Measuring Pore Water Pressure Variation Inside Saturated Triaxial Specimens of Low-Plastic Composite Clay under Strain-Controlled Cyclic Loading

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ABSTRACT

As a step forward in an ongoing investigation on behavior 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 behavior is the increase in excess pore water pressure in both monotonic and cyclic loadings as a consequence of increase in inclusion content, this paper focuses on formation of such pressure distribution inside the specimens in cyclic loading, by utilizing a miniature inner pressure transducer inside triaxial specimens. Specimens of pure clay and mixed material containing 40% (volumetric) ceramic beads and 60% clay were tested. Under strain-controlled cycles of 1.5% single amplitude, the expected increase of excess pore water pressure was captured at both ends and also inside the sample, which is in agreement with previous findings in this regard.

Keywords:
Composite clay; Cyclic triaxial loading; Excess pore water pressure; Inner transducer; Loading frequency

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 behavior of composite clays [1-5]. Based on the findings of these researches, the prominent feature of composite clay behavior is the increase in clay-fraction deformation by the increase in 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 such increase of EPWP inside the specimens, in addition to traditionally observations at both ends of the specimen. The main reason of capturing inside the specimens was to ensure that the mixed specimen is a uniform element of soil in terms of EPWP change, and to assure that the reported literature is not only a consequence of some heterogeneity at ends of the mixed specimens. 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 the 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 behavior, only some relevant studies are reviewed here. Readers may also find more extensive reviews concerning physical properties in the references that will be pointed out through the paper.

To investigate mechanical behavior of clay-aggregate mixtures especially in the aspect of EPWP development, Jafari and Shafiee [1-2] 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 [3] 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 Tavakoli [4] 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 the increase in average EPWP with an increase in 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 evidence of such trend of behavior was measurement of pore water pressure at both ends of the specimen [1-5]. The principle assumption in element testing (such as triaxial shearing) is uniformity of stress and strain distribution throughout the specimen; consequently, the specimen represents a point in real geometry. As the inclusions in the mixed material increase possibility of heterogeneity of strain and stress distribution throughout the specimen [1, 3], the observed behavior in previous studies may be questionable as the material behavior: in the reviewed literature, there is no record of any measurement inside the specimens while loading, to assure similar trend of behavior throughout the specimen, as that of both ends. The lack of evidence was the main reason of the current study, which is seeking trend of EPWP change inside the specimens.

3. Experimental Investigation

Cyclic triaxial tests were performed at Geotechnical laboratory of International Institute of Earthquake Engineering and Seismology. In addition to the pore pressure transducers typically installed at top cap and pedestal of the triaxial apparatus, an IPT was also placed at the middle elevation of the specimen. The IPT was installed on the pedestal of the apparatus and sealed to avoid any leak of pressure out of the cell, see Figure (1). 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 pressure measurement.

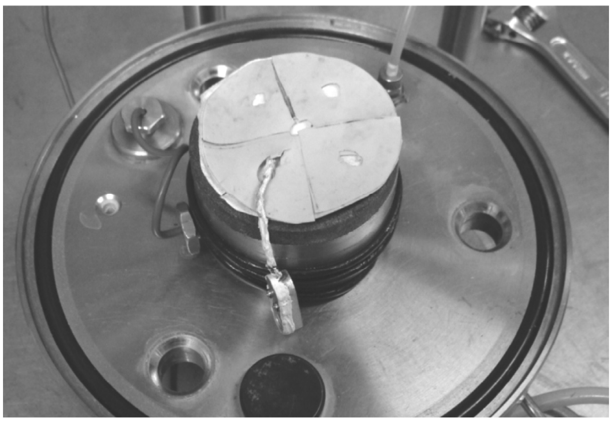

Figure 1. Inner Pressure Transducer (IPT) installed on triaxial apparatus pedestal (Bottom anti-friction may also be observed that is placed on porous stone).

3.1. Installing the Inner Pressure Transducer

The IPT consists of a miniature sensor installed in an aluminum case, see Figure (2) to (4). The miniature sensor, see Figure (2), must be in contact with water, while preserved from soil grains, to measure pore water pressure. As shown in Figure (3), a small porous stone separates soil grains from water. Sensor wires are also sealed by a very strong glue to avoid any contact between wires and surrounding water; even a small leak of water to wires chamber could lead to noticeable noise in records of the sensor.

The largest possible specimen dimensions were preferred for this study to minimize the effect of inner pressure transducers on behavior of the specimen. Satisfying ASTM standard [6] 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 (vertically aligned) with 10 mm width, see Figure (4).

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 with the relative density (D_r) equal to 30%. As expected, in the highly permeable sandy material, the IPT measurement agreed well with magnitudes of EPWP at both ends. Figures (5) and (6) show typical results of the test on the loose sandy specimen under cycles of 0.1 Hz frequency and 0.1% single amplitude of strain (ε_{SA}), and 1 Hz frequency and 1% single amplitude of strain, respectively. The observed fluctuations at final cycles of 1 Hz loading, see Figure (6), occurred after the specimen failed due to liquefaction. The IPT was installed satisfactorily at all.

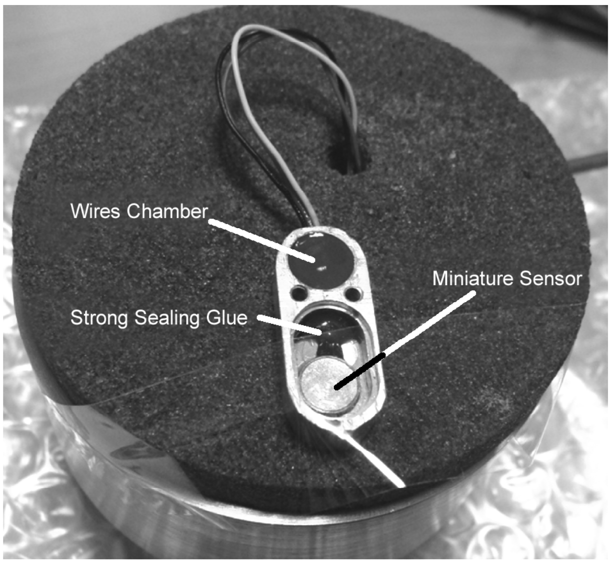

Figure 2. Inner pressure transducer (IPT) while being installed on triaxial pedestal.

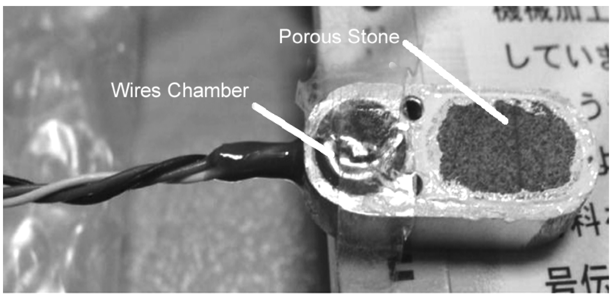

Figure 3. Miniature sensor is sealed from soil grains by a small piece of porous stone.

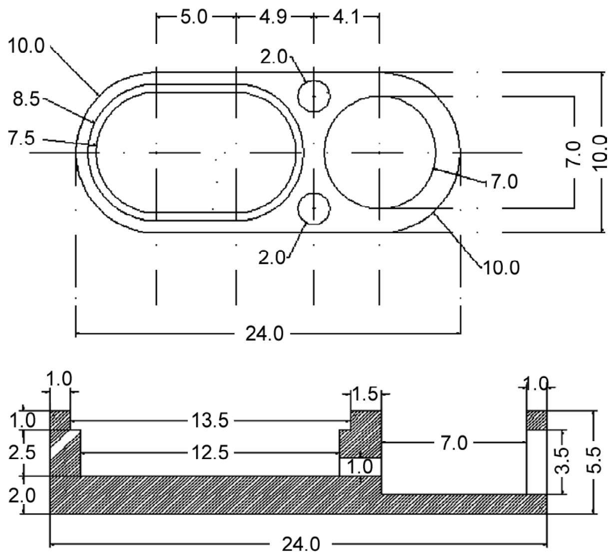

Figure 4. Dimensions of the designed case for inner pressure transducer (IPT) (mm).

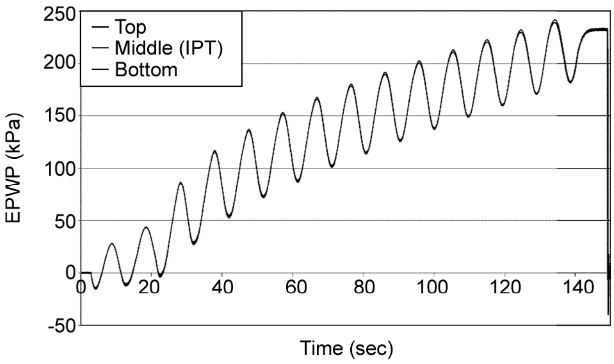

Figure 5. Typical change of excess pore water pressure with time at both ends and inside the sand specimens during cycles of loading (f = 0.1 Hz, ε_{SA} = 0.1%).

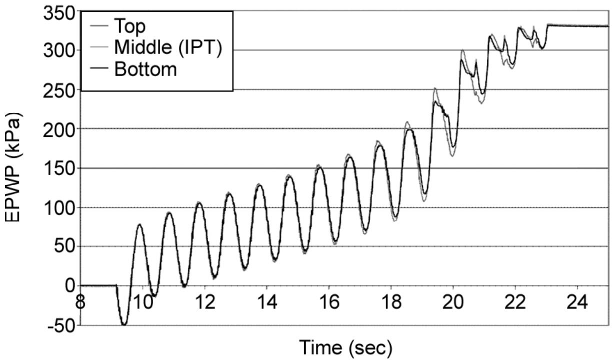

Figure 6. Typical change of excess pore water pressure with time at both ends and inside the sand specimens during cycles of loading (f = 1 Hz, ε_{SA} = 1%).

3.2. Materials and Method of Compaction

Probable heterogeneity of the mixed clay response would be mainly devoted to the local variation of matrix (clay) soil properties among inclusions. Such heterogeneity also includes EPWP, 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 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.

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 (7) and (8), 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 [7]) 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 [8] was chosen to avoid formation of denser bottom layers compared with top ones, especially for pure specimens.

Figure 7. Pure clay specimens for cyclic triaxial test.

Figure 8. Mixed clay specimens for cyclic triaxial test.

The compaction was performed by a tamping hammer, small enough to compact the areas adjacent to IPT and its wire efficiently, while the IPT remains safe from any hit by the hammer. Figure (9) shows the hammer and the position of the IPT while the bottom layers of the specimen were compacted. Anti-frictions were utilized at both ends to facilitate uniform lateral deformation along specimen height, see Figure (1).

3.3. Saturation and Consolidation

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 (up to 3 or 4 days) to reach a B-value not less than 95% at

Figure 9. Position of the IPT during compaction of the specimens by tamping hammer.

top, middle (measured by the aid of IPT) and bottom of the specimen. Measured B-values ranged satisfactorily 95% to 98%. To increase saturation efficiency, CO_2 and de-aired water circulation was directed from top of the specimen to its bottom, to avoid accumulation of air bubbles on top of the specimen.

To prefer a proper effective confining pressure and normally consolidating the specimen (over consolidation ratio less than 1), Oedometer tests were performed on specimens that were compacted similar to triaxial ones. The pre-consolidation pressure (P_c) was determined as 200 kPa for the level of compaction preferred in this study.

The specimens were then consolidated to 300 kPa effective confining stress isotropically, and subjected to 50 undrained cycles of shear strain with single amplitude of 1.5%.

B-value was measured both after applying backpressure, and after the consolidation [6]. It was noticeable that after consolidation, B-values dropped from the initial 95%-98% magnitudes, to values among 85%-89%, but after 20 to 40 hours, it gradually reached the initial value again. Increase in backpressure instantly after consolidation did not change the reduced B-value (85% to 89%), which was another proof of the specimens saturation. This behavior (initial drop of B-value after consolidation, and its slow gradual increase by time) may be devoted to the specimen soil-structure strengthening after 300 kPa consolidation. However, based on ASTM standard for cyclic triaxial testing [6], “If the B-value is equal to or greater than 0.95 or if the B-value versus backpressure plot indicates no further increase in B-value with increasing backpressure, initiate consolidation”. These conditions were satisfied by the specimens in this study.

3.4. Loading Frequency

To find the proper frequency of loading, not so far from the range of standard cyclic tests [6], a range of loading frequencies (from 0.005 to 1 Hz) were initially tested in cyclic triaxial apparatus on pure clay specimens. The tests aimed to prefer the largest frequency magnitude that does not lead to formation of heterogeneity in pure specimens. The tests were conducted on pure specimens in loading frequencies of 0.005, 0.01, 0.1 and 1 Hz, results of which are shown in Figure (10). In this figure, U_{max} and U_{min} stand for maximum and minimum measured EPWP in a cycle, normalized to effective confining pressure. U_{max}- U_{min} is consequently a measure of EPWP amplitude during a cycle.

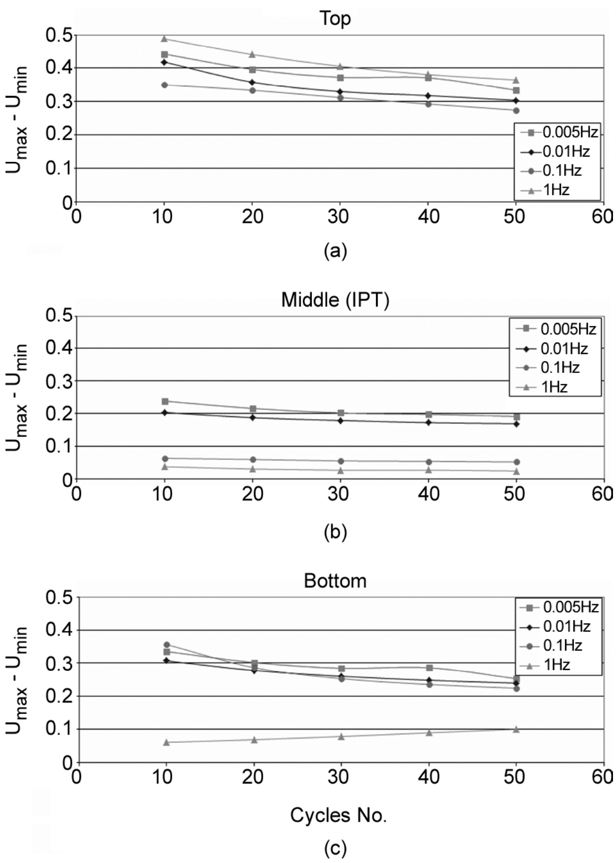

Figure 10. Effect of frequency of loading on excess pore water pressure fluctuation during loading cycles at a) top; b) middle; c) bottom of the specimens.

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

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

3.5. Cyclic Loading

Finally, pure and mixed clay specimens were loaded cyclically at the rate of 0.005 Hz and single amplitude of 1.5%. Figure (11a) to (11c) show results of the tests at top, middle and bottom of pure and mixed specimens, respectively. In this figure, U_{res} stands for the residual EPWP at the end of a cycle, normalized to effective confining pressure. As clearly observed, increase in residual EPWP is captured, which is induced by increase in inclusion content. The same trend may be observed in term of maximum EPWP change, normalized to effective confining pressure, which is mentioned as U_{max} in Figures (12a) to (12c). As the specimens liquefied quickly, the mentioned trend may be clearly observed during initial 10 cycles, specially the case for U_{res}, as observed in Figure (12).

The typical observed behavior, which is shown in Figures (11) and (12), is in agreement with previous ones as stated in the literature, and assures that the increase of EPWP with increase of inclusions in a mixture is a characteristic behavior of the material, occurring throughout the mixed specimen.

3.6. Discussion on Experiment Results

The increase in excess pore water pressure due to increase of inclusion content of the composite clay is mainly devoted to the concentration of deformation on clayey part. In strain-controlled loading, as the experiments described in this paper, the calculated strain is based on the total initial length of the specimen. However, in a mixed specimen, the

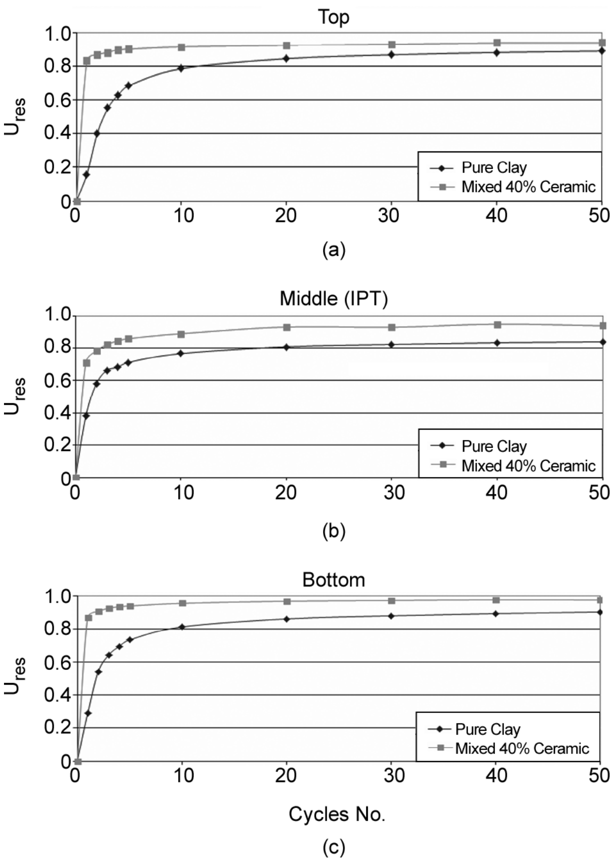

Figure 11. Normalized residual excess pore water pressure change with increase in cycles at frequency of 0.005 Hz: a) top; b) middle; c) bottom of the specimens.

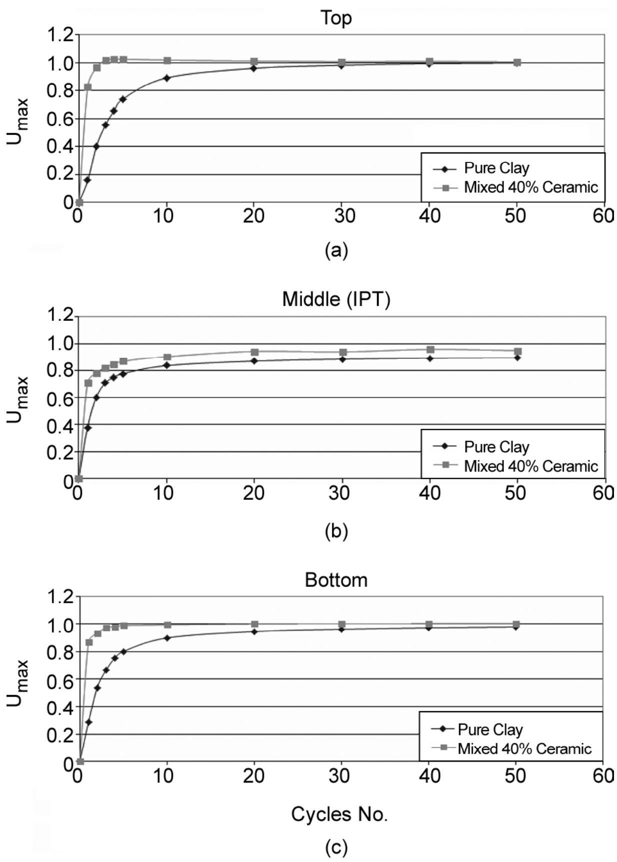

Figure 12. Normalized maximum excess pore water pressure change with increase in cycles at frequency of 0.005 Hz: a) top; b) middle; c) bottom of the specimens.

inclusions do not deform and the real strain only occurs in the clayey fraction; consequently, the real strain is greater than the calculated one. This idea is confirmed in this study by measuring the EPWP inside the specimens. However, the same trend of behavior may not be observed in stress-controlled tests [4].

The residual EPWP at the end of a cycle (U_{res}), and the maximum measured EPWP in a cycle (U_{max}), both normalized to effective confining pressure, were calculated in this paper, to assure the reliability of the results. As shown in Figure (13), the measured values at the middle part (IPT) have some phase difference from that of both ends. This means that measuring EPWP of different locations of the specimen in a specific time (end of a cycle, as Ures is calculated) may give rise to some misleading results. Consequently, U_{max}, is a better variable to be considered as the specimen behavior in terms of EPWP change.

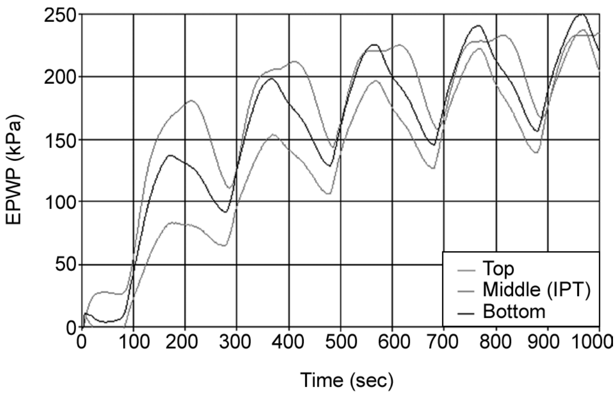

Figure 13. Excess Pore Water Pressure (EPWP) change at the middle and both ends of the specimen at frequency of 0.005 Hz and cyclic single strain amplitude of 1.5%.

4. Conclusion

A series of experimental investigations were conducted to observe the increase in excess pore water pressure inside specimens of mixed clay material, due to inclusion content, as a trend of behavior of composite soils.

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 clay 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.

Tests on specimens of pure and mixed clay in the preferred frequency showed increase in excess pore water pressure by adding inclusions to the clay, measured inside the specimen and at both ends. Such trend of behavior is in agreement with previous studies in this regard. It also confirms the trend as a characteristic behavior of the material, occurring throughout the mixed specimen, fulfilling element testing requirements.

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Nomenclature

w_{opt}: Optimum Water Content
D_r: Relative Density
EPWP: Excess Pore Water Pressure
IPT: Inner Pressure Transducer
ε_{SA}: Single Amplitude of Strain
G_s: Specific Gravity
LL: Liquid Limit
PL: Plastic Limit
PI: Plasticity Index
ASTM: American Society for Testing Materials
CO_2: Di Oxide Carbone Gas
Hz: Hertz
U_{max}: Maximum measured EPWP in a cycle, normalized to effective confining pressure
U_{min}: Minimum measured EPWP in a cycle, normalized to effective confining
U_{res} : Residual EPWP at the end of a cycle, normalized to effective confining pressure