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CYCLIC BEHAVIOR OF COMPOSITE CLAYS

Ali SHAFIEE[1], Mohammad Kazem JAFARI[2] and Najmeh JALALI[3]

SUMMARY

Composite clay is a mixture of clay, as the main body and aggregates which are floating within the clayey matrix. Cyclic undrained behavior of composite clays in its natural or compacted state e.g., core material of embankment dams has a great importance for the geotechnical engineers. A laboratory testing program was conducted on kaolin-gravel and kaolin-sand mixtures to investigate effects of aggregate on the cyclic behavior of the mixtures during strain-controlled cyclic loadings. Following experimental tests, an analytical approach was applied to see the behavior of composite clay cores for an actual case of embankment dams. Laboratory test results reveals, when aggregate content is raised pore pressure and shear modulus rise. Analytical results suggest that heterogeneous behavior of composite clays should be considered in design of embankment dams.

INTRODUCTION

Composite soils with properties between cohesive and granular materials are found in nature enormously. Composite clays are kind of composite materials, which are usually broadly graded and encompass clay to sand, gravel, cobble and even boulder, while the clayey matrix governs the mechanical behavior. It is a current practice to use composite clays as the core of embankment dams. Meanwhile a review of published literature reveals, although physical properties, such as consistency limits, compaction characteristics, dry density and permeability of aggregate-clay mixtures has been studied well (e.g., Seed et al. [1], Day [2], Hsu and Saxena [3] and Shelly and Daniel [4]), while its mechanical properties especially its dynamic properties received less attention. This may be due to the limitations for investigating behavior of composite clays embodies large grains in laboratory. Thus if it is necessary, laboratory triaxial tests could be accomplished on materials of modified gradation. This modification could even be reduced to conducting test only on pure clay with assumption of conservative estimation of mechanical soil properties. While Jafari and Shafiee [5] showed that in the case of cyclic undrained loading on compacted composite clays, this assumption is questionable. Therefore, a comprehensive laboratory testing program on this type of soils with different cohesive-non cohesive ratios and two different aggregate sizes were defined. The investigation described in this paper first presents the effects

[1] Assistant professor, International Institute of Earthquake Engineering and Seismology (IIEES), Tehran, Iran, e-mail: shafieea@iiees.ac.ir
[2] Associated professor, IIEES, Tehran, Iran
[3] M.Sc. student, IIEES, Tehran, Iran

of aggregate on behavior of compacted composite clays during cyclic triaxial undrained loading. Test results will be analyzed emphasizing the effect of aggregate content. Then an analytical approach were used to compare behavior of compacted composite clays for an actual case of embankment dams.

TESTED MATERIALS AND PROCEDURE

Seven types of clay-gravel and clay-sand mixtures were used in this study. Commercial kaolin clay was selected as the cohesive part. The kaolin had a specific gravity of 2.74 and its liquid limit and plasticity index were 69% and 38% respectively. Both the used sand and gravel were composed of subrounded aggregates with a specific gravity of 2.66. The soil passing sieve No.10 and remaining on sieve No.12 with a mean grain size of 1.84 mm was selected as sandy materials and the soil passing sieve No.1/4 and remaining on sieve No.4 with a mean grain size of 5.55 mm as gravelly materials. Kaolin was mixed with respective amounts of sand and gravel to obtain various mixtures. The seven samples of kaolin-aggregate were mixed in volumetric proportion and named as *K100*, *K80S*, *K80G*, *K60S*, *K60G*, *K40S* and *K40G*. The first letter is an abbreviation of Kaolin, second number is the volumetric clay percent in the mixture and the third letter indicates type of aggregate in the mixture (S for Sand and G for Gravel).

All the specimens, typically 50 mm in diameter and 100 mm in height were compacted in 6 layers, with a dry density of 95% of maximum dry density obtained from standard compaction test method (ASTM [6]) and water content of 2% wet of optimum. Table 1 presents the specimens initial dry density and water content. This type of specimen preparation may result in higher density of bottom layers, while authors attained layers of the same density by setting the number of hammer tips (Shafiee [7]).

Table 1. Specimens properties

Specimen type	Initial dry density (gr/cm^3)	Initial water content (%)
K100	1.35	32.0
K80S , *K80G*	1.42	27.0
K60S , *K60G*	1.57	21.4
K40S , *K40G*	1.69	16.8

The specimens were saturated with a Skempton B-value in excess of 95 %. Then specimens were isotropically consolidated under three different effective confining stresses of 100, 300 and 500 kPa. Following consolidation, undrained cyclic triaxial tests were carried out under strain-controlled condition. Strain-controlled approach were preferred over stress-controlled for cyclic loading tests, since previous researches strongly suggest that shear strain is a more fundamental parameter for studying pore pressure generation than shear stress (Matasovic and Vucetic [8]). Tests were performed under shear strain amplitudes of 0.75% and 1.5%. A sine loading frequency of 0.01 Hz was applied for specimens tested at confining stress of 100 kPa while a frequency of 0.005 Hz used for confining stresses of 300 and 500 kPa. The loading frequency was chosen so that pore pressure equalization through specimen was ensured. The tests were continued until 50 cycles of loading.

PORE PRESSURE GENERATION

A typical test result is shown in figure 1, conducted on a specimen of 40% sand content (i.e. K60S) at confining stress, σ'_{3C} of 500 kPa and a shear strain amplitude, γ_c of 1.5%. γ_c is computed as 1.5 times of axial strain, ε_a. A reduction in deviatoric stress will occur when loading proceeds, as seen in figure 1, meanwhile normalized pore pressure, will increase. Figures 2 and 3 show variation of u_r^* (which is pore pressure normalized to initial confining stress and computed where shear strain is zero) in terms of number of loading cycles, *N* in kaolin-gravel mixtures for shear strain amplitudes, of 1.5% and 0.75% at various initial confining stresses. The results are presented for cycles number 2, 5, 10, 20, 30, 40 and 50. As seen, it is apparent that irrespective of exerted γ_c and initial confining stress, higher pore pressure is generated for the soils with higher aggregate content. Thus u_r^* is highest for *K40G* specimens and lowest for *K100* ones. To see whether the observed trend can be extended to other types of composite clays, test results for kaolin-sand mixtures are shown for γ_c of 1.5% and 0.75%, through figures 4 and 5. As seen, similar observations hold for kaolin-sand mixtures and any increase in sand content apparently causes more u_r^* to be developed. Herein u_r^* is highest for *K40S* specimens and lowest for *K100* ones.

DEFORMATION PROPERTIES

Deformation properties including shear modulus were estimated for different mixtures. Figure 6 show variation of shear modulus, G versus number of loading cycles, N for kaolin-gravel and kaolin-sand mixtures, for a typical γ_c of 0.75% and σ'_{3C} of 100 kPa. As seen in both figures, adding aggregates causing shear modulus to be increased. An interesting feature seen in these figures is that mixtures containing more aggregates, due to higher pore pressure generation (see figures 2 to 5) show more decrease in shear modulus when loading proceeds.

ACTUAL CASE OF EMBANKMENT DAMS, AN ANALYTICAL APPROACH

The previous findings regarding pronounced effect of aggregate content on pore pressure generation during cyclic loading deserves more attention especially for practical applications. To discuss this matter more carefully, Masjedsoleiman embankment dam in Iran which has a core of composite clay was selected. The height of the dam is 170 m from riverbed, while its crest length is 480 m. Figure 7 shows a cross section of the dam modeled by the PLAXIS code [9]. Table 2 summarizes the important mechanical properties for the different embankment dam materials. As shown in this table, three different types of core materials were used: A-a core composed of pure clay, B-an homogeneous core containing 40 percent aggregates, named *K40* and C-an heterogeneous core composing of 60% pure clay and 40% aggregate blocks (in this case aggregates modeled as rigid blocks separately) . To see response of the dam with different cores, it was subjected at the foundation base, to an accelogram of the type shown in figure 8. Then pore pressure response of the dam at a point 60 meters above the foundation level (see point A in figure 7) were monitored. Table 3, presents maximum excess pore pressure, $\Delta u_{\max}$ developed in each case. As shown in table 3, with the assumption of homogeneous core, less pore pressure developed in the core composed of *K40* with respect to that of pure clay. This observation which is in contrast with the cyclic triaxial test results (see figures 2 to 5) is due to the stiffer mechanical properties of *K40* with respect to *K80* (see table 2). Meanwhile, table 3 shows that for the heterogeneous case (i.e. when clay

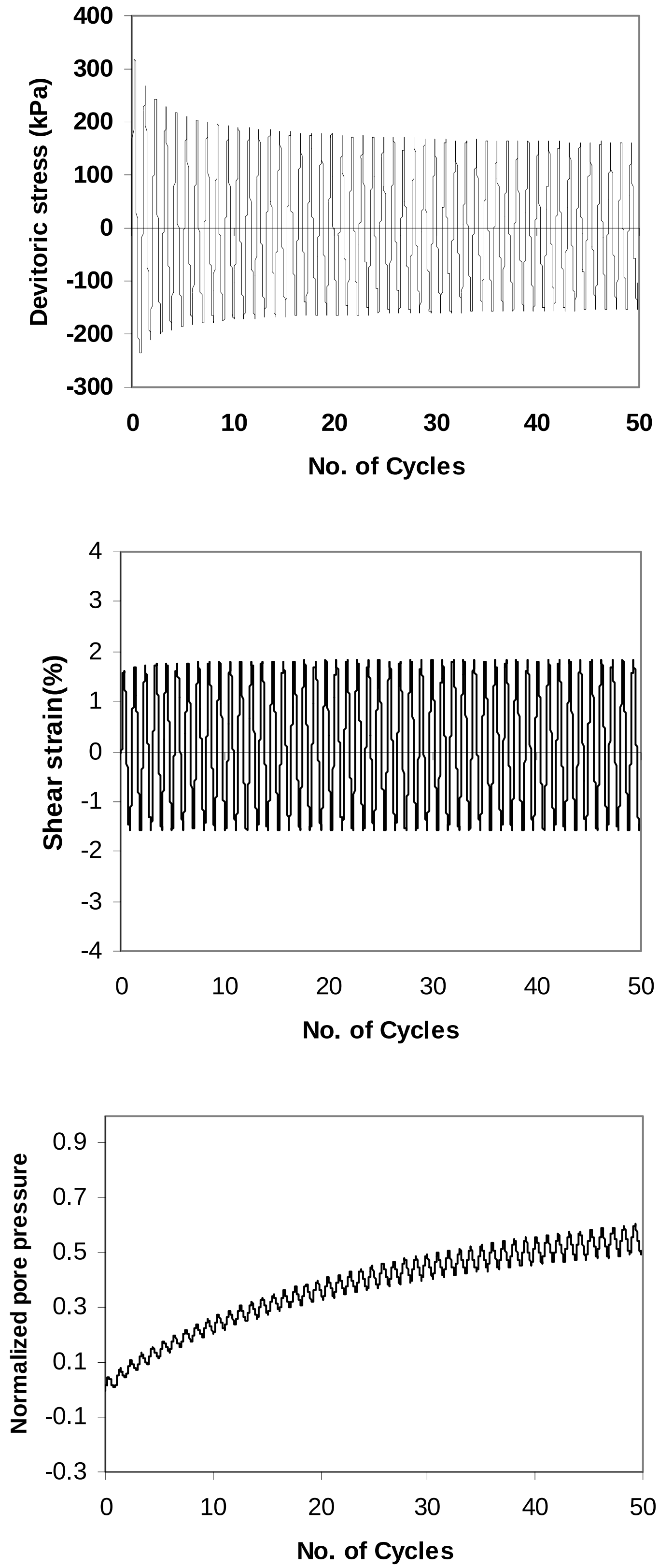

Figure 1: A typical result of cyclic triaxial tests on *K60S* at σ'_{3C} of 500 kPa and γ_c of 1.5%

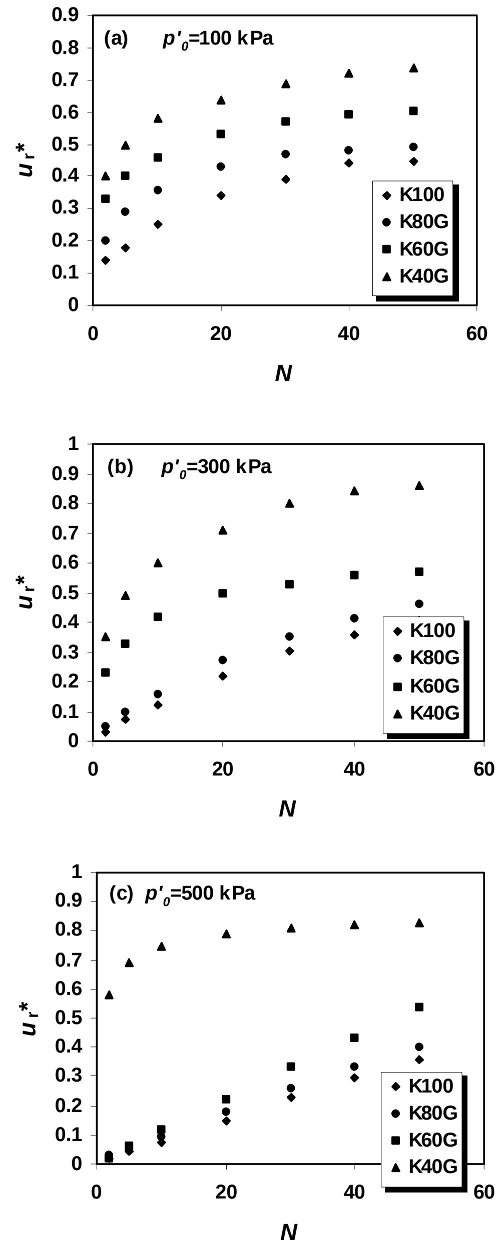

Figure 2. Variations of u_r^* in kaolin-gravel mixtures at different confining stresses, $\gamma_c = 1.5\%$

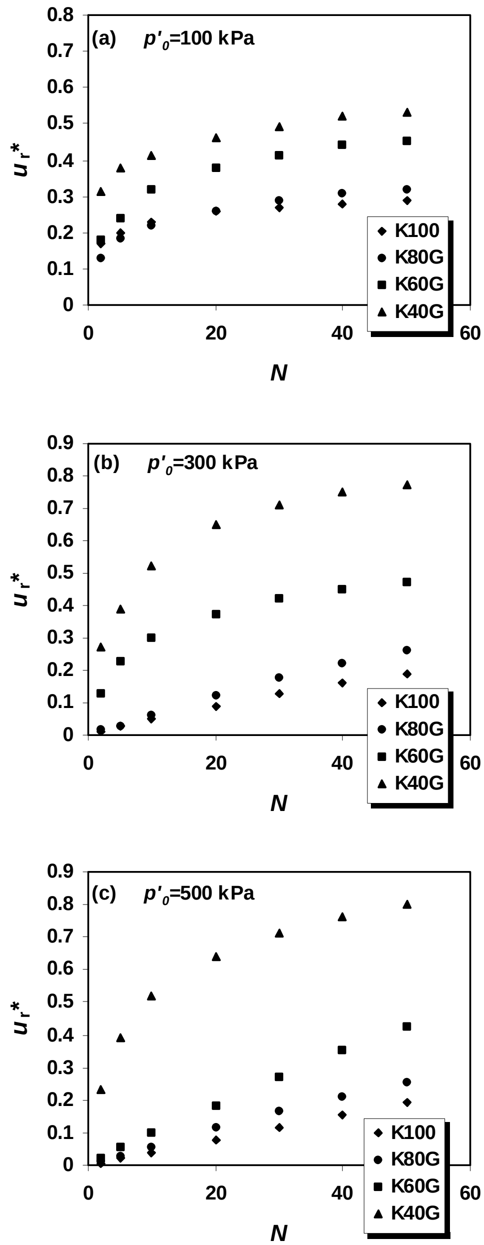

Figure 3. Variations of u_r^* in kaolin-gravel mixtures at different confining stresses, $\gamma_c = 0.75\%$

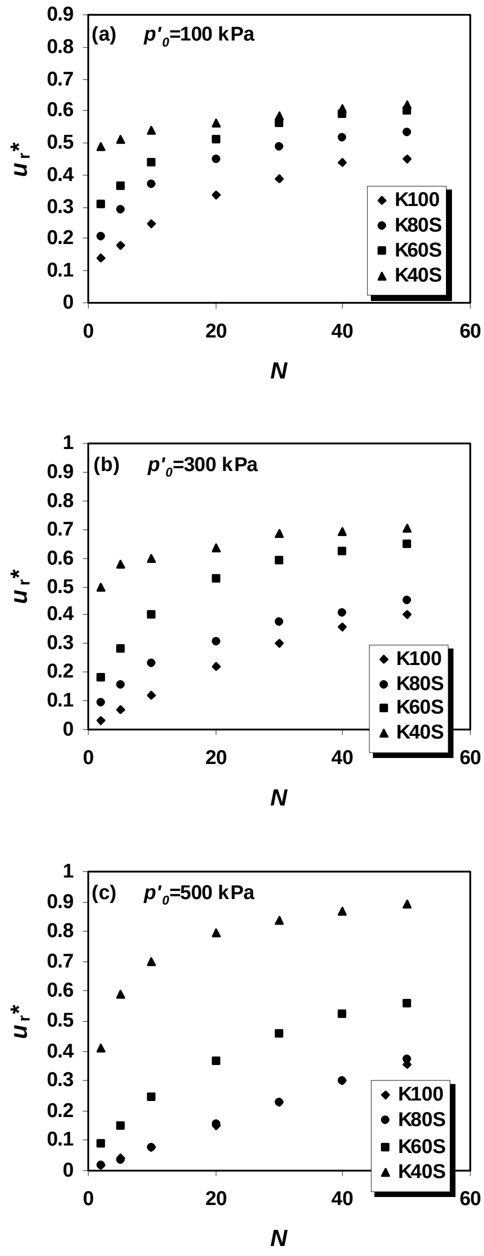

Figure 4. Variations of u_r^* in kaolin-sand mixtures at different confining stresses, $\gamma_c = 1.5\%$

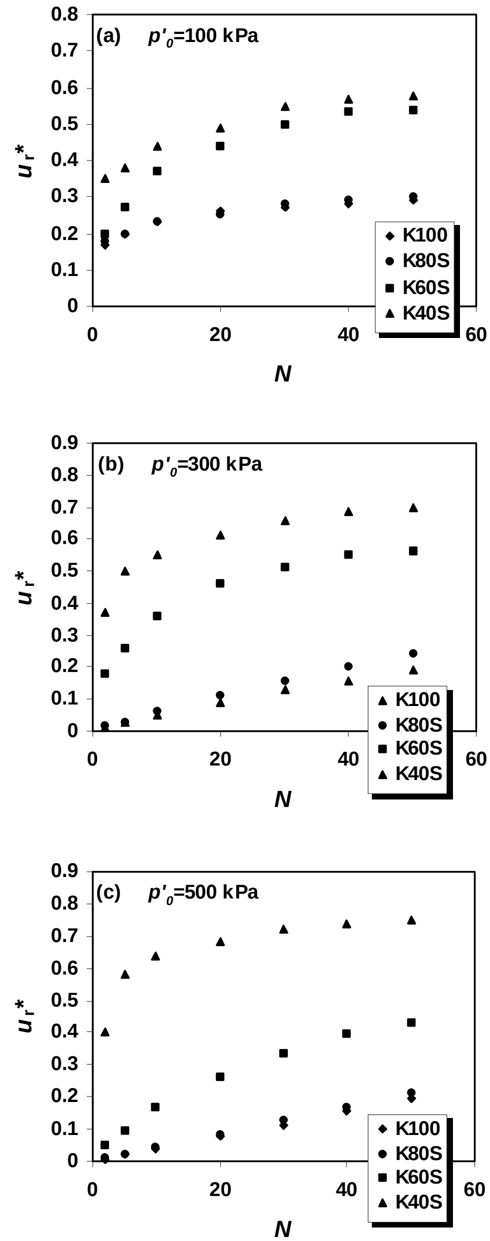

Figure 5. Variations of u_r^* in kaolin-sand mixtures at different confining stresses, $\gamma_c = 0.75\%$

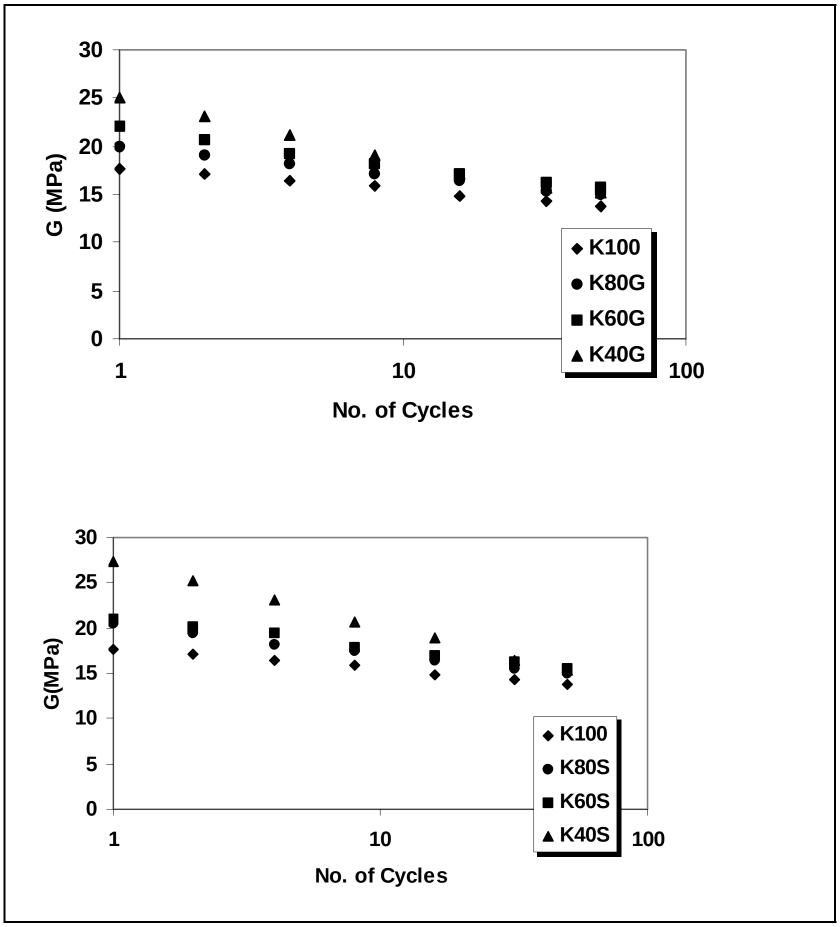

Figure 6. Shear modulus versus number of loading cycles, for kaolin-gravel and kaolin-sand mixtures, for a typical γ_c of 0.75% and σ'_{3C} of 100 kPa.

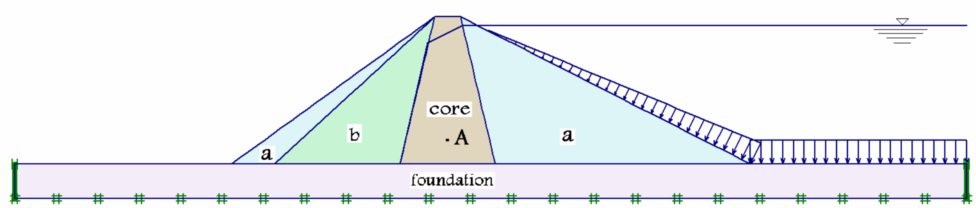

Figure 7. **A cross section of the Masjedsoleiman dam modeled by the PLAXIS code**

Table 2. Mechanical properties of dam materials

	Material model	Young modulus (kPa)	Poisson's ratio	Cohesion (kPa)	Friction angle (°)
Foundation	Elastic	$1.09*10^7$	0.30	-	-
Shell, a	Mohr-Coulomb	$8.60*10^4$	0.35	0.20	45.0
Shell, b	Mohr-Coulomb	$6.40*10^4$	0.35	0.20	41.0
Core- pure clay	Mohr-Coulomb	$1.75*10^4$	0.35	0.20	24.7
Core-*K40*	Mohr-Coulomb	$3.28*10^4$	0.35	0.20	33.0
Aggregate blocks	Elastic	$2.10*10^7$	0.10	-	-

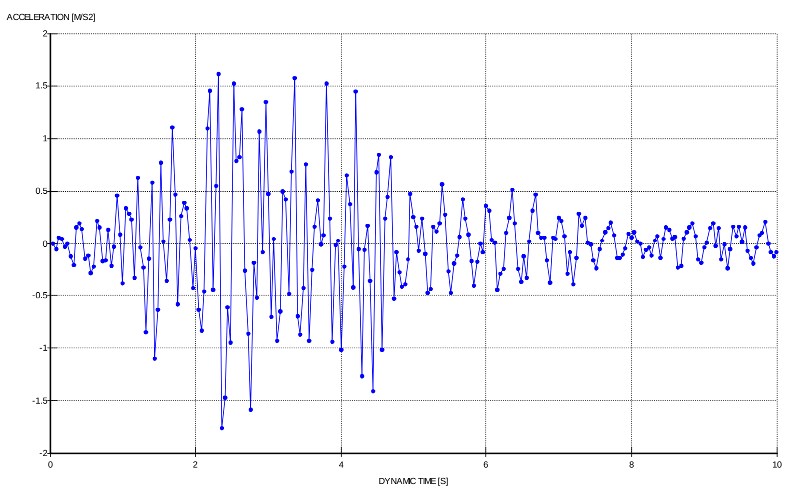

Figure 8. Accelerogram applied at the foundation base

and aggregates modeled separately), results are consistent with laboratory tests. As seen, for the heterogeneous case, $\Delta u_{\max}$ is about 3.5 times more than that of *K80*. This shows that inappropriate modeling of composite clays behavior can mislead designers.

Table 3. maximum excess pore pressure for different cores

	$\Delta u_{\max}$ (kPa)
Pure clay	23.0
Homogeneous core, *K40*	7.6
Heterogeneous core, 60% clay+40%aggregate blocks	67.0

CONCLUSIONS

An experimental study followed by an analytical approach was performed on the compacted mixtures of kaolin-sand and kaolin-gravel at different initial confining stresses to investigate effect of aggregate on the mechanical behavior of the mixtures during cyclic loading. The following conclusions may be drawn based on this experimental study:

1. Increasing aggregate content either gravelly or sandy, causes more pore pressure to be developed;
2. Increasing aggregate content causes shear modulus to be increased. An interesting feature is that mixtures containing more aggregates, due to higher pore pressure generation show more decrease in shear modulus when loading proceeds;
3. Inappropriate modeling of heterogeneous behavior of core materials of embankment dams can mislead the designers;
4. Analytical results are consistent with experimental results, only when pure clay and aggregates modeled separately.

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