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Seismic settlements of shallow foundations on liquefiable soil with a clay crust

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ABSTRACT

A simplified analytical methodology is presented for the computation of the seismic settlements of strip and rectangle footings resting on liquefiable soil with a clay crust. It is based on results of fully-coupled dynamic numerical analyses, performed with a critical-state constitutive model, and captures the physical mechanism of settlement accumulation, which is associated to a "sliding-block" type of punching failure through the clay crust and within the liquefied sand layer. More specifically, liquefaction-induced settlements are correlated to the seismic excitation characteristics and the post-shaking degraded static factor of safety, while the effect of shear-induced dilation of the liquefied subsoil is also taken into account. Analytical predictions are evaluated against experimental observations from centrifuge and large-scale experiments, as well as, against in-situ observations from the City of Adapazari, during the 1999 Kocaeli Earthquake. Finally, easy to use, performance-based design (PBD) charts are developed for quick application of the proposed methodology in practice.

1. Introduction

Since the devastating effects of the Niigata (1964) earthquake, in Japan, the seismic behavior of shallow foundations resting on liquefiable subsoil has drawn the attention of many researchers, who attempted to understand the mechanisms of the foundations liquefaction performance and derive relevant design criteria.

Attention was initially focused upon case-studies of liquefaction-induced foundation damage and a number of researchers (e.g. [1–4]) attempted to correlate the observed damage to the foundation and building dimensions, as well as to soil profile characteristics. Nevertheless, these efforts were hindered by the large number of uncertainties involved in the interpretation of the in-situ observations.

In view of the above objective difficulties, several attempts were made to investigate the phenomenon through centrifuge and large scale shaking table experiments (e.g. [3,5–10]) or advanced numerical techniques (e.g. [11,12]), highlighting various aspects of the liquefaction-affected foundation performance. Karamitros et al. [13] recently reviewed the most important findings from the above efforts. Furthermore, under the light of selective numerical simulations, they provided insight to the prevailing physical mechanisms that dominate the effects of excess pore-pressure buildup in the region underneath the foundation, seismic settlement accumulation, bearing capacity degradation and superstructure inertia.

Despite all above research efforts, a widely accepted performance-based design (PBD) methodology for footings on liquefiable sand has not been yet established. As a result, all currently available seismic codes treat liquefiable soils as extreme ground conditions and do not allow the construction of shallow footings without previous ground improvement (e.g. vibro-compaction, deep soil mixing or use of high-performance drains) for complete mitigation of liquefaction in the subsoil.

Still, there is ample evidence that the presence of a sufficiently thick and shear resistant non-liquefiable soil crust (e.g. clay, dense or dry sand, gravel, or improved soil), between the foundation and the liquefiable subsoil, may drastically enhance shallow foundation performance. For instance, Acacio et al. [3] investigated the behavior of shallow foundations in the City of Dagupan, during the Philippines 1999 Earthquake, and extended the pioneering work of Ishihara [14] by correlating the observed foundation damage to the thickness of the liquefiable sand layer H_{liq} and that of the overlying non-liquefiable crust H_{crust}, both normalized against the embedment depth D. It was thus shown that, in this specific case, damage became negligible for crust thicknesses ranging between $2D$ and $4D$, even for large values of H_{liq}/D.

To establish an integrated PBD methodology for surface foundations on liquefiable soil profiles, one should ensure analytical means for the computation of (a) the post-shaking bearing

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capacity of the foundation, as well as the relevant degraded static factor of safety FS_{deg}, and (b) the accumulating dynamic settlements ρ_{dyn}.

Note that these criteria are quite different in nature and should be thus evaluated independently. Namely, the degraded static factor of safety refers to a short period after the end of shaking, before earthquake-induced excess pore pressures have dissipated, so that its design value may be well below the conventional values for static loads, and close to unity, e.g. $FS_{deg}=1.0$ to 1.5. On the other hand, dynamic settlements are long-living, as they will persist for the remaining life of the structure, permanently affecting its operation. Furthermore, unlike FS_{deg}, allowable dynamic settlements cannot be uniquely defined, since they are related to both safety and serviceability requirements, and should be thus specified depending on the type of structure and the return period of the design seismic actions.

This paper focuses upon the second design criterion above, i.e. the accumulating dynamic settlements at the presence of a non-liquefiable clay crust between the foundation and the liquefiable soil. The first design criterion, i.e. the post-shaking degraded bearing capacity of the foundation, is addressed in a previous companion paper by Karamitros et al. [15]. Still, it is briefly discussed in the following, for the sake of independent reading, as it enters the computation of dynamic settlements and is also an inseparable part of the PBD practice.

2. Numerical analyses methodology

The present study has been based on seventy-seven (77) plane strain parametric analyses for strip foundations, as well as thirty-two (32) three dimensional analyses for square and rectangular footings. The problem configuration and the mesh used for the 2-D and 3-D numerical analyses are presented in Fig. 1a and b, respectively. Namely, the strip foundations were $B=5$ m wide with average bearing pressure $q=40$–140 kPa, corresponding to static factors of safety $FS_o \approx 1.5$–5.0. Similarly, the square footings were $B=5.25$ m wide with average bearing pressure $q=100$–150 kPa, corresponding also to static factors of safety $FS_o \approx 1.5$–2.5. In order to investigate the effect of the footing's aspect ratio L/B, six (6) analyses were performed for $L/B=1.67$–5.00 and $q=125$ kPa. Furthermore, all footings were considered rigid and massless, taking into account that liquefaction of the subsoil, together with the failure mechanism activated during settlement accumulation, will act as a natural seismic isolation to the foundation and will minimize superstructure inertia effects [13].

As shown in Fig. 1, the foundations rested on top of a non-liquefiable clay crust, with undrained shear strength $c_u=25$–40 kPa and thickness $H=2$–14 m in the 2-D analyses and $H=2$–6 m in the 3-D analyses. This crust was underlain by a $Z_{liq}=6$–21 m thick liquefiable sand layer of $D_r=40$–60% relative density. The response of the non-liquefiable clay crust was simulated with the Mohr-Coulomb elasto-plastic constitutive model. On the other hand, the highly non linear response of the liquefiable subsoil was simulated with "NTUA Sand", an advanced critical-state constitutive model which has been developed and implemented to the commercial Finite Difference Codes FLAC [16] and FLAC3d [17] at the Foundation Engineering Laboratory of NTUA.

Details on the "NTUA Sand" and the associated numerical implementation have been presented by Andrianopoulos et al. [18,19] and Karamitros [20]. In summary, the model combines the bounding surface plasticity theory with a vanished elastic region and it can predict a number of important aspects of the dynamic behavior of sands, such as shear strength degradation and damping increase with

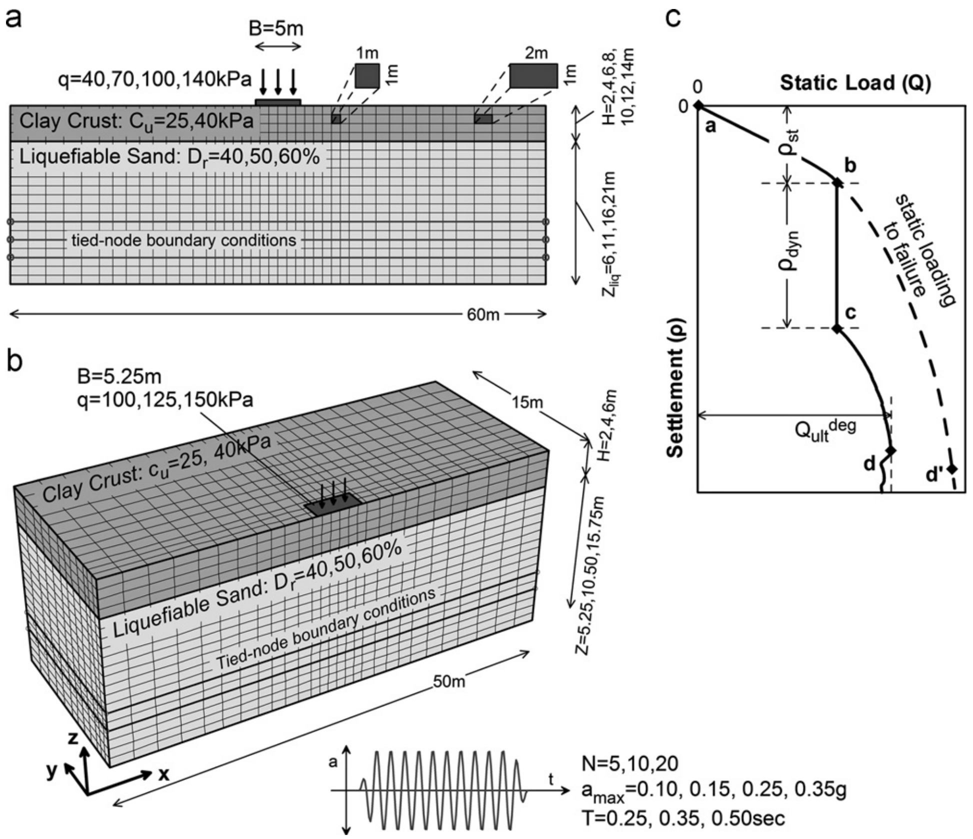

Fig. 1. (a) Numerical model used for the parametric analyses and range of input parameters for strip foundations, (b) numerical model used for rectangular foundations and (c) typical load–settlement curve.