Soil Dynamics and Earthquake Engineering 31 (2011) 1426–1439

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

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

Sand fabric evolution effects on drain design for liquefaction mitigation

George D. Bouckovalas [a], Achilleas G. Papadimitriou [b],*, Dimitrios G. Niarchos [c], Yannis Z. Tsiapas [d]

[a] Geotechnical Department, School of Civil Engineering, National Technical University of Athens, Greece
[b] Department of Civil Engineering, University of Thessaly, Pedion Areos, 38334 Volos, Greece
[c] Massachusetts Institute of Technology, USA
[d] University of Texas at Austin, USA

ARTICLE INFO

Article history:
Received 27 November 2010
Received in revised form
26 May 2011
Accepted 27 May 2011
Available online 12 June 2011

ABSTRACT

This paper revisits the seminal work of Seed and Booker (1977) [21] on the design of infinitely permeable drains for liquefaction mitigation. It is shown that their basic mathematical assumption for the rate of earthquake-induced excess pore pressure generation overlooks sand fabric evolution effects during cyclic loading and eventually leads to underestimation of the drain effectiveness. This is because such effects cause peak excess pore pressures to be attained at the early stages of partially drained shaking, followed by a gradual attenuation even if shaking continues undiminished, a response feature not predicted by the original formulation. In addition, special emphasis is given to the analytical relation describing the excess pore pressure build-up until liquefaction in undrained tests. This relation was considered unique in the original work, for reasons of simplicity, thus neglecting sand fabric evolution effects that may differentiate it for various sands, densities and loading conditions. Hence, a revised analytical formulation is proposed, which takes into account both above effects of sand fabric evolution. The paper provides a quantitative assessment of their influence on drain effectiveness and establishes a new set of charts for drain design. Experimental measurements from shaking table tests, as well as robust numerical simulations are shown, which underline the necessity for the revised solution and design charts.

1. Introduction

Gravel piles, accompanied by vibratory compaction of the surrounding loose sand deposits, have been traditionally used worldwide to mitigate liquefaction during earthquakes. In such cases, the main function of the gravel piles is twofold: they increase the liquefaction strength of the sand by increasing the insitu density, and also retard the excess pore pressure build-up by triggering radial drainage, from the sandy ground towards the more permeable gravel piles. In principle at least, the presence of the relatively stiffer gravel drains may also lead to redistribution of the shear stresses and strains induced by seismic shaking, so that the stresses and strains applied to the improved ground are reduced and the margins of safety against liquefaction are thus enhanced [1–4]. Nevertheless, for the gravel pile configurations, which are usually employed in practice (i.e. with area replacement ratios a_s=10–25%), the reduction in ground stresses and strains is marginal and may even be overshadowed by the possible amplification of the seismic shaking within the improved ground [4–6].

Nevertheless, when this method is applied within an urban environment, or in order to improve existing foundations, vibration must be partially or totally avoided during pile installation, so that ground improvement relies solely upon the drainage function of the gravel piles [7–13]. Thus, prefabricated plastic or metal pipe drains have recently started to replace the traditional gravel piles in such applications, as they cause limited environmental impact, while they require simpler mechanical equipment and less working space [14–18]. Furthermore, these new drain types are much more permeable than gravel piles, and better protected against clogging due to sand and silt infiltration, so that they diffuse concerns expressed in the past [19,20] about the actual capacity of gravel piles to trigger drainage in the field.

Seed and Booker [21] were pioneers in proposing an analytical method for the evaluation of radial drainage effects on earthquake-induced excess pore pressures, for the case of uniform ground and for drains of infinitely large permeability ('perfect' drains). Their method can be handily applied via design charts, which account consistently for soil properties and seismic motion characteristics. As such, it has been widely established in practice today, even for drains with large but finite permeability, having been adopted by a number of contemporary design handbooks

---

* Corresponding author. Tel.: +30 24210 74140; fax: +30 24210 74169.
E-mail addresses: gbouck@central.ntua.gr (G.D. Bouckovalas), apapad@civ.uth.gr (A.G. Papadimitriou), dgniarchos@gmail.com (D.G. Niarchos), gia_tsiap@hotmail.com (Y.Z. Tsiapas).
URL: http://apapad.users.uth.gr (A.G. Papadimitriou).

0267-7261/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.soildyn.2011.05.019