Consolidation behaviour of clay slurry and lumpy soil as observed from model tests

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ABSTRACT
Lumpy soil is a common waste material from dredging or excavation and is often used as backfilled material. Lumpy soil has both intra-lumpy porosity (within the soil lumps) and inter-lumpy porosity (in between the soil lumps). Thus, consolidation behaviour can be quite different from that of normal soil. In this paper, the consolidation behaviour of both clay slurry and lumpy soil under vacuum preloading as observed from laboratory model tests is studied. Pore-water pressure distributions in the soil, ground settlement, and other soil properties were monitored during the experiments. The results indicate that lumpy soil induces large settlement and pore pressure dissipation at the initial stage of loading and the rate of consolidation decreases dramatically after the inter-lumpy voids close up. In contrast, uniform marine clay experiences slower but consistent rate of consolidation. Under the same consolidation stress, lumpy soil ends up with a lower shear stress than marine clay. This may be because the overall void ratio of the lumpy soil is still higher than uniform soil after consolidation.

RÉSUMÉ
L'argile en morceaux est un matériau fréqeumment rencontré dans le dragage de sol en cours de construction, et usuellement utilisé comme le matériau pour remblayer ensuite. Comme le sol avec double porosité, qui a à la fois la porosité intragranulaire dans l'enceinte des morceaux de sol et la porosité intergranulaire entre les morceaux de sol, le comportement de consolidation de l'argile en morceaux peut être très différent d'autre matériau pour remblayer. Un autre matériau fréquemment utilisée à Singapour est boue d'argile. La méthode de pré-chargement à vide est idéale par rapport à la méthode de surcharge par remblayer pour la consolidation de boue de sol, qui est trop mou pour la surcharge à appliquer. Le comportement de consolidation de boue d'argile et argile en morceaux sous le pré-chargement à vide est examiné avec l'utilisation d'essais laboratoire. La distribution de pressure de l'eau interstitielle dans le sol, le tassement du sol et les autres propriétés du sol sont surveillé pendant les expériences. Les résultats d'essais sont présentés dans cet article.

1 INTRODUCTION

Dredged soil either in lumpy or slurry form has been used as fill for land reclamation. Lumpy soil consists of intra- and inter-granular porosity and the consolidation behaviour can be very different from that of other soils. Even when the clay lumps themselves are stiff, the soil matrix as a whole is as compressible as soft soil because of its heterogeneous property (e.g. intra-lumpy porous).

One method that could be used to improve the properties of clay is to vacuum preloading. In the field, the nominal design vacuum pressure is 80 kPa. To understand the consolidation process of both lumpy and slurry soil and to evaluate the soil properties after consolidation, laboratory model tests were carried out. The test results and analyses are presented in this paper.

2 LUMPY SOIL PROPERTIES AND VACUUM PRELOADING SYSTEM

2.1 Lumpy Soil Properties

Similar to fractured porous medium, a lumpy clay system consists of low permeable blocks surrounded by high permeable void space. Thus, it has both intra-lumpy porosity, within the soil lumps, and inter-lumpy porosity, in between the soil lumps. Loading reduces the inter-lumpy porosity through the squashing, crushing, and rotation of clay lumps (Feda 1998). Because of its heterogeneous property, soil matrix may be as compressible as soft soil and leading to large absolute and differential settlement, even though the soil lumps can be stiff. Thus, it makes ground improvement to be necessary before construction (Pooley et al., 2009).

Several case histories of land reclamation using lumpy fill has been reported (Casagrande, 1949; Whitman, 1970; Hartlen and Ingers, 1981; Yap, 2001). The first detailed evaluation of consolidation of a large clay-lump fill during the construction of Logan Airport was performed by Casagrande (1949). He pointed out that the inter-lump semi-fluid clay supported most of the initial pressure caused by soil weight; however, the excess pore water pressure developed within this semi-fluid clay dissipated faster compared to natural marine clay due to the relatively high permeability. Plastic deformation of the clay lumps was then formed by the effective stress incurred at the points of contacts between the lumps along with the pore pressure dissipation. A straight line observed in settlement versus time curve has reassured his point.

Laboratory tests were performed to study the consolidation behaviour of lumpy soil (Leung et al., 2001). As shown in Figure 1, the settlement vs. time curve of 1-D compression test conducted on dredge lumpy sedimentary clay taken from the New Container Terminal site in Singapore showed practically two straight lines on the semi-log scale plot, which implied that the fill underwent substantial settlement almost immediately after loading, and the consolidation rate was considerably faster than it of homogeneous clay. However, this difference decreased rapidly after 20 seconds of loading due to the inter-lumpy void closing up.

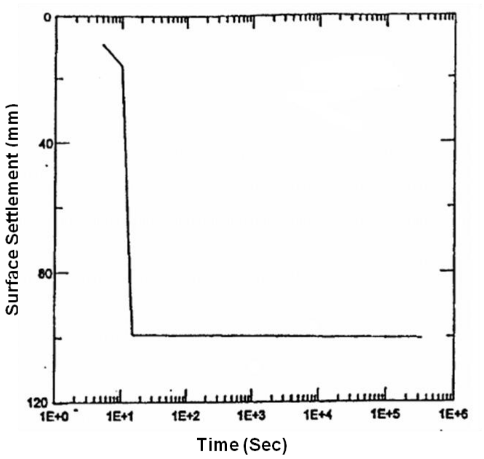

Figure 1. Surface settlement vs. time at 25 kPa of dredge lumpy clay (after Leung et al, 2001)

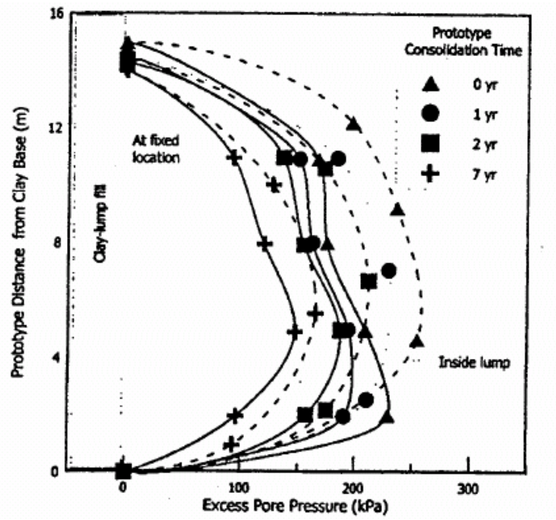

Figure 2. Excess pore pressure isochrones for lumpy fill made up of irregular lumps (after Leung et al. 2001)

Centrifuge model tests were also conducted to exam other factors that influence the consolidation behaviour of lumpy clay fill (Leung et al., 2001; Najser & Pooley, 2005). The excess pore water pressure isochrones obtained in Leung's tests (2001) are shown in Figure 2. Two pore pressure dissipation patterns were observed: one is at inter-lumpy voids and dissipated faster, which is represented by all solid lines in Fig. 2; the other is inside the lumps and responded much more slowly to external loading, which is represented by the dash lines.

Water content after consolidation vs. depth inside the sample from a mini-centrifuge test conducted by Najser & Pooley (2005) is shown in Figure 3. The drainage layer was placed at the base of modle. As it can be observed, water content decreased contineously from surface to base, which implied that some reduction of inter-lumpy prosity has taken place in the upper two thirds of sample; while for the lower one third, inter-lumpy voids may have all been closed up. This effect decrease along with increasing of lump size.

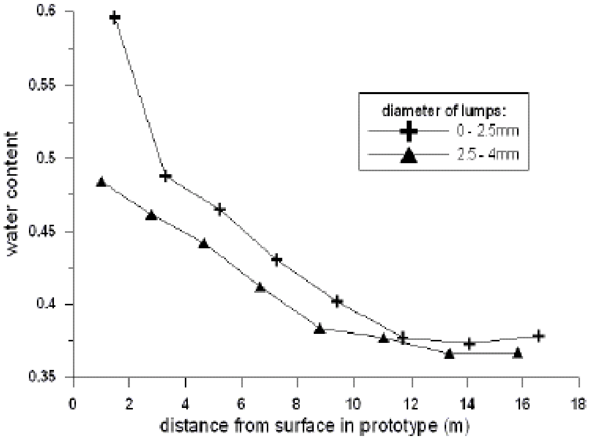

Figure 3. Varation of water content with depth in mini-centrifuge test (after Najser & Pooley, 2005)

2.2 Vacuum Preloading System

Several vacuum preloading systems have been developed over the years, for examples, the Tianjin system, Menard system and Beaudrain system (Chu et al, 2008). In addition to the ease of construction, vacuum preloading also alleviates the stability problem: through applying vacuum loading, the effective stress is increased by the same magnitude of the induced negative pore pressure as a result of the vacuum depressurization. In other words, the effective stress path for a soil element undergoing vacuum follows the path A-D as compared with the path A-B-C in the case of a fill surcharge, as shown in Figure 4. Hence, vacuum preloading systems promotes stability as shown by the stress path A-D which moves away from the failure line K_f as it proceeds with the vacuum pumping, while placing fill surcharge moves the stress path toward the failure line, K_f (Spaulding et al. 1993).

The one adopted in this research is Menard vacuum system (Spaulding et al. 1993). It is a representative of the membrane type of vacuum preloading techniques that have also been used elsewhere in the world (Holtz, 1975; Chu et al. 2000). The system consists of installing an airtight impervious membrane (e.g. PVC) over the soft saturated cohesive clayey soil to be consolidated, as shown in Figure 5. Vertical drains are used together with horizontal drainage pipes to distribute vacuum pressure and discharge pore water. The vacuum pressure is then created below the membrane and in the soil along the drains. Using a combination of air-water pumps, a vacuum pressure of 80 kPa can be applied and maintained throughout the consolidation period.

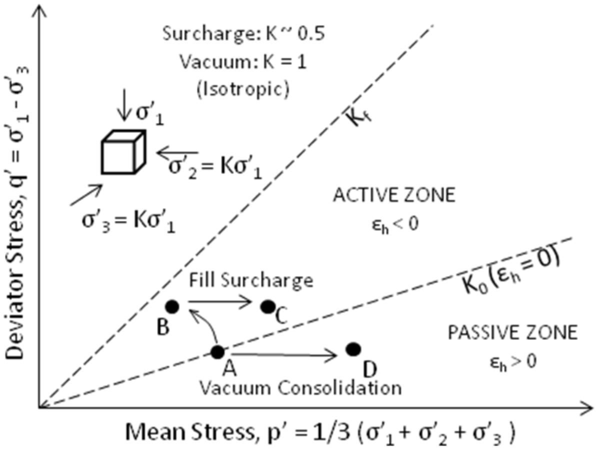

Figure 4. Vacuum on q-p diagram (modified after Spaulding et al. 1993)

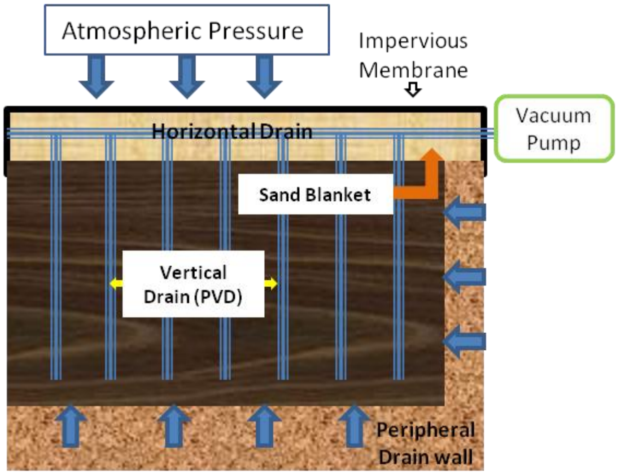

Figure 5. Structure of Menard vacuum preloading system (modified after Spaulding 1993)

3 MODEL TEST ARRANGEMENTS

3.1 Materials

Lumpy soils tested in this experiment were handmade soil balls prepared by compressed kaolin with water content 46.8%. Two different sizes were made, 6 cm and 3 cm in diameter respectively, to simulate the lumpy soil in situ, as shown in Figure 6. Water was then added in the tank before testing as lumpy soils were usually dumped into water in practice.

Figure 6. Clay balls made for simulating lumpy soil

Besides lumpy soil, two types of marine clay was also tested in this experiment, from Tuas (MC1, water content 89.7%) and Marina South Pier (MC2, water content 72.4%) in Singapore. Both of these sites contain grayish marine clay with high water content, and were found to comprise a heterogeneous composition of clayey fines, silt, organic materials, sand, shells, etc. The difference between them is that MC2 contains a large portion of sand and can be classified as silty sand. The physical and geotechnical properties of the soils used in this study are summarized in Table 1.

Table 1. Characteristics of tested soils.

Property	Kaolin	MC1	MC2
Specific Gravity	2.54	2.54	2.46
Liquid Limit, LL (%)	69	43.6	30.4
Plastic Limit, PL (%)	38	21.9	23.2
Plasticity Index, PI (%)	31	21.7	7.2
Fine Content (%)	100	72.3	24.3
Soil Classification	Clayey Silt	Organic Clay	Silty Sand

3.2 Test Setup

A fully instrumented consolidation tank as shown in Figure 7 was adopted for the model tests. The tank was 30 cm in diameter and 100 cm in height. Six miniature pore pressure transducers (PPT) were installed into the sample to measure pore water pressure at different locations. A Colbond® CX 1000 band drain with a width of 100 mm and a thickness of 5.3 mm was used in the model tests. To facilitate the pore pressure measurements, the vacuum pressure was applied through the bottom. However, this does make a difference in simulating the real site situation as the hydrostatic pressure in the model test is negligible. Approximately -80 kPa of vacuum loading was applied and kept throughout each model test to simulate the optimum vacuum that can be achieved *in situ*.

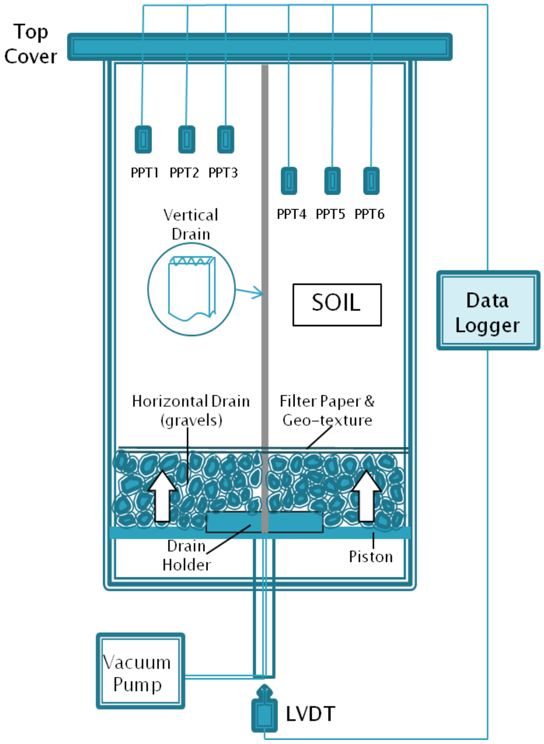

Figure 7. Schematic of model setup

4 COMPARISON OF TESTING RESULTS

4.1 Consolidation Curves

Figure 8 illustrates the percentage of strain versus time curves during consolidation measured by LVDT. Lumpy soil experienced tremendous settlement almost immediately after vacuum loading, yet the rate of consolidation decreased almost to zero after inter-lumpy voids closed up. This observation fits the results of both Casagrande (1949) and Leung (2001). Pre-loading therefore is suggested in backfilling of lumpy soil since settlement happens primarily in its initial phase. On the contrary, homogenous marine clays (MC1 and MC2) showed much slower but relative consistent consolidation rate during the whole test. MC2 has higher consolidation rate than MC1 due to the proportion of sand of the former, which may play a role of drainage during consolidation.

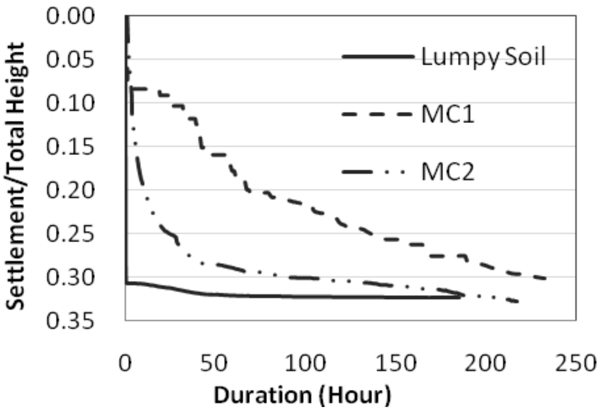

Figure 8. Percent settlement versus time curves

4.2 Pore Water Pressure Distribution

Pore pressure changes were monitored by PPTs throughout the consolidation process. Figure 9 shows pore water pressure (PWP) records of PPT 4, 5 and 6 for lumpy soil as an example.

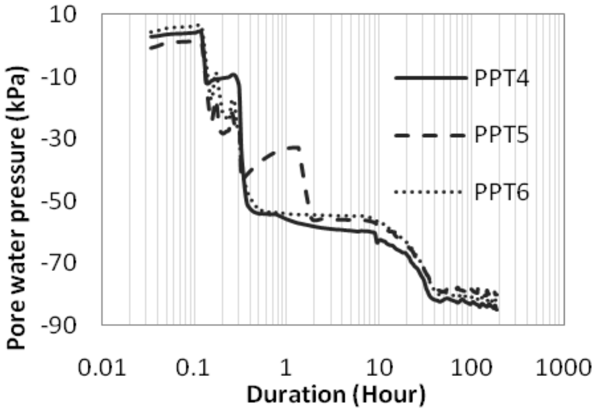

Figure 9. PWP changes during consolidation in Lumpy Soil (PPT 4, 5, 6)

Fluctuations in the pore pressure measurements were observed during the test, as shown in Figure 9. The aame phenomenon was obtained in all the three tests. This is largely due to the fluctuations in the vacuum loading supplied by the vacuum pump. PWPs slightly increasd on occasion. The phenomenon of pore pressure stagnation with continuing settlement could be partially due to the artesian effect. During the consolidation, the soil element near the drain consolidated first, and the stress distribution in the soil could become non-homogeneous because of this. This induced artesian pressure would tend to neutralize the pore pressure dissipation or even elevate the pore pressure in the soil sample.

Figure 10 shows the distributions of excess pore water pressures along the radial direction of the vertical drain at different time intervals. The initial excess pore water pressures at the various locations were normalized to 0 kPa. The measurements by the PPTs contribute to a family of curves called isochrones.

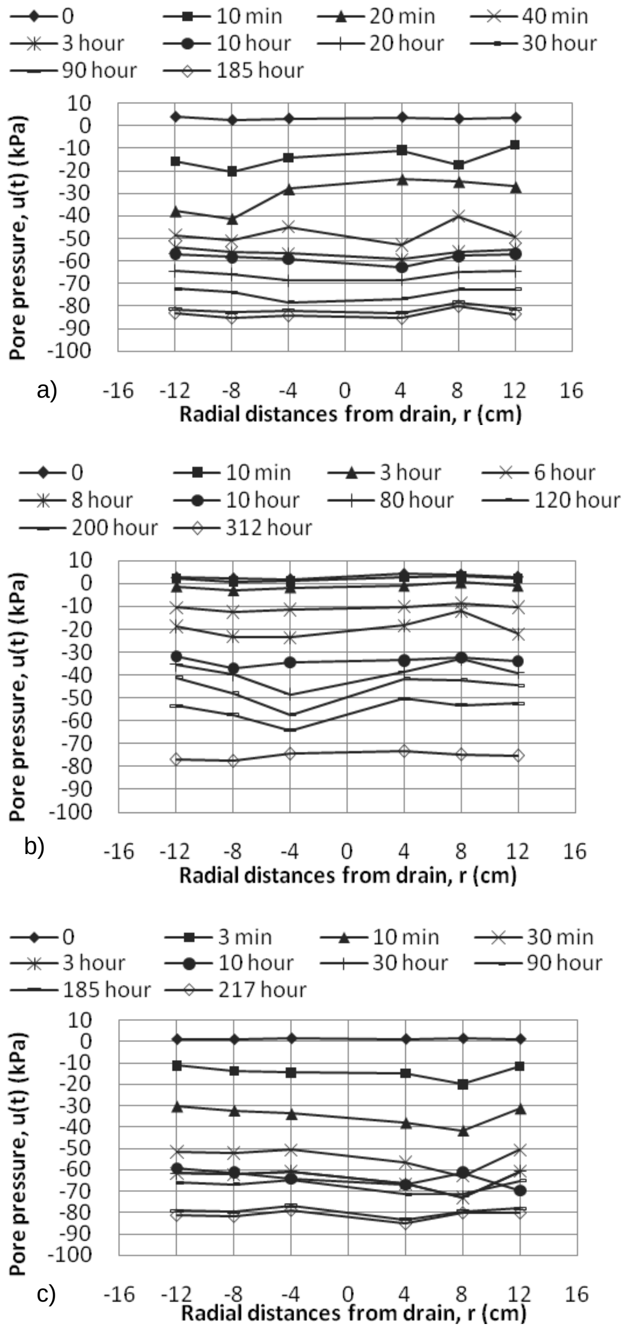

Figure 10. Isochrones of pore water pressure dissipation of a) lumpy soil b) MC1 c) MC2

As shown in Figure 10a), a large reduction of pore water pressure (50 kPa) occurred with 40 min of consolidation, which implied the dissipation of PWP within inter-lumpy voids. On the contrary, dissipation of PWP in homogenous organic clay (MC1) happened much slower, mainly after 10hr of consolidation, as observed in Figure 10b). MC2 (Figure 10c) showed similar dissipation rate as lumpy soil because of the sand content. Another point which should be noticed here is that, in the first 40min, reading of the six PPTs in lumpy soil differentiated much more from each other, compared to MC1 and MC2. This phenomenon may be due to the different PWP dissipation pattern of inter- and intra-lumpy voids: the PPTs that happened to be positioned at inter-lumpy void recorded faster dissipation ratio, while those buried within the lump experienced slower ratio. Such dissipation disappeared after 40min probably because soil became more homogenous along with the inter-lumpy voids closing up.

4.3 Water Content Reduction and Shear Strength Gained

At the end of each test, each sample was extruded from the tank and was cut open along the vertical plane. Remaining inter-lumpy voids can be observed in consolidated lumpy soil sample, as shown in Figure 11.

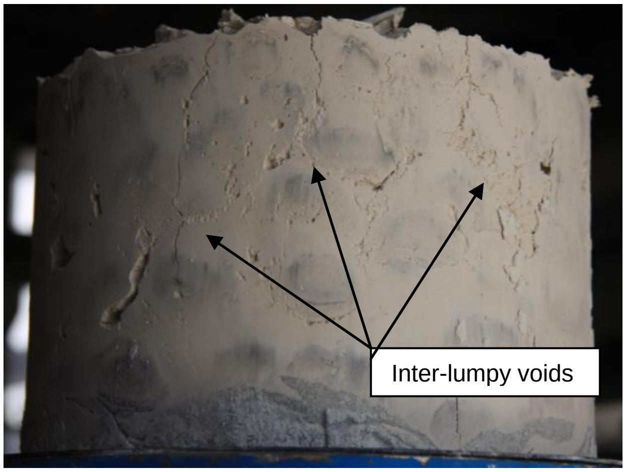

Figure 11. Extruded lumpy clay after consolidation

Water content (w/c) at the tip of each PPT was recorded as shown in Figure 12, taking lumpy soil as an example. As it can be observed in Figure 12, the water content varied with positions, of which the ones closer to the vertical drain were lower than that at the position further away from the drain, which implies the different grade of inter-lumpy voids degradation. This generally fits the observation made by Najser and Pooley (2005) as shown in Figure 3: the inter-lumpy voids of the part near center drain had already been closed up during consolidation, while there might still be some voids left at the outer part of sample that is further away from the drain. Water content was found to be generally higher at 8cm depth than at 12cm depth, because of the vertical drainage layer at the bottom at the tank.

Average water content before and after consolidation, as well as undrained shear stress S_u tested on consolidated samples are shown in Table 2. The fact that final w/c of lumpy soil (38.7%) is lower than initial w/c of clay lump (46.8%) shows that consolidation of intra-lumpy voids (within lumps) did occur after inter-lumpy voids closed up. One can also be observed that lumpy soil experienced more water content reduction during consolidation, and was generally the same level of final water content as MC1 and MC2; however, lower average S_u value was obtained for consolidated lumpy soil. This phenomenon revealed that fractures within soil matrix, which were formed by the inter-lump voids, may perform as shear band in compression test, thus reducing the shear stress.

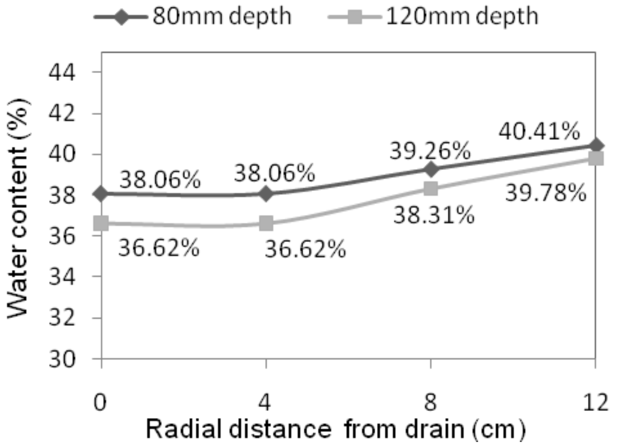

Figure 12. Final water content at different positions within sample (lumpy soil)

Table 2. Water content properties and undrained shear stress of three samples tested

	Avg w/c before test (%)	w/c of soil ball (%)	Avg w/c after test (%)	Avg Su (kPa)
Lumpy	98.2	46.8	38.7	10.3
MC1	89.7	-	35.1	21.5
MC2	72.4	-	27.3	15.5

4.4 Degree of Consolidation

Degree of consolidation of soil versus time can be calculated either by consolidation settlement, or by pore pressure reduction. For determining the average degree of consolidation regarding to settlement, $\bar{U}_s$, Asoka method (1978) was proposed to predict the ultimate settlement, S_{ult}. $\bar{U}_s$ was then computed as the percentage of $S(t)/S_{ult}$, where S(t) is the settlement at any instant of time. Thus, we can expecte that calculated $\bar{U}_s$ should follow the same pattern with the consolidation curves as in Figure 9.

Isochrones of excess pore water pressure as presented in section 4.2 were used to determine the average degree of consolidation regarding to pore water pressure reduction, $\bar{U}_p$, by the formula:

$$\bar{U}_p = \left[1 - \frac{\int u(t)\,dr}{U_i \times D} \right] \times 100\% \qquad [1]$$

where u(t) is excess pore water pressure remaining at any time; *t* is the radial distance; u_i is initial excess pore pressure (0 kPa); and D is the diameter of the consolidation tank (30cm). Applying this equation to the isochrones using the trapezoidal method, $\bar{U}_p$ can be calculated.

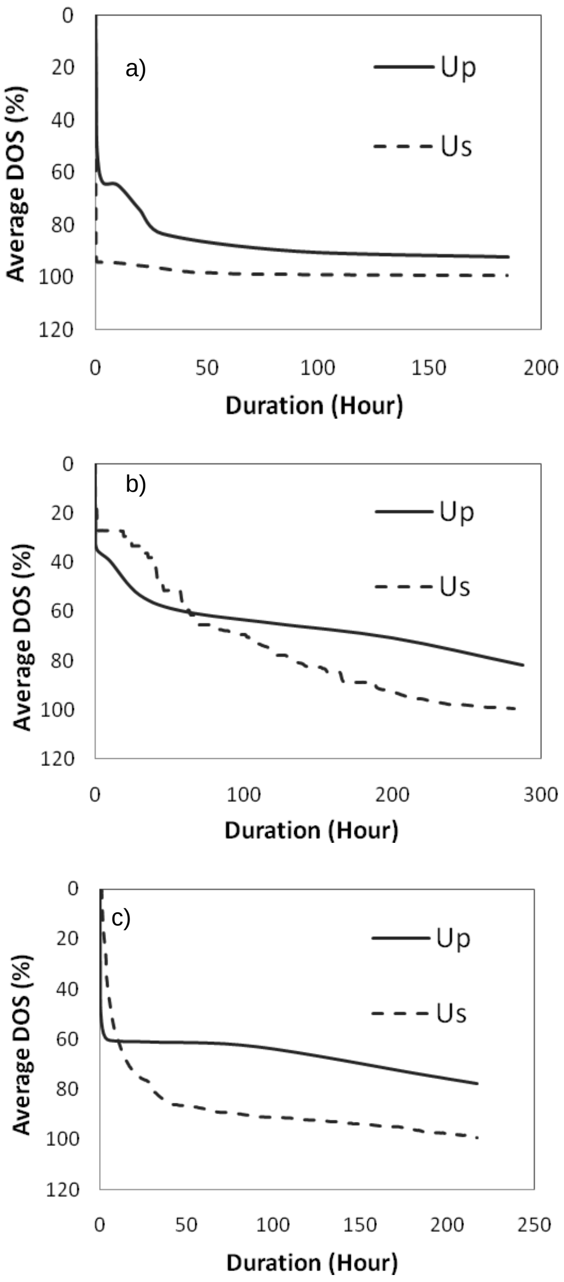

Figure 13. Variation of $\bar{U}_s$ and $\bar{U}_p$ with time of a) lumpy soil b) MC1 and c)MC2

Figure 13 shows degree of consolidation calculated for all three tests. Discrepancies can be observed between $\bar{U}_s$ and $\bar{U}_p$. It can be observed in Figure 13(a) that pore water pressure dissipation lags behind soil settlement at all times in lumpy soil. Heterogeneous property of lumpy soil played an important role in this phenomenon; while for homogenous clay MC1 and MC2, this discrepancy is mainly due to the artesian effect as described in section 4.2. MC2 (Figure 13c) acted in a more similar way to lumpy soil than MC1 (Figure 13b), again due to a higher sand content.

5 CONCLUSIONS

In this study, the consolidation behaviour of lumpy soil and two types of marine clay under vacuum preloading were evaluated using laboratory tests. The pore-water pressure and settlement were monitored during the experiments. The water content reduction and the corresponding undrained shear strength increment were also analysed. Degree of consolidation was calculated based on both settlement and pore water pressure and the results were compared.

Lumpy soil showed large settlement and large pore pressure dissipation at the initial stage of loading. However, the rate of consolidation decreased dramatically after the closing up of inter-lumpy voids. In contrast, homogeneous marine clay experienced slower but consistent rate of consolidation. Consolidated lumpy soil also resulted in slightly lower shear stress than marine clay, maybe because fractures formed by the inter-lump voids may perform as shear band in compression test, thus reducing the shear stress.

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