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Influence of soil saturation on the free field response of liquefiable soils

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Abstract

The present paper presents analysis of the influence of the soil saturation on the free -field response of liquefiable soils. Analyses are conducted using a finite element program developed for partially saturated soils subjected to cyclic loading. The performances of the proposed model are analysed by simulation of undrained triaxial tests with different water saturations. The finite element program is then used for the analysis of the influences of the soil saturation, density and position of the water table on the liquefaction of a soil layer subjected to cyclic loading. Results show that the soil saturation significantly affects the liquefaction of partially saturated sandy layers. The decrease in the soil saturation results in a reduction of liquefaction risk.

1. Introduction

Researchers reported examples of soil liquefaction during moderate and large earthquakes, such those of Loma in 1989, Kobe in 1995, Chi-Chi in 1999, Kocaeli in 1999 and Bhuj in 2001 (Bird & Bommer, 2004; Chen, Hou, Cao, et al., 2008; Tang, Liu, Liu, Zhao, 2012). Since soil liquefaction could induce serious damages in buildings and infrastructures, intensive researches have been conducted on this issue. These researches focused mainly on saturated soils. In practice, the soil layer near the ground surface is generally not saturated. Recently, some researches have been conducted on the liquefaction of unsaturated soils (Bian & Shahrour, 2009; Martin, Finn, & Seed, 1978; Yang, 2002; Yoshimi, Tanaka, & Tokimatsu, 1989). They showed that a small reduction in the soil saturation could cause significant increase in the sands resistance to liquefaction. The investigation of the influence of soil saturation on the response of liquefiable soils to seismic loading is required for both the design of underground structures concerned by these soils and for the use of air bubbles injection technology for liquefaction mitigation (Yegian, Eseller-Bayat, Alshawabkeh, & Ali, 2007).

This paper concerns analysis of the influence of soil saturation on the liquefaction of sandy soil layers in free-field condition. First, the paper presents the constitutive model, which was developed for the partially saturated sandy soil under dynamic loading, the performances of this model are then illustrated through modelling laboratory tests conducted on partially saturated soils. The numerical model is finally used for analysis of the influence of the soil saturation on the free-field response of a sandy layer subjected to cyclic loading.

2. Numerical model

Bian and Shahrour (2009) proposed a numerical model for the analysis of liquefaction of partially saturated sandy soils. This model is based on Coussy theory (2004). By

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neglecting the soil suction, the increments of the total stress $\delta\sigma$, pore pressure δp_w, water flux δm_w and deformation $\delta\varepsilon$ are governed by the following equations:

$$\begin{aligned}\delta\sigma &= C:\delta\varepsilon - M'\tfrac{\delta m_w}{\rho_w}I \\ \delta p_w = \delta p_a &= M' tr(\delta\varepsilon) - M'\tfrac{\delta m_w}{\rho_w}\end{aligned} \quad (1)$$

C stands for the drained elastic tensor; M' is the Biot modulus, which depends on the water compressibility K_w, porosity n and water saturation S_w:

$$\frac{1}{M'} = \frac{n_a}{K_a} + \frac{n_w}{K_w} = \frac{n(1-S_w)}{p_w + p_{a0}} + \frac{nS_w}{K_w} \quad (2)$$

K_a is the bulk compressibility, p_{a0} is a reference pressure.

The formulation proposed in Eq. (1) is similar to the (u-p) formulation of Zienkiewicz (Zienkiewicz & Shiomi, 1984), but with a Biot modulus depending on the water saturation, porosity and pore pressure. For saturated soils ($S_w = 1$), Eq. (1) is equivalent to Zienkiewicz's equation for saturated soil. Consequently, this model could be used for both saturated and unsaturated soils.

The response of partially saturated soils is controlled by the balance equation, the diffusion equation, and the conservation of the mass. The balance equation could be written as follows:

$$div(\sigma) - \rho\ddot{u} = 0 \quad (3)$$

σ is the total stress tensor, $\ddot{u}$ is the acceleration of the soil skeleton and ρ is the soil density. For partially saturated soils, the density could be written as follows:

$$\rho = (1-n)\rho_s + nS_w\rho_w \quad (4)$$

The water flux is governed by the generalized Darcy's law:

$$\frac{\vec{w}}{\rho_w} = -k_{ins}\frac{k_w^{rl}}{\mu}[grad(p_w) + \rho_w\ddot{u}] \quad (5)$$

$\vec{w}$ denotes the pore-water mass flux. k_{ins} and k_w^{rl} designate the soil intrinsic permeability and the relative permeability, respectively. μ is the viscosity of the pore water. The diffusion equation for the pore water is sufficient, because of the assumption of zero flux of the pore air. The presence of the pore air affects the pore water diffusion. When a soil becomes unsaturated, the air replaces first water in the large pores; consequently, water must flow through small pores with increased tortuosity. Since the space available for the water flow reduces, the permeability with respect to the water phase decreases rapidly. The relative permeability depends on water saturation:

$$k_w^{rl} = \sqrt{S_w}\left(1 - (1 - S_w^{\frac{1}{m}})^m\right)^2 \quad (6)$$

The parameter m could be determined from laboratory tests. The overall mass conservation must consider the relative mass flow of both pore-water and pore-air. Considering the absence of overall creation and null gas flux, the mass conservation results in the following equation:

$$\dot{m}_w = div(\vec{w}) \quad (7)$$

3. Constitutive equations for studied sandy soil

The elastoplastic constitutive model MODSOL (Khoshnoudian & Shahrour, 2002; Ousta & Shahrour, 2001) is used to describe the soil behaviour. This model can reproduce the soil behaviour under monotonic and cyclic load. The shear modulus and the bulk modulus are determined as follows:

$$K = K_0\left(\frac{p}{p_a}\right)^N A(p,q);\ \ G = G_0\left(\frac{p}{p_a}\right)^N \quad (8a)$$

$$A(p,q) = \left[1 - \frac{1}{9}\cdot\left(\frac{1-v_0}{1-2v_0}\right)\cdot N\cdot\left(\frac{q}{p}\right)^N\right]^{-1} \quad (8b)$$

p_a is a reference pressure; N is a constitutive parameter; p and q designate the mean stress and the deviatoric stress, respectively.

The model uses two loading surfaces. The first surface f_m describes the soil behaviour under monotonic loading:

$$f_m = q - M_f pR_m \quad (9)$$

The hardening parameter R_m depends on the deviatoric plastic strains ε_d^p:

$$R_m = \frac{\varepsilon_d^p}{b + \varepsilon_d^p} \quad (10)$$

The parameter b describes the hardening curvature of the loading surface.

The expression of M_f in the deviatoric plane depends on the Lode's angle θ and friction angle φ:

$$M_f = \frac{6\sin\varphi}{3 - \sin\varphi\sin 3\theta} \quad (11)$$

A non-associated flow rule is used with the following gradient of the plastic potential:

$$\frac{\partial g_m}{\partial p} = \frac{\exp(-\alpha_0\varepsilon_d^p)}{M_c p}\left(M_c - \frac{q}{p}\right);\frac{\partial g_m}{\partial q} = \frac{1}{M_c p} \quad (12a)$$

$$M_c = \frac{6\sin\varphi_{cv}}{3 - \sin\varphi_{cv}\sin 3\theta} \quad (12b)$$

φ_{cv} is the characteristic angle.

The cyclic loading surface is given by the following expression:

$$f_c = q^l - p^l R_c \quad (13a)$$

$$q^l = \sqrt{s_{ij}^l s_{ij}^l}, s_{ij}^l = \sigma_{ij} - p^l\alpha_{ij}, p^l = \alpha_{ij}\sigma_{ij} \quad (13b)$$

$$R_c = \frac{\varepsilon_{dc}^p}{b + \varepsilon_{dc}^p} \quad (13c)$$

R_c controls the isotropic hardening of the cyclic surface, ε_{dc}^p denotes the plastic deviatoric deformation, which is initialized at each loading inversion. The unit tensor α_{ij}