INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING

Anisotropic Fabric of Sands

Anisotropie Structurale du Sable

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SYNOPSIS

Undisturbed and disturbed sands whose fabric anisotropy had been made clear by means of optical microscope and thin sections were tested to examine the essential bearing of fabric anisotropy on their mechanical properties such as shear strength and bearing capacity with the following conclusions: 1) In the undisturbed and disturbed sands deposited under the action of gravitational force, their fabric is generally characterized by the anisotropic alignment of their constituent particles even though they show differing degree of imbrication due to the action of water flow at the time of their sedimentation. 2) The shear strength anisotropy of sand increases not only with the increase of flatness of its particle shape but also with the decrease of its void ratio and applied confining pressure σ_3. 3) The fabric anisotropy of sand results in its anisotropic response of ultimate bearing capacity and modulus of subgrade reaction.

INTRODUCTION

According to the studies by Oda (1972) and Arthur and Menzies (1972), sands deposited in air or in water show anisotropic shear strength in their triaxial compression tests which is attributed to the preferred alignment of long axes of particles parallel to a bedding plane. The authors now discuss various factors which may control the parallel alignment of particles observed in disturbed and naturally deposited sands. The authors also demonstrate an important bearing of the fabric anisotropy on soil-engineering properties such as shear strength, ultimate bearing capacity and modulus of subgrade reaction.

FABRIC ANISOTROPY OBSERVED IN UNDISTURBED SANDS

Undisturbed samples of three sands were obtained by pushing carefully a thin wall sampler (7.5 cm in internal diameter and 20 cm in height) into typical sand formations naturally deposited under different sedimentary conditions (Tone river sand, Kugenuma beach sand and Sengenyama sand). Their particle arrangements were stabilized by infiltrating a binder of polyester resin into voids without disturbance after their drying up. As shown in Fig. 1, two thin sections which were made to be parallel to a vertical plane (V-section) and a horizontal plane (H-section) were prepared from each of stabilized sands. (Detailed procedures have been described by Oda (1972)). The axis X

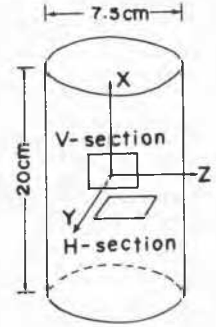


Fig. 1 Preparation of two thin sections

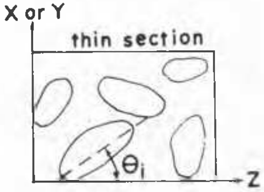


Fig. 2 Orientation of apparent long axes on thin section

in Fig. 1 was selected as the vertical direction, and the axis Z as the horizontal direction corresponding to the flow direction of water at the time of particle sedimentation.

The fabric anisotropy due to the parallel alignment of particles was investigated by measuring the angles between apparent long axes of about 250 particles and the reference axis Z on each thin section by means of the microscope and thin section (Fig. 2 and Oda (1972)). Figs. 3(a) and (b) show frequency histograms for the V-and H-sections of the Tone river sand. The sand is an alluvial deposit whose relative density is less than 10%. In the V-section of Tone river sand (Fig. 3(a)), there can be found a unimodal distribution curve having a clear peak at θ_i =-30°. The tendency that the preferred direction inclines at an acute angle to the horizontal is due to the effect of water flow at the time of sedimentation (Johansson (1965)).

The Kugenuma beach sand is also an alluvial deposit whose relative density is about 60% much larger than that of the Tone river sand. The frequency histograms of the sand are shown in Figs. 4(a) and (b). While its frequency curve of the V-section (Fig. 4(a)) is nearly similar to that of the Tone river sand (Fig. 3(a)), the both H-sections are different with each other. That is, the there can be also found a clear peak at θ_i = ±90° in the H-section of the Kugenuma beach sand. From Figs. (3) and (4), we can conclude that river and beach sands are generally characterized by fabric anisotropy due to pronounced preferred orientation. They have, however, different degree of imbrication due to the effect of water flow at the time of sedimentation.

The Sengenyama sand is a diluvial deposit whose relative density is larger than 90%. Judging from its relative density, it seems to be an over-consolidated sand. The frequency histograms for the Sengenyama sand, as shown in Fig. 5, are almost the same to those for the Tone river sand (Fig. 3). Consequently, it can be said that the over-consolidated sand also shows the anisotropic fabric characterized by the parallel alignment of particles whose preferred direction inclines at an acute angle to the horizontal.

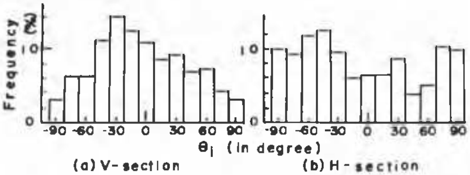


Fig. 3 Frequency distribution of θ_i for the Tone river sand

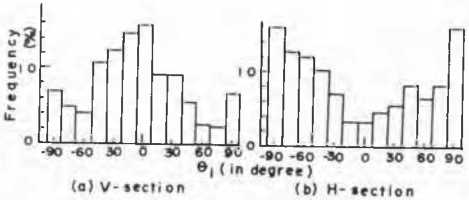


Fig. 4 Frequency distribution of θ_i for the Kugenuma beach sand

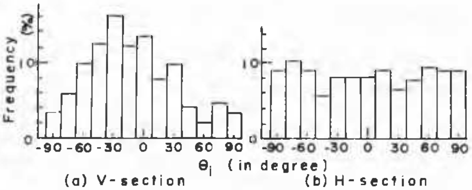


Fig. 5 Frequency distribution of θ_i for the Sengenyama sand

FABRIC ANISOTROPY OBSERVED IN DISTURBED SANDS

Fifteen disturbed sands were collected from various localities. Axial ratios of these sands range from 0.5 to 0.7. Axial ratio is an index for characterizing their particle shape, and shape of particles becomes similar to that of sphere with the increase of axial ratio up to 1 (Oda, 1975). These fifteen sands were individually poured into vacant molds (5 cm in diameter and 10 cm in height) and were compacted by repeated vibrations up and down by hands for the sake of getting relative densities ranging from 60% to 80%. These compacted sands were stabilized by resin and their V-sections were made. A vector magnitude I_V for each thin section was determined as an index for representing the intensity of fabric anisotropy by the following equation (Curray (1956) and Oda (1972));

$$I_V=\frac{100}{n}\sqrt{(\Sigma\sin 2\theta_i)^2+(\Sigma\cos 2\theta_i)^2}\quad(\%)$$

where n is the total number of measurements. The vector magnitude shows the intensity of parallel alignment of apparent long axes on thin sections and varies from 0% which means complete random orientation of apparent long axes to 100% which means their complete parallel alignment.

As clearly demonstrated in Fig. 6, the value of I_V on the V-section increases with the decrease of axial ratio. It is also said that statistically significant preference of particle orientation can be found in sands having their axial ratios less than 0.65. At the same time, the authors also observed that the preferred direction becomes closer to the horizontal when its particles become more slender or more platey, and no

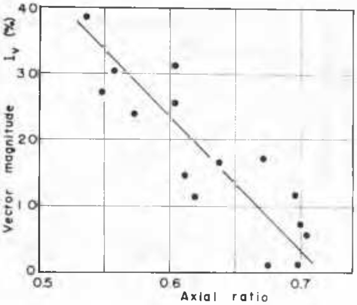


Fig. 6 Relation between I_V and axial ratio

preferred direction can be observed on all H-sections irrespective of their shape characteristic.

Solid and broken lines in Fig. 7 show frequency distributions of θi on the V-sections of the Toyoura sand deposited in water and in air respectively. (Axial ratio of the sand is 0.605). Judging from the similarity of both frequency curves, whether particles are deposited in air or in water has no essential effect on their parallel alignment.

ANISOTROPIC RESPONSE IN SHEAR STRENGTH OF SAND

According to the studies by Oda (1972) and Arthur and Menzies (1972), the maximum shear strength is mobilized in a drained triaxial compression test when the maximum principal stress σ_1 is applied perpendicular to its bedding plane and, on the other hand, the minimum shear strength is mobilized when σ_1 is applied parallel to the plane. These features were considered to be due to the preferred alignment of particles parallel to the bedding plane.

Here, the authors propose a strength ratio R_s as an index to evaluate the intensity of the anisotropic response in the drained triaxial compression test, as follows;

$$R_s = \frac{(\sigma_1 - \sigma_3)H}{(\sigma_1 - \sigma_3)V}$$

where $(\sigma_1 - \sigma_3)V$ is the maximum deviator stress mobilized when σ_1 is perpendicular to the bedding plane and $(\sigma_1 - \sigma_3)H$ is the maximum deviator stress mobilized in the same sand when σ_1 is parallel to the plane. In order to examine the relation between R_s and a shape factor of particles, tests were performed on seven sands whose axilal ratio were different with each other. (Experimental conditions are as follows; relative density = 40-100%, confining pressure = 0.5-3.0 kg/cm^2, and strain rate = 0.125 - 0.2%/min.)

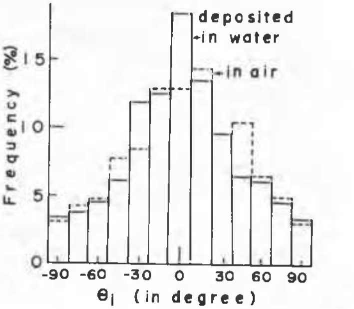


Fig. 7 Frequency distributions of θi in the Toyoura sand deposited in air or in water

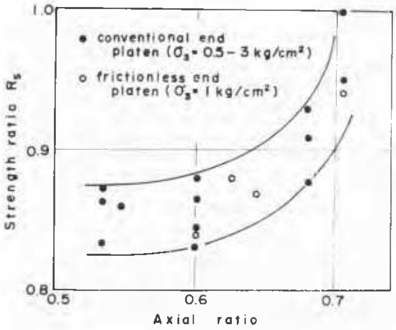


Fig. 8 Relation between R_s and axial ratio of sands deposited in water

Fig. 8 shows a statistically significant relation between R_s and the axial ratio for the seven sands deposited in water. A well-defined zone can be found with the marked tendency that the strength ratio decreases when particle shape of sand becomes closer to spherical one. This well accords with the fact that the intensity of parallel alignment of particles on a V-section increases with the decrease of axial ratio (Fig. 6). Scattered test results must be due to the following two facts; (1) the strength anisotropy becomes more remarkable in a sand having a larger relative density (Arthur and Menzies, 1975) and (2) the strength anisotropy decreases with increasing applied confining pressure σ_3 (Fig. 9).

From these experimental results, we can conclude that the anisotropic shear strength of sand must be most remarkable when the following three conditions are satisfied: 1) the sand is composed of slender or platey particles, 2) the sand is densely compacted under the action of gravity, and 3) the sand

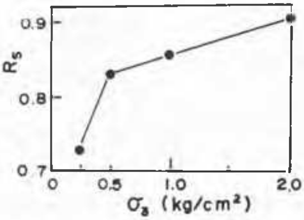


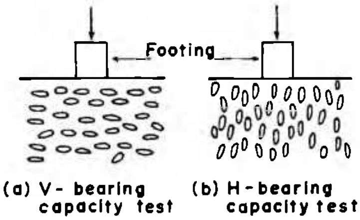
Fig. 9 Effect of confining pressure on strength ratio of the Toyoura sand

is failed at low confining pressure as in the case of failure of a shallow foundation.

ANISOTROPIC RESPONSE OBSERVED IN ULTIMATE BEARING CAPACITY OF SAND

In order to examine an anisotropic response of sand in a bearing capacity test, the Toyoura sand was poured into a vacont steal sided box whose length, width and depth were 30 cm, 7 cm and 20 cm respectively. By stiffening the soil box, its lateral deflection was restricted less than 0.01 mm over the range of strip footing penetration up to failure and plane strain condition of test was nearly satisfied. A smooth footing lubricated by two membranes and silicon grease whose size was 3.5 cm in width and 6.7 cm in length was penetrated perpendicular (V-bearing capacity test) to or parallel (H-bearing capacity test) to the bedding plane, as shown in Fig. 10. The comparison of these two types of test make it possible to evaluate qualitatively the effect of sedimentary structure on the ultimate bearing capacity and modulus of subgrade reaction.

Experimental results are given in Figs. 11 and 12. The ultimate bearing capacity and modulus of subgrade reaction are both larger in the V-bearing capacity test than those in the H-bearing capacity test, especially when the tested sand was well compacted. This anisotropic response is due to the preferred alignment of particles parallel to the bedding plane.



(a) V- bearing capacity test **(b) H-bearing capacity test**

Fig. 10 Two types of bearing capacity test

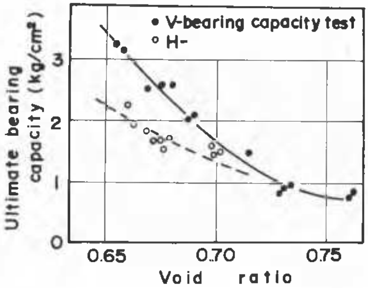


Fig. 11 Anisotropic response on ultimate bearing capacity of the Toyoura sand

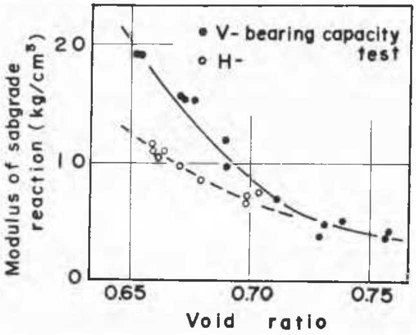


Fig. 12 Anisotropic response on modulus of subgrade reaction of the Toyoura sand

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