2-D Seismic Soil-Structure Interaction Study
Transbay Transit Center
San Francisco, California

J.A. Fernandez, P. Singh & S. Vahdani
Fugro Consultants Inc., California, USA

S.A. Ashrafi, G. Ballantyne & J. Abruzzo
Thornton Tomasetti

SUMMARY:
The Transbay Transit Center (TTC) will be located in downtown San Francisco, California, and will serve 11 transportation systems including the future High Speed Rail. The proposed structure is 1,500 feet long, and consists of 6 stories, including below-grade trainbox and 5.4 acre rooftop park. Series of two-dimensional seismic soil-structure interaction (SSI) analyses were performed, including fully-coupled direct solution approach as well as substructuring approach. "Scattered" motions, soil springs and dashpots were developed at different locations along the structure. Results of fully-coupled solution were used to validate substructuring approach. Results showed that the traditional approach of directly applying "free field" ground motions to the base of the structure do not capture kinematic and inertial effects for large, buried and flexible structures. Analyses showed adjacent structures in urban setting can have significant impact on structural response. Also, response of buoyant structures is considerably different than that of a typical structure.

Keywords: soil-structure interaction, substructuring, site response, SASSI

1. INTRODUCTION

The Transbay Transit Center (TTC) will be located in downtown San Francisco, California (Fig. 1), and will serve 11 transportation systems including the future California High Speed Rail. The proposed structure is approximately 1,500 feet long, with a 300-foot extension planned at a later stage. The TTC consists of 6 stories, including a below-grade 2-level trainbox and a 5.4 acre rooftop park. The heavy rooftop park causes that response of the structure predominantly in the first mode.

The configuration and geometry of the TTC structure, the subsurface conditions along it, the presence of several highrise structures in the immediate vicinity of the TTC, and buoyancy of the structure contribute to the complexity of the seismic soil-structure interaction (SSI) effects for the TTC (Fugro, 2012). More details on the TTC structure, the soil-structure interaction (SSI) challenges, and the general analysis methodology are presented in Ashrafi et al. (2012).

2. SOIL-STRUCTURE INTERACTION CONSIDERATIONS

2.1. Structure – Soil – Structure Interaction Effects

The TTC structure is adjacent to major structures including pile-supported 60-story-high 301 Mission St. building and 199 Fremont St. building, both within 5 feet of TTC trainbox. Additionally, there are several other 10 to 30 story buildings located around the proposed TTC structure (see Fig. 1). Lastly, a buttress is planned to be constructed adjacent to the 301 Mission St. highrise tower to provide support to that structure during the construction of the TTC. The presence of the highrises and the buttress can potentially affect the dynamic response of the TTC. Therefore, a key aspect analyzed was structure-soil-structure interaction (SSSI), wherein the presence of adjacent structures and the buttress in front of 301 Mission St. tower were explicitly modeled.

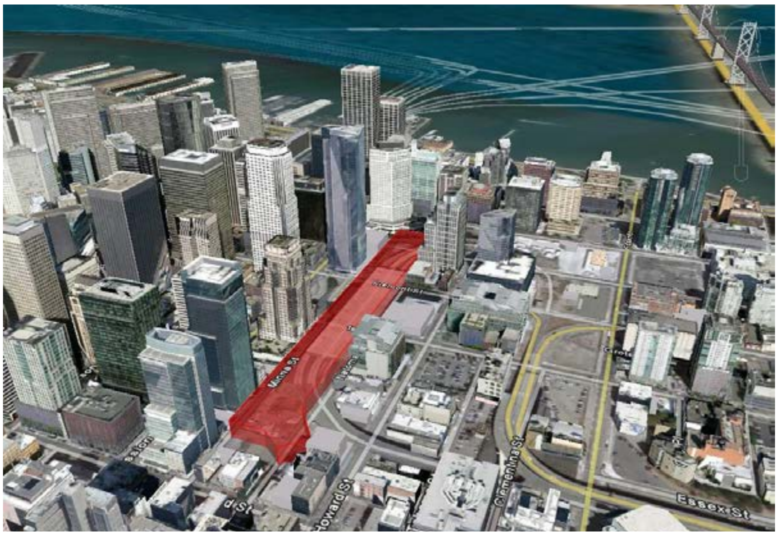

Figure 1. TTC Location and Adjacent Structures

2.2. Variation in Subsurface Conditions

In general, subsurface conditions are similar deeper below surface, but the shallower deposits generally become weaker / softer from west to east. Particularly, the structure crosses the historic San Francisco shoreline, and the subsurface conditions east of the shoreline include thicker fill and Young Bay Mud deposits as compared to the conditions west of the historic shoreline. The effects of variable soil conditions were incorporated in the SSI analyses. However, the structure is relatively rigid in its longitudinal direction and tends to average the ground motions along its length. Therefore, in evaluating the varying subsurface conditions, the averaging effect of the structure on the ground motions was incorporated.

2.3. Structure and Soil Column Periods

The TTC development includes an urban park at the roof level. Other floors of the TTC superstructure are relatively light. As a result, the majority of the mass participation of the superstructure is in the first vibration mode. The fundamental period of the structure, particularly in the transverse direction, is on the order of 1.5 to 1.6 seconds. The fundamental period of the soil column above the bedrock is approximately 1.5 seconds, and that closely matches the first mode period of the TTC structure. The close proximity of the predominant structural period and site fundamental period results in significant amplification of ground motion within the structure. The amplification of ground motions in that period range was observed during equivalent linear evaluation of the dynamic response of the structure. Detailed structural analyses considered nonlinear structural response. The sensitivity of the SSI results to this proximity of periods was evaluated by conducting analyses for average as well as stiffer and softer soil properties.

2.4 Variation in Structural Configuration

Most of the 1,500-foot length of the TTC is generally similar in structural properties. However, there are some areas with appreciable variation in structural properties that were addressed as part of the SSI analyses within practical limitations of 2-D evaluations. The structure has an end wall at the west end, but at the east end, the structure will not have a rigid wall, but a temporary cap, which will eventually be removed to construct the 300 feet long extension on the east side. The extension will be separated from the main TTC structure using a seismic joint; therefore the main TTC structure will not have an end wall on the east end. Further, the west side of the structure will have a throat opening towards the south for the train entrance. The throat will connect to a tunnel through a seismic joint. The presence of end wall and throat near the west end can cause significantly higher racking stiffness near the west end of the TTC compared to the rest of the TTC. The effect of increased stiffness near the west end was incorporated in the SSI analyses. The effect of the end wall stiffness is limited to the throat area of the trainbox and drops off further from the west end.

2.5 Effects of Embedment on Free-Field Ground Motions

Due to the kinematic SSI and radiation damping effects, ground motions adjacent to the proposed TTC structure are different from the free-field ground motions. These effects were incorporated by conducting a set of SSI analyses and developing ground motions that incorporate kinematic SSI effects, or "scattered" ground motions. Corresponding springs and dashpots were also developed.

2.6 Buoyancy and Tiedowns

Due to the depth of excavation for the trainbox and shallow groundwater level, the TTC will be buoyant. The buoyancy forces will be countered using tiedowns. Due to buoyancy, there will be very little to no contact force along the base of the structure, therefore very little to no friction is anticipated along the base of the trainbox. Further, due to tiedowns and buoyancy, the vertical movement of the base of the trainbox is restricted. These effects were incorporated in the SSI analyses.

3. IDEALIZED SOIL MODELS FOR SSI ANALYSES

The soil conditions along the TTC include roughly 15 to 20 feet of very loose to medium dense fill, up to 15 feet of medium dense dune sand, 20 to over 75 feet of very soft to soft Bay Mud and medium dense to dense Marine Sand layers, 0 to 45 feet of dense to very dense Colma Sand, 100 to 145 feet of stiff to very stiff Old Bay Mud, underlain by bedrock. The depth of the bedrock ranges from 190 to 230 feet. The thickness of the Young Bay Mud and Marine Sand deposits increases substantially east of the historic San Francisco shoreline.

Five idealized soil profiles were developed to account for the variability in the subsurface conditions along the longitudinal direction of the TTC (AMEC, 2010). Ground motions were developed (AMEC, 2010) at the bedrock level for three earthquake scenarios, Ground Shaking Level 1 (GSL-1), GSL-2 and GSL-3. GSL-1 is defined as a ground motion with a return period of 50 years. GSL-2 is defined as the larger of the ground motion with a return period of 975 years and the 84th percentile ground motion calculated from deterministic seismic hazard analyses. GSL-3 is defined as the ground motion with a return period of 2,475 years. These ground motions were propagated through each of the five idealized soil profiles using equivalent linear and non-linear site response analyses. Seven sets of time histories for each ground motion level were evaluated at each profile location. Therefore, a total of 140 site response analyses were conducted for each level of shaking. The results of these site response analyses were used as input to the SSI analyses presented herein.

The TTC trainbox is a relatively rigid structure in the longitudinal direction and is expected to integrate the response to ground motions along the trainbox rather than responding to an individual soil profile. Since 3-D SSI analyses were not performed, an averaging scheme of the soil properties was developed to incorporate the effect of structural stiffness in 2-D models. As part of this approach, strain-compatible dynamic soil properties (strain-compatible shear wave velocity and damping values) from the site response analyses from any three adjacent soil profiles were averaged to obtain idealized strain-compatible profile of a soil zone. A total of three such soil zones were developed, with each zone consisting of three soil profiles. Zone 1 included soil profiles 1, 2 and 3; Zone 2 included soil profiles 2, 3 and 4; and Zone 3 consisted of soil profiles 3, 4 and 5.

For each soil zone and ground motion level, there are a total of 84 strain-compatible soil properties profiles (3 soil profiles, 7 ground motions, 2 components, 2 site response methods). The idealized mean profile for each zone was developed as the average of those 84 strain-compatible profiles. The variation in the profiles was considered by developing upper and lower estimates defined as the mean ± one standard deviation profiles. As an example, the idealized strain-compatible profiles of shear wave velocity for the three soil zones and for the GSL-2 ground motions are presented on Fig. 2.

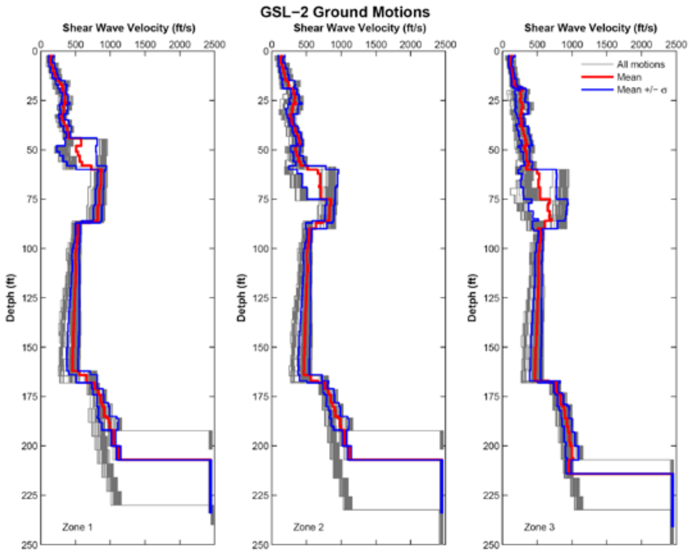

Figure 2. Idealized Strain-Compatible Profiles of Shear Wave Velocity For GSL-2

4. SOIL-STRUCTURE INTERACTION ANALYSES

The SSI analyses were performed with the computer program SASSI 2000 (Lysmer et al., 1999a; 1999b). SASSI (System for Analysis of Soil-Structure Interaction) is a computer program used to solve a wide range of dynamic soil-structure interaction problems in two or three dimensions. SASSI solutions have been validated against several published analytical or closed form solutions and against other computer programs (Lysmer et al., 1999a). Additionally, SASSI has been applied to many engineering projects, including power plants, offshore structures, underground structures, etc.

4.1 SASSI Models

Two dimensional SASSI models were developed to evaluate the SSI effects of the Transbay Transit Center (TTC) in the transverse and longitudinal direction. A brief description of the cross-sections evaluated is given below and Fig. 3 shows the location of these models.

- Grid Line 6 – GL6 was evaluated to study: 1) the effect of west end wall of the trainbox, and 2) the effect of the varying structural properties due to the western throat for the incoming train lines. GL6 is located within Soil Zone 1.

- Grid Line 15 – GL15 represents the typical structural cross-section for the western superstructure. This cross-section is located approximately in the middle of Soil Zone 2.

- Grid Line 21 – GL21 represents the typical superstructure for the middle building. Since GL21 is also located within Soil Zone 2, the idealized soil profile is the same as GL15. However, the structural configuration of GL21 is different from that of GL15.

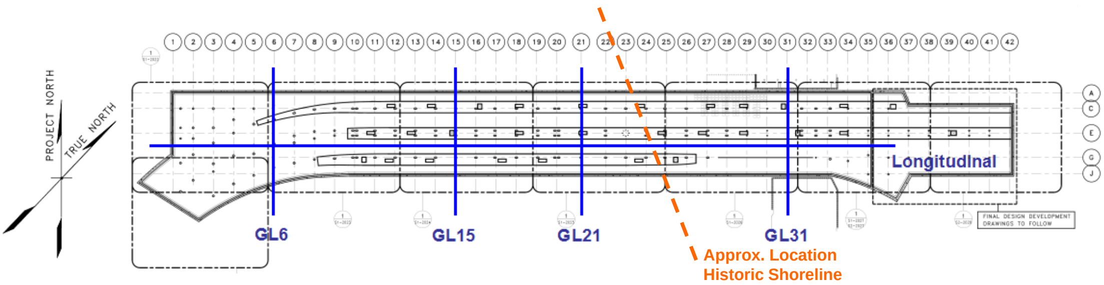

Figure 3. Locations of the Sections Analyzed

- Grid Line 31 – GL31 is located close to the east end of the first phase of the TTC construction. The area around GL31 involves several considerations: 1) the eastern side of the TTC, where GL31 is located, lies east of the historic San Francisco coastline, therefore the subsurface conditions are softer than those at locations to the west (e.g. GL6, GL15 and GL21); 2) the adjacent 301 Mission St. and 199 Fremont St. buildings are located very close to the TTC structure in the vicinity of the GL31 cross-section; and 3) the proposed buttress underneath the TTC and adjacent to the 301 Mission St. building is located at this cross-section. The SSI analyses for GL31 included modeling of buildings located at 301 Mission and 199 Fremont and the proposed buttress. Soil Zone 3 idealized soil profile was used for the SSI evaluation for GL31.

Figs. 4 and 5 show the SASSI models for GL15 and GL31. Additionally, the following variations to some of these models were also considered in the SSI analyses:

- GL15 model along with a typical 30-story highrise building (approx. 30 feet away from the TTC);

- GL31 cross-section without considering the buildings located at 301 Mission St. and 199 Fremont St., and the proposed buttress; and

- Longitudinal TTC model explicitly modeling the variation of subsurface conditions along the longitudinal direction.

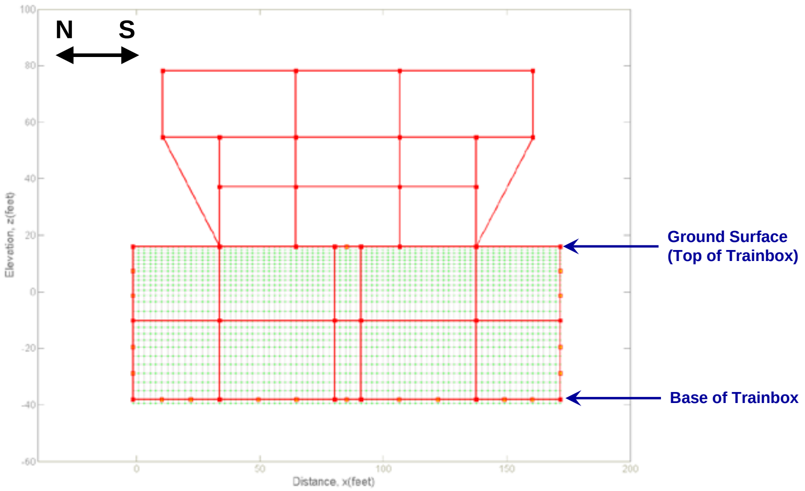

Figure 4. SASSI Model for GL15 Section

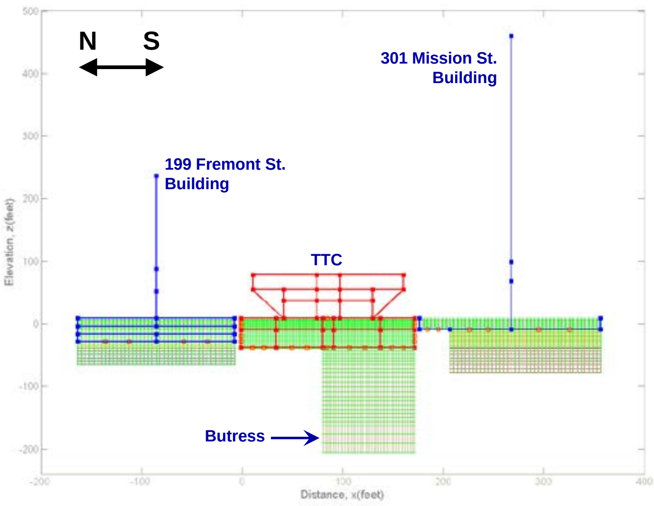

Figure 5. SASSI Model for GL31 Section

4.2 Structural Elements

4.2.1. TTC

The structural elements were modeled as linear elastic beam elements. The trainbox and the superstructure elements were explicitly modeled in the transverse direction. Secant stiffness values were provided for the structural members to reflect the stiffness at the expected deformed shape. To incorporate inertial effects, masses were lumped at each structural node for each model.

4.2.2. Adjacent Structures

The basements of adjacent structures were modeled as beam elements, similar to the TTC trainbox. The superstructures for adjacent structures were modeled as “stick” models with lumped masses to capture the first three vibration modes. The pile foundations of adjacent buildings were modeled as solid element blocks with equivalent shear modulus and material damping. The properties of the equivalent solid element blocks were estimated such that the lateral response was similar to the pile-soil matrix by calibrating the response through 3-D PLAXIS models.

4.3 Buoyancy and Tiedowns

Since the TTC structure is buoyant with very little to no contact force along the base of the structure, very little to negligible friction is anticipated along the TTC base. To model this low friction contact surface, a layer of solid elements was introduced along the base of the TTC trainbox. This layer was assigned very soft properties with low shear wave velocities and a damping ratio of 0.05. This layer is referred to as soft “soil” layer herein. To evaluate the effect of friction along the base, parametric studies included a full-friction case, where no soft soil layer was modeled and the native soil was considered to be in direct contact to the TTC base, and a no-friction case.

4.4 Analysis Approach

The SSI evaluation of the TTC comprised of the following three steps:

4.4.1. Direct Solution

Fully coupled, single step evaluations were conducted for each 2-D cross-section using the SASSI models that included the soil above the bedrock as well as the TTC structure with mass. Kinematic as well as inertial SSI effects were inherently evaluated. The masses were lumped at each structural node. These analyses provide a direct response of the equivalent linear TTC structure. An advantage of the Direct Solution approach is that the results can be used to provide validation for the substructuring approach, discussed below. A limitation of this approach is that only a relatively simple representation of the structure can be included in the SASSI model, and the nonlinearities in the structure are not incorporated.

4.4.2. Substructuring Approach

The substructuring approach consists of two steps: 1) evaluation of the kinematic SSI effects by conducting SASSI analyses using a massless TTC structure, and 2) evaluation of the inertial effects using a structural model supported on springs and dashpots and driven by ground motions developed during Step 1. Kinematic SSI evaluations were conducted using a SASSI model with massless TTC to develop “scattered motions” that are affected by the presence of the TTC. Scattered motions were developed for each peripheral node on the trainbox. Additionally, springs and dashpots were also developed for corresponding locations of the scattered motions. The springs and dashpots were used in a non-linear Perform 3D model. The scattered motions were applied at the far end of the springs and dashpots and the response of the structure, including inertial effects, was analyzed in Perform 3D.

4.4.3. Nonlinear Structural Evaluation

Once the substructuring approach using a linear Perform 3D model was validated against the direct solution results, detailed structural analyses were conducted using nonlinear Perform 3D models for the final structural design.

4.5 Substructuring Validation

Fig. 6 shows a comparison of the substructuring approach results from Perform 3D linear model with the direct solution results from SASSI. As shown on the figure, the response of the Perform 3D model using the substructuring approach is very similar to the SASSI direct solution. Fig. 6 also shows that there is significant amplification of the ground motions at the roof level in the period range of approximately 1.4 to 1.6 seconds, which corresponds to the fundamental site period as well as the first vibration mode of the structure.

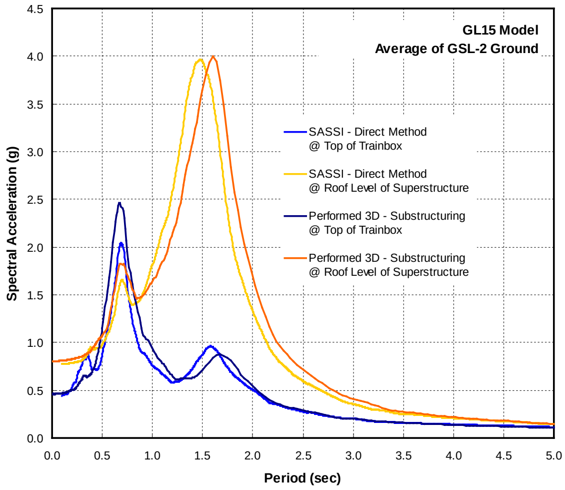

Figure 6. Comparison of Substructuring Approach from Perform 3D and Direct Method From SASSI

5. SASSI ANALYSIS RESULTS

Fig. 7 presents a response spectrum comparison of free-field, scattered, and direct (full solution) motions for GL15 models. The different motions are compared at the base and top (ground level) of the trainbox. As shown on the figure, the free-field motions change from the base of the structure to the ground surface whereas the scattered motions generally integrate the free-field base and ground surface motions. The full solution motions include the inertial effects of the structure and accordingly are considerably different from the free-field motions.

Fig. 8 shows the changes in the spectral acceleration transfer function from bedrock to top of trainbox (ground surface) from free-field to kinematic to kinematic plus inertial response. The free-field response shows the site period to be approx. 1.4 to 1.5 seconds. The kinematic scattered motion largely follows the free field. However, once the mass of the trainbox is introduced (but not the superstructure), the structure has a prominent translational response (at a period of 0.7 seconds) due to lack of friction along the base. Once the mass of the superstructure is introduced, there is a predominant response at the first mode of the structure, which is relatively close to the site period of 1.5 seconds for the simplified equivalent linear structure considered in this evaluation.

5.1 Parametric Studies

5.1.1. Effect of Varying Soil Conditions

Direct method analyses were also performed for the mean ± one standard deviation of the strain-compatible soil properties profiles. Fig. 9 compares acceleration response spectra at the top of the trainbox for the mean and the mean ± one standard deviation of the strain-compatible profiles for the GL31 model. The spectral response generally shifts to longer periods for the softer profiles. At the period predominant structural response, approximately 1.6 seconds, the ground motions due to the mean strain-compatible profile are higher than the response from the upper and lower profile cases.

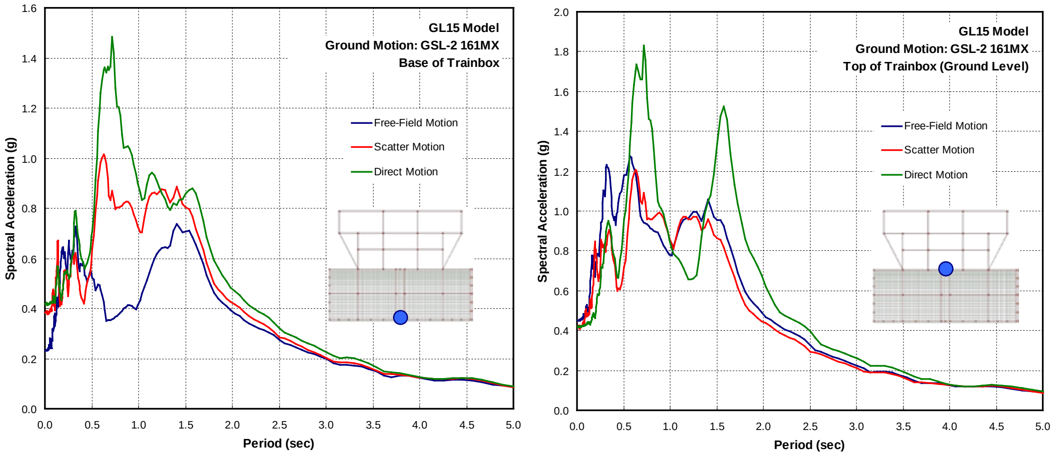

Figure 7. Response Spectra of Free-Field, Scatter, and Direct Motions for GSL-2 GL15 Model

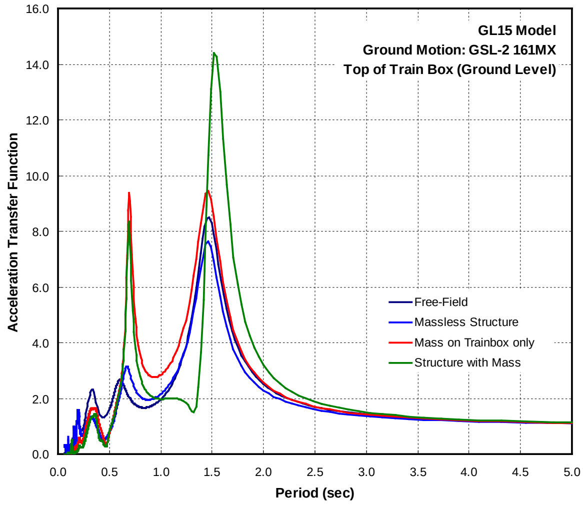

Figure 8. Acceleration Transfer Functions (Bedrock to Ground Surface) for GL15 Model

5.1.2. Effect of Varying Soil Profile in Longitudinal Direction

Parametric analyses were performed by (1) explicitly modeling the variation of subsurface conditions along the longitudinal direction, and (2) assuming a uniformly layered site with average soil parameters of Soil Zone 2. The responses were very similar for both soil cases, highlighting the averaging effect of the relatively rigid TTC structure in the longitudinal direction.

5.1.3. Effect of Adjacent Buildings

Fig. 10 shows the comparison of the acceleration response spectra at the top of the trainbox for the GL31 model with and without adjacent structures (i.e. 301 Mission St. and 199 Fremont St. buildings and proposed buttress). This figure shows that the presence of the adjacent buildings and buttress stiffens the response of the TTC, increasing the ground motion amplitude at low periods and decreasing the amplitude at longer periods. For structural design purposes, the case with TTC only (with no adjacent structures) is more critical, because it causes higher ground motion amplitudes in the period range of interest for the structure (i.e. 1.6 seconds). Furthermore, the impact of the adjacent structures on the spectral acceleration is more than the impact of varying soil conditions along 1,500 feet of the TTC even though the soil conditions vary significantly (Figs. 8 and 10). For the trainbox, the structure-soil-structure interaction results in increased seismic pressures, but those are offset by reduced static pressures since the soil mass in those areas is replaced by structures. For the case of a typical 30-story highrise structures at a distance of 30 feet or more, the SSI effect on the TTC is very small and can be ignored for practical purposes.

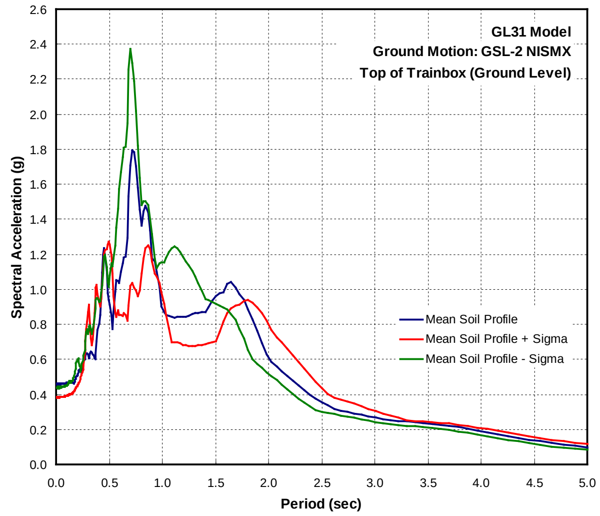

Figure 9. Effect Of Soil Variability on Acceleration Response Spectra - GL31 Model

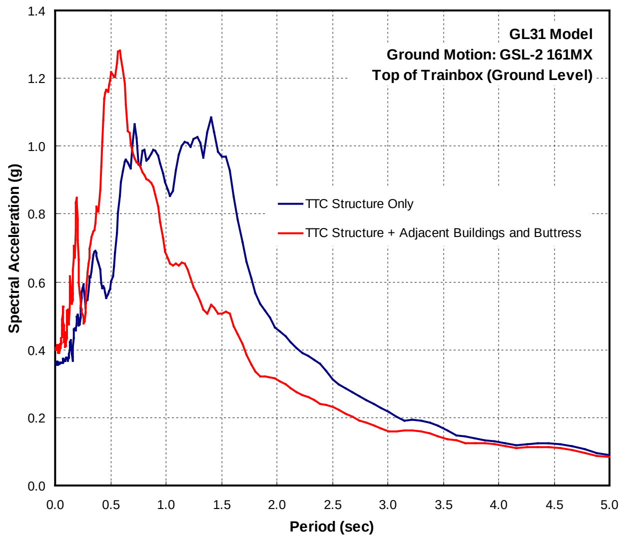

Figure 10. Effect of Adjacent Buildings and Buttress on GL31 Model

5.1.4. Effect of Buoyancy and Tiedowns

The little to no friction along the TTC base due to buoyancy causes increased acceleration compared to the case of full friction along the base (Fig. 11). Further, since there is no contact along the base, the seismic loads are imparted and resisted purely along the sides of the TTC. The seismic pressure increment along the trainbox walls is higher compared to the pressure obtained from the Mononobe-Okabe (Mononobe, 1924; Okabe, 1924) solution. While the Mononobe-Okabe solution is for active walls, it was considered a relevant comparison given the relatively large lateral movement due to lack of base friction. For GSL-2, GL31 location the average seismic pressure increment was 31H psf uniform pressure, where H is the height of the trainbox. This is considerably higher than values obtained from Mononobe-Okabe (Mononobe, 1924; Okabe, 1924), likely because of the lack of friction along the base of TTC, causing the entire lateral load to be resisted along the trainbox walls.

6. CONCLUSIONS

Results showed that the traditional approach of directly applying free-field ground motions to the base of the structure do not capture kinematic and inertial effects for large, buried and flexible structures. Additionally, analyses showed that adjacent structures in urban setting can have significant impact on structural response to earthquake loading. Also, this study showed that the response of buoyant structures is considerably different than that of a typical structure.

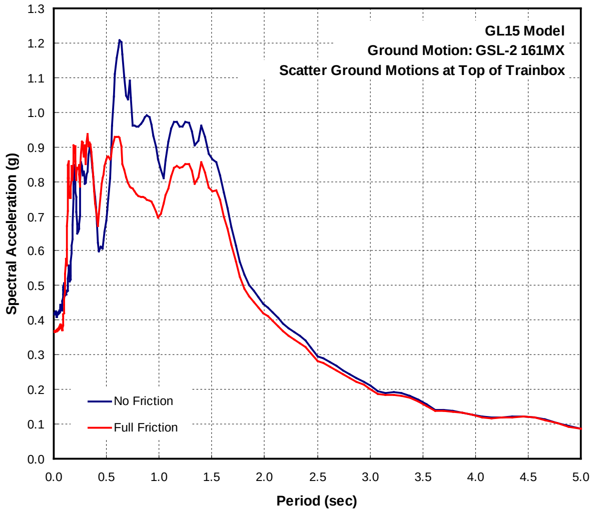

Figure 11. Effect of Reduced Friction along the TTC Base

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