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Dynamic centrifuge tests of structures with shallow foundations on soft clay reinforced by soil-cement grids

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Abstract

Centrifuge model tests are used to examine the dynamic response of structures supported by shallow foundations on soft clay reinforced by soil-cement grids. The centrifuge models involved a deep, lightly over-consolidated clay profile with three different soil-cement grid configurations. Structures on square shallow foundations were located over the central part of each soil-cement grid system. The models were subjected to multiple shaking events with peak base accelerations ranging from 0.006 to 0.546 g. The recorded responses of the structures and reinforced soil profiles were used to define the dynamic moment-rotation-settlement responses of the shallow foundations across the range of imposed shaking intensities. While the soil-cement grids were effective at controlling foundation settlements in most cases, the more significant foundation settlements which developed for the weakest soil-cement grid configuration under the stronger shaking intensities produced a rocking response of the structure and caused extensive crushing of the soil-cement below the edges of the shallow foundations. Analysis methods for predicting the demands imposed on the soil-cement grids by the inertial loads from the overlying structures and the kinematic loading from the soil profile's dynamic response are evaluated for consistency with the observed damage patterns. The experimental data have been archived and provide a basis for future studies to evaluate numerical and design analysis methods.

Keywords: Soil-cement grid reinforcement; Dynamic response; Single degree of freedom system; Rocking foundation; Dynamic kinematic loads; Inertial loads (**IGC:** E08/E01/E12/E14)

1. Introduction

Soil-cement ground reinforcements can be an effective means for the mitigation of earthquake-induced ground displacements and foundation settlements for a range of structure types, soil conditions, and seismic motions (e.g., Kitazume and Terashi, 2014; Bruce et al., 2013). Soil-cement ground reinforcements may be constructed as discrete columns or grid systems using deep mixing methods (DMM), trenching, jet grouting, or other methods. The seismic response and performance of soil-cement reinforcements have been studied using case histories (e.g. Tokimatsu et al., 1996; Yamashita et al., 2012; Tokunaga et al., 2015), dynamic centrifuge model tests (e.g. Adalier

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et al., 1998; Kitazume and Maruyama, 2006; Ishikawa and Asaka, 2006; Rayamajhi et al., 2014; Takahashi et al., 2006), and numerical analyses (e.g. Namikawa et al., 2007; Bradley et al., 2013; Nguyen et al., 2013; Puebla et al., 2006). Although these studies have demonstrated the effectiveness of soil-cement reinforcement for a range of situations, the data required to develop or validate design methodologies for all situations encountered in practice is insufficient.

A schematic of possible damage to a soil-cement grid supporting a structure on a shallow foundation during seismic loading is shown in Fig. 1. Damage to the upper portion of the soil-cement grid could be caused by excessive shallow foundation contact stresses that develop under the inertial loads from the overlying structure (Fig. 1a). Damage throughout the soil-cement grid could be the result of the excessive dynamic kinematic loads that develop because of the stiffness contrast between the grid and surrounding soils (Fig. 1b). Currently available experimental and case history data do not provide sufficient information to quantify the possible effects that partial damage to the soil-cement grids, by either of the mechanisms illustrated in Fig. 1, may have on their ability to limit shallow foundation settlements.

This paper summarizes the results of centrifuge model tests examining the dynamic response of structures supported by shallow foundations on soft clay reinforced by soil-cement grids. The models were designed to examine the ability of the soil-cement grids to limit the settlement of the shallow foundations even when the dynamic loading causes significant damage to the soil-cement grids. The centrifuge models examined a 23-m-thick (prototype), lightly over-consolidated clay profile with three different soil-cement grid configurations: an "embedded" soil-cement grid that penetrated the underlying dense sand layer and had an area replacement ratio $A_r = 24\%$, an "embedded" grid with $A_r = 33\%$, and a "floating" grid in the upper half of the clay layer with $A_r = 33\%$. A 2.3-m-thick (prototype) bearing layer of coarse sand was placed over the grid-reinforced clay profile. Structures on square shallow foundations were then placed over the central part of each soil-cement grid system. The models were subjected to 13 shaking events with peak base accelerations (PBAs) ranging from 0.006 to 0.546 g. The dynamic responses of the structures and reinforced soil profiles are described, including the dynamic moment-rotation-settlement responses of the shallow foundations across the range of imposed shaking intensities. Damage to the soil-cement grids, which included extensive crushing near the edges of the shallow foundations and minor cracking at larger depths for the weakest soil-cement grid at the strongest shaking intensities, is described and related to the observed foundation settlements. Methods for predicting the demands imposed on the soil-cement grids by the inertial loads from the overlying structures and the kinematic loading from the soil profile's dynamic response are evaluated for consistency with the observed damage patterns. The results of these model tests and analyses provide insights on the response of soil-cement grids supporting structures on shallow foundations in soft clay deposits. The experimental data have been archived and provide a unique basis for future studies to further evaluate numerical and design analysis methods.

2. Centrifuge models

Two centrifuge tests were performed using the 9-m radius centrifuge at the University of California at Davis and the data archived for general distribution (Khosravi et al., 2015c,d,e). All tests were performed at a centrifugal acceleration of 57 g. The recorded data and model dimensions were converted into prototype units according to the scaling laws as described by Kutter (1995). All data are presented in prototype units unless otherwise specified.

All tests were performed in a hinged-plate model container. This container allows large and permanent shear strains while limiting lateral strains under static loading. The inner dimensions of the container in model scale were 1,755 mm long (100.0 m in prototype), 650 mm wide (37.0 m in prototype), and 516 mm tall (29.4 m in prototype). A 3-mm-thick rubber membrane (model scale) was attached inside the container to make it water tight.

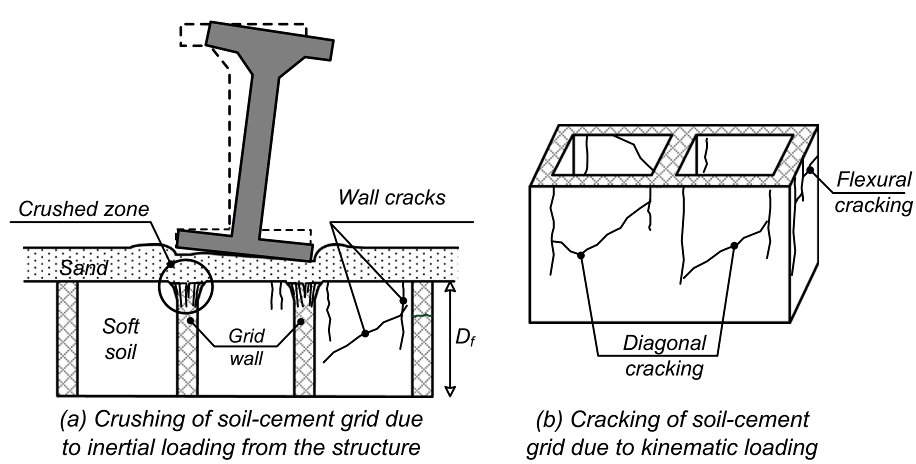

Fig. 1. Schematic of possible damage to a soil-cement grid supporting a structure on a shallow foundation during seismic loading.

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