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Prediction Of Seismic Response And Damage Mitigation For Pile-Supported Wharf Structures

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Abstract. Many ports in the US are located in areas of high seismicity and remain vulnerable to damage from large earthquake events. Waterfront structures such as pile-supported wharves are particularly vulnerable to damage associated with lateral spreading of the underlying loose soil fills. This paper describes results of analyses to understand the performance of a typical pile-supported wharf and the effectiveness of mitigation measures. The analyses use a sub-structuring approach in which the 'free-field' response of the soil fill is simulated using finite element analyses that are able to represent the complex non-linear stress-strain properties of sands under seismic loading using the model proposed by Dafalias and Manzari (DM, 2004). Ground deformations and excess pore water pressures are then treated as boundary conditions in modeling the response of the pile-supported wharf structure, using a macro-element proposed by Varun and Assimaki (2012) to represent local soil-structure interaction. The paper presents the performance of the pile-supported wharf for a suite of 56 ground motions, and highlights the occurrence of deep-seated failure mechanisms in the supporting rows of piles. The effects of lateral spreading in the soil fill can be addressed by installing full-depth Pre-fabricated Vertical (PV) drains at locations behind the crest of the fill. Analyses with this mitigation system show that structural damage is limited to the pile-deck connections enabling much simpler designs for structural retrofitting

Keywords. Earthquake Engineering, Numerical Modeling, seismic mitigation, soil-structure interaction

1. Introduction

Maritime trade accounts for 80-85 % of international trade and port facilities are exposed to a variety of natural hazards including earthquakes, tsunamis, and hurricanes that can lead to significant disruptions in operations and economic losses. The 'Great Hanshin' earthquake (Japan, 1995) resulted in almost complete destruction of the port facilities resulting in huge short and long-term economic losses for the city of Kobe. Many US ports are located in areas with significant seismic hazards on both the West coast (Oakland, Los Angeles, Long Beach, and Seattle) and East coast (Charleston, SC, and Savannah, GA). Hence, there is a constant need to evaluate the seismic risk, and suitable mitigation measures for existing waterfront facilities that can be implemented without severe disruption to ongoing port operations.

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This paper focuses on the performance of a common type of wharf structure comprising a pile-supported deck that typically supports a rail-mounted container crane, Figure 1. The seismic vulnerability of these types of structures is primarily due to the lateral spreading and slope failure within the embankment fills, which often comprise loose granular fills (mostly constructed prior to current seismic design codes). Piles embedded within these fills can be subjected to extremely lateral loading due to downslope “spreading” in seismic events.

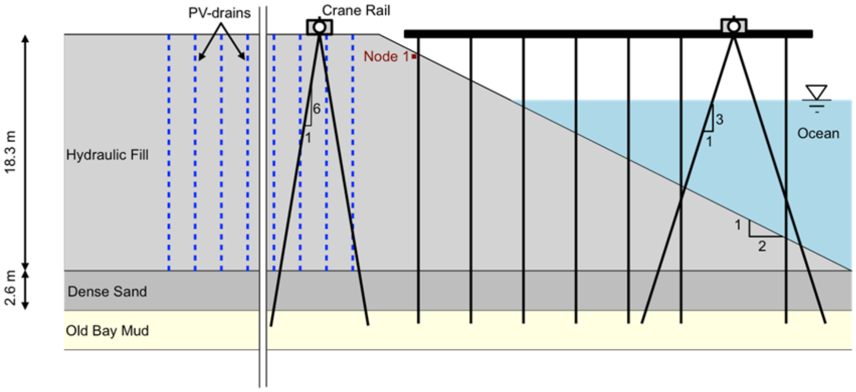


Figure 1. *Typical pile supported wharf structure (Oakland, Berth 60-63) and potential location of PV-drains for mitigation of seismic damage*

The performance of the structure is evaluated using an uncoupled substructure approach, which involves separate analyses of the free-field response of the soil mass (i.e., without structural elements) and of the wharf structure (piles, deck, and crane). This research builds on prior research by Vytiniotis [1], Varun [2] and Shafieezadeh [3]. The interaction between the free field and pile-deck models is handled through ‘macro-elements’ [2] that require the time histories of free-field displacements and pore pressures at locations along each of the piles as input motions. The research evaluates structural damage for a reference wharf structure for a suite of selected earthquake ground motions. It further evaluates the effectiveness of current soil improvement scheme that uses an array of PV drains to prevent pore pressure accumulation on the landward side of the wharf (Figure 1, proposed by [4]) in limiting the structural damage in wharf structures during seismic loading.

2. Soil-Structure Interaction

2.1. Soil-Structure Interaction for Pile Foundations

The seismic design of pile foundations in loose granular soils poses several difficulties in analysis and design: liquefaction is associated with a large reduction in shear stiffness of the supporting soil and can induce large shear forces and bending moments within the piles leading to severe cracking and formation of plastic hinges at specific locations [5]. After liquefaction, the residual strength of the soil may be less than the shear stresses needed for slope equilibrium and significant lateral spreading or downslope displacements can also occur (i.e., post-shaking lateral spreading can cause substantial increases in pile cap displacements above those for the non-liquefied case). In addition, the moving soil can exert damaging pressures against the piles, leading to failure. Such failures were prevalent during the 1964 Niigata and 1995 Kobe earthquakes. Lateral spreading is particularly damaging when the piles are embedded in soil profiles including both liquefiable and non-liquefiable (stable) soil layers.

2.2. Ground Motions and Free Field Analysis

The NEES-GC team [3] selected a suite of 56 ground motions that are typical of firm-site conditions in coastal California using records from the Next-Generation Attenuation of Ground Motions (NGA) project [6], with moment magnitude M=5.5-8.0, located 15-60 km from rupture zone, representative of a C site class. A subset of 15 ground motions were randomly selected from the NGA database at rupture distances less than 15 km.

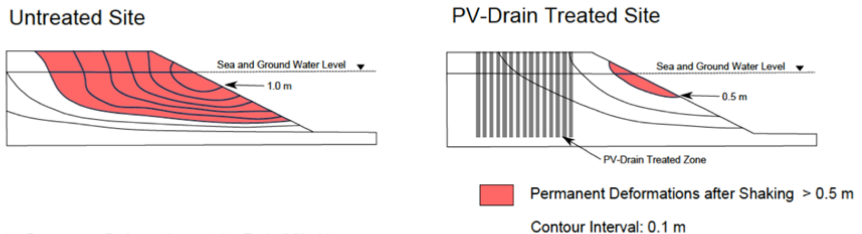
Vytiniotis [1] used the selected suite of earthquake ground motions to predict the free field response at the reference site (i.e., the seismic ground response with no structure present). The response of the loose sand fill was computed using a coupled deformation-flow finite element analyses with appropriate free-field boundary conditions using OpenSees, an object-oriented FE analysis framework [10]. The Dafalias and Manzari effective stress soil model (DM2004) [7] was used to simulate the mechanical response of sand in cyclic shearing. This model predicts reasonably well both the monotonic and the cyclic behavior of sand measured in laboratory tests, and is able to capture the effects of void ratio and confining stress in the mechanical behavior of soils with a single set of model parameters. Analyses were performed by calibrating the DM2004 [7] model with lab data for Toyoura sand (the loose fill corresponds to D_r=40% and the dense sand to D_r=80%). Vytiniotis [1] also investigated the effectiveness of installing an array of PV-drains as a method of mitigating seismic risk by using the same suite of free field ground motions. The PV-drains system offers a less intrusive solution for retrofitting the berth (Figure 1), than conventional compaction methods that would require a complete reconstruction of the piled-wharf structure. The current research uses free field analyses to compare the response of: 1) the current unimproved piled wharf structure; and 2) the wharf retrofitted with a PV drain system.

The soil profile, Figure 1, comprises three basic layers: a 18.3 m thick (hydraulically-placed) loose sand fill (D_r=40%), overlying a 2.6 m base of dense sand (D_r=80%) and an underlying stiff-to-hard clay. Figure 2 compares the free field predictions of permanent deformations (Figure 2a) and excess pore pressures (Figure 2b) for the reference loose-fill (“untreated” case) and with the PV-drains mitigation system for one strong acceleration record (nga0753, Figure 2c). For the “untreated slope” large excess pore pressures develop behind the crest of the slope and drive deep-seated ground movements. The PV-drains prevent built up of excess pore pressure and reduce significantly the downslope lateral spreading.

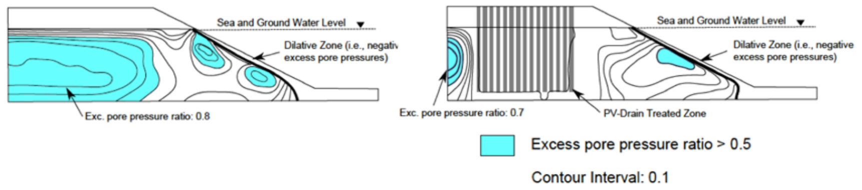
2.3. Overview of the Macro-element Formulation

The current analyses use a macroelement developed by Varun [2] that can capture efficiently the response of piles in cohesionless soils subjected to cyclic lateral loading and can account for soil liquefaction. The soil resistance around the pile circumference is modeled along using a nonlinear Winkler spring, while a viscous damper represents radiation damping that varies with non-linear material behavior.

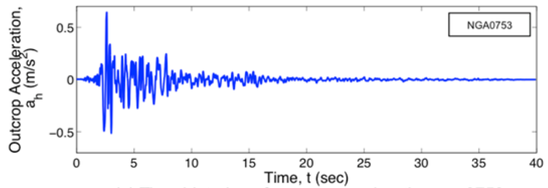
Varun [2] observed the formation of a zone around the pile where pore pressures are considerably different from those in the far field due to local soil-structure interaction. In order to incorporate the effects of changes in effective stress at the soil-pile interface Varun [2] introduced a pore pressure generator that modifies the drained response to account for local pore pressure generation and dissipation, using the "liquefaction front" concept originally proposed by Iai [8]. The macroelement can simulate the formation of a gap between the pile and soil by reducing the overall soil resistance (Varun, 2010).



(a) Permanent Deformations at the End of Shaking



(b) Excess Pore Pressure Ratios at the End of Bracketed Duration



(c) Time histories of outcrop acceleration nga0753

Figure 2 *Free Field Response (a) Contours of Permanent Deformations at the End of Shaking, (b) Contours of Excess Pore Pressure Ratio at the end of Shaking and (c) Time history of Outcrop Acceleration*

The macroelement was originally developed using a series of 3D finite element simulations using the finite element program Dynaflow incorporating the multi-yield plasticity model of Prevost [9], and was later validated with using full-scale, forced vibration test data from a blast-induced liquefaction test bed and centrifuge data for earthquake loading of piles with superstructure [2]. Varun conducted 3D finite element parametric investigation of a single pile in liquefiable soil to interpret the controlling parameters.

Figure 3 shows the typical elemental response of the macroelement calibrated for loose and dense Toyoura Sand (D_r=40% and D_r=80% respectively) [11]. The imposed sinusoidal horizontal displacement and linear build-up of excess pore pressure causes a degradation of the stiffness and the total resistance of the macroelement. The degradation effect is more prominent in the loose sand.

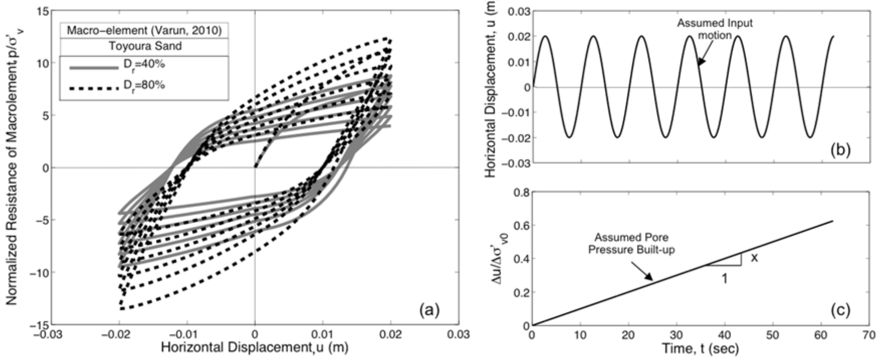


Figure 3 *Macroelement Response for medium and dense Toyoura sand under assumed sinusoidal horizontal displacement and linear excess pore pressure built-up*

3. Seismic Response of Pile-supported Wharf Structure

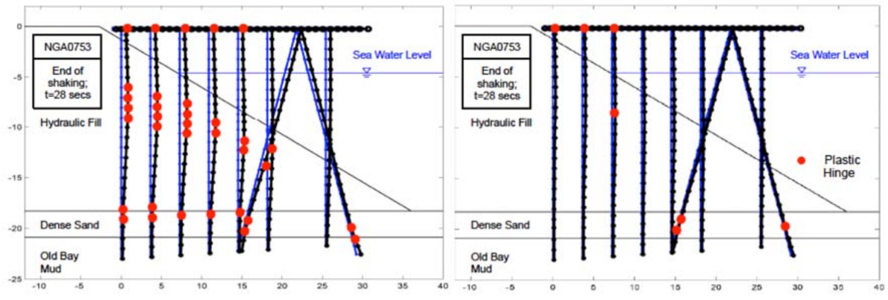
3.1. Structural Model

This section summarizes the 2D dynamic response of the reference wharf structure (Figure 1). The pile-soil model comprises three components at: 1) 2-D beam-column elements representing the behavior of precast and prestressed piles, 2) vertical spring elements describing the vertical pile-soil interaction, and 3) macroelements describing the horizontal response of the pile-soil interaction. Each macroelement has a free field boundary where the corresponding time histories of free field displacements and excess pore pressure ratios (e.g., Figures 2a,2b) are imposed as input motions for the dynamic analyses.

The berth structure consists of 7 rows of vertical and 2 rows of batter pre-stressed reinforced concrete piles supporting a 30 m long, 0.46 m thick reinforced concrete deck (Figure 1). A 2-D finite element (FE) model of this wharf has been developed in OpenSees [10]. Vertical loads from the superstructure are transferred to the underlying soil through the shear resistance along the shafts of the piles and the end bearing resistance developed at tips, while lateral loads are resisted by the bending action in the vertical piles (the batter piles provide both bending and axial resistance). The pile nodes have three degrees-of-freedom and are simulated using the actual section and moment of inertia properties, while the non-linear beam-column elements are capable of simulating the formation of plastic deformations within the element. The properties of the reinforced piles are represented with an aggregated section in which the moment-curvature response is described by an elastic, perfectly plastic constitutive law with maximum section yielding moment properly calibrated for the pile section of the reference wharf structure.

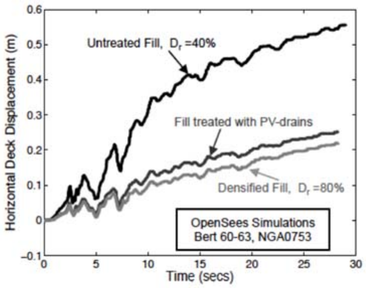
The deck structure is responsible for transferring the dead and live loads of the wharf structure to the underlying foundation. Due to its large thickness and high rigidity, the deck acts as a diaphragm wall in the horizontal plane. The deck is modeled with linear elastic, beam-column elements, and additional constraints are imposed (by tying the deformations of all the deck nodes to each other) to prevent flexural deformation of the deck. The pile-deck connections are modeled in a simplified way by imposing the same degrees of freedom at the pile head and the connecting pile deck nodes.

Simplified modeling of the vertical soil-pile interactions with elastic springs was judged appropriate as the loading was predominantly horizontal and the vertical displacements are very small. In the lateral direction, the soil-pile interaction is modeled using the macroelement developed by Varun [2], with input parameters calibrated using the proposed methodology and assuming standard engineering soil properties of Toyoura sand [1].



(a) Untreated Soil

(b) PV-drains mitigation system



(c) Time histories of horizontal displacements for node 1 under different soil improvement scenarios

Figure 4 *Structural Performance of Berth 60-63 founded (a) on untreated soil and (b) soil treated with PV-drains mitigation system. (c) Time histories of horizontal displacement of the deck.*

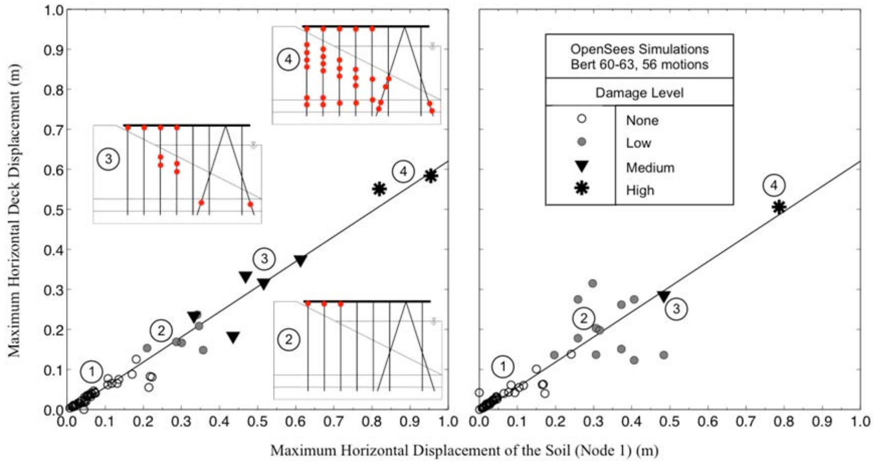
3.2. Results

Figures 4a and 4b show the pile deformations and the locations of plastic hinges when the wharf is subjected to the nga0753 base acceleration for the untreated fill and PV-drains mitigation cases, respectively. The results show that the PV-drain system is effective in reducing wharf deformations and pile damage. Figure 4(c) presents the time histories horizontal displacement of the deck. These results show a large reduction in the lateral deck deformation (0.55m vs. 0.26m). Indeed the results with PV-drains are comparable to the response achieved for the case where the fill is well compacted (D_r=80%) for this specific outcrop ground motion record.

Figure 5 presents collectively the results of the 56 ground motion records for the "untreated" scenario with the PV-drain mitigation system. The results are grouped into 4 classes of damage level: (1) No damage, where structural response is elastic; (2) Light damage, where failure occurs only at the pile-deck connections; (3) Moderate damage, where plastic hinges develop along the piles; and (4) Heavy damage associated with the creation of a plastic collapse mechanism of the supported wharf (shown schematically at Figure 5).

For the "untreated" scenario, only two of the suite of selected ground motions caused extensive damage to the structure, 6 produced moderate damage and 6 light damage. The structure remained elastic for the other 42 ground motions with small permanent displacements, as shown in Figure 5. There is also a very good linear correlation between the maximum deck displacement and the corresponding maximum free field movement (referred to node 1, Figure 1) as reported by Vytiniotis [1] for free-field slope movements.

Results with the PV-drain mitigation system generally led to smaller permanent deformations of the deck and less structural damage to the piles. In fact, the results indicate a shift of the level of damage of the structures from moderate to light damage. Only one case caused extensive damage to the structure, 1 produced moderate damage and 11 light damage. Analyses with PV-drains mitigation show that structural damage is primarily limited to the pile-deck connections (damage class 2, Figure 5b) and can be more easily addressed with seismic retrofitting.



(a) Untreated Soil (b) PV-drains mitigation system

Figure 5 *Damage-level response for (a) Untreated Soil and (b) PV-drain mitigation system*

4. Conclusions

The use of the sophisticated macroelement in the analyses provides significant advantages over the full 3D finite element analyses for simulating complex SSI for piles especially in terms of modeling complexity and computational time. The macroelement captures efficiently the fundamentals mechanics of saturated granular soil-pile interaction. Moreover, the macroelement is easily calibrated using standard laboratory test data and can thus be used in practice.

The major conclusion is that the permanent deformations of the structure are primarily governed by the lateral spreading of the soil and therefore mitigation measures must control downslope soil deformations. The proposed PV-drain system (located behind the crest of the slope) is effective in reducing lateral spreading in the loose hydraulic fill (for a reference wharf structure, Figure 1). Uncoupled analyses of the pile deck show that the mitigation system reduces the lateral deformation of the deck and the damage in the piles. Further studies are now needed to investigate the general validity of these results for other waterfront structures.

Acknowledgements

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