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Seismic performance of a pile-supported wharf: Three-dimensional finite element simulation

Lei Su[a], Jinchi Lu[b], Ahmed Elgamal[c,*], Arul K. Arulmoli[d]

[a] Visiting Researcher, Dept of Structural Eng., University of California, San Diego, La Jolla, CA 92093-0085, United States
[b] Associate Project Scientist, Dept of Structural Eng., Univ. of California, San Diego, La Jolla, CA 92093-0085, United States
[c] Professor, Dept of Structural Eng., University of California, San Diego, La Jolla, CA 92093-0085, United States
[d] Principal, Earth Mechanics Inc., 17800 Newhope Street, Suite B, Fountain Valley, CA 92708, United States

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ABSTRACT

Considerable three-dimensional (3D) effects are involved in the seismic performance of pile-supported wharves. Such effects include the pile-to-pile interaction mechanisms as dictated by the behavior of the surrounding soil. This interaction might be further affected by potential ground slope settlement/heave, and the constraint of pile connectivity along the relatively rigid wharf deck. In order to capture a number of these salient response characteristics, a 3D finite element (FE) study is conducted herein. The prototype system motivating this study is presented, along with the corresponding numerical details. A realistic multi-layer soil profile is considered, with interbedded relatively soft/stiff strata. Effect of the resulting seismically-induced ground deformation on the pile-supported wharf system is explored. Specific attention is drawn to the noteworthy potential changes in axial force due to variation in pile embedment depth, and the ground slope deformation. The analysis technique as well as the derived insights are of significance to general pile-wharf-ground system configurations.

1. Introduction

Seaports are among the large-scale constructed facilities that are particularly vulnerable to damage and loss of function due to seismic activity [1,16,34,41,53,55,6]. In the U.S., port operations are generally reliant on pile-supported wharf structures [13,52]. Damage to such structures has been observed in many recent seismic events, including the 1989 Loma Prieta and the 2010 Haiti earthquakes [24,26,54,56]. This highlights the need for further understanding of the seismic soil-structure interaction (SSI) response characteristics of such wharf-ground systems [3,30,58].

A large number of reported numerical studies have been concerned with idealized two-dimensional (2D) seismic response models of the wharf and surrounding ground (e.g., [45,44,12,49,64]). To optimize the underwater bulkhead configuration, Yan *et al.* [58] performed 2D FLAC static and dynamic soil-structure interaction analyses for the Port of Los Angeles Berth 145–146 Upgrade. A similar modeling approach was adapted to predict the seismic response of wharf structures at the Ports of Oakland and Los Angeles [11,39]. Arulmoli *et al.* [4] carried out a 2D dynamic finite element (FE) DYNAFLOW analysis of a wharf-dike-backland system, investigating the pile pinning effects. Using OpenSees, Yang *et al.* [59] conducted 2D FE simulations to develop fragility curves for a typical wharf structure. Employing advanced structural and soil modeling procedures , Shafieezadeh *et al.* [47] performed 2D nonlinear plane-strain seismic analyses. The simulated results showed that the pile-deck connection is a vulnerable location, and batter piles were found to be susceptible to large tensile axial forces. More recently, a fully nonlinear 2D FE study was conducted [10,9] exploring the seismic performance of marginal wharves with conventional and improved pile-deck connection conditions. In this idealization, the piles were represented by nonlinear fiber section beam-column elements with prestressing steel. The pile elements were connected to the 2D soil mesh using nonlinear *p-y*, *t-z*, and *Q-z* spring relationships. System response was assessed including crane damage and port downtime for three different hazard levels.

In order to more accurately incorporate plan irregularities, interaction of adjacent wharf sections, and pile-to-pile interaction considerations, three-dimensional (3D) numerical studies have been conducted. Takahashi [51] employed a 3D FE mesh to analyze results of an idealized pile-supported wharf centrifuge model. Donahue *et al.* [14] investigated the Port of Oakland Berth 24/25 recorded seismic response using Winkler-type nonlinear soil springs [2,20,21]. The resulting response was found to be strongly dependent on the defined spring properties. A similar 3D soil spring modeling approach was

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[*] Corresponding author.
E-mail address: elgamal@ucsd.edu (A. Elgamal).

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employed by Doran *et al.* [15] in a push-over seismic evaluation study. Addressing liquefaction, Shafieezadeh *et al.* [48] conducted 3D nonlinear studies of a typical pile-supported wharf. The numerical model employed nonlinear fiber section beam-column elements for the deck and the piles, and soil macro-elements to capture the force-deformation of the coupled soil-pile system. The results showed that a 2D wharf representation may not fully account for involved 3D response characteristics.

The study reported herein [50] employs a full 3D FE simulation framework, in order to capture and further elucidate a number of salient characteristics associated with the pile-ground and pile-to-pile interaction mechanisms. As such, the actual SSI of pile-ground geometric configuration is captured, without need for the above-mentioned 2D idealizations, related to definition of soil-springs that connect the pile beam elements to the surrounding soil mesh. A wharf-ground configuration derived from the Port of Los Angeles Berth 100 layout [22] is considered. The FE computations were performed using OpenSees [37], a nonlinear analysis platform for simulating seismic response of structural and geotechnical systems [17,18,33].

The following sections of this document outline: i) specifics and model properties of the wharf-ground system, ii) details of the employed FE modeling techniques, iii) results of the conducted numerical simulations, and iv) insights derived from the study. Finally, a number of conclusions are presented and discussed.

2. Computational framework

All simulations were conducted using the open source computational platform OpenSees (http://opensees.berkeley.edu, [37]). This platform allows for developing applications to simulate the performance of structural and geotechnical systems subjected to static and seismic loading.

Implemented in OpenSees [60,61] is an analysis framework for saturated soil response as a two-phase material following the *u-p* formulation of Chan and Zienkiewicz *et al.* [8,63], where *u* is displacement of the soil skeleton, and *p* is pore pressure. This implementation is based on the following assumptions: small deformation and rotation, solid and fluid density remain constant in time and space, porosity is locally homogeneous and constant with time, soil grains are incompressible, and solid and fluid phases are accelerated equally. Hence, the soil layers are represented by effective-stress fully coupled solid-fluid brick elements, seamlessly capable of accounting for soil deformations and the associated potential changes in pore-pressure [32].

The employed soil constitutive models [19,40,61] were developed based on the multi-surface-plasticity theory [42,43]. In employing these models, the shear stress-strain backbone curve was represented by the hyperbolic relationship with the shear strength based on triaxial compression (reached at a shear strain of 12%). As such, soil is simulated by the implemented [62] OpenSees materials PressureIndependMultiYield and PressureDependMultiYield.

The FE matrix equation is integrated in time using a single-step predictor multi-corrector scheme of the Newmark type [40,8] with time integration parameters γ=0.6 and β=0.3025. For each time step, the solution is obtained using the modified Newton-Raphson approach with Krylov subspace acceleration [36,7]. On this basis, the initial tangent stiffness of the system (after application of gravity) is used for all steps and iterations to achieve the prescribed tolerance (normalized displacement increment less than 10^{-4}). Finally, a relatively low level of stiffness proportional damping (coefficient =0.003) is employed to enhance the numerical system stability, with the main damping emanating from the soil nonlinear shear stress-strain hysteresis response [29].

3. Piles and soil-pile interface

The piles and deck are simulated by 3D nonlinear fiber-section and elastic beam column elements, respectively [36]. To represent the geometric space occupied by the pile, essentially rigid beam-column links (EI =10^4 times the linear EI of the pile) are used normal to the pile vertical axis [18]. The 3D brick elements representing the soil are connected to the pile geometric configuration at the outer nodes of these rigid links [31] using zerolength elements and the OpenSees equalDOF translation constraint [18,57]. These zerolength (zeroLengthSection) elements are used to: i) axially connect the rigid link to the adjacent soil node, and ii) provide for skin-friction yield shear force along the soil-pile interface (according to the assumed soil-pile friction angle and adhesion) limited by:

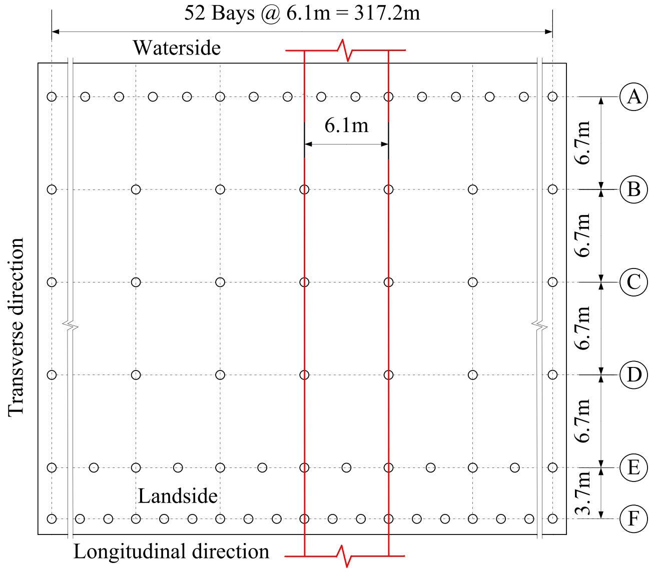
$$F_{skin\ friction} = (c_A + \sigma\ tan\ \delta)\cdot l\cdot h/N$$

where l is the pile perimeter; h is the center to center contributing height (according to the adjacent soil element heights), δ is the soil-pile friction angle, c_A is the soil-pile adhesion, σ is the lateral effective stress, and N is the number of zeroLengthSection elements along the pile perimeter.

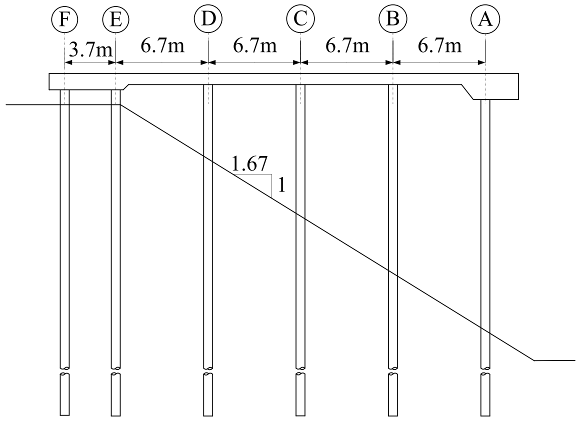
4. Finite element model

The employed pile-supported structural and ground configuration (Fig. 1) is typical of such facilities in the U.S. Southwest (e.g., Container Wharves at the Port of Los Angeles, California). As shown in Fig. 1a, this 317.2 m long wharf structure is composed of a reinforced concrete deck supported on six rows of vertical pre-cast concrete piles (rows A through F as shown in Fig. 1).

Along its longitudinal direction (Fig. 1a), the wharf consists of a



(a) Plan view



(b) Side view (Transverse cross-section)

Fig. 1. Wharf configuration.