Mechanical Behaviour of a Clayey Soil Consolidated in the Sea Water

by

Masayoshi SHIMIZU and Hironobu SOKABE*

Department of Civil Engineering
* Chuugoku Mokuzai Comp., Ltd

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Synopsis

CIU triaxial tests and oedometer tests were carried out on the sample remoulded with the natural sea water and that with the freshwater to investigate the effect of the change of the deposition environment when terrestrial soils are used in marine geotechnical works.

The following conclusion is derived :

In the case when the pore fluid is the sea weater, shear strength is raised and the compressibility is lowered compared with the case when the pore fluid is the freshwater. Therefore terrestrial soils would be given desirable properties when they are used in marine works.

1. INTRODUCTION

In this investigation it is aimed to examine the change in mechanical behaviour or physical properties of terrestrial clayey soils when they are deposited and reconsolidated in the sea-water environment. The subject is related to engineering cases such as reclamations of foreshore or eventually of offshore.

The change of the deposition environment from the freshwater to the sea water results in the change of chemical constituents of the pore fluid of the soils used in the reclamation works. It has been well known that the change in the constituents of the pore water, particularly, of clays may affect, depending on the type and concentration of the electrolytes in the pore fluid as well as the mineralogical properties of clays, their mechanical and physical properties. The behaviour of marin sediments themselves, of which the pore fluid is the sea water, has been the engineering problem, and also terrestrial soils such as quick clays, of which the pore water has almost no salinity, have been discussed.

Several reports show that certain marine sediments exhibit peculiar characteristics: unexpectedly high ratios of undrained shear strength to effective overburden pressure; apparent overconsolidation pressure, etc. A review of literatures upon the peculiarities is given by Moore et al.(1977).

The mechanism by which quick clays exhibit high sensitivity has been investigated vigorously by many authors. Present knowledge can lead to conclude that the high sensitivity is caused by the natural procedure of leaching of the electrolytes which had been contained in the pore fluid.

In studies on the effects of constituents of the pore fluid on the mechanical behaviour of soils, the method of leaching is often employed. The leaching techniques used in the laboratory have several disadvantages: when the leaching is performed by percolation of some solutions (Moore et al.,1977), the leaching may be incomplete because of the natural variations in permeability; also unnegligible hydraulic gradient is necessary for the percolation, which would cause secondary effects; even if a diffusion procedure is adopted for the leaching as in Torrance(1974), the uniformity of the leaching within a specimen would not be confirmed and a long time is required for the leaching.

Another method by which effects of the constituents of the pore fluid can be investigated is to prepare samples by the sedimentation of a soil in the sea water and in the freshwater. This method seems to be reasopnable because it can simulate the sedimentation process and can reflect the structure of particles which will be formed during the sedimentation. However, the vertical variation in the particle size distribution within the sediment cannot be avoided. Further, considerably long duration will be required for the preparation of samples.

In the present investigation, a method of remoulding of a clayey soil with the freshwater and the sea water at considerably high water content was employed. The detail of the procedure for the preparation of samples will be mentioned later. Unlike the sedimentation method and the leaching method, only a short period was required for the preparation of samples.

Physical properties and mechanical behaviour of the sample remoulded with the freshwater will be compared with those of one remoulded with the sea water, based on the results of triaxial compression tests and oedometer tests carried out on both samples.

2. SAMPLE

Powdered silty soil called "Fujinomori Clay",available in the market, was used in this investigation. The fraction which passed through the 420 μm mesh was served for experiments as the parent sample. Particle size distribution of the sample is given in Fig.1. The specific gravity of soil grains was determined as 2.66.

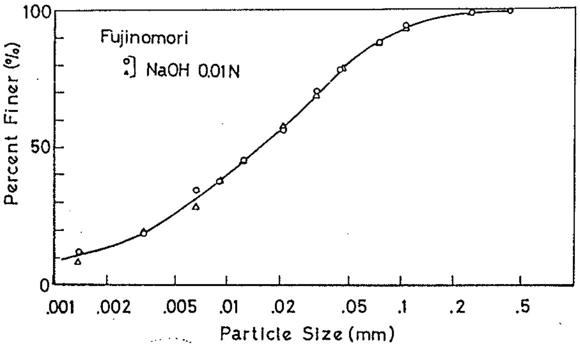

Fig.1: particle size distribution of the sample used.

The parent sample was remoulded either with the distilled water or with the natural sea water to be served for such mechanical tests as triaxial tests and oedometer tests. Prior to the mechanical tests, influences of the salinity on the consistency limits were examined.

The consistency limits were examined on three kinds of pore fluids, i.e., the distilled water, the natural sea water and the condensed sea water. The salinity will be expressed by the chlorine content in the pore waters which was determined by the silver nitrate method. Values of the chlorine content for the distilled water , the natural sea water and the condensed sea water are 0,3 and 6 %,respectively. Liquid limit, plastic limit and plasticity index are shown as a function of the chlorine content of the pore fluid in Fig 2.

So far as it is concerned with the results shown in Fig.2, liquid limit is the highest, plastic limit is the lowest and therefore plasticity index is the highest for the natural sea-water sample. However the variation of the consis-

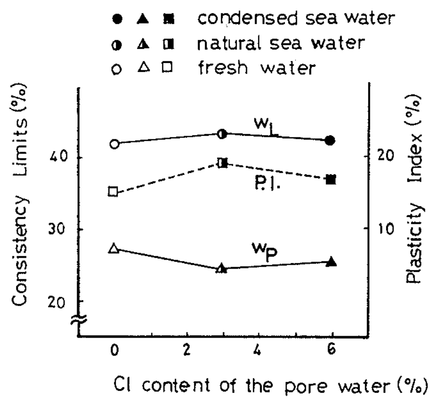

Fig.2: Effects of salinity of the pore fluid on consistency limits

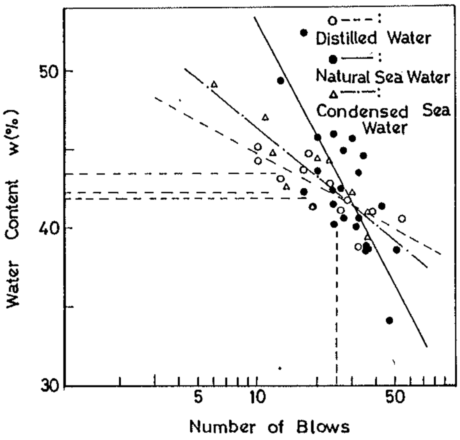

Fig.3: Flow curves obtained from liquid limit tests

tency limits with the chlorine content is not significant but slight. Previous studies also show that no definite tendency of the influence of the salinity on the consistency limits has been obtained.

In Fig.3, flow curves obtained in the liquid limit tests are presented. It seems that the flow index is the largest for the freshwater sample than for other samples. However, the relationship of the salinity of the pore fluid to the flow index is not clear.

X-ray diffraction analyses were carried out on the freshwater sample and on the sea-water sample after drying at the temperature of 110°C in an oven. The results of the analyses showed the predominant clay mineral to be illite with quartz and feldspar comprising the major portion of the non-clay particles for both samples. The minerals occurring in the sea-water sample are not different from the freshwater sample. This indicates that no mineralogical alteration has occurred by remoulding with the sea water.

3. PROCEDURES FOR MECHANICAL TESTS

3.1 Preparation of Specimens

Specimens for mechanical tests were prepared by remoulding the parent sample either with the freshwater (or distilled water) or with the natural sea water. The water content at remoulding was about 100%; the remoulding for an individual batch was performed for a period of 40 hours by using a mortar mixer. Such a remoulding condition was maintained for all the mixing batches.

After being remoulded, the sample was one-dimensionally preconsolidated in a special mould, made of polyvinyl chloride of 153 mm in inner diameter and 220 mm in height. Maximum preconsolidation pressure was 50 kPa. During the preconsolidation, the evaporation of the water squeezed out of the sample was prevented by wrapping whole the mould with a vinyl sheet.

Preconsolidated sample was trimmed to be cylindrical specimens for triaxial tests and oedometer tests. Specimens for the triaxial tests are 3.56 cm in diameter and 8 cm in height; ones for oedometer tests are 6 cm in diameter and 2 cm in height.

3.2 Triaxial Tests

All the triaxial tests are isotropically consolidated undrained compression ones(CIU), which were performed in partly improved GEONOR triaxial cells. The consolidation was first performed under the cell pressure of 100 kPa without back pressure. After that, the entrapped air within the specimen and connection tubes between the specimen and the burette was removed by a flushing technique. The subsequent consolidation pressure was applied with the back pressure of 200 kPa. Employed values of maximum consolidation stress p_c were about 100, 200, 300 and 400 kPa. Some overconsolidated specimens were prepared by unloading to prescribed consolidation pressure p_o from p_c. Employed overconsolidation ratios were 1.5, 2,4 and 8.

During the isotropic consolidation, the volume change of specimen was measured by the use of a differential pressure-meter, which can detect the variation of the water surface level in a burette even when the back pressure is applied. Possible minimum reading of volume change was 4.405×10^{-3} ml in the case of the used type of burette.

Undrained triaxial compression tests were carried out under normally consolidated or overconsolidated state after the isotropic consolidation. During shear, the cell pressure, the pore-water pressure, the axial load and the axial deformation were measured. The pore pressure was measured at the center of the base of a specimen. Cell pressure was held at a prescribed constant value; axial deformation rate was 9.66×10^{-3} %/min; and the compression was continued up to 16% of the axial strain. Detailed description of the measuring system has been given elsewhere (Shimizu,1983;1984).

3.3 Oedometer Tests

Oedometer tests were performed according to JIS A1217-197. A load increment ratio is 1 and a loading time interval is 1440 minutes. Four specimens were tested: two on the freshwater sample and two on the sea-water sample. For the sea-water sample, consolidation moulds were filled with the sea water.

4. RESULTS AND DISCUSSION

4.1 Shearing Deformation and Strength Behavior

(1) Normally Consolidated Specimens

Results of triaxial tests will be discussed and the shearing behavior of the sea-water sample is compared with that of the freshwater sample. Stress-strain relations of normally consolidated specimens are shown in Figs.4(a) and (b). Corresponding effective stress paths are given in Figs.5(a) and (b).

From the comparison of Figs.4(a) and (b) it seems that there is a high degree of qualitative similarity in the stress-strain behaviors between freshwater and sea-water samples, i.e., as is usually seen for normally consolidated clays, deviator stress increases steeply with increasing axial strain until it reaches about 5 % and subsequently increases very slightly with larger strain. However, the tendency for the deviator stress to continue to increase with larger strain is remarkable for the sea-water sample but not for the freshwater sample although the tendency is not so clear in the figures.

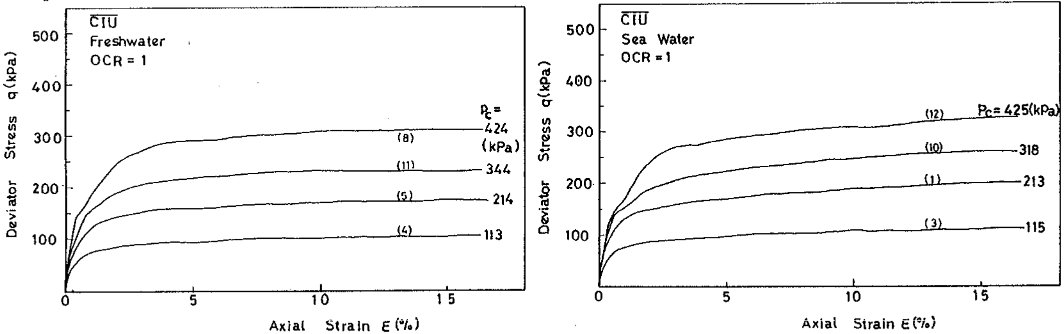

Fig.4: Stress-strain relations resulted from CIU triaxial tests on normally consolidated specimens (a) for the freshwater sample and (b) for the sea water sample.

Effective stress paths will be compared in Figs.5(a) and (b). For both samples, positive pore-water pressure well develops as the deviator stress increases. For each sample, a linear failure envelope could be drawn and strength parameters in terms of effective stresses were determined as shown in the figures. For the sea-water sample, the effective angle of friction ϕ' was determined as 33.5° and for the freshwater sample 31.8°. Apparent cohesion c' is zero for both samples.

A detailed observation of Figs.5(a) and (b) will lead to the following: for any specimen of the sea-water sample, deviator stress develops after the effective path reaches the failure envelope, and it is not the case for the freshwater sample. This would explain the fact, pointed out already concerning with Fig.4(b), that the deviator stress for the sea-water sample tends to increase with relatively large strain.

In Fig.6, the change in the pore-water pressure due to dilatancy, Δu_D, is shown as a function of the axial strain, where Δu_D is given by

$$\Delta u_D = \Delta u - B.\Delta\sigma_m.$$

Δu is the change in pore-water pressure occurring with undrained deformation, B is the pore-water pressure coefficient, and the term $B.\Delta\sigma_m$ expresses the change in pore-water pressure induced by the change in the isotropic component of total

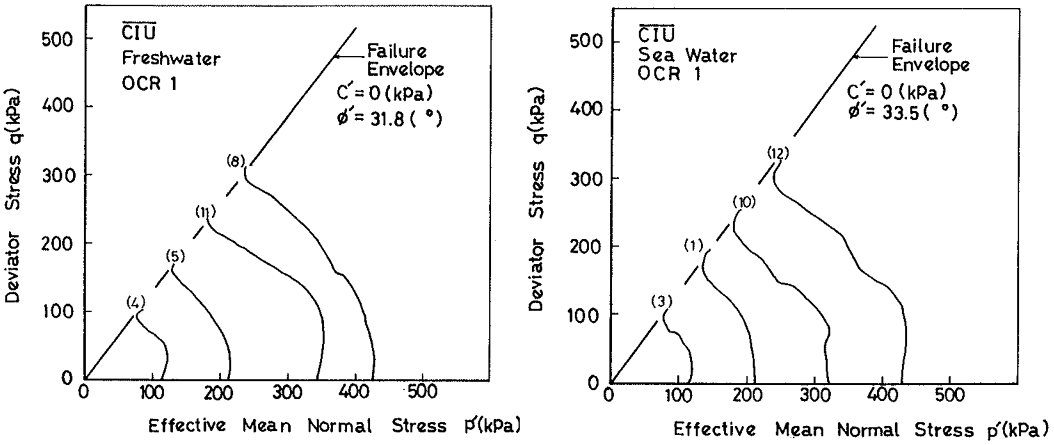

Fig.5: Effective stress paths resulted from CIU triaxial tests on normally consolidated specimens (a) for the freshwater sample and (b) for the sea-water sample.

stress, σ_m. Therefore Δu_D is considered as the change in pore-water pressure due to the change in the deviatoric component of stress. In the figure, Δu_D is divided by isotropic consolidation stress p_0 to be normalized.

From Fig.6 it is seen that, when the strain is relatively small, Δu_D increases for both samples, and that, when the strainning is further developed, it is held approximately constant for the freshwater sample, while it decreases for the sea-water sample. This indicates that the sea-water sample tends to positively dilate when strain so largely develops that the failure occurs and that the freshwater sample does not positively dilate when the strain largely develops.

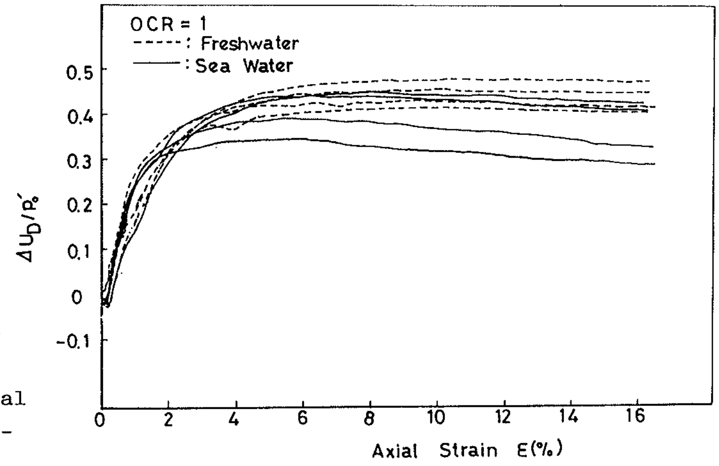

Fig.6: Variations of the change in the pore-water pressure due to dilatancy with axial strain for CIU triaxial tests on normally consolidated specimens.

(2) Overconsolidated Specimens

Shearing behaviour of overconsolidated specimens will be discussed and it will be examined if there is the difference in the effects of overconsolidation Stress-strain curves and the effective stress paths for overconsolidated specimens are presented in Figs.7 and 8, respectively.

A brief comparison of Figs.7 (a) and (b) gives no qualitative difference in the behaviour between the freshwater sample and the sea-water sample. For both samples, stress-strain behavior is similar as that for normally consolidated specimens although specimens were overconsolidated; deviator stress at any value of strain is higher when OCR is relatippvely small than when OCR relatively large because the maximun consolidation stress was held at 400 kPa for all specimens.

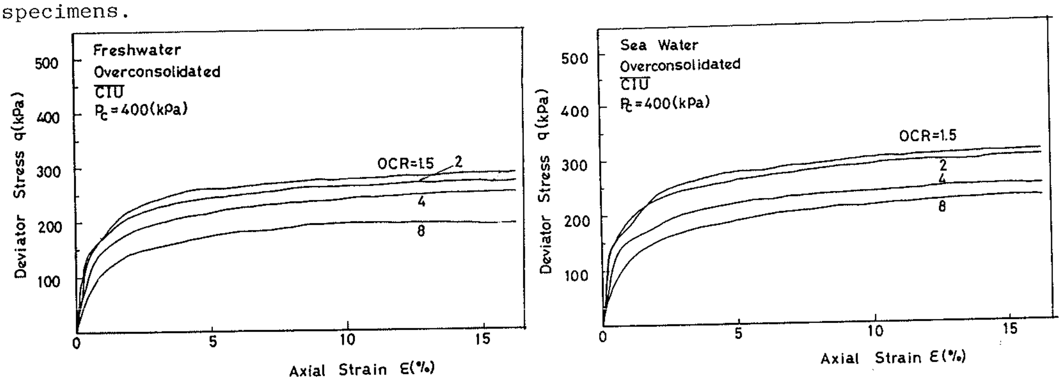

Fig.7: Stress-strain curves on overconsolidated specimens (a) for the freshwater sample and (b) for the sea-water sample.

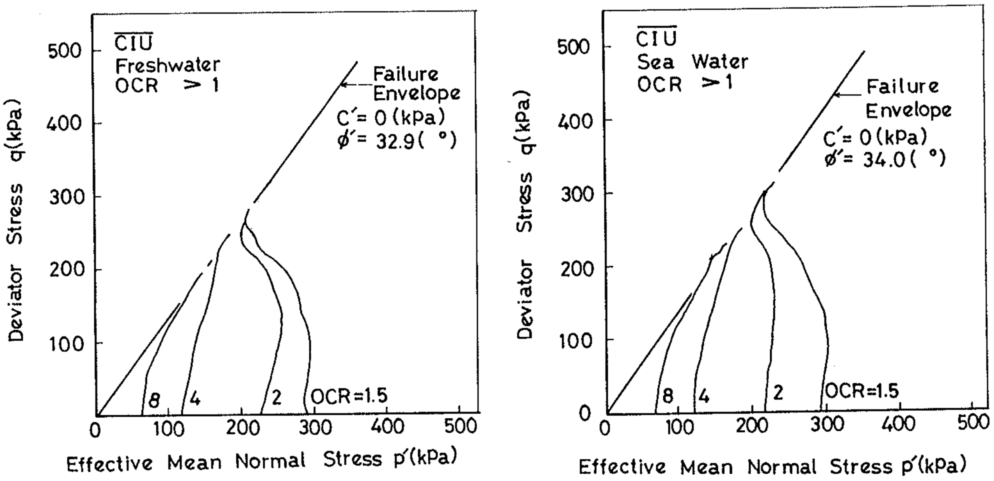

Fig.8: Effective stress paths on overconsolidated specimens (a) for the freshwater sample and (b) for the sea-water sample.

In Figs.8(a) and (b), where the effective stress paths are presented for the freshwater sample and the sea-water sample, respectively. Determined values of strength parameters in terms of effective stress are also shown. Effective stress paths strongly depend on values of OCR. Recognizable difference in effects of overconsolidation on the stress paths is not seen between the two samples. The effective angle of internal friction is larger for the sea-water sample by about 1° than for the freshwater sample, as in the case of normally consolidated specimens.

Variations of the pore-water pressure due to dilatancy with axial strain are compared between two samples as a function of OCR in Fig.9. For both samples , with increasing values of OCR negative pore pressure tends to develop, i.e., the dilatant behaviour tends to be positive with an increase of OCR. Overconsolidation effects on the dilatancy characteristics are the same for both samples.

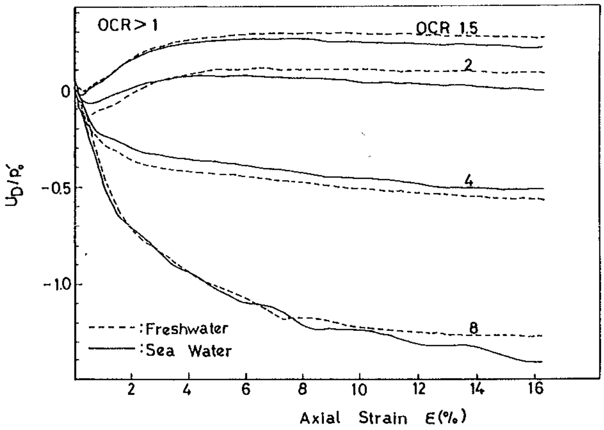

Fig.9: Change in the pore-water pressurte due to dilatancy for overconsolidated specimens.

Fig.10 shows the pore-water pressure coefficient at axial strain of 15 %, denoted by A_f, versus OCR. As OCR increases, A_f decreases. There seems no remarkable difference in the variations of A_f with OCR between two samples.

From the results mentioned so far, the overconsolidation effects are almost similar for the freshwater and sea-water samples. Only difference was seen in the strength parameter,i.e., a larger value of ϕ' was obtained for the sea-water sample than for the freshwater sample. The cohesion intercept c' was zero for both samples although OCR was varied up to 8, which would be explained by the fact that the specimens were prepared by being remoulded and consolidated only for a short period.

(3) Increase in Undrained Shear Strength due to Consolidation

The variations of undrained shear strength c_u with consolidation stress p_o is shown in Fig.11. c_u is defined as a half of the value of deviator stress at the axial strain of 15%. As easily expected from the facts that the angle of friction of the sea-water sample is higher than that of the freshwater sample for

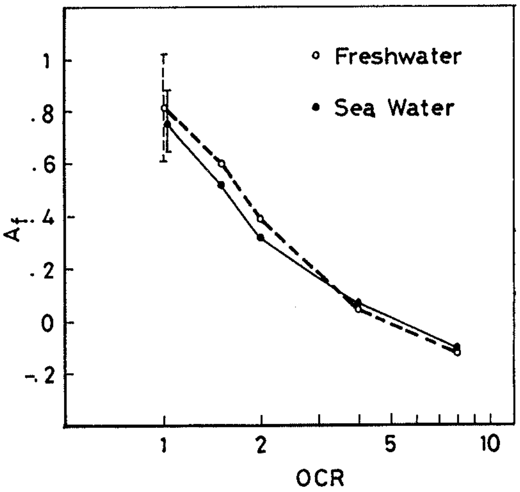

Fig.10: Pore-water pressure coefficient at failure vs. OCR.

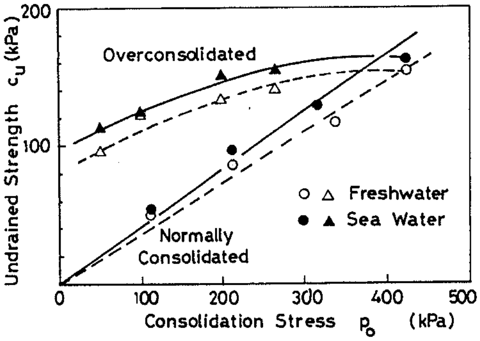

Fig.11: Variations in undrained shear strength with consolidation stress.

both normally consolidated and overconsolidated states and that A_f is not remarkably different between them, c_u is larger for the sea-water sample than for the freshwater sample for a full range of consolidation stress. The ratio of the undrained shear strength to the consolidation stress ,c_u/p_0 is therefore larger for the sea-water sample than for the freshwater sample. However, the difference in the values of the ratio is not so significant.

4.2 Compressibility and Consolidation Behavior

(1) Compressibility

The results from the oedometer tests will be discussed. The compression and consolidation behaviours will be compared, respectively, between the freshwater sample and the sea-water sample.

e - log p relations are shown in Fig.12. From this figure, compression index can be determined as 0.245 for the sea-water sample, and 0.275 for the freshwater sample. Thus the compression index of the sea-water sample is smaller than that of the freshwater sample.

Effects of chlorine content on the compression index have been examined in literatures, but no clear relationship of Cc to the chlorine content has been obtained. The relationship would depend on the types of clays.

(2) Consolidation Behaviour

Fig.13 shows the variation of the consolidation coefficient c_v with the average consolidation pressure p. From this figure it is seen that, except one plot, c_v is larger for the sea-water sample than for the freshwater sample. It is also

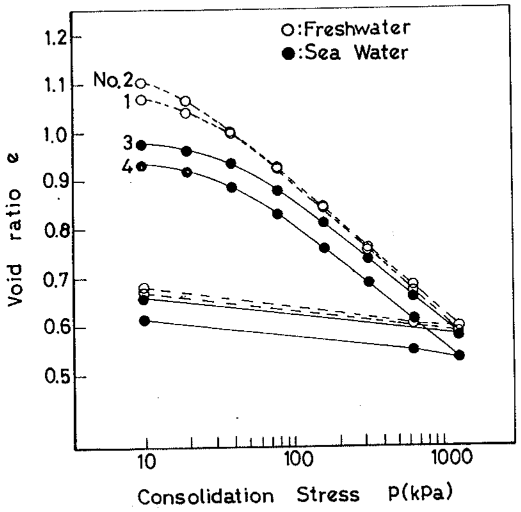

Fig.12: e-log p relations resulted from oedometer tests.

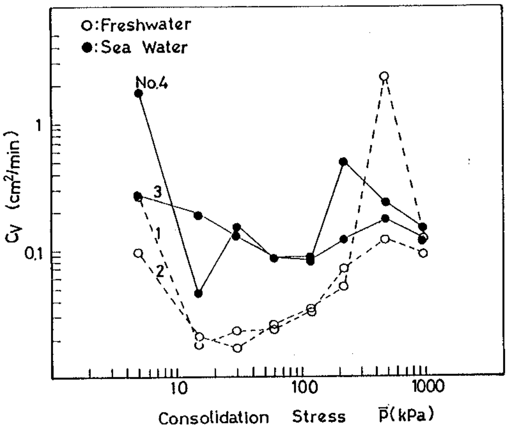

Fig.13: Consolidation coefficient vs. consolidation stress.

seen that the difference tends to be smaller as the pressure increases. Maximum difference in values of cv between two samples reaches one order when p is 30 kPa.

From the results shown in Figs.12 and 13, we can calculate the volume compressibility coefficient m_v and the theoretical coefficient of permeability k. Since for the sea-water sample C_c is smaller and c_v is larger than for the freshwater sample, m_v would be smaller and k would be larger for the sea-water sample than for the freshwater sample. In facts, these predicted behaviours can be seen in Fig.14.

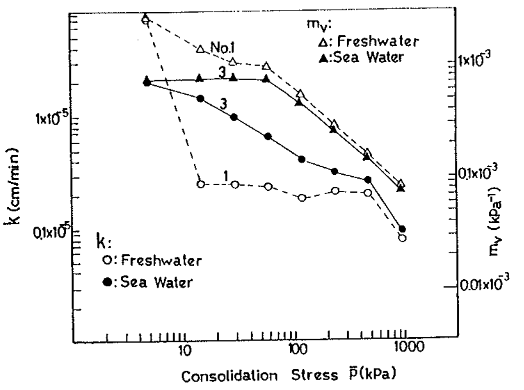

Fig.14: Variations of permeability and volume compressibility coefficient with consolidation stress.

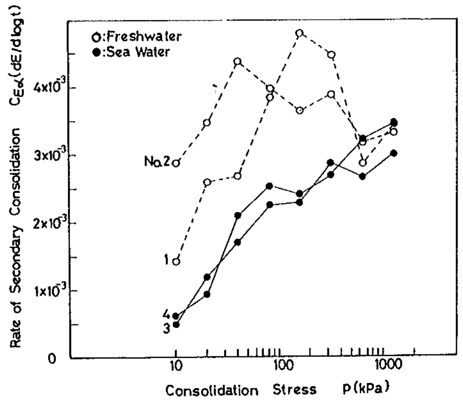

Fig.15: Variations of the rate of secondary consolidation with consolidation stress.

For both samples consolidation time curves were typical ones for normally consolidated clays, i.e., so called primary consolidation was observed and subsequently a linear relation of the settlement to the logarithm of time followed. The rate of secondary consolidation $c_{\varepsilon\alpha}$ can be defined as the gradient of the linear portion .

$$c_{\varepsilon\alpha} = d\varepsilon \ / \ d\log(t/t_0),$$

where ε is the compressive strain, t is the elapsed time and t_0 is the reference time. In Fig.15, variations of $c_{\varepsilon\alpha}$ with consolidation pressure are shown for the freshwater sample and the sea-water sample. For a full range of stress employed, $c_{\varepsilon\alpha}$ increases with increasing consolidation stress for the sea-water sample,but it is not the case for the freshwater sample. When the pressure level is relatively low, the rate of secondary consolidation of the freshwater sample is higher by two or three orders than that of the sea-water sample. However the difference in $c_{\varepsilon\alpha}$ between two samples tends to vanish when the stress level becomes high, e.g., in the order of 500 kPa.

4.3 Discussion

Results of investigations, cited and reviewed by Torrance(1974), upon the effect of leaching show that an addition of salt to remoulded quick clays will cause an increase in remoulded shear strength and a decrease in compressibility. The results obtained in the present investigation do not show very drastic change in the mechanical behaviour. Some effects such as the increase in the effective angle of friction and the decrease in compressibility or decrease in rate of secondary consolidation have resulted for the sea-water sample but they are not so significant.

In general, clay platelets will form aggregates and aggregates themselves would be relatively strong . Particularly in the sea water environment, they would not fail easily under the stress applied. When the bonding is strong, the aggregates will behave as a large particle. This would explain the fact, obtained in the present study, that the deviator stress continues to increase with relatively large strain exhibiting dilatant behaviour for the sea water sample and not for the freshwater sample.

It should be noted that, although the effects of the sea water on the mechanical behaviour are not so significant, they give favorite properties to soils from the engineering standpoint.

5.CONCLUSION

CIU triaxial tests and oedometer tests were carried out on the sample remoulded with the sea water and that with the freshwater to simulate the change in the deposition enviroment when the terrestrial soils are used in the marin engineering works.

Results obtained are as follows:

The sea-water sample behaves as a strain hardening material. The hardening characteristic is remarkable even when strain is so large that the failure condition is going to be reached. The effective angle of friction of the sea-water sample is larger by about 2° than that of the freshwater sample. The sea-water sample exhibits positive dilatant behaviour when the strainning is developed even under the normally consolidated state.

The effect of the overconsolidation on the shearing behaviour was the same for the sea-water sample and the freshwater sample. The only difference in the effect was detected in the shear strength, i.e., as was seen in the case of normally consolidated condition, the strength parameter of the sea water sample was larger than that of the freshwater sample.

A higher degree of the increase in undrained shear strength due to consolidation was seen in the sea-water sample as had been expected from the difference in strength parameter between two samples.

Compressibility of the sea water sample was less than that of the freshwater sample. Consolidation coefficient was also less for the sea-water sample than for the freshwater sample. Both differences in the compressibility and in the consolidation behaviour vanished when the consolidation stress became higher level of the order of 500 kPa.

It can be concluded that all the mechanical properties of the sea-water sample are not undesirable from the engineering point of view.

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