DEFORMATION CHARACTERISTICS OF HIGHLY COMPRESSIBLE SAND "SHIRASU"

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ABSTRACT

In order to clarify the deformation characteristics of volcanic deposits, "Shirasu", drained triaxial compression tests were performed on compacted specimens having several densities. Isotropic compressibility and deformation behaviour in the early stage of shearing were discussed, and on the some properties compared Shirasu with Toyoura standard sand. Here, the attention up to the point of minimum volume during shear was given. It is shown in the study that Shirasu has a higher compressibility than Toyoura sand, and that the relationships among stress ratio, volumetric strain, and shear strain are formulated by exponential and logarithmic functions. Also, the influence of stress path on the deformation of Shirasu is discussed on the basis of repeated loading test results.

Key words: deformation, drained shear, sandy soil, Shirasu, special soil, stress path, triaxial compression test, volcanic coarse-grained soil

IGC: D 6/D 5

INTRODUCTION

With respect to the shearing strength of Shirasu in drained state, clarifications have been made fairly well so far (Haruyama, 1969). However, many problems remain unsolved concerning the deformation characteristics. Problems related to the deformation is thought to be more important than those of strength from the viewpoint of rupture and settlement of Shirasu foundation. The specimen for drained test of granular materials contracts in the early stage of shear, and subsequently begin to expand after a minimum volume is reached. It is considered that the point of minimum volume at which no volume change takes place may have an important meaning.

The present paper deals with the deformation behaviour of Shirasu during the process of contraction through drained triaxial compression tests. As a result, it is revealed that Shirasu has a higher compressibility compared with Toyoura sand. And the relationships among stress ratio, volumetric strain, and shear strain are formulated. Moreover, it may be said that Shirasu has a higher strength than ordinary sand judging from the previous study (Haruyama, 1976) but is inferior to the sand in deformation judging from this study. In consequence of the high compressibility, Shirasu may be apt to suffer from liquefaction compared with sand. Also, in order to clarify the influence of stress path on deformation characteristics repeated loading tests were performed.

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CONCEPT OF STRESS AND STRAIN IN TRIAXIAL COMPRESSION TEST

The stress acting on the six side of a cubic element with an $xyz$ orthogonal system at any point in a soil mass can be described by nine components of stress; namely the three normal stresses $\sigma_x$, $\sigma_y$, $\sigma_z$ and three shear stresses $\tau_{xy}=\tau_{yx}$, $\tau_{xz}=\tau_{zx}$, $\tau_{yz}=\tau_{zy}$. Its stress condition may be characterized by the stress matrix, $S$, expressed as the sum of a spherical-stress matrix, $S_s$, and a deviator-stress matrix, $S_d$:

$$S = S_s + S_d$$  \hspace{1cm} (1)

$$S_s = \begin{bmatrix} \sigma_x & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_y & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_z \end{bmatrix}$$ \hspace{1cm} (2)

$$S_d = \begin{bmatrix} \rho & 0 & 0 \\ 0 & \rho & 0 \\ 0 & 0 & \rho \end{bmatrix}$$ \hspace{1cm} (3)

$$S_s = \begin{bmatrix} \sigma_x - \rho & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_y - \rho & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_z - \rho \end{bmatrix}$$ \hspace{1cm} (4)

where

$$\rho = \frac{1}{3}(\sigma_x + \sigma_y + \sigma_z).$$

If the deformation corresponding to the above stress states has the strains $\varepsilon_x$, $\varepsilon_y$, and $\varepsilon_z$ in the $x$-, $y$-, and $z$- directions and the six shear strains $\gamma_{xy} = \gamma_{yx}$, $\gamma_{xz} = \gamma_{zx}$ and $\gamma_{yz} = \gamma_{zy}$, then in the same manner the strain conditions may be characterized by strain matrix, $E$, spherical-strain matrix, $E_s$, and deviator-strain matrix, $E_d$, as follows:

$$E = E_s + E_d$$  \hspace{1cm} (5)

$$E_s = \begin{bmatrix} \varepsilon_x & \gamma_{xy}/2 & \gamma_{xz}/2 \\ \gamma_{yx}/2 & \varepsilon_y & \gamma_{yz}/2 \\ \gamma_{zx}/2 & \gamma_{zy}/2 & \varepsilon_z \end{bmatrix}$$ \hspace{1cm} (6)

$$E_d = \begin{bmatrix} \varepsilon_m & 0 & 0 \\ 0 & \varepsilon_m & 0 \\ 0 & 0 & \varepsilon_m \end{bmatrix}$$ \hspace{1cm} (7)

$$E_d = \begin{bmatrix} \varepsilon_x - \varepsilon_m & \gamma_{xy}/2 & \gamma_{xz}/2 \\ \gamma_{yx}/2 & \varepsilon_y - \varepsilon_m & \gamma_{yz}/2 \\ \gamma_{zx}/2 & \gamma_{zy}/2 & \varepsilon_z - \varepsilon_m \end{bmatrix}$$ \hspace{1cm} (8)

where

$$\varepsilon_m = \frac{1}{3}(\varepsilon_x + \varepsilon_y + \varepsilon_z).$$

If the $x$-, $y$-, and $z$-axes are oriented in the directions of the principal stress $\sigma_1$, $\sigma_2$, and $\sigma_3$, and if the octahedral plane is taken, the octahedral normal stress, $\sigma_{oct}$, and the octahedral shear stress, $\tau_{oct}$, are defined by

$$\sigma_{oct} = \frac{1}{3}(\sigma_1 + \sigma_2 + \sigma_3)$$ \hspace{1cm} (9)

and

$$\tau_{oct} = \frac{1}{3} \sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}$$ \hspace{1cm} (10)
respectively.

In a similar fashion, the strain conditions may be expressed by the octahedral normal strain, \( \varepsilon_{oct} \), and the octahedral shear strain, \( \tau_{oct} \), as follows:

\[
\varepsilon_{oct} = \frac{1}{3}(\varepsilon_1 + \varepsilon_2 + \varepsilon_3)
\]
\[
\tau_{oct} = \frac{2}{3}\sqrt{(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2 + (\varepsilon_3 - \varepsilon_1)^2}
\]

For the triaxial compression used in the tests, \( \sigma_1 > \sigma_2 = \sigma_3 \),

\[
\sigma_{oct} = \frac{1}{3}(\sigma_1 + 2\sigma_3) = p
\]
\[
\tau_{oct} = \frac{\sqrt{2}}{3}(\sigma_1 - \sigma_3) = \frac{\sqrt{2}}{3}q
\]
\[
\varepsilon_{oct} = \frac{1}{3}(\varepsilon_1 + 2\varepsilon_3) = \frac{1}{3}v
\]
and
\[
\tau_{oct} = \frac{2\sqrt{2}}{3}(\varepsilon_1 - \varepsilon_3) = \frac{2\sqrt{2}}{3}r
\]

where \( \sigma_1 \) denotes axial stress, \( \sigma_3 \) confining pressure, \( p \) mean principal stress, \( q \) deviator stress, \( \varepsilon_1 \) axial strain, \( \varepsilon_3 \) radial strain, \( v \) volumetric strain, and \( r \) shear strain. These are stress and strain parameters used in the present paper, and are defined as positive when compressed or contracted.

If the soil is assumed to be elastic, isotropic, and homogeneous, the relationships between \( p \) and \( v \), and between \( q \) and \( r \) may be described by the bulk modulus, \( K \), and the shear modulus, \( G \), respectively as:

\[
p = K \, v
\]
and
\[
q = G \, r
\]

In general, however, the soil is not elastic, also during shear process in the test \( v \) and \( r \) are dependent on each other owing to dilatancy.

**SAMPLES AND TESTING PROCEDURES**

Samples used in the tests are Shirasu and Toyoura standard sand. at Tosio in Kagoshima, southern Kyushu, and was geologically in the category of the unwelded part of pumice flow. It was adjusted so as to have the same grain size distribution as that of Toyoura sand. The grain size distribution is shown in Fig. 1 and its physical properties are shown in

**Table 1. Physical properties of samples**

<table>
<thead>
<tr>
<th>Properties</th>
<th>Toyoura sand</th>
<th>Shirasu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific gravity of grains</td>
<td>2.65</td>
<td>2.39</td>
</tr>
<tr>
<td>Uniformity coefficient</td>
<td>1.64</td>
<td>1.64</td>
</tr>
<tr>
<td>Curvature coefficient</td>
<td>0.92</td>
<td>0.92</td>
</tr>
<tr>
<td>Maximum void ratio</td>
<td>0.974</td>
<td>2.052</td>
</tr>
<tr>
<td>Minimum void ratio</td>
<td>0.650</td>
<td>1.250</td>
</tr>
<tr>
<td>Maximum dry density (g/cm³)</td>
<td>1.604</td>
<td>1.062</td>
</tr>
<tr>
<td>Minimum dry density (g/cm³)</td>
<td>1.342</td>
<td>0.783</td>
</tr>
</tbody>
</table>

**Fig. 1. Grain size distribution curve for samples**

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Table 1. The maximum void ratio was determined by pouring softly an air-dried sample using a spoon into a cylindrical mold with the inner diameter of 10.0 cm and the height of 12.7 cm. The minimum void ratio was obtained in case of Toyoura sand by putting the air-dried sample into a cylindrical mold with the inner diameter of 5.0 cm and the height of 10.0 cm in 5 layers and compacting it. In case of Shirasu, it was obtained in the following way: The air-dried sample was put into a mold with the inner diameter of 10.0 cm and a weight of approximately 2.0 kg was placed on it. Then it was vibrated 500 times in the vertical direction by means of a compaction equipment which was composed of a cam with a drop height of about 1.0 cm.

Toyoura sand is composed mainly of quartz and feldspar, while Shirasu consists mainly of glass fragments. The grains of Shirasu are elongate and angular compared with those of Toyoura sand.

The specimens were initially 5.0 cm in diameter and 12.5 cm in height, prepared at four initial void ratios from dense state to loose packing, and then saturated by water. The initial void ratios of Shirasu specimens were 1.294 for $S_a$, 1.426 for $S_b$, 1.589 for $S_c$, and 1.715 for $S_d$; the relative densities were 94.5, 78.1, 57.7, and 42.0 percent, respectively. Those of sand specimens were 0.667 for $T_a$, 0.723 for $T_b$, 0.829 for $T_c$, and 0.933 for $T_d$; the relative densities were 94.7, 77.5, 44.7, and 12.6 percent, respectively.

The saturated specimens were consolidated fully in triaxial cell under the confining pressures ranging from 0.5 to 2.0 kg/cm$^2$, and subjected to deviator stress at a constant rate of strain of 0.8 percent per minute. The specimens were drained from both ends. It was confirmed previously that the pore water pressure or the cavitation due to incomplete drain did not occur at this rate of compression.

RESULTS AND DISCUSSION

Isotropic compressibility

Under the isotropic compression $\sigma_1$ is equal to $\sigma_3$ and therefore $p$ is equal to $\sigma_3$. Within

![Fig. 2. Volumetric strain due to isotropic compression](image)

![Fig. 3. Relation between relative density and coefficient of compressibility](image)
the range of $p$ of 0.5 to 2.0 kg/cm$^2$, the relationship between the volumetric strain, $v_v$, and $p$ is shown in Fig. 2. By definition, the reciprocal of $K$ relates the isotropic compressibility of material, $K_e$. As can seen in Fig. 2, $K_e$ may be expressed as

$$K_e = \lim_{\Delta p \to 0} \frac{d v_v}{d p} = \frac{d v_v}{d p}.$$  

(19)

$K_e$ varies with the relative density for a given hydrostatic pressure. As shown in Fig. 3, in the relative density, $D_r$, exceeding 40 percent, $K_e$ for Shirasu is approximately $(5.0 \sim 17.0) \times 10^{-9}$ (cm$^3$/kg), while $(2.0 \sim 6.0) \times 10^{-9}$ (cm$^3$/kg) for Toyoura sand. As mentioned above, the isotropic compressibility for Shirasu is approximately three times as large as that for Toyoura sand.

**Volume change at the minimum volume under shear**

In the drained shear of the granular materials, the specimen generally contracts in the early stage of shear and dilates thereafter. According to Kirkpatrick (1961), for the

![Fig. 4. Relation between volumetric strain and stress ratio](image)

![Fig. 5. Relation between mean principal stress and volumetric strain at maximum contraction of specimen](image)

![Fig. 6. Relation between shear and volumetric strains at maximum contraction of specimen](image)

![Fig. 7. Stress ratio vs. volumetric strain plotting at maximum contraction of specimen](image)
conventional triaxial compression test, the aggregate friction component of strength, which is independent of the void ratio of material, is mobilized at the minimum volume of specimen. The representative examples of volumetric strain, \( \nu \), vs. stress ratio, \( q/p \), curves are shown in Fig. 4. In the \( v-q/p \) curves, the relationship between the volumetric strain at maximum contraction, \( v_m \), and the mean effective stress at that state, \( p_m \), is expressed by a straight line, as shown in Fig. 5;

\[
K_m = \lim_{p \to 0} \frac{d
u_m}{dp} = \frac{d
u_m}{dp} = \frac{d
u_m}{dp}
\]

where \( K_m \) = coefficient of contraction by triaxial shear.

As seen in Fig. 3, \( K_m \) varies with the relative density and is given by \((1.5 \sim 5.0) \times 10^{-3} (\text{cm}^3/\text{kg})\) for Shirasu and \((1.5 \sim 7.0) \times 10^{-4} (\text{cm}^3/\text{kg})\) for Toyoura sand. The compressibility of Shirasu by shear is approximately 10 times as large as that of sand.

Denoting the shear strain at the minimum volume by \( \tau_m \) and plotting \( \nu_m \) and \( \tau_m \) on the log-log scale, Fig. 6 is obtained. \( \nu_m \) and \( \tau_m \) are linearly related as expressed by the Eq. (21), although data are scattered in the range of small strain owing to errors in the test;

\[
\nu_m = m\tau_m^n
\]

For Shirasu \( m = 0.295, n = 0.80 \), and for Toyoura sand \( m = 0.155, n = 0.70 \).

The values of stress ratio, \( (q/p)_m \), at the minimum volume are, as shown in Fig. 7, 1.5 \( \sim 1.7 \) for Shirasu and 1.1 \( \sim 1.4 \) for Toyoura sand. These values are referred to the angle of internal friction under the state which does not associate volume change during shear.

**Volume change at the peak point of stress ratio**

In the relationship between the volumetric strain and the shear strain at the peak point of stress ratio, no substantial difference has been found between Shirasu and Toyoura sand. Denoting the maximum stress ratio by \( (q/p)_f \) and the volumetric strain by \( \nu_f \) at peak point of stress ratio, \( \nu_f \) and \( (q/p)_f \) are linearly related, as shown in Fig. 8. However, the relationship is different between Shirasu and Toyoura sand. The volumetric expansion of specimen from the point of minimum volume to that of maximum stress ratio, \( (\nu_m - \nu_f) \), and the increase in the stress ratio, \( (q/p)_f - (q/p)_m \), are also linearly related and the case of Shirasu and that of Toyoura sand are represented by the same straight line, as shown in Fig. 9. This shows that the relationship between the dilatancy and the increase in shear strength may be always the same independent of the kind of sand.

![Fig. 8. Relation between stress ratio and volumetric strain at peak point of stress ratio](image)

![Fig. 9. Relation between increase in stress ratio and volumetric expansion](image)
DEFORMATION CHARACTERISTICS OF SHIRASU

Relation between volumetric strain and stress ratio

A few studies have been carried out so far concerning the stress and dilatancy characteristics of sand for drained triaxial test (Tatsuoka and Ishihara, 1971). The volume change is divided into elastic and plastic deformations or into deformation due to the change in shear stress and that which is due to the change in mean principal stress. However, the total deformation is dealt with in the paper.

Through plotting the changes in $v$ and $q/p$ during shear on the log-log scale, Fig. 10 is obtained. From the Fig. 10, the volume change for Shirasu depends not only on $q/p$ but also on the confining pressure, however, that for Toyoura sand may be considered to be described by only $q/p$. $v$ vs. $q/p$ relations are given by two straight lines in Fig. 10. Namely, during the contraction in the early stage of shear,

$$v = a \left(\frac{q}{p}\right)^b, \quad (22)$$

while during the dilating after the shear proceeded to some extent,

$$v = a' \left(\frac{q}{p}\right)^{b'}. \quad (23)$$

Both $a$ and $b$ for Shirasu show different values depending on the confining pressure and the relative density, these increase with the increase in confining pressure and with the decrease in relative density. Both $a$ and $b$ for Toyoura sand increase with the decrease in relative density, but are not influenced by confining pressure.

By plotting $a$ vs. $b$ on the semi-log scale, as shown in Fig. 11, a straight line is obtained, and the relationships between $a$ and the relative density, $D_r$, are shown in Fig. 12. The relationships between $a$ and $b$ concerning Shirasu and Toyoura sand are expressed by the Eqs. (24) and (25), respectively;

$$b = 1.22 \log a + 1.98 \quad (24)$$
Fig. 11. Relation between $a$ and $b$ in Eq. (22)

Fig. 12. Relation between relative density and $a$ in Eq. (22)

Fig. 13. Relation between stress ratio and shear strain for Shirasu
\[ b = 0.58 \log a + 2.03 \]  

When it is necessary to know the values of \( a \) and \( b \), \( a \) can be determined from the curves in Fig. 12 for the given values of \( D \) and \( \sigma \). Then, from the \( a \) vs. \( b \) curve in Fig. 11 the value of \( b \) will be able to estimate. \( a' \) and \( b' \) show constant values depending on the only kind of soil. For Shirasu \( a' = 7.62 \times 10^9, b' = -42.6 \), and for Toyoura sand \( a' = 3.48 \times 10^9, b' = -31.1 \).

According to unpublished test results by the author, even in the specimen which shows only contraction, the Eqs. (22) and (23) are effective. \( q/p \) values of the Eq. (23) increase and decrease with the increase in shear strain for dense and loose specimens, respectively. It is considered that the point where \( q \) vs. \( q/p \) relationship changes from the Eq. (22) into (23) may a peculiar state on the behaviour of materials. That gives the state of minimum volume for dense specimen and of peak value of \( q/p \) for loose specimen. The Eq. (23) may considered to show the behaviour of yielding of the specimen, as described later.

**Relation between shear strain and stress ratio**

In the early stage of shear, \( \log \gamma \) and \( q/p \) are linealy related, as shown in Fig. 13. This linear relation is expressed by the Eq. (26) or (27):

\[ \gamma = \gamma_0 \exp \left( \frac{q}{p} \right) \]  
[26]

or

\[ \log \gamma = \log \gamma_0 + B \left( \frac{q}{p} \right) \]  
[27]

![Fig. 14. Relation between stress ratio and shear strain for Toyoura sand](image1)

**Fig. 14. Relation between stress ratio and shear strain for Toyoura sand**

![Fig. 15. Relation between \( \beta \) and \( \gamma_0 \) in Eq. (26)](image2)

**Fig. 15. Relation between \( \beta \) and \( \gamma_0 \) in Eq. (26)**

![Fig. 16. Relation between relative density and \( \beta \) in Eq. (26)](image3)

**Fig. 16. Relation between relative density and \( \beta \) in Eq. (26)**
where $B = 0.434\beta$.

$\tau_0$ and $\beta$ values for Shirasu vary with the relative density and the confining pressure, on the other hand, these values for Toyoura sand vary with the relative density but are not influenced by the confining pressure, as shown in Fig. 14. Here, the process of expansion is without the consideration.

From the test results of Shirasu, Fig. 15 to 16 are obtained. All experimented data points between $\tau_0$ and $\beta$ are approximately on a straight line as shown in Fig. 15, in which four points of right side belong to the loosest specimen and may be need of special consideration. According to Fig. 16, $\beta$ increases with the increase in confining pressure and decreases with the increase in density. Consequently, from the relation shown in Fig. 15, also, $\tau_0$ shows the same tendency as $\beta$.

Now, from the Eqs. (22) and (27), if the higher order terms are disregarded, the relationship between $v$ and $\tau$ is related by

$$v = c_1 + c_2 \log \tau + c_3 (\log \tau)^2$$

where

$$c_1 = -a \left(\frac{1}{B}\right)^b (\log \tau_0)^b$$
$$c_2 = -ab \left(\frac{1}{B}\right)^b (\log \tau_0)^{b-1}$$
$$c_3 = -\frac{ab(b-1)}{2} \left(\frac{1}{B}\right)^b (\log \tau_0)^{b-2}$$

On the basis of combinations of $\sigma_0$ and $D_0$ of Shirasu, by obtaining the values of $a$ and $b$ from Figs. 12 and 11, respectively, and of $\beta$ and $\tau_0$ from Figs. 16 and 15, respectively, the comparisons between the mathematical relationships of the Eq. (28) and the experimental $v$ vs. $\tau$ data were performed as shown in Fig. 17. A close approximation is found between predicted and observed relationships, and within the early shear strain there is a good agreement. In the case of Shirasu having a considerably high density, namely $S_a$ and $S_b$, disregarding the second order term of $\tau$ in the Eq. (28), it is confirmed that predicted and

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**Fig. 17.** Experimental data and predicted curves
observed $v$ vs. $\tau$ relationships hold to a good approximation.

**Repeated loading tests**

For the purpose of investigating a singularity of the point of minimum volume in detail, repeated loading test were performed on Shirasu specimens with different void ratios under confining pressure of 2.0 kg/cm². The typical results of this series of test are shown as a state path in Figs. 18 to 23. The numbers next to dots of state paths indicate the order of loading and unloading, and correspond to each Figure, for example, the state path represents a virgin loading portions 12, 45, etc., unloading 23, 56, etc., followed by reloading 34, 67, etc. The specimen sheared up to the point 2 after consolidation is unloaded up to the point 3 and reloaded to the state represented by the point 5, and so on.

![Fig. 18. Relation between stress ratio and shear strain for repeated loading test at initial void ratio of 1.343](image)

When the specimen is loaded to a certain level of stress ratio, little change in shear and volumetric strains will occur on unloading. On reloading, irrecoverable displacements will not be largely developed until the virgin stress level is reached.

On the log $\tau$ vs. $q/p$ curves shown in Figs. 18 and 19, since the points 2 and 4, 5 and 7, 8 and 10, etc. continue smoothly, it may be understood that the relationship between shear strain, $\gamma$, and stress ratio, $q/p$, is independent on the stress path of unloading and reloading. In each of reloading path, large irrecoverable displacements will be developed after the origin level of stress ratio, this experimental evidence may indicate that the points of origin stress level, 4, 7, 10, etc. are the start of yielding with Shirasu. Similar property has been obtained for the experiments on sand by Arnold and Mitchell (1973). As the path of virgin loading portion, 1245, in Figs. 18 and 19 appears similar to that of reloading, 34 and 56, it is considered that the yielding of virgin compression can be determined. Applying the same method to the virgin compression as reloading curve, the yielding may begin in the vicinity of the point 8. That is, beyond the stress level of the
Fig. 20. Relation between shear and volumetric strains for repeated loading test at initial void ratio of 1.343

Fig. 21. Relation between shear and volumetric strains for repeated loading test at initial void ratio of 1.559

Fig. 22. Relation between stress ratio and volumetric strain for repeated loading test at initial void ratio of 1.343

Fig. 23. Relation between stress ratio and volumetric strain for repeated loading test at initial void ratio of 1.559

point 8, the ratio of the increment of shear strain, \( r \), to the increment of stress ratio, \( q/p \), begins to increase largely.

Then, reference to the \( v \) vs. \( \log r \) curves shown in Figs. 20 and 21 indicates that the vicinity of the point 8 will be the point of minimum volume of the specimen. Up to this point, the mode of reloading curves is identical with the loading curves, the points 4 and 7 lie on a smooth line in reloading curves. In Figs. 20 and 21, consequently, the determination of the points 4 and 7 is impossible. However, the point 8 can be determined immediately. The behaviour between \( v \) and \( r \) after the point 8 is widely different from that before the point 8, and shows the tendency of contraction during unloading.

Such the yielding points as the points 4 and 7 also will be able to found for \( \log v \) vs. \( \log(q/p) \) curves shown in Figs. 22 and 23. Since the straight lines 12, 45, and 78 do not lie on the same line, the relationship between \( v \) and \( q/p \) is considered to be dependent on stress path, in the similar way, for the relationship between \( v \) and \( r \) the same property will be too obtained from Figs. 20 and 21.
CONCLUSIONS

In order to clarify the deformation characteristics of highly compressible sand "Shirasu", drained triaxial compression tests and repeated loading tests carried out in the range of confining pressure of 0.5 to 2.0 kg/cm². The isotropic compressibility and the relations among shear strain, volumetric strain, and stress ratio in the early stage of shear were investigated. As a result, it was revealed that Shirasu showed higher compressibility than sand. Namely, the isotropic compressibility for Shirasu is about three times as large as that for Toyoura sand, and the contraction caused by shear for Shirasu is about 10 times as large as that for Toyoura sand.

The formulas of the volumetric strain vs. stress ratio and the shear strain vs. stress ratio relationships were derived from test results, and the relationships between volumetric and shear strains was predicted on the basis of the above two formulas. A satisfactory agreement was found between predicted and observed values. Also, from the repeated loading tests, shear strain vs. stress ratio relationship did not seem to have any effect on behaviour of the stress path, while the volumetric strain vs. stress ratio and the volumetric strain vs. shear strain relationships were dependent on the stress path. And the point of minimum volume had an important influence on deformation characteristics.

In dealing with Shirasu from the engineering standpoint, especially concerning the ground settlement and liquefaction, it is necessary to lay stress more on the deformation characteristics caused by its high compressibility.

NOTATION

\[ D_r = \text{relative density} \]
\[ K_r = \text{isotropic compressibility} \]
\[ K_m = \text{coefficient of contraction by triaxial shear} \]
\[ p = \text{mean principal stress} \]
\[ q = \text{deviator stress} \]
\[ q/p = \text{stress ratio} \]
\[ v = \text{volumetric strain} \]
\[ \tau = \text{shear strain} \]
\[ \varepsilon_1, \varepsilon_3 = \text{axial and radial strains, respectively} \]
\[ \sigma_1 = \text{axial stress} \]
\[ \sigma_3 = \text{confining pressure} \]

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(Received September 2, 1976)