FLOW CHARACTERISTICS OF CLAYS

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ABSTRACT

Based on a critical review of the available data in creep tests previously published by many investigators, a new concept of flow envelope is presented and substantiated for normally consolidated clays. It is shown that the flow envelope is expressed by a simple equation irrespective of the type of clays, water content, drainage condition and stress history. This fact provides a clue from field observations for more proper understanding of the dividing line between the secondary compression-type deformation and the plastic flow-type deformation. A flow envelope for a lightly overconsolidated clay is also obtained, which suggests that even a moderate overconsolidation is effective in suppressing the rate of the subsequent flow.

In order to elucidate the loading path dependency of stress-dilatancy relationship, a series of drained incremental creep tests were performed on a normally consolidated clay. The results indicate that while a linear relationship between volumetric strain and deviatoric strain holds for each increment of sustained loads, its slope is larger than that predicted by a theory of quasistatic equilibrium but it is finally reduced to the value associated with an equilibrium state as the increment value of effective stress ratio decreases.

Key words: clay, creep, dilatancy, effective stress, failure, overconsolidation, secondary compression, time effect

IGC: D6

INTRODUCTION

General

It is a well known fact that two types of remarkable time effects are involved in clay deformations crosslinkedly or separately. One is attributed to the rheological nature of clay skeleton which is reflected in such phenomena as stress relaxation, creep rupture or secondary compression. The other is hydrodynamic time lag which plays a principal role in the process of primary consolidation. On the other hand, it has also been recognized that behavior of clays when subjected to deviatoric stress is substantially dominated by the laws of friction, since clay can be considered as a granular material composed of numerous thin plate-shaped particles. Therefore, it is probably reasonable to expect that, as Barden (1968) has pointed out, some form of effective stress ratio will be a more fundamental parameter even in the rheology of clays. From this point of view flow characteristics of clays will be studied in this paper.

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Aim and Scope

While there is an urgent demand for careful field observations in the construction of embankments on a deep deposit of soft clay using the precompression technique, as mentioned by Jonas (1964), no suitable criteria have yet been established to distinguish from field observations between the secondary compression type deformation and the plastic flow type deformation, and to correlate the field observations with the result of laboratory creep tests.

After a detailed study of available creep data a new concept of flow envelope will be proposed for normally consolidated and lightly overconsolidated clays, and then it will be shown that such a proposal will be a great help in attacking the above-mentioned problem. In addition to this, the interrelationship between flow and dilatancy of normally consolidated clay is studied for further understanding of the mechanism of creep deformation of clays. The concept of reduced time due to effective stress ratio will also be discussed briefly in connection with the typical patterns of creep curves.

TEST PROCEDURE

The clay used in the experiments conducted by the author was obtained from Fujinomori, Kyoto. The physical properties of it are given in Table 1. Samples were prepared by pouring the de-aired clay paste having the water content of about 56 per cent into an oedometer 25 cm in diameter and consolidating it one-dimensionally under a vertical stress of 0.5 kg/cm². The large sample was then extruded from the oedometer and divided into smaller specimens, which were stored for several months prior to the triaxial testing. All of the tests were carried out in a constant temperature room at 19.5±0.5°C. The triaxial equipment developed by the Norwegian Geotechnical Institute was used. The specimens were of cylindrical shape 3.57 cm in diameter and 8.00 cm in height. Vertical filter strips were employed to accelerate consolidation prior to shearing. In this case radial drainage only was allowable because of the adoption of the frictionless end platens (Rowe and Barden, 1964). The specimen was encased in two rubber membranes with a layer of silicone grease between them. Axial surface tractions were measured with a proving ring or a load cell. Axial displacements were measured with a dial gauge with the sensitivity of 0.001 cm. Volume changes were read from a 10 or 20 cm³ capacity burette. A companion dummy burette was used to correct for the amount of evaporation from the burette. Pore-water pressure measurements in undrained shear tests, were made by using a pressure transducer devised by the DYNISCO and in this case a back pressure of 1.00 kg/cm² was applied for about three hours prior to the shearing process.

Table 1. Index properties of a wide range of clays

<table>
<thead>
<tr>
<th>Soil Name</th>
<th>Stress History</th>
<th>L. L. (%)</th>
<th>P. L. (%)</th>
<th>Clay Content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fujinomori clay</td>
<td>remolded</td>
<td>43.6</td>
<td>26.1</td>
<td>32</td>
</tr>
<tr>
<td>San Francisco Bay mud</td>
<td>undisturbed</td>
<td>93</td>
<td>45</td>
<td>75</td>
</tr>
<tr>
<td>Frodsham clay</td>
<td>remolded</td>
<td>45</td>
<td>21</td>
<td>—</td>
</tr>
<tr>
<td>Osaka clay</td>
<td>remolded</td>
<td>63.5</td>
<td>27.4</td>
<td>30</td>
</tr>
<tr>
<td>Kaolin</td>
<td>remolded</td>
<td>80</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Osaka Umeda clay</td>
<td>undisturbed</td>
<td>69.2</td>
<td>32.5</td>
<td>30</td>
</tr>
<tr>
<td>Osaka alluvial clay</td>
<td>remolded</td>
<td>54.1</td>
<td>31.1</td>
<td>68</td>
</tr>
</tbody>
</table>
THE EXISTENCE OF A FLOW ENVELOPE

New Proposal of a Flow Envelope for Normally Consolidated Clays

Generally speaking, effective stress ratio, $\sigma_d/\sigma_m'$, increases with time in the undrained creep test on normally consolidated clays. $\sigma_d$ denotes deviator stress which equals $(\sigma'_1 - \sigma'_3)$ and $\sigma_m'$ denotes mean effective stress which equals $(\sigma'_1/3 + 2\sigma'_3/3)$, where $\sigma'_1$ denotes maximum principal stress and $\sigma'_3$ denotes minimum principal stress in terms of effective stress. The phenomenon is reasonably explained by the generation of porewater pressure due to the negative dilatancy. Even if the value of $\sigma_d/\sigma_m'$ is kept constant throughout a test, the case of drained creep, the value of logarithmic strain rate, $d\varepsilon_d/d\log t$, does not always remain constant, where $\varepsilon_d$ denotes the deviatoric strain and $t$ the elapsed time.

Therefore, by plotting the successive change of $d\varepsilon_d/d\log t$ against $\sigma_d/\sigma_m'$ on a semi-logarithmic paper, the locus associated with one specific test will be obtained on the plane. This locus is newly designated as a flow path, where the term, flow, is introduced by taking notice of the irreversibility of clay deformation in creep.

In view of the results of triaxial creep tests performed on undisturbed samples of normally consolidated Osaka Umeda clay in the undrained state, Murayama, Kurihara and Sekiguchi (1970) have assumed the existence of a line which is represented by the broken line on Fig. 1. This figure was newly constructed by adding the results of a test, in which $\sigma_d$ being equal to 0.60 kg/cm$^2$, to the original plotting which had already been published by Murayama, Kurihara and Sekiguchi (1970). Details of the test procedure are beyond the scope of this study, therefore they should be referred to the original paper. However, it will be appropriate to remark here that creep rupture was observed in seven tests where $\sigma_d$ was equal to 1.99 kg/cm$^2$ or larger than it, and failure did not take place in four tests where $\sigma_d$ was less than 1.99 kg/cm$^2$. As can be seen in Fig. 1, the flow paths associated with these four tests tend to approach the broken line, and the flow paths finally leading to creep rupture are also located below the broken line until they enter the steady-state creep, where the onset of steady-state creep is well represented by the inflection point of each flow path (Murayama et al., 1970). Thus the broken line can be considered as an envelope of the flow paths associated with the transient creep where rate of strain decreases with time. Consequently, it can be pertinentely designated as a flow envelope, and is expressed in this case by the equation.

### Table 2. Test conditions of a wide range of clays

<table>
<thead>
<tr>
<th>Soil Name</th>
<th>Test Type</th>
<th>$\sigma_d$ (kg/cm$^2$)</th>
<th>$T$ (°C)</th>
<th>Source of Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fujinomori clay</td>
<td>drained</td>
<td>1, 2</td>
<td>19.5±0.5</td>
<td>Author</td>
</tr>
<tr>
<td>San Francisco Bay mud</td>
<td>undrained</td>
<td>2</td>
<td>22.8±0.3</td>
<td>Arulanandan, Shen and Young, 1971</td>
</tr>
<tr>
<td>Frodsham clay</td>
<td>drained</td>
<td>0.7, 2.8, 5.6</td>
<td>21.1±1.1</td>
<td>Barden, 1969</td>
</tr>
<tr>
<td>Osaka clay</td>
<td>drained</td>
<td>2</td>
<td>20</td>
<td>Karube, 1968</td>
</tr>
<tr>
<td>Kaolin</td>
<td>undrained</td>
<td>4.2, 7</td>
<td>25±0.5</td>
<td>Walker, 1969</td>
</tr>
<tr>
<td></td>
<td>drained</td>
<td>4.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Osaka Umeda clay</td>
<td>undrained</td>
<td>3</td>
<td>20</td>
<td>Murayama, Kurihara and Sekiguchi, 1970</td>
</tr>
<tr>
<td>Osaka alluvial clay</td>
<td>undrained</td>
<td>3</td>
<td>20, 35, 50</td>
<td>Kurihara, 1971</td>
</tr>
</tbody>
</table>
Fig. 1. Flow envelope and flow paths constructed from undrained creep tests on undisturbed Osaka Umeda clay, after Murayama, Kurihara and Sekiguchi (1970)

\[
\log \frac{ds}{d\log t} = 1.46 \frac{\sigma_a}{\sigma_m} - 3.28.
\]

(1)

Based on his insight, Shibata (personal communication) presented the encouraging suggestion that such a flow envelope might be specified uniquely, irrespective of the type of clay soils.

In order to substantiate the hypothesis on the existence of the flow envelope more firmly, the author will make in this section a critical study of available data obtained from creep tests carried out by many investigators including the author.

Flow paths rearranged from the results of creep tests on five kinds of normally consolidated clays are shown in Fig. 2. The index properties and test conditions of the
clays are given in Table 1 and Table 2, respectively. In drained tests, deviatoric strain is calculated by the equation

$$\varepsilon_d = \varepsilon_1 - \frac{1}{3}\varepsilon_v,$$  \hspace{1cm} (2)

where $\varepsilon_1$ denotes the axial strain, and $\varepsilon_v$, the volumetric strain. It should be noted that in the case of Frodsham clay, $\frac{ds_1}{d\log t}$ is directly plotted as the ordinate because of the lack of informations concerning the volume change. Fig. 2 indicates that most of the plots fall in a rather narrow band irrespective of the type of clays, drainage condition, consolidation pressure, or stress history. The broken line on the figure represents the flow envelope assumed by Murayama et al. (1970). This line can be considered as the lower bound of a flow envelope. The following equation may hold as the upper bound of a flow envelope:

![Fig. 2. Flow envelope and flow paths of normally consolidated clays](image-url)
\[
\log\frac{\Delta \epsilon_d}{\epsilon} = 1.46 \frac{\sigma_d}{\sigma_m'} - 2.80.
\]

(3)

Then, from Eqs. (1) and (3), the mean line of a flow envelope can be expressed as follows:

\[
\log\frac{\Delta \epsilon_d}{\epsilon} = 1.46 \frac{\sigma_d}{\sigma_m'} - 3.04.
\]

(4)

These are also drawn on the figure.

As can be seen in Fig. 2, all of the flow paths obtained from drained creep tests on Fujinomori clay show the tendency to approach the flow envelope vertically. It should also be noted in this clay that two flow paths under relatively high sustained loads tend to move downward after once approaching the flow envelope. A similar phenomenon will be observed in Figs. 4 and 5. The test conditions for this clay are given in Table 3.

### Table 3. Results of drained tests on normally consolidated samples of Fujinomori clay

<table>
<thead>
<tr>
<th>Test No.</th>
<th>(\sigma_0) (kg/cm²)</th>
<th>(\sigma_d) (kg/cm²)</th>
<th>(w_t) (%)</th>
<th>(w_f) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8-2</td>
<td>1.00</td>
<td>0.90</td>
<td>32.60</td>
<td>32.19</td>
</tr>
<tr>
<td>11</td>
<td>2.00</td>
<td>0.60</td>
<td>31.36</td>
<td>30.97</td>
</tr>
<tr>
<td>12</td>
<td>2.00</td>
<td>1.20</td>
<td>29.97</td>
<td>29.20</td>
</tr>
<tr>
<td>T-1 (1)</td>
<td>2.00</td>
<td>0.30</td>
<td>30.08</td>
<td>29.95</td>
</tr>
</tbody>
</table>

Note: These results are shown in Fig. 2.

Fig. 1 shows that the flow path ultimately leading to creep rupture tends to pass through the dangerous state defined by a pair of critical values, \((\sigma_d/\sigma_m')_c\) and \((\Delta \epsilon_d/\epsilon)_c\). This state corresponds to the initiation of steady-state creep, and is well represented by the inflection point of the flow path. However, such a flow path as having a definite inflection point is not obtained in the case of San Francisco Bay mud. Since it has been reported by Arulanandan et al. (1971) that the value of \(\sigma_d/\sigma_m'\) at the critical state was 1.44 in this mud, the flow path leading to creep rupture would have to rise abruptly if the value of \(\sigma_d/\sigma_m'\) approaches 1.44.

The aforementioned \((\Delta \epsilon_d/\epsilon)_c\) is possibly related to the empirical constant in the equation proposed by Saito and Uezawa (1961) and/or the creep coefficient introduced by Singh and Mitchell (1969). On the other hand, the critical value, \((\sigma_d/\sigma_m')_c\), is probably correlated with the limiting slopes of the Coulomb-Mohr envelope \(\phi_d'\) or \(\phi_m'\) proposed by Šuklje (1967) and the yield value parameter \(\phi_d\) discussed by Shibata and Karube (1969).

Next, the temperature dependency of flow envelope is briefly studied. Kurihara (1971) has investigated the temperature dependency of creep rupture in clays based on the rate process theory. Here, the results of undrained triaxial tests performed on remolded samples of Osaka Alluvial clay are reexamed with particular reference to the flow envelope. Flow paths rearranged from the test results previously published by Kurihara (1971) are shown in Fig. 3.

The figure also indicates that every flow path finally reaching the state of creep rupture has the definite inflection point which signs the onset of steady-state creep, and that these points are located on the narrow band of flow envelope in the case in which the constant triaxial cell temperature, \(T\), of 20 or 35°C was employed throughout the shearing process. Rupture was not observed in a test in which \(T=35°C\) and \(\sigma_d=2.0\) kg/cm².
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On the contrary, the inflection point in the flow path under the condition of T=50°C does not lie on the flow envelope. This may be responsible for the considerable reduction in viscosity of adsorbed water, although the possibility of the reduction in the angle of frictional resistance itself still remains. The accuracy of pore-water pressure measurements under the elevated temperature may be somewhat doubtful, since the time to failure is frequently shortened. Details are, however, beyond the scope of this investigation. In spite of some uncertainty with respect to the temperature dependency of flow properties, it might be concluded that the significance of flow envelope need not be reduced within the normal condition of thermal state.

Further Assessment of Flow Envelope

It is pointed out in the previous section that the inflection point on a flow path corresponds to the onset of steady-state creep, where deviatoric strain starts to develop at a constant rate. Consequently, it will be of interest to compare the results from constant strain-rate tests with those from creep tests in connection with the flow envelope. The flow paths obtained from two types of undrained tests, constant strain-rate test and creep test, are shown in Fig. 4. Tests were performed on the remolded samples of normally consolidated Fujinomori clay. Test conditions are given in Table 4. The figure indicates the following: The flow paths associated with the constant strain-rate tests, Test No. S-6 and S-7, lie on a band of the flow envelope and move
along it until they reach a critical point. The point has a pair of values, (1.35, 0.083), in the co-ordinate system, \((\sigma_d/\sigma_m', \, d\varepsilon/d\log t)\). The inflection point in Test No. S-7 seems to correspond to the onset of steady-state creep, whereas in Test No. S-6 straining was interrupted at the state, \(\varepsilon_a=3.86\%\), for an alternative purpose.

The value of \(d\varepsilon_d/d\log t\) in a constant strain-rate test is calculated by the equation

\[
\frac{d\varepsilon_d}{d\log t} = 2.3\cdot \frac{d\varepsilon_d}{dt} = 2.3\varepsilon_a,
\]

where \(\varepsilon_a\) is axial deviatoric strain, which coincides with \(\varepsilon_i\) in the undrained state.

Once taking a maximum value, effective stress ratio begins to decrease slightly in Test No. S-6. The phenomenon may be responsible for the fact that Fujinomori clay is a remolded clay with somewhat poorly-developed structure. The flow paths under sustained loads tend to move towards the flow envelope, although under the relatively
Table 4. Results of undrained tests on normally consolidated samples of Fujinomori clay

<table>
<thead>
<tr>
<th>Test No.</th>
<th>$\sigma_c$ (kg/cm²)</th>
<th>$\sigma_d$ (kg/cm²)</th>
<th>$\omega$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>1.00</td>
<td>0.40</td>
<td>33.72</td>
</tr>
<tr>
<td>7</td>
<td>1.00</td>
<td>0.60</td>
<td>33.75</td>
</tr>
<tr>
<td>2</td>
<td>2.00</td>
<td>0.80</td>
<td>31.45</td>
</tr>
<tr>
<td>13</td>
<td>2.00</td>
<td>1.20</td>
<td>29.97</td>
</tr>
<tr>
<td>15</td>
<td>2.00</td>
<td>0.60</td>
<td>32.58</td>
</tr>
<tr>
<td>16</td>
<td>2.00</td>
<td>0.90</td>
<td>32.54</td>
</tr>
<tr>
<td>40</td>
<td>2.00</td>
<td>1.20</td>
<td>30.04</td>
</tr>
<tr>
<td>41</td>
<td>2.00</td>
<td>0.90</td>
<td>30.34</td>
</tr>
<tr>
<td>S-6</td>
<td>2.00</td>
<td>—</td>
<td>30.35</td>
</tr>
<tr>
<td>S-7</td>
<td>2.00</td>
<td>—</td>
<td>30.36</td>
</tr>
</tbody>
</table>

Note: The results of these tests are shown in Fig. 4.

The nominal rate of strain in the two tests, S-6 and S-7, is $5.13 \times 10^{-4}$ (min⁻¹).

Fig. 5. Flow characteristics of lightly overconsolidated Fujinomori clay
high sustained loads the flow paths exhibit the trend to deviate from the flow envelope after approaching it.

The foregoing statement were exclusively concerned with the behaviors of normally consolidated clays. In order to study the effect of overconsolidation on the subsequent flow properties of clays, the flow paths in a lightly overconsolidated Fujinomori clay, overconsolidation ratio being equal to 2, are shown in Fig. 5. Constant strain-rate tests and creep tests were carried out on this clay. Test conditions are given in Table 5.

As shown in the figure, despite the rather complicated features in each flow path under sustained loads, the following equation representing the flow envelope for a lightly overconsolidated clay may hold:

$$\log \frac{d\sigma}{d \log \sigma'} = 1.46 \frac{\sigma}{\sigma'} - 3.66 .$$  \hspace{1cm} (6)

Fig. 5 also indicates that the flow paths associated with two constant strain-rate tests pass through almost the same critical point as shown in Fig. 4 despite the difference in the rate of shearing. The border-line between the creep leading to failure and the creep which does not reach failure seems to exist near the line of $\sigma/\sigma' = 1.35$. The value corresponds well to the abscissa of the inflection points of two flow paths obtained from two constant strain-rate tests. This fact affords a method for computing the critical value in flow from a conventional constant strain-rate test.

Comparing the flow envelope for a lightly overconsolidated clay with the one for normally consolidated clays, such a conclusion may be tentatively drawn that even a moderate overconsolidation is effective in reducing the rate of the subsequent flow. It may also suggest the validity of a moderate surcharge in suppressing the subsequent development of secondary compression in the field.

<table>
<thead>
<tr>
<th>Test No.</th>
<th>$\sigma_{cp}$ (kg/cm²)</th>
<th>$\sigma_{cp}$ (kg/cm²)</th>
<th>$\sigma_{d}$ (kg/cm²)</th>
<th>w (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>2</td>
<td>1</td>
<td>0.6</td>
<td>33.63</td>
</tr>
<tr>
<td>27</td>
<td>2</td>
<td>1</td>
<td>1.2</td>
<td>34.13</td>
</tr>
<tr>
<td>29</td>
<td>2</td>
<td>1</td>
<td>0.9</td>
<td>33.04</td>
</tr>
<tr>
<td>30</td>
<td>2</td>
<td>1</td>
<td>1.05</td>
<td>32.24</td>
</tr>
<tr>
<td>17</td>
<td>4</td>
<td>2</td>
<td>0.9</td>
<td>30.26</td>
</tr>
<tr>
<td>19</td>
<td>4</td>
<td>2</td>
<td>3.3</td>
<td>30.65</td>
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<td>21</td>
<td>4</td>
<td>2</td>
<td>2.7</td>
<td>30.70</td>
</tr>
<tr>
<td>22</td>
<td>4</td>
<td>2</td>
<td>2.1</td>
<td>31.08</td>
</tr>
<tr>
<td>23</td>
<td>4</td>
<td>2</td>
<td>—</td>
<td>31.74</td>
</tr>
<tr>
<td>24</td>
<td>4</td>
<td>2</td>
<td>—</td>
<td>31.50</td>
</tr>
<tr>
<td>25</td>
<td>4</td>
<td>2</td>
<td>1.2</td>
<td>31.24</td>
</tr>
<tr>
<td>26</td>
<td>4</td>
<td>2</td>
<td>2.4</td>
<td>31.14</td>
</tr>
<tr>
<td>28</td>
<td>4</td>
<td>2</td>
<td>1.8</td>
<td>30.69</td>
</tr>
</tbody>
</table>

Note: The results of these tests are shown in Fig. 5. The nominal rate of strain is $2.9 \times 10^{-3} \text{ (min}^{-1})$ in Test No. 23, whereas $4.4 \times 10^{-4} \text{ (min}^{-1})$ in Test No. 24.
INTERRELATIONSHIP BETWEEN FLOW AND DILATANCY

While the foregoing treatment has been restricted to the deviatoric deformation, shearing deformation and volumetric deformation are interrelated processes in clays; therefore it will be of importance for the requirement of the logical consistency to incorporate the interrelationship between flow and dilatancy into the rheological treatment of clay deformation.

A series of $\sigma_m'$-constant drained creep tests have been carried out on remolded samples of Fujinomori clay for the purpose. Fig. 6 shows a plot of volumetric strain versus deviatoric strain in Test No. 8, with some relevant times being marked on each curve (Walker 1969). As shown in the figure, a linear relationship between $\varepsilon_0$ and $\varepsilon_d$ holds for each curve after an immediate shear strain has occurred without volume change. By correlating the value of $\frac{de_v}{de_d}$ along the straight section on each curve with $\sigma_d/\sigma_m'$, the stress-dilatancy relationship during the incremental drained creep tests will be clarified. In order to investigate the effect of loading history on the stress-dilatancy relationship, a set of data obtained from Test No. T-1 and T-2 are plotted in Fig. 7. The broken line in Fig. 7 is obtained by connecting the final points of each curve associated with the loading processes. This curve seems to correspond to the one obtained from a drained test with a sufficiently slow rate of strain.

Figs. 6 and 7 indicate that the value of $\frac{de_v}{de_d}$ decreases as shearing proceeds. Comparing the results in Test No. T-1 with those in T-2, it may be clear that the value

![Graph showing time-dependent accumulation of volumetric and deviatoric strains in drained tests ($\sigma_c=1\text{kg/cm}^2$)]
of $\frac{d\varepsilon_\text{v}}{d\varepsilon_\text{d}}$ is dependent on the increment ratio of $\sigma_\text{d}/\sigma_\text{m}'$ as well as the magnitude of $\sigma_\text{d}/\sigma_\text{m}'$. When a relatively larger increment of $\sigma_\text{d}/\sigma_\text{m}'$ is instantly applied, the amount of immediate component in shear strain increases remarkably and the curve associated with it tends to approach asymptotically to the continuous curve mentioned above after taking larger slopes at the early stage of the curve.

Fig. 8 shows a plot of $\frac{d\varepsilon_\text{v}}{d\varepsilon_\text{d}}$ versus $\sigma_\text{d}/\sigma_\text{m}'$. The points associated with two tests, Test No. T-2 (1) and T-2 (2), in which larger increment value of $\sigma_\text{d}/\sigma_\text{m}'$, 0.60, was superimposed, locate considerably above those obtained from Test No. T-1, in which smaller increment value of $\sigma_\text{d}/\sigma_\text{m}'$ was employed.

Although the value of 0.6 in $\sigma_\text{d}/\sigma_\text{m}'$ was also superposed on the previous increment at the eighth step of Test No. T-1, the value of $\frac{d\varepsilon_\text{v}}{d\varepsilon_\text{d}}$ was not so large as the case of T-2. This is possibly attributed to the fact that in Test No. T-1 the sample had already been stressed until the value of $\sigma_\text{d}/\sigma_\text{m}'$ reached 0.90 prior to the reloading processes, (7) and (8).

In view of the results of Test No. T-1, a straight line can be drawn on Fig. 8. This line can be expressed as

$$\frac{d\varepsilon_\text{v}}{d\varepsilon_\text{d}} = 1.21 - 0.77(\sigma_\text{d}/\sigma_\text{m}').$$

(7)

The value of $\frac{d\varepsilon_\text{v}}{d\varepsilon_\text{d}}$ at the later straight line of the curve obtained from Test No. T-2 (1) takes almost the same magnitude as that in Test No. T-1 (3). On the other
hand, the value of $\frac{d\varepsilon_v}{d\varepsilon_a}$ associated with Test No. T-1 (1) takes a considerably large value.

The following aspects are also remarked in view of the results shown in Figs. 6 and 7:

Once taking note of the quantity, $d\varepsilon_v/d\varepsilon_a$, the time dependency of shearing strain and dilatancy under sustained loads is successfully masked. As shown in Fig. 7, the volumetric strain accumulates even when effective stress ratio is reduced, whereas the recoverable component of shearing strain is clearly observed at the same time. It appears from Fig. 6 that the volume change reaches the state of equilibrium comparably fast, about seven days after the application of load increment.

For a summary of this section, the following inference may be possible (Fig. 9): When a large increment of $\frac{\sigma_d}{\sigma_m'}$ is superimposed immediately and then maintained constant, as loading path (1) in Fig. 9, the deviatoric and volumetric strains accumulate in a linearly crosslinked form at ever decreasing rate until effective stress ratio reaches a critical value. The observed value of $d\varepsilon_v/d\varepsilon_a$ must then be larger than that predicted by a theory assuming a quasi-static process. After enough time has elapsed, however, each line associated with each load increment approaches the equilibrium stress-strain curve like (3) on Fig. 9 and stops there. Then, the slope of tangent at any point on the curve (3)' is uniquely correlated with effective stress ratio. Loading path (2)' on Fig. 9 schematically represents the associated path of the second increment of creep. When the increment value of $\frac{\sigma_d}{\sigma_m'}$ is small enough, the slope of the line (2)' coincides with that of a tangent at the terminal point.
REDUCED TIME DUE TO EFFECTIVE STRESS RATIO

The results shown in Figs. 2, 4 and 5 indicate that the creep curves of Fujinomori clay over a time range from $10^{-4}$ to $10^{4}$ min have the following feature: The creep curve at lower effective stress ratio is convex to the log time axis as indicated by curve A in Fig. 10; consequently the value of $\frac{d\varepsilon_d}{dt}$ log t monotonously increases with time. At higher effective stress ratio it is sigmoidal or concave to the log time axis, therefore the value of $\frac{d\varepsilon_d}{dt}$ log t starts to decrease after it has taken a maximum value, as indicated by curve B in Fig. 10.

It should be noted that the phenomenon cannot be exclusively attributed to the decrease of water content during the process of creep, because almost the same observations were made in the undrained creep tests, Fig. 4 or Fig. 5, as well as the drained creep, Fig. 2.

It has been well realized in connection with the settlement analysis that the relative amounts of immediate and delayed compression of clay are sensitive to the loading history, e.g., pressure increment ratio $\Delta P/P$. Barden (1968) has discussed such a rheological aspect of compressibility of clay and peat with the aid of a viscoelastic model with the element of nonlinear viscosity. This model exhibits such a compression-time behavior as shown in Fig. 11 under sustained effective pressure without hydrodynamic time lag.

The curves in this figure suggest that each is part of a common sigmoidal curve, which may be called as master curve (Meredith, 1958). In this case, it appears that the increase of pressure increment ratio is equivalent to reduce the time along the log time axis. Therefore, this procedure is designated as reduced time due to pressure increment ratio. On the basis of such a point of view, the re-examination of the results shown in Fig. 11 leads to the following conclusion: A suitable shift of each curve along the log time axis produces a common sigmoidal
FLOW CHARACTERISTICS OF CLAYS

Table 6. Reduced time due to pressure increment ratio (after Barden, 1968)

<table>
<thead>
<tr>
<th>Pressure increment ratio ΔP/P</th>
<th>0.1</th>
<th>0.2</th>
<th>0.5</th>
<th>1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shift along log time axis</td>
<td>0</td>
<td>1.2</td>
<td>2.8</td>
<td>4.0</td>
</tr>
</tbody>
</table>

curve, the magnitude of horizontal shift being given in Table 6, where the curve associated with ΔP/P=0.1 is adopted as the reference curve. Because Barden’s model yields some satisfactory, theoretical results with respect to the rheological problems of clay compressibility, it may be expected that such a concept of reduced time is also applicable to the phenomenon observed for Fujinomori clay. A serious difficulty, however, exists in the behavior of clay during undrained creep. Namely, the effective stress ratio changes remarkably despite the maintenance of deviatoric stress. The possibility of introducing the concept of reduced time due to effective stress ratio is, therefore, left unclarified.

Finally, with regard to the reason why such a rather singular phenomenon was observed particularly in this clay, we cannot present a pertinent explanation at the present time. It may be, however, imagined that the reduction in retardation times induced by the application of sustained loads produced more dominant influences on the deformation-time relationship than the acceleration of strain-rate induced by the increase of effective stress ratio, which thus resulted in the observation of the creep curve like Curve B in Fig. 10.

CONCLUSIONS

The principal results derived from the foregoing rheological treatment are as follows:
1. The existence of a flow envelope is substantiated for normally consolidated clays. The flow envelope can be expressed by the equation

\[ \log(\frac{dc_d}{dt} \log t) = 1.46\sigma_d/\sigma'_d - 3.04 \pm 0.24. \]  

2. A knowledge of a pair of values, \( \sigma_d/\sigma'_d \) and \( d\varepsilon_d/d \log t \) provides a more proper insight into the problem, especially, where plastic flow type deformations of clays are involved.
3. A linear relationship between volumetric strain and deviatoric strain holds during the incremental drained creep. The slope, thereby, depends on the loading history.
4. A flow envelope for a lightly overconsolidated clay is also obtained. This suggests the effectiveness of a moderate overconsolidation to suppress the rate of the subsequent flow.

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NOTATION

The following symbols are used in this paper:
\( d\varepsilon_d/dt = \) deviatoric strain rate
\[ \frac{de}{d \log t} = \text{deviatoric logarithmic strain rate} \]
\[ P = \text{effective pressure} \]
\[ \frac{\Delta P}{P} = \text{pressure increment ratio} \]
\[ t = \text{true time} \]
\[ T = \text{temperature} \]
\[ w = \text{water content} \]
\[ w_i, w_f = \text{initial and final water content, respectively} \]
\[ \epsilon, \epsilon_v = \text{principal strains} \]
\[ \epsilon_d = \text{deviatoric strain} \quad (= \epsilon_1 - 1/3 \epsilon_3) \]
\[ \epsilon_v = \text{volumetric strain} \]
\[ \sigma_i', \sigma_s' = \text{principal normal stresses} \]
\[ \sigma_0 = \text{consolidation pressure} \]
\[ \sigma_{00}, \sigma_{0p} = \text{initial and present consolidation pressure, respectively} \]
\[ \sigma_d = \text{deviator stress} \quad (= \sigma_i' - \sigma_s') \]
\[ \sigma_m' = \text{mean effective stress} \quad (= (\sigma_i' + 2\sigma_s')/3) \]
\[ \phi', \phi_s' = \text{limiting slopes of the Mohr's envelope} \]
\[ \phi_y' = \text{yield value parameter in terms of effective stress} \]

REFERENCES


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