Soil Dynamics and Earthquake Engineering 100 (2017) 396–409

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

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

# Seismic performance of strip foundations on liquefiable soils with a permeable crust

V.E. Dimitriadi*, G.D. Bouckovalas, A.G. Papadimitriou

National Technical University of Athens, School of Civil Engineering, Geotechnical Department, 9 Heroon Polytechniou Str., 15780 Zografou, Greece

ARTICLE INFO

*Keywords:*
Bearing capacity
Ground improvement
Liquefaction
Numerical analyses
Performance-based seismic design
Shallow foundations
Settlement

ABSTRACT

Modern seismic codes dictate that the use of shallow foundations on liquefiable soils may be considered only after appropriate ground improvement. No further instructions are given regarding the improvement depth, or what changes if the surface layer (crust) does not liquefy. Hence, it is standard practice to improve the entire liquefiable soil layer below the foundation, whatever its depth or thickness. This study examines the seismic performance of strip foundations laying on a two-layered soil profile, consisting of a bottom layer of liquefiable sand and a (manmade or natural) permeable crust on top. Regardless of its origin, this crust does not develop (significant) excess pore pressures during shaking and is stronger and stiffer than the underlying liquefied sand. The problem is investigated numerically, through fully coupled non-linear dynamic finite-difference analyses. Following the identification of the governing response parameters, a set of multi-variable relations is developed for the approximate assessment of the seismic footing settlements and the bearing capacity degradation due to liquefaction appearing below the permeable crust.

## 1. Introduction

The operational (and potentially the structural) integrity of constructions resting on shallow foundations is exposed to a number of serious threats when earthquake-induced liquefaction is anticipated. For example, the progressive accumulation of seismic settlements may well overcome the allowable limits and thus cause operational failure and possibly structural damage. In addition, as a result of excess pore pressure generation and related shear strength degradation in the soil, the bearing capacity of the foundation also degrades considerably, even leading to failure. In such extreme soil conditions, the conventional design approach dictates the use of deep foundations, which bypass the liquefiable strata and transfer the loads of the superstructure to deeper and stronger soil layers. Pile installation is commonly accompanied by soil improvement, in order to mitigate soil liquefaction, thus reducing the bending moments applied upon the piles due to inertial loading from the superstructure.

Contrary to the conventional design approach, a number of experimental and theoretical studies (e.g. [1–5]) suggest that pile installation may be avoided, if a non-liquefiable layer exists on top of the liquefiable sand and its existence is appropriately taken into consideration. Particularly, experimental evidence reported in the foregoing studies shows that the presence of a surface soil layer (crust) of adequate thickness and shear strength, may restrain the accumulation of excessive seismic settlements and prevent post-shaking bearing capacity failure, triggered by the occurrence of liquefaction below this crust. The above effect is also verified through numerical analyses [6]. Despite their conceptually innovative character and well-established outcome, the previous studies do not constitute a complete design approach, as to the required geometry and soil properties of this crust. As a consequence, the above foundation solution is not adopted in current engineering practice, where deep foundation schemes are still typically selected.

In the above context, the present study examines the problem of the performance-based design of strip footings, resting on a two-layered soil profile consisting of a (non-liquefiable) permeable crust over liquefiable soil. Seismic performance is evaluated in terms of (dynamic) settlements that accumulate during shaking, as well as in terms of the (post-shaking) degraded bearing capacity. Section 2 describes the background of the studied problem emphasizing on the related literature, while Section 3 outlines the employed numerical methodology. Then, Section 4 presents the typical seismic response of strip footings laying on such two-layered soil profiles, highlighting the governing response parameters. In the sequel, Section 5 emphasizes on the post-shaking degraded bearing capacity of such footings, while Section 6 evaluates their dynamic settlements. The paper ends with a discussion on the range of application of the proposed methodology, as well as pertinent concluding remarks. It is noted that the paper also includes an

* Corresponding author. Present address: 20 Ipirou Str., 15231 Chalandri, Attiki, Greece.
*E-mail address:* valiaciv@gmail.com (V.E. Dimitriadi).

http://dx.doi.org/10.1016/j.soildyn.2017.04.021
Received 3 May 2016; Received in revised form 15 March 2017; Accepted 30 April 2017

**Nomenclature**

| | |
|---|---|
| $a$ (m) | radius of the gravel drain/pile |
| $a_{max}$ (g) | maximum acceleration at the base of the soil profile |
| B (m) | width of the strip foundation |
| $D_{r,o}$ (%) | relative density of the liquefiable sand layer |
| $D_{r,imp}$ (%) | relative density of the permeable crust |
| $FS_{deg}$ | degraded factor of safety against bearing capacity failure |
| $H_{imp}$ (m) | thickness of permeable crust |
| $H_{total}$ (m) | total thickness of the soil profile |
| $K_s$ | stress parameter related to the mobilized shear strength along punch-like failure |
| $k_{eq}$ (m/s) | permeability coefficient of the permeable crust |
| $k_{drain}$ (m/s) | permeability coefficient of the gravel drain material |
| $k_{sand}$ (m/s) | permeability coefficient of the liquefiable sand |
| $m_{v,3}$ (1/kPa) | coefficient of volume compressibility of the liquefiable sand |
| N | number of loading cycles of the applied seismic excitation |
| $N_{\gamma1,deg}$, $N_{q1,deg}$ | bearing capacity factors for degraded friction angle of the permeable crust |
| $N_{\gamma3,deg}$, $N_{q3,deg}$ | bearing capacity factors for degraded friction angle of the liquefiable sand |
| $p_\alpha$ (kPa) | atmospheric pressure |
| $P_1$, $P_2$ (kN/m) | horizontal forces acting on lateral boundaries of (punch-like) moving soil block |
| $P_{int}$ (kN/m) | reaction force at the base of (punch-like) moving soil block |
| $Q_{ult,deg}$ (kN/m) | degraded bearing capacity load of the footing, at the end of shaking |
| q (kPa) | uniform applied footing pressure |
| $q_{ult,deg}$ (kPa) | degraded bearing capacity of the footing, at the end of shaking |
| $T_1$, $T_2$ (kN/m) | shear forces acting on lateral boundaries of (punch-like) moving soil block |
| $T_{exc}$ (s) | (predominant) period of the applied seismic excitation |
| $T_{soil}$ (s) | fundamental elastic period of the soil column |
| U | excess pore pressure ratio |
| $U_i$ | excess pore pressure ratio within each of the i layers of the soil profile |
| $U_1$, $U_2$, $U_3$ | excess pore pressure ratio within the permeable crust (i = 1), the transition layer (i = 2) and the liquefied sand (i = 3) |
| $U_{max}$ | maximum allowable excess pore pressure ratio within the permeable crust, under free field conditions |
| $V_{s,imp}$ (m/s) | shear wave velocity within the permeable crust |
| $V_{s,sand}$ (m/s) | shear wave velocity within the underlying sand (not when liquefied) |
| $v_{max}$ (m/s) | peak velocity of the applied seismic excitation |
| W (kN) | weight of (punch-like) moving soil block |
| $Z_{liq}$ (m) | thickness of the liquefiable sand |
| z (m) | depth measuring from the top of the soil profile |
| $\alpha$ | percentage of $H_{imp}$, which corresponds to the thickness of the transition zone |
| $a_s$ | replacement ratio of gravel piles or drains used for manmade permeable crust |
| $\beta$ | percentage of $U_{max}$, which occurs under the footing and within the permeable crust |
| $\gamma$ (Mg/m$^3$) | (uniform) total unit weight of all layers in the soil profile |
| $\gamma_1$ (Mg/m$^3$) | total unit weight of the permeable crust |
| $\gamma'$ (Mg/m$^3$) | (uniform) buoyant unit weight of all layers in the soil profile |
| $\rho_{dyn}$ (m) | dynamic settlements of the strip footing |
| $\sigma'_{vo}$ (kPa) | effective vertical stress |
| $\tau_{max,deg}$ (kPa) | degraded peak shear strength due to excess pore pressure buildup |
| $\varphi$ (°) | initial peak friction angle |
| $\varphi_{deg}$ (°) | degraded friction angle due to excess pore pressure buildup |
| $\varphi_i$ (°) | initial peak friction angle within each of the i layers of the soil profile |
| $\varphi_1$, $\varphi_2$, $\varphi_3$ (°) | initial peak friction angle within the permeable crust (i = 1), the transition layer (i = 2) and the liquefied sand (i = 3) |
| $\varphi_{i,deg}$ (°) | degraded friction angle within each of the i layers of the soil profile |
| $\varphi_{1,deg}$, $\varphi_{2,deg}$, $\varphi_{3,deg}$ (°) | degraded friction angle within the permeable crust (i = 1), the transition layer (i = 2) and the liquefied sand (i = 3) |

Appendix, which presents an example application of the proposed methodology.

## 2. Background

The issue of the seismic performance of shallow foundations on liquefiable soil has been amply studied in the literature, by means of field observations, experimental and numerical studies. Field observations refer to earthquake events, where liquefaction-related phenomena have been widely demonstrated, e.g. the Niigata 1964, Luzon 1990, Christchurch 2011 earthquakes. For instance, Acacio et al. [7], based on field observations from the Luzon 1990 earthquake, identified a great number of structures founded on shallow foundations, which experienced settlements, frequently exceeding pertinent allowable performance limits. However, in some cases, the existence of a non-liquefiable layer at the ground surface (crust) of sufficient thickness prevented accumulation of excessive settlements, thus ensuring the acceptable performance of the superstructure. Field observations, which further validate the above beneficial effect, have also been compiled and presented by Sitar and Hausler [5] as well as Bray and Dashti [8].

Centrifuge tests were also conducted by Sitar and Hausler [5] and examined the seismic performance of strip and square foundations resting upon a compacted zone of liquefiable sand. The obtained results clearly indicate the reduction of foundation settlements with increasing thickness of the performed compaction. Additionally, Liu and Dobry [1] conducted a series of centrifuge experiments to examine the liquefaction performance of shallow foundations on top of locally compacted liquefiable sand. Significant reduction of seismically-induced settlements was observed, even when the compacted layer did not extend to the entire thickness of the liquefiable layer. Comparable qualitative results and useful conclusions as to the mechanisms of seismically induced settlements of buildings on shallow foundations have also been published by Dashti et al. [9]. Furthermore, Bray and Dashti [8] provide useful insight and suggest guidelines regarding the assessment