PM4SAND and UBCSAND Constitutive Soil Models for Seismic Soil-Structure Interaction Analysis of an Anchored Sheet Pile Wall System

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ABSTRACT

Seismic soil-structure interaction analyses were performed to evaluate seismic performance of anchored sheet pile wall system. The analyses were carried out using UBCSAND and PM4SAND soil constitutive models for liquefiable soils. Model calibration was performed to determine input parameters for the seismic analysis. The calibration considered some important aspects that significantly affect the results of the numerical simulation, including cyclic resistance ratio, the development of the excess pore water pressure, the overburden effect, the static shear stress effect, and the modulus reduction and damping. Soil liquefaction and seismic response of the sheet pile wall system estimated using PM4SAND model agree reasonably with the those estimated using UBCSAND model. Use of different soil models with proper model calibration can capture possible range of the expected response.

RÉSUMÉ

Des analyses d'interaction sismique sol-structure ont été réalisées pour évaluer la performance sismique du système de mur de palplanches ancrées. Les analyses ont été effectuées à l'aide des modèles constitutifs des sols UBCSAND et PM4SAND pour les sols liquéfiables. L'étalonnage du modèle a été effectué pour déterminer les paramètres d'entrée pour l'analyse sismique. L'étalonnage a pris en compte certains aspects importants affectant de manière significative les résultats de la simulation numérique, notamment le rapport de résistance cyclique, l'augmentation de la pression interstitielle, l'effet de surcharge, l'effet de cisaillement statique et la réduction et l'amortissement du module. La liquéfaction du sol et les réponses sismiques du système de palplanches estimées à l'aide du modèle PM4SAND concordent raisonnablement avec celles estimées à l'aide du modèle UBCSAND. L'utilisation de différents modèles de sol avec un bon calibrage du modèle peut capturer la portée possible de la réponse attendue.

1 INTRODUCTION

Liquefaction of soil presents a significant hazard to waterfront structures. Finite element or finite difference analysis for soil liquefaction during earthquake can be assessed using advanced soil constitutive models which consider the development of excess pore water pressure. UBCSAND (Beaty and Byrne, 2011), PM4SAND (Boulanger and Ziotopoulou, 2017), Pressure Dependent Multi Yield 02 (Yang et al., 2008), and SANISAND (Dafalias and Manzari, 2004; Taiebat and Dafalias, 2008) are several constitutive models that have been developed for liquefaction simulation.

The UBCAND and PM4SAND models have been used in engineering practice. UBCSAND is a two-dimensional effective stress plasticity model that predicts the shear stress-strain behavior of the soil using an assumed hyperbolic relationship and the build-up of excess pore water pressure during cyclic loading (Beaty and Byrne, 2011). PM4SAND is a critical state compatible, stress-ratio controlled, bounding surface plasticity model, developed to approximate the range of behaviors important to geotechnical earthquake engineering practice (Boulanger and Ziotopoulou, 2017).

Using both models can provide insight into the model response and suggest the approximate range of simulation results. Poor agreement between results obtained using two different models can identify issues with the simulation and lead to subsequent improvements.

In this study, seismic soil-structure interaction analyses were performed to evaluate seismic performance of an anchored sheet pile wall system. The soil profiles and structure properties were adapted from published literature and do not represent any local site or structure. Sandy soils were modeled using UBCSAND and PM4SAND soil constitutive models to analyze the development of excess pore water pressure.

2 SUBSURFACE CONDITIONS

The soil profiles at the site are shown in Figure 1. The total height of the steel sheet pile wall is about 22.5 m and the top of the wall is at approximately El. + 2.0 m. The sheet pile wall is connected to an anchor wall using high strength steel tie rods which are installed near top of the wall and spaced at 2 m. The anchor wall is located 20 m behind the sheet pile wall.

The natural subsurface soils consist of 8 m to 20 m thick dense sands, overlying a 2.5 m thick clay layer which is underlain by dense silty sand to sand. The backfill behind the wall typically consist of sand with thicknesses varying from approximately 12 m right behind the sheet pile wall to 8 m at the anchor wall location. The backfill sand is estimated to be loose with a fines-corrected $(N_1)_{60cs}$ value of 9.

The $(N_1)_{60cs}$ of the dense sand is estimated to be 40 and that of the dense silty sand to sand is estimated to be 25 to 30.

The mean water level is located at approximately 2 m below top of the sheet pile wall.

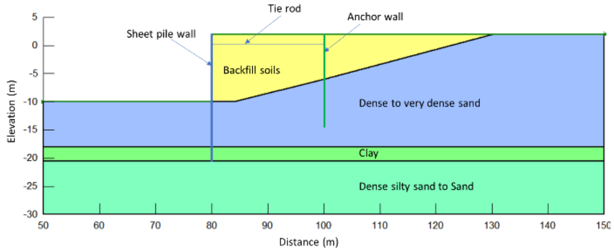

Figure 1. Soil profile, sheet pile wall and anchor wall

3 EARTHQUAKE MOTIONS

Dynamic analyses of the sheet pile wall-soil system were carried out using earthquake motions from the Chi Chi (Taiwan, 1999), Loma Prieta (Northern California, 1989), and Landers (California, 1992) earthquakes. The design motions were defined as bedrock outcrop motions. Response spectrum matching and baseline correction of the earthquake motions were performed before their use in the dynamic analyses. The Response Spectra of the earthquake motions, obtained for 5% damping are presented in Figure 2. The magnitude of the earthquakes and the duration of the modified motions are summarized in Table 1.

Table 1. Earthquake motions

Earthquake	Moment Magnitude	Duration (s)
Chi Chi	7.6	60
Loma Prieta	6.9	40
Landers	7.3	45

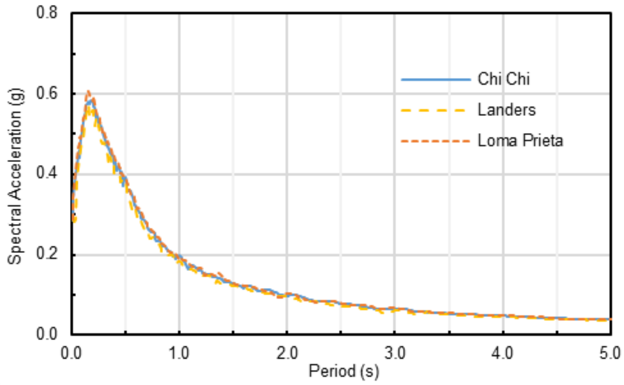

Figure 2. Response spectra of the spectrally matched earthquake motions

4 CONSTITUTIVE MODEL CALIBRATION

The calibration of the UBCSAND (version 904aR, 2011) and PM4SAND (version 3.0, 2017) models considered some important aspects that significantly affect the results of the numerical simulation. The calibration was based on results of single element simulations of cyclic direct simple shear (cDSS) test with stress-controlled loading.

The input parameters were calibrated to give reasonable agreement between simulation results and empirical correlations, including the cyclic resistance ratio (CRR) with $(N_1)_{60cs}$, the development of the excess pore water pressure, the overburden effect (K_σ), the static shear stress effect (K_α), and the modulus reduction and damping.

Generic input parameters for both UBCSAND and PM4SAND include relative density, elastic shear modulus and friction angle.

The soil relative density (D_r) was determined from SPT $(N_1)_{60}$:

$$D_r = \sqrt{\frac{(N_1)_{60}}{46}} \quad [1]$$

The elastic shear modulus was determined as a function of $(N_1)_{60}$:

$$G = G_o p_a (\frac{p'}{p_a})^{0.5} \quad [2]$$

$$G_o = 21.7 * 20 * {(N_1)_{60}}^{0.333} \quad [3]$$

Where p_a is the atmospheric pressure and p' is the 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 for both UBCSAND and PM4SAND.

Liquefaction triggering was defined as the development of 70% excess pore water pressure ratio R_u (i.e., ratio between excess pore pressure and the initial effective overburden stress) or the development of 3.75% shear strain.

4.1 UBCSAND calibration

The parameter m_hfac1 in the UBCSAND formulation is used to adjust the plastic shear modulus with confining stress. Calibration of liquefaction triggering and K_σ effect can be performed using the fitting parameter m_hfac1.

The parameter m_hfac1 was defined by Beaty and Byrne (2011) as a function of $(N_1)_{60}$ and the initial effective stress (σ'_v), shown in equation 4.

$$m\_hfac1 = a_N (\frac{\sigma'_v}{p_a})^{b_N} \quad [4]$$

where a_N and b_N are functions of $(N_1)_{60}$.

The parameter m_urstif used to adjust the plastic shear modulus is a function of the relative change in stress ratio and the loading history. The default formulations of m_urstif were used in this study.

4.2 PM4SAND calibration

The contraction rate parameter h_{po} is a primary input parameter in the PM4SAND formulation used to adjust the plastic shear modulus to elastic modulus. This parameter was defined as a function of $(N_1)_{60}$ and σ_v', similar to Eq. [4] to calibrate the liquefaction triggering and K_σ effect.

The PM4SAND model consists of 21 secondary parameters. C_{kaf} and h_o are the two secondary parameters that need modifications during model calibration. Default values were set for other secondary parameters.

The parameter C_{kaf} controls the effect of static shear stresses on plastic modulus. C_{kaf} was set equal to 2 in this study based on the static shear bias calibration.

The parameter h_o adjusts the plastic modulus to elastic modulus. A h_o value of 1.2 was set to provide reasonable modulus reduction and damping relationships.

4.3 Calibration results

The calibration results are presented in Figures 3 through 11. The calibrated profiles of m_hfac1 (UBCSAND) and h_{po} (PM4SAND) are shown in Figure 3.

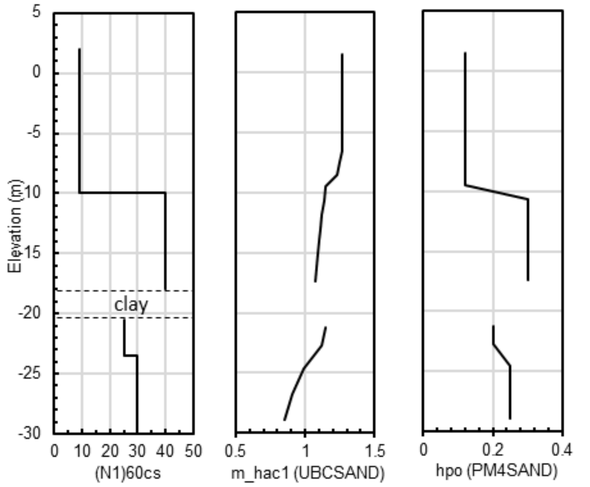

Figure 3. Calibrated parameters m_hfac1 (UBCSAND) and h_{po} (PM4SAND) for soils on land side

The cyclic stress ratio (CSR) causing liquefaction in 15 uniform cycles ($M_w = 7.5$, $\sigma_v' = 100\ kPa$) versus $(N_1)_{60cs}$ are shown in Figure 4. The CSR values estimated by both UBCSAND and PM4SAND agree closely with the liquefaction triggering curve proposed by Idriss and Boulanger (2008).

The number of uniform cycles to liquefaction at different CSR values are presented in Figure 5. The general trends estimated by both UBCSAND and PM4SAND are consistent with those shown in Idriss and Boulanger (2008).

The effect of confining stress on liquefaction resistance is presented through the K_σ factor ($K_\sigma = CRR_{\sigma'v}/CRR_{\sigma'v = 1atm}$) and shown in Figure 6. The K_σ versus σ_v'/p_a relationships estimated by both UBCSAND and PM4SAND agree closely with the correlations proposed by Idriss and Boulanger (2008).

The effect of initial static shear bias α is presented through the K_α factor ($K_\alpha = CRR_\alpha/CRR_{\alpha=0}$) and shown in Figure 7. The general trends estimated by both UBCSAND and PM4SAND are consistent with the relationship proposed by Idriss and Boulanger (2008).

The development of excess pore water pressure during shaking is shown in Figure 8. The excess pore water pressure ratio R_u was estimated for an $(N_1)_{60cs}$ value of 10 and a CSR of 0.12 without static bias. Both UBCSAND and PM4SAND estimated soil liquefaction in 15 uniform cycles. The stress paths from the simulation are shown in Figure 9.

The calibrated modulus reduction (G/Gmax) and damping curves are shown in Figures 10 and 11 respectively. The reduction in shear stiffness with strain estimated by UBCSAND is close to the upper bound of the modulus reduction curve reported by Seed and Idriss (1970) for sand. The shear modulus reduction curve estimated by PM4SAND is close to the average modulus reduction curve reported by Seed and Idriss (1970). Damping ratios estimated by both UBCSAND and PM4SAND are significantly higher than those reported by Seed and Idriss (1970) for shear strains larger than 0.1 %. The large damping was estimated for symmetric load cycles. However, reduced damping is anticipated for typical non-symmetric earthquake shaking (Beaty and Byrne, 2011).

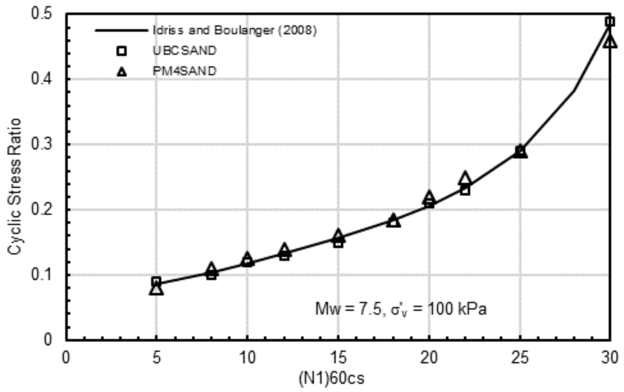

Figure 4. Liquefaction triggering curve

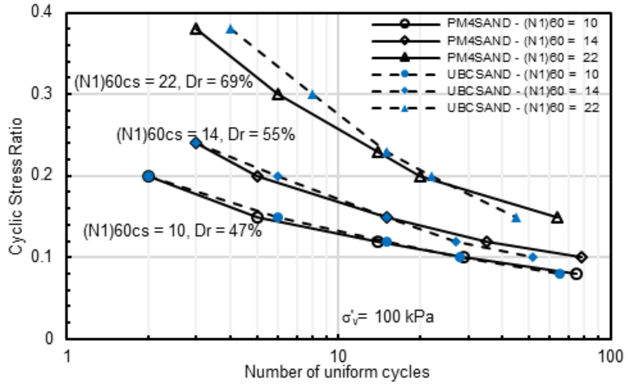

Figure 5. Number of cycles to trigger liquefaction

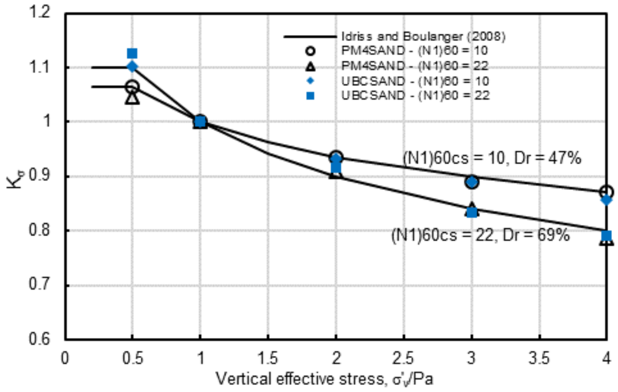

Figure 6. K_σ effect

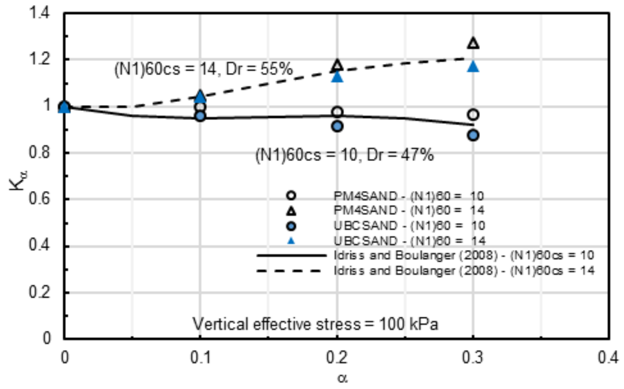

Figure 7. K_α effect

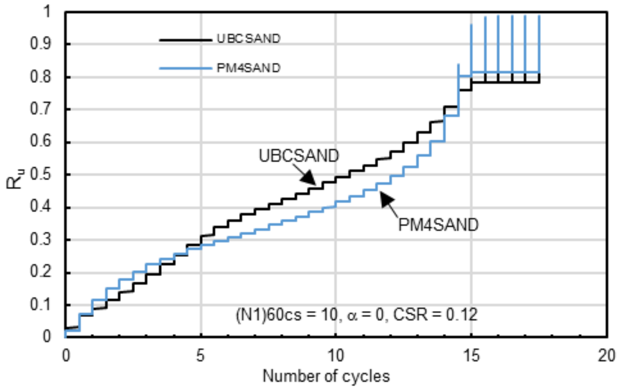

Figure 8. Development of excess pore pressure ratio R_u

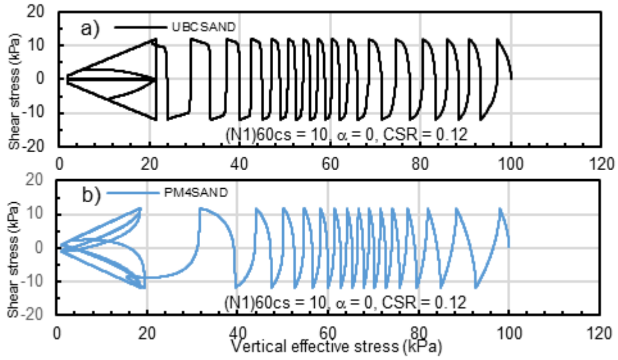

Figure 9. Shear stress vs. vertical effective stress

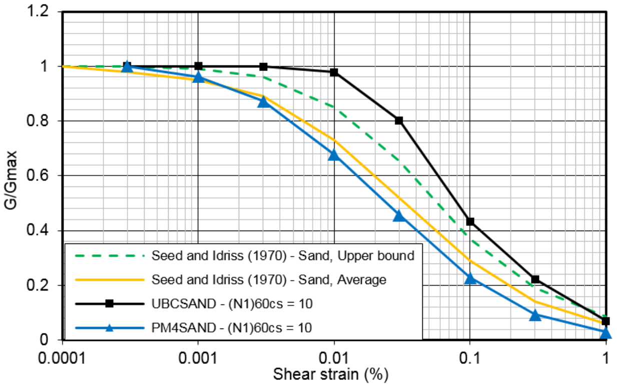

Figure 10. Modulus reduction

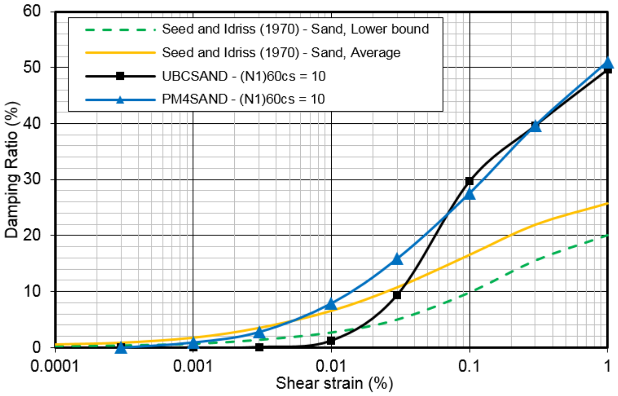

Figure 11. Damping ratio

5 SEISMIC SOIL-STRUCTURE INTERACTION ANALYSIS

5.1 Analysis stages

Coupled soil-structure interaction analyses were carried out using computer program FLAC 2D v.7 (Itasca, 2011).

Two stages were simulated in the analyses of the anchored sheet pile wall system:

- Stage 1 – Static analysis for pre-earthquake conditions;
- Stage 2 – Dynamic analysis with earthquake motions

The dynamic analysis was performed in time domain for the full duration of the input motions and then continued for an additional 5 seconds of dynamic time without any motions. This additional time was to allow for continued decay of the dynamic response. Post-earthquake analysis was not considered in this study.

The analyses were performed using UBCSAND (Case 1) and PM4SAND (Case2) to model liquefiable soils.

5.2 Boundary conditions

The lateral boundaries of the FLAC model were extended at both sides of the model to minimize boundary effects. The lower model boundary was extended to incorporate 10 m thickness of model base.

Free field and compliant base conditions were applied to the lateral boundaries and model base, respectively.

Horizontal component of the design earthquake motions was applied to the base of the model as shear stress time histories.

5.3 Soil Constitutive models and parameters

The sandy soils were modeled using Mohr-Coulomb model in Stage 1. In stage 2, UBCSAND (Case 1) and PM4SAND (Case 2) models were used for sandy soils to simulate the development of excess pore water pressure and potential liquefaction.

The clay layer was modeled using Mohr-Coulomb model in Stage 1. In stage 2 during shaking, the “Default” hysteretic model available in FLAC was used to allow for modulus reduction and damping of the clay. The input parameters of the model were calibrated with the modulus reduction and damping curves for clay proposed by Sun et al. (1988).

The FLAC model and $(N1)_{60cs}$ values used for the FLAC analyses are shown in Figures 12 and 13, respectively. The clay layer and the bottom soil layer do not require $(N1)_{60cs}$ as input for the models used. Therefore, the $(N1)_{60cs}$ for these two layers are shown a value zero in the graphical representation in Figure 13.

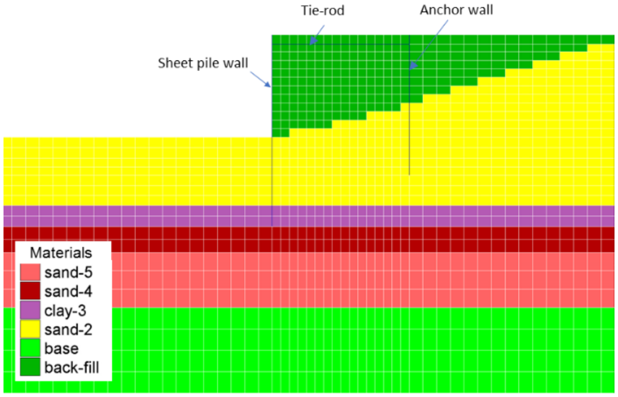

Figure 12. FLAC model

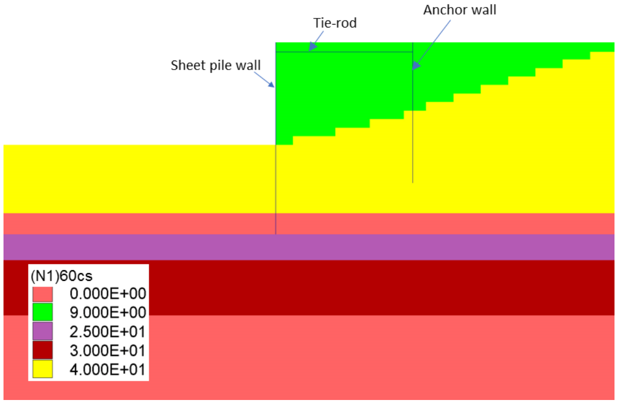

Figure 13. $(N_1)_{60cs}$ values used for the FLAC analyses

5.4 Anchored sheet pile wall

The sheet pile wall and anchor wall were modeled using beam elements. The soil grid interacts with the beam elements through interface springs attached to nodal points. An interface friction angle of 17 degrees was used to simulate the shear interaction between the beam elements and soils.

The tie-rod was modeled using cable elements, which only carry tension forces.

The sheet pile wall, anchor wall and tie-rod were modeled as elastic structures with a Young’s modulus of 210 GPa. The moment of inertia of the sheet pile and anchor walls used in the analyses were 86,000 cm^4/m and 73,000 cm^4/m, respectively.

Hydrodynamic pressure acting on the sheet pile wall during seismic shaking was accounted for by adjusting the grid point mass on the sheet pile wall face using the following formulation (Westergaard, 1933):

$$m(y) = {}^{7}/_{8}\, M_w \sqrt{h.y} \qquad [5]$$

Where m(y) is the variation of mass with depth, y. M_w is the mass density of water, and h is the overall depth of water.

5.5 FLAC analysis results

The maximum excess pore pressure ratio R_u and soil horizontal displacement contours at the end of the analysis using UBCSAND model and Loma Prieta earthquake motion are shown in Figures 14 and 15, respectively. Results from the same earthquake motion using PM4SAND model are shown in Figures 16 and 17.

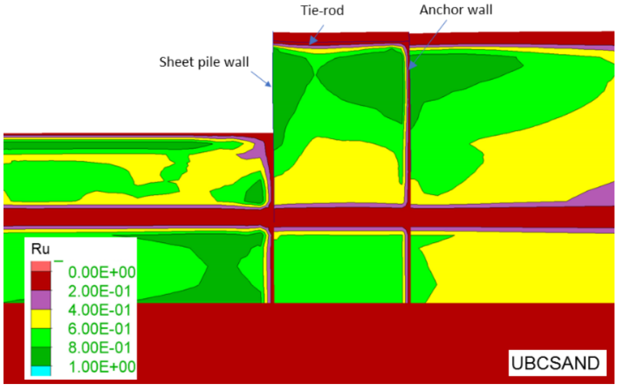

Figure 14. Excess pore pressure ratio R_u (UBCSAND)

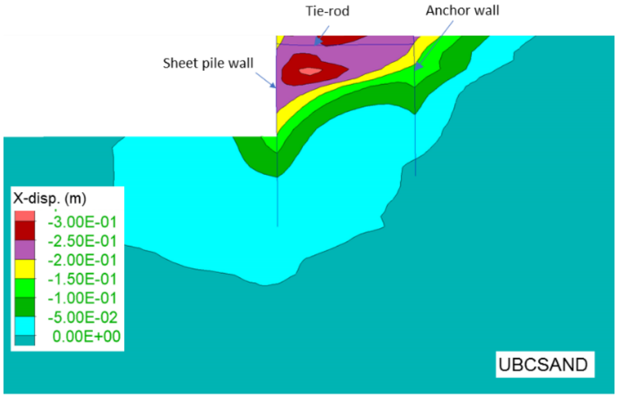

Figure 15. Horizontal displacement (UBCSAND)

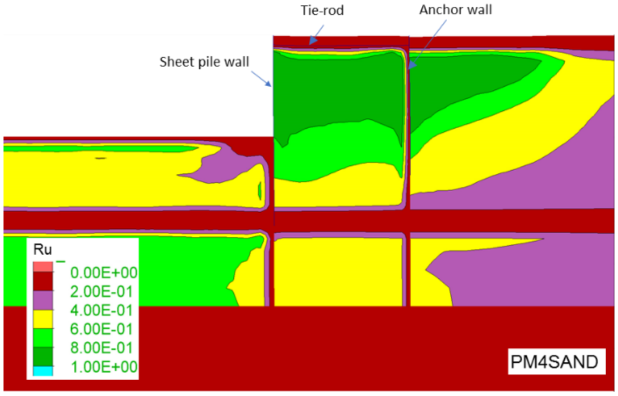

Figure 16. Excess pore pressure ratio R_u (PM4SAND)

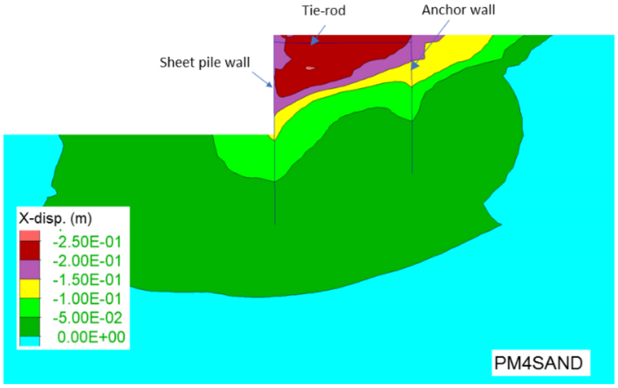

Figure 17. Horizontal displacement (PM4SAND)

The results from both Cases indicate soil liquefaction (R_u > 70%) occurred in the backfill soils. Similar patterns for soil displacement were observed between UBCSAND and PM4SAND. However, the UBCSAND model predicted more liquefaction in front of the wall within the bottom silty sand layer (below the 2.5 m thick clay layer) than that from the PM4SAND model.

The bending moment and lateral displacement profiles of the sheet pile wall using UBCSAND are presented in Figures 18 and 19, respectively. The wall responses using PM4SAND are presented in Figures 20 and 21. For both cases, the maximum bending moments and lateral displacements were estimated to occur at approximately 7 m and 6 m below the top of the sheet pile wall, respectively.

The UBCSAND model estimated the sheet pile wall largest bending moment of about 1000 kNm/m and largest lateral displacement of about 0.23 m. The PM4SAND model estimated the wall largest bending moment of about 750 kNm/m and largest lateral displacement of about 0.2 m. For both cases, the largest bending moment and displacement occurred with the Loma Prieta earthquake motion. The PM4SAND model generally estimated smaller bending moments and displacements than those estimated using the UBCSAND model. As shown in Figures 10 and 11, the PM4SAND model estimated more modulus reduction and damping in the backfill soils than those estimated by the UBCSAND model. This may indicate that the backfill soils modeled using PM4SAND damped more energy than those modeled using UBCSAND, which may lead to less liquefaction, smaller seismic load acting on the sheet pile wall and consequently, smaller bending moments and displacements.

In general, both PM4SAND and UBCSAND models provide reasonable agreement regarding soil liquefaction and deformation patterns. Using both models can suggest an approximate range of sheet pile wall largest bending moments from 750 kNm/m to 1000 kNm/m and largest lateral displacements from 0.2 m to 0.23 m.

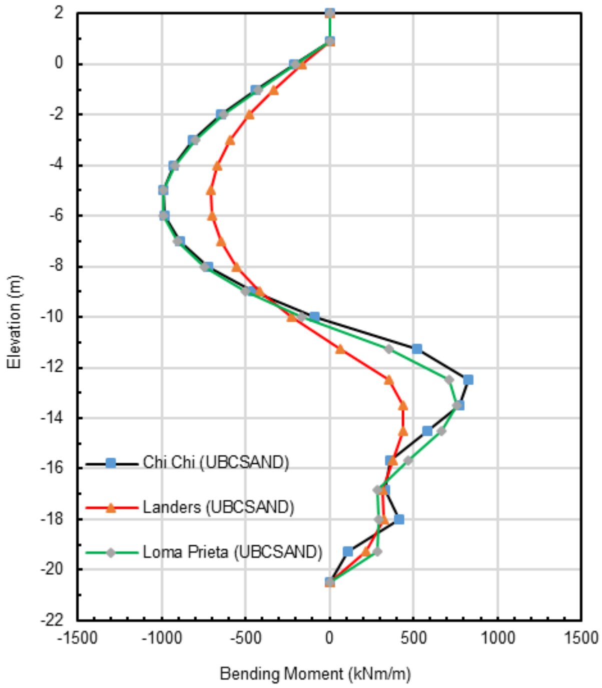

Figure 18. Bending moments of sheet pile wall (UBCSAND)

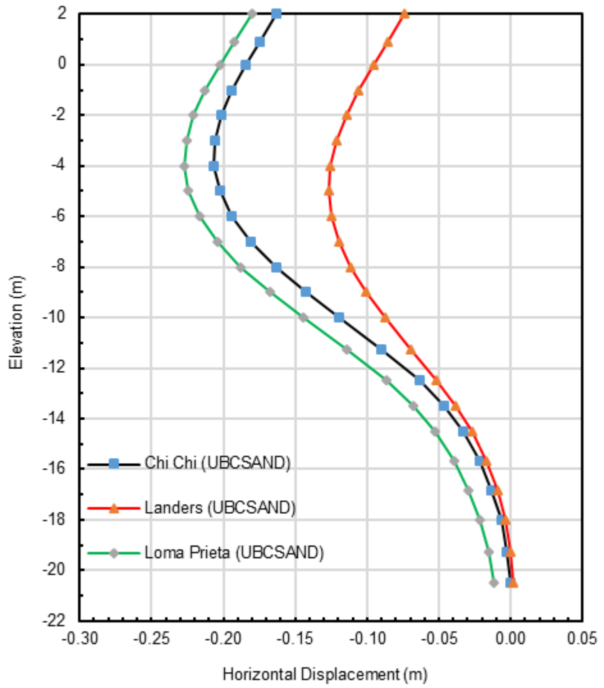

Figure 19. Lateral displacements of sheet pile wall (UBCSAND)

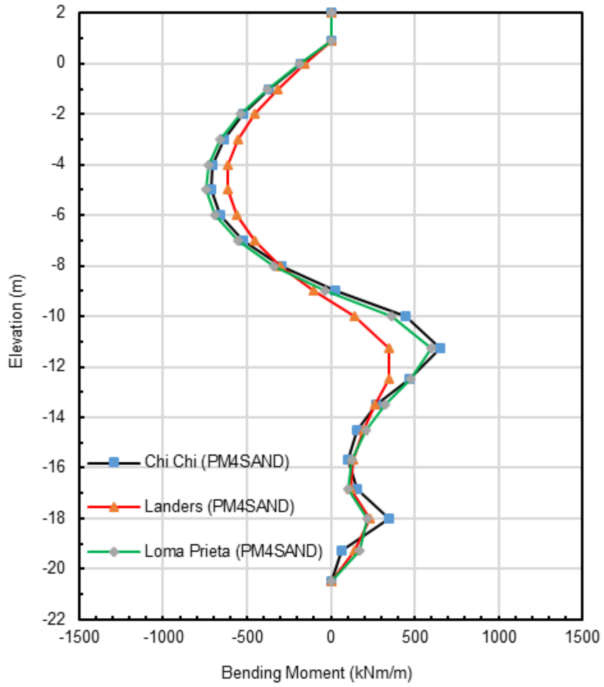

Figure 20. Bending moments of sheet pile wall (PM4SAND)

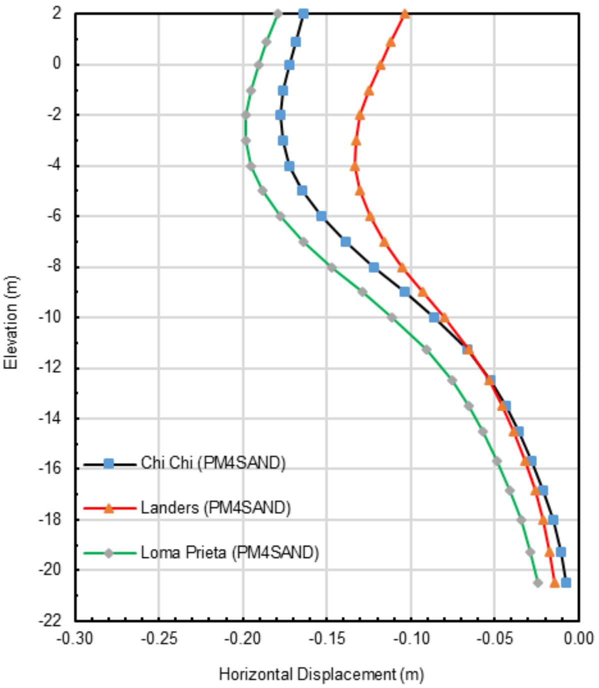

Figure 21. Lateral displacements of sheet pile wall (PM4SAND)

6 CONCLUSIONS AND DISCUSSIONS

The importance of calibration of the UBCSAND and PM4SAND models is emphasized. This is to produce reasonable responses, including number of cycles to liquefaction, development of excess pore water pressure ratio, confining stress and static shear bias effects, and modulus reduction and damping. The calibration led to the development of model parameters that were found to capture the behavior of the anchored sheet pile wall system.

The PM4SAND model produced soil liquefaction and seismic responses of the anchored sheet pile wall system which are consistent with the those estimated using the UBCSAND model.

As all available constitute models for liquefaction simulation may contain some, but different limitations that are not well understood, the use of different soil models with proper model calibration could identify issues with the simulation. Use of different soil models with proper model calibration can capture possible range of the expected response.

7 ACKNOWLEDGEMENTS

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