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3D Seismic Soil-Structure Interaction Modeling of Port and Marine Structures in Liquefiable Soils

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ABSTRACT

Coupled soil-structure interaction modeling of two representative port and marine structures were presented: 1) a berth structure consisting of quay wall, tie rods and anchor walls, and 2) a long pier structure consisting of steel pipe piles supporting capping beams and deck structures. Three-dimensional (3D) seismic numerical modeling using the FLAC3D program was carried out considering the interaction between the soil and structures. The liquefiable soils were modeled using the P2PSAND soil constitutive model. The structures were modeled in 3D with their actual properties.

The development of excess pore water pressure in soils, the soil loss of strength, and liquefaction were modeled in the time-history analyses. The soil-structure interaction was modeled interactively during the earthquake shaking which allows for optimized and realistic response of the structures. The seismic ground and structure response were also discussed in detail.

Keywords: 3D, numerical modeling, soil-structure interaction, liquefaction, ground deformation.

INTRODUCTION

Port and marine structures may be located on steep marine slopes where subsurface soils are liquefiable. Those conditions often result in large deformation of the soil and structures. Typical design may involve 2D geotechnical seismic ground deformation analysis followed by seismic structural design. The post-seismic soil deformation along with p-y curves are often provided to the structural engineer to account for the kinematic effects. The structural assessment is often an uncoupled process from geotechnical analysis. While this process is straightforward, the ground deformation and somewhat simple p-y curves do not fully capture the complex soil-structure interaction during the earthquake. Furthermore, the seismic ground deformation analysis has been practically carried out in 2D due to extensive simulation efforts and limited applicability of 3D soil models. However, the 2D geotechnical modeling in many practical cases is not able to appropriately model the 3D characteristics of the structures.

There are several soil constitutive models that have been widely used for soil liquefaction modeling. However, most of them are 2D models. New 3D soil models such as P2PSand, which is available in FLAC 3D program, have been introduced recently. This study would implement the capability of this 3D soil model for liquefaction simulation and use the FLAC 3D program for 3D soil and structure interaction to provide insight of both the seismic response of both soil and structures.

SOIL CONSTITUTIVE MODEL

Multiple soil models have been developed to simulate the soil liquefaction of sand-like materials in geotechnical earthquake engineering. Some of the popular models are PDMY model (Elgamal et al., 2003; Yang et al., 2003), DM04 (Dafalias and Manzari, 2004), SANISand model series (Taiebat and Dafalias, 2008; Yang et al. 2022), NTUA sand model (Papadimitriou and Bouckovalas, 2002), UBCSand model (Beaty and Byrne, 2011) and PM4Sand model (Boulanger and Ziotopoulou, 2015).

Two 2D constitutive models UBCSAND and PM4SAND have been used widely in practice of geotechnical earthquake modeling. Both programs are available in several geotechnical programs, however, they are only valid for 2D plane strain conditions. More recently, the P2PSAND model has been developed by Cheng and Detournay (2021) to meet an increasing demand for a 3D soil model that can simulate soil response under seismic conditions. The P2PSand model is a practical 3D two-surface plastic constitutive model based on the DM04 model. The model can capture both the theoretical robustness of the PM04 model and the practice-oriented qualities of the UBCSand and PM4Sand models. The P2PSand model is available in the commercially available geotechnical program FLAC3D. Additional theoretical background of the model is presented in Cheng and Detournay (2021).

P2PSand Model Calibration

The model has been numerically calibrated to the liquefaction triggering curve proposed by Idriss and Boulanger (2008) as shown in Figure 1a. The numerical calibration was based on element CDSS (cyclic direct simple shear) test simulation and the CSR (cyclic stress ratio) was calculated based on the shear stress required to reach liquefaction after 15 equivalent cycles. Liquefaction was defined as excess pore water pressure ratio reaching 98% or maximum shear strain reaching 3%. The profiles of CSR versus number of cycles to liquefaction (N) are presented in Figure 1b.

Representative DSS stress-strain responses of the P2PSand model are shown in Figure 2. The results are from element CDSS tests under undrained stress-controlled loading conditions. Figure 2 shows the stress-strain responses for three different relative density (Dr) of 0.33, 0.55 and 0.75 corresponding to relatively loose, medium-dense and dense conditions.

The primary input parameters of the P2PSand model are relative density (Dr) and soil densities. The small-strain shear modulus (G) is calculated using the following equation:

$$G = f(D_r)P_a\left(\frac{p_m'}{P_a}\right)^2 \tag{1}$$

Where: $f(D_r)$=1.24e3$(D_r + 0.01)$, P_a is atmospheric pressure taken as 100 kPa, and p_m' is the soil mean effective stress

The constant volume friction angle ϕ_{cv}' of 33 degrees and K_o (the ratio of horizontal effective stress to vertical effective stress at the start of loading) of 0.5 were used. All other parameters are default or internally calibrated.

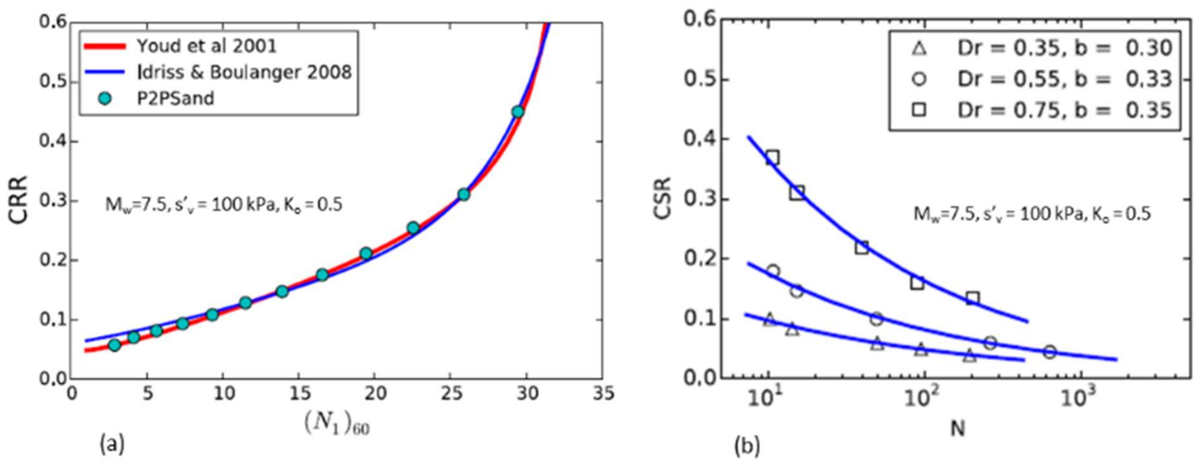

Figure 1. P2PSand model numerical calibration: (a) liquefaction triggering curve, (b) CSR – N relationship (adopted from Cheng and Detournay, 2021)

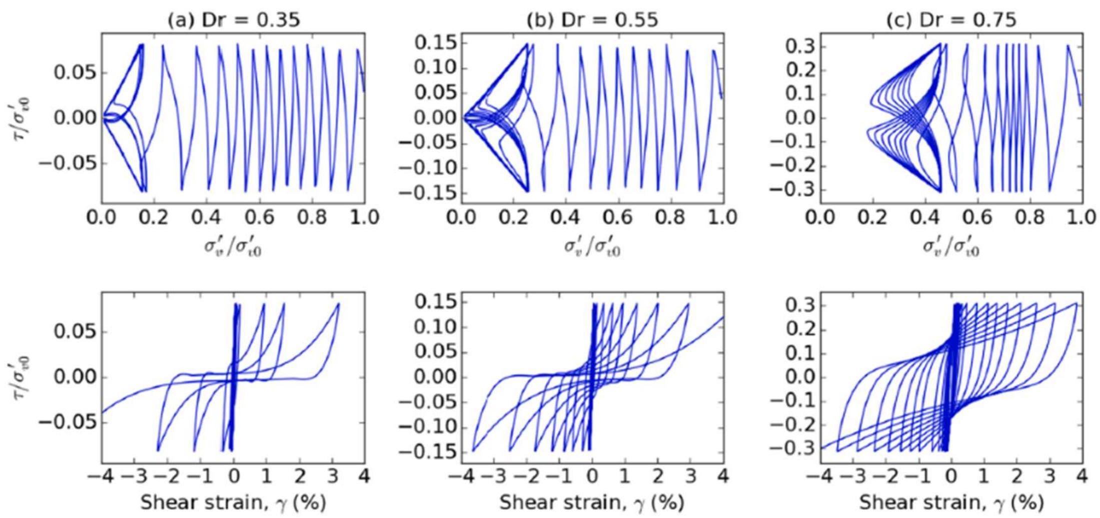

Figure 2. Stress – strain relationship – P2PSand model CDSS testing (adopted from Cheng and Detournay, 2021)

CASE STUDY 1: ANCHORED QUAY WALL SYSTEM

Geometry

Seismic soil-structure interaction analysis was performed to evaluate the seismic performance of an anchored combi-wall system, which retains a soil height of 14.5 m from El. 5.5 m (top of the wall) to El. - 9 m (dredge level). Subsurface soils consist of sand fill above El. + 1m, underlain by a loose sand layer and a medium dense gravel and sand, followed by non-liquefiable stiff silt. The loose sand and possibly part of the gravel and sand layers are expected to liquefy under the simulated earthquake record. Liquefiable soils were modeled using the P2PSAND model to analyze the development of pore water pressure, soil loss of strength and liquefaction during the earthquake. The soil parameters and their constitutive models are summarized in Table 1. The water table in the model was at El. +1 m. The model geometry is shown in Figure 3.

Table 1. Soil parameters – case study 1

Soil layer	Elevations (m)	Unit weight (kN/m^3)	Relative Density Dr	Gmax (MPa)	Soil model
Compacted fill	+1 to +5	19	0.73	Eq. (1)	P2PSand
Loose sand	-25 to +1	18.5	0.35	Eq. (1)	P2PSand
Gravel and sand	-35 to -25	20	0.73	Eq. (1)	P2PSand
Stiff silt	below -35	18	-	150	Mohr-Coulomb

The quay wall includes king piles of 1422 mm outer diameter, 25 mm thick steel pipe piles extended to the top of the gravel and sand layer at El. -25 m. The king piles have a center-to-center spacing of 2.89 m. Infill sheets AZ26-700 were installed between the king piles and were extended to El. - 15 m. The quay wall is supported by an anchor wall using high strength tie rods ASDO 500 M125/115 which connect the king piles and anchor wall. The anchor wall is sheet piles AZ48-700 which were placed at 30 m behind the quay wall and extended from El. +4 m to El. -4 m. The structures are shown in Figure 4a.

Earthquake Record

The purpose of this study is to demonstrate the capability of 3D modeling of soil-structure interaction modeling under seismic conditions and therefore, only one earthquake Tabas (Iran, 1978) was used as input time-history. The Tabas record and its response spectrum are shown in Figure 4b.

Modeling of Seismic Soil-Structure Interaction

Coupled soil-structure interaction analyses were carried out using the program FLAC 3D v.7 (Itasca Consulting). The soils were modeled using hexahedral zones with mixed discretization scheme. The king piles of the quay wall were modeled using pile elements, the infill sheets and the anchor wall were modeled using liner elements, and the tie rods were modeled using cable elements. An interface friction angle of 17 degrees was used for the soil and structure interaction. The structures were modeled in 3D with their actual properties.

Two stages were simulated in the analyses including stage 1) static analysis for pre-earthquake conditions, and stage 2) dynamic analysis with earthquake motion applied to the model base as shear stress time-histories. The lateral boundaries of the FLAC model were extended at both sides of the model to minimize boundary effects. Free field and compliant base conditions were applied to the lateral boundaries and model base, respectively. Hydrodynamic pressure acting on the quay wall during seismic shaking was also considered in the simulation.

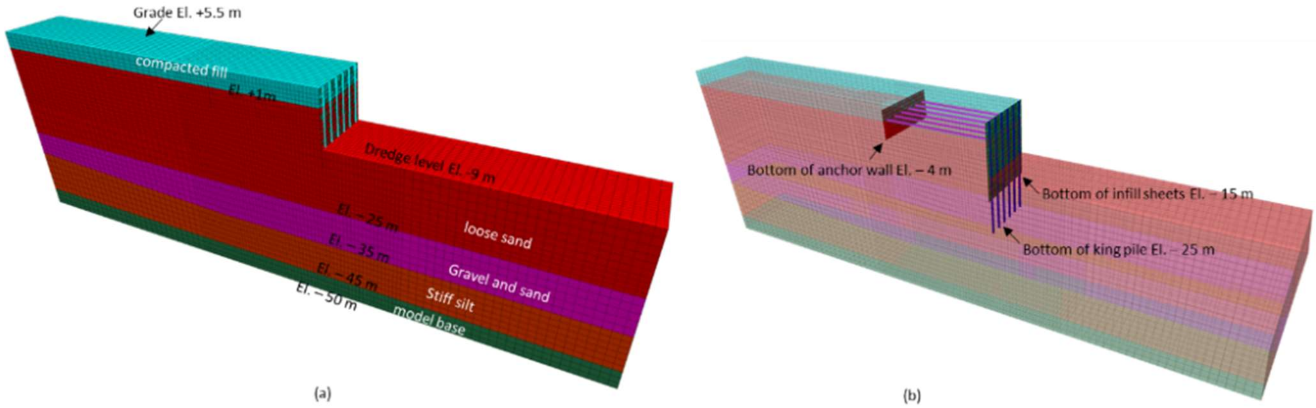

Figure 3. (a) model geometry with filled zones filled, (b) model geometry with transparent zones showing structures

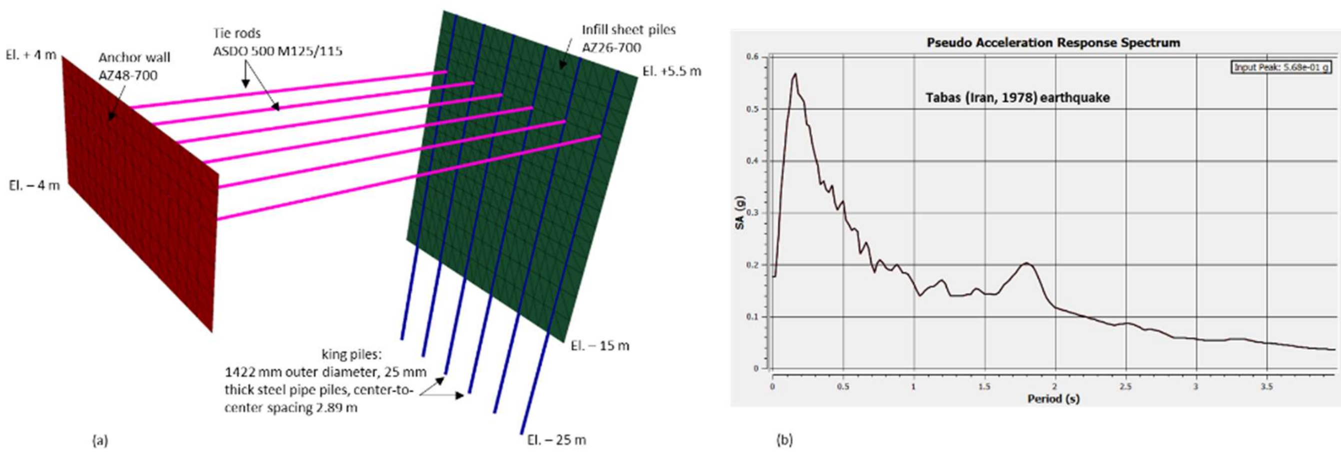

Figure 4. (a) quay wall structures, (b) response spectrum of input earthquake record Tabas (Iran, 1978).

Deep Soil Mixing Grid to Reduce Seismic Deformation

Preliminary analyses indicate large soil and structure deformation due to earthquake shaking, which may not satisfy the performance-based design criteria in practical projects. 3D modelling has shown its great advantage to model actual 3D deep soil mixing (DSM) grid to reduce the seismic deformation which otherwise has to be modeled as simplified 2D zones/columns and does not capture the 3D boxing effect. In this study, DSM grids of 10 m x 10 m were installed both behind and in front of the quay wall. The grids were installed below the compacted fill layer (below El. +1 m) at onshore areas and below the dredge level (El. – 9 m) at offshore areas. The DSM grids were extended to the bottom of the loose sand layer (El. -25 m) and are shown in Figure 5.

The grids were modeled using a Mohr-Coulomb model with a shear strength of 750 kPa based on a representative unconfined shear strength q_u of 1500 kPa of soil-cement mixing, a secant modulus E_{50} equal to $300q_u$, and a Poisson's ratio of 0.3.

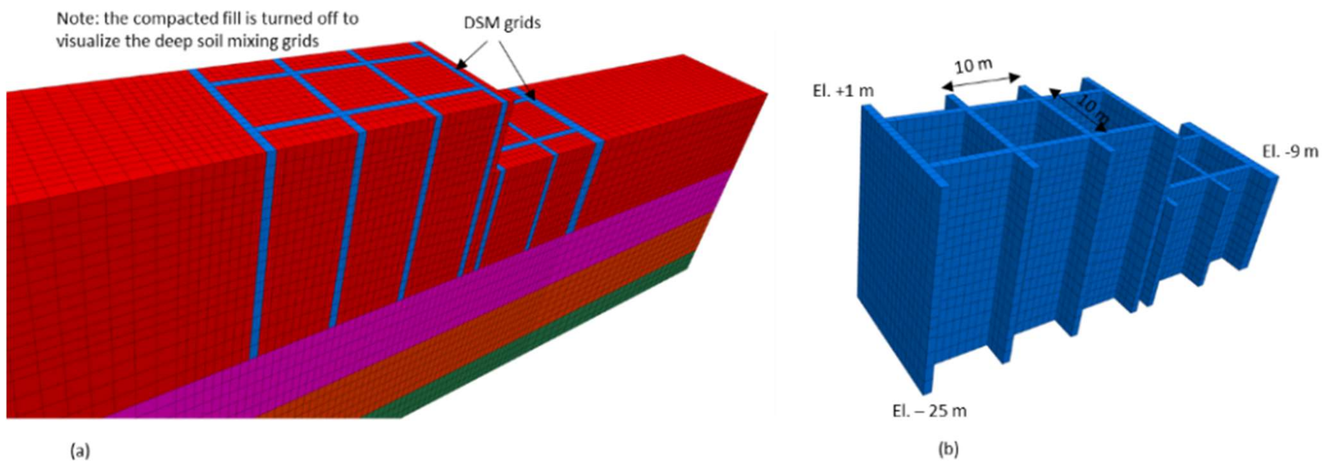

Figure 5. (a) Soil reinforcement using deep soil mixing (DSM) grids, (b) details of the DSM grids

FLAC Analysis Results

For existing soil conditions, the soil horizontal displacements at the end of the earthquake and maximum excess pore pressure ratio R_u contours are shown in Figure 6. The results indicate largest soil displacements in the order of 1 m and soil liquefaction (Ru > 0.7) occurred behind the quay wall. The deformations of the quay wall and anchor wall are shown in Figure 7a, which indicates deflection of about 1 m at top of the quay wall. The bending moments of the king piles are also shown in Figure 7b.

With soil reinforcement using DSM grids 10 m x 10 m, the soil displacements and R_u contours are shown in Figure 8. Much smaller soil displacements in the order of 0.35 m were estimated behind the quay wall. No liquefaction was estimated within the DSM boxes. The DSM grids generated a boxing effect that effectively restrains the excess pore pressure development and soil displacement particularly within the DSM boxes. The quay wall displacement time-histories with and without soil reinforcement are shown in Figure 9, which indicates wall displacement of about 0.35 m with DSM grids compared to 1 m without soil reinforcement.

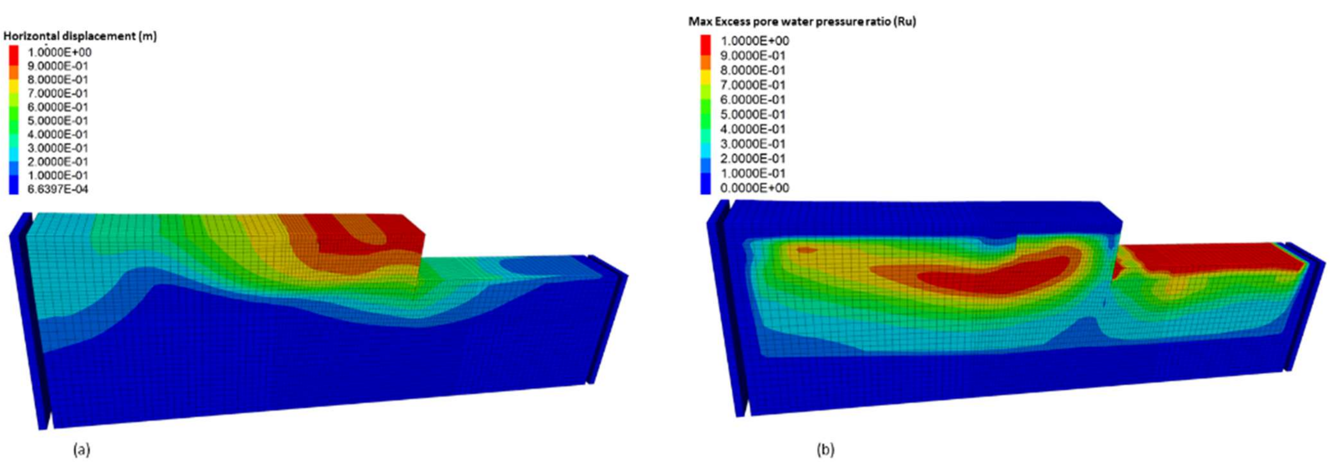

Figure 6. Existing soil conditions (a) soil horizontal displacement contours (m), (b) max excess pore pressure ratio (Ru)

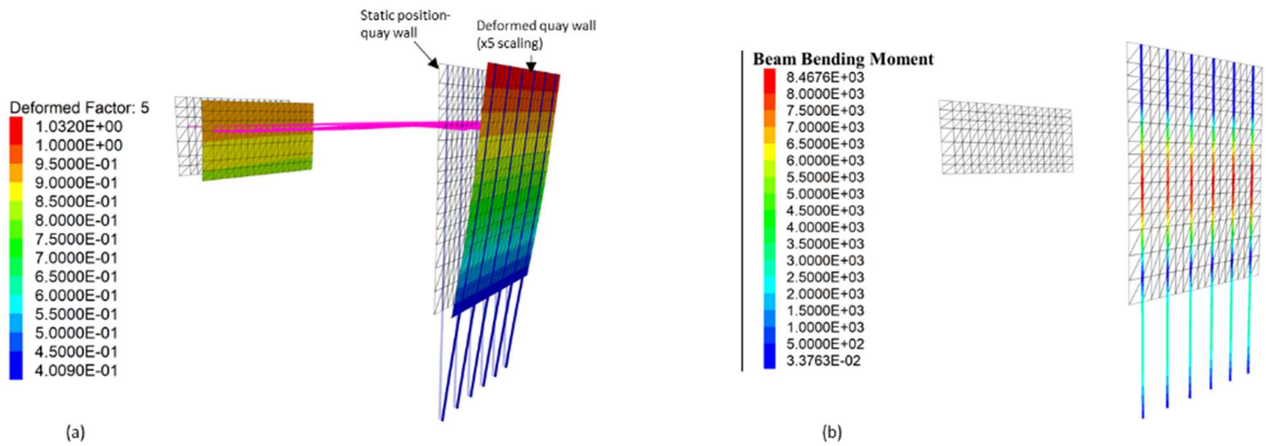

Figure 7. Existing soil conditions (a) quay wall deformation (m), (b) bending moment of king piles (kNm)

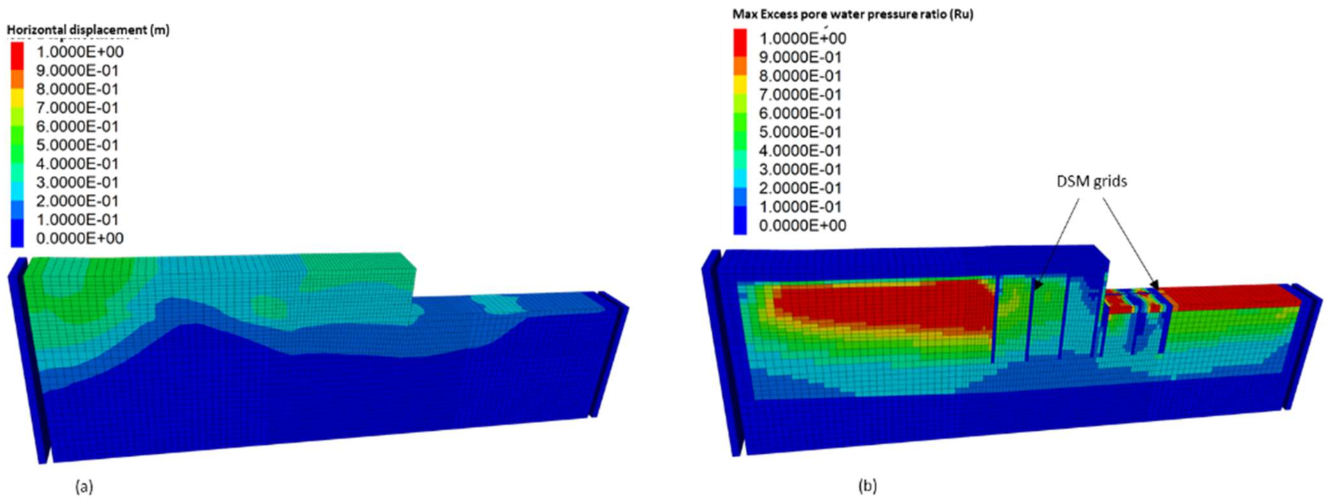

Figure 8. DSM reinforcement (a) soil horizontal displacement contours (m), (b) max excess pore pressure ratio (Ru)

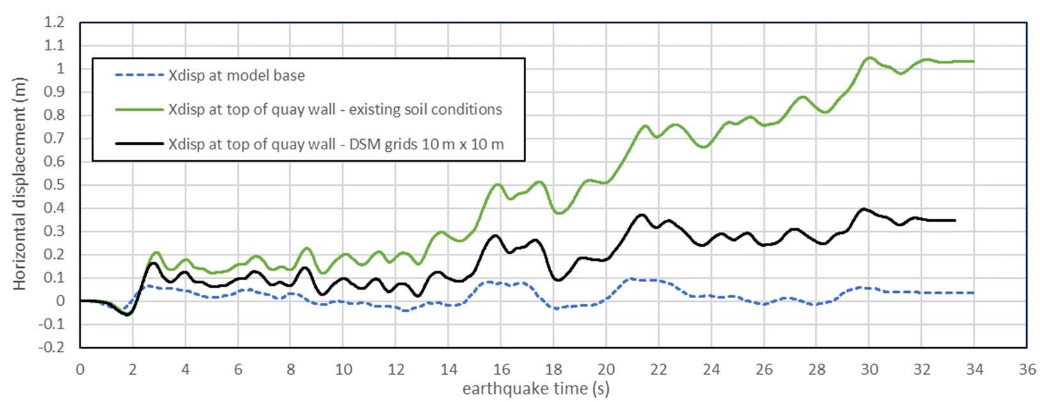

Figure 9. Time-histories of quay wall displacements (top of wall) under existing soil conditions vs. DSM reinforcement

CASE STUDY 2: LONG PIER STRUCTURE

In this case study, a long pier structure was simulated to analyze the post-seismic deformation of the pier subject to large ground deformation of the nearshore slope due to liquefaction. The marine slope starts from the onshore area (grade level at El. +6 m) then slopes down toward the ocean at approximately 4H:1V (horizontal: vertical) slope and was dredged to El. -11 m at about 45 m away from the shoreline. The subsurface soils consist of compacted fill (at onshore area), loose to dense sand layers, underlain by stiff silt. The soil stratigraphy is presented in Figure 10 and the soil parameters are shown in Table 2.

The pier is approximately 198 m long by 19 m wide. The elevation of the deck is approximately El. 7 m. The pier consists of 14 bents at 15 m spacing. Five bents located at the nearshore slope are supported on both vertical piles and inclined piles (1H:4V) and others are supported on vertical piles. All the piles are 1067 mm outer diameter, 19 mm thick steel pipe piles extended to El. -45 m. Capping beam with nominal dimensions of 1400 W x 1600 H is used to connect the piles at each bent and support the deck with an equivalent concrete thickness of 1.5 m. The structures are shown in Figure 10.

The Landers (1992) earthquake was used as the input record for seismic soil-structure modeling. The acceleration and displacement time-histories of the record, measured at the model base, are shown in Figure 12.

Table 2. Soil parameters – case study 2

Soil layer	Elevations (m)	Unit weight (kN/m^3)	Relative Density Dr	Gmax (MPa)	Soil model
Compacted fill	+0 to +6	19	0.66	Eq. (1)	P2PSand
Loose sand	-22 to seabed	18.5	0.41	Eq. (1)	P2PSand
Medium sand	-30 to -22	19	0.69		P2PSand
Dense sand	-35 to -30	19	0.78	Eq. (1)	P2PSand
Stiff silt	below -35	18	-	150	Mohr-Coulomb

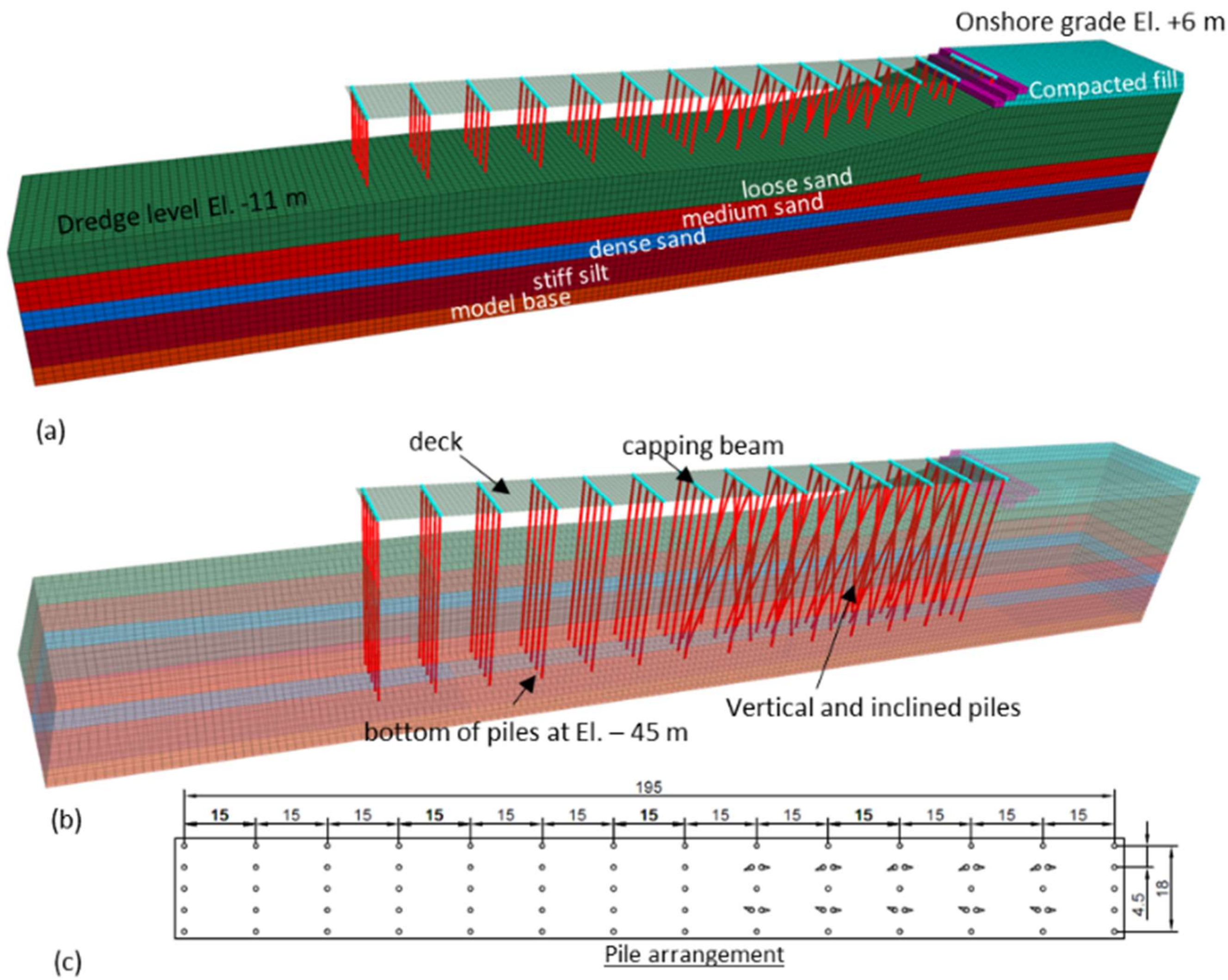

Figure 9. (a) model geometry with filled zones filled, (b) model geometry with transparent zones showing structures, (c) pile arrangement

FLAC Analysis Results

The soil deformation at the end of the earthquake and maximum excess pore pressure ratio R_u contours are shown in Figure 10. It is noted that in Figure 10a, the deformation was scaled 5 times for better visualization. The results indicate largest soil displacements were estimated at the nearshore slope and can be in the order of 1.5 m to 2 m. Associated soil liquefaction (Ru > 0.7) was estimated within the sand layers (Figure 10b). Outside the slope area, ground deformation reduced to about 0.2 m to 0.4 m at the flat dredged area.

The deformation of the structures is shown in Figure 11. Due to soil deformation, piles closer to the nearshore slope tend to move more than those at the flat dredged area. However, since all the piles are connected to the capping beams and deck which have high rigidity in the earthquake direction, the pile displacements were settled in the middle range of about 0.5 m which is significantly less than the largest soil displacements at the nearshore slope. The displacement time-histories of the top of a representative pile are shown in Figure 12. The capping beams and the deck practically had the same displacement as the piles.

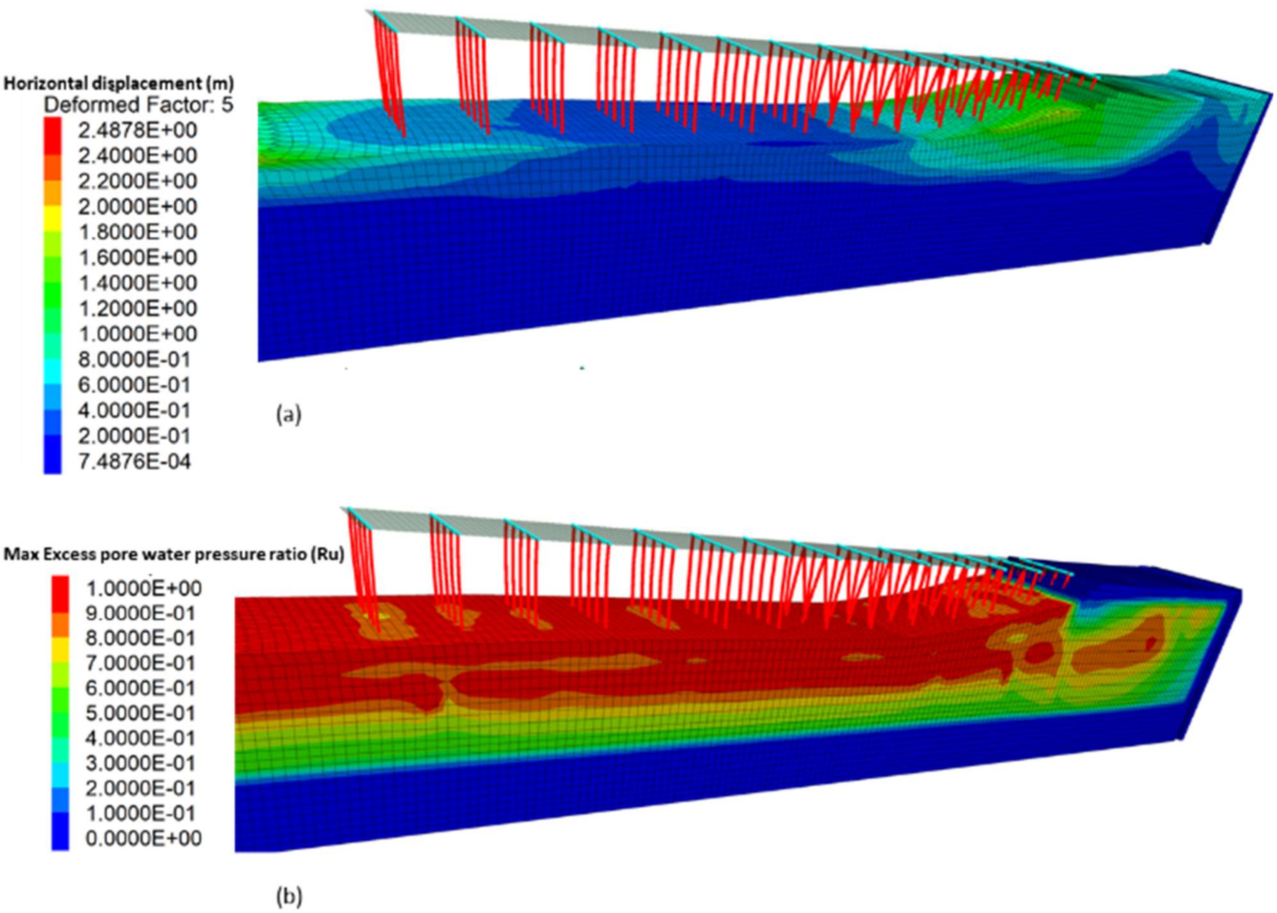

Figure 10. (a) soil horizontal displacement contours (m), (b) max excess pore pressure ratio (Ru)

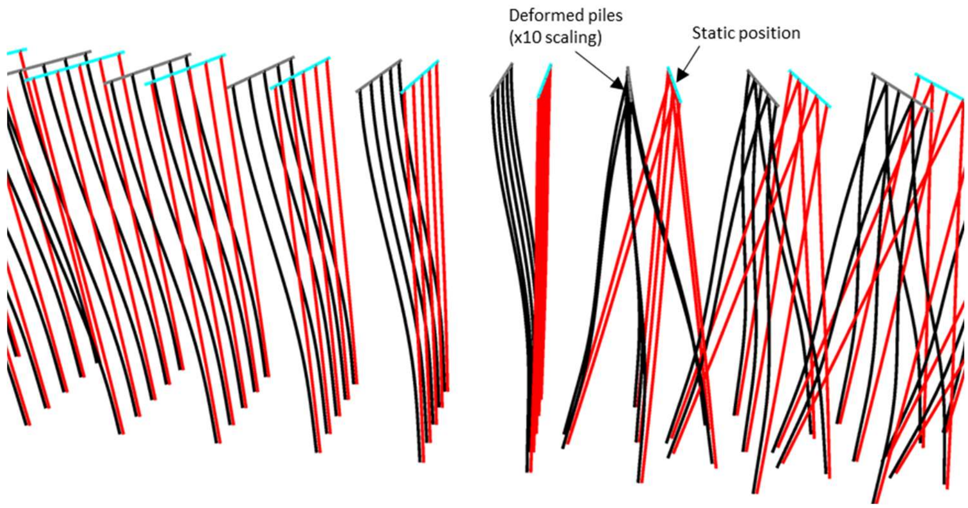

Figure 11. Deformation of the structures

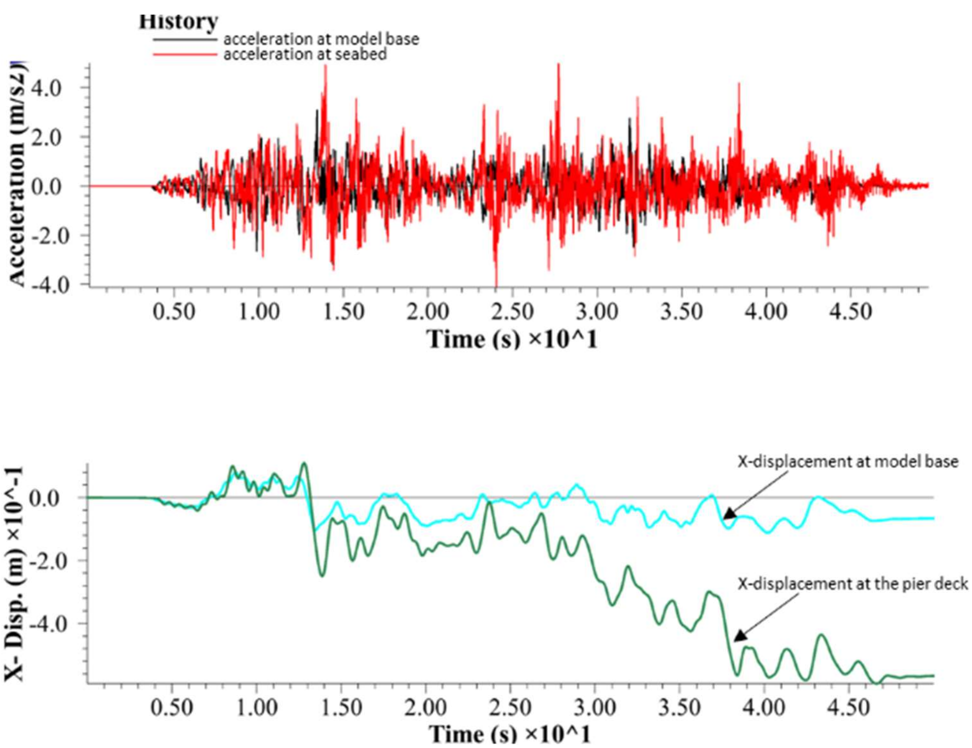

Figure 12. (a) Acceleration time-histories (m), (b) X-displacement time-histories

CONCLUSIONS

3D modeling of seismic soil-structure interaction was presented through two case studies which demonstrate the advantages of modeling both the soils and structures in 3D under a single simulation. The 3D modeling can simulate liquefaction patterns such as development of excess pore water pressure, liquefaction triggering, loss of strength, stiffness reduction and typical stress-strain loops using the 3D P2PSand model. The P2PSand model follows the state-of-the art theorical background and can be calibrated to widely used correlations and test results.

The soil and structure interaction and subsequent structural response during and after the shaking can be modeled realistically without the need of exporting the ground deformation and soil springs as input for a separate structural program. The structural response does not aim to replace independent structural assessment but to supplement and provide a cross-check for critical soil-structure interaction design.

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