On the Deformation Behavior of Soil under Delayed Consolidation

By

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Abstract

In the present paper, some theoretical studies are performed, from the viewpoint of a long-term consolidation, in regard to the quasi-overconsolidation behavior of soil known as the p_c-effect. Using the concept of a state boundary surface, it is shown that such soil has an elastic component with respect to deformation. In spite of the above characteristics, the time effect for soil under delayed consolidation, and the loading effect for overconsolidated soil are generally not identical. This suggests that the state paths for both types of soil at a subsequent loading would be different from each other, even if their starting points are the same on the $e-\log \sigma_v'$ plane.

1. Introduction

In light of the recent tendency to erect ever larger structures, it is often the case that the bearing capacity of alluvial ground is not sufficient to support such heavy structures, so that terrace or upper diluvial strata situated at deeper levels must be regarded as the bearing layers. However, this kind of strata is still rather young in geological age compared with deeper diluvium; thus it has a small overconsolidation ratio (OCR). In the geological sense, it often happens that the loading histories of these strata do not exceed the present effective overburden load, resulting in the occurrence of problems regarding settlement behavior of structures upon them. In this paper, the deformation behavior of soil under delayed consolidation is investigated through the concept of a state boundary surface, with respect to quasi-overconsolidation characteristics.

2. Precompression Effect Due to Delayed Consolidation

Bjerrum[1,2] turned his attention to the phenomenon that the preconsolidation pressure, p_c, is sometimes larger than the effective overburden pressure, p_o, due to the time effect, even in normally consolidated clay. He called such charac-

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teristics of the soil under delayed consolidation the precompression effect (p_c-effect). The p_c-effect increases in proportion with p_o, and the ratio p_c/p_o of a layer in the same sedimental age increases with the amount of secondary compression occurring under the actual surcharge. Since the secondary compression increases with the plasticity of clay, it is known that the ratio p_c/p_o increases with the plasticity index I_p.

In the Osaka area, the most populated district in Western Japan, the so-called Tem-ma sand/gravel layer which corresponds to old alluvium or a terrace form has always been treated as the bearing layer of buildings and heavy structures. The bearing capacity of the clay layer just beneath this sand/gravel layer should then be investigated where the thickness of the upper stratum is not sufficiently thick. These diluvial clay layers (called Ma 12 and Ma 11), of the uppermost part in the Osaka Group are the youngest ones. Hence, it is believed that they have experienced neither a great decrease in overburden load due to erosion nor a tectonic lateral pressure due to folding. Therefore, their overconsolidation characteristics are quite small compared with older diluviums (Ma 10, *etc.*). Thus, we cannot neglect deformations under a new loading. At the large-scale reclaimed lands along Osaka Bay, for instance, non-negligible settlement continues even now, many years after the completion of the reclamation. Although this settlement is found to be occurring in the deep sediment, the mechanism is still not clear from the viewpoint of soil mechanics[3)].

The reason for the slight overconsolidation characteristics of the Osaka upper diluvial clay seems to be past small-scale changes in ground water level or the above-mentioned p_c-effect accompanied with a delayed consolidation of the normally consolidated clay, *i.e.,* quasi-overconsolidation characteristics. Wroth and Parry[4)] explained the difference in the distribution of p_c and OCR with depth for an ordinary overconsolidated clay subjected to loading histories due to changes in ground water level, and for a quasi-overconsolidated clay after delayed consolidation under constant surcharge, as shown in Fig. 1. In contrast to the decrease in OCR with depth occasioned by changes in ground water level, the apparent OCR due to delayed consolidation can be expected to be approximately constant with depth, although this may depend to some extent on the age of the deposit and its rate of formation. As there exists a finite correlation between the coefficient of earth pressure at rest, K_0, and OCR[5)], one can obtain OCR when the in situ K_0-value is known. If K_0 is constant with depth, it may be supposed that the overconsolidation characteristics of the clay are no longer than in a quasi-state.

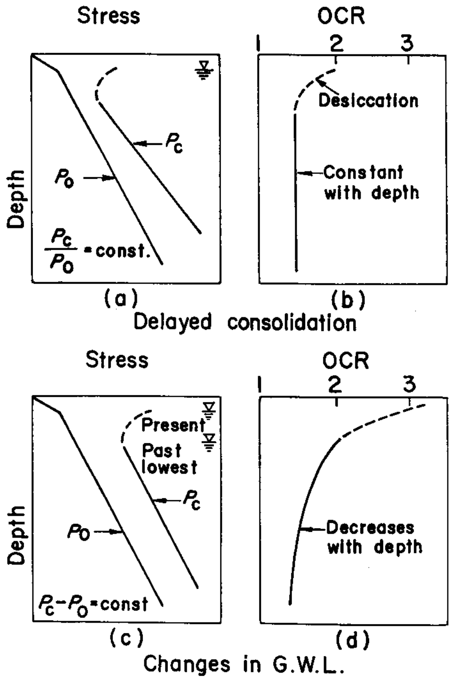

Fig. 1. Variation of p_c and OCR with depth from delayed consolidation and ground water movements (Wroth and Parry).

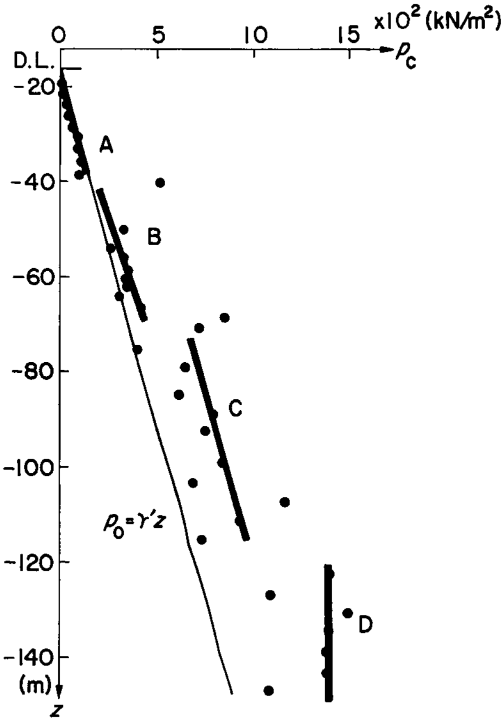

Fig. 2. Overconsolidation characteristics of clay layers under the sea bed in Osaka Bay.

Fig. 2 indicates the overconsolidation characteristics of clay layers under the sea bed at a site about 5 km away from the Sen-nan coast in Osaka Bay. From this figure it is clear that the alluvium A just beneath the sea bed is in a state of normal consolidation ($p_c \fallingdotseq p_o$), the upper diluvium B (Ma 12) is in quasi-overconsolidation ($p_c/p_o \fallingdotseq$const), C is slightly overconsolidated ($p_c - p_o \fallingdotseq$const) and the diluvium D is highly overconsolidated by the tectonic process ($p_c \gg p_o$).

3. State Boundary Surface and Effective Stress Path

3.1 State Boundary Surface

The state boundary surface, so termed as defined by Roscoe *et al.*,[6] is the exsistence boundary of soil-like material based on the experimental fact that the combination of pore amount with stress can exist only within a finite boundary. They have shown the state boundary surface in the pore-stress space which is constructed by the mean effective principal stress, $p = (\sigma_1' + \sigma_2' + \sigma_3')/3$, the principal stress difference, $q = \sigma_1 - \sigma_3$, and the void ratio, e. Inside this spatial surface, it is recognized that there exists a void ratio-effective stress plane (swelling wall) perpendicular to the e–p plane, determined by each OCR. The projection of the upper boundary of this swelling wall to the $p-q$ plane is called the yield locus.

3.2 Stress Path during Delayed Consolidation

Suppose we try to compare some soil experiencing the p_c-effect (time effect) due to delayed consolidation with some ordinary overconsolidated soil with the same amount of porosity. When using the state boundary surface, the problem is whether both kinds of soil are in the same state of stress and take the same stress path under subsequent loading. The figure of deformation should now be in a perfect laterally confined state (K_0-condition), and with this restriction both delayed consolidation and overconsolidation occur.

Wroth[5] has produced Fig. 3 to explain the change in state due to delayed

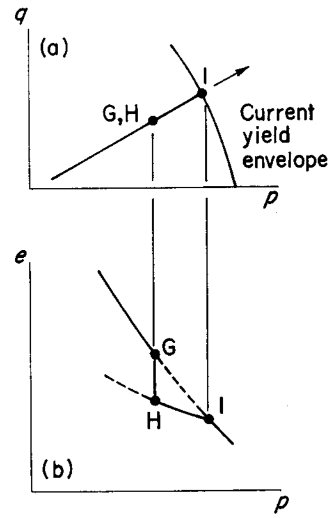

Fig. 3. Change of state caused by delayed consolidation (Wroth).

consolidation. The effective stress state of a soil specimen at a certain depth is represented by point G in Fig. 3(a). In the associated consolidation plot in Fig. 3 (b), the point G represents the void ratio at the end of primary consolidation, reached after all deposition of fresh material has ceased. Between then and now, the soil undergoes a secondary compression moving to state H, while the effective stresses are believed to remain unchanged.

If the soil is now loaded one-dimensionally, its state will move along a recompression curve HI becoming normally consolidated again at I. The vertical stress at state I will be interpreted as the preconsolidation pressure, and the specimen (at state H) will behave in all respects as lightly overconsolidated soil. However, if the effective stresses have not changed between states G and H during the phase of secondary compression, then the value of K_0 at H is the same as that at G, which is relevant to a genuinely normally consolidated soil.

In this description by Wroth, however, there exists a fallacy in that he considers that the effective stresses during secondary compression would remain unchanged. What is constant is the vertical effective stress, σ'_v, not the effective mean stress, p, adopted as the abscissa in Fig. 3. The senior author[7] has cleared quantitatively the variation of principal stresses with time during primary consolidation. According to this study, the confining stress in soil, σ_h, in terms of total stress decreases with time until the final value $\sigma_h = K_0\sigma_v$ (σ_v: a constant vertical total stress) is reached, whereas the coefficient of earth pressure at rest in the state of normal consolidation $K_0^{NC} = \sigma'_h/\sigma'_v$ remains unchanged during consolidation.

During secondary compression, on the other hand, the distortion (shear deformation) of soil element due to drained creep occurs, where the vertical strain ε_v is equal to the volume change ε_{vol} owing to the confined lateral strain. An increase in ε_{vol} with time is associated with an increase in the effective mean stress, σ'_m $(=p)$*. Thus, the horizontal stress σ'_h $(=\sigma_h)$ increases and the principal stress difference $\sigma_v - \sigma_h (=q)$ decreases, since the vertical stress σ'_v $(=\sigma_v)$ remains constant. In conclusion, p increases and q decreases during secondary compression, resulting in increases in K_0-value and the quasi-OCR.

Based on such considerations, let us express the deformation behavior of soil under delayed consolidation by using the concept of a state boundary surface. From the viewpoint of comparison with the overconsolidated soil experiencing loading histories mentioned already, we take two types of soil expressed by the same point D in the void ratio—vertical effective stress plane (Fig. 4, e-log σ'_v plane). One type is after delayed consolidation and the other is in a state of ordinary overconsolidation. In the former (QOC), the initial void ratio e_b shown at point B on the virgin compression line (K_0^{NC}), which corresponds to the state of normal consolidation under present effective overburden pressure, has gradually decreased with time until e_d at point D. In the latter case (OC), on the other hand, the soil once passed as A→B→C, and then along the unloading path CD (swelling line), the void ratio has somewhat increased until point D. The OCR

* No significant time effect between σ'_m and ε_{vol} such as creep or relaxation is assumed.

of the latter soil is defined as $\sigma'_{v,c}/\sigma'_{v,d}$.

Fig. 5(a) indicates the stress paths of the above-mentioned kinds of soil in the pore—stress space (e-p-q space). The swelling path CD for overconsolidated soil

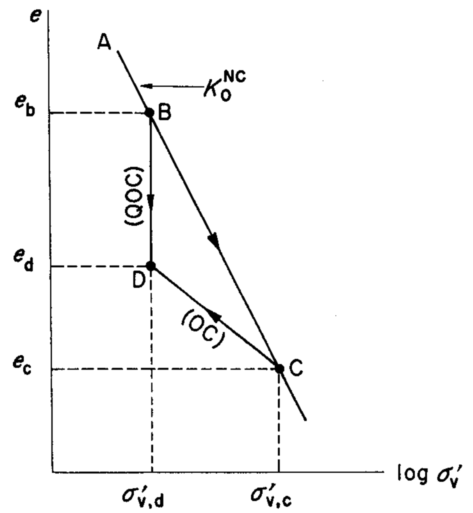

Fig. 4. State paths on the e—log σ'_v plane for QOC-soil and OC-soil.

(OC) lies on the swelling wall [SW] mentioned in **3.1.** In order to draw the spatial path for soil under delayed consolidation (QOC), on the other hand, we must introduce the σ'_v-axis beside the epq-axes and utilize the process shown in Fig. 4 where the path B_3D_3 during secondary compression on the $e-\sigma'_v$ plane is parallel to the e-axis. In Fig. 5(a), the state path starts from point B and moves on an inclined plane (aging plane [AP]), so as to increase p and decrease q. In general, the final point D* does not accord with point D for overconsolidated soil. In this figure the path BD* (secondary compression path) is shown as the upper boundary of the aging wall [AW].

There is no doubt that the K_0^{NC}-line which expresses normal consolidation lies on the state boundary surface. Let it be named [K_0W] for a vertical wall whose upper boundary is the K_0^{NC}-line. Then, both [SW] and [AW] are nearer to the e-axis than [K_0W] and the secondary compression path BD* is inside the state boundary surface, as well as the swelling path CD. This means that soil under delayed consolidation has an elastic component with respect to deformation, just the same as for overconsolidated soil. On the p-q plane in Fig. 5(a) we see the secondary compression path $B_1D_1^*$ (straight line) for soil under delayed consolidation and the swelling path C_1D_1 (curved line in general). For the former, it is clear that the horizontal stress σ'_h increases during consolidation, whereas the vertical

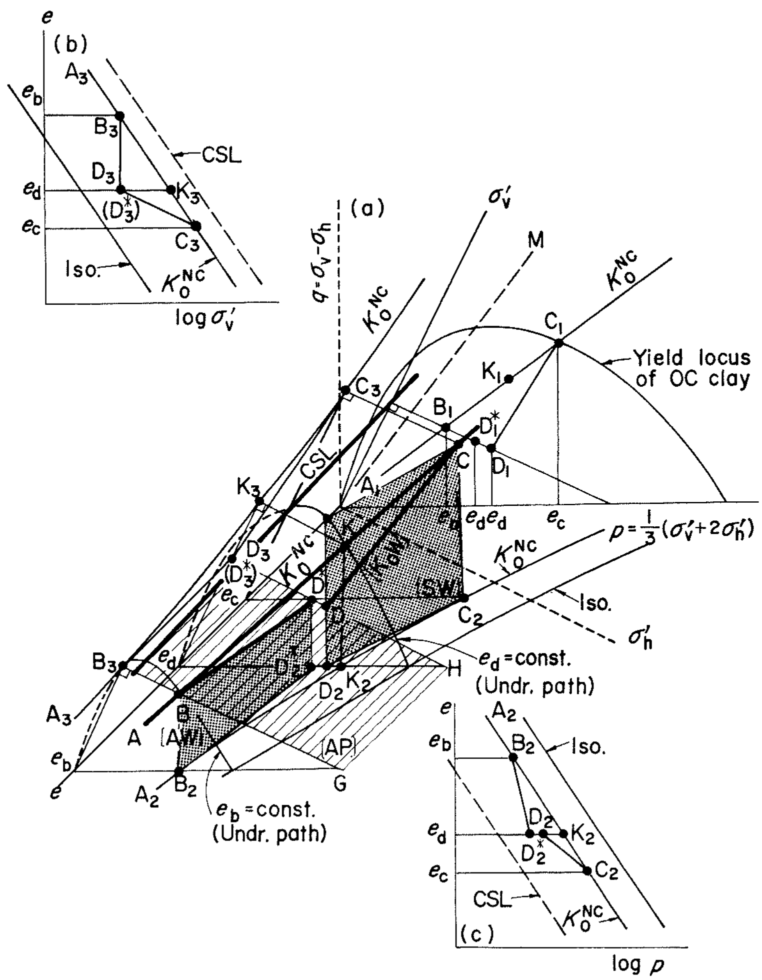

Fig. 5. State paths in the $e-p-q$ space and their projections for QOC-soil and OC-soil.

stress σ_v' remains unchanged, as already explained. Fig. 5(b) is the e-log σ_v' correlation and Fig. 5(c) is the e-log p correlation, both where the projections of the critical state line (CSL) and the isotropic stress line (Iso.) are shown, as well as the state paths for two types of soil. From the p-q plane in Fig. 5(a) and Fig. 5(c), we recognize that two types of soil (QOC and OC) have different states of stress from each other, in spite of their same effective vertical stress σ_v' and their same void ratio e (and also their same vertical strain ε_v). The conclusion is, therefore, that the time effect for soil under delayed consolidation and the loading effect for overconsolidated soil are not identical generally.

3.3 Stress Path at Loading

The above conclusion seems to be of importance, because it suggests that the state paths for both soils (QOC and OC) on successive loading would be different from each other. In Fig. 6(a) which reproduces the p-q plane in Fig. 5(a), undrained paths corresponding to the void ratios for points B, C and D (or D*) are shown by broken lines. Among them the undrained path for point D intersects the K_0^{NC}-line at a point K_1 which is the projection of the spatial point K on the p-q plane. This means that three points, namely K_1, D_1 and D_1^* in Fig. 6(a) are at the same void ratio, e_d. In this figure the inclination η^{OC} or η^{QOC} of two lines connecting the origin with point D_1 or D_1^* gives K_0-values for OC-soil or QOC-soil, according to the correlation, $\eta = q/p = 3(1-K_0)/(1+2K_0)$. For the example of this figure, it is known that the order is $K_0^{OC} > K_0^{QOC} > K_0^{NC}$ (namely, $\eta^{OC} < \eta^{QOC} < \eta^{NC}$).

It is well-known that the effective stress path of overconsolidated clay on reloading is D_1C_1 (conveniently drawn as a straight line in Fig. 6(a)), which intersects the K_0^{NC}-line at point C_1 of the past maximum stress, and then moves on the normal consolidation line (virgin compression line). At loading on soil under

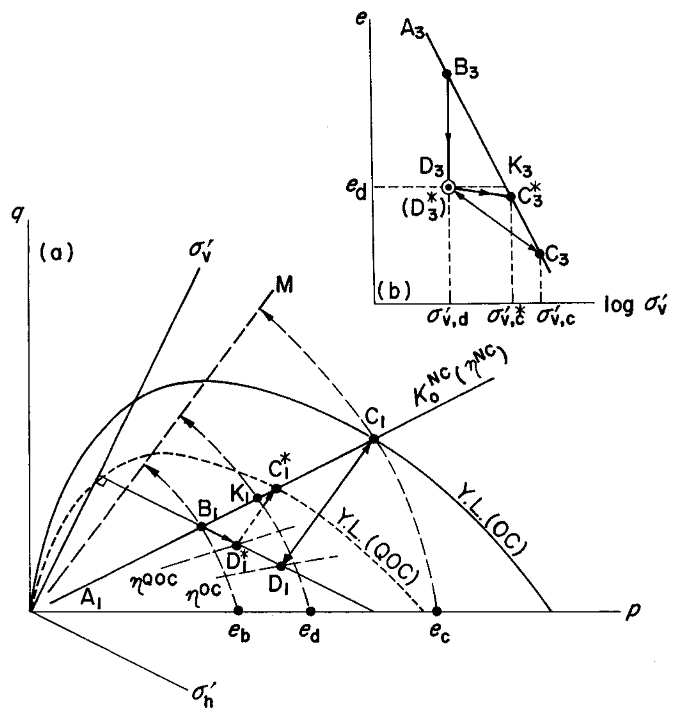

Fig. 6. State paths on the $p-q$ plane and the $e-\log \sigma_v'$ plane for QOC-soil and OC-soil.

delayed consolidation, on the other hand, it is believed that the path starts at point D_1^* parallel to the line D_1C_1 to reach the K_0^{NC}-line at a point C_1^*. Passing through this point C_1^*, a yield locus for QOC-soil is drawn (dotted line), similar to that for OC-soil (full line). Putting this point C_1^* into the e-log σ_v' plane (Fig. 6(b)), one obtains point C_3^*. The (quasi-)overconsolidation ratio for QOC-soil, $OCR^*=\sigma'_{v,c*}/\sigma'_{v,d}$, is thus smaller than that for OC-soil, $OCR=\sigma'_{v,c}/\sigma'_{v,d}$, in this case (identical to $K_0^{OC}>K_0^{QOC}$). The abscissa of point C_3^*,$\sigma'_{v,c*}$, is regarded as the (quasi-)preconsolidation pressure for soil under delayed consolidation, at loading beyond which the soil would behave as normally consolidated. The fact that point C_3^* does not accord with point C_3 should be noted in estimating the settlement due to loading on the upper diluvial strata previously mentioned.

Thompson[8] reported the experimental results, measuring the lateral pressure change in K_0-consolidation throughout primary and secondary consolidations. The test sample was Cambridge Gault clay (G_s=2.72, LL=85 %, PI=55 %), and the K_0-value at the end of primary consolidation was K_0=0.65 – 0.75. As shown in Fig. 7, the lateral pressure (total stress) during primary consolidation

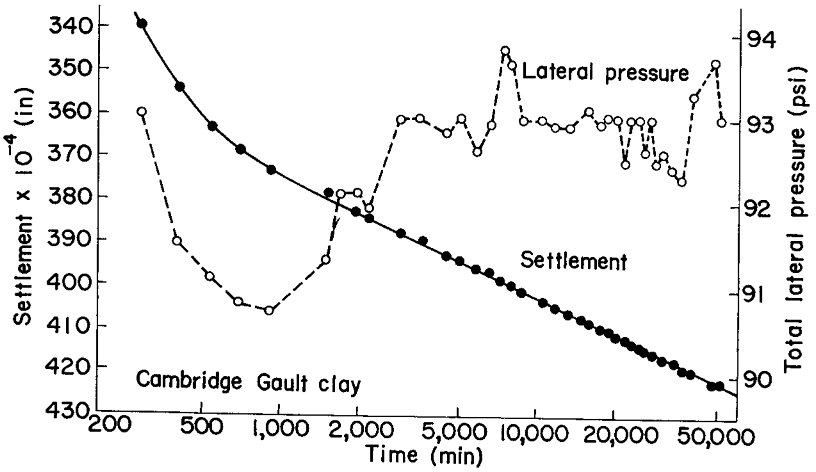

Fig. 7. Settlement and lateral pressure behavior during K_0-consolidation (Thompson).

decreased linearly with the degree of consolidation until the above-mentioned K_0-value was reached. During secondary compression, the lateral pressure increased remarkably at first, and thereafter kept a constant value. It is also shown in the figure that the settlement curve during secondary compression is linear on a logarithmic time scale. These test results support our theoretical consideration with regard to the deformation behavior of soil under delayed consolidation described in the present paper.

4. Recovery of the Rate of Secondary Compression

With regard to secondary compression of clay, several investigations have been performed both theoretically and experimentally, mainly from the viewpoint of such soil properties as rheological characteristics. Using the concept of delayed consolidation proposed by Bjerrum[1,2], it is now possible to treat the behavior quantitatively. Also, useful interpretations can be given for settlement calculation and design of structures.

The explanation of delayed consolidation is clear in Fig. 8 where time para-

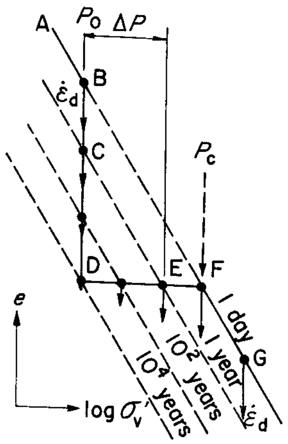

Fig. 8. Explanation of delayed consolidation.

meters after sedimentation of soil are indicated. These parameters mean that the soil has a corresponding rate of secondary compression $\dot{\varepsilon}_d$ where the state path under an effective overburden pressure, p_o, intersects the time parameter. Thus, if we take quasi-overconsolidated clay (D) of 10^4 years after sedimentation, for instance, and then a loading Δp is performed to move till point E, it is considered that the rate of secondary compression would increase to a larger rate when the soil was at point C, which corresponds to the rate of 10^2 years. This is a removal of geological history of 10^4 years and a recovery of the rate of secondary compression by loading. Provided the stress increase reaches the (quasi-)preconsolidation pressure F, a remarkable primary consolidation would occur, and the succeeding rate of secondary compression would be as high as that of the past sedimentation time (B).

The result of various consolidation tests for the diluvial clay in the Osaka south port area indicates an abrupt increase in the rate of secondary compression at the preconsolidation pressure, p_c, as shown in Table 1 and Fig. 9. These cha-

Table 1. Rate of secondary compression of Osaka upper diluvial clay (Ma 12; depth 55.7 m–57.7 m, LL=139.3%, PI=90.8%, C_c=1.41, $p_c=4.4\times10^2$kN/m²).

σ_c' ($\times10^2$kN/m²)	0.4	0.8	1.6	3.2	6.4	12.8	25.6
C_α (%/cycle)	0.17	0.12	0.34	0.41	4.9	6.9	3.1

($C_\alpha = de/d\log_{10}t$)

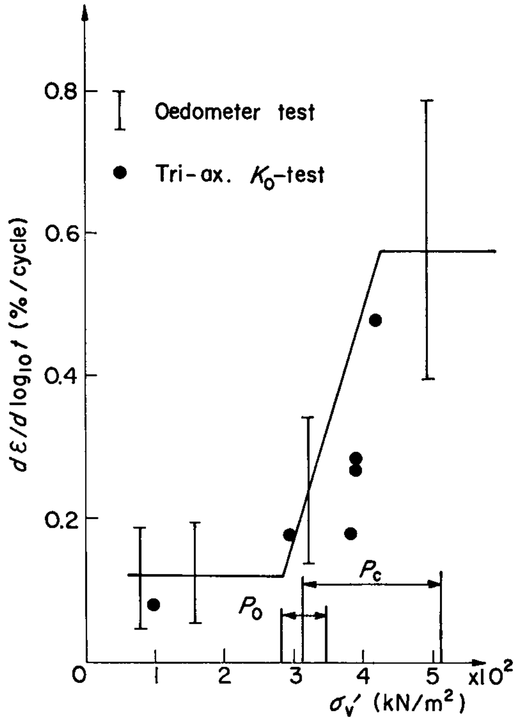

Fig. 9. Correlation between the rate of secondary compression, $d\varepsilon/d\log_{10}t$, and the consolidation pressure, σ_v' (data by courtesy of Dr. Shibata).

racteristics are in accordance with the concept of time- and stress-compressibility interrelationship proposed by Mesri and Godlewski[9].

5. Conclusion

In this paper, some theoretical studies are performed on the deformation behavior of soil under delayed consolidation. Our results may be briefly summarized as follows:

(1) From the site investigation on the overconsolidation characteristics of clay layers under the sea bed of Osaka Bay, it is known that the upper diluvium (Ma 12) corresponds to the soil under delayed consolidation where p_c/p_o is

nearly constant with depth.

(2) It should be noted that it is the vertical effective stress, σ_v', which remains unchanged during secondary compression, not the effective mean stress, p, as had been formerly mentioned by Wroth. An increase in p and a decrease in q are the reasons why the K_0-value and OCR increase under delayed consolidation.

(3) It is shown from considerations using the concept of a state boundary surface that soil under delayed consolidation has an elastic component with respect to deformation, just the same as for overconsolidated soil.

(4) In spite of the above characteristics, the time effect for soil under delayed consolidation and the loading effect for overconsolidated soil are not identical generally, suggesting that the state paths for both types of soil at subsequent loading would be different from each other, even if their starting points are the same on the e-log σ_v' plane.

(5) By loading on quasi-overconsolidated soil due to delayed consolidation, there occur a disappearance of geological history and a recovery of the rate of secondary compression. These phenomena are confirmed by the test results on Osaka upper diluvial clay (Ma 12).

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