Inclusion Effect on Heterogeneity of Excess Pore Water Pressure Distribution in Composite Clay

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SUMMARY:
A series of tests and also numerical analyses were conducted to explore the mechanical behaviour of a mixture of coarse gravel-size particles floating in a matrix of clay. The research is a step forward in an on-going investigation on behaviour of composite clay, which is used as the core material of some large embankment dams all over the world. This paper focuses on a predominant feature of the composite soil behaviour: increase of non-deformable solid inclusions in a mixture leads to formation of heterogeneity of stress field, excess pore water pressure and strain distribution along the specimens. By the aid of numerical analyses, it is clarified through the paper that in addition to loading details, position of inclusions relative to loading direction also affects heterogeneity of stress/strain and excess pore water pressure distribution through the mixture. Despite the former, the latter redistributes with a rate proportional to material hydraulic conductivity, based on the analyses results described in the paper.

Keywords: composite soil, mixed material, heterogeneity, cyclic triaxial, finite element analysis

1. INTRODUCTION

Natural fine-grained soils normally contain a significant proportion of larger bulky particles. There are also slopes made of glacial tills, mudflows or debris flows, consisting of a mixture of large particles and a soft matrix of fines. In such mixtures, which have been used as impervious material for the core of embankments, or as deposit liners, it is believed that the finer fraction would provide sealing while the coarse grains would make the material less compressible and stronger in terms of shear strength.

Focusing on trend of excess pore water pressure development in such materials, an extensive research has been conducted on cyclic behavior of composite clays (Jafari & Shafiee, 2004). Based on the findings of these researches, the prominent feature of composite clay behavior is the increase of clay-fraction deformation by the increase of inclusions as the non-deformable solid fraction of the mixture, especially under strain-controlled loadings. Consequently, as grains volume fraction of the mixture is raised, larger extents of excess pore water pressure (EPWP) may be generated during both monotonic and cyclic loadings.

The main goal of the current investigation is to observe the heterogeneity of effective stress/pore pressure and strain throughout the specimen, by the aid of some experiments and also numerical analyses. For the testing purposes, cyclic triaxial loadings were examined on specimens having one miniature pressure-transducer inside. The numerical analysis was also performed by Plaxis 3D and 2D finite element codes.

2. RESEARCH BACKGROUND

As composite soils are frequently found in nature, their physical (e.g. compaction characteristics and permeability) and mechanical (e.g. monotonic and cyclic shear resistance) properties have been matters of concern, though not as much as those of pure sand, silt or clay soils. As the main focus of this paper is on a mechanical aspect of mixed-soil behavior, only some relevant studies are reviewed here. Readers may find more extensive reviews concerning physical properties also, in the references which will be pointed out through the paper.

To investigate mechanical behavior of clay-aggregate mixtures especially in the aspect of EPWP development, (Jafari & Shafiee, 2004, 1998) commenced a pioneering extensive research on this material, by conducting several monotonic and cyclic triaxial tests. The effect of granular material content, number of cycles, cyclic strain amplitude, grain size and confining pressure on the behavior of the mixture were evaluated. Soroush and Soltani-Jigheh (2009) also explored the same material, focusing mainly on its post-cyclic behavior, and observed the same tendency as the former one. For the sake of brevity, readers are referred to Soroush and Soltani-Jigheh (2009) to review the literature in this regard i.e. the effect of grain content on static and cyclic shear strength of mixed clay soils. The prominent feature revealed by these investigations is increase of average EPWP with increase of aggregate content, especially in higher confining pressures and strain amplitudes. This is mainly devoted to higher strain magnitudes exerted to the clay part of the mixtures (assuming no deformation for the solid inclusions) in comparison with pure clay specimens, under the same strain amplitudes.

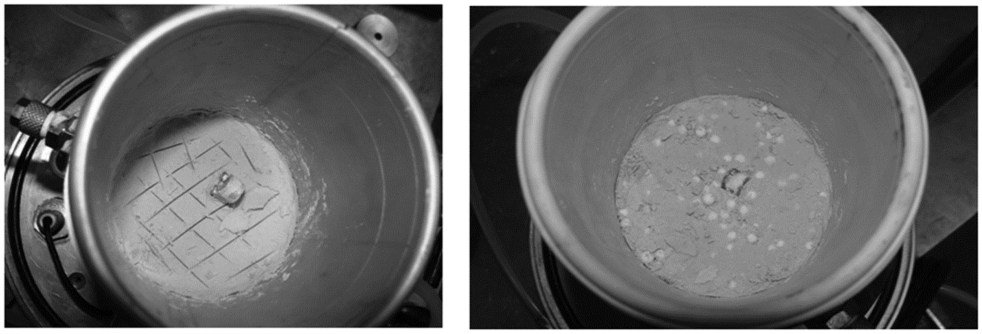
Heterogeneity of the matrix soil of the mixture which is mainly induced during compaction and consolidation of the specimen was the other observed trend of behavior in these studies. Due to existence of granular inclusions, those regions which are between two adjacent grains are believed to be highly compacted and consolidated, despite the so-called far-field areas. This local difference of density would be the source of further heterogeneous effective stress and EPWP distribution in subsequent cycles of strain. However, based on the permeability of the matrix soil, the EPWP heterogeneity tends to uniformity by decrease of loading frequency, as a result of pore water pressure redistribution.

In the above mentioned studies, the only evidences of such heterogeneity was measurement of pore water pressure at both ends of the specimen, and also some scanning electron microscope photographs of horizontal sections of the specimen after the tests (Jafari & Shafiee, 2004). However, in the reviewed literature, there is no record of any measurement inside the specimens while loading, to capture formation of such heterogeneous fields of stress more quantitatively. This lack of evidence was the main reason of the current study, which is seeking heterogeneity of stress (including EPWP) and strain distribution inside the specimens (Jafari & Shafiee, 2004, 1998; Soroush & Soltani-Jigheh, 2009; Shafiee, 2008).

3. EXPERIMENTAL INVESTIGATION

Cyclic triaxial tests were performed at IIEES geotechnical laboratory. Satisfying ASTM standard (ASTM D5311 92. 2007) for largest inclusion size inside a triaxial specimen, 70 mm diameter for triaxial specimens was selected, which contained one inner pressure transducer (IPT) with 10 mm width, placed at the middle elevation of the specimen (Fig. 1). Pore water pressure was captured at three points, i.e. top, middle (by IPT) and bottom of the specimen.

Two types of specimen, i.e. pure clay (LL = 32, PI=12) and mixture of clay with ceramic beads (D= 4 mm, G_s = 3.73) were prepared and tested (Fig. 1). Pure clayey specimen only contained the IPT at the middle part. Totally mixed specimens contained 40% (volumetric) ceramic beads with 4 mm diameter and 60% clay, again with the IPT at the middle part (Fig. 1).



a b

Figure 1. Clay specimens for cyclic triaxial test: a) pure clay specimen; b) mixed specimens

The specimens were compacted in 10 layers to the 95% of maximum dry density of the material (which was equal to 17.2 kN/m^3 for pure clay and 23 kN/m^3 for mixed material, according to ASTM D698 procedure (ASTM D698-07. 2007) at a water content 2% wet of optimum (w_{opt} = 16% for pure clay, and 8.1% for the mixed one). Before placing the material of the next layer, the surface of the compacted layer was scarified to ensure interlock between successive layers. Trial specimens were compacted and a trend similar to under compaction method (Ladd, 1978) was chosen to avoid formation of denser bottom layers compared with top ones, especially for pure specimens. Anti-frictions were utilized at both ends to facilitate a more uniform deformation pattern of the specimen all along its height.

To saturate the specimen, CO_2 circulation was followed by circulation of de-aired water through the specimen, and then 400 kPa backpressure was exerted on the specimen, waiting (up to 3 or 4 days) to reach a B value not less than 95% at top, middle (measured by the aid of IPT) and bottom of the specimen.

The specimen was then consolidated to 300 kPa effective confining stress isotropically, and subjected to 50 undrained cycles of shear strain with single amplitude of 1.5% at a frequency of 0.005 Hz.

Fig.2a to 2c show results of the tests at top, middle and bottom of pure and mixed specimens respectively. U_{res} in this figure stands for the measured residual excess pore water pressure at the end of cycles 1 to 5, and 10, 20, 30, 40 and 50, normalized to the effective confining pressure. It is observed in the figure that the expected increase of excess pore pressure by increase of grain content, which was a prominent feature of previous studies (Jafari & Shafiee, 2004, 1998; Soroush & Soltani-Jigheh, 2009) is clearly observed herein.

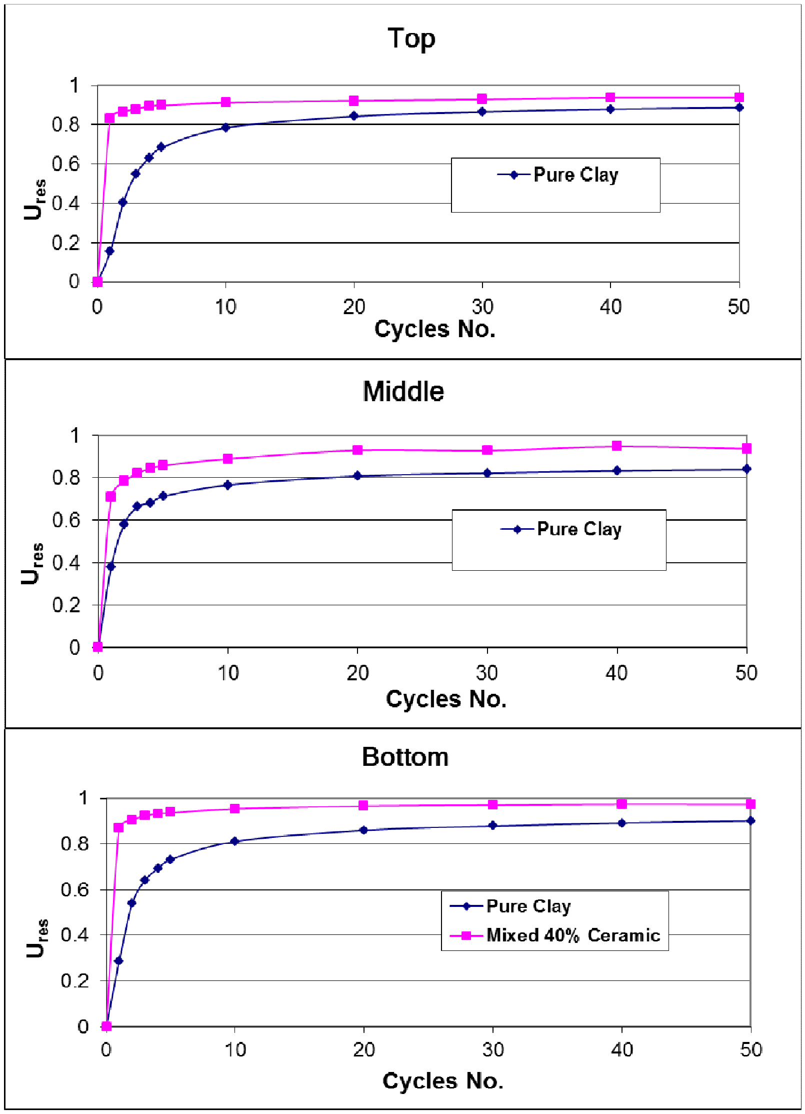


Figure 2. Normalized residual excess pore water pressure change with increase of cycles at frequency of 0. 005 Hz at a) top; b) middle; c) bottom of the specimens

By the aid of IPT, it is confirmed that the element of soil has such behavior thoroughly, and the previous studies which observed only both ends, were not reporting the reaction of apparatus pedestal and load cell with element boundaries.

However, to better observe local heterogeneities among inclusions, hydraulic conductivity of the matrix material has to be decreased, and loading frequency and amplitude to be increased, and also numerous transducers to be installed inside the specimen, both far from inclusions and close to them. Such testing condition is not practically possible (or economical) due to limitations in saturation of fine grained materials and utilizing tiny transducers.

To observe influence of above mentioned factors on heterogeneity of stress and strain distribution in clay-aggregate mixture, numerical studies were also performed.

4. NUMERICAL INVESTIGATION

For a better understanding of the mixed-clay behavior, parallel to experimental investigation, numerical investigation on triaxial specimens of clay was also carried out continuously, results of which assisted better understanding of the observed behavior during experiments. The advantage of the numerical analysis is possibility of capturing the EPWP, as well as stress and strain distribution throughout the specimen, despite the experimental results in which only limited locations were surveyed.

Numerical analyses were performed via Plaxis 3D (version 2010.02) and 2D (version 2010) finite element code (Plaxis. 2010, 2D; Plaxis. 2010, 3D). 3D analyses were performed on dry specimens while for saturated specimens the 2D code was used to avoid time consuming 3D consolidation calculations. Dry analyses were conducted to explore effect of inclusions on stress and strain distribution throughout the specimen, and saturated specimens were also modeled to probe pore water pressure heterogeneity and its redistribution trend with time.

The dimensions of the specimen and also the inclusions diameter were the same as those of real ones in the experiments. However, only few inclusions were modeled to avoid complexity of the geometry and concentrate on qualitative behavior of the inclusions effect on heterogeneity of stress and strain distribution throughout the specimen. In 2D analysis, the inclusions were located only in the axis of symmetry in a nearly half-circular shape to resemble a sphere (Fig. 6).

UBC3D material model of the code was preferred for the matrix soil, which is based on UBC SAND model, capable of liquefaction modeling (Brinkgreve, Broere & Waterman, 2008).

Table 1. Calibrated parameters of UBC3D material model applied in numerical analysis

Parameter	Unit	Description	Magnitude
ϕ_{cv}	Degree	Constant volume friction angle	27
ϕ_p	Degree	Peak friction angle	27.1
c	kN/m^2	Cohesion	5
k_G^e	-	Elastic shear modulus number	500
k_G^p	-	Plastic shear modulus number	200
k_B^e	-	Elastic Bulk modulus number	200
me	-	Elastic Bulk modulus index	0.2
ne	-	Elastic shear modulus index	0.2
np	-	Plastic shear modulus index	0.25
R_f	-	Failure Ratio	0.98
P_A	kN/m^2	Atmosphere pressure	100
σ_t	kN/m^2	Tensile strength	0
e_0		Initial void ratio	0.575
γ_{unsat}	kN/m^3	Unsaturated unit weight	18.5
γ_{sat}	kN/m^3	Saturated unit weight	19.5
k_x	m/sec	Horizontal permeability	4.50E-09
k_y	m/sec	Vertical permeability	3.00E-09

Inclusions were also modeled as linear-elastic solid materials, with a shear modulus nearly one thousand times of that of the matrix in average strain magnitudes, to resemble solid granules behavior in real clay-aggregate mixtures. The geometry of the inclusions was modeled by spheres of 5-9 mm diameter.

To calibrate material model parameters, a series of Oedometer tests and monotonic and cyclic triaxial tests were performed on the clay material. Fig. 3 shows the cyclic triaxial test results and those calculated in the code in similar loading condition. Table 1 shows the calibrated parameters of the material model employed in this study for both 3D and 2D analyses.

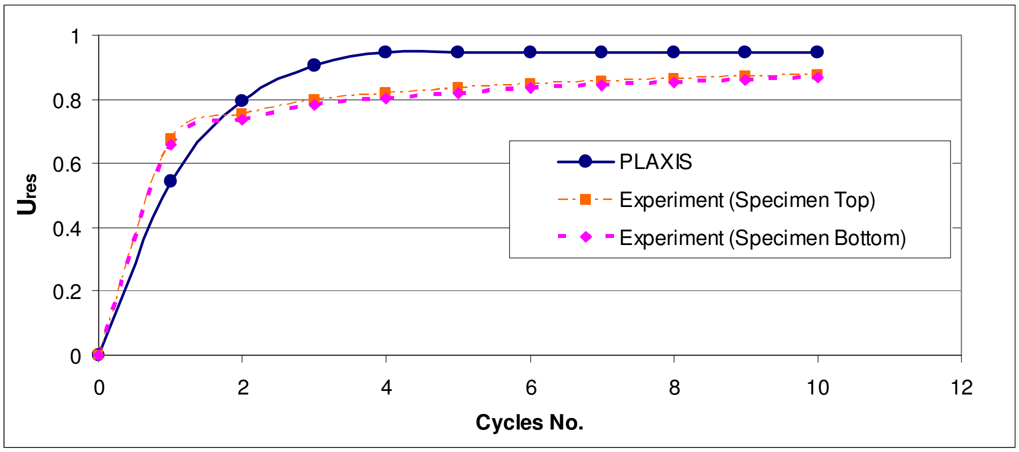


Figure 3. Normalized residual excess pore water pressure change with increase of cycles from cyclic triaxial test and those simulated in Plaxis by UBC3D model

4.1. Analyses on Dry Specimens

During dry analyses, 10 cycles with single amplitude of 1% vertical strain was exerted on the specimen. Inclusions were located in two different patterns: aligned vertically with axial loading direction (Fig. 4a) and aligned horizontally perpendicular to axial loading direction (Fig. 4b).

Fig. 5 shows pattern of volumetric strain change with loading steps (i.e. cycles) in locations (specified in Fig. 4) between and far from inclusions. As evident in this figure, two different patterns of behavior are observed: when inclusions are located vertically aligned, i.e. in the direction of axial loading, there is a concentration of strain through the soil captured between the inclusions; but when inclusions are located horizontally, there is a reduction of strain concentration in the soil, from the average magnitude of strain in other inclusion-free levels of the specimen. The combination of these situations would lead to a stress and strain distribution, totally dependent on the inclusions distance and position relative to loading direction.

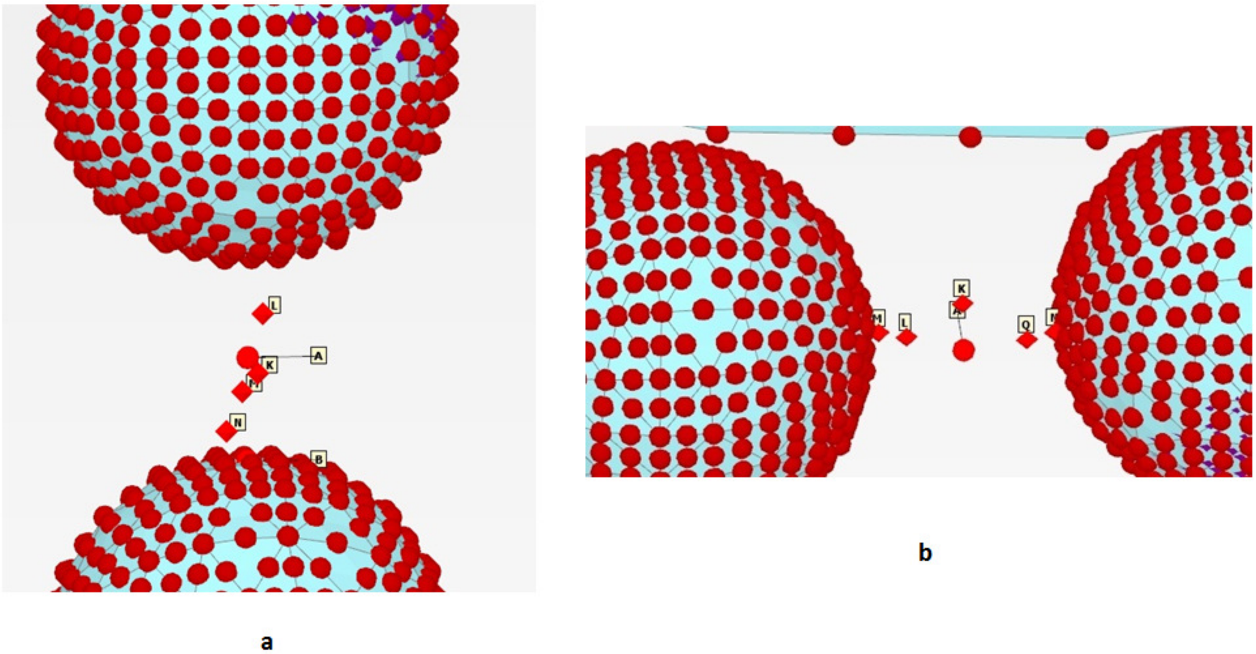


Figure 4. Locations of points where volumetric strain change was captured during analyses:
a) vertically aligned inclusions, b) Horizontally aligned inclusions

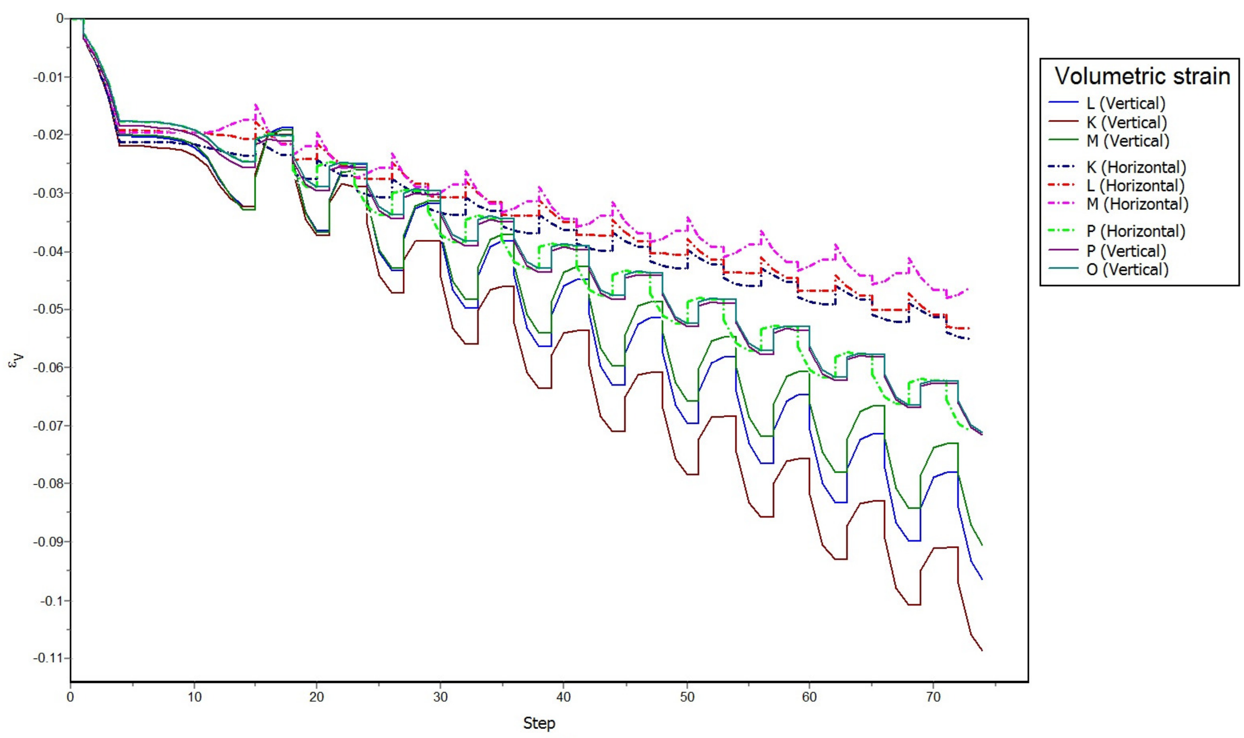


Figure 5. Variation of volumetric strain with loading step in areas between inclusions (points L, K and M in vertical and horizontal position, as shown in Fig. 4, and P and O at specimen top and bottom, far from inclusions)

Based on extensive 3D numerical analyses with different number of inclusions and different patterns of inclusion location and loading direction, it may be qualitatively concluded that inclusions form a heterogeneous filed of stress and strain throughout the surrounding clay. Consequently, stress and strain magnitudes in clay-areas among inclusions may decrease or increase from the expected average magnitudes in inclusion-free areas of the clay. In areas between inclusions aligned vertical to loading direction, lower magnitudes of volumetric strain and mean stress, compared with the expected magnitude in pure specimens, are produced; while between inclusions aligned parallel to loading direction, higher volumetric strain and mean stress are produced. The term "extension path" and "compression path" will be used to describe the trend, respectively.

4.2. Analyses on Saturated Specimens

After some experiences of undrained analyses in 3D code, which were too time consuming and also unstable in calculation with the complex sphere geometries of inclusions, 2D code was preferred for saturated specimens. To ensure reliable results, similar geometries in both 2D (Axisymmetric) and 3D code were modeled and volumetric strain after a 300 kPa confining pressure and 1% axial strain was compared. The similarity of the results was well enough to ensure reliable 2D analyses.

Several analyses were conducted, consolidating the specimen to 300-500 kPa confining pressure, with subsequent 0.1% to 1.5% vertical strain exerted on the material in undrained condition instantly, and then time was given to the material for EPWP redistribution (with all boundaries close to flow in or out). As expected, EPWP magnitude at compression path was more than that of far locations from inclusion (Fig. 6), as shown in Fig. 7. It was also observed that the heterogeneity of EPWP is formed, as a consequence of the non-uniform stress and strain distribution. However, based on the permeability of the matrix material, the pore pressure redistribution would lead to a uniform state throughout the specimen. Fig. 8 and 9 show such trend of behavior clearly.

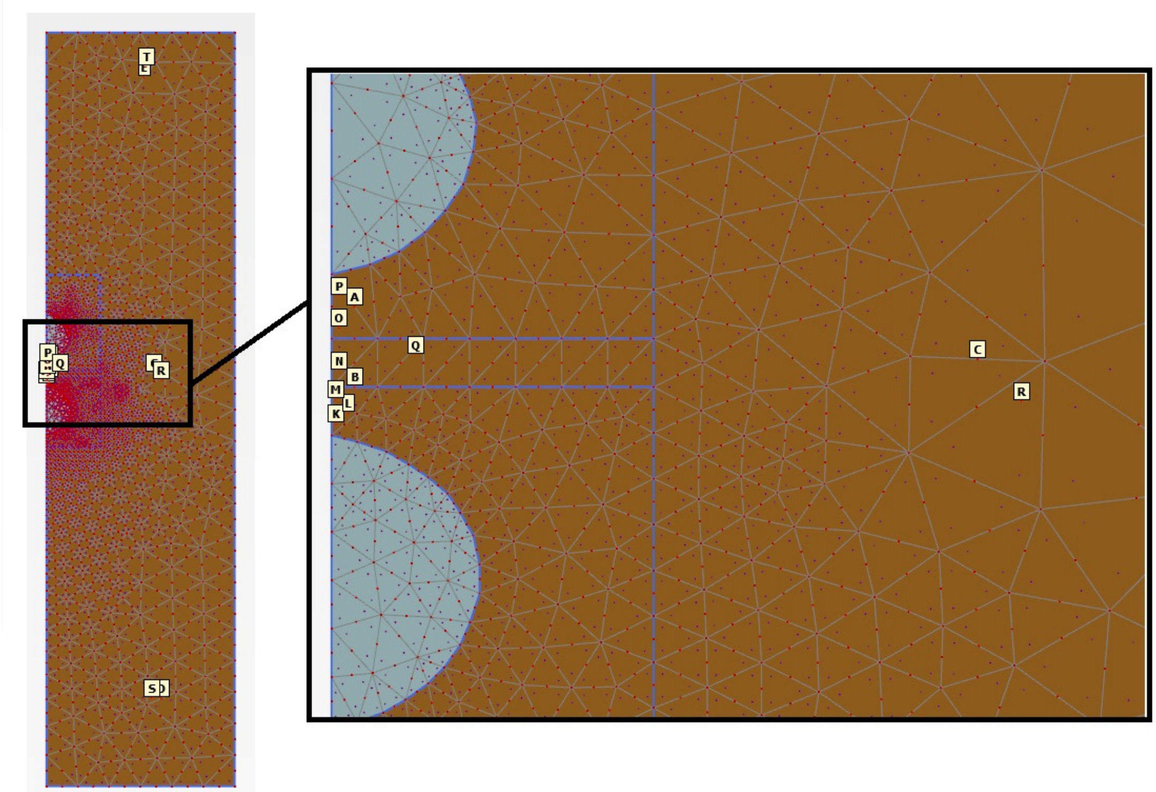


Figure 6. Geometry of the 2D axisymmetric model including locations of the observation points at compression path (P, A, …) and far from inclusions (C, S, …)

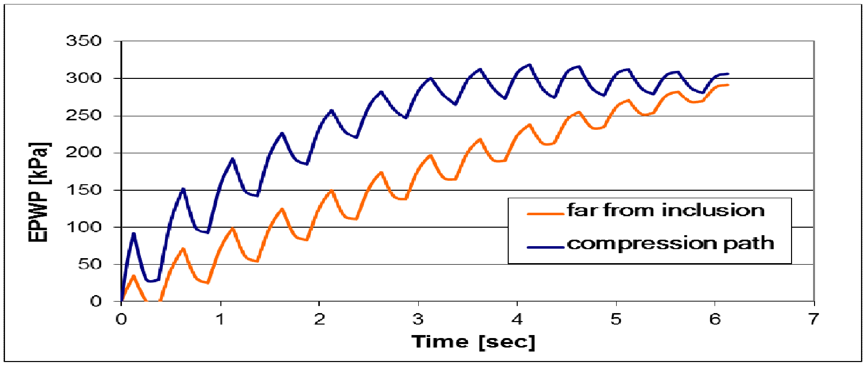


Figure 7. Change of excess pore water pressure with time at compression path and far from inclusions ($k=3\times10^{-11}$ m/s, f = 2 Hz)

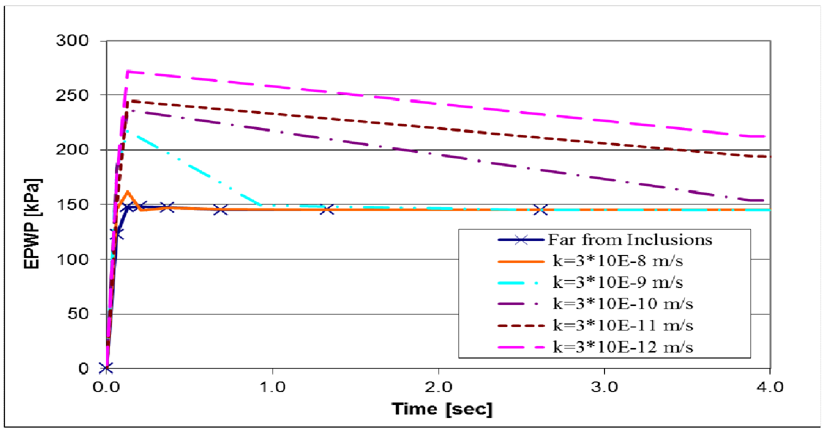


Figure 8. Change of excess pore water pressure with time at compression path and far from inclusions inside clay specimen, after 1.5% monotonic strain

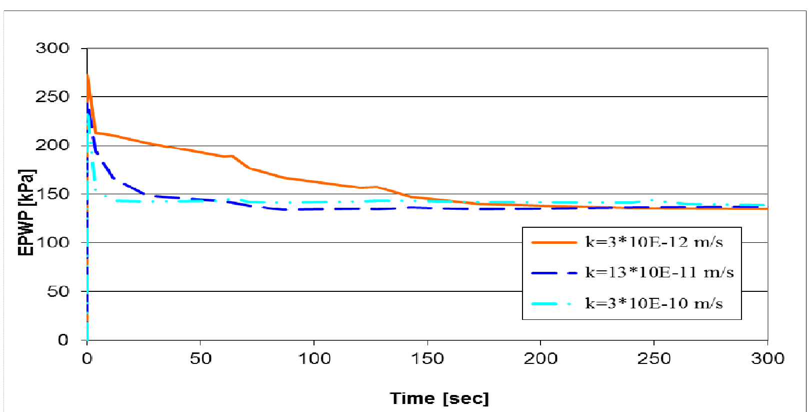


Figure 9. Change of excess pore water pressure with time at compression path inside clay specimen, after 1.5% monotonic strain

Factors such as inclusion distances and dimension, and loading frequency and amplitude also affect the results, which is not shown here in to observe brevity.

As shown in Fig. 9, with decrease of permeability, time required to reach a uniform pore pressure throughout the specimen is increased from nearly 2 second to nearly 200 second, as expected.

5. CONCLUSION

A series of experimental and numerical investigations were conducted to observe formation of local heterogeneities of stress, excess pore water pressure and strain among inclusions, as a trend of behavior of composite soils. Concluding remarks are as follows:

1- Composite clay materials experience higher magnitudes of strain/excess pore water pressure, compared with pure clay ones under the same loading condition. Such behavior was observed throughout the specimen.
2- Heterogeneity of stress and strain distribution in dry specimens was observed in numerical analyses results. Position of the inclusions relative to loading direction, and the distance between inclusions would lead to formation of "compression path" and "extension path" among inclusions. In "compression path" higher magnitudes of volumetric strain and mean stress were observed, compared with the magnitude in pure specimens, while in "extension path", lower magnitudes were observed.
3- Heterogeneous excess pore water pressure distribution in saturated specimens was formed during undrained numerical analyses. However, as qualitatively observed in these analyses, the heterogeneous excess pore water pressure induced among inclusions during loading is redistributed with a rate proportional to material hydraulic conductivity.

REFERENCES

ASTM D5311_92. 2007. Standard test method for load controlled cyclic triaxial strength of soil. Annual Book of ASTM Standards, **04.08**, Soil and Rock (I). ASTM International, West Conshohocken, PA.

ASTM D698-07. 2007. Standard test methods for laboratory compaction characteristics of soil using standard effort. Annual Book of ASTM Standards, **04.08**, Soil and Rock (I). ASTM International, West Conshohocken, PA.

Brinkgreve, R. B. J., Broere, W., Waterman, D. (*Editors*).: 2008, Plaxis, Finite element code for soil and rock analysis, User's manual, 2D version 9.02, Rotterdam, Balkema.

Jafari, M. K. & Shafiee, A.: 1998, Dynamic behavior of mixed materials used for core of Karkhe dam, *In* proceeding of the 11th Europpean conference on earthquake engineering, Balkema, Rotterdam, The Netherlands, p. 179.

Jafari, M. K. & Shafiee, A.: 2004, Mechanical behavior of compacted composite clays, Canadian Geotechnical Journal, **41**(6): 1152-1167. doi:10.1139/T04-062.

Ladd, R. S.: 1978, Preparing test specimens using undercompaction, Geotechnical testing journal, **1**(1): 16-23.

Plaxis. 2010, 2D Finite Element Code, version 2010. Plaxis bv, Delft, the Netherlands.

Plaxis. 2010, 3D Finite Element Code, version 2010. Plaxis bv, Delft, the Netherlands.

Shafiee, A.: 2008, Permeability of compacted granule-clay mixtures, Engineering Geology, **97**: 199-208.

Soroush, A. & Soltani-Jigheh, H.: 2009, Pre- and post-cyclic behavior of mixed clay soils, Canadian Geotechnical Journal, **46**(2): 115-128. doi:10.1139/T08-109.