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CENTRIFUGE AND NUMERICAL MODELLING OF SHALLOW UNDERGROUND STRUCTURES ADJACENT TO TALL BUILDINGS

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Abstract

Shallow underground structures used for public transportation are a key component of sustainable cities. In dense urban environments, underground structures are often built near tall buildings. Although such buildings have the potential to alter ground motions in their vicinity and transmit significant forces to adjacent underground structures during earthquakes, these impacts are not well understood. Centrifuge testing and nonlinear numerical simulations are performed to evaluate seismic interactions between the soil, underground structure, and adjacent midrise or highrise buildings. The response of an 8 m high x 14 m wide embedded cut and cover tunnel structure is first studied without any adjacent buildings present, where numerical model estimates are compared and calibrated with the measured response. Two additional experiments are conducted with a mid-rise and a high-rise model building added near the underground structure to assess the change in the seismic response of the tunnel due to soil-structure-underground structure-interaction (SSUSI). Results indicate that the presence of an adjacent mid-rise building can be adequately modeled using three-dimensional numerical tools suggesting they are appropriate for use in seismic design for these complex interactions. The models show good agreement with experimental measurements in terms of displacements and accelerations on the buried structure. The dynamic lateral thrust acting on the underground structure is shown to roughly follow the adjacent building's base shear in shape and amplitude.

Keywords: site response; soil-structure; centrifuge; numerical modeling; LS-DYNA

1. Introduction

In dense urban environments, underground structures are commonly constructed near tall buildings that can potentially transmit significant forces to the underlying soil and underground structures. The current state of practice for the design of cut-and-cover box structures relies on simplified procedures that cannot account for the presence of other structures or on numerical modeling tools that have not been thoroughly validated against physical model studies. The work presented in this paper is part of a study that employs a combined experimental-numerical approach to evaluate seismic soil-structure-underground structure-interaction (SSUSI) in medium dense, dry sand. The experimental program employed centrifuge testing to study the response of cut-and-cover box structures in isolation and in the presence of a midrise or highrise adjacent structure. The numerical work presented focuses on the validation of three-dimensional (3D) soil-structure models using the centrifuge experimental results.

2. Design of Centrifuge Experiments

The configurations tested in the centrifuge are shown in Fig. 1. The main challenge in the design of the centrifuge tests was to design and construct building models that exhibited the dynamic properties of realistic midrise and high-rise structures and conformed to the height and weight limitations of the centrifuge. The design of the superstructures focused on generating realistic forces and moments under seismic loading. The final design of the simplified midrise structure in centrifuge was representative of a 12-story building with a steel moment resisting frame and captured the height, mass, base shear, and three primary modes of response. The high-rise model required additional simplifications due to limited overhead space in the centrifuge, but captured the fundamental frequency, mass, and base shear of the target structure. The design of the underground structures focused on achieving realistic dimensions and structural stiffness (quantified using the racking to flexibility ratio). The final design of the permanent box structure had dimensions of 8 m high x 14 m wide and a realistic racking stiffness. A full description of the design, construction, and approximations necessary for the centrifuge modeling is presented in Dashti et al. [1].

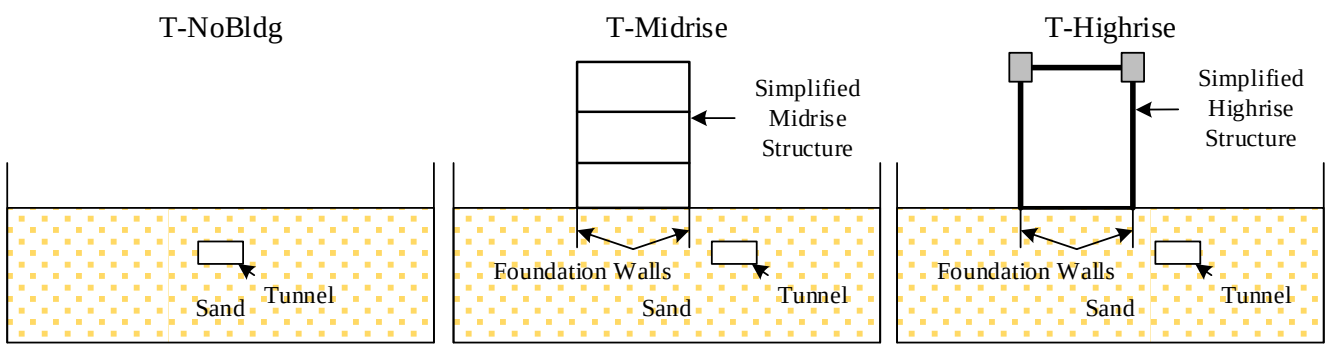

Fig. 1 – Centrifuge test configurations (T: Tunnel).

3. Ground Motions

A suite of ground motions recorded on rock or stiff soil was selected for use as base motions in the centrifuge experiments. The motions were chosen to cover a range of amplitudes, durations, frequency contents, and intensities. The motions achieved in the centrifuge tests were recorded at the base of the model specimens (a depth of 26 m in prototype scale) and were used as prescribed accelerations at the base of the corresponding numerical model. The properties of the achieved motions are summarized in Table 1, and the response spectra are shown in Fig. 2.

Table 1 – Ground motion descriptions.

Record Source		Achieved Motion Metrics		
Event	**Station**	**PGA (g)**	**PGV (cm/s)**	**PGD (cm)**
Northridge (1994)	Newhall – WPC	0.46	49.4	12.1
Loma Prieta (1989)	Santa Crus – L. Obs.	0.1	10.5	0.6
Landers (1992)	Joshua Tree	0.25	21.8	4.4
Chi Chi (1999)	TCU078	0.34	26.9	5.0
Landers (1992)	Lucerne	0.38	32.6	6.8
Kobe (1995)	Takatori	0.45	52.8	16.2

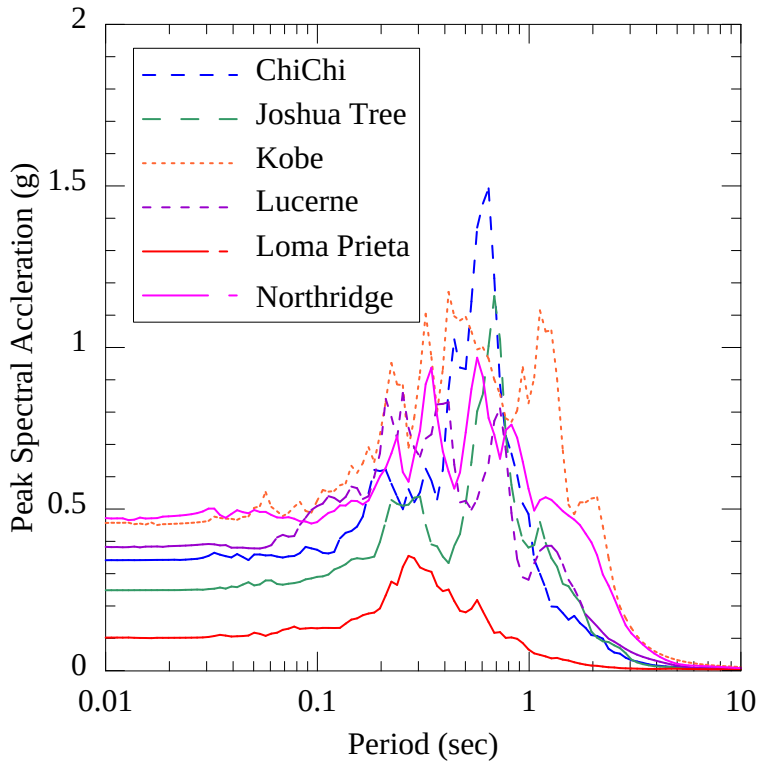

Fig. 2 – Acceleration response spectra (5% damped) of base motions achieved in T-NoBldg.

4. Development of Numerical Models

3D numerical modeling of the centrifuge tests was conducted in the general-purpose finite-element analysis software LS-DYNA. Model development was completed in three phases: 1) calibration of soil properties, 2) calibration of structural properties, and 3) evaluation of combined soil-structure models. Each phase of the calibration process is described in the following sections. All numerical simulations were performed in prototype scale.

4.1 Soil Properties

Dry Nevada sand was used in all centrifuge experiments. The sand had a specific gravity (G_s) = 2.66, minimum dry unit weight ($\gamma_{d,min}$) = 13.7 kN/m3, and maximum dry unit weight ($\gamma_{d,max}$) = 17.0 kN/m3 (corresponding to e_{min} = 0.53 and e_{max} = 0.90). These soil properties are consistent with the properties reported by Dashti et al. [1]

and Hashash et al. [2], which describes the initial numerical simulations of one-dimensional (1D) free-field site response as a part of this research. The sand was dry pluviated into a Flexible Shear Beam (FSB) container to achieve an initial relative density of approximately 55%.

Shear wave velocity profiles were measured during centrifuge testing using a cone penetrometer and multiple sets of bender elements within the model. The measured shear wave velocity profiles were compared with empirical correlations and found to be bounded by those proposed by Seed and Idriss [3] (upper bound) and Bardet et al. [4] (lower bound). The shear wave velocity profile used for all numerical analyses was taken as the average of these two correlations and is shown in Fig. 3.

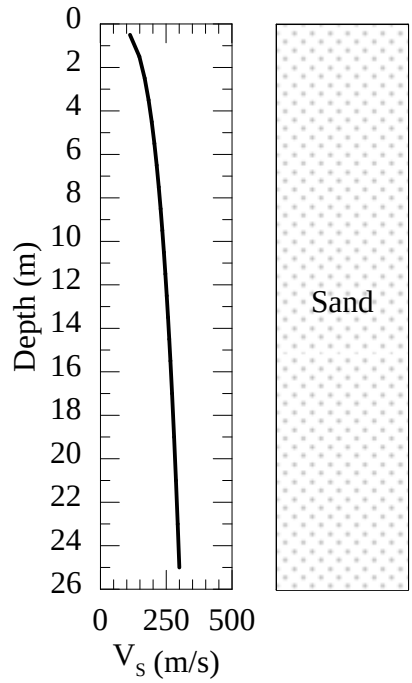

Fig. 3 – Shear wave velocity profile and stratigraphy used in the numerical simulations.

The 1D modeling of site response completed by Hashash et al. [2] illustrated the predictive ability of the Darendeli [5] model when used to define the dynamic properties of dry Nevada sand. To remain consistent with the 1D simulations, strength-corrected versions of the Darendeli [5] modulus reduction curves were used in the 3D analyses. All strength corrections were made using the General Quadratic/Hyperbolic model (Groholski et al. [6]) implemented in the site response software DEEPSOIL (Hashash et al. [7]) and a friction angle of 33 degrees. The modulus reduction curves at selected depths in the model are shown in Fig. 4, which illustrate the pressure dependence of the Darendeli [5] model. In LS-DYNA, the hysteretic soil model (MAT_079) was used to model the cyclic soil behavior. The hysteretic soil model requires specification of soil density (ρ), bulk modulus (K), and a backbone curve in the form of shear stress (τ) versus shear strain (γ). The hysteretic soil model in LS-DYNA implements Masing-type hysteretic behavior. Masing-type hysteretic behavior is a function only of the backbone curve and therefore no additional damping parameters are required for the hysteretic soil model.

The viscous damping was applied using the frequency-independent damping formulation implemented in LS-DYNA with bounding frequencies of 0.1 Hz and 30 Hz. The level of viscous damping applied to each soil layer was equal to D_{min} from the Darendeli [5] correlation. All soils were modeled using constant-stress eight-node solid elements. The specification of the selected soil properties was verified by comparing the results from a 3D shear beam model in LS-DYNA to the 1D models analyzed using DEEPSOIL.

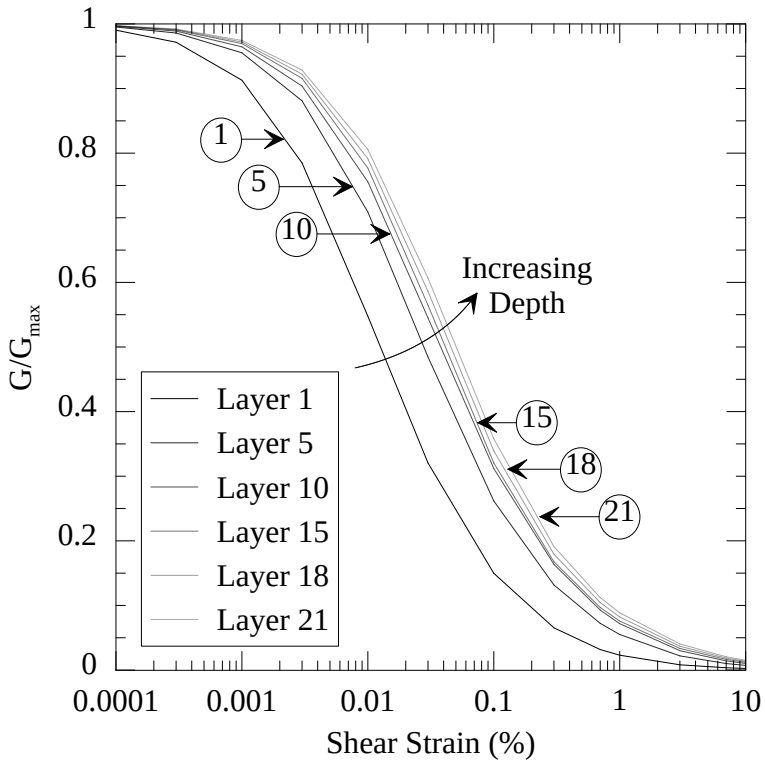

Fig. 4 – Selected modulus reduction curves used in the numerical simulations.

4.2 Structural Properties

The superstructures were constructed using A500 high strength steel. The foundations, excavation walls, and tunnel were constructed using 6061-T6 aluminum. The structural properties used in the numerical models are consistent with the properties reported by Dashti et al. [1] and Gillis [8] which describe previous work completed in this research program. All structural parts were modeled using the elastic material (MAT_001) in LS-DYNA. The superstructure parts were modeled using beam elements. Superstructure members were modeled using the Belytschko-Schwer [9] beam formulation. The column and beam fuses of the centrifuge model were simulated numerically using the same material properties with a reduced section. The foundation elements, excavation walls, and tunnel lining were modeled using four-node shells.

Viscous damping was applied using the frequency-independent damping formulation implemented in LS-DYNA with bounding frequencies of 0.1 Hz and 30 Hz. The modal response and damping characteristics of the model structures were determined by an impulse test. The structural models had damping ratios ranging from approximately 1.25 to 1.5 %. However, the numerical models were found to exhibit better agreement with the centrifuge recordings with a damping ratio of 1 %.

4.3 Combined Soil-Structure Models

The combined soil-structure model for T-Midrise is shown in Fig. 5. The combined models have dimensions (in prototype scale) of approximately 52 m x 107 m and are composed of 25,000 to 30,000 elements. To model the behavior of the FSB centrifuge container, equal degree-of-freedom boundary conditions were applied in the horizontal plane at each depth along the boundaries of the model. At the base of the model, nodes were fixed in the vertical direction while base shaking was applied as prescribed horizontal accelerations, modeling a rigid base. Base horizontal shaking was applied parallel to the long axis of the model.

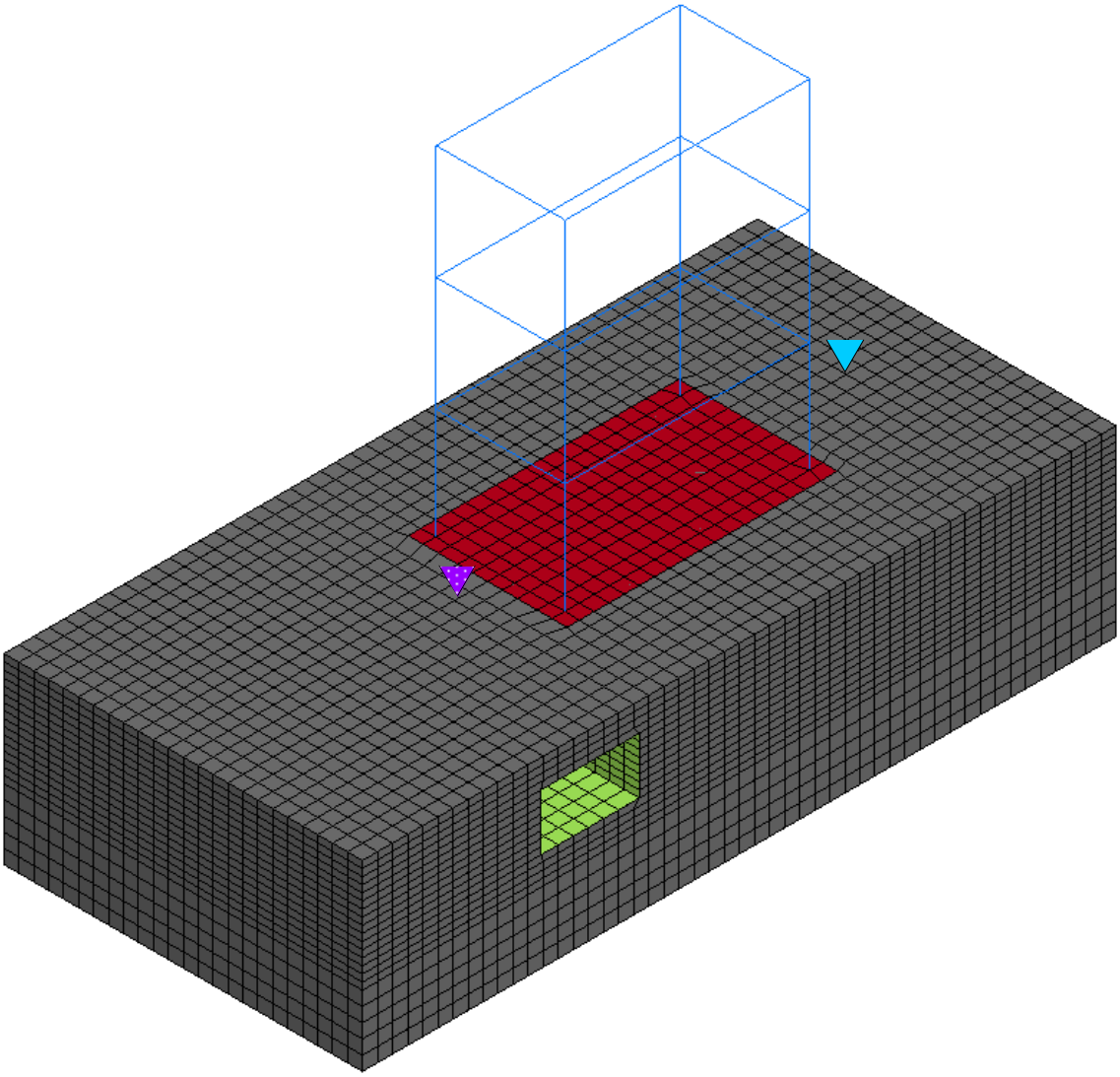

Fig. 5 – Three-dimensional LS-DYNA model of T-Midrise.

5. Comparison of Numerical and Centrifuge Results

Selected results from the numerical models are shown in Fig. 6 through Fig. 8. Fig. 6 compares the peak ground acceleration (PGA) profile, acceleration time histories, and acceleration response spectra (5% damped) for the far-field array of the T-Midrise numerical model (as shown in Fig. 5) to the centrifuge recordings when subjected to the Joshua Tree motion. The plots show that the numerical model accurately predicts the PGA of the far-field array throughout the depth of the profile. The time histories and response spectra also show very good agreement with the centrifuge recordings. Similar results are shown in Fig. 7 for the accelerometer array on the tunnel wall (as shown in Fig. 5). Again, very good agreement is seen in PGA on the wall as well as acceleration time histories and response spectra, indicating a successful prediction of soil-structure interaction effects on accelerations recorded at different locations with respect to the buried structure.

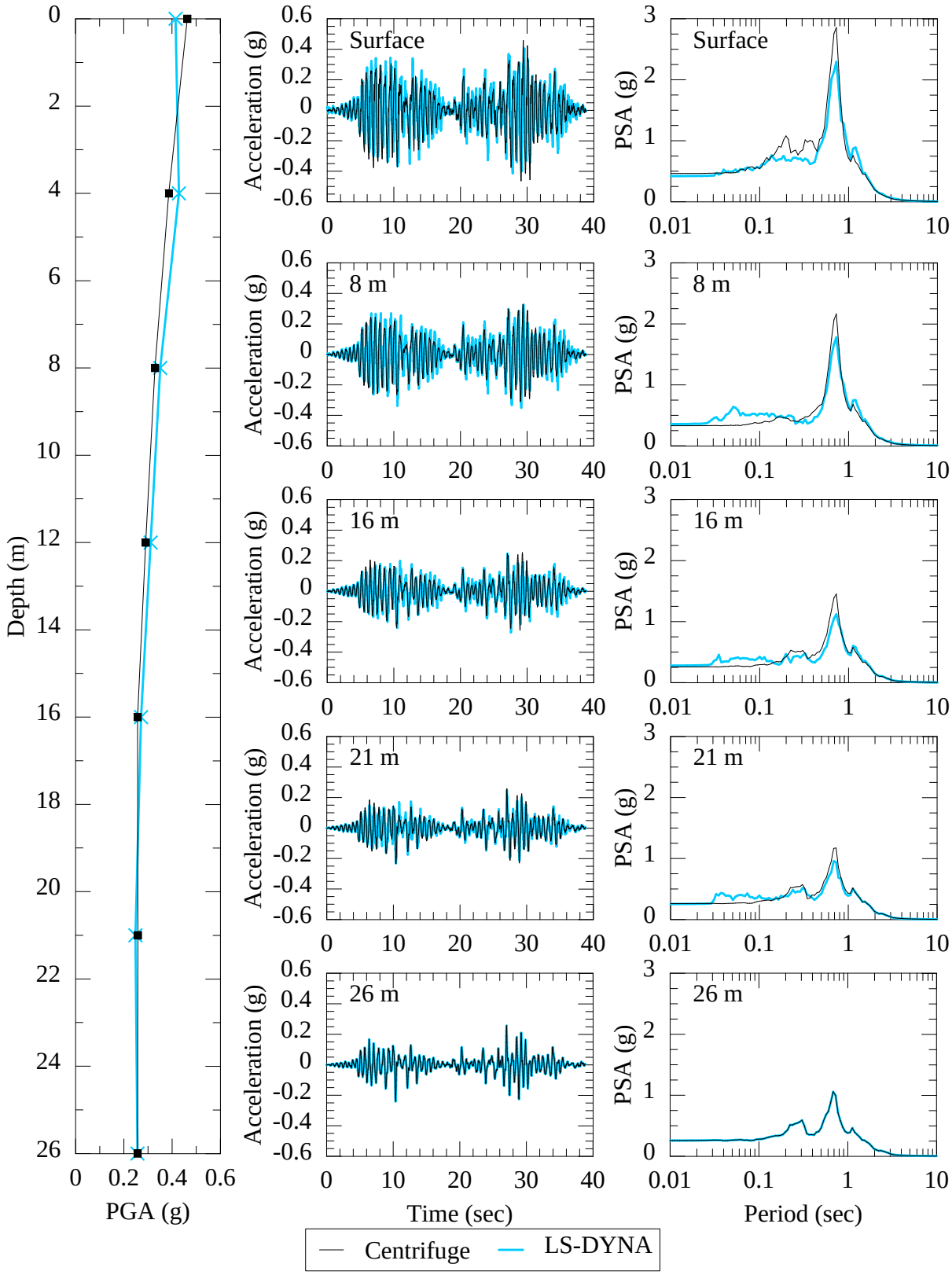

Fig. 6 – Numerical and experimental comparison of far-field accelerometer array from T-Midrise subjected to the Joshua Tree input motion.

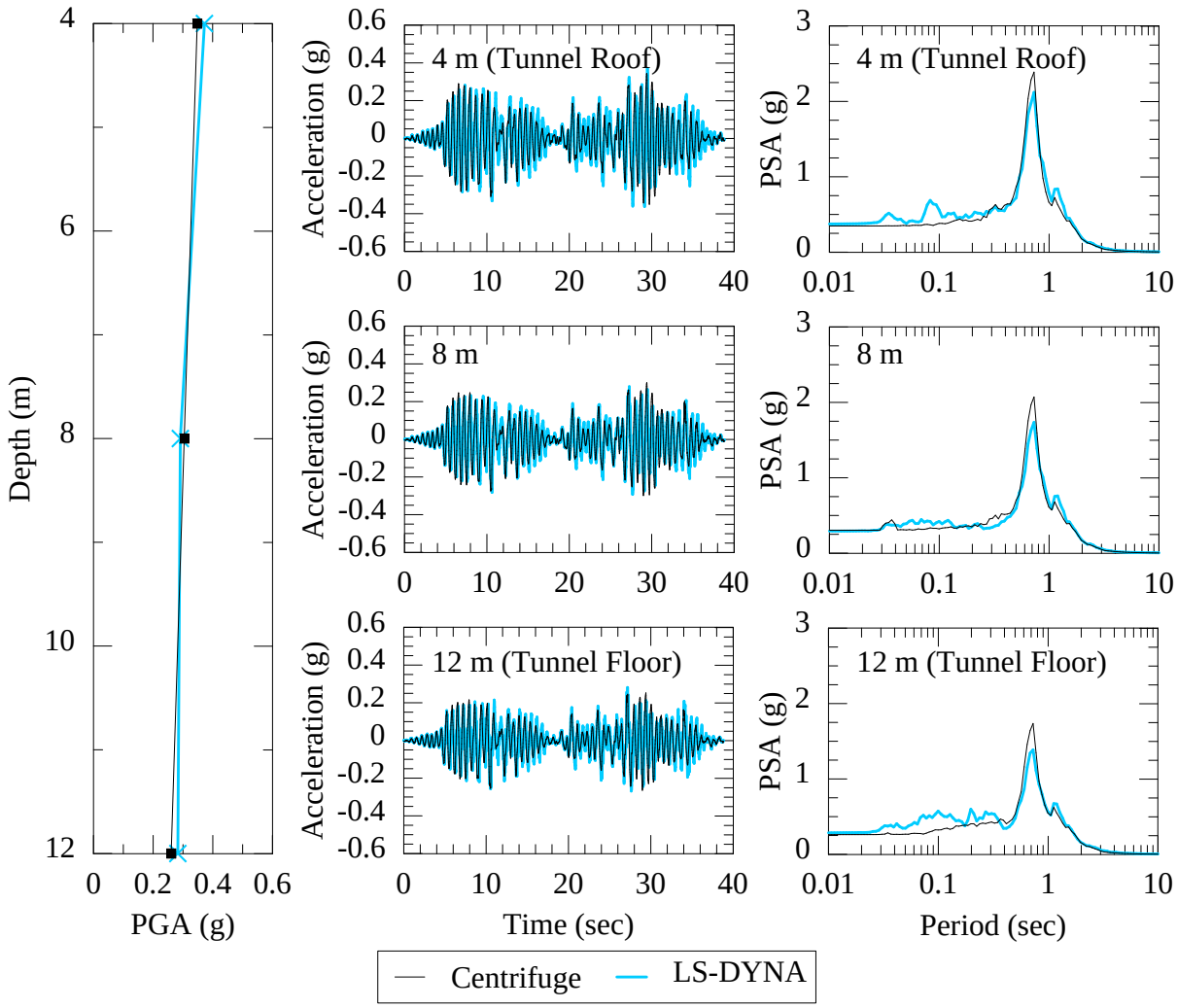

Fig. 7 – Numerical and experimental comparison of tunnel wall accelerometer array from T-Midrise subjected to the Joshua Tree motion.

Displacements were calculated from the centrifuge recordings by double-integrating the accelerometer recordings. These displacements were compared to the displacements calculated in the numerical model in Fig. 8 and are shown relative to the base of the tunnel wall. Negative displacements represent movement towards the building foundation and positive displacements represent movement into the tunnel (away from the building). The profiles shown in Fig. 8a are the maximum relative horizontal displacements in both directions. There are small variations in the profile at each depth, however the numerical model captures the overall shape and magnitude of relative displacement at the top of the wall.

Earth pressures acting on the tunnel walls were measured in the centrifuge using tactile pressure pad sensors. The sensors were positioned to allow measurement of the pressures acting over the full height of the tunnel (a length of 8 m at prototype scale). Fig. 8b compares the earth pressure profiles under static (pre-shaking) conditions and at the time of maximum thrust acting on the tunnel wall closest to the foundation of the midrise structure. The profiles of dynamic earth pressure increment (the difference between the pressure at time of maximum thrust and the pressure under static conditions) are shown in Fig. 8c. The centrifuge measurements and numerical model exhibit good agreement under static conditions and are similar (but slightly larger) in magnitude to the theoretical at-rest earth pressures. The slight increase in earth pressures near the bottom of the tunnel result from the influence of the building load in close proximity to the tunnel. The dynamic response of the model is in good agreement over much of the tunnel height, with the largest differences between the measured and predicted responses occurring between 4 m and 8 m depth. Some variation is expected as the

prediction of earth pressures is highly-sensitive to the modeling of the soil-structure interface. In the models presented, the interface was considered tied (the interface nodes of the soil and tunnel elements are shared and have no relative displacements). While this interface is not a perfect analogue for the centrifuge model, it demonstrates that even simplified interface models can adequately capture the system-level response of complex underground systems.

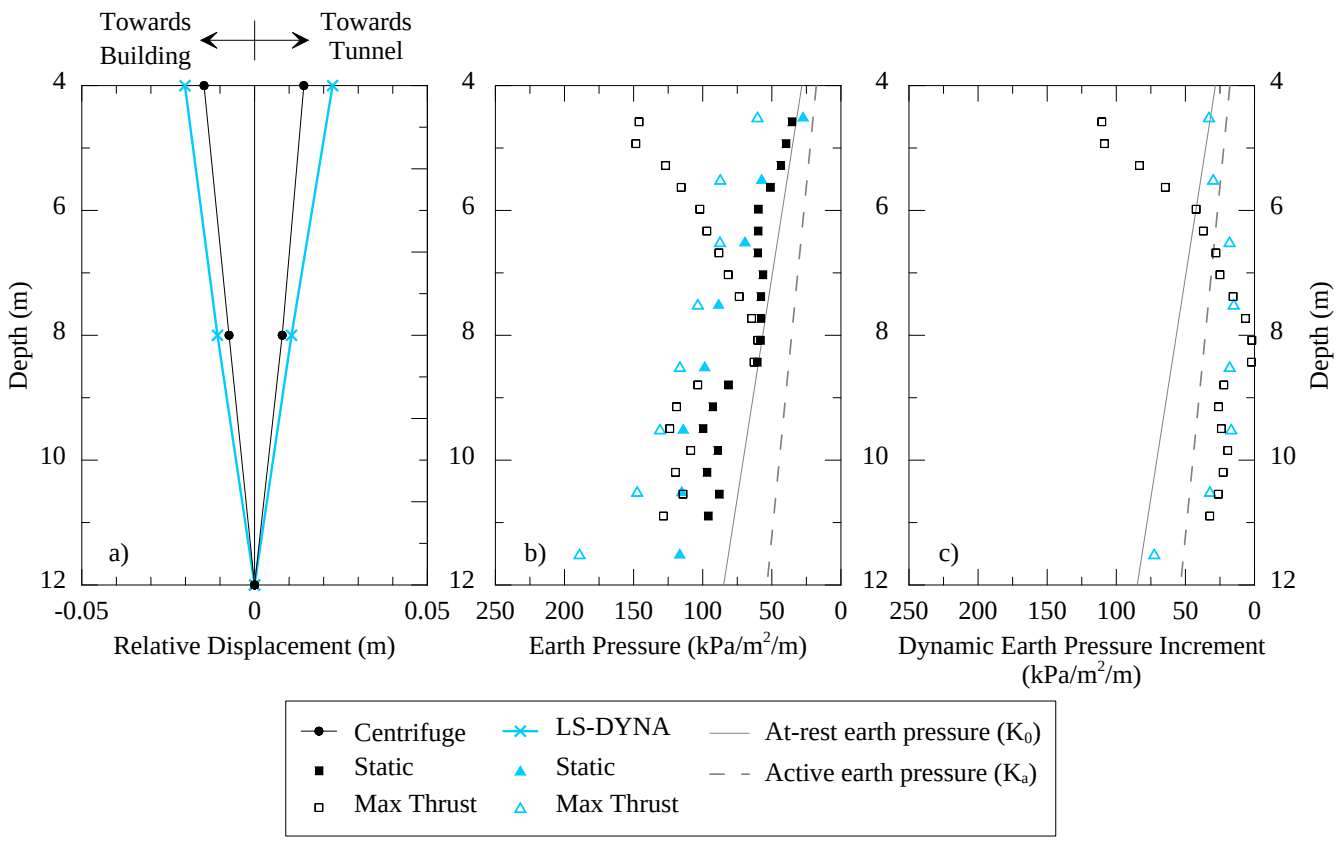

Fig. 8 – Numerical and experimental comparison of tunnel wall maximum relative horizontal displacements and earth pressures from T-Midrise subjected to the Joshua Tree motion.

6. Conclusions

This paper presents the results of numerical simulations completed to evaluate the predictive capability of 3D numerical models relative to the behavior observed in centrifuge tests. Soil and structural material properties were calibrated in isolation and then evaluated in combined soil-structure models. The presented comparisons illustrate that numerical models can adequately predict accelerations in the far-field and on the walls of the tunnel. The measured and predicted wall displacements exhibited similar trends with depth and were in agreement in total relative horizontal displacements. Comparisons of earth pressures show that the measured and predicted behavior are in good agreement with the theoretical earth pressure profile under static conditions. The measured and predicted earth pressure profiles under dynamic conditions show some variation at the top of the tunnel, but exhibit similar trends at depth. The observed differences indicate that the system-level response can be adequately modeled using simplified models with well-defined input parameters. However, additional comparisons are required to adequately define the predictive capabilities and limitations of numerical modeling of earth pressures under dynamic soil-structure interaction.

7. Acknowledgements

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