Soil Dynamics and Earthquake Engineering 90 (2016) 381–394

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

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

A performance-based approach for design of ground densification to mitigate liquefaction

Hadi Shahir [a,*], Ali Pak [b], Peyman Ayoubi [c]

[a] Department of Civil Eng., Faculty of Eng., Kharazmi University, Tehran, Iran
[b] Department of Civil Eng., Sharif University of Technology, Tehran, Iran
[c] California Institute of Technology, Pasadena, CA, USA

ARTICLE INFO

Article history:
Received 12 September 2015
Received in revised form
1 September 2016
Accepted 10 September 2016

Keywords:
Ground densification
Liquefaction
Performance-based design
Coupled analysis
Shallow foundation
Settlement

ABSTRACT

In performance-based geotechnical earthquake engineering, the required degree and spatial extent of ground densification for mitigation of liquefaction beneath a structure should be determined based on the acceptable levels of performance of foundation. Currently, there is no solution for evaluation of the amount of settlement and tilt of footings constructed on a densified ground which is surrounded by a liquefiable soil. This implies the need for numerical procedures for simulation of seismic behavior of shallow foundations supported on both liquefiable and densified subsoil. In this paper, the dynamic response of shallow foundations on a densified ground is studied using a 3D fully coupled dynamic analysis. For verification of the numerical model, simulation of a series of centrifuge experiments has been carried out and the results were compared with the experimental measurements. After verification of the numerical model, a comprehensive parametric study has been performed to develop a methodology for estimating the effectiveness of subsoil densification in reducing liquefaction-induced settlement of shallow foundations. Range of problem variables were considered in a way that the possibility of bearing capacity failure is low enough. The proposed methodology can be utilized for development of a performance-based design procedure for liquefaction hazard mitigation by soil densification.

1. Introduction

Settlement and tilt of structures due to liquefaction are among the major causes of damage during earthquakes. One of the main approaches for reducing adverse effects of liquefaction on shallow foundations is ground improvement. Among the variety of ground improvement methods, the densification-based methods such as vibroflotation, dynamic compaction, and sand compaction piles have attracted more attention due to their effectiveness, wide range of application, and relatively low cost.

The effectiveness of densification as a liquefaction mitigation procedure has been successively reported by observation of negligible damage of shallow foundations built on densified zones during major seismic events. Watanabe [1] reported that three oil storage tanks constructed on an improved ground by the vibroflotation method, suffered negligible damage and maximum 2–3 cm uniform settlement during the 1964 Niigata, Japan earthquake, while, nine tanks built on nearby natural ground experienced settlements up to 50 cm. Ishihara et al. [2] reported that three oil storage tanks built on sandy ground densified by compaction piles, incurred no damage during 1978 Miyagiken-Oki, earthquake, even though liquefaction occurred adjacent to the tanks. During the 1995 Hyogoken Nanbu (Kobe) earthquake, more than one hundred 5-story residential buildings supported by shallow foundation upon improved ground by sand compaction piles, were not subjected to significant liquefaction hazard, except five buildings that had unacceptable performance in terms of tilt greater than 1% [3].

The acceptable performance of shallow foundations located on densified ground has also been investigated by performing shaking table and centrifuge model tests [4–7]. All experimental studies indicate that the settlement of a structure can be significantly reduced by subsoil densification down to an adequate depth beneath the foundation and sufficient lateral extent beyond the foundation edges. The observations, however, reveal that some deformations should be expected even though the total liquefiable depth with considerable width has been improved.

For liquefaction hazard mitigation using the densification method, three basic values should be determined, i.e. depth, lateral extent, and degree of improvement (percent increase in relative density D_r). In the current design practice, the need for the ground

* Corresponding author.
E-mail address: shahir@khu.ac.ir (H. Shahir).

http://dx.doi.org/10.1016/j.soildyn.2016.09.014
0267-7261/

improvement is usually decided based on the semi-empirical methods for assessment of liquefaction triggering potential of a soil in the ground level neglecting the influence of the existing structure. If ground improvement has to be carried out, and densification is selected as the appropriate method, the degree of improvement is obtained based on the preferred safety factor against liquefaction. It is conventionally suggested that the densified zone should extend vertically down to the bottom of the layer susceptible to liquefaction and laterally by a distance equal to the densification depth from the edge of the footing [8]. In this design procedure, it is not known that how the treated soil-foundation system will respond to the earthquake shaking and how effective the improvement will be in reducing the foundation settlement.

In recent years, geotechnical design codes are being shifted from the classical limit equilibrium approach toward the performance-based approach [9]. In the case of foundation engineering, the basic philosophy of the performance-based design relies on the control of foundation displacements. Therefore, any performance-based design procedure for soil improvement by densification method should address the three values of depth, lateral extent, and degree of improvement based upon the limiting amounts of the foundation settlement that is deemed acceptable.

In the US-Taiwan workshop on soil liquefaction, the need for enhanced procedures, i.e. using 3D analytical procedures calibrated with field and model test observations, for evaluating the degree and spatial extent of improvement required to obtain a desired level of performance was emphasized [10]. The need to account for the soil–structure interaction in both natural and improved soils was also noted by workshop participants. Such analytical and numerical procedures should be able to capture the main features of the seismic response of shallow foundations rested on a saturated granular soil deposit subjected to seismically induced liquefaction. Very few numerical models have been used for simulating the seismic response of a shallow foundation supported by a densified sand zone within a liquefiable deposit. Cooke [11] implemented finite difference code for predicting the performance of a treated ground for mitigation of the liquefaction at bridge piers founded on shallow foundations. For simulation of liquefaction, a 2D (plane strain) uncoupled effective stress analysis was used. The results of verification analyses showed that the predicted excess pore water pressures are not reliable and the permanent displacement of structures and the improved soil zones are simulated 0.5–2 times the actual values. Elgamal et al. [12] implemented a 3D fully coupled numerical model to investigate the liquefaction-induced settlement of shallow foundations and the influence of soil compaction on reducing the settlement. In their analysis, the foundation was modeled as a surface load. Dashti et al. [13] used centrifuge experiments to investigate the effect of different parameters on shallow foundation settlement. The results showed that the settlement started after one strong excitation and soon became more than the free field settlement. Karamitros et al. [14] implemented NTUA-SAND into commercial finite different code (FLAC) and studied the effect of different parameters on shallow foundation settlement and on degraded bearing capacity of a liquefiable soil with a clay crust.

The numerical study presented in this paper, addresses the effects of ground improvement by densification method on mitigation of the liquefaction of saturated sand deposits underlying foundation of structures. In this regard, a 3D finite element code for fully coupled dynamic analysis of saturated porous media has been utilized. For constitutive modeling of sand behavior, a well-calibrated bounding-surface plasticity model capable of accounting for the monotonic and cyclic responses of saturated sand in a wide range of densities and confining pressures has been used. Another main feature of the proposed numerical code is taking the variation of permeability into account during the liquefaction process. The numerical tool has been verified by simulating a series of centrifuge experiments performed on model footings on liquefiable and improved subsoil. The verified numerical tool has been used for development of a performance-based design procedure in order to diminish the liquefaction hazard by soil densification. Concerning this issue, a parametric study has been performed to develop a general methodology for quantitative estimation of the effectiveness of densification in reducing the liquefaction-induced settlement of foundations.

2. General formulation of the numerical model

In this study, numerical simulations have been performed using the Finite Element platform OpenSeeS [15], and a novel implementation of variable permeability [16]. In the following, the general formulation of the numerical code is presented.

2.1. Coupled dynamic finite element formulation

For a fully coupled analysis, equilibrium or momentum balance for the soil-fluid mixture, momentum balance for the fluid phase, and mass balance for the whole system of soil and fluid must be satisfied. The relative velocity of fluid phase was neglected because it has little influence in dynamic problems in which high-frequency oscillations are not important such as earthquake [17]. The governing equations are then reduced to well-known u-P formulation. The primary variables in this form of equations are solid displacement and fluid pressure. Using the finite element method for spatial discretization, the u-P formulation is as follows:

$$M\ddot{U} + \int_v B^T \sigma' \, dV - QP - f^{(s)} = 0 \tag{1a}$$

$$Q^T\ddot{U} + HP + S\dot{P} - f^{(p)} = 0 \tag{1b}$$

where M is the mass matrix, U is the solid displacement vector, B is the strain-displacement matrix, σ' is the effective stress tensor, Q indicates the discrete gradient operator coupling the motion and flow equations, P is the pore pressure vector, S is the compressibility matrix, and H is the permeability matrix. The vectors $f^{(s)}$ and $f^{(p)}$ include the effects of body forces, external loads, and fluid fluxes. Details of theses matrices and vectors can be found in Zienkiewicz et al. [17].

2.2. The constitutive model

The critical state two-surface plasticity model developed by Dafalias and Manzari [18] was employed for modeling the monotonic and cyclic behavior of sand. One of the main features of this model is a single set of parameters for different relative densities. The formulation of the model is based on the bounding surface plasticity theory within the critical state soil mechanics framework. A schematic representation of the two-surface model in the π-plane is shown in Fig. 1. More information about this model is presented in [18].

Shahir et al. [16] calibrated the model constants for Nevada sand using the monotonic and cyclic triaxial tests data performed by Arulmoli et al. [19]. The model has 15 constants which are divided into 6 categories based on their functions. A list of the model constants is shown in Table 1. In Fig. 2, the model simulations along with the experimental results for drained monotonic compression constant-p tests conducted on soil samples with initial relative density of about 40% and 60% are shown. Figs. 3 and 4 present two simulations of undrained cyclic test conducted on