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Monotonic and cyclic simple shear response of gravel-sand mixtures

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ABSTRACT

Understanding the factors that affect the monotonic and cyclic response of gravelly soils during earthquake events is critical to infrastructure design. In this study a large-size Cyclic Simple Shear (CSS) device was utilized to perform monotonic and cyclic shear tests on mixtures of either subrounded 9 mm Pea Gravel or angular 8 mm Crushed Limestone (CLS8) with subrounded Ottawa C109 sand. Tests were performed in constant volume conditions and shear wave velocity was measured for each specimen. Monotonic and cyclic test results at D_r = 47% show that there is an optimum mixture percentage that results in the greatest shear strength and resistance to liquefaction (40% Sand for Pea Gravel Mixtures and 60% Sand for CLS8 Mixtures). The effects of particle angularity, cyclic stress ratio, and initial vertical stress on monotonic and cyclic response of loose and dense gravel mixtures were investigated and are presented. Comparison of the results from the cyclic simple shear tests with existing liquefaction triggering charts suggests the need for improved charts for gravelly soil liquefaction evaluation.

1. Introduction

Understanding the response of gravelly soils during seismic events is critical to robust performance-based design. Historical (1964 Alaska, USA; 1975 Haicheng, China; 1976 Tangsham, China; 1983, Borah Peak Idaho, USA; 1994 Armenia; 1995 Kobe, Japan) as well as recent earthquakes (2008 Wenchaun, China; 2014 Cephalonia, Greece; 2016 Kaikoura, New Zealand) have demonstrated that gravelly soils are susceptible to liquefaction [1,13–15,24,30]. However, the response of gravelly soils both during and following seismic events is not well understood as there are few well-documented case histories and limited laboratory test data. To properly design and evaluate gravelly soil sites for liquefaction susceptibility, a study of the factors that affect gravelly soil shear response under a variety of conditions is needed.

Laboratory testing of soils allows for the investigation of parameters that affect shear response under controlled conditions and parametric evaluations can be performed for loading scenarios where field case-history data is sparse. Several studies have evaluated the monotonic and cyclic shear response of gravelly soils. Holtz and Gibbs [17] performed consolidated drained triaxial tests on mixtures of sand and gravel with different percent gravel contents and found that the shear strength of gravelly soils increased with increasing the gravel content up to 50–60%. The authors also found that increasing particle angularity increased the shear strength of the gravelly soil. Rashidian [25] performed a study of sand and gravel mixtures prepared very loose (relative density less than approximately 20%) and showed that during undrained monotonic loading specimens with up to 90% gravel content displayed a contractive behavior. Chang and Phantachang [7] performed constant load monotonic simple shear tests on angular crushed aggregates mixed with either poorly-graded or well-graded sand in different percentages. The authors concluded that gravelly soils can be categorized as either sand-like, gravel-like, or in-transition based on gravel content. In both the well-graded and poorly-graded mixtures, increasing gravel content reduced shear resistance. Initial vertical stress was shown not to have an effect on the normalized shear stress ratio (τ/σ'_v), which ranged from 0.40 to 0.60 for the drained simple shear tests.

The cyclic response of gravelly soils has also been investigated in the laboratory. Wong et al. [29] studied the liquefaction response of gravelly soils using large-scale triaxial tests and concluded that uniform gravels exhibit slightly higher resistance to liquefaction than well-graded gravelly soils, but that membrane compliance affected the measured response. Banerjee et al. [3] performed cyclic triaxial tests on dense gravelly soils from Oroville dam and found that the dense gravel exhibited many similarities to dense sand under cyclic loading. Specimen preparation technique was found to have little effect on shear response. Evans and Seed [9] tested Watsonville gravel in triaxial devices, and found that the cyclic stress ratio (CSR) for liquefaction in 10

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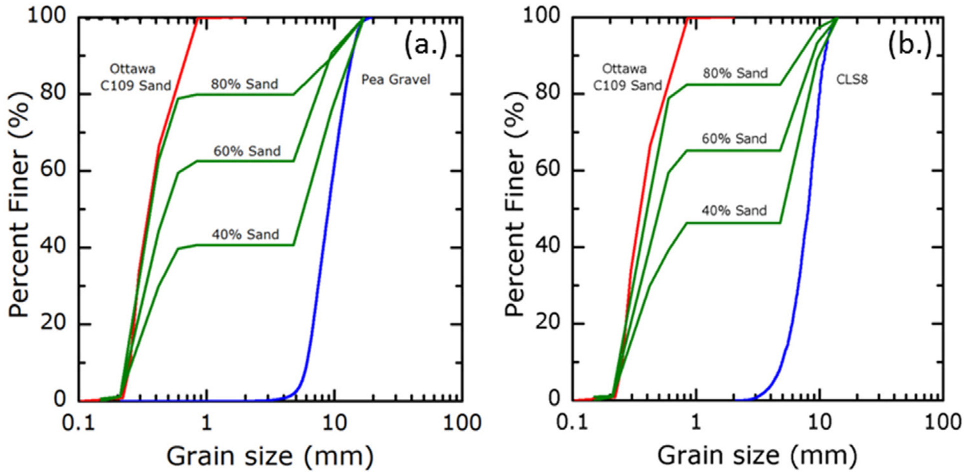

Fig. 1. Grain Size Distributions for (a) Pea Gravel mixtures and (b) CLS8 mixtures.

cycles was only 0.143. Evans et al. [10] showed that membrane compliance in the triaxial apparatus can overestimate liquefaction resistance by as much as 40%. Hatanaka et al. [16] tested Masado fill that liquefied during the 1995 Kobe earthquake and found that despite its high dry density and gravel content, the gravel fill liquefied at CSRs from 0.15 to 0.23 which is similar to Toyoura sand tested at a relative density of 70%. Evans and Zhou [11] performed undrained triaxial tests of gravel-sand mixtures with gravel contents ranging from 0% to 60% and found that the inclusion of gravel particles increased the liquefaction resistance. Kokusho et al. [22] evaluated the undrained cyclic and post-cyclic shear strength of granular soils with different particle gradations utilizing a triaxial test apparatus. The authors found that the liquefaction strength of well-graded granular soils is similar to poorly-graded sands with identical relative densities. Chang et al. [6] performed cyclic simple shear tests of gravel-sand mixtures with a D_{50} value for the gravels of 5.3 mm. The authors found that the transition from sand-like to gravel-like response was in the 50–70% gravel content range. The authors measured shear wave velocity (V_S) of each specimen and found that adding gravel to sand-like specimens increased V_S. A comparison of cyclic data with Andrus and Stokoe [2] showed that the Andrus and Stokoe [2] curve, which is based on field-liquefaction case history data, should be shifted to lower values of V_{S1}. In summary, while laboratory testing of gravelly soils has been undertaken, most testing has been performed using triaxial devices (which are prone to membrane compliance issues) and the influence of several parameters (particle angularity, density, vertical stress) still remains to be investigated. Study of these parameters aids in the understanding of gravelly soil response that has been observed in the laboratory (including uniform gravel tests in [18]) and in the field (with limited data) during earthquake events.

A large-size Cyclic Simple Shear (CSS) device was utilized to perform monotonic and cyclic shear tests on mixtures of either subrounded 9 mm Pea Gravel or angular 8 mm Crushed Limestone (CLS8) with subrounded Ottawa C109 sand. Tests were performed at constant volume conditions and shear wave velocity of each specimen was measured for comparison between test data and existing relationships for liquefaction evaluation [2,21,5]. This paper presents some of the first cyclic simple shear data for gravel-sand mixtures, and provides an evaluation of parameters that affect the shear response of gravelly soils under monotonic and cyclic loading conditions.

2. Test materials and methods

2.1. Test equipment

A large-size Cyclic Simple Shear (CSS) device developed at the University of Michigan in collaboration with a laboratory equipment manufacturer was utilized to evaluate the monotonic and cyclic response of gravelly soils. The CSS specimen is 307.5 mm in diameter and the specimen height can range from approximately 100 mm to 120 mm. The development and validation of the CSS device is presented in detail in Zekkos et al. [31]. In addition to monotonic and cyclic, stress or strain controlled, constant load or constant volume simple shear testing, V_S measurements using bender elements and miniature accelerometers can be conducted. In this research, accelerometers were utilized for shear wave velocity measurements since they were found to yield identical V_S values with bender elements, but the latter were getting damaged often by the gravelly soils. Details of the accelerometer setup and measurement is given in Hubler [20] and Zekkos et al. [31].

2.2. Test materials

The materials tested in this study included a uniform sand (Ottawa C109 sand) and two uniform gravels (9 mm Pea Gravel and 8 mm Crushed Limestone (CLS8)). These uniformly-graded materials were extensively tested (and the results are presented in [18]) before studying gravel-sand mixtures of Pea Gravel with Ottawa C109 sand and CLS8 with Ottawa C109 sand. Gravel-sand mixtures were prepared at mixture percentages (by weight) of 80% Sand/20% Gravel, 60% Sand/40% Gravel, and 40% Sand/60% Gravel. These mixtures will be referenced by their sand percentage throughout this paper. Two different types of gravels of similar size were used for testing so that effects of particle angularity could be assessed. The grain size distributions of the Pea Gravel mixtures are given in Fig. 1a, while the grain size distributions of the CLS8 mixtures are given in Fig. 1b. The 80% Sand, 60% Sand, and 40% Sand specimens have gap-graded distributions for the Pea Gravel mixtures and CLS8 mixtures. The relevant properties of the Pea Gravel and Ottawa C109 sand mixtures are given in Table 1, and the properties of the CLS8 and Ottawa C109 sand mixtures are given in Table 2. The evaluation of the maximum density of gap-graded

Table 1
Properties of Pea Gravel/Ottawa C109 sand mixtures.

Properties	Pea Gravel	60% Gravel/ 40% Sand	40% Gravel/ 60% Sand	20% Gravel/ 80% Sand	Ottawa C109 Sand
G_S	2.74	2.70	2.69	2.67	2.65
$\gamma_{d,max}$ (kg/m^3)	1741	2114	1978	1848	1733
$\gamma_{d,min}$ (kg/m^3)	1546	1960	1818	1665	1512
e_{max}	0.772	0.379	0.477	0.602	0.752
e_{min}	0.574	0.279	0.358	0.443	0.529