
		1.5	201.6	177.36	12.0
	15	0.5	74.23	69.30	6.64
		1.0	86.38	85.14	1.44
		1.5	159.6	145.56	8.79

*σ_H is normal stressing on interface of horizontal inclusions.

(2) The comparison between theoretical values and experimental results was in good match.

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