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Cyclic pore pressure build-up in sand-clay mixtures under various loading paths

A. Shafiee
California State Polytechnic University, Pomona, USA

H.R. Tavakoli
Noshirvani University of Technology, Iran

M.K. Jafari
International Institute of Earthquake Engineering and Seismology, Iran

ABSTRACT: Undrained behavior of aggregate-clay mixtures in its natural or compacted state, e.g., core material of embankment dams, has great importance for geotechnical engineers. Previous studies have shown that excess pore pressure plays an important role when dealing with cyclic/dynamic behavior of aggregate-clay mixtures. An extensive testing program was conducted on compacted sand-clay mixtures to investigate various effects of aggregates on the cyclic behavior of the mixtures under strain- and stress-controlled cyclic loads utilizing triaxial and torsional shear equipment. Clay content was varied from 100 to 40% by weight in tested specimens. Specimens were tested under vertical effective stresses of 100, and 500 kPa. Strain-controlled cyclic triaxial and torsional shear tests reveal when sand content is raised, excess pore pressure increases. On the other hand, reverse trend is observed in cyclic stress-controlled tests, and pore pressure decreases with sand content. It is also found that more pore pressure is developed in triaxial tests with respect to torsional shear tests. It is shown that dissipated energy can be used to describe trend of excess pore pressure build-up in sand-clay mixtures.

1 INTRODUCTION

Nowadays, compacted aggregate-clay mixtures are successfully used as the core of embankment dams. These materials which were referred to as composite clays by Jafari and Shafiee (2004), are usually broadly graded and encompass clay as the main body, and sand, gravel, cobble and even boulder which are floating in the clay matrix. Moraine, which consists of unsorted materials of glacial origin, is a good example for this type of composite soils. Moraine has been used extensively in North America and northern countries as fill material for impervious cores in zoned embankment dams or for the main body of homogeneous dikes (ICOLD, 1989). It has also served as relatively good quality foundation for water retaining structures. It is also a current practice to employ the mixture of high plastic clay with aggregates as impervious blankets in waste disposal projects (Lundgren, 1981; Abeele, 1986; Chapuis, 1990; Pandian et al., 1995). Jafari and Shafiee (2004) carried out a series of strain-controlled monotonic and cyclic triaxial tests on gravel-clay and sand-clay mixtures to investigate the effects of aggregate on the mechanical behavior of the mixtures. Compression monotonic test results revealed that the angle of shearing resistance increased with aggregate content. Also, when aggregate content was raised, pore pressure rose in both monotonic and cyclic loading. It was also found that the presence of aggregates within a cohesive matrix led to formation of a heterogeneous field of density in the clayey part of the mixture. A review of the published literature reveals that experimental studies on aggregate-clay mixtures have mainly focused on shear strength parameters, particularly in compression loading and shear strength either increases with aggregate content or remains constant until a limiting aggregate content, then increases as the aggregate content increases. To explore all features of mechanical behavior, there is a need to investigate pre failure along with failure behavior of the mixtures subjected to various loading paths. The present study addresses cyclic pore pressure build-up in sand-clay mixtures under strain- and stress-controlled tests, and when subjected to the rotation of principal axes in the triaxial and torsional shear device.

2 MATERIALS AND PROCEDURE

2.1 *Tested materials*

Pure clay with two mixtures of sand-clay were used in this study. The clay had a specific gravity of 2.70, liquid limit of 42% and plasticity index of 18%. X-ray diffraction analysis revealed that the clay was mainly composed of kaolinite with some illite, montmorillonite, and quartz. The sand used in the study was retrieved from a riverbed and composed of subrounded particles with a specific gravity of 2.65. The aggregates used as sand material were passed through a 4.75 mm sieve and was retained on a 3.35 mm sieve, with minimum and maximum void ratios of 0.667 and 0.803, respectively. Gap graded gradation was considered for the aggregates to minimize the effect of particle size distribution of sand on the mechanical behavior of the mixture. Three mixtures were obtained by mixing 100, 60 and 40% of clay by weight with sand. A minimum of 40% clay content was considered since this is a limit value for materials used as cores in embankment dams.

2.2 *Sample preparation and testing procedure*

The specimen preparation technique was chosen to model as precisely as possible the in situ condition of the core materials of embankment dams. All specimens, typically 76 mm in height and 38 mm in diameter for triaxial tests, and 100 mm in height, and 100 and 50 mm in external and internal diameter respectively for torsional shear tests were prepared with a dry density of 95% of the maximum dry density obtained from the standard compaction test method and water content of 2% wet of optimum. Table 1 presents the initial dry density and water content of the specimens. The specimens were saturated with a Skempton B-value in excess of 97%. The specimens were then isotropically consolidated under effective stresses of 100 and 500 kPa. Fallowing consolidation, undrained cyclic triaxial and torsional shear tests were carried out under strain- and stress-controlled condition. The cyclic tests were continued until 50 cycles of loading. A loading rate of 0.004 Hz for cyclic tests was chosen so that pore pressure equalization through the specimen was ensured. Strain-controlled tests were performed under strain amplitudes of 0.75 and 1.5%, while stress-controlled tests were performed under cyclic stress ratios (CSR) of 0.11 and 0.18.

3 TEST RESULTS AND DISCUSSIONS

3.1 *Effect of sand content on excess pore pressure build-up*

Jafari and Shafiee (2004) showed that both drained shear strength and excess pore pressure increase when aggregate content is raised under strain-controlled monotonic and cyclic tests. Figure 1 typically shows normalized residual pore water pressure, u^*_N under strain-controlled tests. Figure 1 clearly shows that excess pore pressure increases with sand content under either

Table 1. Properties of the specimens.

Specimen	Initial dry density gr/cm^3	Initial water content (%)
100%Clay	1.63	20.2
40%Sand-60%Clay	1.89	13.0
60%Sand-40%Clay	1.99	11.1

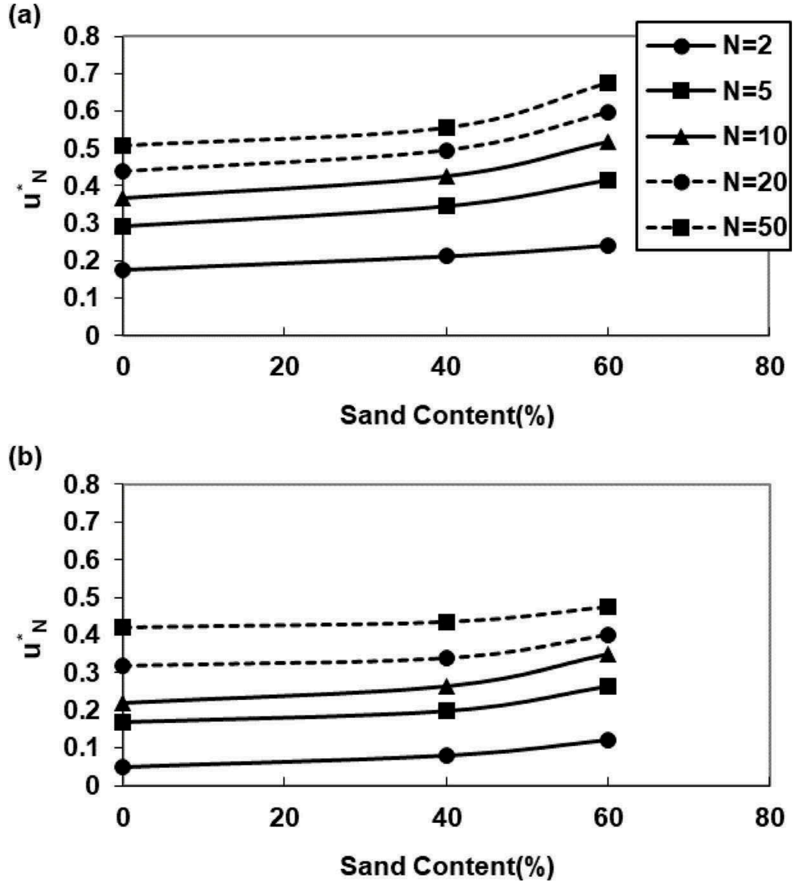

Figure 1. Excess pore pressure in strain-controlled tests, shear strain amplitude=0.75%, initial confining stress=100 kPa (a) triaxial test, (b) torsional shear test (N=number of loading cycles).

strain-controlled cyclic triaxial or cyclic torsional shear test. The increase in pore pressure with sand content can be attributed to the higher deformation of clay, when sand content is raised, as depicted in Figure 2. If we assume all the deformations happen in the clayey matrix of sand-clay mixtures, then under an identical level of strain, the clayey part of soils with higher amount of sand content experience higher deformation, leading to higher excess pore water pressure. If axial strain in the pure clay is $\Delta L/L$ (Figure 2a), then axial strain in the clayey part of sand-clay mixture with a clay content of K ($K<1$) will be $\Delta L/KL$ (Figure 2c), which is greater than $\Delta L/L$.

Figure 3 shows excess pore pressure build-up in sand-clay mixtures under stress-controlled tests. As observed, and on oppose to the strain-controlled tests excess pore water pressure decreases when sand content is raised. This type of behavior can be explained by the aid of monotonic test results on pure clay and 60%sand-40%clay mixture (Figure 4). For example, under an identical stress ratio (=shear stress/initial confining stress) of 0.4, the amount of axial strain in sand-clay mixture, and pure clay is 0.15 and 0.70% respectively (upper figure). Consequently, under an axial strain of 0.15 and 0.70%, the amount of normalized pore pressure in sand-clay mixture and pure clay will be 0.09, and 0.23 respectively (lower figure). Thus, under an identical stress ratio, pore pressure decreases with sand content. In addition, higher pore pressure is developed in cyclic triaxial tests with respect to cyclic torsional shear tests under either strain- or stress-controlled tests (Figures 1 and 3)

Figures 5 compares sand-clay mixture behavior under strain- and stress-controlled tests. As seen, in the strain-controlled tests, pore pressure increases, and significant degradation

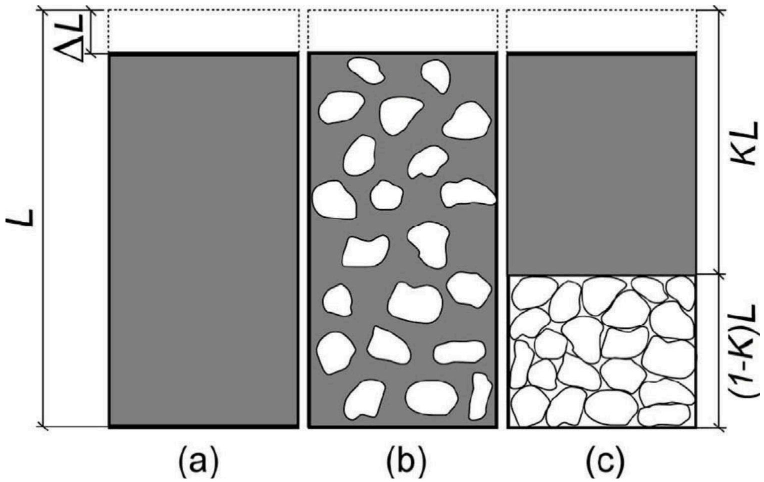

Figure 2. Schematic diagram of axial strain in (a) pure clay (b) sand-clay mixture (c) idealized sand-clay mixture (Jafari and Shafiee, 2004).

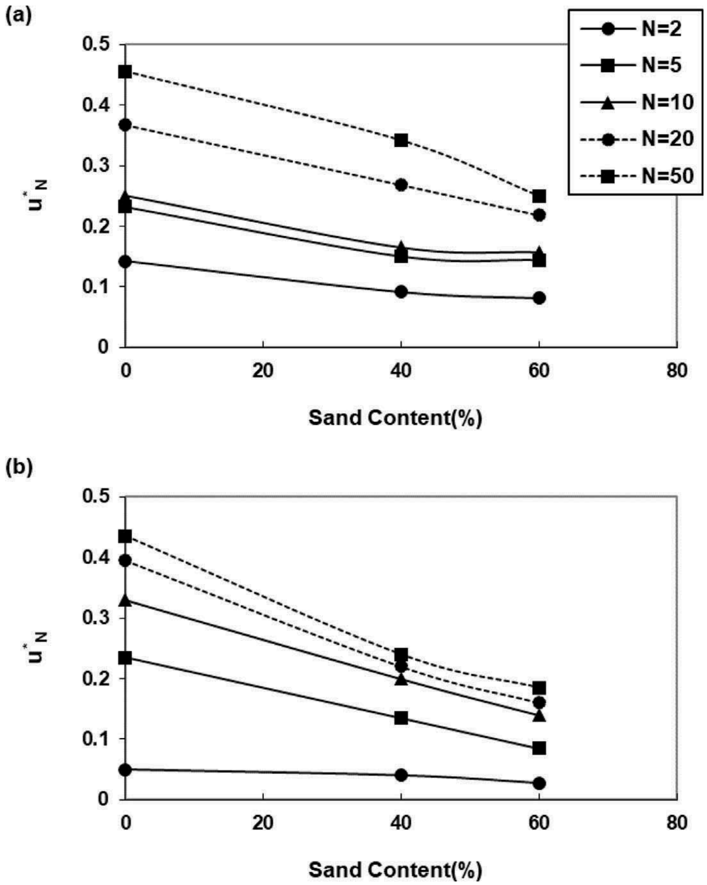

Figure 3. Excess pore pressure in stress-controlled tests, CSR=0.18, initial confining stress=100 kPa (a) triaxial test, (b) torsional shear test (N=number of loading cycles).

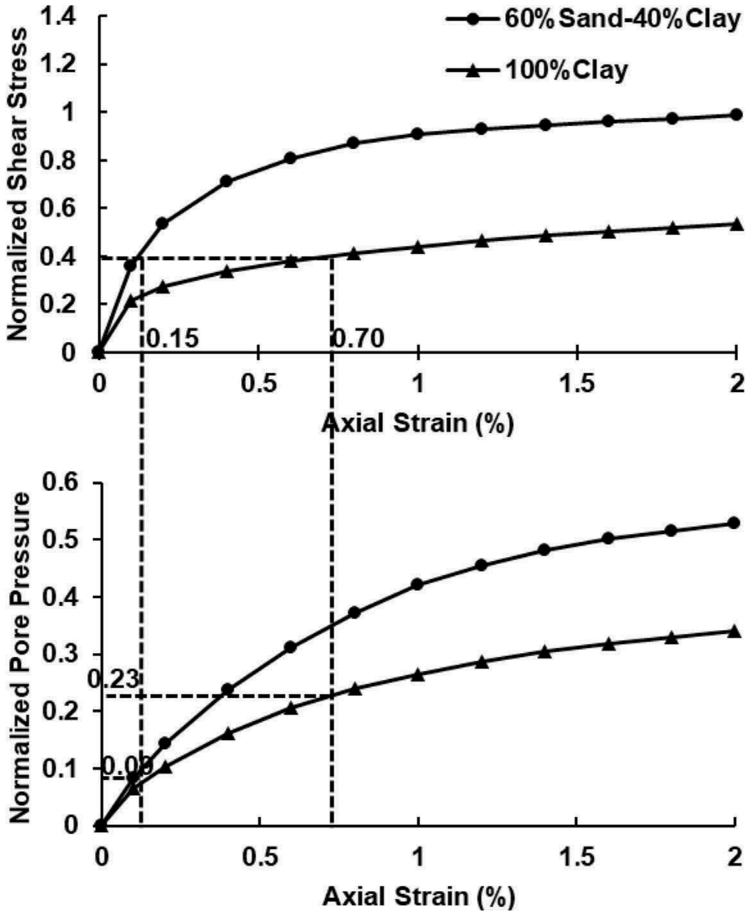

Figure 4. How excess pore pressure decreases with sand content in a stress-controlled test (initial confining stress=100 kPa)

happens with number of cycles. In addition, stress path progressively moves toward the failure envelope. On the other hand, in the stress-controlled tests, pore pressure increases for a few cycles, with a minor degradation, after which the behavior is stabilized, in such a manner that almost no change in pore pressure and stiffness is observed.

4 A PORE PRESSURE MODEL FOR SAND-CLAY MIXTURES

4.1 *Energy approach*

Classical approaches for pore pressure models are mainly based on cyclic stress or strain amplitude. However, results of current study shows that pore pressure is highly dependent on loading path, and could be much different under stress- and strain-controlled loading. Here, we correlate excess pore pressure to dissipated energy, which considers the effects of both shear stress and shear strain variations during cyclic loading. Figure 6, for instance, shows variation of u^*_N in terms of normalized dissipated energy ($\Delta w/p'_0$) for specimens tested in this study under cyclic triaxial conditions, with an initial effective confining stress of p'_0=500 kPa. Herein, Δw is dissipated energy per unit volume per each cycle of loading, which is equal to the area of hysteretic loop in the shear stress- shear strain space. It is interesting to note that irrespective of loading path (stress- or stress-controlled test), and amplitude of loading, u^*_N

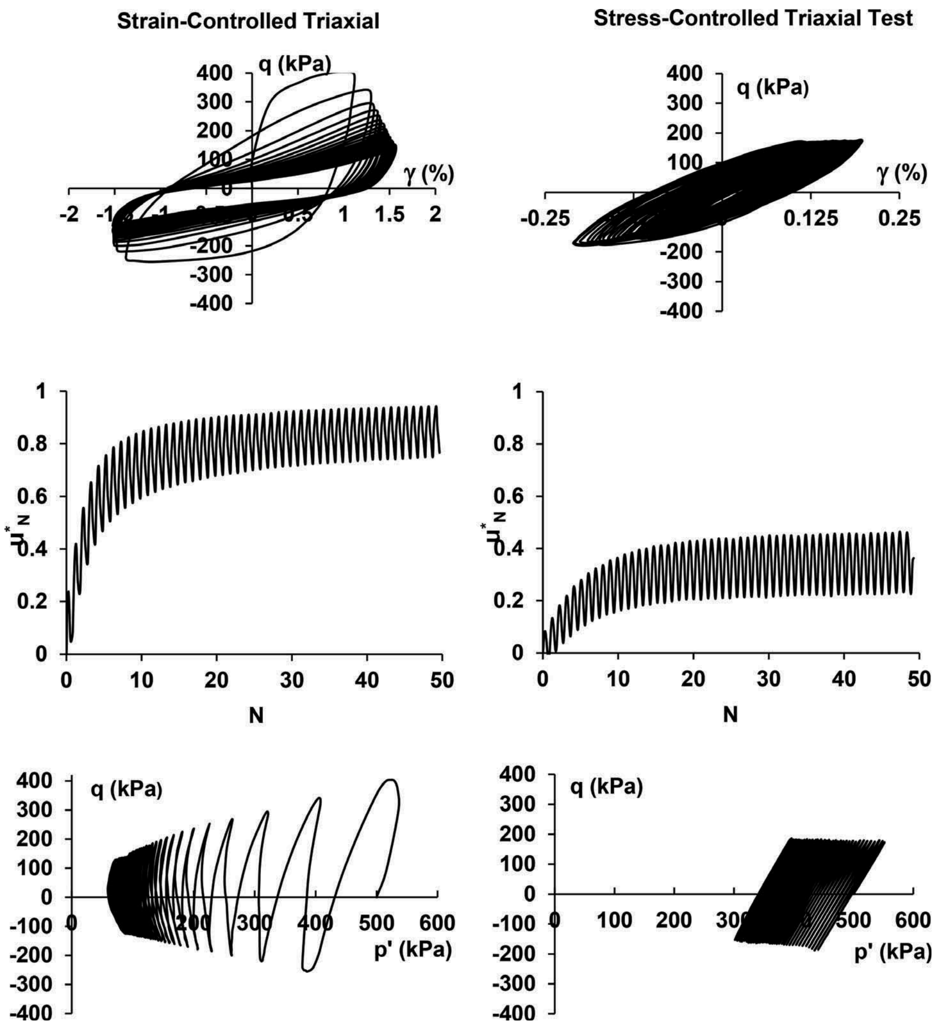

Figure 5. Cyclic triaxial strain-controlled (initial confining stress=500 kPa, and shear strain amplitude=1.5%), and stress-controlled (initial confining stress=500 kPa, CSR=0.18) test results on 60%sand-40%clay specimens (q=deviatoric stress, γ=shear strain, N=number of loading cycles, p'=effective mean stress)

exhibits strong relationship with dissipated energy. The proposed pore pressure model is presented by $u^*_N = u^*_N$ (Δw, θ, p'_0, K), in which Δw =dissipated energy in stress-strain space per unit volume each cycle), θ =Lode angle (θ =0, $\pi/3$ rad for cyclic triaxial, and $\pi/6$ rad for torsional shear test), p'_0=mean initial effective stress, and K=clay content in terms of percent. We examined different models utilizing least square approach, and finally came up with the following equation (R^2=0.75):

$$u_N^* = f(\theta)\,\frac{2.2K^{-1.3}\left(\frac{\Delta w}{p'_0}\right)^{0.67}}{1+2.2K^{-1.3}\left(\frac{\Delta w}{p'_0}\right)^{0.67}} \tag{1}$$

where, $f(\theta) = 2.7\cos^2\theta - 4.1\cos\theta + 2.4$

Figure 6 shows how well the model can predict excess pore pressure build-up.

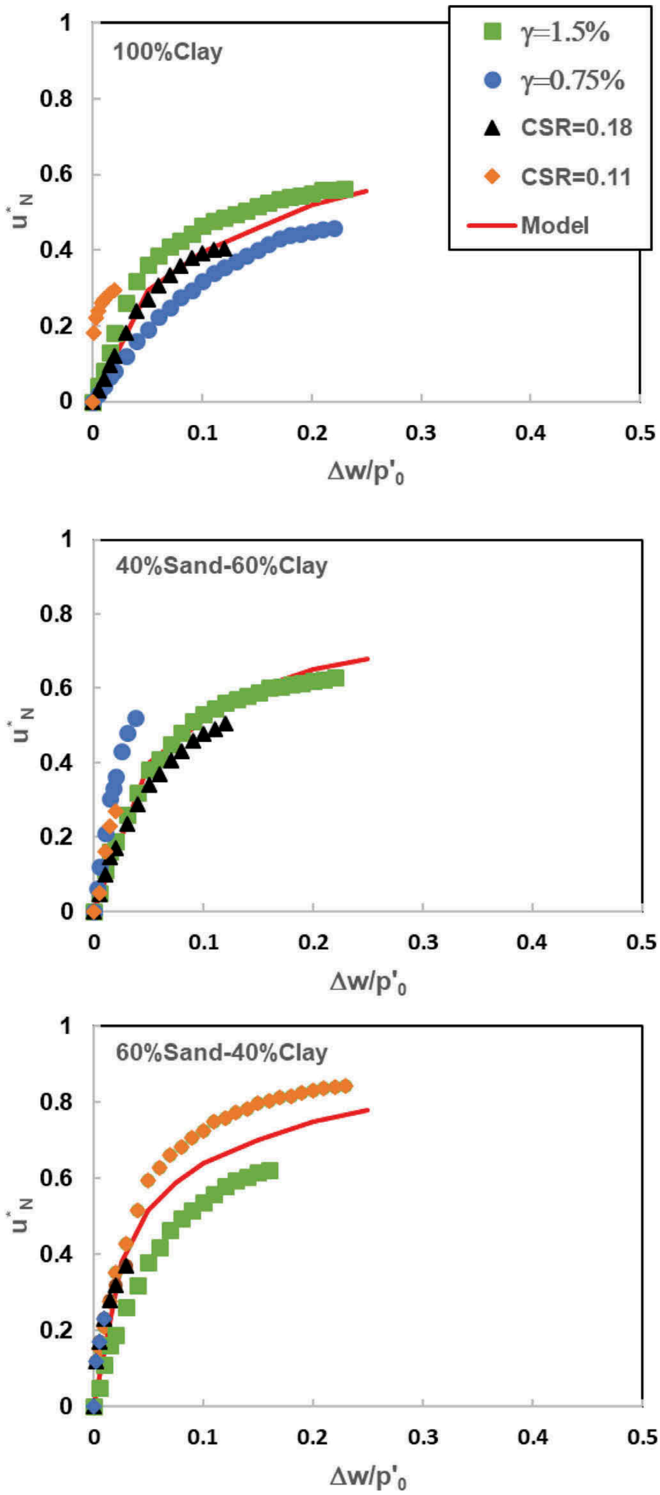

Figure 6. Correlation between excess pore pressure and dissipated energy in cyclic triaxial strain-/stress-controlled tests, γ is shear strain amplitude in strain-controlled tests (initial confining stress=500 kPa).

5 CONCLUSIONS

An experimental study using strain-, and stress-controlled cyclic triaxial and torsional shear tests was performed on compacted mixtures of sand-clay to investigate the effects of loading path on the excess pore pressure in the mixtures. It was found that when sand content is raised, excess pore pressure increases in cyclic strain-controlled tests, significant degradation occurs and stress path progressively moves toward the failure envelope. On the other hand, reverse trend is observed in cyclic stress-controlled tests, and pore pressure decreases with sand content. In stress-controlled tests pore pressure increases for a few cycles, with a minor degradation, after which the behavior is stabilized, in such a manner that almost no change in pore pressure and stiffness is observed. It was shown that more pore pressure is developed in triaxial tests compared to torsional shear tests. Finally, it was shown that dissipated energy can be successfully used to predict trend of excess pore pressure build-up in sand-clay mixtures, irrespective of loading path.

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