USE OF STRONG MOTION RECORDS TO VALIDATE DYNAMIC SOIL-FOUNDATION-STRUCTURE INTERACTION MODELS FOR PILE SUPPORTED WHARVES

Stephen Dickenson[1], Songtao Yang[2], Doug Schwarm[3] and Matt Rees[4]

[1] New Albion Geotechnical, Inc., Corvallis, OR
[2] CH2M Hill, New York, NY
[3] Atlas Geotechnical, Inc., Santa Cruz, CA
[4] CH2M Hill, Swindon, UK

Abstract

This paper provides interim results of an on-going investigation of the seismic response and performance of instrumented pile supported wharves at the ports of Los Angeles and Oakland, California. The first phase of the project has focused on the synthesis of geotechnical, structural, and strong motion data at three port sites instrumented by CSMIP. Geophysical investigations performed for this study provide V_s data in unimproved, liquefiable hydraulically-placed fill at a CSMIP strong motion station and in adjacent zones of fill improved with stone columns. Strong motion recordings obtained at the Port of Oakland Berth 36-38 and Port of Los Angeles Berth 404 have been used to validate a practice-oriented 2D nonlinear, effective stress geomechnical model for low- to moderate-levels of ground shaking and structural response.

Introduction

This investigation addresses the effects of long-duration ground motions on the Soil-Foundation-Structure-Interaction (SFSI) and seismic performance of key port structures in California. The project is examining the effectiveness of current seismic design codes and performance-based provisions (ASCE Seismic Standards, in preparation; CSLC MOTEMS, 2010; POLA, 2010; POLB, 2012) for achieving the defined performance requirements for large magnitude earthquakes that generate long-duration ground motions. The topic is important because: (a) recent experience demonstrates that loss of serviceability at port terminals is strongly correlated with permanent ground deformations, and (b) long-duration ground motions have much greater potential for generating damaging wharf and embankment deformations at lower force levels relative to stronger, but brief, seismic loading. The project is proceeding in two phases that include four primary tasks;

1. Collection and analysis of CSMIP strong motion data at two major ports
2. Validation of a dynamic SFSI model for modern pile supported wharves;
    a. Port of Oakland (Berth 36)
    b. Port of Los Angeles (Berth 404)
3. Application of SFSI model for design-level ground motions
    a. Port of Oakland (Berth 55)
    b. Port of Los Angeles (Berth 404)
4. Application of SFSI model for long-duration ground motions

This paper provides an interim report on the results of the first phase of the project involving Tasks 1 and 2. The collection and synthesis of geotechnical, geophysical, and structural data, as well as construction documentation has been completed for two CSMIP strong motion instrumentation arrays at ports. The extensive characterization of geotechnical and structural conditions at the CSMIP instrumented wharves located at the ports of Los Angeles and Oakland, California has led to the development of models for simulating the nonlinear effective stress response of dynamic SFSI. The model behavior under low- to moderate-levels of ground motion has been evaluated to validate and calibrate modeling procedures for soil constitutive models, cyclic soil-structure interaction for deep foundations, and structural response.

Project Background

Dynamic SFSI of pile-supported wharves represent a complex geotechnical and structural interaction problem. The combination of inertial loading and kinematic effects due to seismically-induced ground displacement (i.e. displacement demand) imposes foundation loads that are commonly out-of-phase and quite variable depending on vertical and lateral location relative to the sloping face of terminal wharves. Observed failures to wharf foundations are often associated with geotechnical failures (liquefaction, cyclic degradation, slope instability). Field reconnaissance and inspection at ports after moderate to large earthquakes routinely finds that damage to waterfront structures is directly related to permanent ground deformation and large displacement demand on pile foundations, cutoff walls and anchor systems, and appurtenant structures (ASCE TCLEE, 1998; PIANC WG34, 2001; ASCE COPRI, in press).

The adoption of performance-based seismic design provisions at major ports and marine oil terminals in California necessitates the reliance in engineering practice on numerical models for simulating dynamic SFSI of wharf and embankment structures. Recent investigations of the seismic performance of pile supported wharves have developed enhanced methods of analysis (e.g.; Chiaramonte et al., 2011; Shafieezadeh et al. 2012); however, the lack of well-documented, instrumented field case histories has precluded thorough validation of analysis methods for simulating dynamic SFSI of these structures. The lack of model validation can lead to a poor understanding of the uncertainty involved in seismic analyses and an over-confidence in the analysis results. The application of performance-based design of pile-supported wharves requires a clear understanding of this dynamic SFSI and methods of analyses for evaluating both inertial and kinematic loads on the wharf structure. Specific aspects of analysis that warrant consideration for long-duration motions include; (a) fatigue and plastic hinge development in piles as a function of row location, (b) stress concentrations at pile-wharf deck connection, and (c) patterns of deformation in the rockfill embankment, backfill and foundations soils.

An important facet of this investigation is the calibration of the numerical SFSI model for the two selected wharves using strong motion records from CSMIP stations for the following cases involving small to moderate levels of shaking;

Port of Oakland, Berth 38, M_w 6.9 October 17, 1989 Loma Prieta Earthquake

The 1989 experience at the Port of Oakland provides a significant case history involving moderate levels of ground motion, extensive liquefaction, and widespread damage to pile foundations, all of which add complexity to the numerical modeling. While Berth 38 was not instrumented in 1989, motions from the CGS-SMIP *Oakland Outer Harbor Wharf* station (Berths 24/25), along with other local motions, have been used by several investigators in validation studies using various dynamic models for both wharves (Norris et al. 1991; Singh et al. 2001a, b; Wang et al. 2001; Roth and Dawson 2003; Donahue, et al. 2005; Dickenson and McCullough 2006).

Port of Los Angeles, Pier 400, M_w 4.7 May 17, 2009 Inglewood Area Earthquake

The 2009 earthquake provides a rich set of recorded motions at Pier 400 at lower levels of shaking (0.113g free-field, 0.21g on the wharf structure) that have been used for validating the SFSI model for elastic response of the wharf.

The CSMIP arrays of strong motion instrumentation at these two locations make them particularly well suited for in-depth seismic performance analysis. Instrumentation in the free-field, at multiple locations on the wharf structures, and in one case within an improved portion of the foundation soils (CDSM treatment in weak soils) has provided opportunities and challenges for numerical modeling. In order to validate the numerical models a major effort has been undertaken to collect supporting information and data required for robust nonlinear SFSI modeling. This has included; port reports on geotechnical site characterization, dynamic soil properties, geotechnical interpretation and design (Fugro West 2001a, b, c), structural seismic design and detailing (Priestley 2000; Weismair et al 2001), construction materials and methods (Degen et al. 2005; Fugro West 2004), as-built drawings (POLA 2002), and large-scale physical model testing of pile-wharf deck connections (Krier et al. 2008; Lehman et al. 2013; Restrepo et al. 2007).

This investigation focusses on both the calibration of a practical dynamic SFSI modeling procedure and the application of the validated model for evaluating the impact of long-duration motions on the seismic performance of modern wharf structures at two major ports in California. The numerical dynamic SFSI modeling is being performed using the commercially available program FLAC. This program has been selected for application due to the wide usage in port engineering practice (e.g., Roth et al. 2003; Roth and Dawson 2003; Arulmoli et al. 2004; Moriwaki et al. 2005, Yan et al., 2005) and the vast experience of the project team with this code for port and waterfront applications. The project team has found by experience that the utilization of an “off the shelf” computed code is not sufficient for port applications without numerous enhancements. Several key aspects of the dynamic SFSI model developed by the project team for use on this project investigation include;

a. The 2D FLAC model is being used for nonlinear, coupled effective stress modeling.
b. Modeling excess pore pressure generation and cyclic degradation in soils is critical for long-duration motions. A recently refined version of the effective stress plasticity model UBCSand (Beaty 2009) is being used for liquefaction triggering and post-liquefaction behavior of sand.

c. Near-surface, lateral pile-soil response will reflect the characteristics of the piles, nature of the inertial loading provided by the wharf deck and contributing loads, the embankment slope, and the nature of the soil and/or rock fill along the upper portion of the pile. Pile embedment through rock armor layers and quarry run fill presents issues related to particle size effects on pile-soil p-y behavior. Physical modeling studies of piles in rock fill have demonstrated the limitations of continuum models for lateral pile response (Boland et al 2001a, 2001b; McCullough 2003; Kawamata 2009). This aspect of dynamic pile behavior is being addressed for the sloping, rock fill and armor conditions at both ports.
d. The mass of a gantry crane will be incorporated in the modeling. While this investigation has not focused on the dynamic response characteristics of the crane a range of dynamic loads on the wharf representing is being evaluated.

The response of the two wharves used as test-bed applications is currently being evaluated (Phase 2) to assess the relative contributions, and phasing, of kinematic and inertial loading on the pile foundations. The progressive and cumulative impact of kinematic loading of the wharf foundations due to foundation deformations is anticipated to be a key consideration for long-duration seismic loading.

Validation of the Numerical Dynamic SFSI Model

Port of Oakland, Berth 38; M_w 6.9 October 17, 1989 Loma Prieta Earthquake

The seismic performance of the Seventh Street Terminal (Berths 35 through 38) pile-supported wharf at the Port of Oakland during the 1989 Loma Prieta Earthquake has been modeled by several investigators, as previously noted. The ground surface motions of approximately 0.25g to 029g, extensive liquefaction with nominal lateral spreading and post-seismic ground settlement, and widespread damage to piles (predominantly batter piles) provide an important case study for seismic loading approaching Operating Level Event (OLE) levels at the Port of Oakland. Field observations indicated permanent ground surface lateral displacement of the rock dike on the order of 15 to 30 cm, with approximately 13 to 30 cm of settlement (Egan et al. 1992, Singh et al. 2001a). In addition, the majority of the batter piles and approximately 20 percent of the vertical piles failed at the pile/deck connection (Singh et al. 2001). It was also noted by Singh et al. (2001) and Oeynuga (2001) that many of the vertical piles probably failed at the approximate interface between the Bay Mud/hydraulic fill and the dense sand, based on the results of pile integrity testing. These failures were likely due to pinning of the piles in the dense sands while lateral forces due to permanent ground deformations pushed on the upper portions of the piles in the rock fill.

This case study was initially evaluated using a simple, yet calibrated and adequate, excess pore pressure generation model for the hydraulically-placed sand fill (McCullough 2003; Dickenson and McCullough 2005). Berth 38 was modeled with the design geometry shown in Figure 1 and numerical model grid, soil layers, and structural elements shown in Figure. The soil and structural properties used in the model are provided by McCullough (2003). The nearest recorded acceleration time history was recorded at the ground surface approximately 1.5 kilometers from Berth 38 at the Port of Oakland Outer Harbor Wharf. The two horizontal components of the recorded motions were vectorally combined to produce a motion perpendicular to Berth 38. The combined motion was deconvolved to the base of the numerical model (El. –21 m) using the equivalent linear model SHAKE.

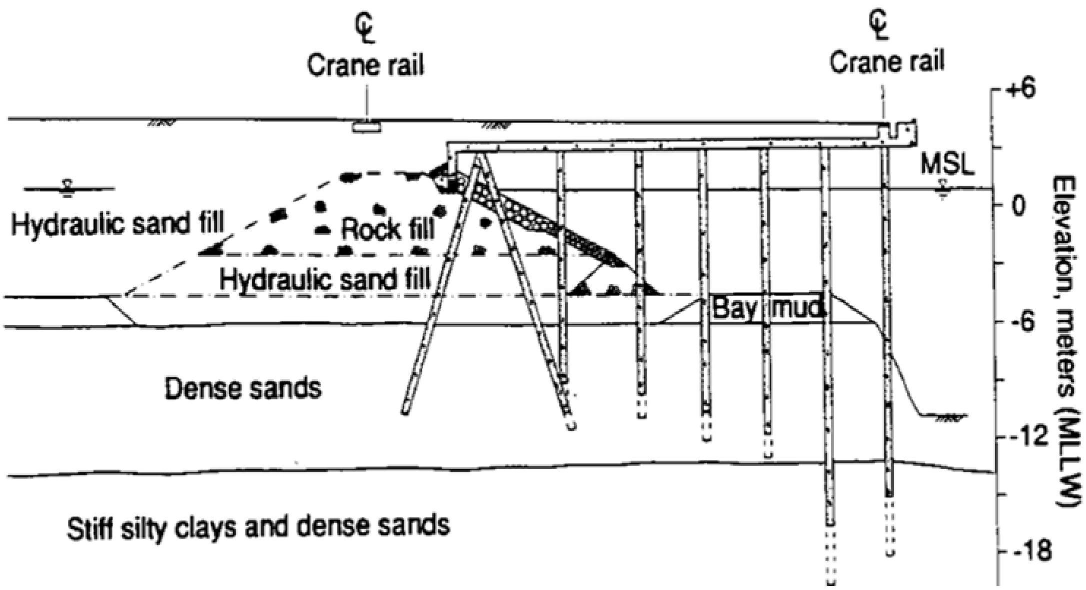

Figure 1. Pile-supported wharf at the Port of Oakland Seventh Street Terminal, prior to the 1989 Loma Prieta Earthquake (Egan et al. 1992).

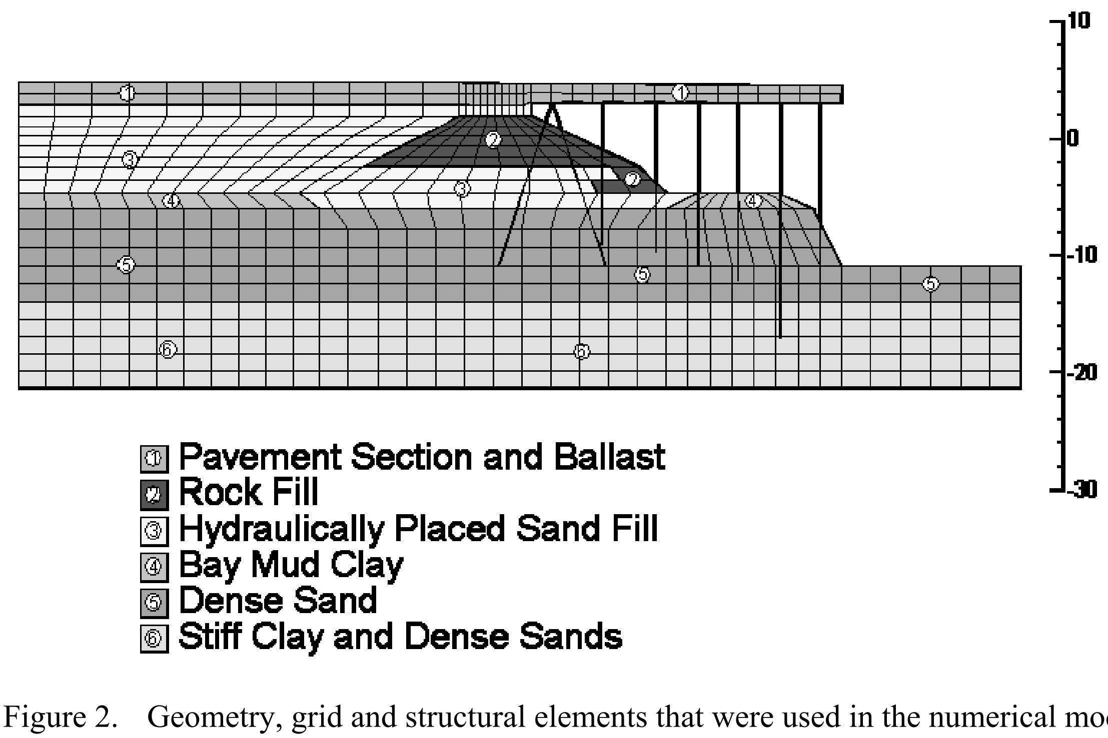

Figure 2. Geometry, grid and structural elements that were used in the numerical model of the Port of Oakland Seventh Street Terminal, Berth 38.

The results of the numerical analysis are illustrated in Figure 3. The analysis predicted a horizontal displacement of the rock dike at the ground surface of 27 cm and a vertical settlement of 22 cm, both in agreement with the observed values of 15 to 30 cm and 13 to 30 cm, respectively. In addition, FLAC predicted plastic hinge development at the top of the all the piles (at the location of the first structural node below the wharf deck). In addition, plastic hinge development at depth was predicted (Figure 3) at the Bay Mud/hydraulic fill and dense sand interfaces. It is significant to note that modeling efforts using FLAC by several groups (Singh et al. 2001a, b; Wang et al. 2001; Roth and Dawson 2003; Dickenson and McCullough 2006) have resulted in computed ground deformations at the top of the crest of the sloping fill ranging from roughly 10 cm to 46 cm; demonstrating the variability of modeling results by experienced practitioners due to reasonable differences in geotechnical and structural material properties, ground motion modeling, and other aspects of the modeling.

The FLAC model has been re-applied in this investigation using an updated pore pressure generation algorithm, UBCSand (Beaty 2009), and slight modifications to the beam elements used to model pile response. The modeling results are comparable with similar patterns of excess pore pressure distribution, ground deformation, and plastic hinge development in piles.

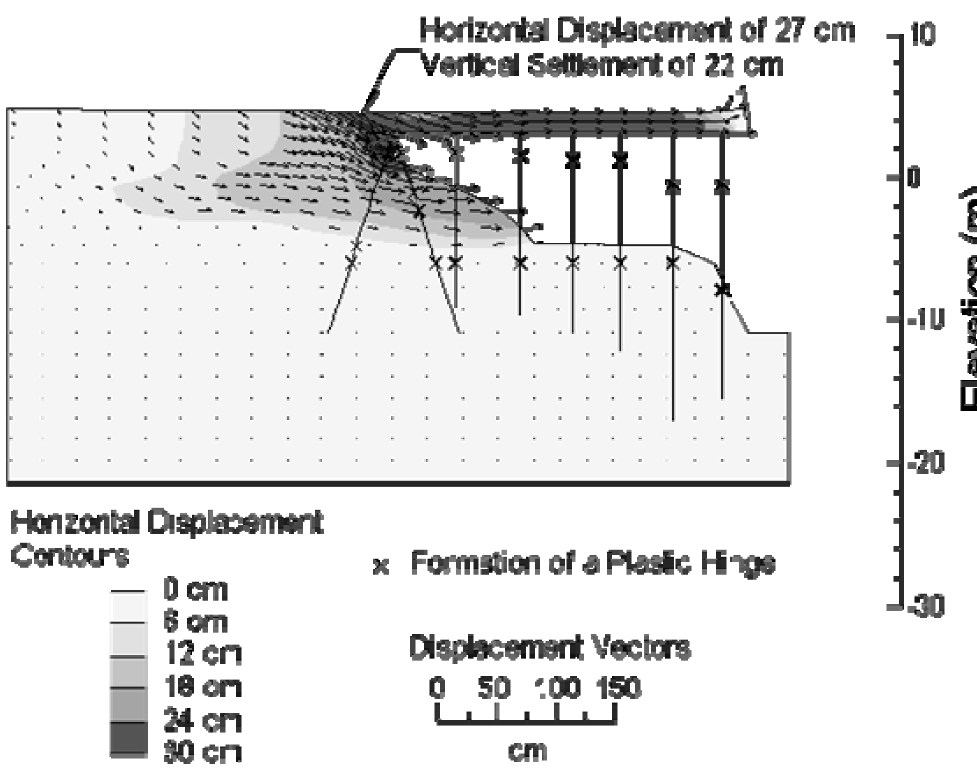

Figure 3. Numerical simulation of seismic performance of Berth 38, Seventh Street Terminal, Port of Oakland during the 1989 Loma Prieta Earthquake.

Port of Los Angeles, Pier 400, Berth 404; M_w 4.7 May 17, 2009 Inglewood Area Earthquake

Pier 400 at the Port of Los Angeles provides an extremely valuable case study for this investigation. The wharf represents recent design and construction practices, and constitutes a very important terminal at the port. The wharf and embankment configuration is similar to other major terminals at the Port of Los Angeles and the adjoining Port of Long Beach, yet the Pier 400 site is particularly valuable due to the extensive CSMIP strong motion array along a portion of the wharf, as shown in the Figure 4. CSMIP stations #14284 and #14256 provide 3 free-field and 15 structural accelerometers, respectively. The type and configuration of the piles (24" octagonal prestressed concrete piles; seven piles per bent) are consistent with contemporary port design in California.

The Pier 400 instrumentation array provides a very worthwhile case study for elastic dynamic response of a new wharf. The wharf SFSI model has been validated using motions from the 2009 M 4.7 Inglewood Area earthquake, an event that produced peak horizontal accelerations of 0.113g in the free-field and 0.21g on the wharf at Pier 400. While this was a relatively low intensity, very short duration event the data from this earthquake provided a valuable opportunity for validating the SFSI model for small- to moderate-strain wharf-embankment interaction.

Geotechnical Site Characterization

The geologic cross section and structural configuration at Berth 404 are provided in Figure 5. As defined by Fugro West (2001a, b, c); from youngest to oldest the soil profile consists of;

1. Hydraulic fill consisting of predominantly silty sand, with layers of sandy silt and silt with clay balls. The construction sequence associated with dredging, characteristics of fill based on borrow area, and the influence of placement techniques on density are addressed by Fugro West (2001a, b) and Foxworthy et al. (1998). A review of post-construction boring logs in the area adjacent to the strong motion arrays at Berth 404 indicates that the SPT penetration resistances of the sand portions of the fill vary with location due to the cumulative influence of; fines content, method of placement, and deposition above or below water level). In the unimproved fill the 33-percentile $(N_1)_{60}$ above the water level (elevation 15 ft to 0 ft) is roughly 23 blows/ft, while the corresponding value below the water level (elevation 0 ft to -34 ft) is 13 blows/ft, indicative of sand vulnerable to liquefiable at design level ground motions.
2. A thin layer of soft harbor bottom sediments (Unit 1 – Harbor Bottom Sediments).
3. An approximately 15- to 35-ft thick layer of generally fine sand and find sand with silt of alluvial deposition (Unit 2 – Younger Channel Sands).
4. An approximately 15- to 20-ft thick layer of sand with silt or silty fine sand of marine deposition (Unit 3 – Marine Sands).
5. A 30- to 35-ft (maximum) thick sequence of paleochannel infill (Unit 4 – Older Paleochannel Infill) composed of very silty fine sand (Unit 4a) overlying silt and clayey silt.
6. A thick, highly layered (sands, silts, clays) sequence of transgressive marine deposits (Unit 7 – Undifferentiated Deposits).

7. An 80- to 100-ft thick sequence of alluvial fine to medium sand with gravel (Unit 8 – Older Allluvial Deposits) that correlates with the onshore Gaspur Aquifer.

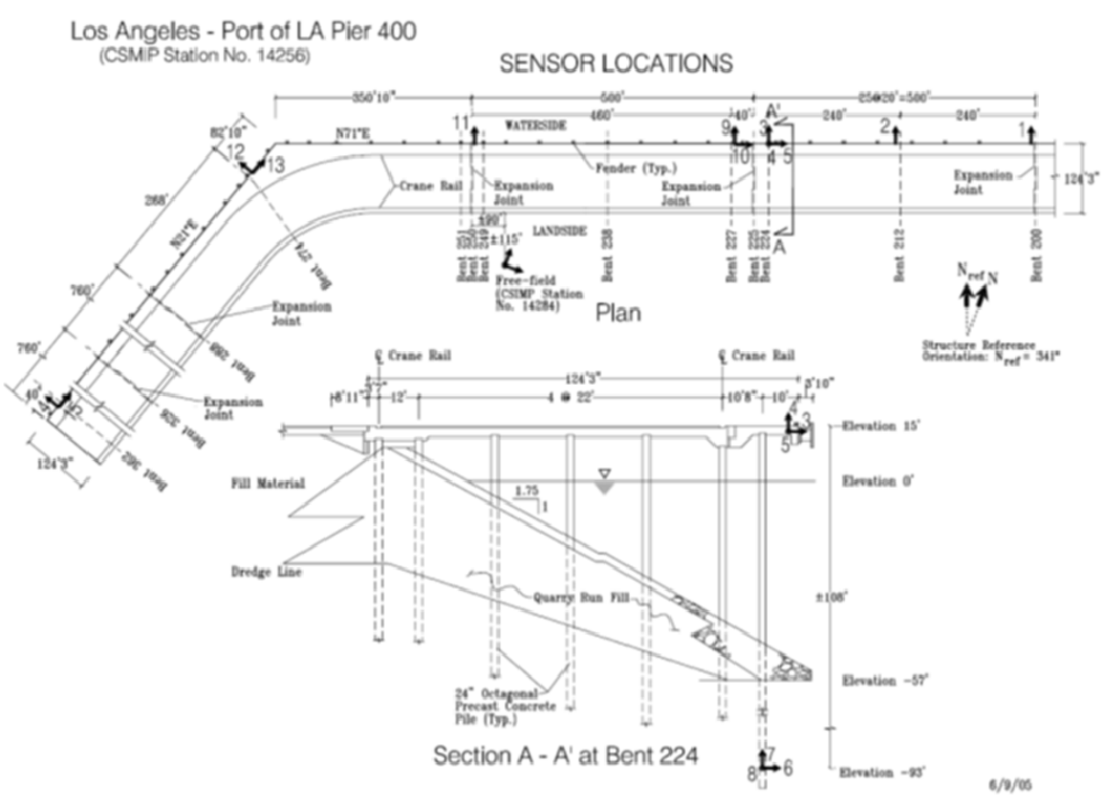

Figure 4: CSMIP Instrumentation Array at the Port of Los Angeles Pier 400 (CGS - CSMIP Station 14256), Center for Engineering Strong Motion Data (CESMD)

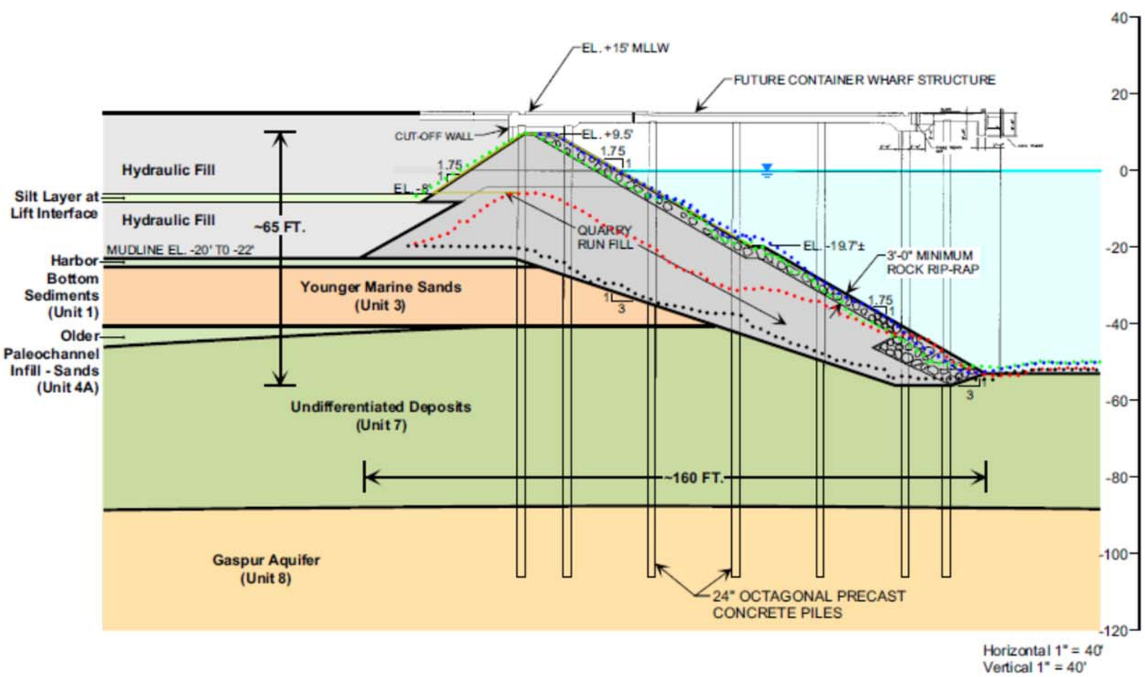

Figure 5: Geologic and structural section at Berth 404, Pier 400, Port of Los Angeles Los Angeles (Fugro West, 2004).

Ground Motions during the 2009 Inglewood Earthquake

Low-amplitude, short-duration ground motions from the M 4.9 Inglewood Earthquake were recorded at the Berth 404 strong motion instrument array. The PGA values in the free-field and on the wharf structure (transverse direction) were 0.11g and 0.21g, respectively. These motions are useful for validating the FLAC model for largely elastic behavior of the soils and structure. In order to model this event the input ground motions can be obtained by the following procedures; (i) the free-field ground surface motion can be deconvolved to the elevation corresponding to the base of the FLAC model (base transmitting boundary), and/or (ii) motions from a local vertical downhole array could be used directly. At this time the analyses have focused on the use of the downhole recordings made at the Vincent Thomas Bridge West Arrays 1 and 2 (CESMD 2013). The arrays are located adjacent to the approach and anchorage to the bridge. At a depth of 100 ft, the depth to the strong motion instruments in both vertical arrays and closest to the depth of the base of the FLAC model, the shear wave velocities at the Vincent Thomas Bridge West and East Arrays bracket (725 to 1050 ft/sec) the Berth 404 site (850 ft/sec) demonstrating somewhat uniform conditions with respect to low-strain stiffness.

This Vincent Thomas Bridge West Array is located approximately 1.8 miles from the Berth 404 site. It is acknowledged that there may be significant changes in the ground motions at prescribed depths (> 100 ft) at the Berth 404 site relative to the Vincent Thomas Bridge site. For the sake of this investigation, which is focusing on the validation of the 2D numerical model, the use of the downhole strong motions records (adjusted for a given depth within firm soil) from the Vincent Thomas Bridge site is considered reasonable as the comparison will be made between the Spectral Amplification Ratios ($SA_{\text{Berth 404}}/SA_{\text{VT Bridge}}$) computed using; (i) the recorded motions, and (ii) the ground surface motions computed with FLAC divided by the input motion (i.e. Vincent Thomas Bridge motions). Examples of these Spectral Amplification Ratios for recorded motions are provided in Figure 6a for the Berth 404 ground surface free-field motion, and in Figure 6b for the Berth 404 motions recorded on the wharf deck (transverse component). The orientations of all motions used are within a 20 degree azimuth of each other and no vector manipulation of the records was made (*and not possible due to the lack of recordings in all components during this event*). These two plots are intended to provide a *very approximate* indication of dynamic soil and structural response at Berth 404 for low levels of seismic loading.

Geophysical Investigation at Berth 404

At the outset of this investigation there were no post-construction shear wave velocity measurements at Pier 400. While shear wave velocities could have been estimated in the fill and underlying native soils using correlations with field penetration resistance (SPT, CPT) the research team, POLA, and CSMIP committed to a geophysical investigation using active and passive surface wave techniques (MASW, SASW, and ReMi) to develop the V_s profile across Berth 404 and in close proximity to the CSMIP free-field strong motion instrument station 14284. The geophysical survey provided useful data for seismic site characterization ($(V_s)_{30} \approx$ 207 m/sec) and provided an opportunity to evaluate the V_s profiles through both unimproved fill and zones of fill treated with stone columns. The latter was considered a worthwhile effort for measuring “composite” low-strain behavior of the treated soil mass. This data has been compared to the results of estimation procedures commonly used to define the equivalent, composite shear stiffness used in 2D dynamic models.

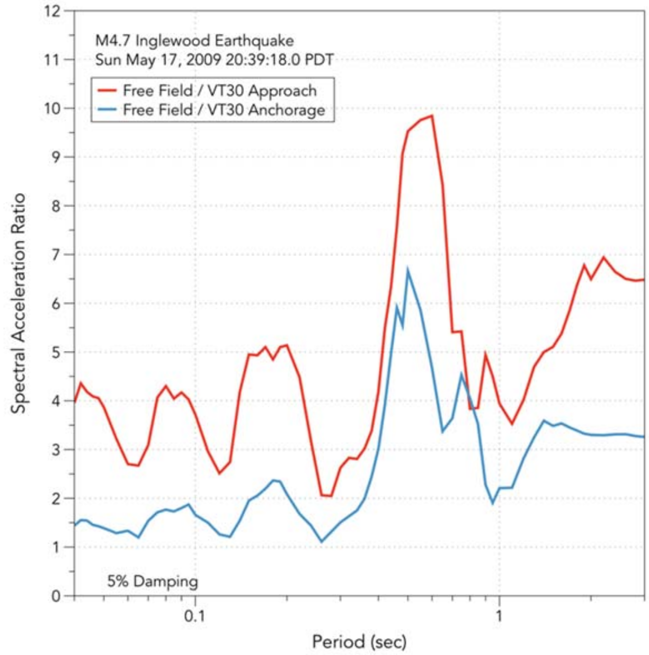

Figure 6a: Spectral amplification ratios for free-field ground surface motion at Berth 404 and motions recorded at a depth of 100 ft at the Vincent Thomas Bridge West Arrays.

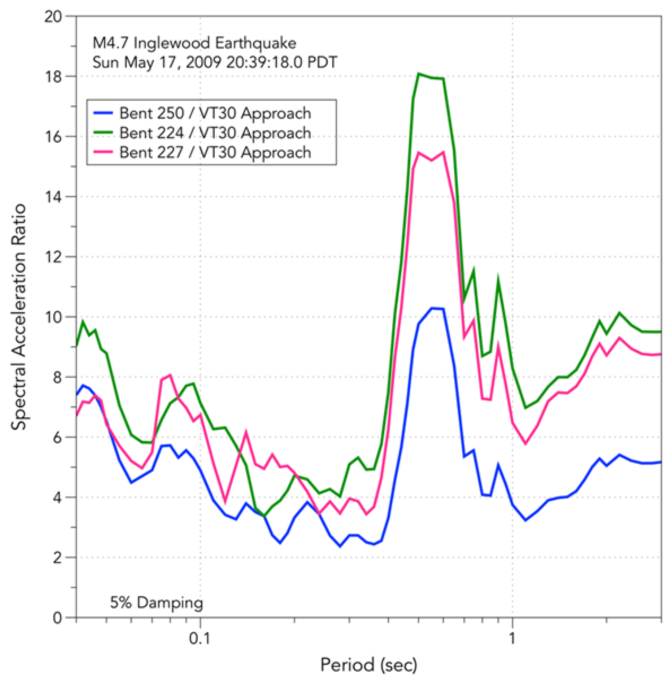

Figure 6b: Spectral amplification ratios for structural response (wharf deck) at Berth 404 and motions recorded at a depth of 100 ft at the Vincent Thomas Bridge West Arrays.

The locations of the geophysical arrays are shown in Figure 7. The arrays located south of CSMIP Free-Field Station 14284 are in areas of the unimproved hydraulically-placed fill. Arrays A-5 through A-8, and A-10 are located in the area of ground improvement by stone columns. The locations of these arrays relative to the stone column layout are provided in Figure 8. The surface wave arrays were located along the mid-points of Rows H – M and M – R, each zone having a different spacing of stone columns and Area Replacement Ratios (ARR). Based on post-construction documentation the approximate average ARR values in the two zones were 14% and 18%, although the diameter of the stone columns was noted to change significantly between the sandy fill and layers of silt-rich soil (Degen et a 2005; Fugro West 2004).

The results of the surface wave investigation are plotted in Figure 9. The agreement in the V_s profiles through native soils beneath the hydraulic fill layers is very good. The V_s trends in the unimproved and improved fill are highlighted in Figure 9a. As expected the "composite" V_s values are greater in the zone of treated soil, although the difference in the values is only roughly 7% to 12%. This data is currently being evaluated to determine the possible influence of geophysical modeling assumptions (plane waves) and 3D nature of the stone column improvement on the "composite" V_s values provide. This is a unique data set that is also being used to assess strain-compatibility concepts as applied for the dynamic behavior of stone column treated soils (Baez 1995; Rayamajhi et al. 2012).

SUMMARY OF OBSERVATIONS DURING PHASE 1 EFFORTS

Several topical lessons have been learned during Phase 1 analysis efforts, including:

1. The geophysical investigation using active and passive surface wave measurement techniques provided a valuable data set for shear wave velocity in hydraulically-placed fill at Berth 404, Port of Los Angeles. Key findings and potential implications are;
   a. The increase in V_s due to stone column placement was roughly 10% for the Area Replacement Ratios (roughly 14% to 18% on average).
   b. The rather low increase in V_s may have implications for modeling composite shearing behavior of ground treated with stone columns.
   c. Additional work is underway to evaluate the applicability of the surface wave techniques (SASW, MASW, and ReMi) in treated soils.
2. The 2D geomechanical model can reasonably predict seismically-induced permanent deformations, accelerations, and excess pore pressure generation for the low- to moderate-levels of shaking experienced in the two case histories. This appears to be true even though a relatively simple Mohr-Coulomb constitutive model was used in conjunction with two different stress-based pore pressure generation models to represent dynamic pore pressure generation.
3. Cyclic lateral behavior of piles in sloping rock fill can be fairly well modeled using a continuum numerical model if the difference between upslope and downslope SSI spring stiffness is accounted for.

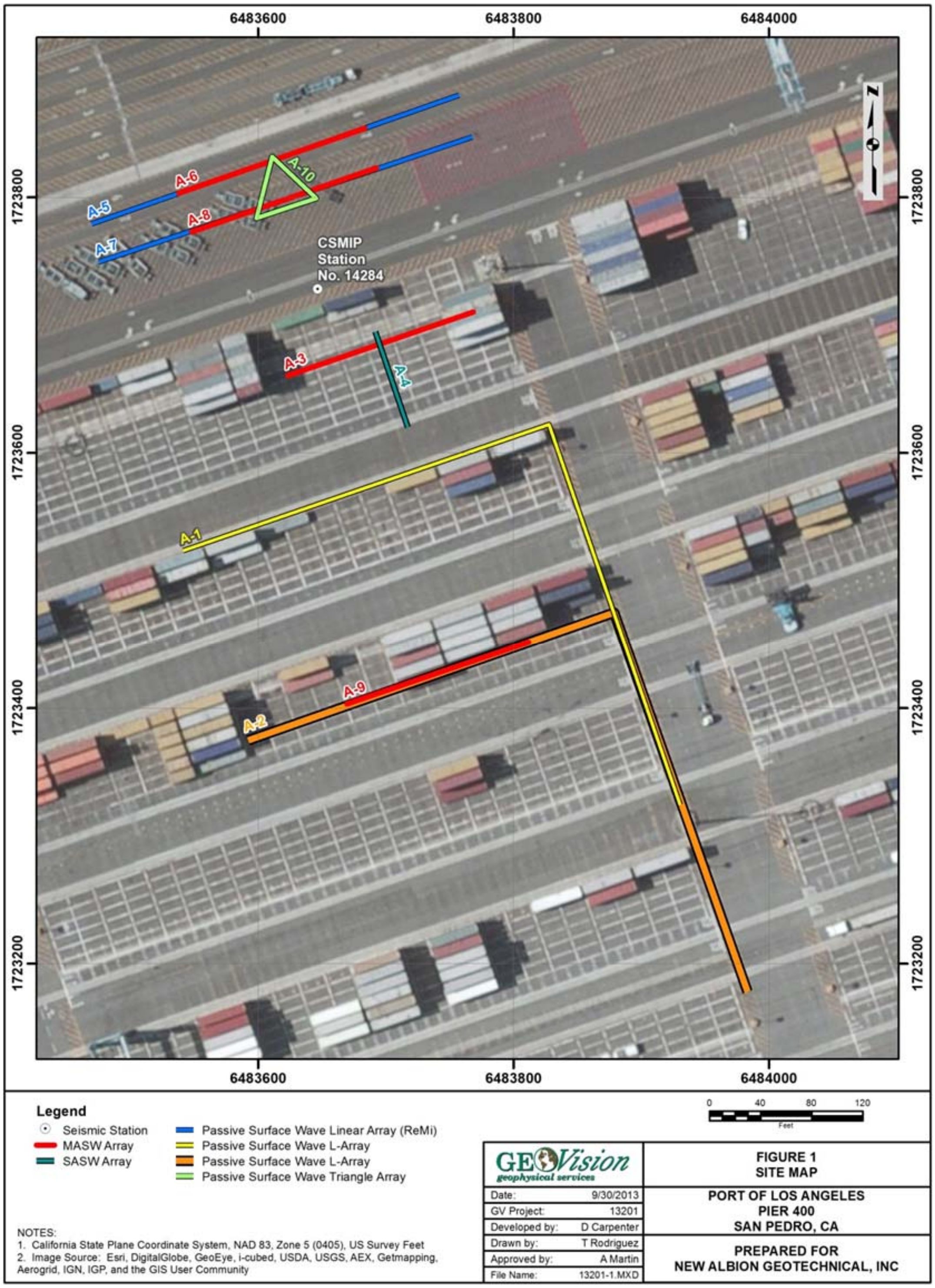

Figure 7: Location of geophysical arrays for surface wave velocity investigation at Port of Los Angeles Berth 404 (GEOVision 2013).

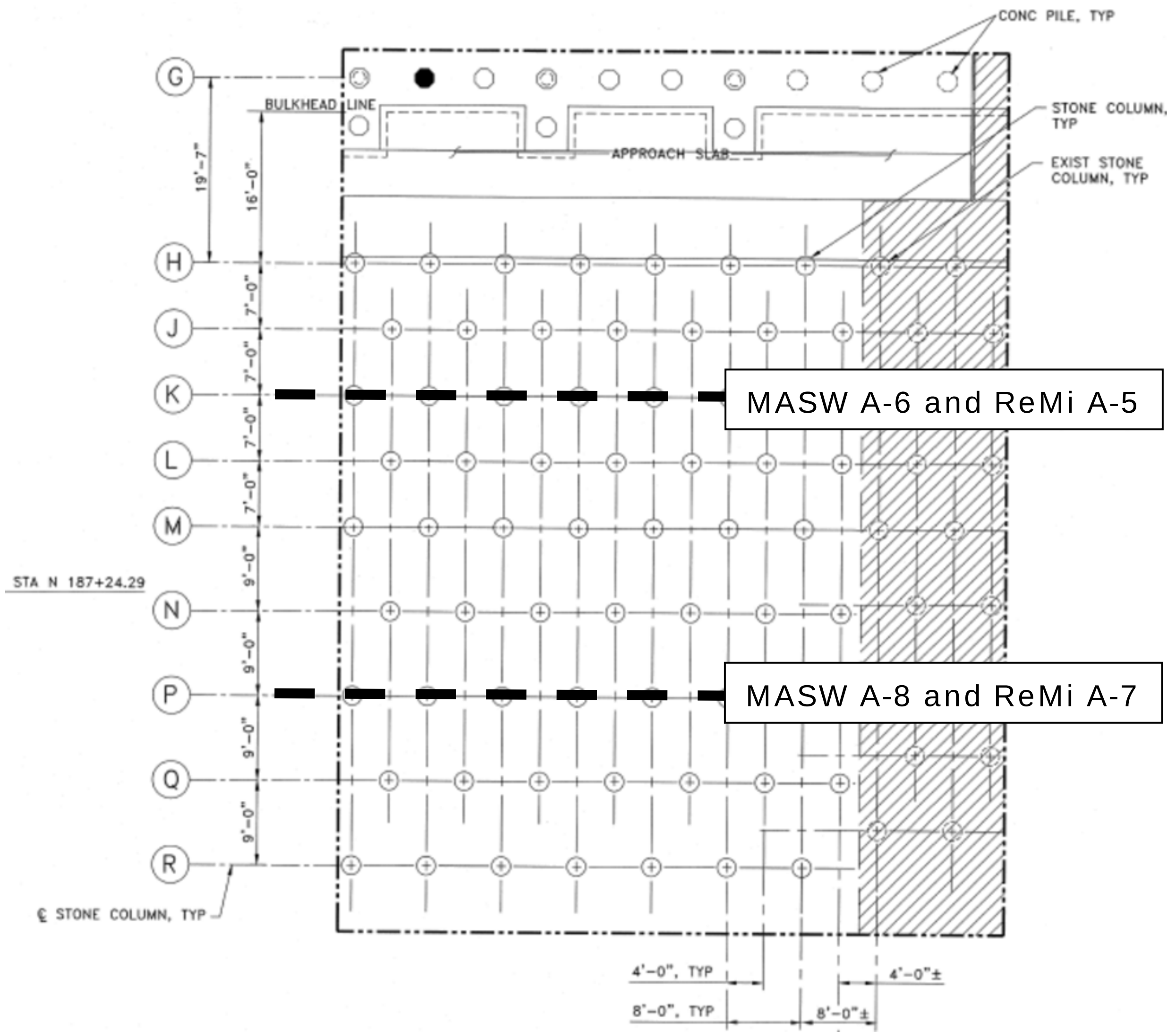

Figure 8: Location of geophysical arrays for surface wave velocity investigation of hydraulic fill treated with stone columns at Berth 404 (after POLA, 2005).

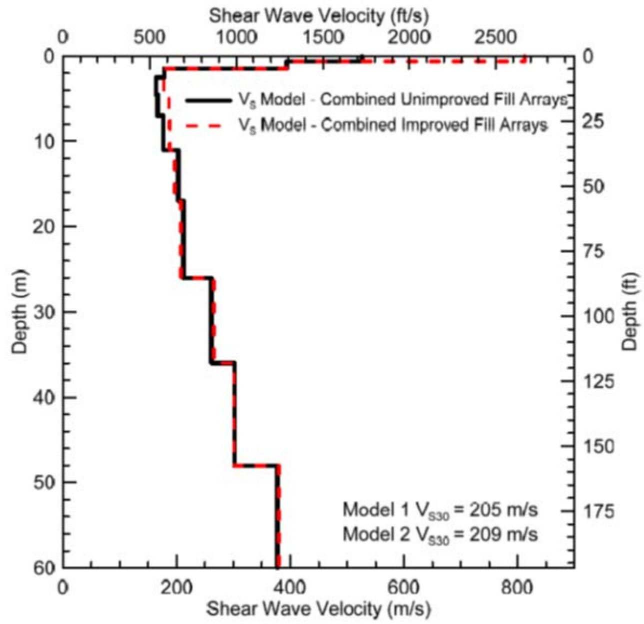

Figure 9a: Comparison of shear wave velocity profiles across the Berth 404 site (GEOVision 2013).

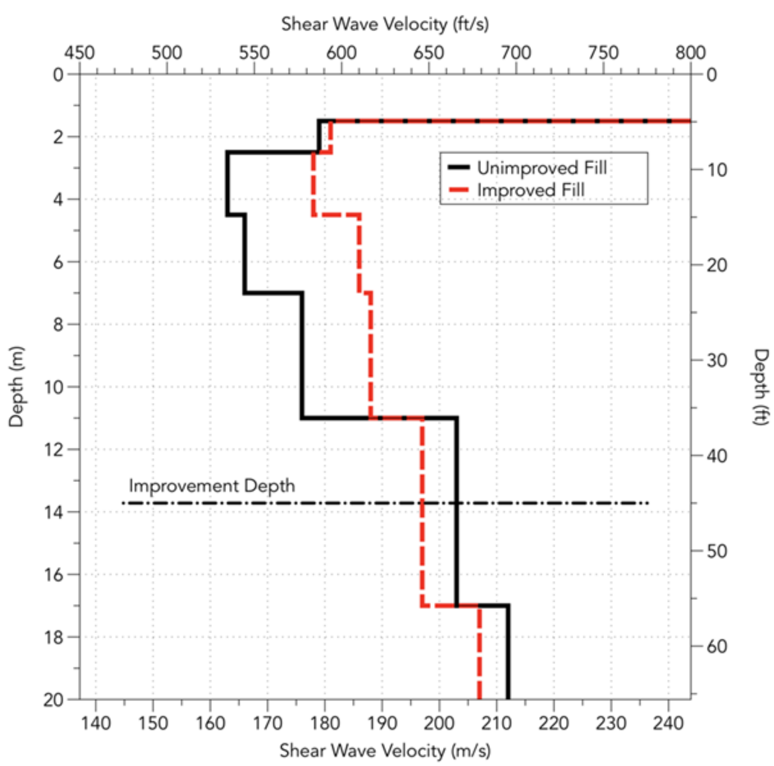

Figure 9b: Comparison of shear wave velocity profiles focusing on zones of unimproved hydraulic fill and adjacent fill improved with stone columns.

4. A simple, practice-oriented procedure for modeling pile response in rockfill includes a nominal "pseudo-cohesion" for the rock to account for the individual rock particle interaction with the pile elements (McCullough 2003; Dickenson and McCullough 2006). This simplification notwithstanding, methods of refining this approximation to account for interlocking and dilation of the rockfill should be pursued (e.g. Kawamata 2009). This is considered an important aspect of the modeling for large-amplitude, long-duration shaking due to significant pile-soil interaction for the "seismic piles" (i.e. rear, landward rows) associated with inertial loading near the pile head, and due to possible deep-seated ground failures (displacement demand) that could provide excessive loads at the interface of the rockfill and underlying soils.
5. It is clear that large pile moments develop at depth when there is even moderate soil displacement due to global behavior of the rock dike and foundation soils. These moments are only-predicted through the use of analysis methods that have the capability to model the global wharf-embankment system.

PROJECT FOCUS FOR PHASE 2 OF THE INVESTIGATION

Calibrating the numerical dynamic SFSI models against recorded behavior is considered a necessary step prior to simulations involving long-duration and higher levels of ground motion. In Phase 2 of this investigation the computed response under long-duration ground motions will be evaluated in light of the seismic performance criteria for wharves at the two major ports. Subsequent tasks involve detailed analysis of the modeling results and seismic performance assessment to identify predicted behaviors that have significant implications for current seismic design methods for wharves. Examples include;

a. Structural failures, particularly those associated with moderate permanent ground deformation caused by long-duration shaking at moderate levels, will be evaluated from initiation through the end of ground shaking using the time histories of forces and displacements. This assessment will incorporate member strength/capacities for the concrete, steel and pre-stress, using the strain limits and plastic hinge lengths, as described in the MOTEMS (2010) and Port of Long Beach Wharf Design Criteria (February, 2012).
b. The relationship between permanent ground deformation and pile response in soils exhibiting excess pore pressure generation that is less than that required for "full liquefaction" (i.e., excess pore pressure ratios of 0.5 to 0.9) will be investigated in detail. The soil constitutive model for excess pore pressure generation and cyclic behavior is well suited to represent shear displacement that would not be indicated in a conventional uncoupled liquefaction susceptibility and slope deformation evaluation.
c. Strain softening of normally consolidated fine-grained soils is a pertinent aspect of the analyses, particularly where soil stiffness is important for deformations in embedded piles. Characteristics of transient and permanent deformations of embankment.
d. Phasing of inertial loads and kinematic loads in the piles and pile-deck connection, and
e. Displacement demand on piles as a function of row location (landside versus waterside).

The sequence of the Phase 2 investigation will include baseline analyses using OLE and CLE motions that are readily available from recent applications at POLA, and which follow guidelines set forth in the Port-Wide Ground Motion study (EMI 2006). Subsequent analyses will be performed using long-duration motions. A suite of motions will be used with "seed" motions scaled and/or spectrally matched to prescribed Intensity Measures. The dynamic response of the wharf and embankment will be evaluated for each analysis. These analyses will be repeated for the Berth 55 strong motion instrumentation array at the Port of Oakland. It is anticipated that the improved understanding of the relationships between duration of strong shaking, permanent deformation of the ground and pile foundation, and post-earthquake functionality will have practical implications on performance-based design of port structures in California.

Acknowledgements

The authors gratefully acknowledge the significant and on-going contributions made by the following individuals. Collectively, these individuals have provided technical documentation, access to projects archives, acceleration time histories, and research results pertinent to the project. The research team has benefitted from active communication addressing nuances of the analysis and design, construction, and post-construction history at the project sites; Port of LA Berth 404 and Port of Oakland Berth 55.

Tony Gioiello, Peter Yin and Hugo Cisneros; Port of Los Angeles
Matt Pollard, Cornelia Dean and Danya Pollard; Fugro West, Inc. (Ventura, CA)
Imee Osantowski and Steve Low; Port of Oakland
Tony Martin; GEOVision (Corona, CA)
Nason McCullough; CH2M Hill (Corvallis, OR)
Arul Arulmoli; Earth Mechanics, Inc. (Fountain Valley, CA)
Luke Leffingwell; APM Terminals Los Angeles
Moh Huang, Shirley Rowley and Tony Shakal; CSMIP (Sacramento, CA)
Dawn Lehman; University of Washington (Seattle, WA)
Jose Restrepo; University of California (San Diego, CA)

References

Arulmoli, K., Martin, G.R., Gasparro, M.G., Shahrestani, S., and Buzzoni, G. (2004). Design of Pile Foundations for Liquefaction-Induced Lateral Spread Displacements, *Proc. Geo-Trans 2004; Geotechnical Engineering for Transportation Projects*, Vol. 2, 1673-1680, ASCE Geotechnical Engineering Special Publication No. 126, July, Los Angeles.

ASCE (in preparation). Seismic Design of Pile-Supported Piers and Wharves, prepared by the ASCE Standards Committee on Seismic Design of Piers and Wharves.

ASCE COPRI (in press). The March 2011 Great Tohoku Earthquake; Investigation of Port and Harbor Structures, Percher, M., and Dickenson, S. (editors), ASCE, Reston, VA.

ASCE TCLEE (1998). Seismic Guidelines for Ports, Werner, S. (ed.), TCLEE Ports Lifeline Committee, TCLEE Monograph #12, ASCE, Reston, VA.

Beaty, M. (2009). Summary of UBCSand Constitutive Model, Versions 904a and 904aR, Beaty Engineering, LLC, prepared for the short course *Seismic Deformation Analyses of Embankment Dams considering Liquefaction Effects*, Sept. 22 – 24.

Baez, J.I. (1995). A Design for the Reduction of Soil Liquefaction by Vibro-Stone Columns, Ph.D. dissertation, Univ. of Southern California.

Boland, J.C., Schlechter, S.M., McCullough, N.J., Dickenson, S.E., Kutter, B.L., and Wilson, D.W. (2001a), Data Report: Pile-Supported Wharf Centrifuge Model (SMS02), Dept., Civil, Construction & Environmental Engineering, Oregon State Univ.

Boland, J.C., Schlechter, S.M., McCullough, N.J., Dickenson, S.E., Kutter, B.L., and Wilson, D.W. (2001b), Data Report: Pile-Supported Wharf Centrifuge Model (JCB01), Dept., Civil, Construction & Environmental Engineering, Oregon State Univ.

Center for Engineering Strong Motion Data (CESMD). On-line archive for strong motion data. POLA Pier 400 Berth 404; (**http://www.strongmotioncenter.org/cgi-bin/CESMD/stationhtml.pl?stacode=CE14256&network=CGS**) Vincent Thomas Bridge Geotechnical Array West 1 & West 2 (**http://www.strongmotioncenter.org/cgi-bin/CESMD/stationhtml.pl?stacode=CE14783&network=CGS**)

Chiaramonte, M.M., Arduino, P., Lehman, D.E., and Roeder, C.W. (2011). Seismic Analyses of Conventional and Improved Marginal Wharves, *Jrnl. Earthquake Eng. Struct. Dyn.*, 00; 1 -19.

Degen, W., Baez, F., and Rose, M. (2005). Dry Bottom Feed Stone Columns at Pier 400, Phase II – An evaluation of CPT-based soil classification before and after treatment, *Proc. US-Japan Workshop "New Applications & Challenging Soils for Ground Improvement Technologies*, September, Kyoto, Japan.

Dickenson, S.E. and McCullough, N.J. (2006). "Modeling the Seismic Performance of Pile Supported Foundations for Port and Coastal Infrastructure," Proc. of Seismic Performance and Simulation of Pile Foundations in Liquefied and Laterally Spreading Ground, Boulanger and Tokimatsu (eds.), Geotechnical Specialty Publication No. 145, ASCE, 173-191.

Donahue, M.J., Dickenson, S.E., Miller, T.H., and Yim, S.C. (2005). "Implications of the Observed Seismic Performance of a Pile-Supported Wharf for Numerical Modeling," Earthquake Spectra, EERI, 21(3), 617-634.

Egan, J.A., Hayden, R.F., Scheibel, L.L., Otus, M., and Serventi, G.M. (1992). Seismic repair at Seventh Street Marine Terminal, *Proc. Grouting, Soil Improvement, and Geosynthetics*, ACSE Geotechnical Specialty Publication No. 30, Vol. 2.

Earth Mechanics, Inc. (2006). Port-Wide Ground Motion and Palos Verde Fault Study, Port of Los Angeles, California, Final Report, prepared for the Port of Los Angeles, Project 02-131-11, December, 22.

Foxworthy, J., McNeilan, T., and Alcorn, A. (1998) Interim Pier 400 Landfill Status Report, *Proc. Ports '98*, ASCE, Vol. 1., 551 – 560.

Fugro West (2004). Stone Column Ground Improvement Pier 400 Container Wharf Phase 2, Port of Los Angeles, California, prepared for the Port of Los Angeles, March.

Fugro West, Inc. (2001a). Final Geotechnical Framework Report, Pier 400 Landfill Project, Port of Los Angeles, California, prepared for the Port of Los Angeles, April.

Fugro West (2001b). Geotechnical Data Report Pier 400, Stage 2, Post-Fill Investigation, Port of Los Angeles, prepared for the City of Los Angeles, Harbor Department, July.

Fugro West (2001c). Geotechnical Study Pier 400 Container Wharf Phase 2, Port of Los Angeles, California, prepared for the Port of Los Angeles, November.

GEOVision (2013). Report Surface Wave Measurements, Port of Los Angeles, Pier 400, Berth 404, Los Angeles County, California, prepared for New Albion Geotechnical, Inc., Report 13201-01, August 5.

Kawamata, Y. (2009). Seismic Performance of Pile-supported Container Wharf Structures in Rockfill, Ph.D. dissertation, School of Civil & Construction Engineering, Oregon State University, Corvallis, Oregon.

Krier, C.J., Restrepo, J.I., Blandon, C.A. (2008). Seismic Testing of Full-Scale Precast Prestressed Pile to Deck Connections, UCSD Structural Systems Research Project, Report No. SSRP-06/26, Univ. of California, San Diego, Dept. of Structural Engineering, prepared for the Port of Los Angeles, January.

Lehman, D.E., Roeder, C., Stringer, S.J., Jellin, A. (2013). Seismic performance of improved pile-to-wharf deck connections, *PCI Jrnl.*, Summer, 62-80.

McCullough, N.J. (2003). The Seismic Geotechnical Modeling, Performance, and Analysis of Pile-Supported Wharves, Ph.D. dissertation, Dept, of Civil Engineering, Oregon State University, Corvallis, Oregon.

McCullough N. and Dickenson, S. (2004). The Behavior of Piles in Sloping Rock Fill at Marginal Wharves, *Proc. Ports 2004*, ASCE, May, Houston, TX.

Moriwaki, Y., Tan, P., and Choi, Y. (2005). Nonlinear analyses for design of piles in liquefying soils at port facilities, *Proc. of Seismic Performance and Simulation of Pile Foundations in Liquefied and Laterally Spreading Ground*, Boulanger and Tokimatsu (eds.), Geotechnical Specialty Publication No. 145, ASCE, 192-1203.

Norris, G., Siddharthan, R., Zafir, Z., Abdel-Ghaffar, S., and Gowda, P. (1991). “Soil-Foundation-Structure Behavior at the Oakland Outer Harbor Wharf”, *Proc. SMIP91 Seminar on Seismological and Engineering Implications of Recent Strong Motion Data*, California Department of Conservation, Division of Mines and Geology, SMIP, held in Sacramento, CA, May 30, p. 11-1 to 11-11.

Oyenuga, D., Abe, S., Sedarat, H., Krimotat, A., Salah-Mars, S., and Ogunfunmi, K. (2001). Analysis of Existing Piles with Missing Data in Seismic Retrofit Design at the Port of Oakland, *Proc. Ports 2001*, Norfolk, VA.

PIANC WG 34 (2001). Seismic Design Guidelines for Port Structures, Iai, S. (ed.), Working Group #34, International Navigation Association (PIANC), A.A. Balkema Publishers, 474 p.

POLA (2002). Pier 400 Container Wharf Phase II – Berths 404-406, Record Set, Stone Column Layout – Bents 200 to 204 (Drawing SC-4), prepared by City of Los Angeles, Harbor Department, Engineering & Construction Division.

POLA (2010). The Port of Los Angeles Code for Seismic Design, Upgrade and Repair of Container Wharves (POLA Seismic Code 2010), City of Los Angeles Harbor Department.

POLB (2012). Port of Long Beach Wharf Design Criteria, Version 3.0 (February).

Priebe, H.J. (1995). The design of vibro replacement, *Ground Engineering*, December.

Priestley, M.J.N. (2000). Pier 400 Strength and Ductility of Wharf Piles, prepared for the Port of Los Angeles, Report #00/01, August.

Rayamajhi, D., Hguyen, T.V., Ashford, S.A., Boulanger, R.W., Lu, J., Elgamal, A., and Shao, L. (2012). Effect of Discrete Columns on Shear Stress Distribution in Liquefiable Soil, *Proc. GeoCongress 2012*, ASCE.

Restrepo, J.I., Yin, P., Jaradat, O.A., and Weismair, M. (2007) Performance of New Pile-Deck Connections Under Earthquakes, *Proc. Ports 2007*, ASCE, San Diego, CA.

Roth, W.H. and Dawson (2003). Analyzing the Seismic Performance of Wharves, Part 2: SSI Analysis with Non-Linear, Effective-Stress Soil Models, *Proc. TCLEE 2003: 6th US Conference & Workshop on Lifeline Earthquake Engineering*, Long Beach, CA.

Roth, W.H., Dawson, E.M., Mehrain, M., and Sayegh, A. (2003). Analyzing the Seismic Performance of Wharves, Part 1: Structural-Engineering Approach, *Proc. TCLEE 2003: 6th US Conference & Workshop on Lifeline Earthquake Engineering*, Long Beach, CA.

Shafieezadeh, DesRouches, R., Rix, G.J., and Werner, S.D. (2012). Seismic Performance of Pile-Supported Wharf Structures Considering Soil-Structure Interaction in Liquefied Soil, *Earthquake Spectra*, EERI, 28(2), 729-757.

Singh, J.P., Tabatabaie, M., and French, J.B. (2001a). Geotechnical and Ground Motion Issues in Seismic Vulnerability Assessment of Existing Wharf Structures, *Proc. Ports 2001*, ASCE, April.

Singh, J.P., Tabatabaie, M., and French, J.B. (2001b). Importance of Seismological-Geotechnical-Structural Handshake in Performance-Based Design of Waterfront Structures, Port of Oakland Wharf & Embankment Strengtheing Program (WESP).

Wang, Z.L., Egan, J., Scheibel, L., and Makdisi, F.I. (2001). Simulation of earthquake performance of a waterfront slope using fully coupled effective stress approach, *Proc. 2nd Intern. FLAC Symposium*, Lyon, France, October, 100-108.

Weismair, M., Shahrestani, S., Lim, A., Priestley, M.J.M., and Lam, I.P. (2001). Seismic Design of Port of Los Angeles Pier 400 Container Wharf, *Proc. Ports '01*, ASCE

Yan, L., Arulmoli, K., Weismair, M., Aliviado, R., and Lam, I.P. (2004). Seismic Soil-Structure Interaction Analyses of an Underwater Bulkhead and Wharf System, *Proc. Geo-Trans 2004; Geotechnical Engineering for Transportation Projects*, Vol. 1, 547-555, ASCE Geotechnical Engineering Special Publication No. 126, July, Los Angeles.