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Determination of seismic compression of sand subjected to two horizontal components of earthquake ground motions

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ABSTRACT

The objective of this Technical Note is to investigate the ratio of seismic compression of sand subjected to two mutually perpendicular horizontal components of earthquake ground motions simultaneously to its counterpart for single component of horizontal motions. By using a verified, fully coupled and inelastic finite element procedure, sand specimens with various relative densities (Dr=45%, 60% and 100%) are subjected to each of the horizontal components of motion separately, and then simultaneously, with the vertical strains and corresponding ratio computed for each case. In total, 296 shallow crustal horizontal motions (i.e. 148 sets of horizontal motions) with various earthquake magnitudes, site to source distances, durations, and site conditions recorded in active tectonic regions are used in the analyses. The results showed that the ratio generally ranges from 1.52 to 2.32, and it increases with earthquake magnitude and relative density of sand but decreases with epicentral distance. These results can be used in conjunction with seismic compression correlations for single component of motion to estimate its counterpart for multiple components of motion, thereby increasing the accuracy in predicting the severity of seismic compression under multi-directional seismic motions.

1. Introduction

The accrual of contractive volumetric strains in unsaturated soils caused by cyclic loading is defined as the seismic compression, which has been recognized as one of the main causes of significant damages to buildings and other structures during earthquakes (e.g., Refs. [1–3]). As a result, in the past decades, a large amount of studies have been carried out to understand seismic compression and to predict its magnitude. On the one hand, several approaches for predicting the severity of seismic compression were proposed by other researchers (Refs. [2,4,5]). On the other hand, a series of laboratory studies have been carried out to understand the effects of environmental and compositional factors on the magnitude of seismic compressions (Refs. [1,3,6,7]).

However, most of existing studies are limited to the seismic compression based on one component of horizontal earthquake motions, while during earthquakes the ground usually moves in more than one horizontal direction, resulting in shaking that varies not only in magnitude but also in direction. To account for the effect of multi-dimensional loading, traditionally, the seismic compression computed for one dimensional loading is increased by a constant coefficient of two that was recommended by Pyke et al. [6]. This constant coefficient was determined on the basis of a very limited number of analyses and inherently assumes that the motions in the two directions are similar, without considering the effects of the characteristics of earthquake motions as well as soil properties.

The objective of this Technical Note is, therefore, to investigate the ratio of seismic compression for two, mutually perpendicular horizontal components of earthquake ground motions simultaneously imposed on a soil specimen to its counterpart for one component of horizontal motion. Due to the difficulty of most existing apparatuses in applying multi-directional loads, in this study, a verified, fully coupled and inelastic finite element procedure incorporating the reduced order bound surface hypo-plasticity model is employed. Firstly, the model is calibrated using cyclic direct simple shear test data for dry, Silica No. 2 sand. Secondly, the calibrated numerical soil model is then subjected to each of the horizontal components of motion separately, and then simultaneously, with the vertical strains and the corresponding ratio computed for each case. In total, 296 shallow crustal horizontal motions with various earthquake magnitudes, site to source distances, durations, and site conditions recorded in active tectonic regions are used in the analyses and the results are presented and discussed.

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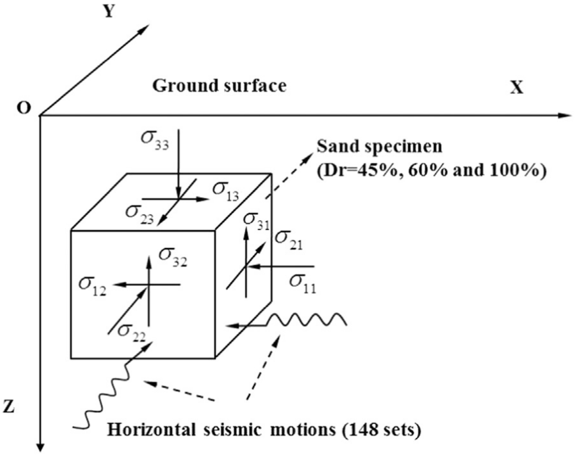

Fig. 1. Modelling of sand specimen subjected to horizontal seismic motions.

2. Numerical analysis

2.1. Verified numerical procedure and constitutive model

Due to the limitations of most existing apparatuses in the capability of applying multi-directional loads, especially for the random seismic motions on the soil specimens, a verified, fully coupled and inelastic finite element procedure SUMDES (Ref. [8]) is employed. The capability and application of this procedure in performing dynamic response analysis of site under multidirectional earthquake shaking has been successfully verified by comparing the predictions with both field and centrifuge records (Refs. [9,10]). A fully nonlinear, fully coupled dynamic response analysis of soil under multidirectional loading conditions, therefore, could be performed using this procedure. The constitutive model employed in this study is a reduced-order bounding surface hypoplasticity model (Refs. [8,11]), which is capable of realistically simulating the soil behavior under a wide range of loading conditions such as the compression- and dilation-induced effective stress change.

2.2. Database of input motions

To investigate the effects of multiple seismic motions on the seismic compression of soil, simple shear tests performed on sand with various relative densities under multi-directional seismic motions are simulated as shown in Fig. 1. It was reported by several researchers that only slight densification occurs when a vertical acceleration less than 1*g* is applied alone, therefore, the current study mainly focus on the seismic compression of sand induced by horizontal ground motions only. To take into account of the effects of the characteristics of earthquake motions, 296 shallow crustal horizontal motions (i.e., or 148 sets of horizontal motions) with various earthquake magnitudes, site to source distances, durations, and site conditions recorded in active tectonic regions are used in the analyses. The database is from the strong ground motion data for active shallow regions (Ref. [12]). These recordings are from worldwide shallow crustal earthquakes near active plate margins; subduction and intraplate events are excluded. The selection criteria were categorized by: site condition, earthquake magnitude, site to source distance, and duration. The ground motion data was then sorted into three bins according to moment magnitude (M): 5–6; 6–7; and 7+. Further sorting into four bins was made based on site-to-source distance (R): 0–10 km; 10–50 km; 50–100 km; and 100–200 km. The groups of the input motions are shown in Table 1. In order to obtain shear strain time histories from the above database of earthquake acceleration time histories, a dynamic site response analysis was performed by Lee [13] using the equivalent linear site response code SHAKEVT. Strain-controlled shearing tests are then simulated.

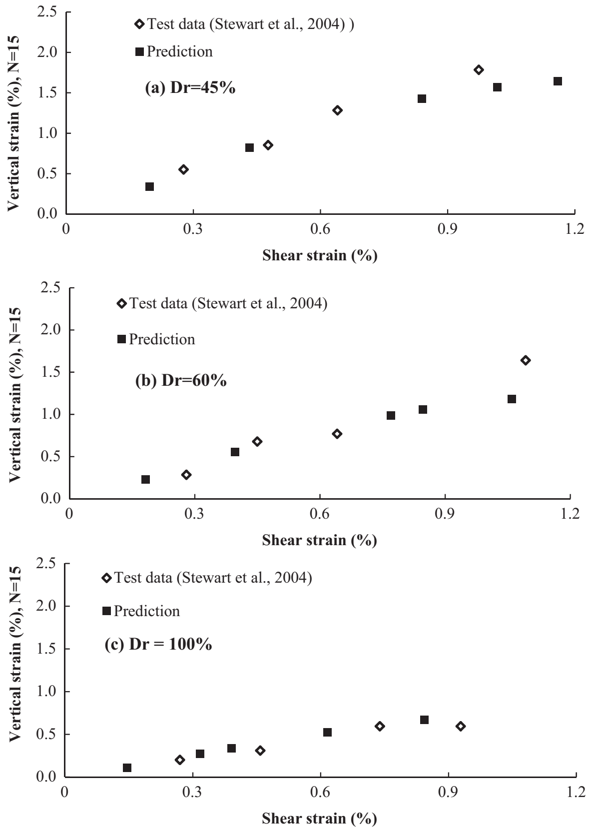

Fig. 2. Comparison of the predictions of vertical strain against shear strain with the test results for clean Silica No. 2 sand specimen with various relative densities (a) Dr=45%, (b) Dr=60% and (c) Dr=100%.

Table 1
Groups of input earthquake records used in the study.

Magnitudes range *M*	Range of epicentral distance *R*/km	Magnitudes *M*				Epicentral distance *R*/km				Group no
		Mini. value	Max. value	Median value	Mean value	Mini. value	Max. value	Median value	Mean value	
5–6	0–50	5.0	6.0	5.40	5.50	8.2	36.6	12.20	17.29	15
	50–100	6.0	6.0	6.00	6.00	52.4	78.3	65.30	64.88	15
6–7	0–50	6.0	6.9	6.40	6.39	11.8	49.9	31.35	31.29	45
	50–100	6.0	6.7	6.60	6.38	51.6	86.6	65.30	66.12	15
	100–200	6.0	6.8	6.70	6.66	51.6	124.7	86.60	89.03	15
7–8	0–50	7.1	7.6	7.40	7.38	14.3	48.7	33.80	31.48	20
	50–100	7.3	7.6	7.60	7.49	51.7	96.8	71.60	76.88	11
	100–200	7.3	7.6	7.60	7.49	102.8	199.1	128.40	135.03	12