Soil Dynamics and Earthquake Engineering 110 (2018) 212–231

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

Effects of drainage control on densification as a liquefaction mitigation technique

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ABSTRACT

Ground densification is among the most popular techniques for liquefaction mitigation employed in practice. Yet, the effects of densification, especially in combination with strategies that enhance or inhibit drainage to or from the densified area, on the performance of the soil-foundation-structure system are not well understood. This paper describes dynamic centrifuge experiments to evaluate these effects, considering 3- and 9-story, moment-resisting frame structures with different embedment depths, founded on layered liquefiable soil deposits. The experiments compared structures mitigated with densification alone, and mitigated with a combination of densification and either prefabricated vertical drains (enhancing drainage) or a flexible impermeable latex barrier (inhibiting drainage) around the densified area. Ground densification tended to reduce the foundation settlement, although not to acceptable levels (based on limiting values typically considered in design and performance assessment), but amplified the drift and acceleration demands on the superstructure. The addition of a flexible impermeable barrier around the densified area did not have a notable influence on foundation settlement. However, it increased the excess pore pressures under the edges of the 3-story structure by inhibiting outward flow, amplifying its foundation rotation compared to the case with densification alone. In the case of the heavier and deeper, 9-story structure, adding a barrier around the densified zone restricted the locally inward flow from the adjacent loose soil. This helped reduce net pore pressures under the edges of the structure after strong shaking, foundation rotation, and seismic demand on the superstructure. Enhancing drainage around the densified zone, on the other hand, notably reduced permanent foundation settlement and rotation during all motions nearly to acceptable limits, but amplified accelerations, imposing additional seismic demands on the structure, which could lead to damage if not considered in design. These results demonstrate the importance of considering the structure's dynamic properties and force-deformation behavior, foundation and ground motion properties, and soil-structure interaction when planning the geometry of ground densification and drainage.

1. Introduction

Ground densification is among the most common techniques for mitigating the liquefaction hazard. Ground densification or improvement has been effective in reducing the potential for liquefaction triggering and the resulting permanent soil deformations in the free-field, away from structures [25]. Yet, it may not reduce foundation settlement and tilt to acceptable levels [26,27]. Densification may also increase accelerations imposed on the foundation and superstructure over a range of frequencies, which can lead to damage if not accounted for in design. The extent of this increase at different frequencies depends on the properties of the soil, structure, and ground motion. Indeed, [27] showed that ground densification can improve certain measures of performance of the soil, foundation, and structure, but there are tradeoffs, and the improvement may not be enough to change the overall post-earthquake repair outcomes for the system. Hence, additional strategies may be warranted to improve the effectiveness of ground improvement for the overall performance of the soil-foundation-structure system.

In combination with densification, techniques designed to control drainage into or out of the densified zone are appealing. Minimizing inward flow from the adjacent unmitigated ground toward the densified region may limit the pore pressures under the foundation. Limiting flow away from the densified soil may also help reduce localized volumetric

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https://doi.org/10.1016/j.soildyn.2018.03.018
Received 28 December 2017; Received in revised form 12 March 2018; Accepted 16 March 2018
0267-7261/

strains in the foundation soil due to loss of water during shaking. However, preventing outward flow may maintain high pore pressures under the foundation for a longer duration, thereby amplifying shear deformations and, hence, foundation's settlement and tilt.

Alternatively, the opposite scenario of enhancing drainage around the densified zone may act to limit net excess pore pressures generated underneath the structure, reducing shear strains. However, enhancing drainage may simultaneously increase the volumetric strains caused directly by drainage during shaking. The relative importance of these mechanisms and their effects on net foundation settlement and tilt, accelerations imposed on the foundation and superstructure, and drift demands on the structure are not well understood.

The tradeoffs associated with drainage control – either by means of enhancing or inhibiting flow – on the effectiveness of densification have not yet been evaluated systematically. In this paper, we describe a series of dynamic centrifuge experiments performed at the University of Colorado Boulder (CU) facility to examine the influence of drainage control on the effectiveness of ground densification. In these experiments, simplified and scaled structural models representing the key dynamic properties of 3- and 9-story, moment-resisting, steel frame structures were placed on a layered liquefiable soil deposit. The seismic response of these structures was first investigated without mitigation. Subsequently, the entire thickness of the loose, liquefiable layer underneath was densified. Then, ground densification was combined with prefabricated vertical drains (PVDs) and with a flexible impermeable latex barrier around the boundaries of the densified zone. In this way, drainage was either enhanced or inhibited from the densified volume of soil under the structure, without a notable change in shear stiffness. The effectiveness of the mitigation strategies was evaluated in terms of the performance of foundation (settlement, tilt, and acceleration demand) and superstructure (roof accelerations, as well as force and deformation demands). Accelerations, excess pore pressures, and soil deformations were also monitored both in the far-field and near-field.

2. Background

Seismically-induced soil liquefaction has caused substantial damage to building structures in previous earthquakes. For example, excessive settlement and tilt of foundations [4], bearing capacity failure [5,10], and failure of structural elements and foundation slabs [11] have been observed due to liquefaction. Mitigation techniques are often employed on liquefiable soils with the aim of either avoiding triggering or reducing the effects of soil softening on structures. Examples of mitigation techniques include: ground densification, ground reinforcement, and drainage. In some cases, multiple methods are combined to improve the effectiveness of remediation. For example, stone columns are designed to provide stiffness, enhance drainage, and densify the surrounding soil during installation with vibration [31,32].

Ground densification has been among the most common mitigation methods [34,38], and can be combined with methods that control drainage. Due to their ease of construction and low cost, flexible flow barriers (e.g., soil bentonite slurry walls) are sometimes used for liquefaction mitigation (among other applications) to protect the densified volume of soil against inward flow from the adjacent unmitigated ground. In other cases, ground densification can be combined with PVDs or other forms of drains to reduce the extent of pore pressure generation and, thereby, increase soil stiffness and resistance to deformations over time [9,21]. Although these combined techniques have been used in practice, there are no well-documented case histories available to evaluate the influence of drainage control on the effectiveness of ground densification considering the presence and response of a building.

Centrifuge tests were performed by [2] to investigate the effectiveness of ground densification when confined with water barriers for a hypothetical bridge site (without considering the structure itself). This combined mitigation method reduced surface settlements satisfactorily, but did not control lateral spreading. [7] modeled single-degree-of-freedom (SDOF) linear-elastic structures in centrifuge on a liquefiable deposit with and without an in-ground latex water barrier (without densification). The authors conceptually identified the main mechanisms of deformation responsible for foundation settlement as two general categories of volumetric and deviatoric. In reality these mechanisms co-exist and interact. Hence, they are difficult to separate or evaluate independently in an experimental study. However, it is possible to evaluate their relative importance based on their definition, mechanics, and influencing factors (particularly when a mitigation strategy is introduced). The presence of a latex barrier in the [7] study was hypothesized to reduce volumetric deformations due to partially-drained cyclic loading ($\varepsilon_{p\text{-}DR}$), which could reduce net foundation settlements. However, it could amplify or de-amplify the extent and contribution of sedimentation ($\varepsilon_{p\text{-}SED}$) and shear strains due to partial bearing capacity loss ($\varepsilon_{q\text{-}BC}$) and soil-structure interaction induced building ratcheting ($\varepsilon_{q\text{-}SSI}$), depending on the properties of the structure and ground motion.

More recently, [22] showed via centrifuge modeling that soft, in-ground flow barriers in sand may increase damping and reduce soil surface accelerations in the free-field during strong seismic events. These experimental results were subsequently used to validate numerical simulations of soft barriers, considering different materials under dynamic loading [23]. The numerical results showed that barriers tend to increase damping, but decrease soil's bearing capacity, which may amplify net foundation settlements. After validation of their numerical models, [14] conducted a parametric study to relate the reduction in seismic demand with a barrier in the free-field to soil properties and ground motion intensity.

The influence of densification combined with PVDs was investigated by [39] on the response of a thick deposit of saturated, soft clay. The mitigation's effects, particularly on increased soil strength and reduced excess pore pressures, were confirmed by both laboratory and in-situ testing. [36] analytically evaluated the effectiveness of dynamic compaction together with vibro stone columns in free-field conditions. The analytical results were compared with field measurements in terms of SPT blow counts before and after improvement, measuring increased resistance to liquefaction triggering. After verification and validation of a numerical model based on field tests, [24] performed a parametric study to assess the effects of silt content, hydraulic conductivity, impact energy, and time lag between impact cycles on the effectiveness of dynamic compaction and vibro stone columns. The results showed that combined densification and enhanced drainage can effectively avoid liquefaction triggering in silty soils with hydraulic conductivities as low as 10^{-8} m/s. In addition, use of drains was shown to improve the efficiency of ground densification in the free-field by enhancing the flow rate.

Despite the valuable insight gained from prior field, experimental, analytical, and numerical studies related to the performance of combined mitigation techniques, the tradeoffs associated with controlling drainage around the densified area are still not well understood near a shallow-founded structure with realistic dynamic properties. Prior studies have either modeled soil and mitigation without a structure, or modeled the structure as a rigid mass or a linear-elastic SDOF system not capable of damage and nonlinear behavior. [26,27] showed that the structure's dynamic properties and force-deformation behavior can have a strong influence on inertial interaction and, hence, the effectiveness of mitigation techniques even in terms of foundation settlement and tilt. Thus, the influence of inhibiting or enhancing drainage in combination with ground densification needs to be systematically studied, while considering the performance of the entire soil-foundation-structure system and a range of conditions, providing the motivation for this experimental study.