INPUT GROUND MOTION FOR LONG LINEAR STRUCTURES: THE CASE HISTORY OF THE BART TRANSBAY TUBE

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ABSTRACT :

The seismic vulnerability studies for the San Francisco Transition Structure (SFTS) of the Bay Area Rapid Transit system (BART) involved global structural dynamic analyses which modeled the response of the rigid and massive SFTS to the west and the Transbay Tube (TBT) to the east, a 5.8 km immersed railway tunnel connecting the city of Oakland to San Francisco, in California. This paper presents the approach adopted to develop input for the seismic response of the long TBT tunnel in the global analyses. The required input was in the form of 1) displacement time histories at every joint location along the entire length of the TBT, and 2) properties for the nonlinear soil springs connecting the TBT to the free field. Adopting an approach for the development of input time histories along the TBT involved addressing a number of issues relevant to the seismic response of long linear structures. These include ground motion attenuation, seismic wave incoherence, input depth, two-dimensional effects, and selection of appropriate soil models. These issues are discussed here in the context of the BART SFTS project.

KEYWORDS: Immersed tunnel, multiple support excitation, ground motion attenuation, site response, nonlinear soil spring, BART

1. INTRODUCTION AND APPROACH

The Bay Area Rapid Transit District's (BART) Transbay Tube (TBT) is a 5.8-km-long immersed light rail tunnel that connects the cities of San Francisco and Oakland (Figure 1). Two large transition (ventilation) structures are present at either end of the TBT. The San Francisco Transition Structure (SFTS) retrofit project dealt with assessing the vulnerability of the seismic joint connecting the SFTS (to the west) to the Transbay Tube (TBT) to the east. The factors contributing to the seismic displacement demand at the seismic joint are: 1) the instability of the shoreline where the SFTS is located, and 2) differential dynamic response of the massive and rigid SFTS structure relative to the longer and more flexible TBT tunnel. To evaluate the displacement demand on the seismic joint global analyses of the SFTS/TBT system was performed (SC Solutions Inc., 2007). Inputs to the global analyses needed to incorporate the effects of shoreline instability are described in detail by Chen et al. (2008), while inputs needed to incorporate the seismic response of the rigid SFTS are discussed by Singh et al. (2008). This paper presents the approach adopted to develop inputs to the global analyses associated with the dynamic response of the TBT, a long spatially extended structure.

Figure 2 shows a schematic of the components required to address the dynamic response of the TBT in the global analyses. These are: 1) 3-component displacement time histories at the TBT elevation; and 2) non-linear soil springs attached to the tunnel and transmitting the free-field ground motion. Development of those input components was achieved by means of site response analyses and nonlinear push-over analyses. Selecting an approach for the site response analyses involved primarily: 1) development of the input "rock" outcrop motion, and 2) addressing issues related to the propagation of ground motion from competent "rock-like" material to the elevation of the TBT centerline. The former included consideration of wave passage effects and attenuation of seismic waves along a long structure for a particular earthquake scenario. The latter considered issues such as input depth, two-dimensional effects, soil constitutive models and incoherence. All these issues are relevant to the seismic response of long linear structures in areas of high seismicity.

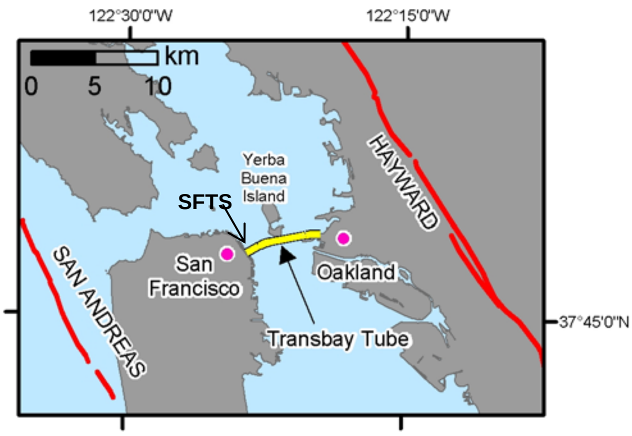


Figure 1. Project Location

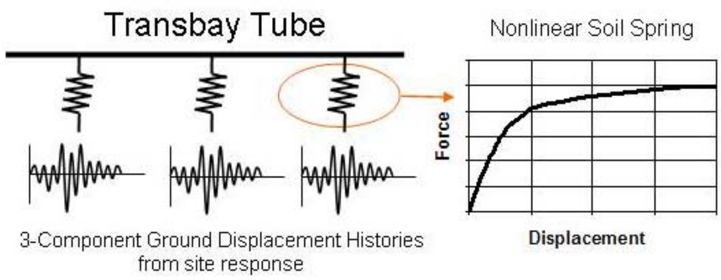


Figure 2. Input components for dynamic response of TBT

2. SITE CHARACTERIZATION

To characterize the stratigraphy and soil conditions along the TBT, geotechnical, geological and geophysical data were integrated and interpreted (Fugro, 2005; Fugro, 2007). Figure 3 presents the interpreted longitudinal geologic profile along the length of the TBT. Soil conditions vary considerably along the TBT. The most important variations, affecting both the ground motions and the soil springs are: 1) the depth to competent (rock) material, 2) the soil properties and stiffness in the vicinity of the TBT, and 3) the thickness of overburden above the TBT.

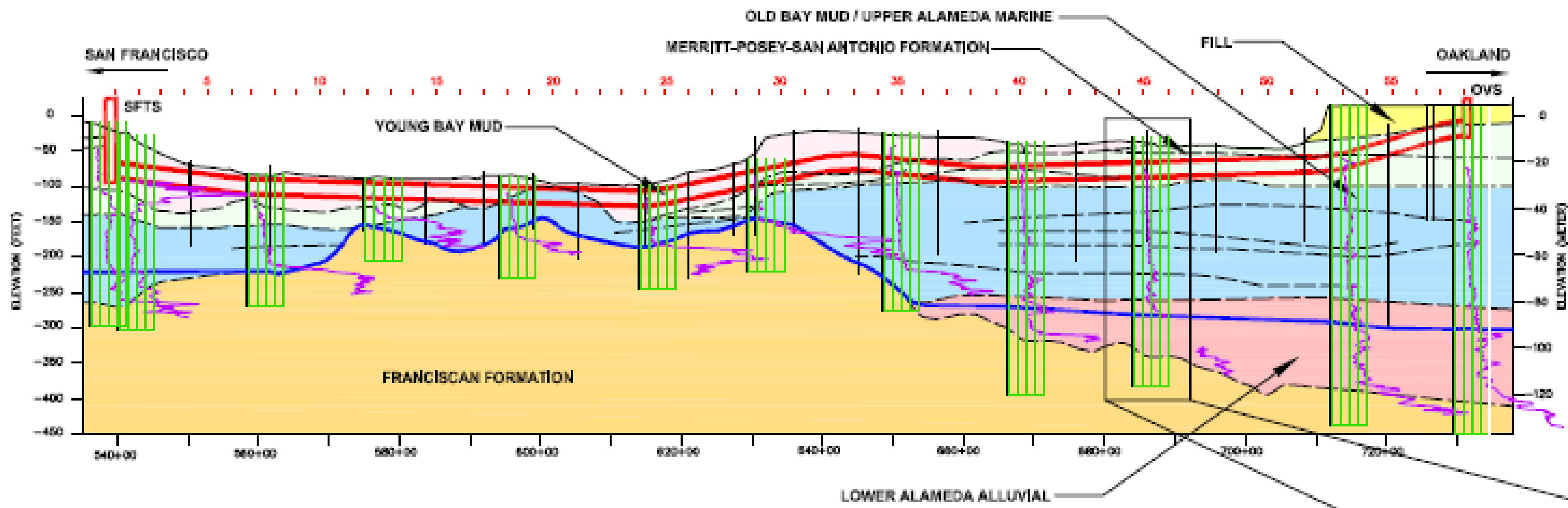
At the west end of the alignment Franciscan bedrock is encountered at a depth of approximately 75 m and generally shallows eastwards towards Yerba Buena Island (YBI). Since the bay also deepens to the east in this area, the thickness of the soil column above rock progressively reduces. In these areas, the TBT trench is largely in relatively soft Young Bay Mud (YBM). This unit is underlain by stiffer clays and sands of the Merritt-Posey-San Antonio formation (MPSA), stiffer Pleistocene Old Bay Clay (OBM), and, in places, dense sand of the Upper Alameda Marin formation (UAM). With the exception of the SFTS area, where the thickness of overburden soil reaches ~ 12 m, much of the western half of the alignment is overlain by 2 to 3 m of overburden. To the east of YBI the Franciscan bedrock slopes towards the east to elevations of approximately -120 m near the Port of Oakland Shoreline, with an associated increase in the thickness of the soil column. In this area, the TBT trench is surrounded mainly by stiffer clay and dense sand of the MPSA formation. Deeper units consist primarily of OBM interrupted by denser sand. The OBM is underlain by the Lower Alameda Alluvial formation (LAA), which consists of a stiff clay "cap" over layers of dense sand. The approximate location of the stratigraphic contact between those two subunits is shown with the thick line at an approximate elevation of -90 m. There is an abrupt increase in the overburden thickness at the Oakland Shoreline where fill was placed after the construction of the Tube to create the Port of Oakland.

Figure 4 shows an idealized cross-section of the trench excavated to place the immersed tube tunnel. The trench backfill materials consist of loosely placed, poorly graded gravel (Foundation Course and Special Fill) and sand (Ordinary Fill) with low fines content. Values of normalized cone penetration test (CPT) tip resistance range between 2 to 4 MPa and 3 to 6.5 MPa for the gravel, and the sand, respectively, with median values around 3.2 and 5.0 MPa. Because of the low CPT tip resistances, the soil in the trench was considered to be liquefiable. For the purpose of developing nonlinear soil springs to transmit the input ground motions from the soil to the tube, two conditions where examined: 1) a condition where the soil has liquefied, and 2) a stone-column retrofit condition where the soil was considered non-liquefiable.

3. INPUT MOTION FOR SITE RESPONSE ANALYSES

3.1. Design Spectrum for Outcropping Rock

The ground motion design criteria for BART were specified at the SFTS location (west end of TBT alignment on



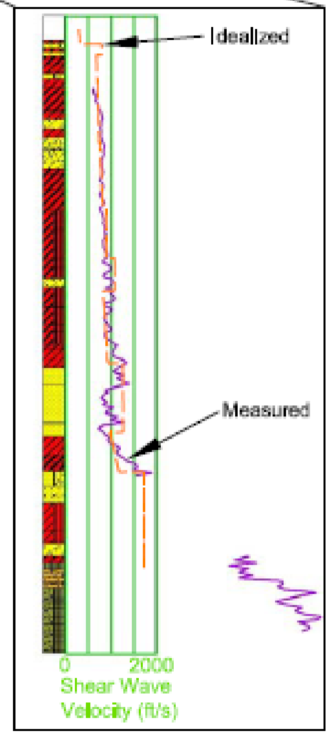


Figure 3. Longitudinal Geologic Profile.

Young Bay Mud: Holocene-age, normally consolidated, very soft to stiff, high plasticity clay.
Merritt-Posey-San Antonio Formation: Pleistocene-age, very dense sand interbedded with overconsolidated stiff to very stiff clay.
Old Bay Mud / Upper Alameda Formation: Pleistocene-age, over consolidated, very stiff to hard, high plasticity clay.
Lower Alameda Formation: Pleistocene-age, dense to very dense sand and gravel interbedded with hard over-consolidated low plasticity clay.
Franciscan Formation: Late Jurassic to early Late Cretaceous-age, thickly bedded to massive sandstone with thinly interbedded siltstone and claystone.

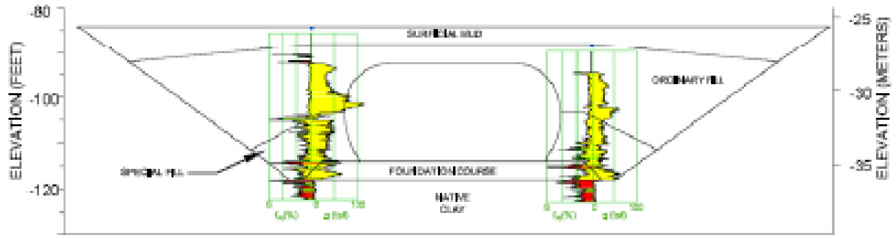


Figure 4. Idealized Trench Cross-Section and Example Friction Ratio and Cone Penetration Tests.

Figure 2). Those criteria were largely based on probabilistic methods and were specified in terms of design response spectra computed using soft rock site classifications and a series of five attenuation relationships derived from Western US ground motion data. The controlling scenario events from the hazard calculations were a Moment magnitude (M) 8.1 event on the San Andreas fault and a M7.25 event on the Hayward fault at distances of 14 and 10 km, respectively from the TBT. Although, the soft rock site classifications are often associated with NEHRP (1997) Site Class B/C boundary (i.e. a shear wave velocity of 760 meters/second[m/s]), a review of the database of the attenuation relationships used in the hazard calculations suggested that the soft rock attenuation relationships used for the project were based on data from sites with an average shear wave velocity of about 540 m/s. In addition to the design spectra, seven spectrally matched time histories were provided in the design criteria for time domain dynamic analyses. Figure 5a presents the design spectra and all seven spectrally-matched time histories for the project. Figure 5b shows the acceleration, velocity and displacement time history Yermo (one of the seven motions presented here).

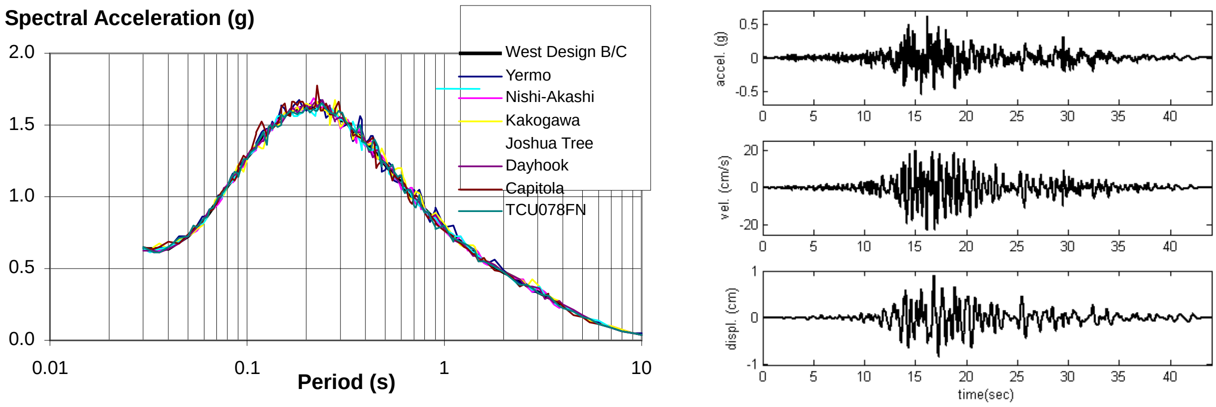


Figure 5. a) Design spectra on rock outcrop for the Design Basis Event (DBE) at the SFTS location (5% damping) and b) acceleration, velocity and displacement time history of Yermo.

3.3. Modification to the Rock Outcrop Motions

Prior to conducting site response analyses the design "rock-outcrop" motions were modified to account for: a) time delay in the arrival of the seismic wave at various points along the TBT, and b) the attenuation of ground motion. Because spatial incoherence of the ground motion affects mostly high frequencies and considering that the dynamic response of the TBT is a relatively low frequency phenomenon it was decided that ground motions would not be modified for spatial incoherence.

The first factor takes into account the differential stresses imposed on the structure as different parts of the structure simultaneously experience different phases of the ground motion time history. Due to the considerable length of the Tube, the arrival time at one end of the Tube can be 2 to 2.5 seconds later than at the other end. A time-shift was applied to the rock outcrop motions based on an apparent wave velocity at the bedrock level of 2.5 km/s.

Although ground motion design criteria are frequently specified in terms of uniform hazard spectra the analyses of spatially extended structures need to be addressed in terms of specific earthquake scenarios. Since the Tube is located between two relatively active faults (Figure 1), both San Andreas and Hayward Fault earthquakes were considered. Figure 6a shows the ratio of the 5% damped acceleration response spectra at three representative locations (i.e., joints along the TBT shown on Figure 3) with respect to the spectrum at the reference location (SFTS) for the San Andreas scenario events. There is a period dependence of the reduction factor suggesting a slower rate of attenuation for longer structural periods compared to the shorter ones. This dependence increases with increasing distance from the fault. For the purpose of conducting site response analyses at different cross-sections along the TBT, both the horizontal and vertical input ground motions were scaled to reflect the attenuation of ground motion with distance using a single, period-independent reduction factor. Because the response of the tube is primarily controlled by the long period motion, the proposed reduction factors for the horizontal ground motion correspond to a structural period of

1.0 second. Figures 6b shows those reduction factors a function the joint number (i.e., or equivalently location along the TBT) for the two earthquake scenarios considered in this study.

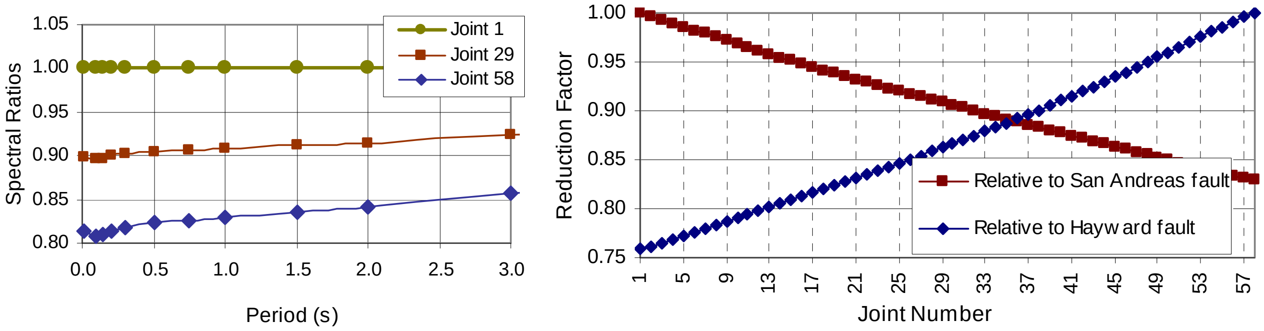


Figure 6. Ground motion a) Spectral ratios (5% damping) and b) Reduction factors with respect to reference location

4. SITE RESPONSE ANALYSES

4.1. Overview

Site response analyses were performed to propagate the design rock outcrop motions from the input depth to the elevation of the TBT centerline. The primary issues to address were: input depth, selection of soil model, two-dimensional effects, and incoherence. For the purpose of conducting site response analyses, idealized soil profiles were first developed along the tube at the locations where shear wave velocity and unit weight data were available (Figure 3). The properties were interpolated in the lateral direction to generate 58 idealized profiles along the TBT length, corresponding to the locations of the joints between tube segments.

4.2. Input Depth

Of particular importance when selecting the input depth for site response analyses is the compatibility of the shear wave velocity of the underlying "halfspace" with the soil type used in the derivation of the target rock spectra. For the BART project, the selection of input depth was further complicated by the differences in the weathering conditions and the elevation of rock along the alignment. As shown on Figure 3 the alignment can roughly be classified into three areas: 1) deeper bedrock areas near the western end of the TBT, 2) shallow bedrock areas to the south of YBI and along the western part of the Bay, and 3) deep bedrock areas east of YBI towards Oakland. Relatively hard/dense layers of the LAA formation are mapped above bedrock in the two deep bedrock areas. Significant thicknesses of weathered rock are identified primarily in the shallow bedrock areas. Detailed evaluations of the shear wave velocity of the LAA formation showed that the unit is composed of: 1) an upper lean clay cap, and b) underlying layers of dense sand and very hard clay. The average shear wave velocity of the clay cap is typically on the order of 350 m/s, whereas the shear wave velocity of the underlying sand layers is often over 550 m/s. In the shallow bedrock areas, the soil layers above rock are typically Old Bay mud with shear wave velocities on the order of 250 m/s. Additionally, the Franciscan Formation often includes a weathering profile with shear wave velocities ranging from 1,000 to 2,000 m/s. To be as consistent as possible with the attenuation relationships used to derive the target spectra, the input depths was defined (see thick blue line on Figure 3) at a depth where the average shear wave velocities in the 30 m below it of approximately 540 m/s, i.e., similar to the average Vs of the generic rock from the rock attenuation relationships. In general, the blue line represents: a) the top of the Alameda formation in deep bedrock areas near the SFTS, b). the top of weathered bedrock for shallow rock locations to the south and west of the Yerba Buena Island, and c). the top of sand layers within the LAA in the deep rock areas east of YBI. In the deep bedrock areas, sensitivity analyses with respect to the input depth suggested that changing the depth at which the ground motions are input result in approximately 20 percent reductions in tube level ground motions in the period range from about 1.5 to 4 seconds.

4.2. Soil Model

To assess the effect of the soil model on the ground motions at the TBT elevation, preliminary site response analyses were conducted at selected locations along the TBT using three different computer programs: SHAKE (equivalent linear analyses), FLAC (nonlinear finite difference analyses), and TESS (Pyke, 2006, nonlinear finite element). Figure 7 presents an example of velocity and displacement time histories computed at the TBT centerline using the three different programs in combination with the Yermo spectrally matched input motion. Those time histories are similar in terms of both amplitude and shape of the waveforms. The two nonlinear analyses predict permanent displacement at the end of shaking. This is associated with: 1) the non-symmetric character of the input ground motions, 2) high ground motion levels which result in yielding within some of the weaker soil layers; and 3) limitations of the 1D approach. The general similarity of the estimated displacement time histories from the three programs justified the continuation of the use of the equivalent linear method (SHAKE) to perform the site response analyses for this project.

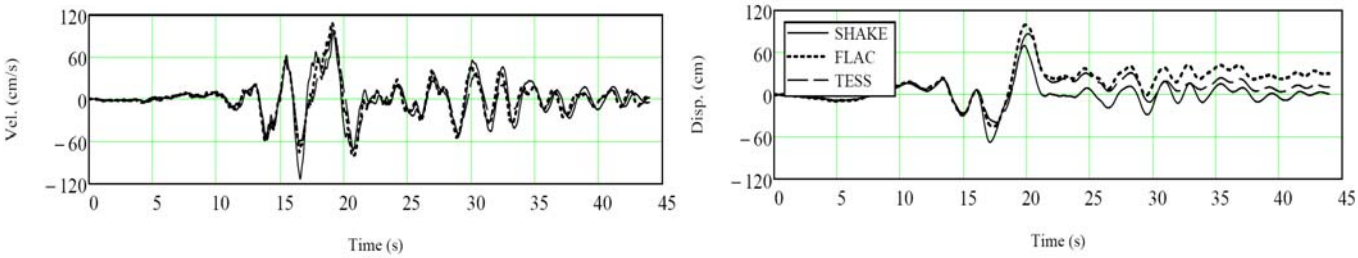


Figure 7. Comparison of velocity and displacement time histories from three different programs

4.3. 1-Dimensional versus 2-Dimensional Effects

The axial strains induced in the TBT depend on: 1) the ground strain along the TBT, and b) the relative stiffness of soil and structure (TBT in the axial direction). Variation in soil conditions along the TBT result in differential ground motions and ground strains. Differential ground response may be accentuated by 2-dimensional effects where abrupt changes in stratigraphy occur. To assess the significance of 2-dimensional effects a two-dimensional (QUAD4M) model was constructed between Joints 1 and 11 where changes in subsurface conditions were considered significant. The ground strains computed from the 2-dimensional site response were compared with those obtained from a series of one-dimensional site response SHAKE analyses conducted at each joint location. Representative results are shown on Figure 8a for the Yermo input motion. While the locations of maximum ground strain are slightly different, the magnitudes obtained from the 2-dimensional and one-dimensional analyses were similar. Hence, one-dimensional site response analyses were considered sufficient for developing input ground motions along the TBT.

4.5. Typical Results from the Site Response Analyses

Tube level ground strains resulting from differential site response shown on Figure 8b for the Yermo motion. Ground strains were computed as the ratio of the peak differential displacement between adjacent joints to the length of the corresponding tube segment. In general, large ground strains are observed along the western end of the alignment (i.e., joints 1 to 10) where the soil profile changes rapidly in terms of stratigraphy, overburden thickness and depth to rock, and differential levels of nonlinearity are introduced in the YBM underlying the Tube. Relatively large strains are also observed near the Oakland shoreline (Segments 51 to 53) as a result of the abrupt change in the overburden thickness.

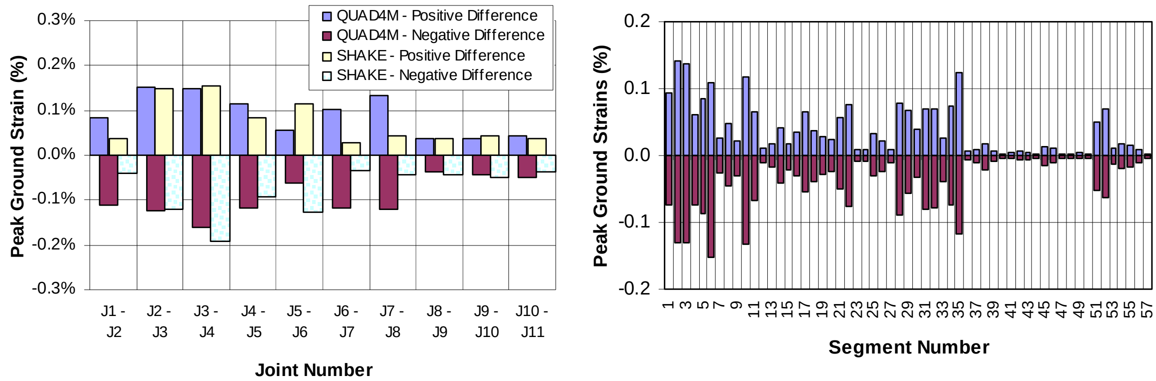


Figure 8. a) Comparison of peak ground strains from 1-D and 2-D analyses, and b) Peak ground strains along TBT (Yermo)

5. TUBE-SOIL INTERACTION

5.1. Methodology

The Tube level ground motions computed from site response analyses represent free-field ground motions away from the TBT trench. Those ground motions are altered by the presence of the Tube, the trench and the Trench backfill materials. Those interactions are modeled by inputting the free-field ground motions at the far end of nonlinear Tube-soil springs. 3-D and 2-D finite element analyses were conducted using the computer program PLAXIS to generate longitudinal and transverse (horizontal and vertical) Tube-soil load-deflection characteristics, respectively. The backbone curves were developed by "pushing" the tube in the required direction and calculating the resistance offered by the surrounding soils. Analyses were performed to:1) develop the shape of the backbone curve for four idealized cases representing the dominant profiles, in terms of stratigraphy, encountered along the TBT; and 2) evaluate the variation in the stiffness and strength of the springs as a function of overburden above the Tube. Design springs were then developed for each joint between two tube segments (i.e., every ~ 100 meters) based on the profile and overburden at that location.

5.2. Soil Properties

The soils in the PLAXIS analyses were modeled using a Mohr-Coulomb constitutive model. Two sets of analyses were performed, representing liquefied soil conditions, and non-liquefied conditions to develop lower-bound and upper-bound springs, respectively. The soil strengths for each unit were characterized using either depth-, or stress-dependent parameters. The soil stiffness for the far field, native soils was modeled using modulus values commensurate with typical strain values calculated in the free field site response analyses. In the lower-bound case, soil in the trench was modeled using an undrained strength ratio (Su/p') equal to 0.12 and 0.2 for the Special Fill and Ordinary Fill, respectively (refer to Figure 4). In the upper-bound case, the trench soils were modeled with a friction angle ranging between 38 and 42 degrees.

5.3. Non-Linear Soil Springs

A typical 3-D model of the TBT used in the PLAXIS analyses is shown on Figure 9a. Typical deformation patterns for these analyses are shown on Figure 9b. A wedge-shaped failure develops above the tube as the soil above the tube moves with the tube. The failure wedge is largely contained within the trench, however, the zone of influence may extend out further to the native soil, depending on the stiffness of the native soil. The associated longitudinal springs are shown on Figure 9c. Figure 10 summarizes the variation in the capacity of the nonlinear springs along the TBT after taking into consideration the soil conditions near each joint and the thickness of overburden. In general, the springs are stronger in areas with high overburden (e.g., to the west near SFTS, to the east approaching the Oakland Shoreline, and east of Yerba Buena Island). The springs also stronger when the TBT trench is surrounded by stiffer clay (e.g., MPSA-C, or OBM) compared to the softer YBM to the west of the alignment. Similar trends were observed for the stiffness of the soil springs.

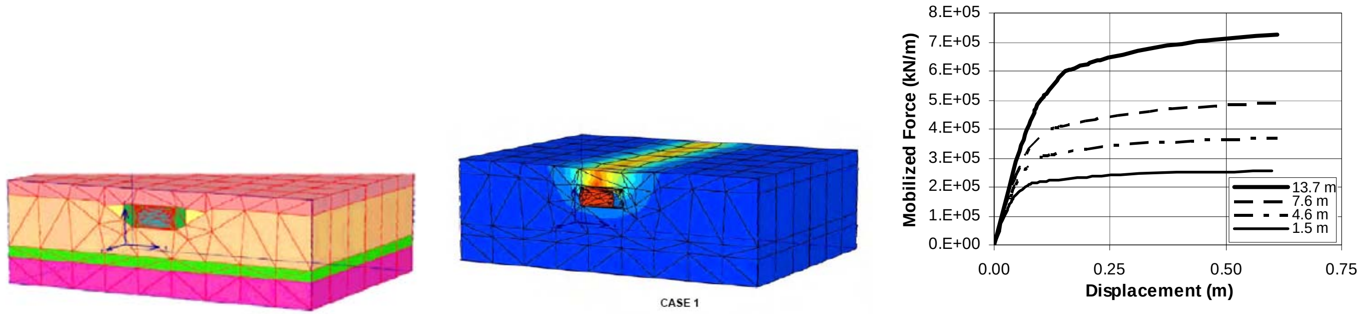
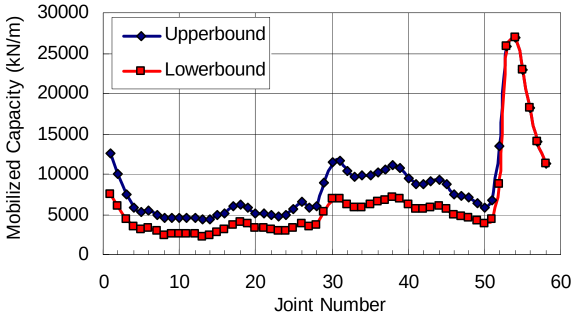


Figure 9. a) Typical Plaxis mesh, b) Deformation patterns, and c) typical nonlinear soil springs



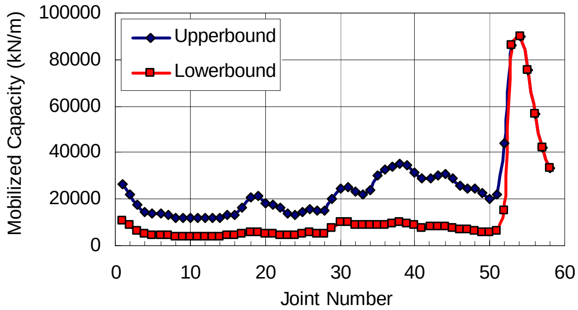


Figure 10. Capacity of the nonlinear soil spring a) longitudinal direction, b) transverse direction

6. SUMMARY

The vulnerability of the seismic joint connecting the San Francisco Transition Structure (SFTS) and the Transbay Tube (TBT) was assessed by means of structural global analyses. This paper provides a case history describing the development of spatially varying multiple-support ground motion inputs and consideration of soil-structure interaction effects. The rock outcrop motions were modified to take into account the travelling wave effect and ground motion attenuation along the extent of the structure for design earthquake *scenario* events. Site response analyses were subsequently performed to propagate the input motions from rock to the elevation of the TBT centerline. Those analyses took into consideration the compatibility of the soil stiffness at the input depth compared to that used to develop the design target spectra, potential 2-D effects, and effects of the specific soil model on the estimated ground motions. Results from the global analyses showed that among the vulnerabilities of the SFTS/TBT system was the potential for large axial strains along the length of the TBT. Axial tube strain appears to be correlated with: 1) overburden thickness, 2) stiffness of soils surrounding the trench, 3) abrupt changes in geometry and stratigraphic units. The approach adopted for this project may be applicable to long structures located in areas of high seismicity and facing varying soil conditions along their length.

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