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Numerical investigation on the behavior of the gravity waterfront structures under earthquake loading

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ABSTRACT

Lateral Spreading, which usually occurs as a consequence of liquefaction in gently sloped loose saturated sand layers, is known to be a major source of earthquake-induced damages to structures such as quay walls, bridge piers, pipelines, and highway/railways. Therefore evaluation of the liquefaction potential and using appropriate methods for prediction of the adverse consequences of lateral spreading is of great importance. In this study, numerical modeling has been used to study lateral spreading phenomenon behind rigid waterfront structures. Coupled dynamic field equations of the extended Biot's theory with **u**–P formulation are used for simulating the phenomenon. A fully coupled finite element code utilizing a critical state two-surface plasticity constitutive model has been applied and variation of permeability coefficient during liquefaction is taken into account. The developed code has been verified against the results of centrifuge experiment of VELACS No. 11. The numerical results are compared with the observed data consisting of seaward displacement of the wall, tilting and the generated pore water pressure in the soil. After validation, the influence of permeability and relative density of the soil on the residual deformation of the quay walls and on the generated pore water pressure are investigated. At the end, the effect of ground improvement on the seismic stability of the quay walls is investigated.

1. Introduction

Gravity quay walls are the most common type of construction of docks because of their durability, ease of construction and capacity to reach deep seabed levels. Although the design procedure for gravity quay walls is reasonably well established for static loads, their analysis under seismic loads requires further investigation. This fact was revealed after occurrence of severe damages to the waterfront structures in earthquakes such as Kobe, Japan (Ishihara, 1997) and Chi–Chi, Taiwan (Lee, 2005).

During strong ground shakings, the pore water pressure in cohesionless saturated soils builds up. This increase in the excess pore pressure not only causes the lateral forces on the walls to increase, but also reduces the effective stress of the soil foundation and backfill, which may result in liquefaction. Liquefaction and lateral spreading are known to be the major sources of earthquake-induced damages to waterfront structures in a number of past earthquakes such as earthquake in Los Angeles 1994, Kobe 1995, Aegion 1995 and Bhuj 2001 (Madabhushi et al., 2008). Therefore, evaluation of liquefaction potential and using appropriate methods for prediction of the adverse consequences of lateral spreading is of great importance.

Seismic damages to gravity quay walls are typically evaluated in terms of horizontal displacement, settlement, and tilting. Historically, several experiments have been carried out to physically model the behavior of the quay walls or embankments subjected to seismic loading using shaking tables or centrifuges. One of the centrifuge tests in this regard was conducted by Kutter (1982). His experiments were focused on the deformation of embankments under earthquake loading and investigating the subsequent post-earthquake deformations. Following these tests, some other centrifuge tests were conducted on the embankments and quay walls in the course of the VELACS (Verification of Liquefaction Analysis using Centrifuge Studies) project in 1993 (Arulanandan and Scott, 1994). VELACS model#11 was related to the quay walls with liquefiable backfill. Ghalandarzadeh et al. (1998) carried out 1 g shaking table tests on the quay walls and investigated the variation of pore pressure due to wall movement and wall velocity. They concluded that seismic design of retaining structures without considering the backfill liquefaction, which is the case in most design codes, can be far from safety. Lee (2005) conducted a series of 2-D centrifuge tests to investigate the seismic response of caisson-type walls embedded in soils with various permeabilities. He found that the rotational mode of displacement is dominant for pore pressure generation in deeper

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layers, while the translational mode is dominant for the same in shallow layers. Zeng (2005) studied the effect of liquefaction on the stability of three types of retaining walls (gravity, cantilever, and anchored sheet pile walls) through centrifuge experiments.

There have been some studies on the behavior of the quay walls using numerical investigation. Zienkiewicz et al. (1993) simulated VELACS No. 11 experiment numerically using Pastor-Zienkiewicz constitutive model (Pastor et al., 1990) and could predict the pore

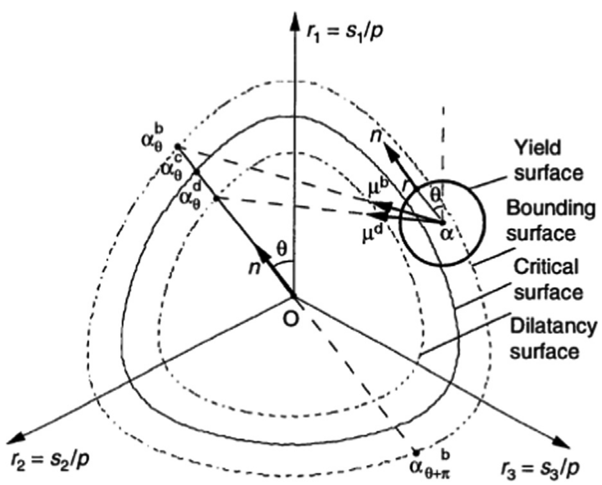

Fig. 1. Schematic illustration in the normalized π-plane of the Manzari and Dafalias (1997) model.

Table 1
Material Parameters for NEVADA sand (Manzari and Dafalias, 1997).

Elastic	G_0	3.14×10^4
	K_o	3.14×10^4
	a	0.6
Critical State	M_c	1.14
	λ	0.025
	$(e_c)_{ref}$	0.80
State Parameters	K_{cb}	3.975
	K_{cd}	4.20
Hardening	h_o	1200
	m	0.05
Dilatancy	A	2.64

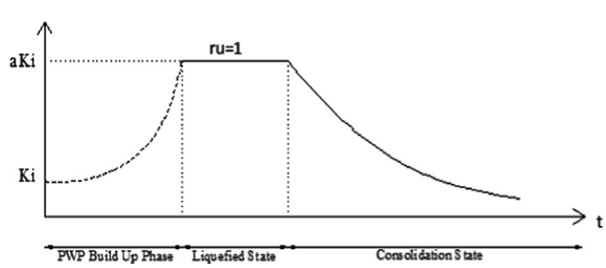

Fig. 2. Schematic view of the proposed permeability function.

water pressure variation and acceleration at different soil depths, reasonably well. Madabhushi and Zeng (1998) performed numerical simulation of a flexible, cantilever retaining wall with dry and saturated backfills under earthquake loading using the finite-element program SWANDYNE. Their numerical simulation was able to model the wall acceleration, bending moment, and displacement, recorded in the centrifuge tests for dry backfill slightly better than that for the saturated backfill.

Dakoulas and Gazetas (2008) used the elasto-plastic constitutive model of Pastor-Zienkiewicz (Pastor et al., 1990) and performed effective stress analysis. They examined the displacements of the gravity quay wall of Kobe port as well as variation of pore pressures behind the wall. They found that by increasing the density of the weak backfill soil, the earthquake-induced displacement and excess pore pressure will decrease. There has been some other numerical investigations such as Alyami et al. (2009) and Arablouei et al. (2011) in which different numerical approaches have been employed to simulate the behavior of the quay walls under earthquake.

In this study, numerical modeling has been used to study the lateral spreading phenomenon behind rigid waterfront structures. In order to perform numerical simulation of lateral spreading and also designing the structures exposed to its effects, the dynamic interaction of the soil solid phase with the pore fluid phase should be considered in a fully coupled manner by solving two differential equations of the load equilibrium and fluid flow continuity. In this work, study of the dynamic response of the quay wall systems on liquefiable soils is conducted using the finite element program, PISA. This fully coupled non-linear code uses the **u**–P formulation in which u is the solid phase displacement and P is the fluid phase pore pressure. The **u**–P formulation is applicable to dynamic problems in which high-frequency oscillations are not important, such as soil deposit under earthquake loading. A critical state two-surface plasticity constitutive model, proposed by Manzari and Dafalias (1997), has been applied to numerically simulate the behavior of sands and to evaluate the magnitude of deformations occurred in the liquefiable soil. Using a variable permeability function with respect to excess pore pressure ratio is another distinctive feature of the current study.

The well-known VELACS No. 11 experiment (Arulanandan and Scott, 1994) is first analyzed and the results are compared with the observed data consisting of pore water pressure generated in the soil, tilting, and seaward displacement of the wall. After verification, the influence of the relative density of the backfill soil and foundation layers, and the effects of permeability coefficient on the generation of pore water pressure and on the amount of the quay wall horizontal movement are investigated in a series of numerical examples.

2. Numerical formulation

The modeling framework described here is appropriate for saturated porous media, based on the concepts outlined by Biot (1956). In this formulation pore pressures and displacements are computed simultaneously at each time step by using the three

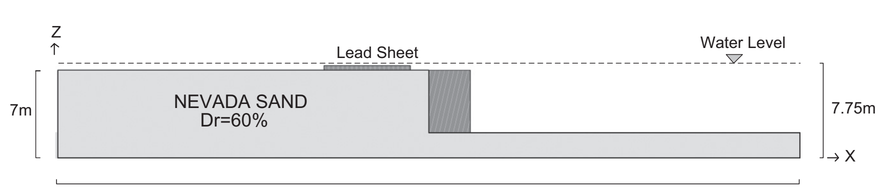

Fig. 3. Schematic view of VELACS No. 11 experiment.