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Non-uniform consolidation around vertical drains installed in soft ground
Consolidation non-uniforme autour de drains verticaux dans un sol faible

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ABSTRACT: Improvement of soft ground, such as that encountered during construction of roads, railways and airports on near-shore or reclaimed shallow-water areas, is often achieved by the use of preload and vertical drains. Design is usually based on Barron's theory although there is evidence that non-uniform consolidation occurs which cannot be explained by such a simplified approach. This paper presents results from experimental plane-strain tests and numerical simulations devised to establish the mechanism of non-uniform consolidation. The results confirm that vertical compression under global K_o conditions involving non-vertical drainage can result in horizontal displacements during the consolidation process and non-uniform water contents at the end of consolidation. Preliminary numerical simulations show that the soil macro-fabric can have a significant effect on these variations.

RÉSUMÉ: L'amélioration des sols faibles, tels que rencontrés lors de la construction de routes, voies ferrées et aéroports dans des régions côtières ou des zones gagnées sur la mer, est souvent réalsée par une charge de préconsolidation combinée à des drains verticaux. En règle générale la conception se base sur la théorie de Barron, bien qu'il y ait des indications que des consolidations non-uniformes se produisent, qui ne peuvent être ecpliquées par une telle approche simplifiée. Cet article présente des résultats d'essais sous conditions de déformations planes ainsi que des simulations numériques ayant pour but d'établir le méchanisme de consolidation non-uniforme. Les résultats confirment que la compression vertical sous conditions Ko avec drainage non-vertical, peut causer des déplacements horizontaux pendant le processus de consolidation et des teneurs en eau non-uniformes à la fin du processus. Dans un premier temps des simulations numériques indiquent que la structure macroscopique du sol peut avoir une influence significative sur ces variations.

1 INTRODUCTION

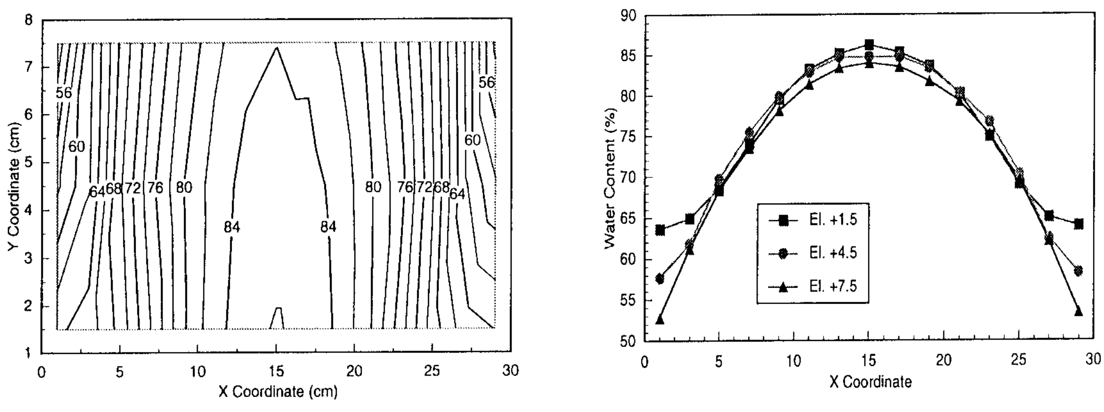
As described by Tanaka (1997), two series of model tests have been performed to study the non-uniform consolidation of a soft clay around a vertical drain. One series involved the consolidation of a clay in a cylindrical consolidometer with a model prefabricated plastic board drain installed in the centre of the slurry prior to consolidation (axi-symmetric case); the other involved the consolidation of a clay slurry in a rectangular tank with drainage material on the end panels (plane-strain case). Tests were performed on slurries with initial water contents varying from 100% to 150% and the maximum consolidation stress in each was 200 kPa applied in two and three increments for the plane-strain and axi-symmetric cases respectively. Although both series of tests are for idealized geometries which do not represent the three-dimensional arrangement of drains installed in practice, they allow an assessment of the likely variation of non-uniformities induced in the ground during the consolidation process. The tests confirm that at the end of the consolidation process there are spatial variations in the water content, and hence other properties, of the clay bed. Although the axi-symmetric case is closer to reality, the interpretation of the results is less straightforward than for plane-strain conditions due to the stiffness and lateral distortion of the drain during the compression of the clay. This results in a complex stress distribution in the clay around the drain which is likely to vary from test to test. Although the test is globally axi-symmetric, the lateral distortion of the central drain results in non axi-symmetric conditions and the problem should be analysed accordingly; clearly this is difficult and would require the drain (or clay) to be modelled with some initial imperfection to initiate deviation from axi-symmetric conditions.

The plane strain tests, although significantly different from the field situation, do have the advantage of being easy to model numerically and the results can be used in developing an understanding of the processes involved. The analyses can also examine the influence of other factors such as friction between the clay and the end panels of the tank. For these reasons, this preliminary study is restricted to numerical simulations of the plane-strain model tests.

2 LABORATORY STUDIES

The clay was consolidated in a rectangular tank 30 cm wide by 8 cm deep; the initial height of the clay was 20 cm and the vertical load was applied through a rigid plate. The two ends of the tank were lined with prefabricated drain material whilst the two sides were transparent acrylic sheets through which the deformations during consolidation could be observed. Coloured noodles were inserted in the clay in contact with the acrylic sheets and the movements recorded by taking video photos which were later used for video analysis. The marine clay was prepared at a water content of approximately 150% and then loaded in two stages, 70 kPa and 200 kPa . After consolidation at the maximum load the test apparatus was dismantled and the water content at a number of points in the clay bed determined.

Figure 1a shows the spatial variation of water contents at the end of consolidation and Figure 1b the horizontal variation of water content at the end of consolidation at three different elevations in the clay bed; near the base (1.5 cm), approximately mid-height (4.5 cm) and near the top (7.5 cm). The spatial variation follows a regular pattern with lower values close to the drains and significantly higher values in the centre. There are differences in the distributions of water content at the different elevations and these could be due to three-dimensional consolidation effects or due to friction between the clay and the drains. The relatively small variation with depth at the centre of



(a) (b)

Figure 1. Spatial and horizontal variations of final water content (experimental)

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the clay suggests that wall friction does not alter the nature of the non-uniformity induced in the clay bed. This can be checked in the numerical simulations by assuming either that the drain is completely frictionless or by assigning an angle of friction (δ) to the clay/drain interface.

3 NUMERICAL SIMULATIONS

3.1 *Material properties and problem idealization*

The clay beds in the model tests were prepared from a clay slurry prepared from a marine clay taken from the seabed of Kobe Port. The clay has a liquid limit of 97%, a plastic limit of 40% and specific gravity of 2.688. The compression and consolidation characteristics of the clay were measured in oedometer tests performed on the clay slurry (Tanaka 1997) and, based on these test data and the index values, the soil parameters were estimated. The simulations are based on the modified Cam clay soil model and the soil parameters and initial conditions used in the analyses are shown in Table 1.

Table 1. Soil parameters, initial conditions and interface element characteristics

Parameter	Value
slope of the normal consolidation line (λ)	0.3331
slope of the swelling/recompression line (κ)	0.0999
slope of the critical state line (M)	0.939
permeability of clay (k_x & k_y)	2.5×10^{-9} m/s
Poisson's ratio (ν')	0.3
void ratio on critical state line at unit stress	3.4492
specific gravity of soil particles (G_s)	2.688
initial water content	150%
initial bulk unit weight	13.10 kN/m^3
initial specific volume (V)	5.032
initial isotropic stress (p')	0.2275 kPa
interface element normal stiffness (k_n)	5.9×10^4 kPa
interface element shear stiffness (k_s)	1×10^3 kPa
interface element shear residual stiffness ($k_{s\ res}$)	100 kPa
interface element nominal thickness (t)	0.0025 m

The simulations were performed using the SAGE-CRISP finite element package and a series of tests were carried out to compare the performance of several meshes; all used quadrilateral consolidation elements to represent the 30 cm wide by 20 cm high cross-section of the clay used in the laboratory tests. Two of the meshes modelled the whole cross-section (one with elements spanning the centre-line, the other with node points along the centre-line) whilst the third took advantage of symmetry and considered just half of the problem. Comparable results were obtained with all meshes and that representing half the problem was used in subsequent analyses; in these the clay bed was represented by a mesh 16 elements wide by 10 elements high with another row of elements to represent the loading platen. The vertical boundary representing the centre-line was modelled as frictionless whilst the outer boundary was modelled either as frictionless or with interface elements to investigate the effect of friction between the clay and the drain. The drainage of the side drains was modelled by setting the nodal pore water pressure values along the outer boundary to zero.

Previous experience indicates that numerical problems can occur when analysing consolidation problems if the initial time step is too small; for these simulations the guidelines of Abid & Pyrah (1988) were used. The initial time step was set to $l^2/(6c_v)$ where l is the width of the element next to the free draining boundary. Although the guidelines were devised for one-dimensional conditions no significant instability problems were encountered in the two-dimensional analyses.

Slip (interface) elements were used to model behaviour between the side-drain and the marine clay and were assigned normal and shear stiffnesses to match the clay. It is also necessary to assign residual values of stiffness; these are used once a limiting condition is reached in the element e.g. slip occurs. The normal residual stiffness was given a relatively high value so that element overlap would not occur. This was felt to be most realistic as in the laboratory test the sample was restrained in the lateral direction at the boundary. The shear residual stiffness was given a value one tenth that of the initial value. In the analyses to date only a limited number of frictional boundary conditions have been examined; completely frictionless and $\delta = 10^{o}$.

The model tests used initially homogeneous clay slurry although it is recognised that many natural deposits have considerable inhomogeneities such as laminations of coarser material within the clay. Such inhomogeneities are often referred to as fabric (or macro-fabric) and for simplicity this generic term will be used in this paper. To examine the possible effects of fabric an analysis was performed in which the row of elements just above mid-height of the simulated clay bed was assigned a higher permeability (400 times that of the clay) to represent a layer of coarser material. This layer was modelled using modified Cam clay, with all other parameters the same as the clay, as the intention of the analysis was to examine the effect of fabric on the drainage conditions not to introduce a material with different deformation characteristics.

A permeability of 1×10^{-7} m/s for the layer of highly permeable soil, compared to 2.5×10^{-9} m/s for the clay, was selected as this is sufficiently different to represent a free-draining layer within the clay but not too dissimilar to cause problems with the selection of a suitable initial time-step for the application of the porewater pressure fixity.

3.2 *Results*

As indicated above, results of the FE analyses for the frictionless case using three different meshes produced almost identical results for displacements and final water content distributions. The horizontal variations of water content at mid-height are shown in Figure 2 and these can be compared to the experimental results in Figure 1b. The significant non-uniformity induced in the experiments is predicted by the analyses and whereas in the experiments the non-uniformities may be

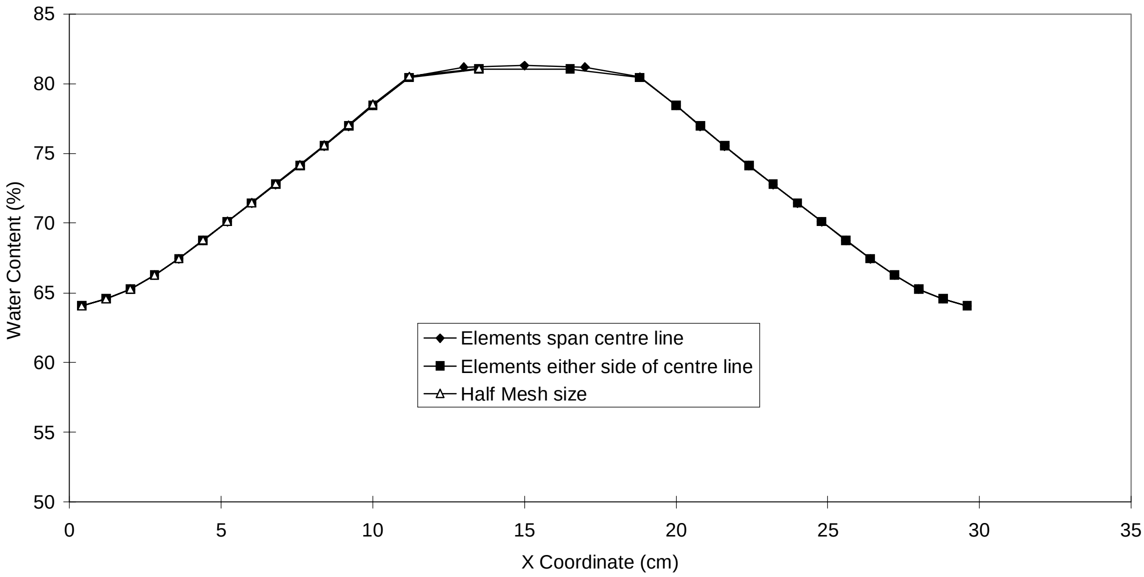

Figure 2. Horizontal variations of water content at mid-height of clay (simulations)

attributed to the three-dimensional consolidation process and/or friction at the ends of the tank, the predictions show that significant non-uniformities are induced by the consolidation process alone. In the figures the x coordinate is measured from the edge of the tank. To examine the effects of side friction on the induced non-uniformities, some analyses were performed with non-zero values of wall friction. Although a detailed investigation has not been carried out, the indications are that the likely effect of wall friction on the induced non-uniformity is slight.

The predicted horizontal and vertical displacements at mid-height in the clay bed are shown for three locations in Figure 3; near the centre (x=12cm), mid-way between the centre and the side boundary (x=6.4cm) and close to the edge (x=0.8cm) of the clay. Although the horizontal and vertical scales are different it is clear that the consolidation is not one-dimensional. Close to the edge points in the soil initially move towards the drain and then mainly downwards with a horizontal component back towards the centre; thus, the soil adjacent to the drain is initially subjected to consolidation with compressive lateral strain followed by vertical compressive strain. For the clay in the centre of the tank the vertical compression (denoted by downward displacement) is accom-panied by initial lateral tensile strains (outward horizontal displacements) followed by lateral compressive strains. The simulations indicate that the consolidation process is accompanied by com-

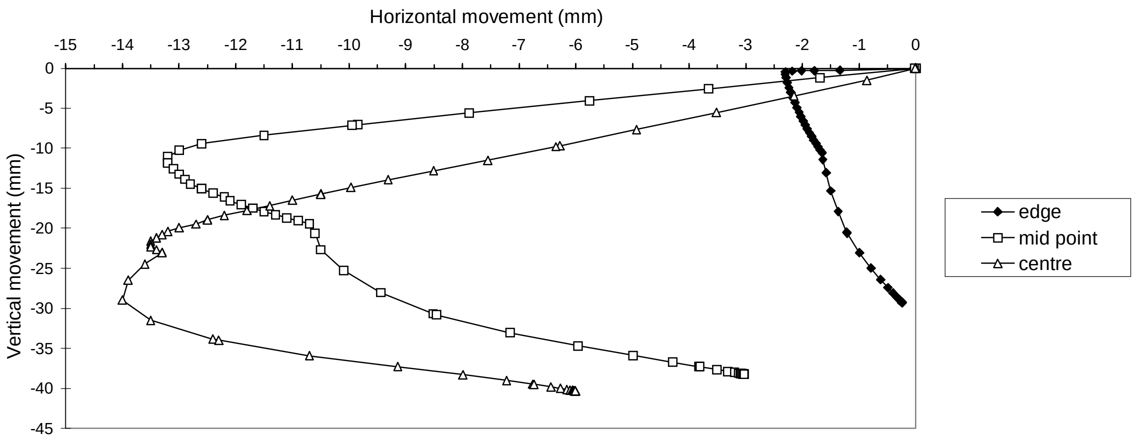

Figure 3. Horizontal and vertical displacements at mid-height of clay (simulations)

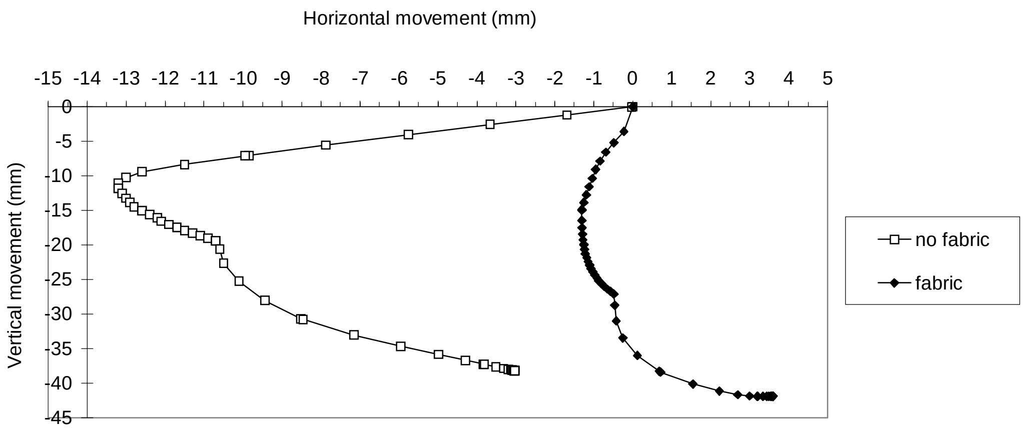

Figure 4. Effect of "fabric" on horizontal and vertical displacements at mid-height of clay (simulations)

plex displacement patterns as observed in the laboratory which confirm the conclusions of Al Tabaa & Wood (1991) that the clay around a vertical drain cannot be uniformly consolidated. As the clay close to the side-drains consolidates it becomes stiffer and attracts load away from the centre where a soft centre remains because a high percentage of the applied load is carried by the hardened, consolidated soil at the edges. More detailed comparisons between the laboratory tests and the numerical simulations are currently being carried out.

The above results are for clay beds prepared from an initially uniform slurry although in practice the soil will possess "fabric". The horizontal and vertical displacements at the mid-point and at mid-height of a clay bed in which there is a horizontal layer of more permeable soil at its centre are shown in Figure 4 together with those for an initially homogeneous clay. The types of movement are significantly different and, whilst horizontal movements do occur, suggest that the consolidation process is closer to one-dimensional conditions; this results in a more uniform distribution of water content at the end of consolidation (Fig. 5).

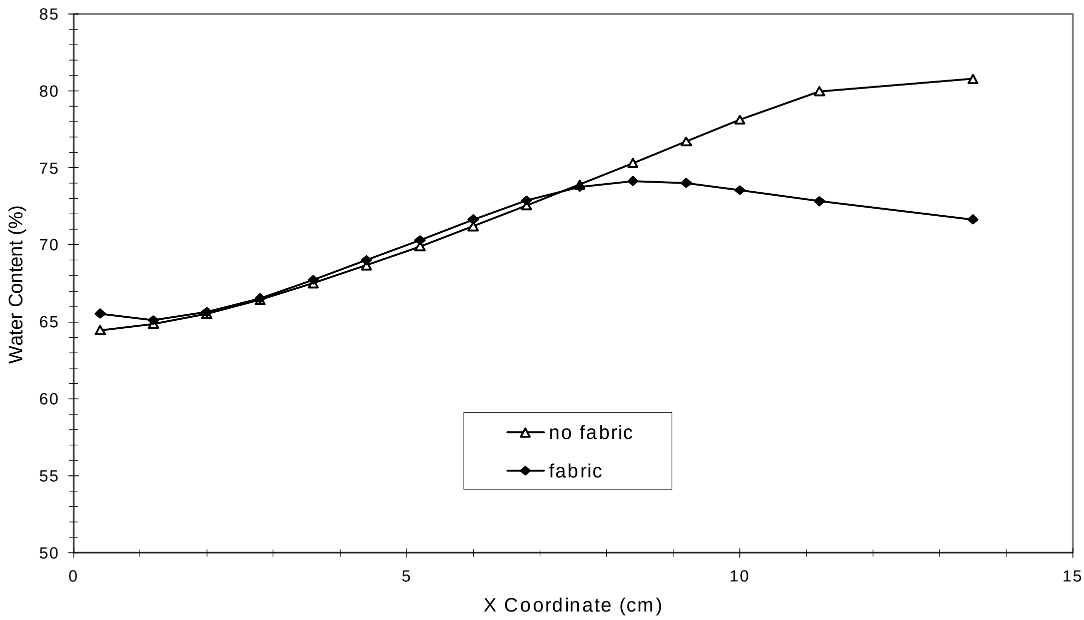

Figure 5. Effect of "fabric" on horizontal variation of water content at mid-height of clay (simulations)

4 CONCLUSIONS

This preliminary investigation has confirmed that the use of vertical drains to accelerate the consolidation of soft clays leads to non-uniform conditions at the end of the consolidation process. This is due to the complex process of three-dimensional consolidation.

If laminations or other fabric features are present in the soil this will alter the way the excess porewater pressure is dissipated. This affects not only the rate at which consolidation occurs but the pattern of consolidation throughout the clay; this will affect the extent of the induced non-uniformities. In the particular case of horizontal laminations the effect is to reduce the non-uniformities caused by the introduction of vertical drains; the extent of this reduction will be dependent on the spacing and continuity of the fabric.

Although not presented in this paper, laboratory tests show that the overall spatial variation in water content for globally axi-symmetric conditions is less than that observed for plane-strain conditions. It should be noted, however, that for axi-symmetric test conditions, significant local variations in water content are observed and these can be attributed to stress concentrations caused by distortion of the drain. These distortions, and resulting variations in water content, are non-axi-symmetric.

It is recommended, therefore, that further work into the non-uniform consolidation around vertical drains takes account of three-dimensional consolidation effects, the effects of soil macro-fabric and the lateral distortion of the drain creating non-axi-symmetric conditions.

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