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Key predictors of structure settlement on liquefiable ground: a numerical parametric study

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ABSTRACT

Excessive building settlement and tilt on liquefiable soils has led to significant damage in previous earthquakes. The state-of-practice for evaluating liquefaction-induced building settlement still primarily relies on semi-empirical free-field relationships that have repeatedly been shown as unreliable and inaccurate during field and physical model studies. This is because these methods ignore the presence of the building, soil-foundation-structure interaction, and some of the dominant mechanisms of deformation near buildings. In a comprehensive numerical parametric study, the dynamic response of the soil-foundation-structure (SFS) system was assessed with a wide range of soil, structure, and ground motion characteristics. The primary objectives were: first, to identify the key predictors of foundation settlement and study their relative importance and interdependence; and second, to provide a comprehensive and mechanistically-sound dataset for the future development of a probabilistic predictive model of building settlement. The numerical simulations involved fully-coupled, 3-dimensional, nonlinear dynamic analyses of the SFS system, previously validated using centrifuge experimental results. For the conditions considered, the key predictors of building settlement were identified as the cumulative absolute velocity (CAV) of the outcropping rock motion, the relative density of, thickness of, and depth to the liquefiable layer(s), presence of a low-permeability cap, followed by foundation length-to-width ratio, embedment depth, contact area, and bearing pressure. The structure's inertial mass and height/width ratio as well as the initial fundamental period of the structure and site were comparatively less influential. The relative importance and influence of most input parameters were shown to depend on ground motion intensity (e.g., CAV) and soil relative density.

1. Introduction and background

Soil liquefaction and the resulting ground deformations continue to cause extensive damage to buildings, even those designed based on advanced regional regulations. For example, excessive settlement, tilt, and lateral displacement due to soil softening damaged a large number of buildings on shallow foundations and their surrounding lifelines in Christchurch following the 2010–2011 sequence of earthquakes [12,6]. In many cases, it was not economical to repair the damaged structures, and they had to be demolished. Future earthquakes in major cities around the globe are expected to continue causing liquefaction-related damage to building structures and other engineered facilities. Yet, there are still no reliable engineering procedures for predicting liquefaction-induced ground displacement near structures, which is a necessary step for reliable mitigation of this hazard.

Buildings on softened ground were observed to settle more than the soil in the free-field, and the contact pressure and shear stresses imposed by buildings were shown to influence their settlement during the 1990 Luzon (Philippines) Earthquake (e.g., [40]). Excessive structural settlement was evident due to the liquefaction of relatively thin deposits of loose, saturated silt and silty sand during the 1999 Kocaeli (Turkey) Earthquake [2,3,36]. A building's settlement and tilt were shown to be directly related to its foundation contact pressure and height/width (H/B) ratio during this earthquake [36]. Overall, these observations point to the importance of the structure's presence and dynamic properties in relation to those of the underlying soil profile when evaluating their potential for seismic settlement. Despite the valuable insight that can be gained from field observations, the relative importance and influence of various parameters on the structure's response cannot be determined in a systematic manner from case histories alone.

Reduced-scale shaking table and centrifuge tests have been used in

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the past to study the response of shallow foundations (mostly modeled as a rigid mass) atop thick and uniform deposits of loose, saturated, clean sand (e.g., [43,25,13]). In a few cases, the researchers also examined the influence of soil densification on building settlement [13,25]. These tests generally confirmed the importance of foundation pressure and area on its settlement, which was often greater than those in the free-field. A series of four centrifuge experiments was later performed by Dashti et al. [7,8] to identify the dominant mechanisms of building settlement on layered liquefiable soil deposits. These tests employed elastic single-degree-of-freedom (SDOF) structural models with more realistic fundamental frequencies (as opposed to a rigid mass) on liquefiable ground to better capture inertial interaction. The relative importance of a limited number of testing parameters (e.g., structure's footprint dimensions, contact pressure, H/B, liquefiable layer's relative density and thickness, presence of a silt cap, and base motion properties) on the performance of shallow-founded structures was evaluated experimentally. Conceptually, the study classified the primary settlement mechanisms as: (1) volumetric types, i.e., rapid drainage (ε_{p-DR}), sedimentation (ε_{p-SED}), and consolidation (ε_{p-CON}); and (2) deviatoric types, i.e., partial bearing capacity loss (ε_{q-BC}) and soil–structure interaction (SSI) induced building ratcheting (ε_{q-SSI}). Despite their limitations, physical model studies in general provide valuable insight into the underlying mechanisms of deformation. These results can be used for the validation of advanced numerical models, prior to simulating more complex systems and loading paths for a larger number of variables.

The presence of a structure has been shown in prior research to influence the three-dimensional (3-D) static and dynamic stress field and drainage patterns in the underlying ground, which significantly affect the potential for liquefaction triggering, soil-foundation-structure interaction (SFSI), and the resulting accelerations and deformations [7,8]. Nonetheless, the current state-of-practice for estimating liquefaction-induced building settlement still relies heavily on semi-empirical relations that assume free-field conditions—without a structure (e.g., [39,15]). In these methods, the interactions among soil, foundation, and structure and their subsequent influence on key mechanisms of displacement are ignored. Hence, these methods cannot reliably evaluate the consequences of liquefaction, the need for ground improvement, and the subsequent evaluation of the proposed mitigation strategy.

Solid-fluid, fully-coupled, dynamic analyses of the soil-foundation-structure system can provide valuable insight into soil nonlinearity, SFSI, and structural performance on softened ground. Triggering of liquefaction, post-liquefaction instability, and the resulting ground and building movements can be modeled in a single time-domain analysis. These numerical models are, however, complex and have many parameters. They must be validated against physical model studies or well-documented case histories for a range of soil, structure, and ground motion properties before used in practice or in a parametric study.

Recently, numerical studies seeking to characterize the behavior of foundations on liquefiable ground have become significantly more sophisticated and broader in scope. Naesgaard et al. [33] performed a pioneering numerical study of 2-D models representing strip foundations on liquefiable soils. The study focused on the effects of foundation bearing pressure as well as the thickness and limiting strain of the liquefiable material in soil profiles consisting of a cohesive clay crust. Therefore, although its conclusions provided valuable insight for subsequent studies, they were limited to specific scenarios.

Karamitros et al. [16] performed 3-D numerical simulations to evaluate the influence of different parameters on the settlement of rigid blocks (as shallow foundations) and the degradation of bearing capacity on a liquefiable soil profile with a clay crust. Although the results and approach of this study were quite insightful, there were a number of limitations. The study considered a relatively limited range of soil and foundation properties, which can now be expanded upon with new computational tools and speed. The study also modeled the structure as a rigid block, not properly representing the inertial interaction effects on base shear, moment, and deformations.

Shahir et al. [37] used 3-D numerical simulations to correlate the settlement of shallow, rigid box structures (similar to [16]) to their dimensions or to the dimensions of the surrounding densified ground. Hong et al. [14] subsequently conducted a 2-D numerical parametric study to evaluate the effects of structural dimensions and ground motion properties on foundation settlement and tilt. However, this study considered only one ground motion scaled to different intensities, and may have therefore neglected the effects of motion's frequency content or duration.

Recently, studies such as these have been extended into the development of predictive models for foundation settlement. Bray and Macedo [5] used a numerical parametric study consisting of over 1300 analyses of 2-D, linear-elastic models to investigate the influence of several parameters on settlement, and characterized that influence in a predictive model. This represents a significant advancement in the direct applicability of this type of research, and builds on the previous studies to provide a tool for forward prediction in addition to furthering understanding of the mechanisms involved. As in some of the previous studies (e.g., [33,14]), the assumption of 2-D plane strain conditions is best suited for very long foundations (e.g., strip footings), and has been shown to misrepresent the deformations (both volumetric and deviatoric) of shorter foundations (e.g., mat or spread footings) by Karimi and Dashti [18,19]. Additionally, even though a number of studies used 3-D simulations (e.g., [16] and [37]), the range of parameters considered in all prior studies is still limited and may not capture the influence of certain potentially-important parameters including the length-to-width ratio of the foundation, its embedment depth, and the presence of multiple liquefiable layers with and without a low-permeability cap. The current study benefits from and builds on the work of prior researchers to include additional parameters and more realistic stress conditions in 3-D.

Although insightful, most of the previous numerical studies did not adequately characterize the key predictors of building settlement (in terms of superstructure, foundation, soil, and ground motion properties), for a number of reasons. Previous numerical models were validated using physical model studies, but they did not always include a wide range of soil, structure, and ground motion properties in their validation (with the exception of [14]). In this study, the numerical model was validated using an expanded set of centrifuge tests by Dashti et al. [7,8] with variations in the properties and layering of the soil profile, dynamic properties and geometry of the structures, and characteristics of the base motion. Hence, the applicability of previous studies was limited. Second, running a large number of fully coupled, 3-D, dynamic simulations with adequate variations in the properties of the system and input ground motion has been computationally demanding and impractical in the past. Third, previous studies that included the structure either modeled it as an added pressure or a rigid block. Although the influence of inertial mass and height of center of gravity on foundation's settlement can be studied with a rigid block, a notable overestimation of the structure's stiffness with a rigid block can lead to an inaccurate estimation of its fundamental period and therefore, the inertial demand on foundation's base shear and moment. A rigid block does not allow evaluating the full influence of inertial interaction and the relative importance of the building's dynamic properties on its ratcheting behavior. These simulations may misrepresent a critical mechanism of displacement due to SSI-induced building ratcheting (as shown experimentally by Dashti et al. [7,8]) and the resulting effects on excess pore pressures, accelerations, and total settlement and tilt of the foundation.

A comprehensive numerical parametric study was performed with a wide range of soil, structure, and ground motion Input Parameters (IPs), to evaluate their influence and relative importance on the performance of shallow-founded structures. This was made possible by parallel computing on supercomputers at the University of Colorado Boulder.