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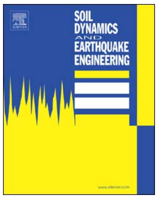

Influence of index properties on shape of cyclic strength curve for clay-silt mixtures

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ABSTRACT

Failures initiated in clay layers during recent earthquakes have emphasized the need to understand the cyclic behavior of clays. To systematically study the cyclic behavior, seventeen soils, prepared as mixtures of kaolinite and montmorillonite with quartz, and twelve natural soils were tested in a cyclic simple shear device. Cyclic strength curves were developed for 2.5%, 5% and 10% double amplitude shear strains. These curves were used to examine the influence of mineralogical composition, plasticity characteristics and shear strain on the cyclic resistance of the mixtures. A power function was used to represent the cyclic strength curves. Based on the results of this study, the mixtures were found to become increasingly resistant to cyclic loading as the plasticity index increased. Moreover, the soils with montmorillonite as the clay mineral were noted to have consistently higher cyclic resistance than the soils with kaolinite as the clay mineral. By examining the power functions, it was found that the cyclic strength curve became increasing flatter as the plasticity index increases in soils having kaolinite as the clay mineral. However, the opposite trend is observed in soils having montmorillonite as the clay mineral. The results presented in the literature for 37 soils were compared with those obtained in this study and found to be in good agreement.

1. Background

Seismic design currently focuses on addressing problems associated with liquefaction of sands. Sangrey and France [1] noted that knowledge of the peak strength of clays after cyclic loading is needed in many situations including the design of structural foundations after an earthquake, stability of slopes and foundations subjected to wave loads, and the loading on soils as a result of traffic. Although clays are often considered to be stable under earthquake conditions, there are several documented failures involving clay layers following an earthquake. A few amongst these failures are the Anchorage Landslide following the 1964 Alaska Earthquake [2,3], the damage to the Moss Landing Marine Laboratory after the 1989 Loma Prieta Earthquake [4], and the severely damaged buildings founded on clays following the 1985 Mexico Earthquake [5]. These case histories have demonstrated the need to address the current deficiencies in the understanding of the cyclic behavior of clays.

Recently, several studies have begun looking at the effect of different factors, including plasticity, overconsolidation, the magnitude of initial static shear stresses, and the characteristics of the cyclic loading functions on the cyclic behavior of cohesive materials. The results are briefly summarized in Table 1. As can be observed in Table 1, the results presented in the literature can be contradictory. For example, Bray and Sancio [6] and Bray et al. [7] tested undisturbed soils from Adapazari, Turkey in both cyclic simple shear and cyclic triaxial apparatuses and used the results to develop *cyclic strength curves* (plots of number of cycles versus the cyclic stress ratio, *CSR*) at constant confining pressures of 40 kPa and 50 kPa. They observed that cyclic strength curves could not be successfully generated for soils with plasticity indices greater than 18 as these soils were unable to generate significant cyclic strains even after a large number of cycles. However, for soils with plasticity indices less than 18, two generalized cyclic strength curves were developed. The first cyclic strength curve represented the *cyclic resistance*, a measure of a soil's ability to withstand cyclic loading, of the soils with plasticity indices less than 12; while the second curve represented the cyclic resistance provided by soils with plasticity indices greater than 12, but less than 18. Moreover, from the results presented, the cyclic resistance of the soils with plasticity indices between 12 and 18 was higher than the cyclic resistance provided by the soils with plasticity indices less than 12. Guo and Prakash [19],

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Table 1
Summary of the effect of various factors on the cyclic resistance of cohesive materials.

Factor Increased	Cyclic Resistance	Reference and Condition
Confining Pressure or Consolidation Pressure	Increase	(a) for soils with the same plasticity index [6,7]
		(b) for marine clays from Bohai Bay, China [8]
	Decrease	(a) for normally consolidated soils subjected to the same frequency of loading [9]
Overconsolidation Ratio	Increase	(a) for Drammen clay with a constant preconsolidation pressure [10,11]
		(b) based on empirical equations used to estimate the cyclic stress ratio and the cyclic resistance ratio for a magnitude 7 earthquake [12]
		(c) for Keuper marl silt with a constant initial void ratio [13]
Loading Frequency	No effect	(a) for a standard test material with a constant initial density and confining pressure [14,15]
		(b) for soils under constant confining pressures subjected to the same number of cycles of loading [16]
	Increase	(a) for batch consolidated laboratory prepared kaolin samples [17]
		(b) for normally consolidated Bangkok clay samples under constant confining pressures at 5% double amplitude shear strain [9]
		(c) for isotropically consolidated soils under constant confining pressures [18]
		(d) for marine clays under constant confining pressures [8]
Plasticity Index	Increase	(a) for soils under constant confining pressures after the same number of cycles of loading [6,7,19]
		(b) for soils with a constant initial void ratio [20]
		(c) under a constant confining pressure after 30 cycles of loading at 1 Hz [21]
		(d) for normally and isotropically consolidated soils [22]
	Decrease	(a) for soils with a constant initial void ratio [20,23]
		(b) for soils with constant initial densities [24,25]
	No effect	(a) for normally and isotropically consolidated soils subjected to a constant frequency of loading [26]
Initial Static Shear Stress	Increase	(a) for soils subjected to a constant confining pressure after 30 cycles of loading [20]
		(b) for normally consolidated Bangkok clay samples subjected to a constant confining pressure after 5% double amplitude shear strains [9]
		(c) for Drammen clay samples [11]
	Decrease	(a) for intact samples with a constant overconsolidation ratio after a fixed number of cycles of loading [27]
Number of Cycles or Shear Strain	Increase	(a) for soils subjected to a constant confining pressure and constant initial static shear stresses [21]
		(b) for intact samples subjected to a constant initial static shear stress and overconsolidation ratio [27]
		(c) for soil specimens compacted at 98% of the maximum dry density with an initial moisture content 2% wet of the optimum under constant confining pressures [28]
Pore Pressure	Decrease	(a) for soils subjected to a constant confining pressure and constant initial static shear stresses at 100 cycles of loading [29]
		(b) for kaolin clay under confining pressures of 100 kPa at a constant initial void ratio [30]

from the results in El Hosri et al. [23], presented the effect of the plasticity index on the cyclic strength curves of silts and mixtures of silts and clays at an initial void ratio of 0.644. They noted that for soils with plasticity indices less than 5, the cyclic resistance decreased as the plasticity index increased. However, for soils with plasticity indices greater than 5, the cyclic resistance was observed to increase as the plasticity index increased. Sandoval [24] and Prakash and Sandoval [25] also showed that the cyclic resistance decreased as the plasticity index is increased from 2 to 4 in soils with constant initial densities.

Nabeshima and Matsui [31] tested Toyoura sand mixed with non-plastic and plastic fines at constant relative densities in a stress-controlled cyclic torsional shear device. They surmised that the addition of kaolin clay to Toyoura sand caused a weakening of the soil skeleton, accelerating the process required to cause flow liquefaction or equivalently, a reduction in cyclic resistance. However, cyclic resistance increased when Toyoura sand was mixed with non-plastic fines as it resulted in an increase in the density of the soil for a given effective stress. Chang et al. [32], Dezfulian [33], and Amini and Qi [34] also showed that the addition of silt to sand will increase the cyclic resistance of the sand at a given void ratio. On the contrary, Shen et al. [35], Troncoso and Verdugo [36], Troncoso [37], Finn et al. [38] and Vaid [39] presented results for a constant dry density showing that adding silt to sand will reduce the cyclic resistance of the sand. Beroya et al. [40] concluded that the dominant clay mineral in mixtures of silt with clay significantly influences the cyclic behavior of the silt. They noted that the cyclic resistance was dependent on the plasticity index, but the plasticity index was not a direct indicator of the influence of mineralogy. Kuwano et al. [41] also showed that the mineralogy of the fines is an important parameter to consider in order to completely understand the cyclic behavior of clays. Both Beroya et al. [40] and Kuwano et al. [41] concluded that further research is needed to thoroughly understand the effect of mineralogy on the cyclic resistance of clays. However, little research has been conducted to this end.

The inconsistency in the measured behavior of clays under cyclic loading may be due to the limited number of soils tested. In most of the articles, the conclusions were made based on test results from only one or two types of materials. Further inconsistency in the behavior noted in the literature could be a result of the differences that arise from the choice of various parameters (such as definitions of cyclic stress ratio and failure, frequency of loading, amplitude of loading, etc.) used by the researchers. In some cases, the parameters were not clearly defined so that the cyclic behavior could be understood. To resolve some of these inconsistencies, this study presents a systematic evaluation of the effect of the plasticity characteristics, mineralogical composition and shear strain on the cyclic behavior of clay-silt mixtures.

2. Materials and methods

Seventeen different mixtures of kaolinite with quartz and sodium montmorillonite with quartz were prepared in the geotechnical engineering laboratory of California State University, Fullerton. The kaolinite and montmorillonite used in this study were purchased commercially from Ward's Natural Science, and the quartz was purchased from Pacific Coast Chemicals. The montmorillonite used in this study contained 96% pure montmorillonite with the remaining 4% composed of chlorite, illite/mica, kaolinite and quartz. Similarly, the kaolinite used contained about 95% pure kaolinite. Of the remaining 5%, about 4% was quartz and the remaining 1% contained smectite, chlorite and illite/mica. Using the procedure outlined in the ASTM *Standard Test Method for Particle Size Analysis* [42], hydrometer analyses were conducted on the minerals used in this study. Fig. 1 shows the resulting grain size distribution curves. The maximum particle size of the montmorillonite used was 0.075 mm. For the kaolinite used, the maximum particle size was about 0.02 mm. About 80% of the particles in the montmorillonite used in this study were finer than 0.002 mm. In the kaolinite used, approximately 70% were finer than 0.002 mm. The