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# Strength ellipses of induced anisotropy for a compacted sandy material

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ABSTRACT: This paper presents a study on strength anisotropy in a sandy material with anisotropic fabric formed by press loading. Two series of DS-CD tests (direct shear tests under CD condition) were performed using a developed DS apparatus with a double-jack system. To maintain anisotropic fabric in a sample, a freezing technique was developed. Shear strength of samples in the active shear zone was found to be stronger than that of the passive zone, and the results could be expressed well by an ellipse equation with tilting coordinates of an angle measuring 15° to the horizontal line. To find a reason for the inclination of the axis of strength ellipses, a 2D-DS test was performed by a developed 2D-DS device. The direction of the main shear zone of a sand sample measuring 15° coincided well with that of the ellipses' coordinates, which should be taken into consideration when shear strength from a DS-CD test should be used in a safety analysis of a soil structure.

## 1 INTRODUCTION

Aiming to evaluate shear strength of a compacted weathered granite with anisotropy for such as safety analyses of an embankment, two series of CDDS tests (direct shear tests under CD condition) on sandy soil samples, in which the inherent anisotropy was induced by press loading, were performed using an improved DS apparatus in this study (Mochizuki *et al.*, 2021).

The first directive articles for research on shear strength anisotropy, it is said, was presented by (Bjerrum, 1973) in the 'State of arts reports' in the 8th-ICSMFE conferences, in which a concept of "an extension mode (TE)" for the shoulder part of a slope, "a simple direct shear mode (SDS)" for the middle part and "a compression shear mode (TC)" for the toe part was presented. After that, Bjerrum's discussion became a road map for the following study of shear strength anisotropy.

The most reliable test data on undisturbed clay samples from Osaka city, Japan were presented by (Mikasa, Takada and Oshima, 1987) using the original type of Mikasa's DS apparatus ((MIKASA, 1965), see Figure 1). Test results on clay samples against the N-S surface showed similar trends of anisotropy on shear strength as those on ones of remolded clay. They compared them to those of the E-W direction, and the possibility of secondary loading of tectonic force in the E-W direction on the Osaka layers was found. Whereas (Nishimura, Minh and Jardine, 2007) tried to quantify the anisotropy of London clay using a torsional triaxial test. An introduction of anisotropic shear strength into stability analysis of a slope was tried by (Shogaki and Kumagai, 2008).

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The fabric characteristics and anisotropic nature of granular materials was systematically studied by (Parkin, Gerrad and Willougby, 1968), (Arthur and Menzies, 1972), (Oda, 1972) and (EL-Sohby and Andrawes, 1973), which demonstrated the significance of anisotropic fabric also in cohesionless soils. Regarding the anisotropy of sandy material, however, less publications were published as a study on sand anisotropy appears to be much more difficult to prevent deterioration of anisotropic fabric than that of clay during sampling or forming of them for shear tests.

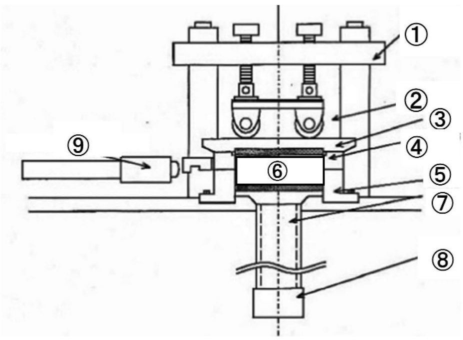
In this study, to overcome the difficulty to maintain anisotropic fabric induced by press loading a freezing technique was introduced, in which an improved DS apparatus was used ((Ishikawa *et al.*, 2009), see Figure 2). It was found that the test results could be expressed well by an ellipse equation with tilting coordinates of an angle measuring 15° for the strength anisotropy of the sandy material. In order to discuss the inclination of the axis of ellipses, a 2D-DS tests (two-dimensional direct shear tests) were performed using a newly developed 2D-DS device (Ohfuji, Ueno and Mochizuki, 1999).

## 2 TEST CONDITIONS AND PREPARATION OF SAMPLES WITH ANISOTROPIC FABRIC

### 2.1 *Improved direct shear apparatus and used material*

Progress of a DS (direct shear) apparatus in Japan was totally different from that in Europe or USA. Figure 1 shows a cross-sectional sketch of the main part of Mikasa's original DS apparatus developed in 1965 (MIKASA, 1965). Vertical stress is applied from the bottom of a sample, the reaction force is supported by the rollers installed at the upper plate, which prevents the upper shear box to lean during shearing. And the resulting function enables performing a CV (constant volume) test as well as a CD test (Takada, 1993). The apparatus was adopted in a code of the Japan Geotechnical Society since 1979 (JGS0561 (Japan Geotechnical Society, 1979)) and has been used widely in Japan.

One shortcoming of the Mikasa's DS apparatus, however, is growing evitable friction between a sample and the shear box wall when performing CD tests on dense sands, which tends to give unexpected over-prediction of shear strength. To eliminate such problems, (Ishikawa *et al.*, 2009) developed a new DS apparatus with a double-jack (DJ) system on the upper shear box, shown in Figure 2. Accuracy of test results on Toyoura sand (standard sand in Japan), was proved to present almost equivalent results obtained by triaxial CD tests.




| | |
|---|---|
| ① | Reaction plate |
| ② | Reaction rolers |
| ③ | Upper plate |
| ④ | Upper shear box |
| ⑤ | Lower shear box |
| ⑥ | Samaple |
| ⑦ | Loading rod |
| ⑧ | Load cell for $\sigma_N$ |
| ⑨ | Load cell for $\tau$ |

Figure 1. Main structure of Mikasa's *DS* apparatus (MIKASA, 1965).

### 2.2 *Test conditions for $CD_{DS}$ tests and preparing test samples*

Table 1 shows the main properties of the material used for specimens, which was made from strongly weathered granite with 20% of fine grains from Tokushima, Japan. It is normally used

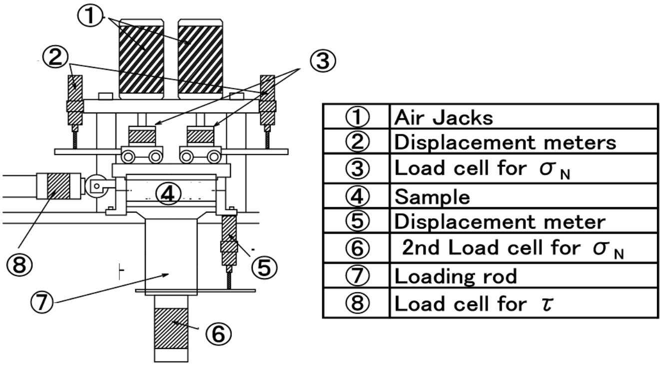



Figure 2. A newly designed $DS_{DJ}$ apparatus with double-jack system (Ishikawa *et al.*, 2009).

for construction of dike, road embankments, earth dams etc. The material was sieved with a 1.2 mm mesh and mixed well. Then, the material was weighted measuring 1 kg each by the quartering method, and water was added to be its optimum water content measuring 14%, which was found from a preliminary compaction test. After forming a sand layer of about 1 cm thickness with 1kg of material in a strong box measuring L52×W19.5×H18cm the layers were pressed with a static load of 600 or 1,200 kN/m$^2$ for one minute to each layer, which compressed into a 0.5 cm layer of a specimen. Twenty times of press loading was repeated to produce a specimen with about 10 cm thickness, which simulated a road embankment construction by heavy roller weight.

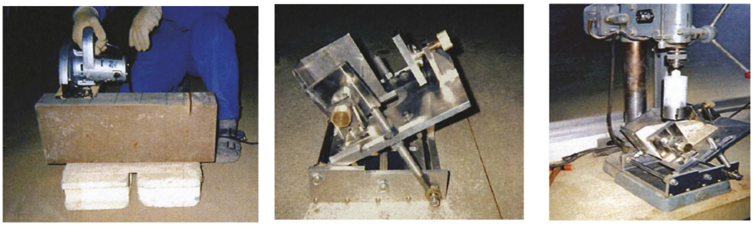
Table 1. Main properties of sand material.

| | |
|---|---|
| $\gamma_s$ (g/cm$^3$) | 2.634 |
| $d_{max}$ (mm) | 1.2 |
| Sand (%) | 79 |
| Silt (%) | 8 |
| $\rho_{dmax}$ (g/cm$^3$) | 1.87 |
| $w_{opt}$ (%) | 13.4 |

After the forming of a specimen with twenty sub-layers, the plate for loading was clicked by handy vices to prevent it from heaving. As an anisotropic fabric formed in soil specimen was not free from disruption due to sampling or forming into a sample, a freezing technique to a sample was developed for these tests. The specimen in the strong box was moved into a freezer at a temperature of minus 45 °C. Here, they are referred to as "a 600 kN/m$^2$ sample or 1,200 kN/m$^2$ sample" in this paper. The surface of which was covered with aluminum foil to prevent the sublimation of water. Table 2 shows test conditions. The procedure of a CDDS test followed the Japanese code of JGS0561.

Table 2. Test conditions (DS-CD test).

| Shear test conditions | |
|---|---|
| Drain condition | CD |
| Melting temperature (°C) | 21 (15 min) |
| Time for consolidation (min) | 20 |
| $\sigma_N$ (kN/m$^2$) | 50, 100, 150, 200, 250, 300 |
| Rate of shear (mm/min) | 0.25 |
| Shear angle, θ (°) | Active zone: 0, 30, 60, 90 |
| | Passive zone: 90, 120, 150, 180 |
| $\gamma_d$ (g/cm$^3$) | 1.74 |



(a)Frozen specimen (b)Boaring stage (c) Core cutter

Figure 3. Process of sampling from a frozen specimen.

Then, a frozen specimen was cut into seven blocks of L7×W19.5 ×D10 cm (Figure 3(b)), and cutting direction were designated for each test on a frozen block. Then, a frozen block was moved to a newly designed coring stage (Figure 3(c)).

Figure 4 shows the definition of shearing angle, δ, of a sample, which is d fined against the shearing direction of a sample to the horizontal stratification, in which a zone of δ=0° to 90° is referred to as the active shear zone, and that of δ=90° to 180° is the passive shear zone. A sliced sample measuring about 2.5cm in height was brought into a cutter-ring of φ60×20 mm by a pre-determined press slowly to avoid deterioration of a sample due to over-loading, and a frozen sample was set into a shear box. Then, the sample was heated up to its melting point of 21 □ for 15 min by a band heater around the shear box, that condition was found in a preliminary test. The samples were sheared loading a designed vertical stress, $\sigma_N$ under CD condition.

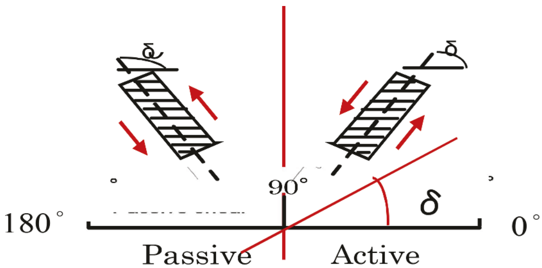



Figure 4. Shearing angleδand Active/Passive zone.

## 3 TEST RESULTS

Figure 5(a) shows τ (shear strength)~ D and Δh~ D relations of CDDS tests sheared to δ = 0° direction for 1,200 kN/m$^2$ samples. Here, D is horizontal displacement and Δh is a change of height (or volume) of a sample due to dilatancy. Curves of $\tau \sim$ D show a distinct peak strength even though the vertical stress, $\sigma_N$, increased. Figure 5(b) shows test results of those sheared to δ=90° direction. Test results of samples of δ = 90° direction did not exhibited such distinct peak strengths.

Figure 6(a) shows test results of 1,200 kN/m$^2$ samples sheard to different angles of δ under the vertical stress of σN=100kN/m$^2$. The $\tau \sim$ D curves sheared to $\delta = 0 \sim 60°$ (the active zone) exhibited distinct peak strengths, though samples of δ=90, 120, 150° (the passive zone) did not show such clear peak strengths. These results suggest that 'inherent fabric in a sample' was destructed more during shearing in the passive zone under CD condition than that in active zone.

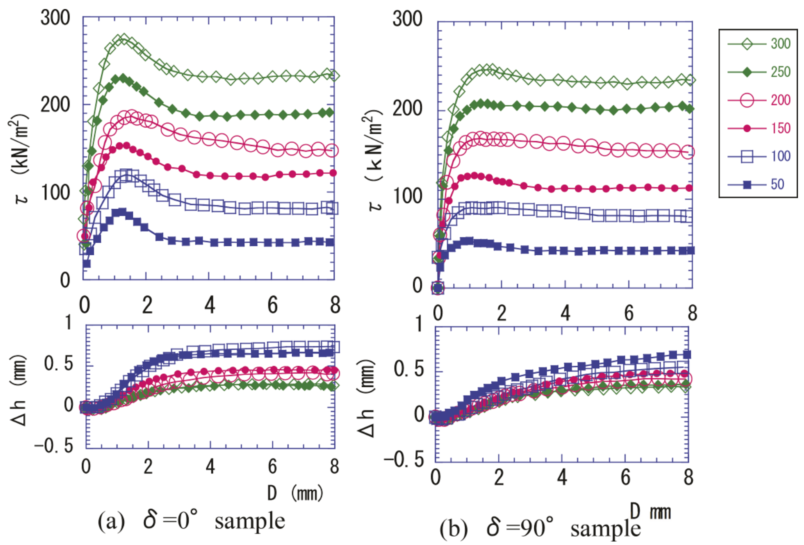



Figure 5. $\tau \sim$ D, $\Delta$h $\sim$ D diagrams of $CD_{DS}$ tests for 1,200 kN/m$^2$ samples.

Figure 6(b) shows test results of 1,200 kN/m$^2$ samples tested under the vertical stress of $\sigma_N$=200 kN/m$^2$, which did not exhibit such distinct difference of peak strengths even for δ=0, 30, 60° samples.

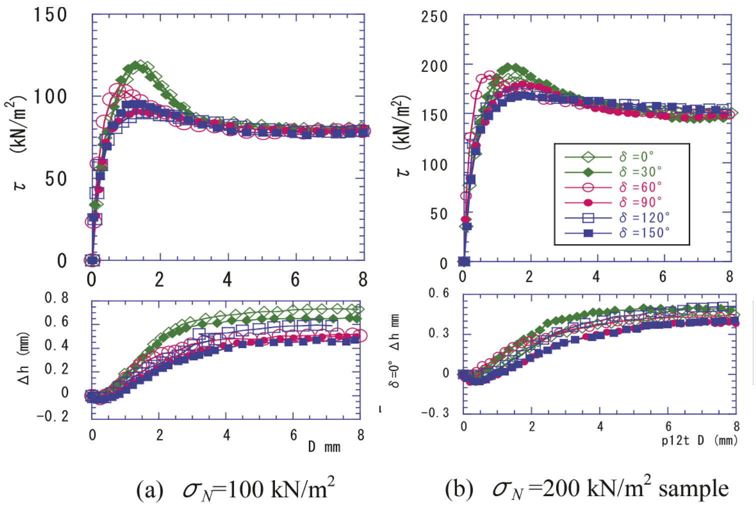



Figure 6. $\tau \sim$ D, $\Delta$h $\sim$ D diagrams of $CD_{DS}$ tests for 1,200 kN/m$^2$ samples with different angles of $\delta$.

It suggests that anisotropic fabric in samples under σN=200 kN/m$^2$ was destroyed during shearing more than that in a sample under σN=100 kN/m$^2$. "An intention ratio of anisotropic fabric/$\sigma_N$" will be an index for shear strength of a sample with anisotropic fabric.

## 4 DISCUSSION OF TEST RESULTS

### 4.1 *Strength ellipses for anisotropy*

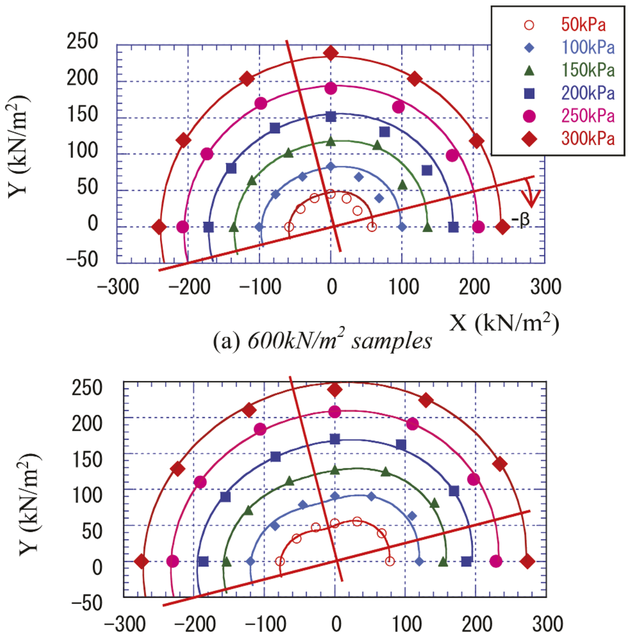
From discussions in the foregoing section, the strength of a sample with anisotropic fabric was found to depend on stress condition and the shearing direction of a sample, δ. When test results of strength anisotropy are introduced into safety analysis of soil structure, formulation of test results of strength anisotropy is a preferable technique. The formulating test data will also work effectively to take an average of data in such a case with un-evitable fluctuating errors. After several preliminary trials, an ellipse equation was found to express the test results of strength anisotropy of samples.

Figure 7(a) shows the resulting elliptical curves for 600 $kN/m^2$ samples. It should be noted that the axis of ellipses tilted measuring β= -15° to the horizontal coordinate of the chart (in the passive zone: see Figure 7(a)), therefore, the direction of the long axis of ellipses was measuring θ=+15°(=δ-β), and that of the short axis was measuring 105°(θ). The results of CDDS tests are well expressed by the ellipsoidal curves, though some scatters of the test data are detected. It should be noted that the degree of flatness of the ellipses decreases along with increases of vertical stress.

Figure 7(b) is a chart of test data for 1,200 $kN/m^2$ samples. Results of CDDS tests showed successfully being represented in ellipses, inclined at an angle measuring 15° to the horizontal coordinate. However, the trend of the elliptical curves was different from that of clay samples with the maximum shear strength at θ=45°.

Shear strength, τf in Equation (1), being a formula of ellipse, was calculated in the following processes:

$$\tau_f = \sqrt{\left[a^2\cos^2(\delta-\beta) + b^2\sin^2(\delta-\beta)\right]} \quad \text{Here, } \theta = \delta - \beta \tag{1}$$




(a) *600kN/m² samples*

(b) *1,200kN/m² samples*

Figure 7. Results of $CD_{DS}$ tests and ellipses of strength anisotropy.

An equivalent radius of the ellipse, Re, is found from Equation (2), and a ratio of flatness, A1 or A2 of an ellipse is calculated from Equation (3), in which parameters, ‘a’ and ‘b’ are a short or a long radius of an ellipse, which were found from test data of δ=0° or 90° samples, respectively for the first approximation of the parameters in this study. Then, Re was calculated by Equation (2), and test results were plotted in a polar chart. Then, shear strength, τf is calculated by Equation (4), which was transformed from Equation (1) using parameters, A and Re instead of parameters, a and b.

$$\text{Equivalent radius of an ellipse: } R_e = \sqrt{[a \times b]} \tag{2}$$

$$\text{Ratio of flatness of an ellipse: } A_1 = \frac{(a - R_e)}{R_e} \text{ or } A_2 = \frac{(R_e - b)}{R_e} \tag{3}$$

$$\tau_f = R_e \sqrt{\left[(1+A)^2 \cos^2(\delta - \beta) + (1-A)^2 \sin^2(\delta - \beta)\right]} \quad \mathit{Here},\ \delta - \beta = \theta \tag{4}$$

### 4.2 *Discussion on the inclination of the primary axes of ellipses to the horizontal coordinate*

In Section 3, the primary axes of strength ellipses were found to be inclined measuring β= -15° to the horizontal line (in the passive zone). To introduce the effect of strength anisotropy into an analysis of soil structures such as road embankments etc., it is necessary to find a reason about the inclination of the axes of the ellipses.

With this view, the development of the shear zone in a sand sample during a DS test was observed using a newly developed 2D-DS device, a sketch of which was shown in Figure 8 (Ohfuji, Ueno and Mochizuki, 1999). A double jack system was installed on the upper plate of the shear box to keep it horizontally with a constant condition of total vertical force, $\sigma_N$. The front surface of the shear box was covered with separated crystal-glass plates to observe the deformation of a sample. The density of sand ($\rho_d$) was 1.655g/cm$^3$ and the size of the sample was L30×H20×D4 cm. Photos were taken at each scheduled interval, and the photo image analyzer was used to detect shear zone in a sand sample of Toyoura-sand (Japanese standard sand).

Figures 9(a) ~ (d) show areas where shear strains, $\gamma_{xy}$, being over 10% in a sample at each displacement of a 2D-DS test, which exhibited progress of expanding shear zones over 10%. The peak strength of a test was detected at D=10 mm (Figure 9(c). Additional broken lines in the figure were drawn to show the direction of β= -15° to the horizontal (in the passive zone). The direction of the shear zone to the horizon in the sample was found to coincide well with the inclination angles of the axis of strength ellipses, which is a reason for the inclination of strength ellipses in Figure 7.

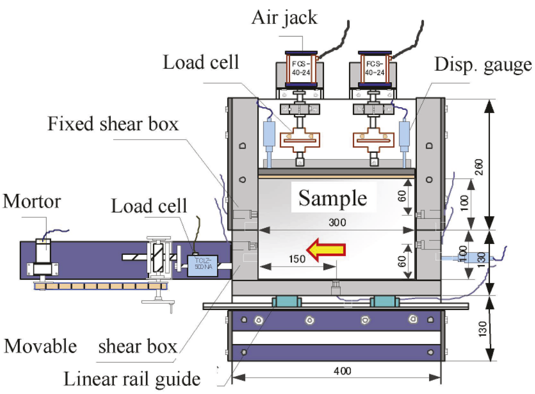



Figure 8. Sketch of a developed 2*D-DS* device (Ohfuji, Ueno and Mochizuki, 1999).

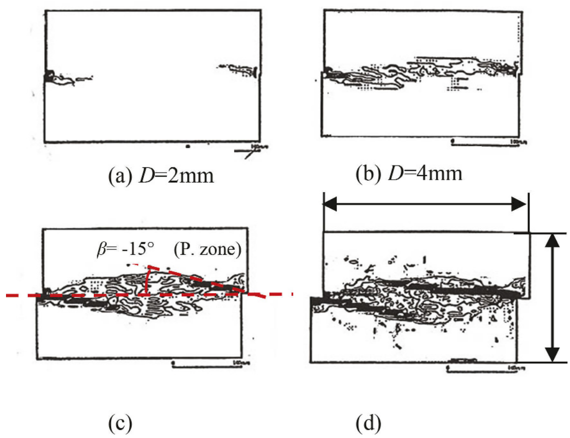



Figure 9. Expanding of a zone over 10% of $\gamma_{xy}$ (Ohfuji, Ueno and Mochizuki, 1999).

It is concluded that an inclined angle measuring θ=15° (θ=δ - β) of the axis of strength ellipses to the horizontal coordinate must be revised when results of DS tests will be used in safety analysis of soil structures. Someone may think it is a particular kind of a negative problem in a DS test, however, it is not, as the only way to observe strength anisotropy in sandy materials is not test data of a triaxial test, but those of a DS test using the improved DS apparatus with double-jack system.

## 5 CONCLUSIONS

This paper presented an experimental study on shear strength anisotropy in a compacted sandy material. Two series of CDDS tests (direct shear tests under CD condition) were performed using an improved DS (direct shear) apparatus. To avoid deterioration of the anisotropic fabric of a sample, which was formed by press loading of 600 kN/m$^2$ and 1,200 kN/m$^2$, a freezing technique was introduced. The samples and test method were chosen to simulate the construction of an actual road embankment. The main conclusions reached in this study are as follows:

(1) A freezing technique of a sample was attributed to preventing deterioration of the anisotropic fabric induced by press loading in a sandy sample. An improved DS apparatus with a double-jack system worked effectively to observe strength anisotropy in sandy samples under CD condition.
(2) Samples in the active shear zone of δ=0°to 60°showed distinct and high peak strengths, whereas those in the passive zone of δ=90°to 150°showed un-clear peak and low strengths.
(3) Strength gap of δ=0° samples to that of θ=90° samples became smaller along with the increase of vertical stress, $\sigma_N$, which was caused by the induced anti-anisotropy behavior or destruction of anisotropic fabric during shearing under CD condition.
(4) It was found that the results can be expressed well by an ellipse equation with tilting coordinates of an angle measuring β= -15° (in the passive zone) to the horizontal coordinate.
(5) Progress of increasing of the shear zone in a sand sample was observed using a newly developed 2D-DS device, and the primary shear zone developed to a direction measuring β= -15° to the horizon in the sample was found, which coincided well with the inclination of the primary axes of strength ellipses for a sample with strength anisotropy induced by press loading. It suggests that the axes inclination of strength ellipses must be revised when the results of the strength anisotropy observed by DS tests will be used in safety analysis of soil structures.

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