EXAMINATION OF SWELLING SOIL STRUCTURE FOLLOWING LIQUID INFILTRATION UNDER CONTROLLED BOUNDARY CONDITIONS

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ABSTRACT

Further understanding of large-scale soil behaviour is gained by studying mechanisms occurring on the microscopic scale. During liquid infiltration in a swelling clay, alterations to the pore-size distribution are anticipated due to changes in water content and density. In a new laboratory test radial flow conditions are applied to unsaturated swelling clay-sand specimens in the triaxial cell (Siemens and Blatz 2006a). Boundary conditions imposed during liquid infiltration include a flexible boundary under which specimens are allowed to swell while cell pressure is increased along a controlled volume strain – mean stress relationship. Following tests specimens are divided into radial sections and Mercury Intrusion Porosimetry (MIP) tests and Scanning Electron Microscopy (SEM) photographs are performed. Final pore-size distributions and clay mineralogical changes are compared to initial conditions. Results show that internal pore size alterations are directly related to boundary conditions imposed during liquid infiltration. Initial and final pore-size distributions will be used for calibration and validation of a capillary tube model for two-phase flow.

RÉSUMÉ

Une compréhension accrue du comportement des sols à pleine échelle est acquise par l’étude des mécanismes agissants à l’échelle microscopique. Durant l’infiltration de liquide dans une argile gonflante, des altérations à la répartition volumétrique des pores sont anticipées en raison des changements de la teneur en eau et de la densité. À l’aide d’un nouvel essai de laboratoire, des conditions d’écoulement radial sont appliquées à des spécimens d’argile sableuse gonflante non-saturés dans une cellule triaxiale (Siemens et Blatz 2006a). Les conditions limites imposées durant l’infiltration du liquide incluent une frontière flexible sous laquelle les spécimens peuvent gonfler pendant que la pression cellulaire est augmentée selon un relation déformation volumique-contrainte moyenne, contrôlée. À la suite des essais, les spécimens sont divisés en sections radiales et des essais de porosimétrie par pénétration de mercure et des photographies par microscopie à balayage d’électron sont effectués. Les répartitions volumétriques des pores finales et les modifications à la minéralogie des argiles sont comparées aux conditions initiales. Les résultats montrent que les altérations internes des pores sont directement liées aux conditions limites imposée durant l’infiltration. Les répartitions volumétriques des pores initiales et finales seront utilisées pour le calibrage d’un modèle de tube capillaire d’écoulement diphasique.

1. INTRODUCTION

Clay-based materials are often employed in engineered barriers due to their swelling nature. These natural barrier materials are generally placed in an unsaturated state during compaction. Over their lifetime, the barriers are subjected to periods of drying and wetting. During drying, the soil will shrink, which causes cracking to develop, but during wetting, the material will swell with increasing water content which may close or ‘heal’ any fractures.

In both swelling and non-swelling compacted clay-sand materials, multi-modal pore size distributions have previously been observed (Garcia-Bengochea et al. 1979, Juang and Holtz 1986). A schematic and plot of a bimodal distribution is illustrated in Figure 1 and Figure 2. The bimodal pore size distribution is due to hydration of the molecules and the compaction energy used during specimen preparation. During hydration, highly plastic clays form peds or groups of clay molecules (Figure 1). Pores within individual peds form the micro-porosity (also known as intra ped pores). Micro-porosity properties, including size and particle distribution, are a function of the water content during preparation (Wan et al. 1990). The size of the micro-porosity is on the same order as that of clay particles (Young and Warkentin 1975, Mitchell 1993, Hillel 1980). Forming water content has also been found to alter the water retention curve (WRC, Blatz et al. 2002) which is likely due to the change in ped properties. During compaction the macro-porosity is formed as a function of the energy used. Macro-porosity (also known as inter ped pores) comprises the space between peds (aggregation of clay minerals) and its distribution is a function of the compaction effort (Wan et al. 1990).

Mercury Intrusion Porosimetry (MIP) and Scanning Electron Microscopy (SEM) testing was completed on a swelling soil. One as-compacted specimen and three (3) specimens subjected to liquid infiltration under controlled boundary conditions were tested. Results show the evolution of porosity associated with the boundary conditions applied during infiltration and demonstrate how the pore size distribution can be used to calibrate and validate a capillary tube model for swelling soil.
2. INFILTRATION SPECIMENS

Test specimens, known as buffer sand buffer (BSB), were prepared in a standard manner as described in Siemens (2006). They were 50:50 (by weight) mixtures of clay and sand. The clay was a Na-bentonite mined in the state of Wyoming with $w_L = 555\%$ and $w_P = 43\%$ (Siemens 2006). Wyoming bentonite is composed of 90% montmorillonite with the remaining 10% being feldspars and quartz (Dixon et al. 2002a). The sand was a well-graded angular silica sand that was prepared as described in Dixon et al. (1994). Equal parts of clay and sand were mixed to 19.4% gravimetric water content and compacted to 1.67 Mg/m$^3$ to give an initial degree of saturation of approximately 85%.

After compaction, specimens were installed in a modified triaxial apparatus described by Siemens and Blatz (2006a). Following equilibration they were subjected to an isotropic compression phase and then radial infiltration under controlled boundary conditions. Boundary conditions included constant volume (CV), constant mean stress (CMS), and constant stiffness (CS) which is a spring-type condition that includes both increase in volume and mean stress at a specified rate. Constant stiffness boundary conditions were applied along a slope of mean stress / volume strain. The two slopes applied were 25 and 75 kPa / % volume strain. Infiltration continued until water inflow, suction, mean stress, and volume equilibrated to a specified target condition. Detailed test results are provided in Siemens and Blatz (2006a).

3. MIP AND SEM SPECIMEN PREPARATION

Triaxial specimens were removed from the apparatus following infiltration testing and their spatial distributions of gravimetric water content and bulk density were measured to calculate dry density and degree of saturation. Specimens were sliced horizontally along compacted layers and then divided into radial sections using a circular cutter. A schematic of radial section sizes and names are shown in Figure 3. The outer two sections were divided into two measurements each of gravimetric water content and wax density while the center section was divided for one measurement of each. Bulk density was measured by determining the mass of the section and then surrounding it with wax. The total mass of soil and wax was then measured. Finally the buoyancy force of the combined soil and wax was measured to determine its volume. The volume of the wax was subtracted since its density was known and then the bulk density was calculated directly.

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Figure 4. SEM photographs of as-compacted and infiltration specimens.

Figure 5. MIP results from as-compacted and infiltration specimens.
After bulk density measurements were completed radial sections were prepared for MIP and SEM testing. The wax was carefully removed and specimens were placed on a tray inside a desiccator containing pure sulphuric acid. The acid created a low relative humidity environment inside the air space of the desiccator that dried the MIP and SEM specimens. Specimens were dried in the desiccator until constant mass was achieved. Both the MIP and SEM test apparatuses used in this research required dried specimens. Previous MIP tests (Wan 1996) on a similar material used specimens that had been prepared in the same manner. The same method of preparation was selected to ensure results would comparable with previous work.

4. SEM AND MIP RESULTS

Results from selected SEM and MIP testing are displayed in Figure 4 and Figure 5. One SEM photograph from the as-compacted and three infiltration specimens are shown in Figure 4. MIP results from the three (3) radial sections are plotted in Figure 5.

4.1 SEM Results

SEM photographs are all shown at similar magnification (2000x) and a scale is shown in the bottom left corner of each photo. The four photographs were taken to identify the macro-pore mode of the specimens. The as-compacted specimen (Figure 4a) shows a large amount of pores that are on the 5-9 µm range. The infiltration specimens (Figure 4b-d) all have less macro-pores evident. Decrease in macro-pore size was observed in all three (3) SEM photographs of infiltration specimens (Figure 4b-d). The 1000 kPa specimens (Figure 4c and d) show significantly less macro-sized pores than the as-compacted and 250 kPa specimens. This was the result of higher mean stresses applied before as well as ped expansion during infiltration. The CS75 had greater increase in mean stress during infiltration compared with the CS25 test, which allowed less bulk expansion of the specimen. This is reflected in the photographs as smaller pores in Figure 4c compared with Figure 4d.

4.2 MIP Results

Pore size distributions from as-compacted and infiltration specimens agree with previous results and expected trends. The as-compacted specimen, Figure 5a, has a bimodal distribution with similar located modes as previously measured (Figure 2). The perimeter section has a higher incremental intrusion distribution compared to the middle and center specimens but with the same modes. The tails at the upper end of the diameter axis which show increases are interpreted as being due to disturbance either during preparation or drying and not representative of actual pore space during tests. On the lower magnification SEM photos that were not included in this paper, cracks were observed around sand particles. The bentonite clay likely shrank away from the sand during drying and resulted in anomalous ‘tails’ at the upper end of the pore size distributions.

Comparing the infiltration specimens to the as-compacted shows decrease in macro-porosity for the three specimens, especially in pores greater than 10 µm. In the micro-pore sizes, a small shift to the left is observed in the infiltration specimens compared to the as-compacted.

Internal changes in pore size distribution are evident along the flow path in the infiltration specimens. The 250 kPa specimen (Figure 5b) has shift to the right in micro-porosity and a shift to the left in macro-porosity from the perimeter to the center. For the 1000 kPa specimens, little change in micro-porosity is observed from perimeter to the center. Conversely, the macro-porosity is least at the perimeter increases towards the center of the specimens.

5. DISCUSSION AND INTERPRETATION

5.1 Change in Pore Size Distribution

Triaxial specimens were subjected to isotropic compression followed by radial infiltration under controlled boundary conditions with water pressure applied at the perimeter. Isotropic compression resulted mainly in collapse of the macro-porosity (Wan et al. 1996, Delage et al. 1998, Cui et al. 2001), while infiltration caused clay ped expansion.

During isotropic compression, macro-pore size reduction is expected to be greater in the higher pressure specimens (1000 kPa). Since the outside of the specimen had access to water throughout infiltration it is expected to experience the greatest ped expansion, which would result in the greatest decrease in macro-porosity. The two (2) 1000 kPa specimens show this behaviour with less macro-porosity compared to the 250 kPa and as-compacted specimens but also a macro-porosity gradient from perimeter to center. Macro-porosity is the least at the perimeter and greater in the center and middle sections in both 1000 kPa specimens (Figure 4 and Figure 5).

5.2 Evidence for Decreasing Conductivity

In soils with bimodal pore size distributions, water transfer is generally taken to occur through the macro-pores while the micro-pores contribute to swelling. Therefore, changes to the macro-porosity will effect the interpreted hydraulic conductivity. Siemens and Blatz (2006b) presented a drained apparatus and hydraulic conductivities for this same material at different void ratios (porosities). The results showed an increase in hydraulic conductivity associated with increasing void ratio. Siemens (2006) showed that the pore size distribution will govern water flow in a capillary tube at small sizes. A simplified example is given in Figure 6. The figure plots flow versus time plotted on a logarithmic axis for two cases that have equivalent flow area. The
first case is a single tube with 14 µm diameter and the second has 100 tubes each with 1.4 µm diameter. Despite having the same flow area the second case shows a two order of magnitude increase in time to achieve the same flow amount. The cause is the reduced pore size that causes greater resistance to flow.

Previous laboratory investigations (Cui et al. 2001, Hoffman et al. 2006) and modelling attempts (Thomas et al. 2003) have proposed decreasing hydraulic conductivity with increasing water content or saturation. They proposed that this caused a decrease in macro-porosity. This MIP and SEM testing gives provide measurements that support interpretation of the flow mechanism occurring at the microscale.

![Figure 6. Equivalent area flow comparison for one (1) large tube and one hundred small tubes (after Siemens et al. 2006).](image)

6. CONCLUSIONS

MIP and SEM testing on a swelling clay is presented. Tests from liquid infiltration specimens and a baseline case were shown and compared. The results were interpreted in terms of the initial and boundary conditions applied during infiltration. Results and interpretation of these tests will be used to calibrate and validate a capillary tube model for swelling clay soils (Siemens et al. 2006).

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REFERENCES


