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Centrifuge modeling of mitigation-soil-foundation-structure interaction on liquefiable ground

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ABSTRACT

Significant progress has been made in recent years toward a better understanding of the liquefaction phenomena. Yet, the combined effects of excess pore pressure generation, permanent soil deformation, and ground shaking, with and without mitigation, on the performance of the soil-foundation-structure system remain poorly understood. Moreover, there is a lack of physical model studies incorporating these important effects for a range of conditions to validate numerical models. This paper presents an experimental study of the performance of 3-story structures with shallow foundations on a saturated soil profile including a thin liquefiable layer. The influence of three different mitigation techniques was evaluated: 1) ground densification; 2) enhanced drainage with prefabricated vertical drains (PVDs); and 3) reinforcement with in-ground structural walls. Densification was observed to slightly reduce excess pore pressures and permanent foundation settlement and tilt, but amplified the demand transferred to the superstructure. Use of PVDs reduced permanent foundation settlement and rotation by reducing the duration of large excess pore pressures, but amplified roof accelerations and flexural drift. The performance of the stiff structural wall depended on the properties of the earthquake motion. During more intense, longer-duration motions, confining the soil and inhibiting flow inside the structural wall led to liquefaction, larger settlements, and larger translational and rotational accelerations on the foundation. In this case, the dissipation of seismic energy through additional foundation movements reduced the moment-rotation demand on the columns. These experimental results emphasize the importance of evaluating the potential tradeoffs of liquefaction mitigation, which may reduce settlement and sometimes tilt, but result in larger transient drifts and damage to the superstructure.

1. Introduction

The risk of damage to the built environment from liquefaction is significant. As an example, more than 50% of city of Christchurch in New Zealand was affected by soil liquefaction during the 2011 earthquake, where soil settlement and lateral displacement caused buildings, especially those on shallow foundations, to settle, tilt, deform, and spread laterally [12,9]. Many of these structures were uneconomical to repair and were therefore demolished. To reduce such losses and impacts in future earthquakes, there is need for economical and innovative technologies to improve liquefaction mitigation for design of new structures and retrofit of existing structures.

Significant progress has been made in recent years to understand the phenomenon of liquefaction and its consequences. Nevertheless, the available simplified procedures do not account for: 1) the influence of structures on pore pressure generation, settlement, and accelerations in soil; 2) the combined effects of liquefaction-induced permanent soil deformation and ground shaking on the performance and damage potential of buildings; or 3) the effects of liquefaction mitigation on the response of the soil-foundation-structure system. The tradeoffs associated with liquefaction mitigation – which may potentially reduce settlement and tilt, but also amplify ground shaking and shaking-related damage to the superstructure – are not well understood. Moreover, there is a lack of physical model studies incorporating these important effects that can be used to validate advanced numerical models. These deficiencies prevent the reliable evaluation of the effectiveness of various mitigation techniques to reduce overall risk and improve the performance of the overall system.

In this paper we describe dynamic centrifuge experiments conducted at the University of Colorado Boulder (CU) to evaluate soil-foundation-structure interaction (SFSI) effects on multi-degree-of-freedom (MDOF), potentially-inelastic building structures on a liquefi-

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able deposit with different mitigation techniques. First, we discuss the development and design of the centrifuge models. Then, we examine the results of centrifuge experiments to evaluate the influence of three types of mitigation on the performance of one type of structure and soil profile.

In these experiments, a three-story steel moment-resisting frame structure on a stiff mat foundation was placed on a layered soil profile, including a thin liquefiable layer. The three mitigation types considered were ground densification, prefabricated vertical drains (PVDs), and in-ground structural walls. The response of the mitigation-soil-foundation-structure system was examined in terms of accelerations, pore pressures, and settlements in the far-field and near the structure, as well as the effects of kinematic and inertial interaction near the structures. The effectiveness of the different mitigation techniques was evaluated in terms of permanent and transient foundation settlement and tilt, roof and interstory transient drifts, floor accelerations, and moment-rotation behavior at the column fuses. The experimental results presented in this paper aim to provide insight into the potential tradeoffs of liquefaction mitigation in the context of building performance and damage potential. The two experiments are a part of a larger experimental-numerical study with different building structures, soil conditions, and mitigation strategies.

2. Background

2.1. Assessment of liquefaction consequences on buildings

Observations of building performance on liquefied sites during previous earthquakes have shown punching settlement, bearing failure, tilt, and lateral shifting of buildings. In the 1964 Niigata (Japan) and the 1990 Luzon (Philippines) Earthquakes, most of the damaged buildings were two to four stories founded on shallow foundations and relatively thick and uniform deposits of clean sand. In contrast, in the 1999 Kocaeli (Turkey) Earthquake, many of the damaged structures were influenced by the liquefaction of thin deposits of silt and silty sand [40,5,6]. Building settlement and tilt were found to be directly proportional to its contact pressure and height/width (*H/B*) aspect ratio [40]. More recently, liquefaction-induced settlements of 1–2 m and tilts exceeding 2° were observed near low- to mid-rise structures in the 2011 Christchurch (New Zealand) Earthquake. The uplift forces from groundwater pressures caused floors to bulge upward and foundations to tilt and become damaged [9].

Despite these well-documented case histories, the relation between key ground motion characteristics and the foundation response and damage potential of buildings due to liquefaction, with or without remediation, are not well understood. Buildings that are significantly tilted may need to be demolished and rebuilt, representing a complete loss, although the structural system may be intact. On the other hand, certain types of mitigation may reduce the liquefaction potential and the resulting settlements, but lead to increased shaking and damage to the structural and non-structural systems of the building.

Due to the uncertainties involved in interpreting case histories and the scarcity of instrumental recordings at key locations, physical modeling under controlled conditions can provide additional insights. Several researchers have used reduced-scale shaking table and centrifuge tests to study the response of rigid, shallow model foundations situated atop deposits of saturated, loose to medium dense, clean sand (e.g., [49,30,16,31]). More recently, Dashti et al. [10,11] employed single-degree-of-freedom structural models with realistic fundamental frequencies (as opposed to rigid blocks) on layered liquefiable deposits and investigated the relative influence of various soil and structural parameters on SFSI. Conceptually, the study classified the primary settlement mechanisms as: (a) volumetric types: partial rapid drainage ($\varepsilon_{p\text{-}DR}$) controlled by 3D transient hydraulic gradients, sedimentation ($\varepsilon_{p\text{-}SED}$) settlements after liquefaction or soil structure break-down, and consolidation ($\varepsilon_{p\text{-}CON}$) volumetric strains as excess pore pressures dissipate; and (b) deviatoric types: partial bearing capacity loss ($\varepsilon_{q\text{-}BC}$) under the static load of structures due to strength loss in the foundation soil resulting in limited punching settlements or tilting of the structure, and soil-structure-interaction (SSI) induced building ratcheting ($\varepsilon_{q\text{-}SSI}$) that occur under the dynamic stresses imposed by structure.

Physical model studies of an entire building-foundation-soil system, particularly with MDOF structures that have a realistic force-deformation behavior are rare. Nonlinear SFSI effects near low- to mid-rise, inelastic structural models on dry sand were investigated in centrifuge by Chen et al. [7] and Mason [32]. The models of building structures had fuses representing hinges of inelastic response. However, the response of MDOF potentially-inelastic structures has not yet been investigated experimentally on liquefiable ground. A detailed evaluation of the demand imposed on the structural elements and their behavior is particularly important when predicting the influence of liquefaction mitigation strategies on building performance.

2.2. Effectiveness of liquefaction mitigation strategies

Liquefaction mitigation techniques have been rapidly evolving over the past few decades, and many new methods have been introduced either to prevent liquefaction or to minimize the resulting settlements. However, the reliability and performance of these methods remain unclear, particularly in terms of their utility in reducing building settlement, tilt, and damage, as summarized below.

2.2.1. Densification methods

Ground densification decreases liquefaction-induced volumetric settlements and simultaneously increases the stiffness and shear resistance of sand. However, it may not reduce permanent and transient tilt [10,11]. It is also expected to amplify foundation accelerations at shorter periods, which may adversely impact the response of the superstructure.

2.2.2. Drainage methods

Drains prevent or delay liquefaction by enhancing dissipation of excess pore pressures. Drains are also an effective tool for preventing void redistribution and the formation of a water lens below a low-permeability crust. Gravel drains have performed well in the past, but this effect has been mainly attributed to increased stiffness and not necessarily enhanced drainage (e.g., [35,17,19,1]).

PVDs are hollow, perforated, plastic pipes wrapped in filter fabric that enhance drainage without notable stiffening [18]. In a series of centrifuge tests on slopes with PVDs under seismic loading, Howell et al. [18] showed that PVDs were effective in reducing the duration of high excess pore pressures and hence, reduced vertical and horizontal displacements in most cases. The characteristics of ground shaking significantly influenced the effectiveness of drains and the resulting deformations. Enhanced drainage amplifies volumetric strains due directly to drainage ($\varepsilon_{p\text{-}DR}$), but limits strength loss and deviatoric-induced building movements [11]. Additional physical model studies are required to better evaluate the influence of drainage alone on the performance of shallow-founded structures.

2.2.3. Reinforcement methods

In-ground structural walls or equivalent methods that add lateral stiffness to the underlying soil (without additional drainage) are relatively easy to construct around existing structures. Hamada et al. [13]; reported the outstanding performance of footings treated by in-ground walls during the 1995 Hyogoken-Nanbu (Japan) Earthquake. Centrifuge model tests (e.g., [1,11,25]) have also shown that sheet pile walls adjacent to existing structures or slopes may curb settlements by up to 50–60%. However, the influence of in-ground walls on SFSI, tilt, and interstory drift are not understood sufficiently.