Effect of cyclic loading on undrained behavior of compacted sand/clay mixtures

H.R. TAVAKOLI [1], A. SHAFIEE [2] and M.K. JAFARI [3]

[1] *Ph.D. Student, Geotechnical Engineering Research Center, International Institute of Earthquake Engineering and Seismology, Tehran, Iran, tavakoli_hr@iiees.ac.ir*

[2] *Assistant Professor , Geotechnical Engineering Research Center, International Institute of Earthquake Engineering and Seismology, Tehran, Iran, shafieea@iiees.ac.ir*

[3] *Professor, Geotechnical Engineering Research Center, International Institute of Earthquake Engineering and Seismology, Tehran, Iran, jafari@iiees.ac.ir*

ABSTRACT :

Compacted aggregate/clay mixtures are frequently used as the core material of embankment dams all over the word. In the seismic zones, the post earthquake static stability of embankment dams, has great importance for the geotechnical engineers. During a seismic event, the compacted embankment material is expected to experience little, if any, strength and stiffness reduction during and shortly after the design earthquake. A series of undrained post cyclic triaxial compression tests after cyclic loading were performed on a medium plasticity sand/clay mixtures. Testing was performed on isotropically and anisotropically consolidated specimens to investigate the effectiveness of aggregate fraction on the mechanical behavior of the mixtures. In addition, monotonic triaxial compression tests were also performed on the same sand/clay mixtures with the same initial condition. The results point out different peculiarities which can be of interest in assessing the mechanical behavior of the mixtures under post seismic shaking. The results show that effect of cyclic loading on post cyclic pore water pressure build-up is significant when pore water pressure build-up is considerably lower than the associated value in monotonic loading. The effect of aggregate content on post cyclic pore water pressure build-up is miner. However, when the aggregate content increases the shear strength increases.

KEYWORDS: sand/clay mixtures; aggregate content; post cyclic; mechanical behavior; embankment dam.

1. Introduction

Compacted aggregate-clay mixtures are currently successfully used as the cores of embankment dams. These materials, called composite clays by Jafari and Shafiee (2004), are usually broadly graded and are composed of clay as the main body with sand, gravel, cobble or even boulders floating in the clay matrix. Miboro and Ohshirakawa dams in Japan (Asao, 1963), Taguaza dam in Venezuela (Sherard, 1981) and Karkheh dam in Iran are some examples of dams with cores composed of aggregate-clay mixtures.

It is also a current practice to employ a mixture of high plastic clay with aggregates as impervious blankets for waste disposal projects (Lundgren, 1981; Abeele, 1986; Chapuis, 1990; Pandian et al., 1995). It is generally assumed that the coarser fraction of such soils imparts a relatively higher shear strength, high compacted density and low compressibility while the permeability of the soil is governed by the proportion and nature of the finer fraction. This generally results in a relatively serviceable and trouble free fill (Garga and Madureira, 1985).

A review of the published literature (Hall,1951; Holtz and Willard,1956; Miller and Sowers,1957; Holtz and Ellis,1961; Patwardhan et al.,1970; Shakoor and Cook,1990; Vallejo and Zhou,1994; Muir Wood and Kumar,2000; Jafari and Shafiee,2004) reveals that experimental studies on aggregate-clay mixtures have mainly focused on monotonic shear strength parameters, 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 post-cyclic behavior of the mixtures subjected to cyclic loading. The present paper describes the post-cyclic characteristics of compacted sand-clay mixtures under monotonic compression loading paths.

2. Materials and Procedure

Materials tested: Pure clay with two mixtures of sand-clay was used in this study. The clay had a specific gravity of 2.70, liquid limit of 42%, and plasticity index of 18%. The grain-size distribution curve for the clay is shown in Fig. 1. X-ray diffraction analysis revealed that the clay was mainly composed of kaolinite with some illite, montmorilonite and quartz.

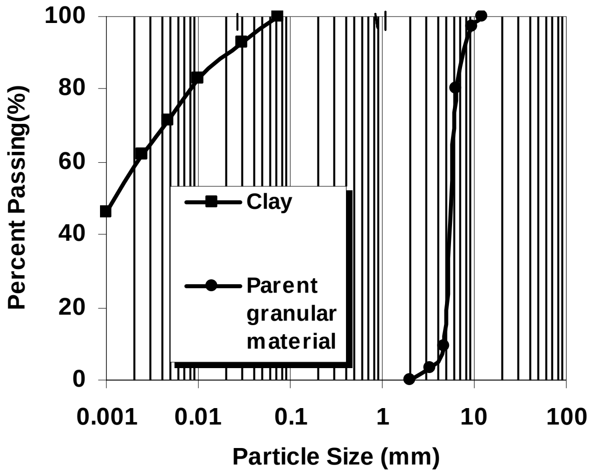

Figure 1: Particle size distribution of materials used in the study

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 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. The 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. Fig. 1 shows the grain-size distribution curve of the parent granular material from which the sand was sieved.

The clay was mixed with different amounts of sand to obtain different mixtures. Three mixtures were obtained by mixing 100%, 60% and 40% of clay with sand in volumetric proportions. A minimum of 40% clay content was considered since this is a limit value for materials used as cores in embankment dams.

Specimen preparation: 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 38 mm in diameter and 76 mm in height, were prepared with a dry density of 95% of the maximum dry density obtained from the standard compaction test method (ASTM D 698-00a, 2002) and water content of 2% wet of optimum. Table 1 presents the initial dry density and water content of the specimens.

Table 1. Specimen properties

Specimen	Initial dry density (gr/cm^3)	Initial water content (%)
clay	1.55	20.1
40%sand-60%clay	1.80	13.0
60%sand-40%clay	1.89	11.1

Appropriate amounts of clay and sand for each layer were first thoroughly mixed. Each layer was then mixed with water at least 24 hours before use and sealed. The material was poured in six layers into a cylindrical mold and compacted. To achieve a greater uniformity of specimens, a procedure similar to the undercompaction technique (Ladd, 1978) was used. For each layer, the compactive effort was increased toward the top by increasing the number of blows per layer. Each layer was then scored after it was compacted for better bonding with the next layer.

To reduce the effect of cap friction during the triaxial test, two thin rubber sheets coated with silicone grease were placed between the lower and upper porous stones and the specimen. Further, the sheets in contact with the specimen were divided into four sectors. This was done to let the specimen deform more easily in the lateral direction. Five drainage holes of about 5 mm in diameter were also provided in the rubber sheets to facilitate the saturation and consolidation process. The specimen preparation technique was verified when repeated testing of similar specimens yielded consistent results.

Test procedure: The specimens were saturated with a Skempton *B* value in excess of 97%. To facilitate the saturation process, CO_2 was first percolated through the specimens (this was more effective for saturation of the low clay content specimens), then de-aired water was flushed into the specimens. Lastly, a back pressure of 200 kPa was incrementally applied to accelerate the saturation rate. The specimens were then isotropically and anisotropically consolidated under vertical effective stresses of 100 and 500kPa ($k=\sigma'_3/\sigma'_1$=1 and 2/3).

Following consolidation, undrained cyclic triaxial tests were carried out under strain-controlled conditions for a number of cycles up to 50 and different cyclic shear strain amplitudes (γ=0.75% and 1.5%) with frequency 0.004 Hz. At the end of cyclic loading, the specimens are left to cure for one hour under zero shear stress. After curing, the specimens are monotonically sheared to failure in the undrained condition with axial strain rate of 0.01 mm/min. The loading rate was chosen so that pore pressure equalization throughout the specimen was ensured. For one test of each group, the undrained monotonic shear test is performed without cyclic loading effect, and the results obtained are used as a basis for comparison.

3. Test Results and Discussion

3.1. Undrained behavior during and after cyclic loading

When a normally consolidated sand-clay mixture specimen is subjected to strain-controlled undrained cyclic loading under triaxial conditions, positive excess pore pressure is generated. It is also found that the mean principal effective stress moves towards the critical state line (CSL). During undrained cyclic loading as is illustrated in Fig.2, a mixture specimen which has reached point B may behave in a similar manner to the over consolidated specimen produced by unloading from point D to point B (Matsui and Abe, 1981; Yasuhara et al., 1983; Yasuhara, 1985). A sand-clay mixture at point B can therefore be regarded as apparently overconsolidated. The undrained strength of an apparently overconsolidated sand-clay mixture may decrease depending on the OCR associated with the distance of point B from point A. When a mixture specimen did not reach a cyclic failure after a certain number of load cycles, monotonic loading was applied in order to investigate its post cyclic undrained static behavior. Figure 3 shows a typical set of relations between deviator stress and mean effective stress in cyclic and post-cyclic tests on sand-clay mixture specimens. Herein, the effective mean stress is defined as $p'=(\sigma'_1+2\sigma'_3)/3$, while the deviator stress is defined as $q=(\sigma'_1-\sigma'_3)$. As seen in Fig.3, stress path is affected by aggregate content significantly. It is also found that the mean principal effective stress moves towards the critical state line (CSL) and stress path is more expand. Where γ, σ'_{cv}, k are shear strain amplitude, consolidated vertical effective stress and consolidated ratio, respectively.

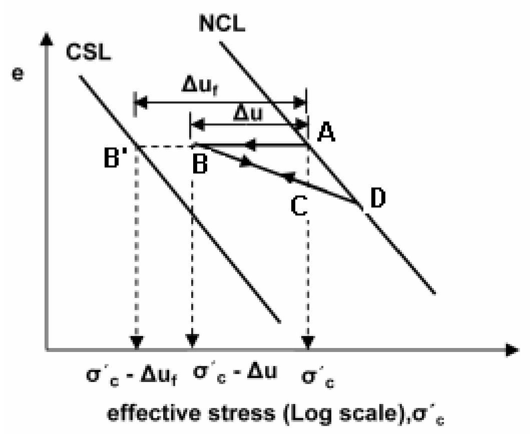

Figure 2: Void ratio versus mean effective stress representation during undrained cyclic loading by drainage (Matsui and Abe, 1981)

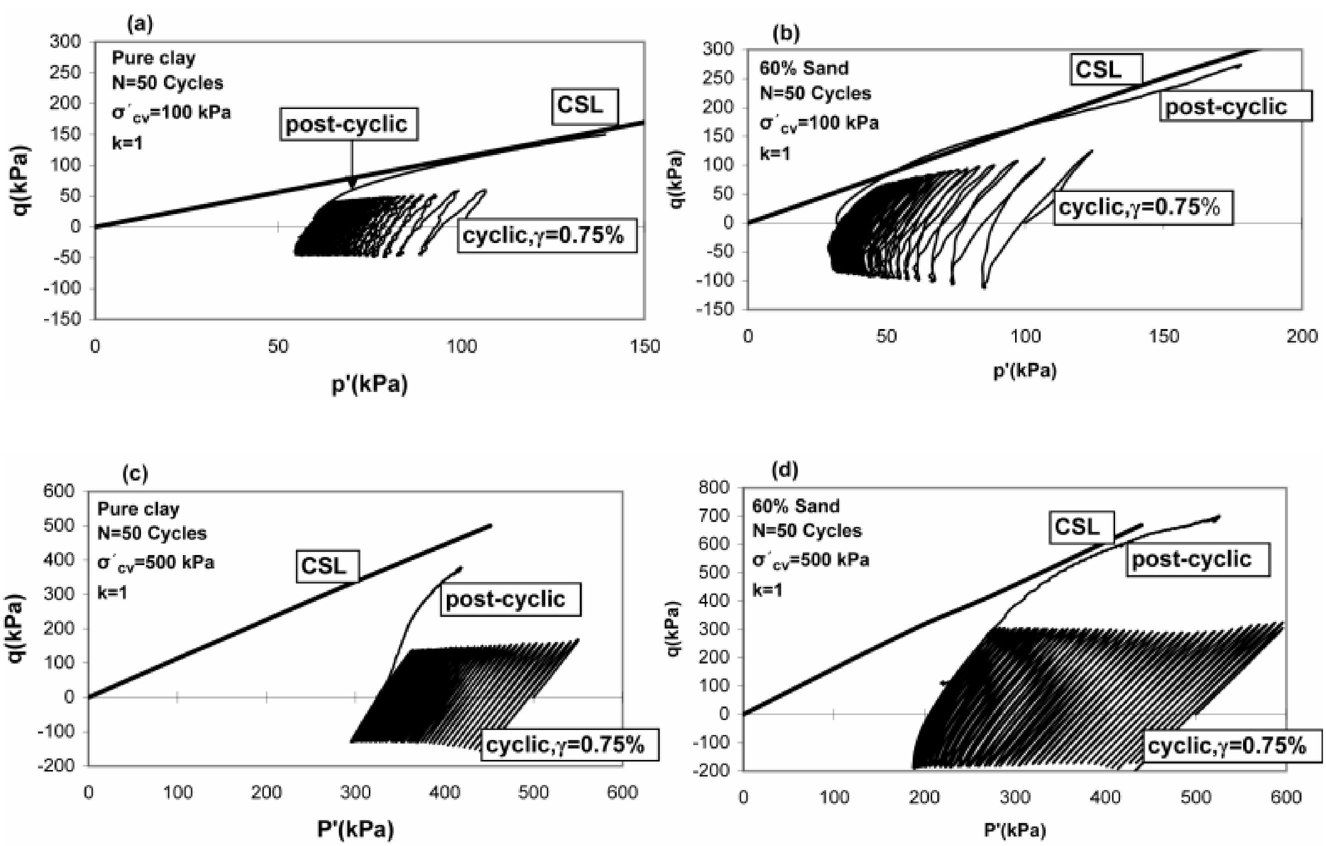

Figure 3: Deviator stress versus mean effective stress curves in cyclic and post-cyclic tests

3.2. pore pressure - strain Characteristics after cyclic loading

For a fundamental understanding of the post cyclic undrained behavior of sand- clay mixtures, it is prudent to observe the pore pressure generation pattern in the mixtures. Figure 4 compares excess pore pressure in terms of axial strain for all mixtures under compression monotonic and post cyclic loading paths. As shown, regardless of the initial confining stress, pore pressure in monotonic loading generally increases with sand content so that is highest for the mixture containing 60% sand and lowest for pure clay. The reason behind this behavior can simply be explained: since the compressibility of the clayey matrix is greater than for individual grains, all of the specimen deformations take place in the clay. Hence, during strain-controlled loading, the clayey matrix of the specimens containing more aggregate experiences more deformation for the same strain level, directly leading to more pore pressure generation. Similar observations were made by Jafari and Shafiee (2004) from the strain-controlled compression monotonic triaxial tests on sand-fat clay and gravel-fat clay mixtures. The results also reveal that the effect of cyclic loading on post cyclic pore water pressure build-up is significant when pore water pressure is considerably lower than the associated value in monotonic loading. In addition, the effect of aggregate content on post cyclic pore water pressure build-up is miner. However, when the aggregate content increases the shear strength increases.

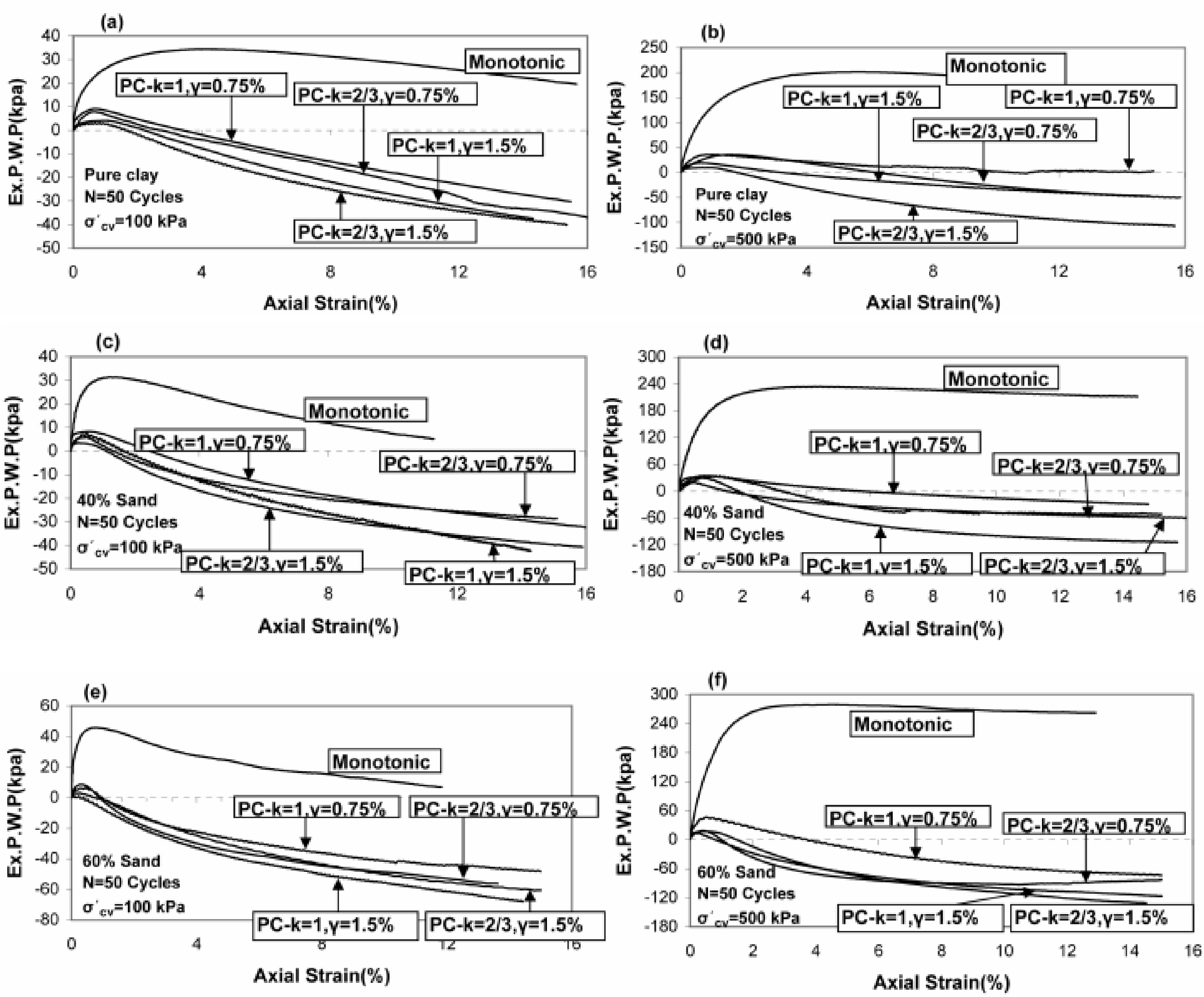

Figure 4: Excess pore pressure versus axial strain curves in Monotonic and post-cyclic tests

In addition, it can be concluded that the cyclic loading induced excess pore pressure or in other words apparent overconsolidation ratio is an important parameter that influences post cyclic behavior of sand-clay mixtures.
It is interesting to note that, in monotonic and post cyclic tests (Fig. 4), all specimens more and less exhibit a peak in pore pressure that is an indication of dilative behavior. The dilative behavior is more evident in post cyclic than monotonic tests and when sand content is raised and/or specimen is anisotropically consolidated (k=2/3), particularly at a low confining stress (i.e., 100 kPa). In addition, the axial strain to the peak decreases with sand content, however, the peak tends to migrate to higher strain levels with an increase in initial confining stress.

3.3. Effective stress path characteristics after cyclic loading

The interesting features of the behavior of compacted sand-clay mixtures, shown by the stress-strain and pore pressure-strain curves, can be better represented by effective stress paths. The effective stress paths for all mixtures in compression monotonic and post cyclic tests are presented in Figs. 5. These Figures show the effect of cyclic loading and sand content. For comparison the results of monotonic undrained tests on the mixtures are also plotted in these Figures. The Figures show that stress paths of sand-clay mixtures with apparent overconsolidation induced by cyclic loading are similar to sand-clay mixtures overconsolidated by a real unloading. As seen in Figs. 5, all specimens experience dilative behavior either on compression monotonic and/or post cyclic loading paths prior to critical state. In addition,

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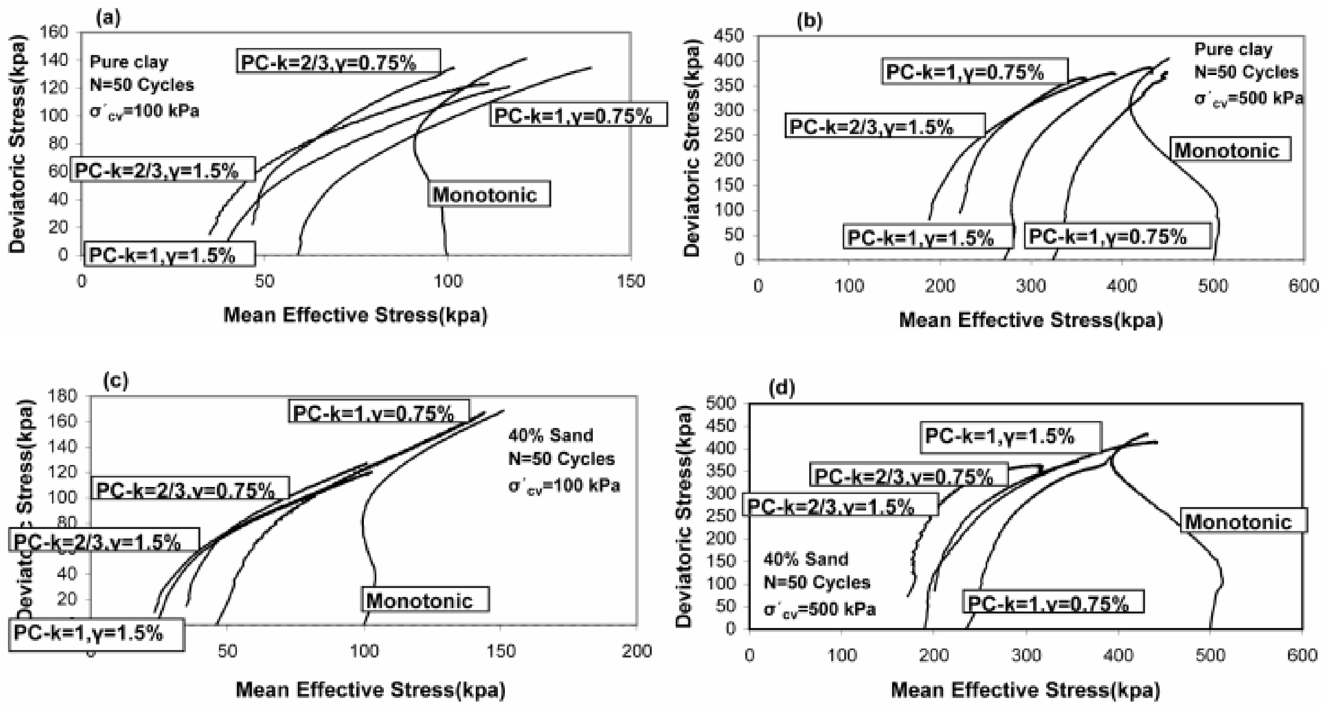

Figure 5: Effective stress path curves in Monotonic and post-cyclic tests

regardless of the sand content and initial stress state, the effective stress paths of post cyclic loading approaches the effective stress path of monotonic loading at high strain levels. In other words, it appears that strength parameters, φ´, and critical state parameter, M, are not influenced by a previous undrained cyclic loading history. Similar observations were made by Yasuhara, (1982, 1985) on Ariake clay.

3.4. Post cyclic degradation of strength and stiffness

Cyclic parameters during and after loading are commonly divided into two categories: strength and stiffness. These characteristics depend on the magnitude of cyclically induced pore pressures and shear strains.. Fig. 6 presents the ratio of undrained strength, $(S_u)_{pc}$, after cyclic loading to the monotonic undrained shear strength, $(S_u)_M$, against the normalized excess pore pressure. As can be seen, the reduction in undrained shear strength is generally less than 14% and 23% as long as the normalized excess pore pressure is less than 0.62 and o.88 for pure clay and 60% sand, respectively.

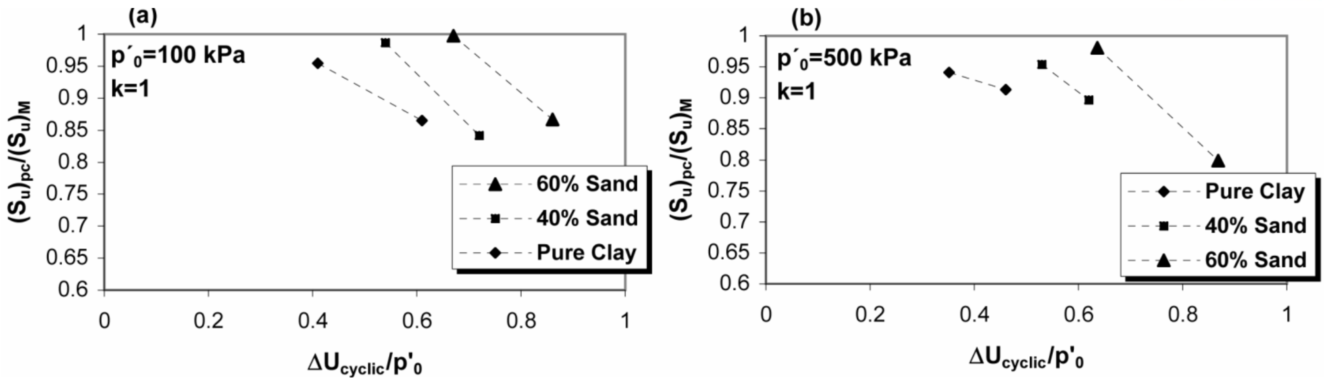

Figure 6: Undrained shear strength ratio versus normalized excess pore pressure

Fig. 7 also shows the ratio of secant deformation modulus, $(E_{50})_{pc}$, after cyclic loading to the modulus obtained from monotonic loading, $(E_{50})_M$, against the normalized excess pore pressure. As can be seen, the reduction in ratio of secant deformation modulus is generally less than 40% and 90% as long as the normalized excess pore pressure is less than 0.62 and o.88 for pure clay and 60% sand, respectively.

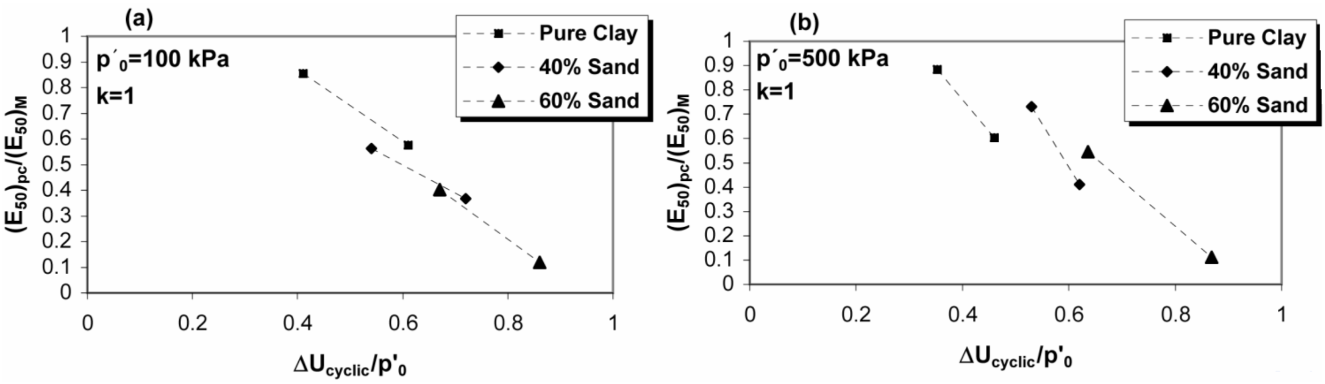

Figure 7: Secant deformation modulus versus normalized excess pore pressure

Test results (Figs. 6 and 7) also reveal that the reduction in the undrained shear strength due to cyclic loading effect is not significant as increasing the apparent overconsolidation, while the reduction in the deformation modulus or stiffness is significant.

4. CONCLUSIONS

In this paper, the undrained shear degradation of saturated compacted sand-clay mixture after strain-controlled cyclic loading have been discussed and clarified. The following conclusions may be drawn based on the experimental study:

1. The effect of cyclic loading on post cyclic pore water pressure build-up is significant when pore water pressure is considerably less than the associated value in monotonic loading. The effect of aggregate content on post cyclic pore water pressure is miner. On the other hand, the effect of aggregate content on cyclic pore water pressure build-up is significant.

2. Stress paths of sand-clay mixtures with apparent overconsolidation induced by cyclic loading are similar to sand-clay mixtures overconsolidated by a real unloading. All specimens experience dilative behavior either on compression monotonic and/or post cyclic loading paths prior to critical state.

3. Post cyclic degradation of compacted sand-clay mixtures is very sensitive to cyclic excess pore pressure

built-up. In particular, degradation in stiffness is more sensitive to cyclic excess pore pressure build-up than that in strength.

4. Post cyclic degradation in strength and stiffness depend on the excess pore pressure generation during cyclic loading that is affected by sand content and shear strain amplitude significantly.

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