ANISOTROPIC DEFORMATION-STRENGTH PROPERTIES OF SOFT SEDIMENTARY ROCK "SHIRASU" ORIGINATED FROM PYROCLASTIC FLOWS

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ABSTRACT

In order to study the deformation-strength behaviour of soft sedimentary rock "Shirasu" derived from pyroclastic flows, drained triaxial compression tests were performed on undisturbed specimens prepared by cutting and trimming from block samples. The specimens were tested with the direction of applied major principal stress inclined at various angles to a bedding plane. An inherent anisotropy in the shearing behaviour of Shirasu was studied from the test results. The anisotropy was dependent on the dip of stratum and the confining pressure related to grain orientations and grain movements during consolidation and shearing. The effect of anisotropy on the shearing behaviour was remarkable under a low confining pressure and disappeared under a high confining pressure. That the shearing strength of sedimentary rocks depends on the direction of the major principal stress at failure and the stress level requires a special attention for the choice of the strength parameters in practical problems.

Key words : anisotropy, deformation, sampling, sedimentary rock, shear strength, Shirasu, triaxial compression test, volcanic soil (IGC : D 6/F 6/C 6)

INTRODUCTION

An anisotropy is distinguished between inherent anisotropy resulting from the orientations of fabric elements due to grain shape and mode of deposition and induced anisotropy resulting from the property of intergranular pressure and deformation associated with stress history (Arthur et al, 1972, 1977). In nature, sedimentary rocks

may substantially have an inherent anisotropy affecting on mechanical behaviour. Especially, the flat grains which fall freely through water might cause the sedimentary strata to have significantly different characteristics wherein each grain orients so as to get approximately parallel alignment to bedding planes. Undrained strength anisotropy of natural clay deposits has been investigated considerably (Lo and Milligan,

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Manuscript was received for review on March 28, 1984.

Written discussions on this paper should be submitted before July 1, 1985, to the Japanese Society of Soil Mechanics and Foundation Engineering, Sugayama Bldg. 4F, Kanda Awaji-cho 2-23, Chiyoda-ku, Tokyo 101, Japan. Upon request the closing date may be extended one month.

1967; Skempton and Hutchinson, 1969), but studies on the deformation-strength characteristics of sands have been confined to the anisotropy of specimens prepared in laboratories because of difficulties of sampling undisturbed specimens (Arthur et al, 1972, 1977; Oda, 1972; El-Sohby and Andrawes, 1973; Yamada and Ishihara, 1979; Haruyama, 1981). While the fabric anisotropy in natural sand deposits was confirmed by Oda and Koishikawa (1977).

Then, pyroclastic flow deposits originated in volcanic activities in the Quaternary epoch are widely distributed on land and under water in southern Kyushu, Japan (Haruyama, 1973). The deposits have the hardness ranging from soft soil to hard rock and will become granular soil when disturbed. The nonwelded and the weak-welded parts of the deposits have been locally called Shirasu (Haruyama, 1979). The mechanical properties of Shirasu are characterized by the peculiar shape and surface texture of grains, the crushing of grains, a high compressibility, the interlocking of grains and the welding effect (Haruyama, 1969 a, 1973, 1977, 1979). However, stress-strain and strength properties of undisturbed Shirasu have not been studied sufficiently because of difficulties of sampling. Fujikawa and Miwa (1979) showed the existence of directional shear strength for sedimentary Shirasu from the results of direct shear tests. Moreover, the authors proved the anisotropic deformation-strength characteristics of man-made deposits of Shirasu in water bath, taking alluvial Shirasu deposits and inshore reclaimed land using Shirasu into consideration (Haruyama, Kitamura et al, 1981).

The present paper aims, as a study on shear characteristics of Shirasu in undisturbed state, at investigating the anisotropy of deformation-strength behaviour from the results of drained triaxial compression tests on the specimens obtained at various inclinations to bedding plane. Although undisturbed sampling is very difficult for Shirasu deposited on land because of

containing a great many gravels, it is considerably easy for Shirasu deposited under water because of tuffaceous-cemented materials composed of fine sand and silt.

SAMPLE AND ITS GEOTECHNICAL PROPERTIES

Shirasu samples used in the tests were obtained from Shomyoji formation belonging to Kakuto group, lake sediments of Kakuto basin, which is mainly composed of mudstone and pumiceous sediments originated from pyroclastic flows and looks like an appearance of tuffaceous-soft sedimentary rock (Fig. 1). Shirasu samples A and B were taken by hand-cut block samplings from open excavation at Shitanda and Yanagizuru in Ebino City, Miyazaki Prefecture, respectively.

On sampling, a fixed azimuth was rigidly maintained with taking the strike and dip of bedding plane into consideration. After cutting out the block sample of 200 mm cube with a straight edge and shovel in-situ, and then fitting the sample in a wooden container, the sample was fixed by pouring plaster into the clearances between block sample and container. After trimming the topface of block, the sample enclosed tightly in the container was transported to laboratory. Cylindrical specimens of 50 mm

Fig. 1. Area of distribution of pyroclastic flow deposits in southern Kyushu, K: Kakuto caldera, Ai: Aira caldera, At: Ata caldera

Fig. 2. Direction of applied major principal stress to the in-situ vertical direction, θ , and dip of the bedding plane, β

Fig. 3. Grain size distribution curves of samples

Table 1. Index properties of Shirasu samples

Sample	Shirasu A	Shirasu B
Strike	N50°W	N20°W
Dip	4°W	20°W
Specific gravity	2.32	2.36
Void ratio	1.25–1.35	1.35–1.45
Dry density (g/cm ³)	1.00–1.03	0.97–1.00
Water content (%)	24–27	20–23
Hardness (mm)	31	27–28

diameter and 100 mm length were prepared by using specimen-trimmer from the block sample which was removed carefully the container and plaster. The quality of undisturbed specimens was satisfied by the primitive method of this handwork sampling.

As shown in Fig. 2, the specimens were tested with the direction of applied major principal stress inclined at 0°, 30°, 45°, 60° and 90° to the in-situ vertical direction of the block samples. This angle of inclination will be designated θ . The grain size distribution and the index properties of Shirasu samples are shown in Fig. 3 and

Fig. 4. Rose diagrams of the directions of apparent long axes of grains for Shirasu from Shomyoji formation (Fujikawa and Miwa, 1979)

Table 1, respectively. The strike and dip corresponding to the bedding plane in the ancient Kakuto lake were measured from laminae in Shirasu strata. The hardness was measured by soil hardness tester (Yamanaka and Matsuo, 1962; Haruyama, 1979). Shirasu samples A and B have almost the same void ratio, but are considerably different from each other in the hardness. The grains consist of angular and stick-like glass fragments.

The angles between apparent long axes of the grains and reference axis were measured on microphotographs for Shomyoji formation (Fujikawa and Miwa, 1979). Its results are shown at every 10° interval of angle on the rose diagram in Fig. 4. The orientations of fabric elements are expressed quantitatively by direction of resultant vector, $\bar{i}$, and magnitude of resultant vector, L , by applying Curaray's equation (Curray, 1956) to the grain fabric:

$$\bar{i} = \frac{1}{2} \arctan \frac{\sum n \sin 2i}{\sum n \cos 2i} \quad (1)$$

$$L = \frac{100}{\sum n} \sqrt{(\sum n \sin 2i)^2 + (\sum n \cos 2i)^2} \quad (2)$$

Fig. 5. Result of consolidation test for Shirasu A

in which i is the angle between the direction of apparent long axis of grain and the reference axis, and n is the number of grains oriented at i . $\bar{i}$ is interpreted as a measure of the central tendency of the distribution, such as the preferred orientation direction of the long axes of grains, and L is related to the intensity of fabric anisotropy and varies from 0% to 100%. L is 0% for a completely random distribution of orientation of grain long axes, whereas 100% for a perfect orientation with exactly the same direction. According to Fig. 4, the horizontal plane has $\bar{i} = N 22^\circ W$ and $L = 2.7\%$, and the vertical plane has $\bar{i} = 26^\circ$ to a horizontal reference axis and $L = 10.3\%$. Therefore, this means that the grains in Shomyoji formation have light preferred orientations parallel to horizontal reference axis in the vertical plane, but almost random arrangement in the horizontal plane.

According to the result of oedometer tests on the specimens of $\theta = 0^\circ$ for Shirasu A, the yield stress due to consolidation is not clear as shown in Fig. 5.

TESTING PROCEDURE

Conventional triaxial compression tests under the consolidated-drained condition were performed on the partly saturated specimens with natural water content. The specimens were subjected to deviator stress at a constant rate of strain of 0.5% per minute under the confining pressures at 49, 196 and 1471 kN/m². The lubricated platens held high vacuum silicon grease between

Fig. 6. Method of measuring the volume of air expelled from a partly saturated specimen

latex discs were used to reduce the effect of end restraints on the specimen. The volume change of the partly saturated specimen under a pressure increment was measured by observing the volume of air which flowed into and out of the specimen. As shown in Fig. 6, the measurement of air volume was performed by adjusting the inverted burette in a acrylic reservoir so that a pressure head in the inverted burette was kept constant all the time. Stress and strain parameters in this paper are defined as positive when representing a compressive state: σ_1 denotes major principal stress (axial stress), σ_3 minor principal stress (confining pressure), ϵ_1 major principal strain (axial strain) and v volumetric strain.

RESULTS AND DISCUSSION

Stress and Deformation Behaviour

The representative relationships between principal stress ratio, σ_1/σ_3 , axial strain and volumetric strain obtained from a series of tests with different θ -values are shown in Figs. 7 and 8 for Shirasu samples A and B, respectively. According to the test results at the lowest confining pressure, $\sigma_3 = 49$ kN/m², the comparison of Shirasu A in Fig. 7(a) with Shirasu B in Fig. 8 shows the effect of hardness on the stress-strain behaviour. The peak values and the initial tangent moduli of stress-strain curves and the volume changes for Shirasu A are greater than those for Shirasu B.

The stress ratio at the same strain from initial stage to peak stage and the peak

Fig. 7. Representative relationships between principal stress ratio, axial strain and volumetric strain for a series of tests on Shirasu A with the different θ -values under different confining pressures

strength become smaller according to the orders of $\theta=0^\circ$, 30° , 90° and 60° for Shirasu A and $\theta=30^\circ$, 0° , 60° and 90° for Shirasu B. The behaviour of volumetric strain-axial strain curves corresponds well to that of stress ratio-axial strain curves. That is, the stress ratio becomes larger, the larger the volume change due to dilatancy is. The difference between Shirasu samples A and B in the stress-strain relations with the θ -value depends on an interlocking of grains caused by the dip of laminae in the speci-

Fig. 8. Representative relationships between principal stress ratio, axial strain and volumetric strain for a series of tests on Shirasu B with the different θ -values

mens, 4° for Shirasu A and 20° for Shirasu B, as discussed later. After the peak strength is passed, the principal stress ratio decreases progressively with an increase in axial strain and appears to have a tendency finally to become constant. The associated volume change of specimen during shear stages shows expansion after contraction, but it may be expected that the specimen is finally sheared under a constant volume. However, the amount of volume change in a critical state (Schofield and Wroth, 1968) is dependent on the θ -value. It is considered that the influence of inherent anisotropy of the specimen on the stress-strain behaviour disappears at large strain after the failure of the specimen, that is, critical state. Moreover, as the stress ratio in the critical state has almost the same value for Shirasu samples A and B, the difference of the peak strength between both Shirasu samples may be caused by the effect of cemented bond due to geological effects.

The effect of the direction of applied major principal stress on the stress-strain behaviour is dependent on the confining pressure, as is evident from Fig. 7. The peak strength and the corresponding expansion which vary with the θ -value are clearly observed at the lower confining pressures, $\sigma_3=49$ and 196 kN/m^2 . The

relationships among stress ratio, axial strain and volumetric strain at $\sigma_3=1471 \text{ kN/m}^2$, however, are independent of the θ -value, in which the peak strength is difficult of determination and the volume change shows only contraction. The decrease of the peak values of stress ratios, the decrease of the initial tangent moduli of stress ratio-axial strain curves and the increase of the axial strains corresponding to the peak strengths are observed with the increase of confining pressure. Now, in the case of $\theta=0^\circ$, the peak value of stress ratio at $\sigma_3=1471 \text{ kN/m}^2$ decreases to only 25% of that at $\sigma_3=49 \text{ kN/m}^2$. In the case of $\theta=90^\circ$, this decrease is about 40%. The difference of this kind caused by confining pressure on the stress-strain behaviour is considered to be closely related to movements of grains under shear stress. The associated dilatancy due to the interlocking of grains affects the strength under the drained shear.

As the expansion of specimen which makes looser interlocking and causes the motions of grains takes place easy in the lower confining pressure, it is considered that the effects of interlocking and dilatancy on the shear strength result in the increase of stress ratio (Haruyama, 1969 b). In the higher confining pressure, the decreases of shear strength due to grain breakage (Miura and Yamanouchi, 1975; Haruyama, 1975) and the diminution of interlocking effects occur. Therefore, it is concluded that the influence of anisotropy of the initial fabric on shearing behaviour of Shirasu specimen varies with the level of confining pressure.

Strength Properties

The angle of shearing resistance, ϕ_d , determined by the Eq. (3) at the peak value of stress ratio is plotted against the θ -value as shown in Figs. 9 and 10 for Shirasu samples A and B, respectively.

$$\phi_d = \arcsin(\sigma_1 - \sigma_3) / (\sigma_1 + \sigma_3) \quad (3)$$

According to the $\phi_d - \theta$ relations at $\sigma_3=49 \text{ kN/m}^2$, the maximum and minimum values of ϕ_d for Shirasu A occur at $\theta=0^\circ$ and 60° , respectively, and the difference between both

Fig. 9. Variations of the angle of shearing resistance with the direction of major principal stress for Shirasu A

Fig. 10. Variations of the angle of shearing resistance with the direction of major principal stress for Shirasu B

the values of ϕ_d is about 8° . Also, those values for Shirasu B occur at $\theta=30^\circ$ and 90° , respectively, and the difference between both the ϕ_d -values is about 5° . The difference in the ϕ_d - θ relations between Shirasu samples A and B is caused by the hardness of Shirasu matrix and the dip of lamina related closely to inherent anisotropy.

Then, according to Fig. 9, the difference between the maximum and minimum values of ϕ_d decreases with the increase of the confining pressure and ϕ_d is independent of the θ -value at the confining pressure above a certain stress level as is seen in the ϕ_d - θ relation at $\sigma_3=1471 \text{ kN/m}^2$. An inherent anisotropy in the specimen is influenced by consolidation and shear stages. In the lower confining pressure, ϕ_d may vary largely with the θ -value because of the specimen maintaining its inherent anisotropy and the high mobility of grains, as is seen in volume change behaviour. In the higher confining pressure, perhaps above a yielding stress due to consolidation or a stress above which grain breakage is produced, ϕ_d is independent of the θ -value because that an initial fabric in the specimen is subject to a disturbance due to contraction during consolidation and that the peak strength is reached at large strains. The lowering in the shear strength caused by grain breakage occurs at the high pressure.

The maximum shear stress in the specimen at the peak strength acts on the failure plane making an angle of α to the major principal plane. It is well known that the relationship between α and ϕ_d is given by the equation, $\alpha=45^\circ+\phi_d/2$, from Mohr-Coulomb's criterion. The dominant direction of the movements of grains during shear orients so as to take up the direction parallel to the failure plane (Kitamura, 1982). Further, the moving properties of grains may be related to the angle between grain orientation and shearing direction. Now, when it is assumed that the preferred orientation of grains corresponds to the dip of lamina, bedding plane, the angle, δ ,

between the dipping plane of lamina and the failure plane in the specimen is calculated by the Eq. (4) as shown in Fig. 11.

$$\delta = |\alpha - |\theta - \beta|| \quad (4)$$

in which β denotes the dip of lamina.

The δ -value varies from 0° to 90° . A precise agreement between the failure plane and the bedding plane will be given at $\delta=0^\circ$. On the other hand, the failure plane will intersect at right angle with the bedding plane at $\delta=90^\circ$. The plottings of ϕ_d against δ for Shirasu samples A and B are shown in Figs. 11 and 12, respectively. ϕ_d at $\sigma_3=49$ and 196 kN/m^2 increase with the δ -value. However, no influence of the δ -value on ϕ_d is observed in the higher stress level, $\sigma_3=1471 \text{ kN/m}^2$.

That the δ -value is larger means that the difference of direction between the preferred orientation of grains and the failure plane becomes larger. Consequently, the mobility of grains in shear zone is subject to the high

Fig. 11. Relationships among ϕ_d , δ and θ for Shirasu A under the different confining pressures

Fig. 12. Relationship among ϕ_d , δ and θ for Shirasu B

Fig. 13. Schematic ϕ_d - θ relations for (a) $\beta=0^\circ$ and (b) $\beta=30^\circ$

resistance due to interlocking and requires largely the expansive dilatancy. Here, it is well considered that δ denotes the degree of interlocking. According to Shirasu A shown in Fig. 11, the maximum δ -value for each stress level is reached at $\theta=0^\circ$, and the minimum δ -value occurs at $\theta=60^\circ$ to 90° .

Then, the ϕ_d - θ relation changes with the dip of bedding plane having direct effect on the grain arrangements. For example, the typical ϕ_d - θ relations for the bedding planes with $\beta=0^\circ$ and 30° are shown in Fig. 13. The maximum strengths occur at $\theta=0^\circ$ and 30° for $\beta=0^\circ$ and 30° , respectively. Also, the minimum strengths occur at $\theta=60^\circ$ and 90° for $\beta=0^\circ$ and 30° , respectively. When the grains which form the stratum have the same property, the equal shear strength is obtained in the equal δ -value independent of the β - and θ -values.

In general, undisturbed soil sampling by using core sampler has been limited to the case in which the major principal stress is applied in the in-situ vertical direction to the specimen without taking an inclination

of stratified deposits into consideration. However, the shear strength of deposits having an inherent anisotropy depends on the direction of major principal stress at failure. The most important consequence of this study for practical problems is that the choice of the strength parameters to be used in stability analysis and calculation of bearing capacity will depend on the assumed slip surface and have to take the dependence of ϕ_d on the stress level into consideration.

Component of Strength

According to the stress-dilatancy equation by Rowe (1962), the relationship between principal stress and dilatancy is expressed as follows:

$$\frac{\sigma_1}{\sigma_3} = \tan^2 \left(45^\circ + \frac{\phi_R}{2} \right) \left(1 - \frac{dv}{d\epsilon_1} \right) \quad (5)$$

in which $dv/d\epsilon_1$ is volumetric-axial strain increment ratio called dilatancy index and ϕ_R is the angle of shearing resistance corrected for the component of strength due to inner and outer works caused by the interlocking (Haruyama, 1969 b). The value of ϕ_R depends on the relative density, pressure range and stress path, and varies between a lower value ϕ_μ , being the angle of intergranular friction, and an upper value ϕ_{cv} , being the angle of shearing resistance at the critical state, and consists of the strength components of remoulding and friction between the mineral particles (Rowe, 1962). The ϕ_R - θ relations for Shirasu sample A and B are shown in Figs. 14 and 10, respectively. ϕ_R of Shirasu A may be subject to variation with the stress level and the θ -value, but ϕ_R of Shirasu B appears to be independent of the θ -value in despite of some scatter in the measurement values. On referring to the test results by Rowe (1962), the effects of remoulding and friction between the mineral particles on the ϕ_R - θ relations corrected for interlocking effect are considered constant for each confining pressure independent of the θ -value.

The fact that ϕ_R of Shirasu A varies with the θ -value shows perhaps that the

Fig. 14. Variations of the corrected angle of shearing resistance with the θ -value for Shirasu A

component except for the strength effect due to the interlocking contributes to the portion of shear strength. It is considered from the comparison of Shirasu A in Fig. 14 with Shirasu B in Fig. 10, both Shirasu having the different hardness and almost the same density, that such component of strength originates from cementing effect due to geological conditions in Shirasu stratum. Then, ϕ_R corrected for the cementing effect may become a constant value independent of the θ -value. It will be seen from the results for Shirasu A in Fig. 14 that ϕ_R at $\sigma_3 = 49$ and 196 kN/m^2 decreases with the increase of the θ -value, and that ϕ_R at $\sigma_3 = 1471 \text{ kN/m}^2$ shows a constant value independent of the θ -value and is approximately equal to $\phi_R = 40^\circ$ for Shirasu B at $\sigma_3 = 49 \text{ kN/m}^2$ in Fig. 10. Therefore, it certainly seems that the cementing effect of Shirasu contributes to the strength at the lower level of confining pressure but disappears at the higher confining pressure because of the significant disturbance of initial fabric due to the contractions of the specimen during consolidation and the large strains causing failure of the specimen.

Consequently, the shear strength of Shirasu A may consist of three components: intergranular friction, dilatancy and interlocking effect and cementing effect. While Shirasu B may be deficient in the last effect of three components.

Relationship between Principal Stress Ratio and Strain Increment Ratio

According to Fig. 15, the relationship between the principal stress ratio and the strain increment ratio is expressed as follows:

$$\frac{\sigma_1}{\sigma_3} = k - m \frac{dv}{d\varepsilon_1} \quad (6)$$

in which the k -value for $dv/d\varepsilon_1 = 0$ corresponds to σ_1/σ_3 at the point of minimum volume of the specimen during shear and at the critical state for the specimen showing

Fig. 15. Relationships between principal stress ratio and strain increment ratio for Shirasu A

Fig. 16. Relationships between k , m and the θ -value for Shirasu A

positive dilatancy after contraction in the early stage of shear, and to σ_1/σ_3 at the critical state for the specimen showing only negative dilatancy, and m is the factor of increase in the shear strength.

k and m , as shown in Fig. 16, are dependent on the θ -value at the lower confining pressure but independent of that at the higher one. Then, k and m for each confining pressure have respectively an approximately equal values at $\theta=90^\circ$ corresponding to the minimum δ -value. k and m also are constant values regardless of the θ -value for the higher confining pressure without having the effect of anisotropic fabric. Therefore, these coefficients depend on the anisotropy and the confining pressure.

CONCLUSIONS

From the results of consolidated-drained triaxial compression tests on undisturbed specimens of soft sedimentary rock "Shirasu" originated from pyroclastic flows, the following conclusions may be drawn:

(1) The anisotropic shearing characteristics depend on the direction of applied major principal stress to bedding plane, the laminations in the specimen, the hardness of Shirasu matrix and the stress level even though specimens are in an equal void ratio. The undisturbed sampling from stratified deposits requires to maintain a fixed azimuth

taking the strike and dip of bedding plane into consideration.

(2) The effect of the direction of applied major principal stress on the shearing behaviour can be explained well by the angle between the failure plane of specimen which controls the dominant direction of the mobility of grains and the bedding plane which controls grain orientations.

(3) The inherent anisotropy in the specimen exerts a strong influence on the peak value of shearing strength under a low stress level and disappears under a high stress level because of the contraction due to consolidation and the large strain causing failure of specimen. The peak strength of Shirasu under a low stress level has the components due to the anisotropic fabric and the cementing effect. However, the shearing strength in the critical state is independent of both of these components.

(4) The relationship between the principal stress ratio and the strain increment ratio depends on the inherent anisotropy and the stress level.

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