

Void structure of Auckland residual soil using X-ray CT scanning

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ABSTRACT

In this paper, the properties of undisturbed Auckland residual soil are related to visualisation of the void structure obtained by X-ray CT scanning. The soil investigated was derived from in situ weathering of the Waitemata group sandstones and siltstones, a process which produces soil with surprisingly variable properties. We performed consolidation tests in a triaxial cell to understand better the origin of this variability. Specimens were consolidated in several stages and after each stage the specimen was allowed to swell in stages back to zero consolidation pressure. It was then taken to another piece of apparatus and X-ray CT scanning performed. Processing of the CT data revealed that the void structure of the residual soil was inhomogeneous. From the images obtained, it was observed that the large voids (macro-voids) present at low consolidation pressures were gradually closed with increasing effective confining pressure. The decreasing size of the large voids is suggested as the cause of the decreasing values for the permeability coefficient with increasing consolidation pressure.

1 INTRODUCTION

The city of Auckland is based on volcanic and sedimentary geology. The sedimentary materials are of tertiary age and consist of sandstones and siltstones. When unweathered these materials have unconfined compressive strengths ranging between about 0.5 and a few MPa. The upper layers of these soft-rocks have been weathered in situ to form residual silty clay soils. The weathering results in highly variable soil as evidenced by the variability in undrained shear strength as shown in Figure 1. We have found that the coefficient of consolidation of Auckland residual clay decreases rapidly with increasing consolidation pressure. This has implications for soil structure interaction as it suggests that for lightly loaded foundations consolidation settlement may be completed during construction, but when the soil-foundation contact pressure is larger, consolidation settlement may still be occurring after construction is complete.

Thinking that a possible cause of the variability in the shear strength and the rapid decrease in the coefficient of consolidation with increasing confining pressure might be a consequence of the void structure developed in the weathering process, we took advantage of the recent acquisition by the University of Auckland of a SkyScan 1172 high resolution micro CT scanning machine. Specimens were consolidated in several stages and after each stage the specimen was allowed to swell in stages back to zero consolidation pressure and then scanned. Processing of the CT data enabled three dimensional visualisation of the void structure within the specimens. From these images it was observed that large voids are present at low consolidation pressures which are gradually closed with increasing effective confining pressure. The decreasing size of the large voids is suggested as the cause of the decreasing values for the coefficient of consolidation with increasing consolidation pressure.

Griffiths and Joshi (1989) and Tanaka et al (2003) investigated the pore size distribution of clay and clayey soils using mercury intrusion porosimetry. They found, like the work in this paper, that the proportion of larger voids reduces faster than the proportion of smaller voids with increasing consolidation pressure. The mercury intrusion technique gives “average” information

about the distribution of void sizes, whereas CT scanning enables the dimensions of individual voids and “tubelike” structures formed from linked voids to be identified.

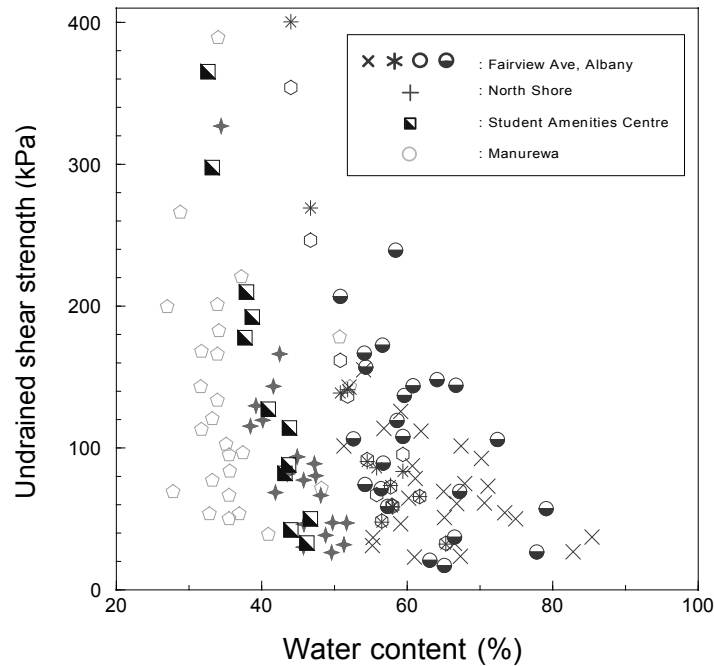


Figure 1: Variability of the undrained shear strength – water content relationship for Auckland residual clay from several locations around the city.

Table 1: Physical properties of the samples

Specific gravity of soil particles	Liquid limit %	Plastic limit %	Plasticity Index %	Natural water content %
Hillcrest sample				
2.694	63.8	30.4	33.4	32.0
Fairview sample				
2.690	73.9	33.1	40.8	37.0

Figure 1 shows the variable nature of the undrained shear strength of Auckland residual clay when plotted against water content. We think that the large voids at low effective stress are a consequence of the weathering process and that they are unlikely to be uniformly distributed throughout the soil, i.e. the void structure is inhomogeneous. If this is the case, the variable void structure could also contribute to the variability of the shear strength at low consolidation pressures.

2 TEST PROGRAM

2.1 Soils investigated and test program

One of the specimens investigated was taken from just south-east of the position where Hillcrest Rd crosses State Highway 1 in the hills behind Orewa. Another specimen was taken from a building site in Fairview Avenue, Albany. Herein we refer to these specimens as the Hillcrest sample and the Fairview sample. Table 1 shows the physical properties of the soils. Block samples were obtained at each site by pushing 200 mm diameter by 200 mm high steel sampling tubes, with a removable low angle cutting shoe, into the soil at the base of a digger excavation with a hydraulic jack reacting against the digger bucket. The tubes were recovered by hand dig-

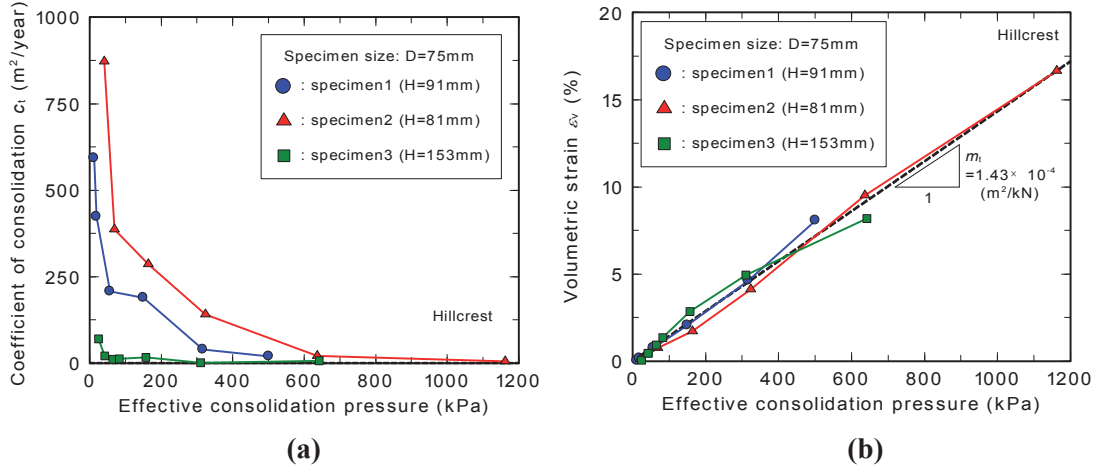


Figure 2: (a) Coefficient of consolidation and (b) volumetric strain plotted against effective consolidation pressure (Hillcrest sample).

ging. In the field, excess soil was trimmed away from the tube and end caps fitted to seal the sample. In the laboratory, the sample was extruded from the tube and cut approximately to size using a band saw and then trimmed to a diameter of 20 mm using a hand operated soil lathe. The trimmed specimens were mounted in a triaxial cell and saturated with the application of back pressure increased in stages to 700 kPa. During the saturation a difference of 10 kPa was maintained between the cell and back pressures. The saturation was checked, a B value greater than 0.95 was taken as saturation. The main purpose of saturating the specimens was so that the measurement of the coefficient of consolidation was not affected by the presence of air in the voids. The specimen was consolidated in stages to effective confining pressures of 20, 50, 100, 200, 400, 800 kPa. At the completion of each stage of consolidation the specimen was allowed to swell back gradually to zero consolidation pressure. It was then taken to the X-ray CT apparatus and scanning performed. The top and bottom caps for the specimen were machined from PVC plastic; these and the rubber membrane remained in place when the specimen was taken from the triaxial cell for CT scanning. After each stage of scanning, the specimen was returned to the triaxial cell, re-saturated, and consolidated to the next effective confining pressure. The completion of consolidation was determined using the “3t” method (JGS 0523-2000), in which the volume change is plotted against the logarithm of elapsed time, the steepest part of the line is determined by visual inspection and its intersection with the zero volume change axis gives the time “t”. Next, a line with the same inclination is drawn from the time “3t” on the zero volume change axis, the time corresponding to its intersection with the consolidation curve indicates the end of consolidation. For the Hillcrest specimen a section 4.4 mm in height and 24 mm x 24 mm in cross section was scanned, the voxel size was a 6 μ m cube so that for each horizontal cross-section there were 3968 x 3968 voxels. For the Fairview specimen a section 17 mm in height and 34 mm x 34 mm in cross section was scanned, the voxel size was a 17 μ m cube so that for each horizontal cross-section there were 2000 x 2000 voxels.

3 TEST RESULTS AND DISCUSSION

3.1 Mechanical properties

Figure 2(a) shows the relationship between the coefficient of consolidation, c_v , and the effective consolidation pressure for the Hillcrest specimen. Figure 2(b) shows the relationship between the volumetric strain and the effective consolidation pressure for hydrostatic consolidation of the Hillcrest sample. This consolidation test was done in a triaxial cell on specimens 75 mm in diameter and 81, 91 and 150 mm tall. The volume change data on the miniature specimens was not used to determine the volumetric compressibility because the specimens were so small and

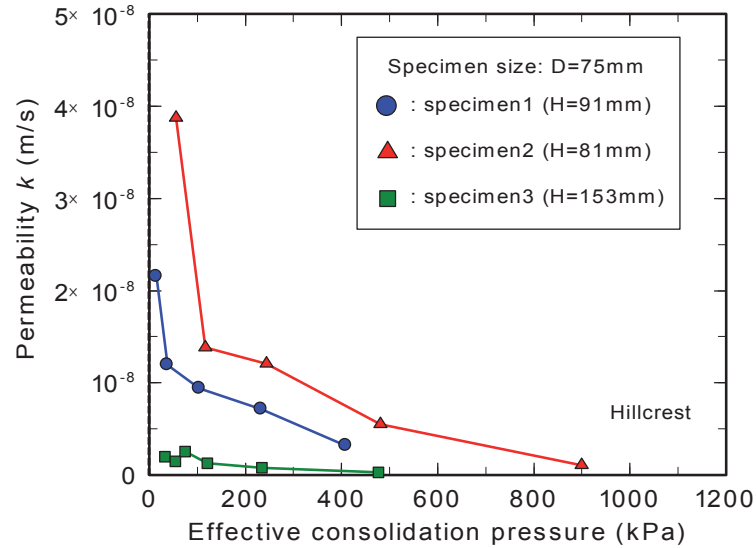


Figure 3: Relationship between permeability and effective consolidation pressure (Hillcrest sample)

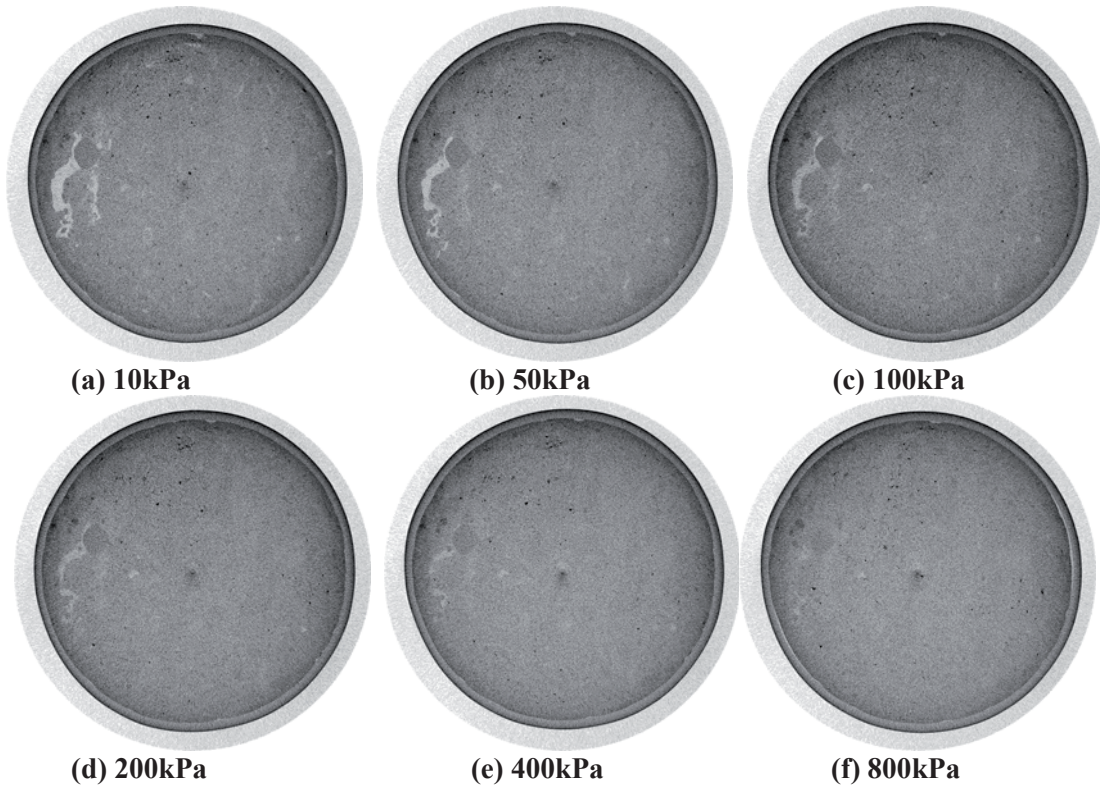


Figure 4: Horizontal section at the height of 1.843mm from the bottom of specimen (Hillcrest sample with specimen diameter of 20mm)

also because of the successive cycles of consolidation and swelling. In Fig. 2(b), it is seen that the volumetric compressibility is almost constant; a value of $1.43 \times 10^{-4} \text{ (m}^2/\text{kN)}$ is indicated. From c_t and m_t (values of the coefficient of consolidation and volumetric compressibility determined in triaxial testing) the permeability coefficient, k , was calculated using: $k = c_t m_t \gamma_w$, where γ_w is the unit weight of water. Figure 3 gives a plot of the permeability coefficient against consolidation pressure showing it decreasing rapidly at pressures up about 100 to 200 kPa.

3.2 Void structure within the specimen

Figure 4 shows the horizontal section, given by reconstruction of the X-ray images, at a height of 1.843mm from the bottom of Hillcrest specimen. In this figure, the white colour shows void and black colour shows soil particles or membranes. Figure 4(a) shows the section of the specimen after consolidation to 10kPa, the left area of this image shows a large macro-void. This macro-void closed gradually with increasing effective confining pressure, being only faintly visible when the consolidation pressure is 200kPa, and even less so at pressures of 800 kPa. Figure 5 shows vertical sections of the three-dimensional images of the void structure of the Fairview miniature specimen. In these figures only larger voids of more than 30 voxels extent in each horizontal direction are plotted. The boundary between the void and the soil particles was determined using the procedures described by Otani et al (2000) and Pender et al (2008). In Figure 5(a), it is seen that the Fairview sample had a void structure which looks tubular running between the lower to upper part of the specimen. The thickness of the “tubes” decreased with increasing effective consolidation pressure. We consider that these observations provide a plausible physical explanation for the rapid decrease in the permeability coefficient with increasing consolidation pressure shown in Fig. 3. Furthermore, we think that the presence of macro-voids in the residual clay, and the consequent inhomogeneity of the clay structure, is the reason for the variability of the undrained shear strength – water content relation shown in Fig. 1.

The void ratios for the soil can be calculated from the CT data. It is of note that the value obtained for each specimen by averaging the CT values calculated for all the cross-sections was very close to the values obtained for the specimens from the usual geotechnical calculations.

4 CONCLUSIONS

We reach the following conclusions from the information presented above:

- the void structure of Auckland residual clay is inhomogeneous at low consolidation pressures,
- as the consolidation pressure is increased the size of the macro-voids, the source of the inhomogeneity, are reduced,
- hydrostatic consolidation data show an order of magnitude reduction in the permeability coefficient as the consolidation pressure is increased from 20 to 800 kPa.

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REFERENCES

- Griffiths, F. J. and Joshi, R. C. (1989) Change in pore size distribution due to consolidation of clays, *Géotechnique* 39, No. 1, pp. 159-167.
- Japanese Geotechnical Society (2000) *Soil test procedures* JGS0522-2000, JGS0523-2000, JGS0524-2000. Japanese Geotechnical Society.
- Otani, J., Mukunoki, T. and Obara, Y. (2000) Application of X-ray CT method for characterisation of failure in soils, *Soils and Foundations*, Vol. 40 (2), pp.111-118.
- Pender, M. J., Kikkawa, N. and Liu, P. (2008) Macro-void structure and permeability of Auckland residual clay, (submitted to *Geotechnique* for publication).

Kikkawa, N., Pender, M., Orense, R. & Liu, P. (2008)
 Void structure of Auckland residual soil using X-ray CT scanning
 Tanaka, H., Shiwakoti, D. D., Omukai, N., Rito, F., Locat, J. and Tanaka, M. (2003) Pore size
 distribution of clayey soils measured by mercury intrusion porosimetry and
 its relation to hydraulic conductivity, *Soils and Foundations*, Vol. 43 (6),
 pp.63-73.

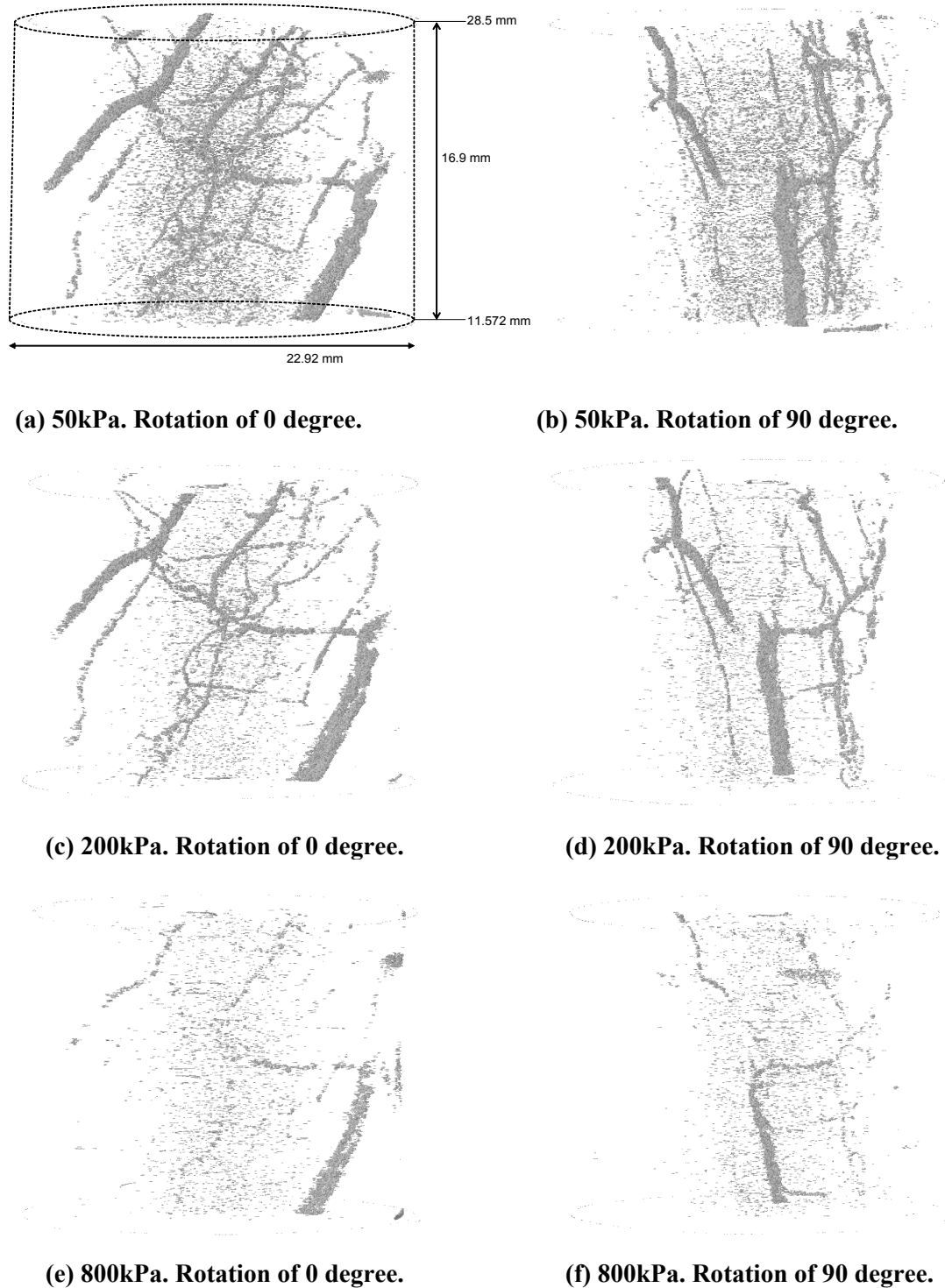


Figure 5: Vertical sections of the three-dimensional view of the void structure of the miniature specimen (Fairview Sample).