Transitional States in 1D Slurry Consolidation

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ABSTRACT
This paper investigates the presence of a unique transition between slurry and normal soil states while undergoing 1-D consolidation with normal pressures applied in steps from 20 to 400kPa. For this purpose a multipurpose large diameter consolidation test apparatus with the facility for measuring internal pore water pressure (PWP) and direct permeability during consolidation process have been devised in the laboratory. Oedometer tests are also done on the soil specimens prepared at 50 kPa consolidation pressure. Test results showed that there exists a unique transition between slurry and normal Terzaghi soil states at consolidation pressure of 50 kPa. Water content at this transition state were found fairly close to the respective liquid limits of both soils. Excess internal pore pressure were found to exceed the net load increment while normal pressure increased from 20 kPa to 50kPa, signifying that internal PWP at slurry stage are dependent on total applied pressure.

1. INTRODUCTION
High water content (or low solids content) materials consist of marine sediments, swamps, industrial wastewater, water treatment sludge, and agricultural wastes. These materials need proper treatment to suit for civil engineering construction needs. One of the improvement methods could be to carry out systematic study of these soils in slurry form. In slurry state conventional one-dimensional consolidation principle does not represent the process of compression. Because, soil grains in slurry state stay apart or exists in flocculated state. The soil skeleton cannot share the applied load till sufficient water escapes out. The rate of drainage depends on permeability of slurry and filter permeability at the drainage boundary. Continuous and controlled compression of the slurry from suspension state shows that there exists a transition point where soil slurry turns to normal soil state and there after Terzaghi’s 1-D consolidation theory becomes relevant. The compressible layer is assumed to be both homogeneous and completely saturated with water and the mineral grains in the soils and the water in the pores are completely incompressible. Darcy’s law is considered to govern the egress of water from the soil pores, and usually both drainage and compression are assumed to be one dimensional.

The formation of an alluvial clay deposit normally goes through sedimentation and consolidation. While the bottom portion undergoes self-weight consolidation, sedimentation continues to take place at the top. Due to the high demand of land on coastal areas, land reclamation on such deposits becomes necessary. However, the deformation behavior of such deposits upon loading is not well understood.

In this paper compression and consolidation characteristics of two selected fine-grained soils such as Kanto Loam (KL) – a natural soil from Japan and an artificial silty clay known as Clay Sand (CS) in Japan, starting from slurry stage are reported. A large diameter 1-D consolidation apparatus has been devised in the laboratory. Slurry making process and methods for assembling the slurry samples are elaborated in Ghosh and Yasuhara (2003). Volumetric compression of soil specimen were measured in addition to the amount of drainage. Three pore water pressure (PWP) devices incorporated within the specimen measure the changes in the excess PWP. Consolidation pressures were applied in steps from 20 kPa to 400 kPa with a load increment ratio of one. Oedometer tests have been performed on the slurry samples compressed to 50 kPa. Changes in the permeability and volumetric compressibility of soils with increasing pressure and their effect on the coefficient of large strain consolidation have been explained.

2. EXPERIMENTAL PROCEDURE
In order to carry out test simultaneously on KL and CS soils two 150mm diameter plexiglas cylinders have been
chosen. The top plate is fitted with a O-ring that moves tightly within the cylinder. It has one hole securely connected to a flexible pipe that collects water to be drained at the top. This has been used to carry out hydraulic flow test to the soil at various stages of consolidation. The air pressure chamber can safely hold a pressure up to 400 kPa. Four holes are made at the bottom plate of each cell for measuring drainage and PWP. Three PWP devices with extended external water tube connections have been arranged. These water tubes are made flexible by boiling in water for about 30 minutes. Their lengths are adjusted with the required level within the cylinder. In order to avoid direct entry of the slurry into the pipes a spherical tip with porous stone (5 to 7mm diameter) is made and it is securely fitted with one end of the water tube (Fig. 1). With this arrangement excess water is filtered from the soil to the PWP device connected to the other end of the water tube. Sensitivity of the PWP device was checked time to time and it was ensured that all air bubbles were flushed out before taking any measurement. In some occasions PWP values struck up to a fix value even after substantial changes found in the other device placed at another level. A little flushing by de-aired water shiringe could be found effective in checking this occasional blockage of the water pipe. The same device was used to drain out water from the permeable geocomposite drain. In addition, facilities for collecting drained water at the top and bottom face during consolidation were made.

![Fig. 1: Test Apparatus with Details of PWP Devices and Measuring Instruments](image)

A 3mm thick nonwoven needle punched geocomposite material has been used as filter cover at the top and bottom drain faces. A compacted coarse sand base is placed at the bottom to cover up pipe connections. The deformation of the sand base and geocomposite filter layer under applied consolidation pressure has been calibrated and adjusted with the actual data obtained for soil. Settlements at various stage of step loading were recorded by a 100mm LVDT.

### Sample Preparation

Initially some slurry was used for making samples for conducting oedometer test. A large cell was used for this purpose. Pre-consolidation of KL and CS are carried out first. Initially consolidation pressure of 20 kPa was applied and after settlement stopped pressure was increased to 50 kPa. To avoid the effect of secondary compression the same pressure has been maintained at least 3 times the primary consolidation time. In the case of standard laboratory oedometer tests, sample diameter (usually 60 mm) to sample thickness (usually 20mm) ratio is 3. Therefore, in the present test series the same ratio is being maintained, which means that standard sample thickness for a 150mm φ cell is 50mm. By some trial processes with the KL and CS slurries it has been estimated how much slurry is required for making 50mm thick sample when it is subjected to 50 kPa pressure till end of primary (EOP) stage of consolidation. It was found that vertical pressure of 50 kPa was just enough to consolidate slurry into standard sample consistency.

### Test Procedure

Sample preparation in a 150mm cylinder and operation sequences for artificial silty clay sample are described in elsewhere (Ghosh and Yasuhara 2003, 2004). PWP are measured at three elevations. Their positions are mapped from initial stage to final stage after consolidation is finished. Tests data revealed that the presence of three flexible pipes within 150mm diameter sample has little effect to the soil consistency. Compacted coarse sand was used for covering pipeline connections at the base. Spherical porous stone tips are affixed with properly honed (OD=3.15mm) pipelines and their positions are set as per requirement of the soil slurry. At the both drain boundaries geocomposite was used as a substitute for filter paper.
Photographs taken after the test shows that these geocomposite filters have had heavy blinding at the exposed face with soil. There was no particle deposition at the opposite face and also there was not any substantial leakage of the slurry through the geocomposite filter.

3. DISCUSSION OF TEST RESULTS

The void ratio vs. consolidation pressure curve presented in Fig. 2 showed two distinct values of compression indexes. The transition point is found around 50 kPa. Bo et al. (2003) have noticed similar observations. In our case for <50 kPa, the initial void ratio of slurry do not have much influence in the normal $c_u$ value. Moreover, for all samples tested with/without drain, this value remains almost unaltered in the normally consolidated range tested at 50 to 400 kPa. It was also found that the transitional stage in consolidation occurred when slurry water content was approaching to liquid limit. Therefore, under the test conditions tried for two fine grained soils, initial water content (or indicative initial void ratio) of the slurry did not seem to have any influence on the compression index (Fig. 2). Standard oedometer tests results were also plotted in Fig. 2 and it showed that compression index in the normal soil state resembles to the same for slurry.

Fig. 3 shows the variation of internal peak excess PWP ratio with applied pressure to the specimen. PWP measured at the middle of the soil are plotted for specimen thickness $H_0=110$mm. While peak excess PWP reduces with the increase in consolidation pressure there is a distinct peak excess PWP at $p=50$ kPa. At this stage i.e. when applied pressure increased from 20 kPa to 50 kPa the excess PWP exceeded the net increase; $\Delta p=30$ kPa. This signifies that in slurry state conventional 1-D consolidation principle does not represent the process of compression. Because, soil grains in slurry state stay apart or exists in flocculated state. The soil skeleton cannot share the applied load till sufficient water escapes out. The rate of drainage depends on permeability of slurry and filter permeability at the drainage boundary. There exists a transition point where soil slurry turns to normal soil state and there after Terzaghi’s one-dimensional consolidation theory becomes relevant. Bo et al. (1999, 2004) described several methods for determining the average void ratio at transition point based on settlement, void ratio, permeability change and pore water pressure changes during compression.

![Fig. 2a: e-log p Plots for Artificial Silty Clay (CS)](image)

![Fig. 2b: e-log p Plots for Kanto Loam (KL)](image)

![Fig. 3a: Peak Excess PWP vs Consolidation Pressure, p for Kanto Loam (KL)](image)

![Fig. 3b: Peak Excess PWP vs Consolidation Pressure, p for Silty Clay (CS)](image)
4. CONCLUSIONS
Transition between slurry and normal Terzaghi soil state occurred at consolidation pressure of 50 kPa. Water content at this transition state found fairly close to the respective liquid limits of the Kanto loam and silty clay. At every loading step there is a unique coincidence among the measured values of the excess PWP, drainage rate and the various stage of primary consolidation. Peak excess PWP represents the state at which soil undergoes maximum rate of compression. ‘e-log p’ curves for slurry state and normal soil state are different and it has two separate $C_c$ values.

REFERENCES

