An experimental investigation on effect of inclusions on excess pore water pressure distribution in composite clay

J. Jalili[1], M. K. Jafari[2] & A. Shafiee[3]
[1,2,3]: *International Institute of Earthquake Engineering and Seismology, Geotechnical research center, Tehran, Iran*
j.jalili@iiees.ac.ir; jafari@iiees.ac.ir; ali_shafiee_iiees@yahoo.com

ABSTRACT
As a step forward in an ongoing investigation on behaviour of composite clay, which is used as the core material of some large embankment dams all over the world, a series of experiments were conducted to explore the distribution of excess pore water pressure along saturated triaxial clay specimens during cyclic loading. As the predominant feature of the composite clay behaviour is increase of excess pore water pressure in both monotonic and cyclic loadings as a consequence of increase of inclusion content, this paper focuses on formation of such pressure distribution inside the specimen by utilizing a miniature inner pressure transducer inside triaxial specimens. Specimens of pure clay, mixed material containing 40% (volumetric) ceramic beads and 60% clay, and pure clay with the inner transducer surrounded by inclusions were tested. Under cycles of 1.5% strain amplitude the expected increase of excess pore water pressure was captured at both ends and also inside the mixed specimen, and also by the transducer surrounded by inclusions, compared with pure specimens, which is in agreement with previous findings in this regard.

RÉSUMÉ
Comme un pas en avant dans une enquête en cours sur le comportement de l'argile composite, qui est utilisé comme matériau de base de certains grands barrages en remblai dans le monde entier, une série d'expériences ont été réalisées pour étudier la distribution de la pression interstitielle le long de l'excès d'eau saturée en argile triaxial échantillons durant le chargement cyclique. Comme la caractéristique prédominante du comportement d'argile composite est l'augmentation de la pression interstitielle de l'eau en excès dans les deux chargements monotones et cycliques comme une conséquence de l'augmentation de la teneur en inclusion, ce document met l'accent sur la formation de la distribution de telles pressions à l'intérieur de l'échantillon en utilisant un capteur de pression miniature intérieure l'intérieur des échantillons triaxiaux. Les échantillons d'argile pure, matériau mixte contenant 40% (volumétrique) billes de céramique et 60% d'argile et d'argile pure avec le transducteur intérieure entourée par des inclusions ont été testés. En vertu de cycles de 1.5% amplitude de la déformation l'augmentation prévue de la pression interstitielle excès d'eau a été capturé aux deux extrémités et aussi à l'intérieur du spécimen mixtes, et aussi par le transducteur entourée par des inclusions, par rapport aux échantillons pure, qui est en accord avec les conclusions antérieures dans ce égard.

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 coarser 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 and post-cyclic behaviour of composite clays (Jafari & Shafiee, 1998; Jafari & Shafiee, 2004; Soroush & Soltani-Jigheh, 2009). Based on the findings of these researches, the prominent feature of composite clay behaviour 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 formation of such pressure distribution inside the specimens, in addition to traditionally measured magnitudes at both ends of the specimen. It is also intended to probe inclusions role on pattern of behaviour in terms of EPWP generation. For the testing purposes, cyclic triaxial apparatus was utilized, with one miniature inner pressure-transducer (IPT) inside the specimen.

The paper firstly provides the reader with a brief research background, and then describes testing method and subsequent findings, leading to final conclusion from the results.

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-clay behaviour, only some relevant studies are reviewed herein.

To investigate mechanical behaviour of clay-aggregate mixtures especially in the aspect of EPWP development, Jafari and Shafiee (1998; 2004) 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 behaviour of the mixture were evaluated. Soroush and Soltani-Jigheh (2009) also explored the same material, focusing mainly on its post-cyclic behaviour, 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.

In the above mentioned studies, the only evidences of such trend of behaviour were measurements of pore water pressure at both ends of the specimen. However, in the reviewed literature, there is no record of any measurement inside the specimens while loading, to capture formation of such fields of stress more quantitatively. This lack of evidence was the main reason of the current study, which is seeking trend of EPWP change inside the specimens.

Another feature of mixed materials is the heterogeneity of EPWP distribution due to inclusions. Due to existence of granular inclusions, those regions which are between two adjacent grains (clayey bridge, figure 1) 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 excess pore water pressure distribution in subsequent cycles of strain. However, the excess pore water pressure heterogeneity tends to uniformity by decrease of loading frequency, as a result of pore water pressure redistribution (Jafari & Shafiee, 2004; Soroush & Soltani-Jigheh, 2009).

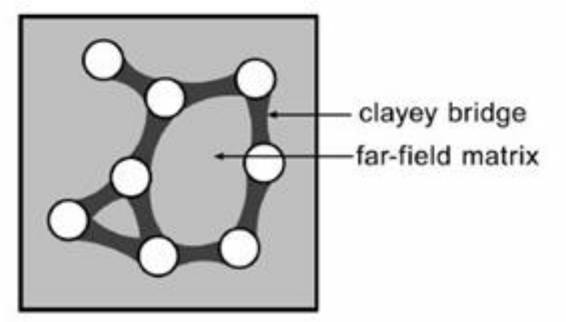


Figure 1. Schematic of clayey bridge and far-field matrix (Jafari & Shafiee, 2004)

To probe inclusions effect on adjacent clay behaviour, in another series of tests the IPT was surrounded by inclusions and the results were compared with specimens containing inclusion-free IPT, as will be stated.

3 EXPERIMENTS

Cyclic triaxial tests were performed at international institute of earthquake engineering and seismology geotechnical laboratory. One IPT was placed at the middle elevation of the specimen (figure 2). Pore water pressure was captured at three points, i.e. top, middle (by IPT) and bottom of the specimen. The IPT had the capacity of 1000 kPa pore water pressure measurement.

Figure 2. Clay specimens for cyclic triaxial test: pure clay specimen with the IPT (inclusion-free) inside

The largest possible specimen dimensions were preferred for this study to minimize effect of inner pressure transducers on behaviour of the specimen. Satisfying ASTM standard (ASTM D5311, 2007) for largest inclusion size inside a triaxial specimen, 70 mm diameter and 140 mm height was selected for triaxial specimens, which contained one inner pressure transducer with 10 mm width.

The main reason of capturing inside the specimens was to ensure that the specimen is a uniform element of soil, as expected from element testing specimens. Probable heterogeneity of the mixtures response would be mainly devoted to the local variation of matrix soil properties among inclusions. Such heterogeneity includes EPWP also, which however, is expected to tend to uniformity by time, due to redistribution of pressure. Formation of such uniformity depends on the permeability of the soil and also the loading frequency. The low-plastic clay with permeability near silt materials was selected to assist better uniformity. Measured value of hydraulic conductivity coefficient of the material, by passing water through the triaxial specimens under specific gradient, showed a magnitude of 3×10^{-9} m/sec.

To find the proper frequency of loading, not so far from the range of standard cyclic tests (ASTM D5311, 2007), a range of loading frequency (from 0.005 to 1 Hz) were initially tested in cyclic triaxial apparatus on pure clay specimens, as will be stated.

Before starting the tests on clay material, a trial test on sand was conducted to assure reliable measurement of the IPT inside the specimen. Different loading frequencies and amplitudes of strain were tested on this sample.

As expected, in the highly permeable sandy material, the IPT measurement agreed well with magnitudes of EPWP at both ends. Figure 3 shows a typical result of the test on the loose sandy specimen under cycles of 0.1 Hz frequency and 0.1% single amplitude of strain.

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, as shown in figures 2 and 4, respectively. 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.

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) at a water content 2.5% 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.

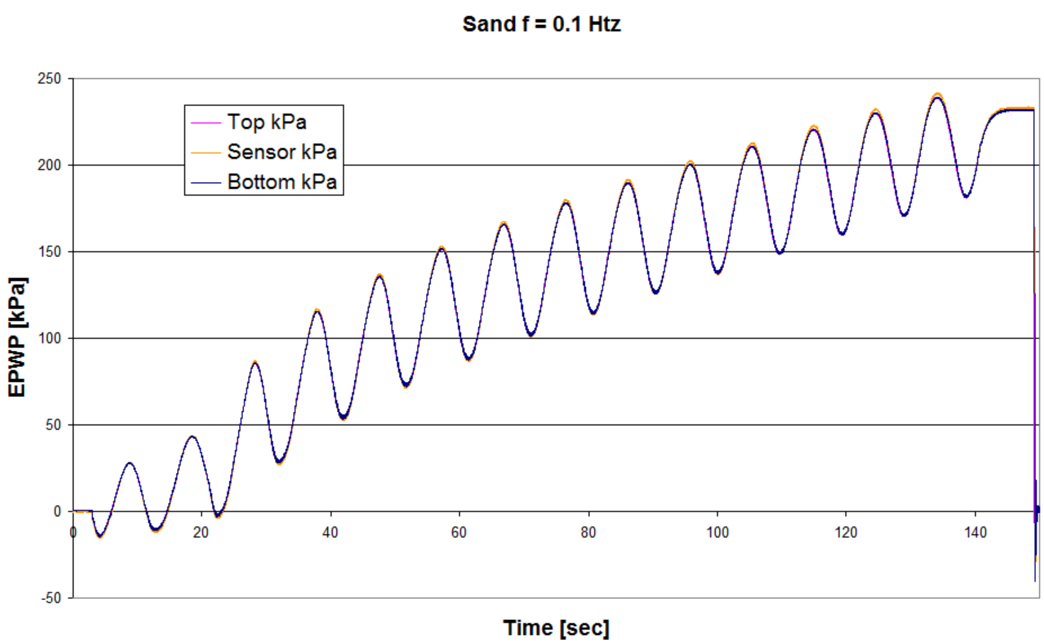


Figure 3. Excess pore water pressure (EPWP) change with time in the test on loose sandy specimen: IPT (mentioned as sensor in the legend) measurement was well in agreement with top and bottom measurements

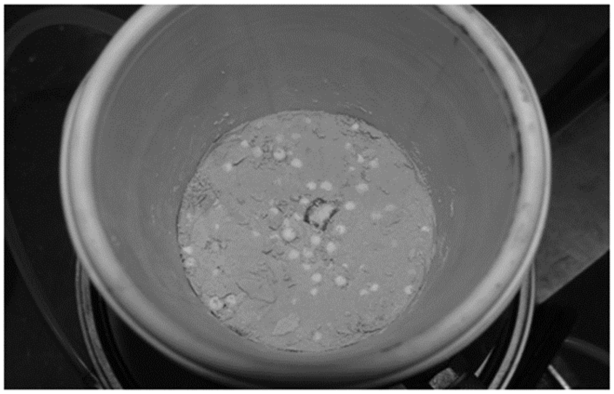


Figure 4. Clay specimens for cyclic triaxial test: mixed specimens containing 40% (volumetric) Ceramic beads

To saturate the specimen, CO_2 circulation was followed by circulation of de-aired water through the specimen, and then 500 kPa backpressure was exerted on the specimen gradually, waiting 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 then subjected to 50 undrained cycles of shear strain with single amplitude of 1.5%.

To probe role of frequency in formation of heterogeneity, the test on pure specimens were conducted with frequencies of 0.005, 0.01, 0.1 and 1 Hz, results of which are shown in figure 6.

As obvious in this figure, by increase of frequency of loading, amplitude of EPWP cycles decrease at the middle part. As also evident in this figure, the trend of decrease of amplitude at the middle of specimens is not the same as those captured at top and bottom, which shows increase of non-uniformity of stress and strain distribution by increase of frequency of loading.

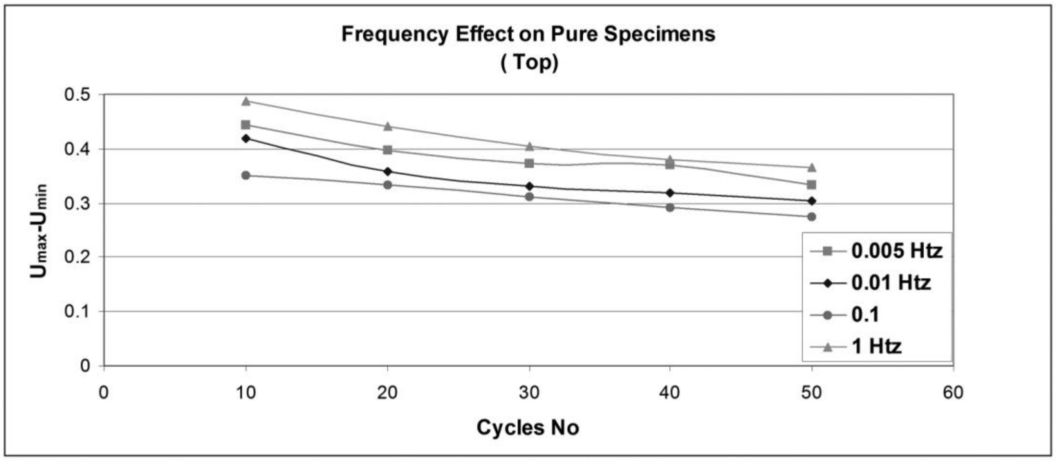
To avoid such frequency effect on EPWP distribution, 0.005 Hz loading frequency were preferred for loading rate.

Figure 7a to 7c show results of the tests at top, middle and bottom of pure and mixed specimens respectively. As clearly observed, increase of EPWP is captured, which is induced by increase of inclusion content. This result is in agreement with previous findings, and confirms that the pattern is formed throughout the specimen.

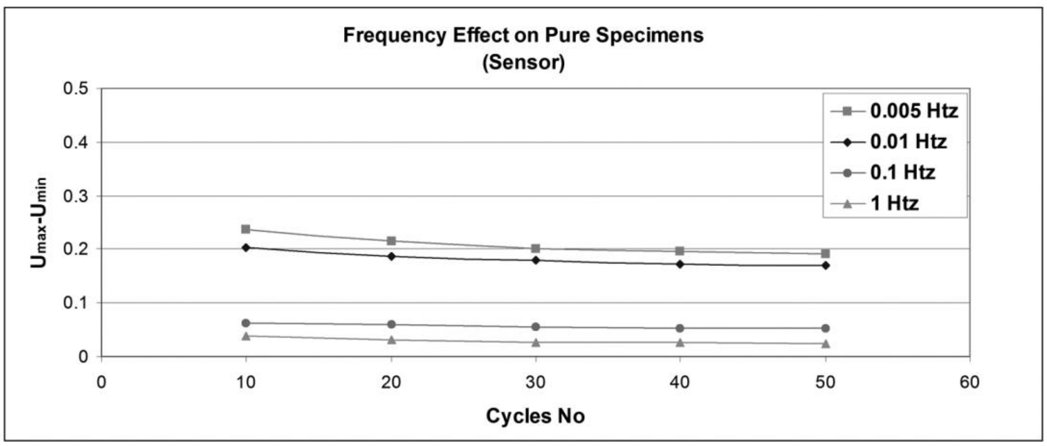
Next step was to examine inclusions effect on formation of local different EPWP generation leading to heterogeneous field of stress, especially in high frequencies of loading. To exaggerate the effect, four inclusions of the same material as previous ones (Ceramic) but with 9 mm diameter were inserted around the IPT, as shown in figure 5. The frequency was kept equal to 0.005 Hz to keep a uniform stress distribution throughout pure specimens. However, it was hoped that the relatively large inclusions will form a high degree of heterogeneity which may be captured in this low frequency of loading.

Figure 5. Clay specimens for cyclic triaxial test: pure specimens, with inclusions around the IPT

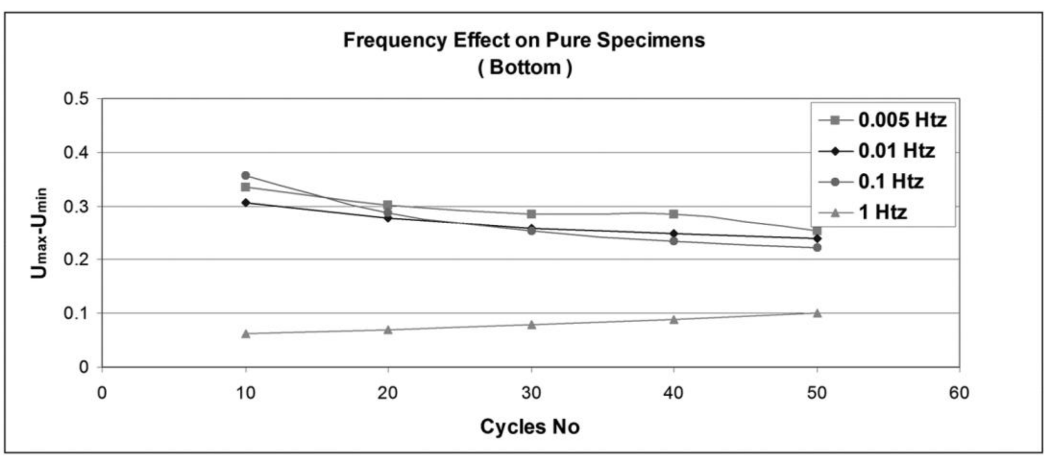
The loading condition was the same as previous tests. Figure 8 shows results of the test on specimens containing inclusion-free and inclusion-surrounded IPT. As evident, increase of EPWP is observed as a consequence of inclusions around the IPT, compared with top and bottom of both specimens which are nearly the same. This confirms role of inclusions on adjacent matrix material, which leads to heterogeneity of stress and strain distribution along the mixed material. Such heterogeneity of EPWP will be dominant in relatively higher frequencies of loading on impervious materials, as the pressure does not have enough time to redistribute while loading.



(a)



(b)



(c)

Figure 6. Effect of frequency of loading on excess pore water pressure fluctuation during loading cycles at a) top; b) middle; c) bottom of the specimens (U = EPWP / Initial Effective Confining Pressure)

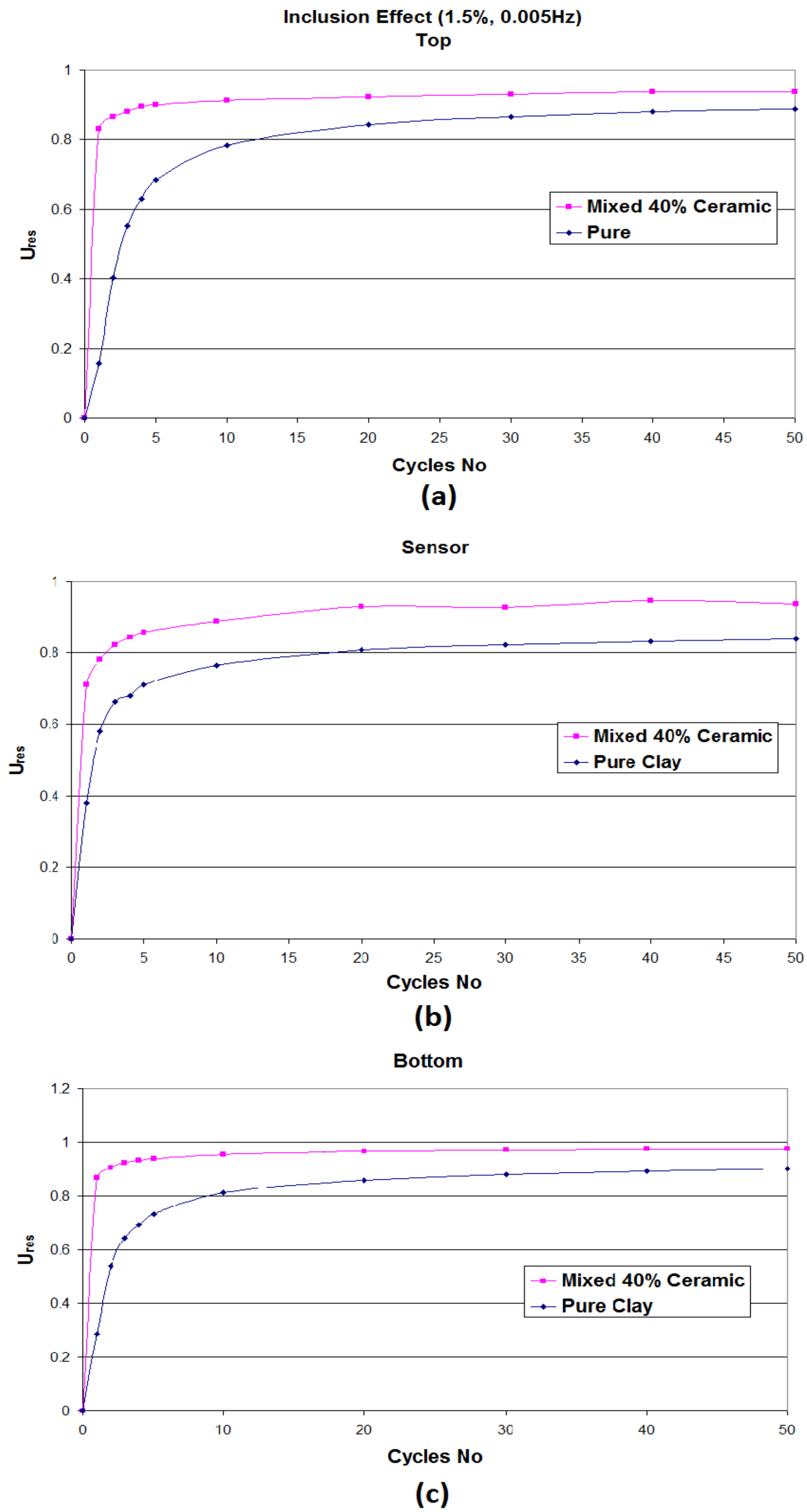


Figure 7. Normalized residual excess pore water pressure change with increase of cycles at frequency of 0. 005 Hz at a) top; b) middle; c) bottom of the specimens (U = EPWP / Initial Effective Confining Pressure)

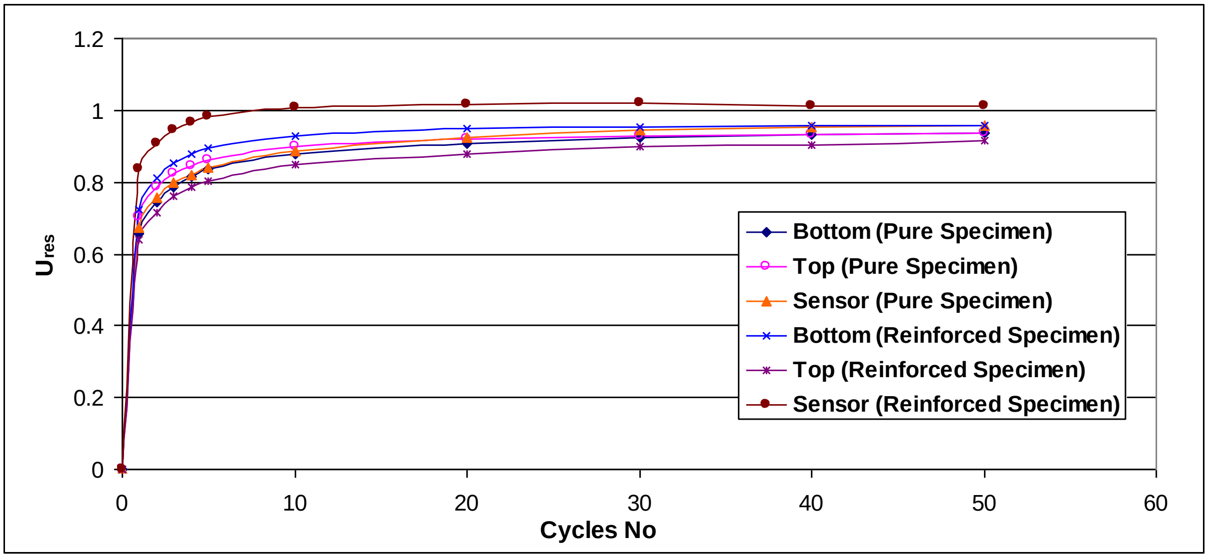


Figure 8. Normalized residual excess pore water pressure change with increase of cycles at top, middle and bottom of specimens having inclusion-free and inclusion-surrounded IPT (vertical) inside

To assure such inclusion effect, the experiment was repeated in the same condition, only differing in IPT position: the IPT was positioned horizontally, as shown in figure 9a, and one 9 mm diameter ceramic bead was positioned with nearly 5 mm distance with the IPT (figure 9b).

Result of this test also confirmed the inclusion effect on increase of EPWP in adjacent soil. As shown in figure 10, the IPT measured higher magnitudes of EPWP compared with top and bottom, which had similar EPWP variation while loading.

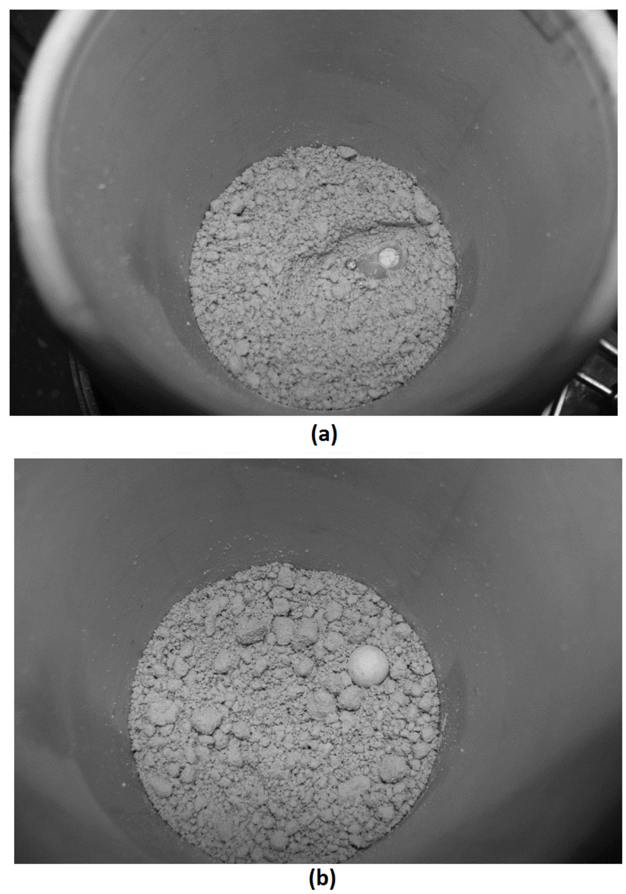


Figure 9. Clay specimens for cyclic triaxial test: pure specimens, with one inclusion adjacent to the horizontal IPT : a) IPT position; b) Inclusion position

4 CONCLUSION

A series of experimental investigations were conducted to observe increase of excess pore water pressure inside specimens of mixed clay material, due to inclusion content, as a trend of behaviour of composite soils. It was also aimed to probe role of inclusions on adjacent matrix soil behaviour.

Heterogeneous excess pore water pressure distribution in saturated specimens may form in high frequencies of loading, depending on the material hydraulic conductivity. In sand specimens, any heterogeneity of pore pressure may hardly be captured even in relatively high frequencies of loading, while in clay specimens, it may be possible to observe the heterogeneity in the standard range of frequencies, depending on its plasticity and permeability.

Based on the results of tests on pure specimens in different loading frequencies, making use of a miniature pressure transducer inside the specimen, the proper frequency to provide uniformity of pressure was preferred to be 0.005 Hz.

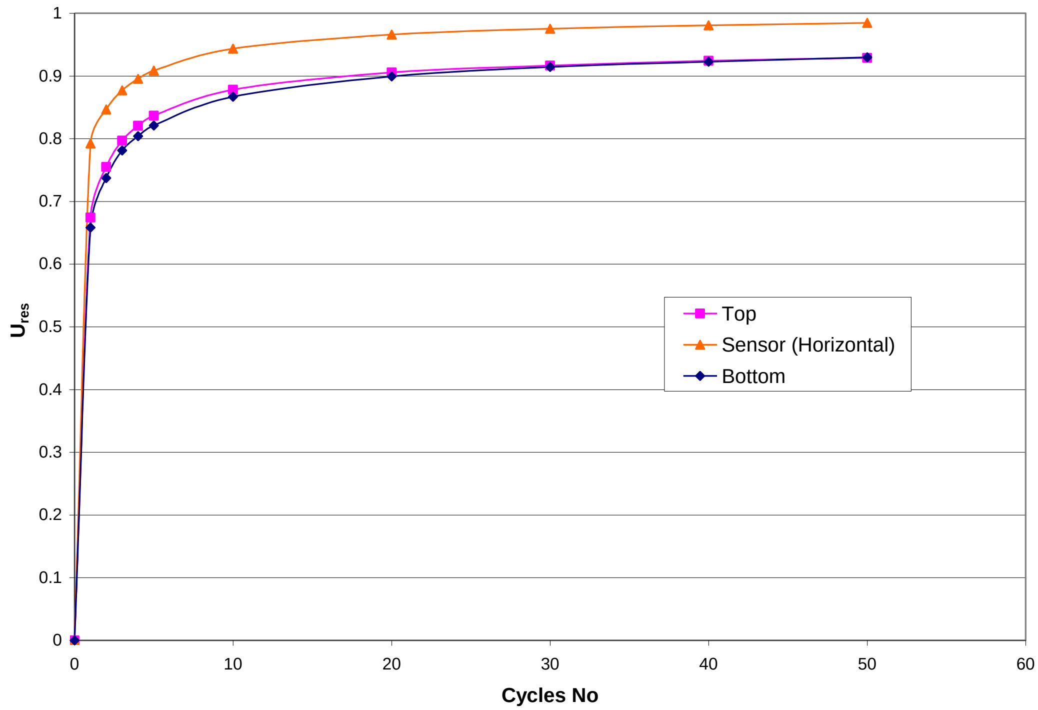


Figure 10. Normalized residual excess pore water pressure change with increase of cycles at top, middle and bottom of specimens having free and inclusion-surrounded IPT (horizontal) inside

Tests on specimens of pure and mixed clay in the preferred frequency showed increase of excess pore water pressure by adding inclusions to the clay, measured inside the specimen and also at both ends, which confirms the trend as a behaviour of a uniform element of soil, as expected from element testing purposes. Such trend of behaviour is in agreement with previous studies in this regard, which assume that deformation only occurs in clayey fraction of the mixture.

Inclusions effect on adjacent matrix soil was also observed making use of relatively large inclusions around the inner pressure transducer. As expected, inclusions affect adjacent matrix soil behaviour leading to heterogeneous field of stress and strain, which in case of excess pore water pressure, will be dominant in relatively higher frequencies of loading on impervious materials, as the pressure does not have enough time to redistribute while loading.

However, this is only a qualitative observation of the trend. For a quantitative investigation of the behaviour, high tech and costly instruments (including very small inner pressure transducers) are required.

Acknowledgements

This study was mainly supported by the International Institute of Earthquake Engineering and Seismology which is acknowledged. Using IPT inside specimens was achieved after a joint research under supervision of professor Koseki at Institute of Industrial Science, The University of Tokyo, who is greatly acknowledged. The authors also thank Mr. T. Sato, Mr. M. Asgari, Mr. G. Hadavi and Mr. S. Azaadmanesh for their assistance in conducting the tests.

REFERENCES

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

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

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

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.

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