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Numerical investigation of the effects of geometric and seismic parameters on liquefaction-induced lateral spreading

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ABSTRACT

The lateral movement of a liquefiable soil layer on gentle slopes is the most visible and devastating type of liquefaction-induced ground failure. Recent earthquakes have shown that this phenomenon causes severe damages to coastal structures, pier of the bridges and life-lines by exerting large lateral forces on the structures. In this paper coupled dynamic field equations of extended Biot's theory with **u**-p formulation are used for simulating the phenomenon and the soil behavior is modeled by a critical state two-surface plasticity model for sands. Furthermore, in this study variation of permeability coefficient during liquefaction is taken into account. The permeability coefficient is related to variation of the excess pore water pressure ratio. At first, two centrifuge tests on liquefiable sand which have gently inclined ground surfaces with different conditions are simulated and numerical results are compared with experimental observations. These comparisons showed that numerical simulations have very good consistency with experimental observations in modeling of excess pore pressures, lateral displacements, and surface settlements. After validation, the effects of different factors such as ground slope, thickness of the liquefiable layer, soil relative density, maximum acceleration of dynamic loading, frequency of input motion and number of load cycles are investigated on the amount of lateral displacement. At the end, by using the results of the conducted extensive parametric study, a new relation is proposed for estimating the magnitude of maximum lateral displacement. Comparison of the results of this equation with experimental records, field observations and other empirical relations shows the advantage of this equation over other previously proposed relations.

1. Introduction

Lateral spreading of the liquefied granular soils induces large displacements, that is one of the most destructive phenomena affecting buildings, roads, pipelines, and other structures. Occurrence of liquefaction in sloping grounds causes large deformations on ground surface, which may reach to several meters in some cases (Wang and Rahman [1]).

This phenomenon was reported as the main cause of damage during the major earthquakes such as Alaska 1964, Loma-Prieta 1989, Hyogoken-Nambu 1995, and Nisqually 2001. Maximum ground surface displacement and it's variation with depth are necessary parameters for seismic design of earthworks and foundations, so during the last decade, researchers have worked on these issues by various means such as physical tests (shaking table and centrifuge tests), sliding block analysis, artificial neural networks, and numerical simulation; to provide better insight into the phenomenon and present a relation for estimating maximum lateral displacement.

Sliding block analysis is the oldest analytical method in this field which was firstly presented by Newmark [2]. Then other researches like Goodman and Seed [3], Sarma [4], Yegian et al. [5], Byrne [6], and Bazair et al. [7] modified and used this method for estimating the amount of lateral displacement.

A wide range of centrifuge and shaking table tests have been employed to study the liquefaction-induced lateral displacement. One of the most comprehensive and well-known experimental studies was conducted on Nevada sand in the course of Verification of Liquefaction Analysis by Centrifuge Studies (VELACS). In addition, Taboada et al. [8], Sharp and Dobry [9], and Sharp et al. [10] investigated the effects of some important parameters on lateral displacement in different conditions using centrifuge experiments. Bethapudi [11] used shaking table (1-g) test to simulate lateral spreading phenomenon.

Various numerical methods have been employed to simulate

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lateral spreading phenomenon. Here, some numerical studies are briefly explained: Uzuoka et al. [12] predicted the lateral spreading of liquefied subsoil based on fluid dynamics principles. They simplified the behavior of the liquefied soil with Bingham model, which is a model for viscous fluids. In this model shear stress has a linear relation with shear strain. Also, Hadush et al. [13] assumed that liquefied soils behave as a pseudo-plastic fluid. Although this method has some theoretical shortcomings, the results of the lateral displacement of this simulation showed good outcome.

Several researchers attempted using advanced constitutive models for sands to simulate this phenomenon. Elgamal et al. [14] numerically simulated VELCAS number 2 experiment and their results for excess pore water pressure and lateral displacements were consistent with experimental observations. Valsamis et al. [15] and [16] simulated VELACS number 2 experiment with FLAC. By implementing a bounding surface plasticity model in the code, they presented a formula to predict maximum lateral displacement. Kanibir et al. [17] and Mayoral et al. [18] also simulated lateral spreading phenomenon.

Hamada et al. [19] based on observations during Nigata 1964 and Nihonkai-Chubu 1983 earthquakes suggested a simple empirical formula for estimating the maximum lateral displacement. They later modified the simple formula to consider a number of other important parameters as well (Hamada et al. [20]). Other researches such as Bartlett and Youd [21], Bardet et al. [22], Youd et al. [23], and Zhang and Zhao [24] have suggested different relations. Recently Valsamis et al. [16] proposed an analysis-based relation to predict lateral soil displacement.

In this paper coupled dynamic field equations of the extended Biot's theory with **u**-p formulation are used and soil behavior is modeled using a critical state two-surface plasticity model (Manzari and Dafalias [25]) for sands. The finite element program, PISA is used for numerical analysis.

In this research at first two different centrifuge tests are simulated to verify the compatibility of the numerical approach with experimental observations and validation of the model. The importance of parameters which affect the amount of lateral displacement are investigated through an extensive sensitivity analysis. These parameters are: Ground surface slope, thickness of the liquefiable soil, relative density of the soil, maximum acceleration of dynamic loading, loading frequency, and number of cycles of the dynamic loading (time duration of dynamic load). Finally, based on the database gathered from the results of the numerical simulations a simple formula is proposed for estimating the liquefaction-induced maximum lateral displacement. The aim of this study is to accurately model the lateral spreading phenomenon and present a simple relation to predict maximum lateral displacement.

2. Numerical formulation aspects

In this research, a fully coupled two-dimensional dynamic analysis, with **u**-P formulation has been used to simulate the lateral spreading phenomenon and to evaluate the magnitude of deformations occurred in liquefiable soils. In this formulation pore pressures and displacements are computed simultaneously at each time step. Momentum balance for the soil–fluid mixture, momentum balance for the fluid phase, and mass balance for the whole system of soil and fluid are satisfied in this method. The primary unknowns are displacement of the solid phase (**u**) and pore fluid pressure (P). The **u**-P formulation is applicable to dynamic problems in which high-frequency oscillations are not important, such as soil deposit under earthquake loading. Using the finite element method for spatial discretization, the u–P formulation of the three partial differential equations mentioned above reduces to the following system of equations (Zienkiewicz and Shiomi [26]):

$$\mathrm{M}\ddot{\mathbf{U}} + \int_V \mathbf{B}^T \boldsymbol{\sigma}' dV - \mathbf{Q}\mathbf{P} - \mathbf{f}^{(\mathbf{s})} = 0 \tag{1}$$

$$\mathbf{Q}^T\dot{\mathbf{U}} + \mathbf{H}\mathbf{P} + \mathrm{S}\dot{\mathbf{P}} - \mathbf{f}^{(\mathbf{p})} = 0 \tag{2}$$

where M is the mass matrix, **U** is the solid displacement vector, B is the strain-displacement matrix, $\boldsymbol{\sigma}'$ 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 $\mathbf{f}^{(\mathbf{s})}$ and $\mathbf{f}^{(\mathbf{p})}$ include the effects of body forces and external loads, and fluid fluxes respectively. $\dot{\mathbf{U}}$ and $\ddot{\mathbf{U}}$ denote the velocity and acceleration of solid phase, respectively.

Numerical integration of the above-mentioned equations and their solution are carried out in the finite element program PISA (SAGE, Chan and Morgenstern [27]). The first version of this program was developed at the University of Alberta, known as SAGE. Later, a commercial version of this program was released with the name of PISA. Pak [28], Shahir [29] and Taiebat [30] further increased the capabilities of this program by completing its formulation to simulate THM (Thermal Hydro-Mechanical) and dynamic problems. In this research, the possibility of accounting for variation in the permeability coefficient of saturated sands during liquefaction has also been implemented in the program.

2.1. Constitutive model for simulating sand behavior

Simulation of sand behavior in this study, is based on soil plasticity constitutive model developed by Manzari and Dafalias [25]. The theories of bounding surface plasticity and general two-surface plasticity are the origins of the formulation of the model. The proposed model is a bounding surface plasticity model considering a small region for the elastic behavior. The model considers a coupling between two surface plasticity concepts with the state parameter to predict sand behavior in general stress space. The peak and the dilatancy stress ratios of the sand were defined by the state parameter. The bounding surface feature takes place in the deviatoric stress space. This feature makes the reverse and cyclic loading response simulation possible. The main advantage of this model is that it has the capability to utilize a single set of parameters for a wide range of void ratios and initial stress states of the same soil. This model possesses the simulative ability of the behavior of drained or undrained saturated sand under monotonic and cyclic loadings. It has 17 parameters divided into 5 categories based on their functions. The calibrated parameters of this model for Nevada sand are shown in Table 1 (Manzari and Dafalias [25]).

Table 1
Material parameters used for Manzari-Dafalias Model [25].

State parameters	K_c^b	3.975	Elasticity parameters	G_0(kPa)	31,400
	K_e^b	2.0		K_0(kPa)	31,400
	K_c^d	4.2		a	0.6
	K_e^d	0.07	Hardening parameters	h_0	800
Critical state parameters	M_c	1.14		m	0.05
	M_e	1.14		c_m	0
	λ	0.025	Dilatancy parameters	A_0	0.6
	$(e_c)_{ref}$	0.8		C_f	100
				F_{max}	100