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SOIL-STRUCTURE INTERACTION ANALYSIS FOR BURIED STRUCTURES IN SOFT, SLOPING SOILS - BART SAN FRANCISCO TRANSITION STRUCTURE

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ABSTRACT :

A case history is presented for soil-structure interaction (SSI) analyses of the San Francisco Transition Structure (SFTS), a massive rigid structure which is part of the BART Transbay Tube (TBT) system in California. A methodology was developed to study the complex SSI problem for the SFTS. This methodology may be applicable for relatively large, buried structures in soft soils and sloping ground susceptible to movement during the design earthquake. The SSI studies included 3D SASSI analyses to develop far-field impedances due to dynamic vibrations, and FLAC 3D analyses to develop near-field nonlinear springs. A methodology was developed to use the near-field spring and far-field impedances obtained from SSI analyses in a global model that included the SFTS as well as the TBT that connects to it. Displacement time histories to drive the global model were also developed as part of this study. Scatter motions were obtained at the base of the SFTS as well as along the TBT. An approach of transitioning of the scatter motions to the free-field motions along the TBT was developed. Permanent drifts due to movement of the slope around the SFTS were incorporated in the development of ground motions.

KEYWORDS: soil-structure interaction, impedance, springs, ground motion, FLAC, SASSI

1. INTRODUCTION

The San Francisco Transition Structure (SFTS) is a part of the Bay Area Rapid Transit (BART) light rail system in a high seismicity region of northern California. The SFTS is a rectangular caisson with over 70 feet of it buried beneath the floor of San Francisco Bay. The SFTS connects the bored tunnels under the city of San Francisco to the west with the immersed Transbay Tube (TBT) tunnel to the east by means of seismic joints. San Francisco Bay is bordered by two major strike-slip faults – the San Andreas fault to the west and the Hayward fault to the east. Analyses were undertaken to assess the vulnerability of the seismic joint connecting the TBT (to the east) to the SFTS (to the west) during the design earthquake, and to identify the need for a retrofit. The project overview and technical approach for this study are presented in detail by Fugro West, Inc. (2007). A structural global model of the SFTS and TBT structures was developed to study the response of the entire SFTS and TBT system. Sources of displacement demand at the seismic joint are related to 1) shoreline instability (Chen, et al., 2008), and 2) the dynamic response of the SFTS relative to the TBT during the design event. This paper presents the soil-structure interaction (SSI) analyses of the SFTS that were conducted to develop inputs for the SFTS area portion of the global model developed for the project. A parallel paper (Travasarou et al, 2008) provides the inputs for most of the TBT section of the model. Global analyses were performed to assess the combined demand to the seismic joint from all sources. The input to the global analyses associated with the dynamic response of the SFTS consisted of soil spring and damping parameters as well as ground motions in the vicinity of the SFTS.

2. METHODOLOGY

The SFTS is a relatively large and rigid buried structure that is expected to have significant interaction with the soil during the design earthquake. Additionally, the bay floor around the SFTS slopes down towards the east and there is potential for slope movement during the design earthquake. Therefore, the soil-structure interaction study for the SFTS involved the: (1) assessment of the transient dynamic response of the buried structure, and (2) evaluation the impact of the slope movement on the response of the structure and the applicable ground motions for the global analyses. To capture the SSI effects for the SFTS, the surrounding soils were divided into two regions: 1) the near field where secondary nonlinearities were modeled, and 2) the far field where the secondary nonlinearities could be ignored.

Near-field nonlinear load-deflection characteristics of the soil-structure system were developed in the transverse, longitudinal, and vertical directions using a series of finite difference analyses and the 3D FLAC computer code. For developing the springs, the SFTS model was brought to force equilibrium under gravity, and then displaced in all directions to record the reaction forces at each node of the SFTS.

The interaction between the SFTS and the far field soils was modeled following the sub-structuring method developed by Kausel et al. (1975) using the 3D finite element computer code SASSI. Following this method, a node at the center of the SFTS base slab was subjected to harmonic vibration at various frequencies in all six directions (translational and rotational) to obtain a fully coupled, complex, and frequency dependent impedance matrix.

For the global model, the far-field impedance matrix computed at the center of the SFTS base slab was used to calculate frequency independent (constant) stiffness (K), dashpot coefficients (C), and virtual mass (M) at several points along the vertical faces and at the base of the SFTS. This KMC system was connected to the near-field spring from FLAC in series. The other end of the near-field spring was connected to the SFTS. This approach is shown schematically on Figure 1.

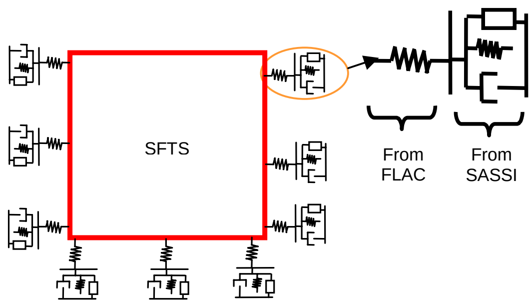


Figure 1. Schematic Showing Soil-Interaction Analysis Approach for the SFTS

Two retrofit options were analyzed for the SFTS: (1) No Slope Retrofit (NSR) option, and (2) Jet Grout (JG) option, where the slope in the vicinity of the SFTS is retrofitted by placing blocks of jet grout downhill from the SFTS.

Ground displacement time histories were applied to the end of the KMC system. Displacement time histories affected by the presence of the buried structure, (i.e., scatter motions), were developed using SASSI, and permanent deformations of the slide plane were obtained using a combination of 3D and 2D FLAC analyses. The slope stability analyses for the SFTS are presented by Chen et al. (2008). Permanent drifts from FLAC were added to the transient scatter motions to obtain the input motions for global analyses. Because the subsurface conditions vary along the TBT and the kinematic interaction effects decrease as the distance from the SFTS increases (i.e., at some distance away from the SFTS, the ground motions are note affected by the presence of the SFTS), an interpolation scheme was developed to transition the motions affected by kinematic SSI to the free-field motions along the TBT. Development of free-field ground motions along the TBT and TBT-free field SSI affects are described by Travasarou et al. (2008).

3. SUBSURFACE CONDITIONS

The soil around the SFTS consisted of soft clay, called Young Bay Mud (YBM) from mudline to a depth of approximately 85 feet. The YBM is underlain by about 30 feet of alluvial dense sand and stiff clay deposits, of the Merritt Posey San Antonio (MPSA) Formation. The MPSA Formation was underlain by approximately 80 feet of Old Bay Mud (OBM), which consists primarily of very stiff marine clays. The OBM was underlain by approximately 50 feet of very dense sands and very stiff to hard clays of the Upper Alameda (UAM) Formation, underlain by bedrock.

Subsurface explorations were conducted in the immediate vicinity of the SFTS and the data were reviewed along with historic data. Based on the available information, the SFTS sits on top of a foundation course consisting of roughly 10 feet of weakly cemented sand and gravel. The YBM extends below the base of the SFTS and foundation course, and the thickness of this layer below the foundation course varied between zero and 8 feet. Available construction records indicate that the YBM was excavated for the construction of the SFTS. On the east side, the excavation connects with the excavation made for construction of the TBT. The SFTS excavation was filled back using YBM, and the backfill therefore has similar engineering properties to the surrounding soils.

4. DEVELOPMENT OF FAR-FIELD IMPEDANCE MATRIX

Dynamic impedances (frequency dependent stiffness and damping) were obtained at the center of the base slab of the SFTS using SASSI. SASSI is a 3D finite element program for solving soil-structure interaction problems for surface as well as embedded structures using the flexible volume method (Lysmer, et. al., 1981). The program is capable of handling externally applied structural loads and seismic forces due to wave propagation to generate fully coupled, complex, and frequency dependent impedance matrices for vibration problems. The analyses assumed a massless SFTS structure since the structure's mass was modeled in the global model. However, additional analyses were conducted which included SFTS mass in order to obtain scatter motions along the TBT in the vicinity of the SFTS. Therefore, a total of four sets of SASSI runs were conducted, consisting of: 1) massless SASSI model for the NSR option to obtain impedances and scatter motions at the base of the SFTS, 2) SASSI model with mass for the NSR option to obtain scatter motions along the TBT, 3) massless SASSI model for the JG option, and 4) SASSI model with mass for the JG option for scatter motion along the TBT.

4.1 Structural Elements and Geometry.

The SFTS structure below the mudline and the opening for the TBT were modeled in SASSI. The 10-foot thick foundation course layer was modeled as part of the structure using brick elements. Because of the symmetry of the SFTS geometry with respect to both the horizontal axes (X and Y) , a quarter model was used for the NSR option to reduce computational time, as shown on Figure 2a. The planes of symmetry (or anti-symmetry) were defined along the XZ and YZ planes. The JG slope retrofit option included installing jet grout blocks near the northeast and southeast corners of the SFTS as shown on Figure 2b. Because of the JG blocks, the SFTS and JG system was not symmetric about the YZ plane. Therefore, a half model was used to analyze the JG case with only the X-axis defined as a plane of symmetry or anti-symmetry.

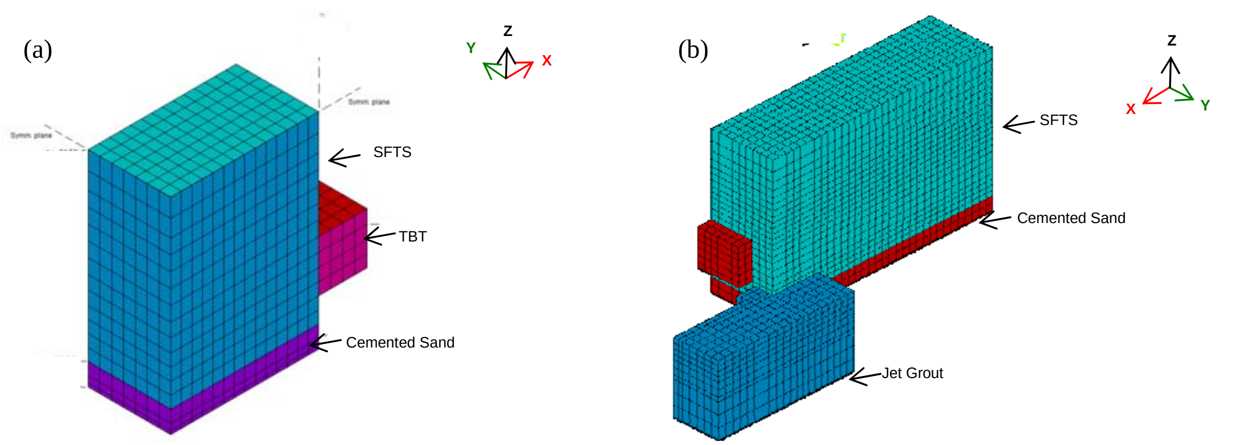


Figure 2. SASSI models for the SFTS: (a) NSR Model, and (b) JG Model

4.2 Soil Properties

The primary soil nonlinearities (due to site response in the free field) were accounted for by performing 1D site response analysis using the computer program SHAKE (Schnabel et al., 1972 modified by Idriss and Sun, 1992) and computing free-field strain-compatible dynamic soil properties. SHAKE runs were conducted for 7 sets of motions for both the San Andreas and the Hayward scenarios to obtain average strain-compatible properties. This average strain-compatible soil profile was used as input to the SASSI models. Figure 3 shows the shear wave velocity and damping profiles from the 14 SHAKE runs and the idealized profile selected as SASSI input profile.

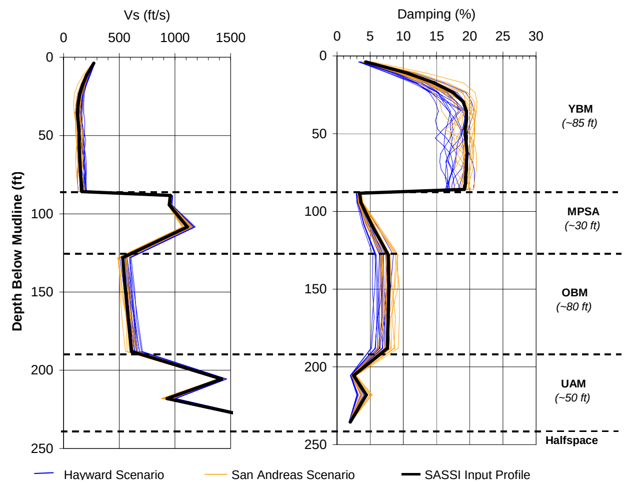


Figure 3. Development of SASSI Input Soil Properties

4.3 Impedance Calculations

Loads were applied at the center of the SFTS base slab and the resulting flexibility matrix was inverted to obtain the impedance matrix. The impedances were calculated for frequencies up to 5 Hz in the X, Y, XX (rotation about X axis), YY (rotation about Y axis), and ZZ (rotation about Z axis) directions, and up to 10 Hz for the Z direction. Figure 4 shows the stiffness and damping values in the X direction for the NSR and JG cases. As shown on the figure, the total impedance of the system in the X direction increases significantly with the addition of the jet grout blocks.

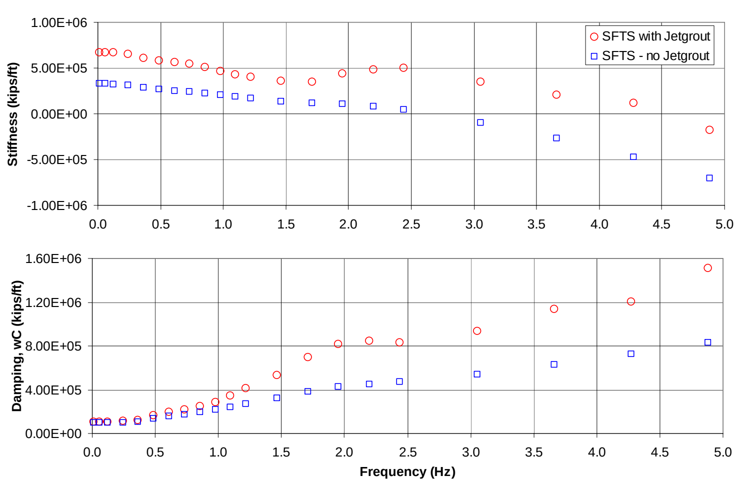
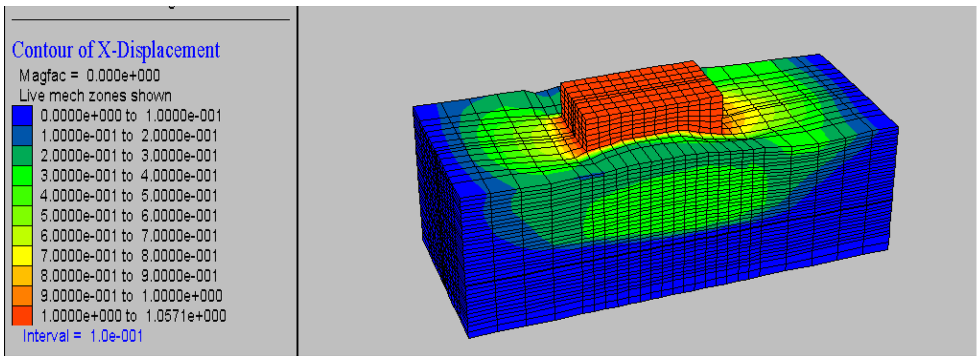


Figure 4. Example of Impedance Results: Stiffness and Damping in X Direction for NSR and JG Models

5. DEVELOPMENT OF NEAR-FIELD SPRINGS

The near-field springs were developed by modeling the SFTS in a three-dimensional finite difference program FLAC. The FLAC 3D model containing the SFTS and the surrounding soils was brought to force equilibrium under 1.0g vertical gravity and the initial at-rest soil pressure acting on the SFTS were recorded. The SFTS was then moved in all six directions (upward, downward, east, west, south, and north) and the reaction forces acting on each node were recorded to obtain the near-field springs. Nodes were divided in 8 strips, each 10 feet in height whereas a single spring was developed for the SFTS base. Figures 5a and 5b show horizontal displacement contours in the east-west direction for moving east, for NSR and JG cases, respectively. The movement of the soil mass around the SFTS is reduced by adding the jet grout blocks. Figures 6a and 6b show the resulting soil springs, which shows significant increase in the passive resistance on the eastern side for the JG case.

(a)



(b)

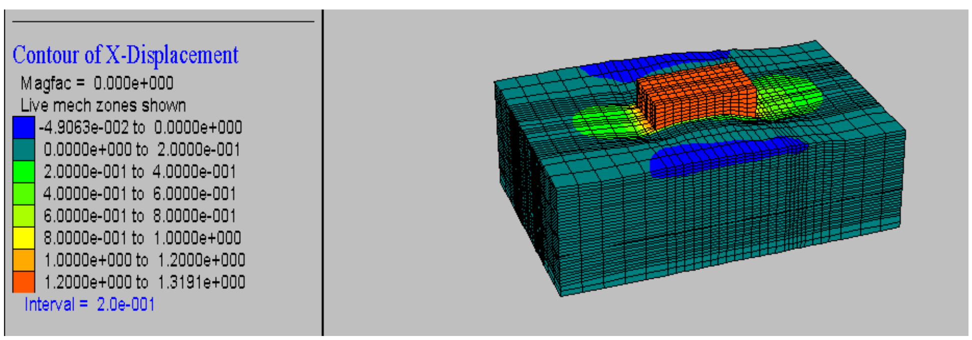
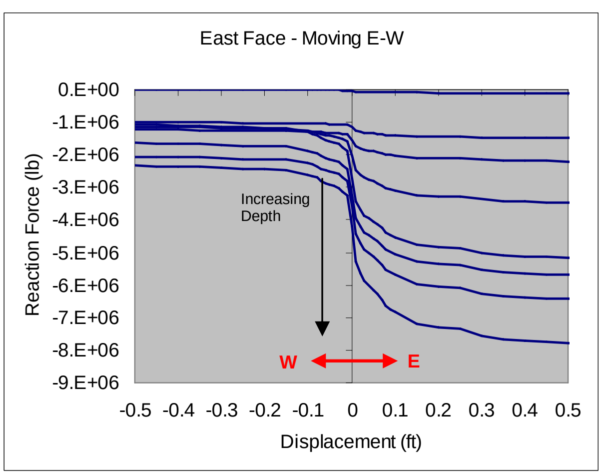
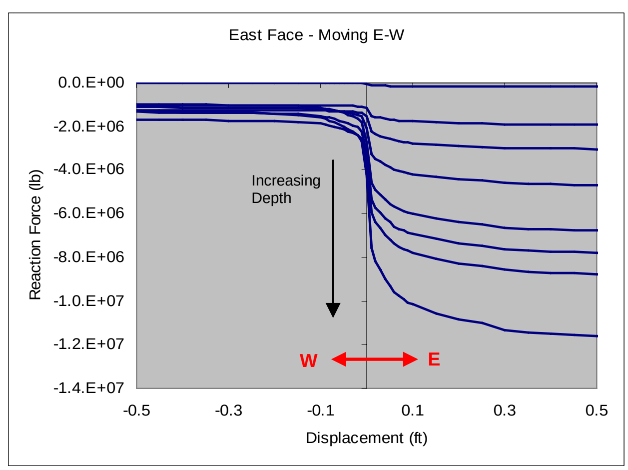


Figure 5. 3D Horizontal Displacement Contours (E-W) for SFTS Moving East: (a) NSR Model, (b) JG Model





(a) NSR Model (b) JG Model

Figure 6. p-y Curves at East Face of SFTS for Movement in the E-W Direction: (a) NSR Model, (b) JG Model

6. DISPLACEMENT TIME HISTORIES

6.1 Scatter Motions at the Base of the SFTS

Scatter motions (i.e., accounting for the kinematic interaction due to the presence of the rigid SFTS structure) were developed at the center of the base slab. Seven sets of scatter motions were obtained for both the San Andreas and Hayward fault rupture scenarios.

Translational and rotational scatter motions were obtained at the base of the SFTS in the X, Y, XX, and YY directions using SASSI. Scatter motions were not generated in the Z direction, and the design rock outcrop vertical motion was used directly in the global analyses. A buried structure tends to average the free-field ground motions near the surface and at the base of the structure. As discussed by Travasarou et al. (2008), the vertical site response effects were considered not significant and; therefore, free-field site response analyses were not conducted for the vertical components of the ground motions. Consistent with this assumption, the ground motions were considered to be identical between the mudline and the base of the SFTS.

Input motions for SASSI analyses in the horizontal directions were obtained from 1-D equivalent linear site response analyses with SHAKE. SHAKE analyses were conducted using the average strain-compatible soil profile (i.e., SASSI input soil profile shown on Figure 3). Design ground motions were applied at the top of the Alameda formation (i.e. horizon compatible with the attenuation relationships used to develop the design ground motions) level as “outcrop” motion, and "within" motions were obtained at the level of the base of the SASSI model by running SHAKE without iterating on the shear modulus and damping values. These motions were then rotated to obtain motions along the X and Y axes, and were baseline corrected before being used for SASSI analyses.

The transfer functions obtained from the SASSI analyses were used to develop scatter motions. As an example, acceleration response spectra of the input motion and scatter motion at the base of the SFTS for one motion (1989 Loma Prieta Earthquake, California - Capitola record – spectrally matched to the design rock outcrop spectra for the project) in the X direction for NSR case is shown on Figure 7.

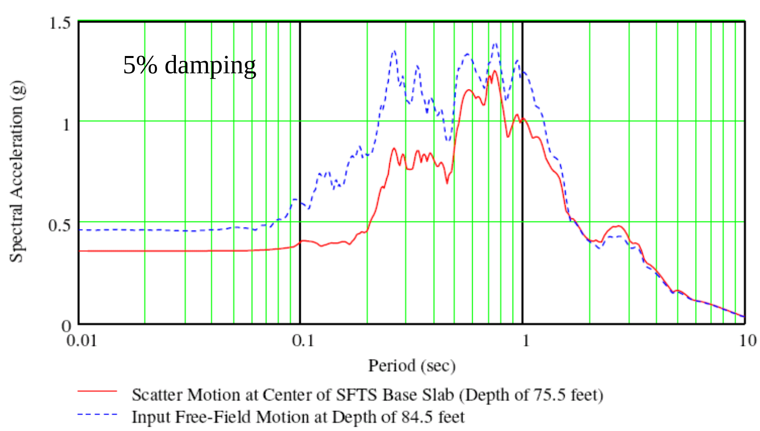


Figure 7. Comparison of Scatter Motion and SASSI Input Motion spectra in X Direction – Capitola Motion

6.2 Scatter Motions Along TBT and Bored Tunnel

A second set of SASSI analyses were conducted using a model that included the SFTS mass. These analyses were conducted to obtain scatter motions along the tube to be applied at the far end of the springs attached to the tube in the longitudinal, transverse, and vertical directions. The development of springs along the TBT beyond the first tube segment (i.e., free field input motions) is presented by Travasarou et al. (2008).

The scatter motions were observed to become similar to the free field motions at a distance of roughly 300 feet from the edge of the SFTS. Therefore, scatter motions were applied along the tube near the SFTS, and transitioned to free-field motions beyond the zone of SFTS influence. A linear interpolation scheme was used to define ground motion in the transition zone between areas near the SFTS that are influenced by the presence of SFTS to the free field ground motion in areas away from SFTS. This is shown schematically on Figure 8.

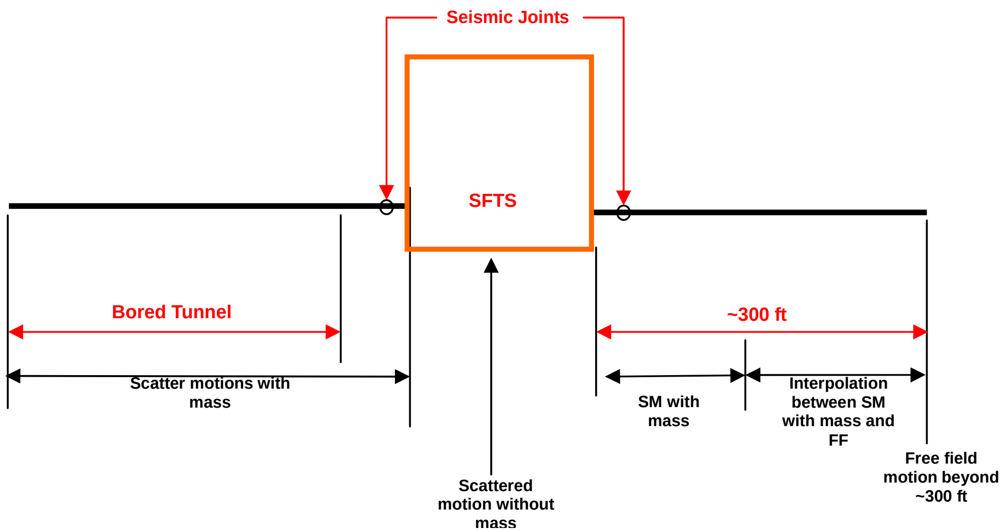


Figure 8. Schematic Showing Transition of Scatter Motions Near the SFTS to Free-Field Motions along TBT

6.3 Permanent Slope Drift

Estimates of permanent displacements were made using nonlinear 2D dynamic analyses. The nonlinear dynamic analyses were conducted using 2-D FLAC and 2-D PLAXIS computer codes. Each of these analyses was conducted for the fault normal component of all seven ground motions. Both polarities of ground motions were analyzed, resulting in a total of 14 runs for each method. Details of slope stability studies are presented by Chen et al. (2008). The resulting displacement time histories from FLAC were passed through a low-pass filter to separate the transient responds and calculate the permanent drifts.

6.4 Input Motions for Global Analyses

The input motions for the SFTS area for the global analyses were developed by combining the scatter motions obtained from SASSI and drift obtained from FLAC analyses. Figure 9 presents the combined FLAC and SASSI motions for the Capitola record. The first plot on Figure 9 shows the displacement time history obtained from FLAC and also the corresponding permanent drift time history. The combined scatter motion from SASSI and permanent drift from FLAC is presented in the second plot on the figure.

7. GLOBAL MODEL

The springs and ground motions developed as part of this study, along with work performed by Chen et al. (2008) and Travasarou et al. (2008), were used to develop input parameters for the global model which included the SFTS, TBT, bored tunnels as well as the seismic joints that connect the SFTS to the TBT and bored tunnels. Details of the global analyses are presented by SC Solutions, Inc. (2007).

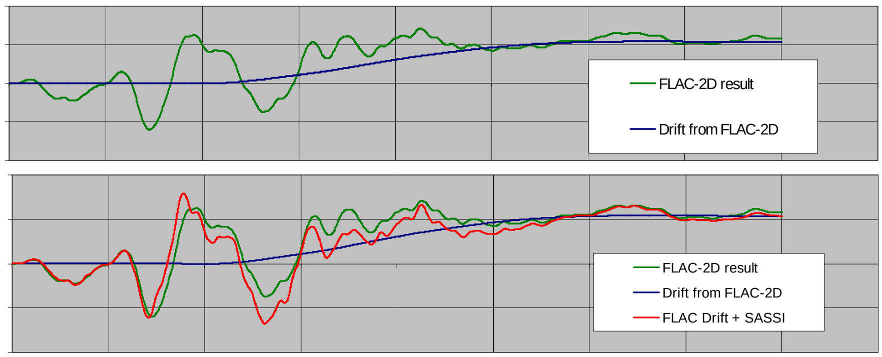


Figure 9. Development of Input Displacement Time Histories for the Global Model

8. CONCLUSIONS

A case history was presented for a problem that required input ground motions, nonlinear soil properties and damping properties to be used in the global structural analyses of a system involving the dynamic response of a rigid massive structure (SFTS) relative to a long flexible structure (TBT). The approach adopted to develop the required data accounted for the effects of soil-structure interaction on the input ground motions and the possible permanent drift resulting from potential displacement of the slope where the structure is founded. This approach was developed for addressing SSI effects of large, buried structures in soft soils and sloping ground. Such approach can potentially find applications for analysis of structures in similar settings, such as ports, transportation corridors, and large buried structures.

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