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A micro-mechanical approach to swelling behavior of unsaturated expansive clays under controlled drainage conditions

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The focus of this work is to elucidate the effect of drainage conditions on the swelling behavior of unsaturated expansive clay soils using a new drainage controlled uniaxial swelling (DCUS) cell developed by the authors. The researc`h would aim at identification of the complicated micro-structures and distinguishing the mechanisms for the micro deferred alteration phenomena (the alteration of the swelling media by the end of the swelling process) of the porous swelling media, by swelling under K_0 constraint, constant volume condition using scanning electron microscopy (SEM) technique taking into account the influence of drainage condition as the remarkable environmental factor. It shall be noted that the micro deferred alteration concerns the phenomena in which the swelling media would be altered (in particle's arrangement and size) in micro-scale, by the end of the swelling process and not during the swelling process. Three types of clay have been evaluated of wide range of plasticities. Results demonstrate the promotion of swelling pressure for specimens compacted statically at optimum moisture level and below the optimum value, as the drainage condition converts to multilateral drainage. Furthermore, irrespective of the type of clay, the sensitivity of swelling pressure value to the drainage conditions increases as the initial dry unit weight increases.

1. Introduction

Swelling porous media are ubiquitous in almost all aspects of life. By the exposure of swelling soils to free polar fluids (like water), induced stresses can be very troublesome in foundations (Moyne and Murad, 2003). Structures founded on expansive soil formations, due to the considerable volume changes of expansive soils upon inundation, are subject to damage ranging from minor cracking of pavements or interior finishes in buildings to irreparable displacements of footings and superstructure elements (Al-Shamrani and Dhowian, 2003). Total and differential volume changes in expansive soils result in considerable distresses and severe damages to overlying structures, particularly to low-rise buildings and buried lifelines (Erguler and Ulusay, 2003). Unsaturated expansive clays are however used for beneficial purposes also. Containment of contaminants is an integral part of environmental protection strategy and unsaturated expansive clays are extensively used for engineered clay barriers and as buffer materials for waste disposal (Sharma, 1998). This application of expansive soils is due to the possession of a remarkable swelling due to water intrusion and therefore restriction of the water and contaminants migration through them. Compacted bentonites for an instance, play a critical role in various waste isolation scenarios and in barriers for commercial land fills (Moyne and Murad, 2003).

The origin of the swelling effect of expansive soils has been widely studied by many researchers, in the effort to reach a fundamental approach to relate swelling potential to basic particle–water–cation interactions. These approaches are based on the net negative total charge on the surface of montmorillonite particles, the Poisson–Boltzmann (PB) Theory and the Gouy–Chapman Diffusion Double-Layer (DDL) Theory. However, they are pure microscopic theories derived from theory and/or laboratory tests. Upscaling methods from microscopic theory to macroscopic effects are very important especially for real-world simulation (Xie et al., 2003).

The problem of clay expansion on moisture imbibition can be considered under various conditions according to the way the water flows into the porous specimen media. The preferential movement of aqueous and non-aqueous liquids or other pollutants, has become a concern for scientists. The problem of preferential flow can be defined as “all phenomena where water and solutes move along certain pathways, while bypassing a fraction of the porous matrix”. Preferential flow is probably the most frustrating process in terms of hampering accurate predictions of contaminant transport in soils and fractured rocks. The presence of macro pores and other structural features, development of flow instabilities caused by profile heterogeneities, and funnelling of flow due to the presence of sloping soil layers that redirect downward water flow are probably the most important causes of

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preferential flow (Šimůnek et al., 2003). In the mean time, the flow pattern in conventional oedometers is limited to the vertical direction only.

Besides, as many environmental studies require consideration of real soil behavior approaches, one may consider soil as a heterogeneous porous media. Heterogeneity, potentially may lead to non uniform distribution of moisture content over the soil specimen during saturation process. Moisture content disparity within the specimen volume may be naturally intensified due to the uniaxial vertical drainage direction in conventional oedometers. On the other hand, typically the flow of water and solute fluxes through heterogeneous porous media is known to be three dimensional (Šimůnek et al., 2003). Additionally, for most soft clay deposits, as horizontal permeability is typically larger than vertical permeability, horizontal drainage often predominates (Indraratna et al., 2005). In practice, the fact has made contractors to install not only vertical, but also horizontal moisture barriers to protect the foundations in Colorado state. Thus, normal gardening can occur outside the barriers and not inside the barriers (Nelson and Miller, 1992). Three dimensional flow into the specimen volume may consequently faint the moisture content disparity, and cause a promotion in swelling pressure, which may not be envisaged by designers. It shall be noted that unlike the bearing capacity of saturated soil, the bearing capacity of unsaturated expansive soil is not a constant and it varies with water content and the swelling potential. Considering the intimate reliance of the foundation bearing capacity upon the swelling potential, neglecting the accurate swelling potential by the designers is harmful for sure.

Despite the importance of the drainage condition consideration, the problem of expansion with horizontal drainage is not thoroughly studied. To predict the effect of drainage condition on the swelling behavior in a reliable way, a new drainage controlled uniaxial swelling cell (DCUS) was designed and fabricated. DCUS cell, when integrated with a closed loop mechanical testing load frame, can be applied to measure the swelling pressure value at a predetermined drainage path. Whereas the drainage paths are isolated, swelling tests can be performed under several predetermined drainage conditions. Possibilities to consider effects of soil heterogeneity and preferential flow, least exposure of specimen to exterior, availability of applying a particular progressive specimen remoulding technique, handy assemblage or disassemblage of the cell parts, and ease of removal of specimens for micro analytical testings could be nominated as the main advantages of the new cell (Assadi, 2007).

However, in the present study, a new approach based on micro-mechanics is developed for explaining the swelling characteristics regarding drainage conditions. Micro-mechanics deals with the relationship between external stresses and strains, and average internal forces and displacements (Sitharam and Nimbkar, 2000). Micro-mechanics is the study of composite material (clay–sand–pore fluid) behavior wherein the interaction between the different constituent materials is examined on a microscopic scale (Tien et al., 2004). Microscopy, links the material characterisation and engineering behavior so that idiosyncrasies in macroscopic behavior could be related to micro-structural features. By developing micro-behavior complementary models corresponding to the main classes of macro-behavior, one could understand the influences of particle morphology, fabric and grain strength (Bolton and Cheng, 2001). In another words, It is essential to obtain new data streams of micro-structural information to complement the macro-behavior of soils. In micro-behavior complementary models, mechanical behavior is described starting from grain scale level, resulting in a development of constitutive theories for behavior of materials at macro level or global response through a process of statistical integration at discrete and micro levels.

To evaluate the drainage conditions effect on swelling behavior of unsaturated expansive soils, eighteen standard constant volume swell tests (ASTM D-4546) were developed on three clayey soils of wide range of plasticities. Furthermore, control tests were accomplished to check the reproducibility.

2. Materials

2.1. Description of the site and its geological history

The natural soil used as the basis of this study is an active high plasticity natural clay obtained from the semi-arid Kochireh mountainous village which is located 16 km from the village of NesaBala, as an index point, (latitude 36°4′28″, longitude 51°20′57″), and 27 km from Taleqan city, of the central province of Tehran. The average annual precipitation is about 250 to 400 mm. Moreover, the village is located at 2405 m above the sea level, by the side of Kochirehrood river, on the south slopes of Taleqan heights.

The climate is considered to be semi-arid and periods of intense rainfalls are followed by long periods of drought. This pattern of wet and dry cycles results in periods of extensive near-surface drying and desiccation clod formation.

The geology of this area consists of Elika formation of the Triassic ages, Ruteh formation of the Permian ages, and Karaj tuffiet due to the observed green veils. Elika formation includes thick bedded to massive lime stones and massive dolomites, besides presence of Fusulina lime stones, Dolomitic lime stones and Cherts may be attributed to the Ruteh formation. The origin of this expansive soil may be related to the weathered sedimentary rocks as the parent materials which contain montmorillonite as a constituent. Furthermore, The moderate alkaline environment ($pH>8.75$) and lack of leaching may favour the formation of montmorillonite minerals.

This site was chosen for this research since it has been studied and documented in previous researches (Ashayeri, 2003; Mirzababae and Yasrobi, 2007). However, none of the previous studies were related to the assessment of the effect of drainage condition on the swelling behavior of clay. Presence of sodium montmorillonite in white to tint green clods, had been reported (Mirzababae and Yasrobi, 2007). As well, presence of amounts of Mica, Feldspar, Carbonate and Quartz were manifested (Ashayeri, 2003). Presence of montmorillonite may be responsible for the observed swelling behavior.

The clay at this site has been diagnosed as extremely problematic due to its swelling characteristics, mainly because of its high smectite content. Such high affinity of this clay to water led to its selection.

2.2. Testing material preparation

The disturbed expansive soil was collected by open excavation, from a depth of 0.5 m from natural ground level, at the location site of Kochireh village, placed in plastic bags, and transported to soil mechanics laboratory of Tarbiat Modares university. It shall be mentioned here that care is taken to obtain soils of a wide range of plasticity while selecting them. The clods were crumbled, air-dried and pulverized repeatedly until all soil aggregations were reduced to minus 2 mm sieve size. The pulverized soil was kept in sealed buckets all along the research period in laboratory with temperature held constant at 23 °C. Since soil plasticity index is one of the crucial factors which affects the swelling behavior, three soil groups were prepared by mixing different bag contents in a trial and error manner, in which two of them were of the same genetic, varied plasticity and the last group, a mixed material with 10% of commercial bentonite. Mixture of bentonite and natural clay were prepared in the oven-dried condition. The soil groups are designated through this paper as G_1, G_2, and G_3 (Assadi and Yasrobi, 2007).

2.3. Properties

The physicochemical conditions of clay pore water directly affect many engineering properties of a soil such as swelling behavior and