Geosynthetics, J. Kuwano & J. Koseki (eds)


# Triaxial tests on sand reinforced with 3D reinforcing elements

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Keywords: 3D reinforcing element, reinforced soil, triaxial test, stress-strain, strength

ABSTRACT: In conventional reinforced soils, the reinforcements are often laid horizontally in the soil. In this paper, a novel concept of soil reinforced with three-dimensional (3D) reinforcing elements is proposed. In the proposed 3D reinforced soil, besides conventional horizontal reinforcements, some vertical and 3D reinforcing elements are also placed in the soil. A comprehensive set of triaxial tests was carried out on sand reinforced with vertical and 3D reinforcing elements (made of galvanized iron sheet and hard plastic sheet). The behavior of sand reinforced with different 3D reinforcing configurations is studied in terms of stress-strain relationship and shear strength of the soil. Comparison is made between stress-strain relationship and shear strength of the soil reinforced with horizontal reinforcements and with 3D reinforcing elements. The influences of the height of vertical reinforcements and confining pressures on strength of reinforced sand are discussed. The experimental results show that 3D reinforcing element not only increases the apparent cohesion of the soil, but it also increases the angle of internal friction significantly, especially with double-sided 3D reinforcing elements. The different configurations of 3D reinforcing elements are discussed.

## 1 INTRODUCTION

The reinforced soil has been widely used in geotechnical engineering, such as construction of road and railway embankments, stabilization of slopes, improvement of soft ground, and so on. Meanwhile, current researches mainly emphasize the strength, mechanism and bearing capacity of the reinforced soil (Haeri et al. 2000, Ingold 1983, Michalowski 2004, Rajagopal et al. 1999). Besides the study on strength properties and mechanism of the reinforced soil, the influence of the kinds of reinforcement materials and reinforcing styles on strength has been studied (Chen & He 2000, Smith & Brigilson 1979, Xie 2003, Xiong & Zhang 1992, Yang & Wang 1999). In conventional reinforced soil, the reinforcements are put horizontally in the soil. In this paper, a novel concept of soil reinforced with three-dimensional (3D) reinforcements is proposed. In order to investigate the real mechanism of soil structures reinforced with 3D reinforcements in practice, the behaviour of axial-symmetric specimens of sand reinforced with horizontal-vertical reinforcing elements was studied by a series of triaxial tests in this paper, where galvanized iron sheet and hard plastic sheet were used for reinforcing elements. The behavior of stress-strain relationship and shear strength of sand reinforced in different 3D reinforcing types is studied. From the experimental results, the comparison of stress-strain relationship and shear strength between horizontal reinforced sand and 3D reinforced one is analyzed.

## 2 CONCEPT OF SOIL REINFORCED WITH 3D REINFORCING ELEMENTS

In soils reinforced with 3D reinforcements, besides conventional horizontal reinforcements, some vertical and 3D reinforcements are also laid in the soil. Typical soil structures reinforced with 3D reinforcements are shown in Fig. 1. 3D reinforcing elements composed of conventional horizontal reinforcing stripes and vertical or triangular reinforcing elements are laid within the structures. Some typical configurations of 3D reinforcing elements can be divided into three cases:

(1) Vertical and 3D reinforcing elements are laid upon conventional horizontal reinforcing elements in soil; these are typically rectangular, triangular, semispherical in shape.
(2) Vertical and 3D reinforcing elements are laid in soil without any horizontal ones; these are spherical and ring shape reinforcements. These vertical and

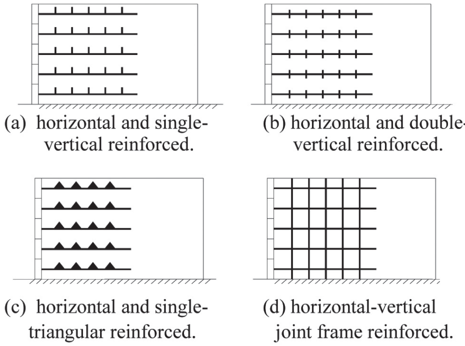



Figure 1. Typical 3D reinforced soil structures.

3D reinforcing elements can be connected to each other by a series of rigid materials.

(3) 3D reinforcements can be performed with joint frame structure composed of horizontal and vertical reinforcing elements.

## 3 EXPERIMENTAL PROCEDURE

### 3.1 *Test materials*

All the specimens of sand were prepared at a unit weight of 16.79 kN/m$^3$, a void ratio of 0.586 and a specific gravity of 2.64, in dry condition within a split cylinder mould. Uniform, clean, quartz beach sand from shores of Fujian Province in China was used. The particle size distribution curve for the sand is shown in Fig. 2. It is seen that the particle sizes of the sand mainly ranged between 0.25-1 mm. The sand has a relatively uniform grain-size distribution with median grain size ($D_{50}$) of 0.54 mm and coefficients of uniformity ($C_u$ ) and curvature ($C_c$) of 2.30 and 1.01, respectively. The reinforcements used in the tests are galvanized iron sheet with a thickness of 0.12 mm and hard plastic sheet with a thickness of 1.0 mm. The friction coefficients between sand and reinforcements (galvanized iron sheet and hard plastic sheet), obtained from direct shear tests, are 0.47 and 0.55, respectively.

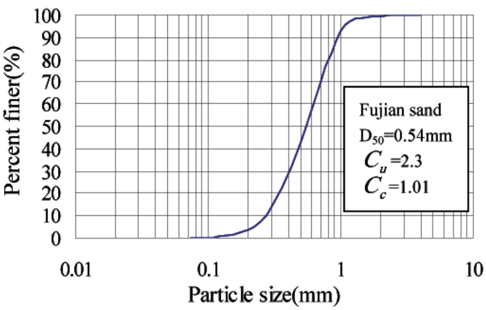



Figure 2. Grain size distribution curve.

### 3.2 *Test procedure*

To investigate the real mechanism of soil structures reinforced with 3D reinforcements in practice, the behaviour of axial-symmetric specimens of sand reinforced with horizontal-vertical reinforcing elements was studied by a series of triaxial tests, including different reinforcement configurations (horizontal, vertical and single-sided or double-sided 3D reinforcing elements) and confining pressures. A summary of these test parameters is given as follows:

(1) Different configurations of 3D and vertical reinforcing elements as shown in Fig. 3, and triaxial tests including 13 cases, as summarized in Table 1.
(2) Four confining pressures (50, 100, 150 and 200 kPa).

A standard medium-sized triaxial shear apparatus was used for testing specimens of unreinforced sand and sand reinforced with 3D and horizontal reinforcing elements. The specimens had a diameter of 61.8 mm and a height of 135 mm. For all the triaxial consolidated undrained (CU) tests, a strain rate ($\dot{\gamma}$)

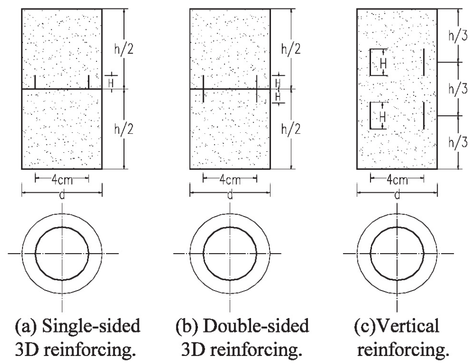



Figure 3. Configuration of 3D and vertical reinforcing elements.

Table 1. Experimental cases of 3D and vertical reinforced sand.

| Case | Vertical reinforcement Style | Height H (cm) | Note |
|---|---|---|---|
| 0 | – | – | Unreinforced |
| 1+ | – | – | Horizontal reinforced |
| 2+* | Single-sided | 1 | 3D reinforced |
| 3+* | Single-sided | 2 | 3D reinforced |
| 4+* | Single-sided | 3 | 3D reinforced |
| 5+* | Double-sided | 2 × 1 | 3D reinforced |
| 6+* | Double-sided | 2 × 2 | 3D reinforced |
| 7+* | Double-sided | 2 × 3 | 3D reinforced |
| 8+ | – | 0.5+0.5 | Vertical reinforced |
| 9+ | – | 1+1 | Vertical reinforced |
| 10+ | = | 2+2 | Vertical reinforced |
| 11+ | | 2+4 | Vertical reinforced |
| 12 | – | 4+4 | Vertical reinforced |

+ With galvanized iron sheet; *With hard plastic sheet.

of 0.5% per minute was adopted. Most of the tests were continued up to a maximum axial strain of 15%.

A standard procedure was adopted for preparing dry cohesionless samples and testing with triaxial apparatus as recommended by Bishop & Henkel (1969) and Head (1982). The samples were compacted in 3-4 layers through tamping with a tamper consisting of a circular disk attached to a steel rod. The relative density ($D_r$) of the sand was maintained around 79.8% for all samples. In triaxial tests, the reinforcing elements are often placed with axial-symmetry. The 3D reinforcing elements used in this study were composed of ring-shape vertical ones (in different heights) fixed upon horizontal one by means of bond, whose diameter was slightly less than that of the specimen. After compacting and leveling each layer of sand, 3D and vertical reinforcing elements were placed in the specimen according to the configurations (see Fig. 3).

## 4 TEST RESULTS AND DISCUSSIONS

### 4.1 *Stress-strain curves*

Typical stress-strain curves for the sand reinforced with 3D and vertical reinforcing elements are presented in Fig. 4. These figures indicate that the peaks of stress-strain curves for most specimens occur at an approximate axial strain of 1.5-3%.

### 4.2 *Strength properties*

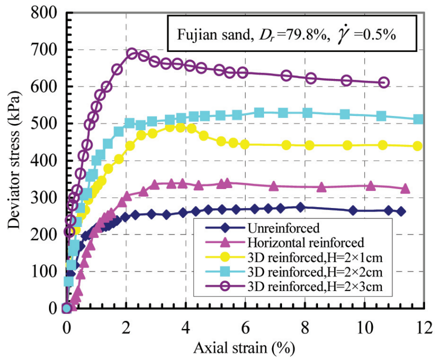
The *p-q* diagrams of specimens for sand reinforced with 3D and vertical reinforcements are presented in Fig. 5. The experimental results indicate that:

(1) For sand reinforced with single-sided 3D reinforcements, both apparent cohesion and the angle of internal friction are increased. As compared with unreinforced sand, the increments of apparent cohesion and the angle of internal friction for the sand reinforced with 3D reinforcements are 9.0-13.1 kPa and 1.3-3.9° respectively.

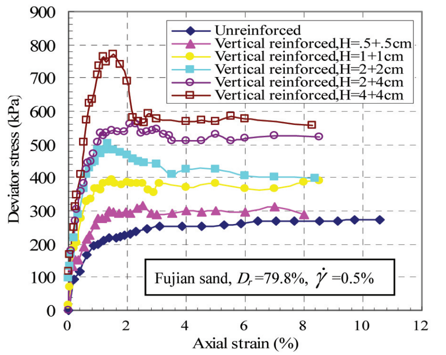
(2) For sand reinforced with double-sided 3D reinforcements, both apparent cohesion and angle of internal friction have increased remarkably. As compared with unreinforced sand, the apparent cohesion and the angle of internal friction of the sand reinforced with 3D reinforcements increased 26.7-48.3 kPa and 8.3-11.6° respectively.

(3) It can be seen that the apparent cohesion for the sand reinforced with double-sided 3D reinforcements (2 × 1 cm high) was 75.2% greater than that of single-sided 3D reinforcements (2 cm high), and the angle of internal friction for the former was 13.5% greater than that of the latter. From this observation, it was found that with the same height of vertical reinforcing elements, the shear strength of sand reinforced with double-sided 3D reinforcing elements is much greater than that with single-sided reinforcing element.

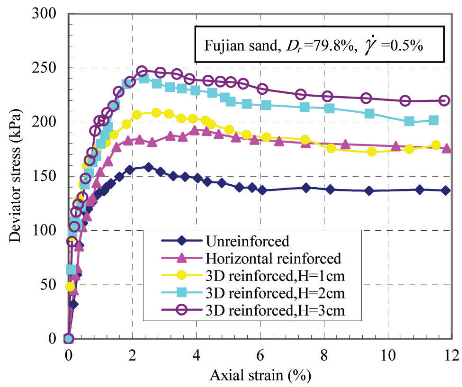
(4) For sand reinforced with vertical reinforcing elements, the angle of internal friction increases significantly, while displaying an increment of




(a) 3D reinforced (galvanized iron sheet, $\sigma_3$ = 100 kPa)

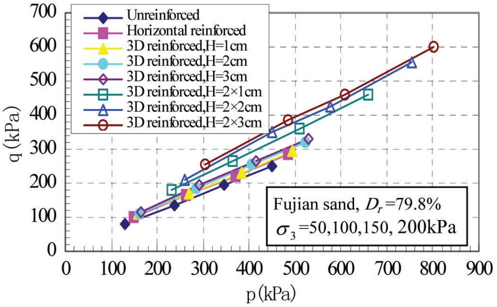



(b) Vertical reinforced (galvanized iron sheet, $\sigma_3$ = 100 kPa)

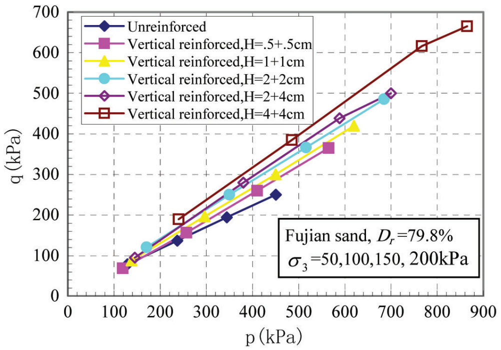



(c) 3D reinforced (hard plastic sheet, $\sigma_3$ = 50 kPa)

Figure 4. Deviator stress versus axial strain under different experimental cases.




(a) 3D reinforced with galvanized iron sheet




(b) Vertical reinforced with galvanized iron sheet.

Figure 5. *p-q* diagram under different experimental cases.

the apparent cohesion. As compared with unreinforced sand, the increments of apparent cohesion and the angle of internal friction for the sand reinforced with vertical reinforcing elements are 5.0-11.3 kPa and 7.7-19.0° respectively.

### 4.3 *Reinforcing effects*

Deviator stresses at failure for specimens of sand reinforced with 3D reinforcing elements under different experimental cases are presented in Fig. 6. It indicates that their deviator stresses increase with increasing the height of vertical reinforcements.

## 5 CONCLUSIONS

In this paper a novel concept of soil reinforced with three-dimensional reinforcing elements has been proposed. A comprehensive set of triaxial tests was carried out on samples of dry sand reinforced with 3D and vertical reinforcements. The following conclusions are drawn from the results:

(1) The experimental results in this paper show that 3D or vertical reinforcing element not only increases the apparent cohesion of the soil, it

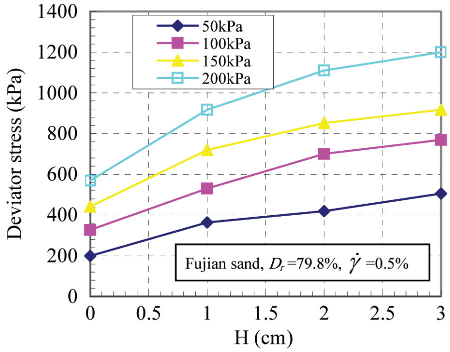



Figure 6. Deviator stresses at failure versus heights of vertical reinforcements (3D reinforced on double-sided).

also increases the angle of internal friction significantly, especially with double-sided 3D reinforcing elements.

(2) The strength of sand reinforced with 3D reinforcing elements increases with increasing height of the vertical reinforcing elements.

(3) For sand reinforced with 3D reinforcing elements with the same vertical height, double-sided 3D reinforcing elements will result in greater increase in strength than single-sided ones.

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