STUDIES ON SEISMIC DESIGN AND PERFORMANCE ASSESSMENT OF CUT-AND-COVER TUNNELS

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SUMMARY
The paper presents studies on essential aspects of performance-based earthquake engineering (PBEE) design of cut-and-cover tunnel structures, performed for the case study of the Doyle Drive Reconstruction Project, located in the Presidio of San Francisco, California, USA. Seismic soil-structure interaction (SSI) analyses based on frequency-domain (SASSI2000 computer code) and time-domain (FLAC computer code) analytic techniques were utilized. Key aspects of site-specific seismic hazard assessment, performance measures, and performance evaluations are presented. The work focuses on parametric studies conducted to investigate the effects of various analytic and design parameters, such as proximity of adjacent tunnel bores, waterproofing membranes, model mesh refinement, and nonlinearities. The performance measures required for the PBEE design approach are developed based on inelastic push-over analyses using the ADINA computer analysis code. The paper highlights the key finding of parametric studies performed based on finite element/finite difference modeling approaches in geotechnical earthquake engineering.

Keywords: Performance-based earthquake engineering, Soil-Structure Interaction, Cut-and-Cover Tunnel

1. INTRODUCTION

Doyle Drive, originally built in 1936, is the existing south access road to the Golden Gate Bridge. The objective of the Doyle Drive Reconstruction Project, depicted in the renderings of Figure 1.1, is to improve the seismic safety of the alignment and restore the site to a national park. Performance-based seismic design criteria were established to ensure the performance of the tunnel structures in the project, for a dual-level earthquake performance requirement: "*Serviceable*/*Repairable Damage*" performance under the Functionality Evaluation Earthquake (FEE), and "*No-Collapse/Repairable*" performance under the Safety Evaluation Earthquake (SEE).

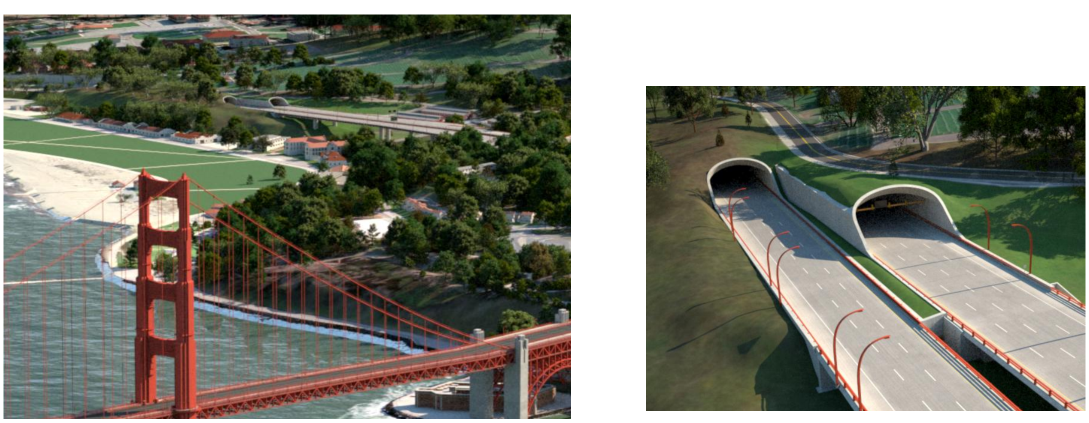


Figure 1.1. Project Overview of the future Presidio Parkway of San Francisco, CA

The performance-based earthquake engineering (PBEE) approach requires that the design, evaluation, construction and maintenance of engineered facilities, whose performance under different levels of earthquake loads responds to the diverse objectives, are adequately addressed. It promises engineered structures whose performance can be quantified and conformed to the owner's requirements. It is based on the premise that performance can be predicted and evaluated with quantifiable confidence to make, together with the owner and project stakeholders, intelligent and informed trade-offs based on life-cycle considerations rather than construction costs alone.

2. SEISMIC HAZARD ASSESSMENT AND SITE RESPONSE ANALYSIS

Seismic response analysis of underground tunnel structures involves selection of seismic input motions based on site-specific seismic hazard assessment and seismic performance criteria, site response analysis, and soil-structure interaction (SSI) analysis.

The SEE performance design of the cut-and-cover tunnel structures were based on the 1,000-year mean return period earthquake. A set of three spectrum-compatible ground motions, with the design acceleration response spectra as target spectra, were developed to represent the Fault-Normal (FN), Fault-Parallel (FP), and Vertical (V) components of the ground motions with respect to San Andreas Fault; they were synthesized using the Manjil, Kocaeli and Chi-Chi earthquake records in the database of the Pacific Earthquake Engineering Research Center (PEER).

Site response analyses were performed to develop the soil layering model parameters and seismic input motions needed for the SSI analyses. These analyses were used to develop strain-compatible layer properties (shear wave velocity and damping ratio profiles), and obtain the corresponding depth-variable free-field motions, as shown in Figures 2.1 through 2.4.

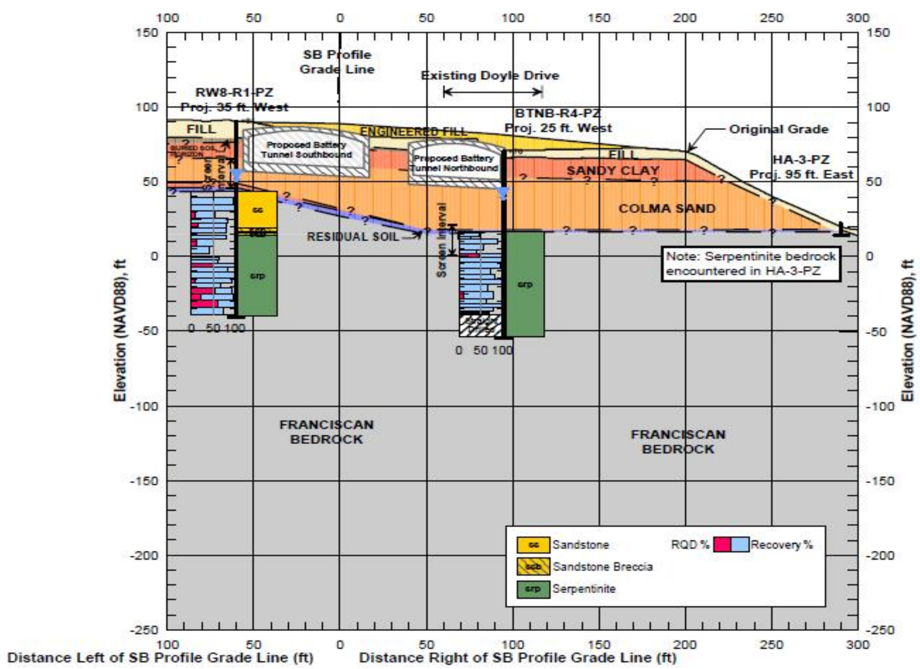


Figure 2.1. Typical soil profile at east end of tunnel footprint

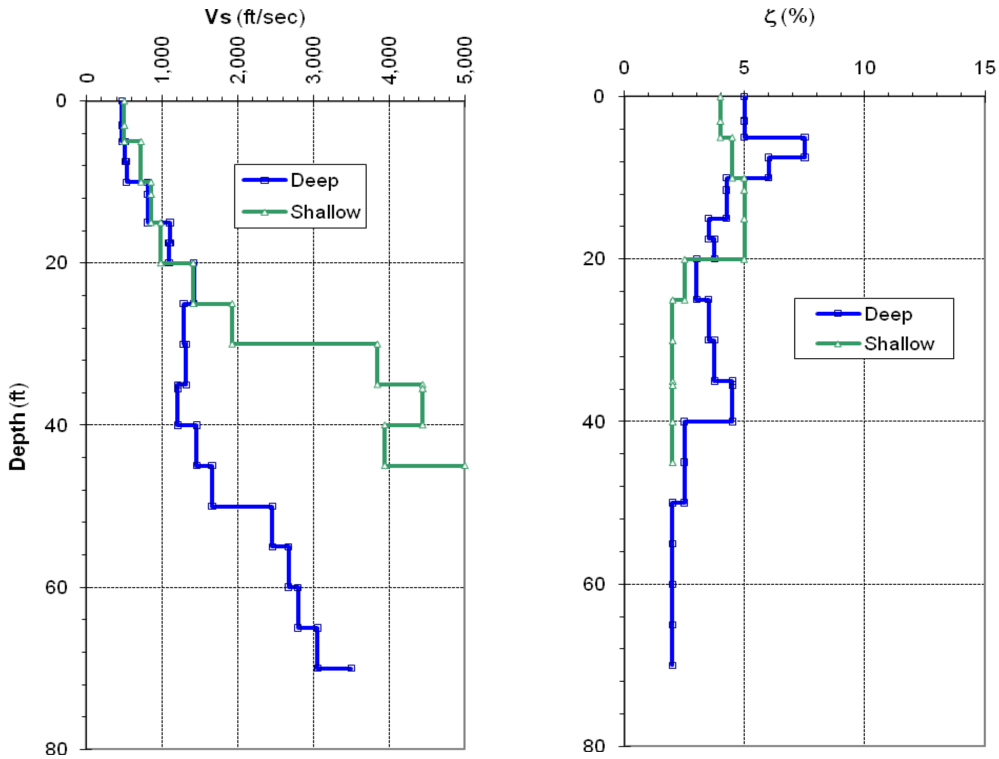


Figure 2.2. Strain-compatible shear-wave velocity and damping profiles

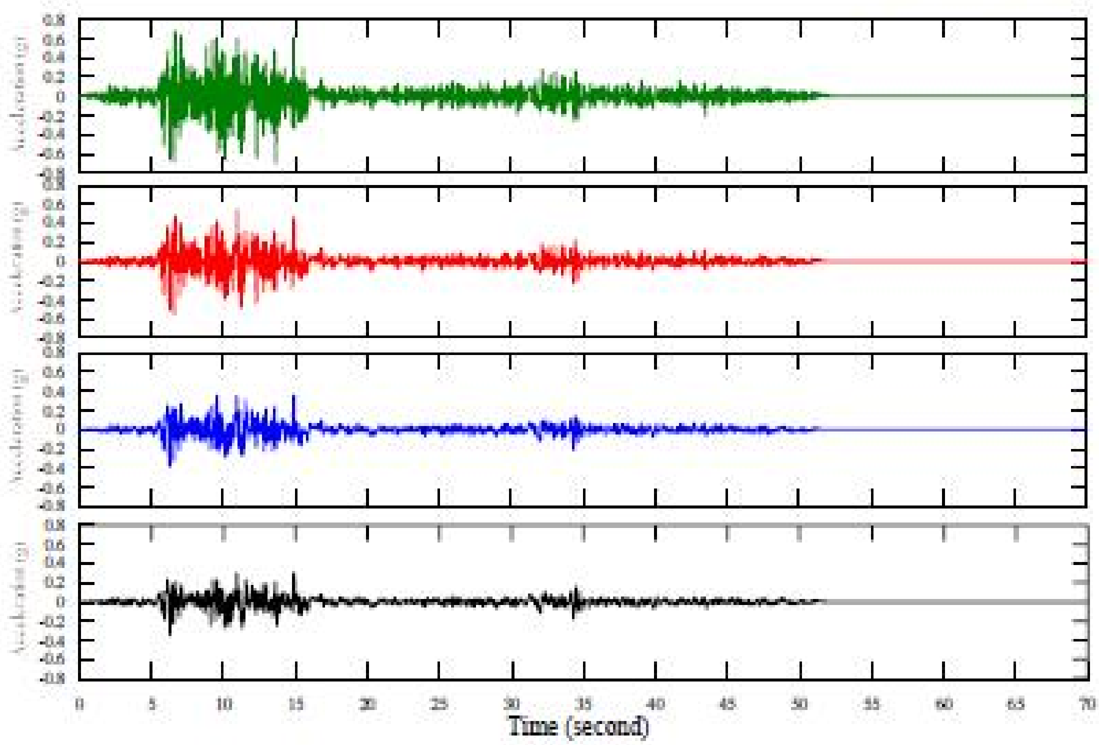


Figure 2.3. Depth-variable free-field accelerations for Manjil-based SEE

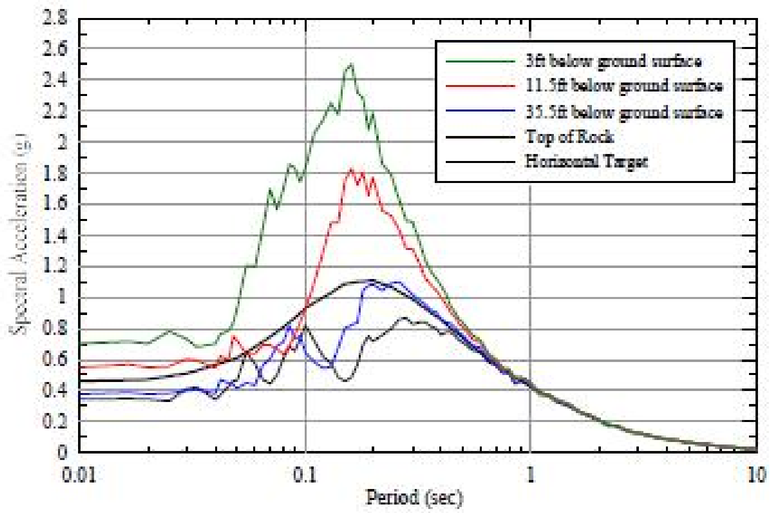


Figure 2.4. Depth-variable free-field accelerations spectra (5% damping) for Manjil-based SEE

3. SOIL-STRUCTURE INTERACTION (SSI) ANALYSES

Racking of the cross-section is considered to be the most critical deformation produced in a tunnel lining under earthquake-induced lateral loading. Soil-structure interaction (SSI) analysis provides a rational method for computing these types of racking deformations. Different approaches have been developed based on both pseudo-static and dynamic analysis techniques. Penzien (2000) developed a quasi-static soil-structure interaction analysis procedure for evaluating the racking deformation of rectangular and circular tunnel linings. Wang (1993) presented methods of analysis for evaluating earthquake effects on underground structures. The common part of these quasi-static solutions is that dynamic (inertial) interaction effects are ignored. Numerical analysis methods are generally needed for the complex nature of the seismic soil-structure interaction of underground structures, especially for cut-and-cover tunnels due to their greater vulnerability to seismic damage.

Among the computer codes for SSI models based on finite element/finite difference and analytical methods, SASSI2000 (Ostadan, 2006) and FLAC (Itasca Consulting Group Inc., 1998) are two of the commonly used ones. In this section, dynamic soil-structure interaction analyses based on frequency-domain (SASSI computer code) and time-domain (FLAC computer code) analytic techniques and results comparisons are discussed. The parametric studies performed to investigate the effects of various design parameters are also presented and discussed in this section.

3.1. SSI Modeling and Analysis

Figures 3.1 and 3.2 depict the features of a SASSI2000 model representative of the set of parametric analyses performed that with a double cut-and-cover tunnel. The tunnel linings are modeled with ‘Beam’ elements and the excavated soil region is modeled by two-dimensional (2D) ‘Quadrilateral Plane Strain’ elements. The distance '**D**' represents the proximity of the adjacent tunnel bore, and the dimension '**h**' indicates the model mesh refinement size. Zero shear strength thin layers of 2D quadrilateral plane strain elements were also included to capture the interface effects between the soil and the waterproofing membrane around the tunnel. By varying the distance '**D**' and altering the stiffness properties of the waterproofing membrane interface elements, the soil-structure interaction and the tunnel-soil-tunnel interaction effects under the three sets of SEE motions were studied. As suggested in Ostadan (2006), the Subtraction Method was used for the impedance analyses; this was validated using the Direct Flexible Volume Method of the program for the set of parametric analyses performed in this study.

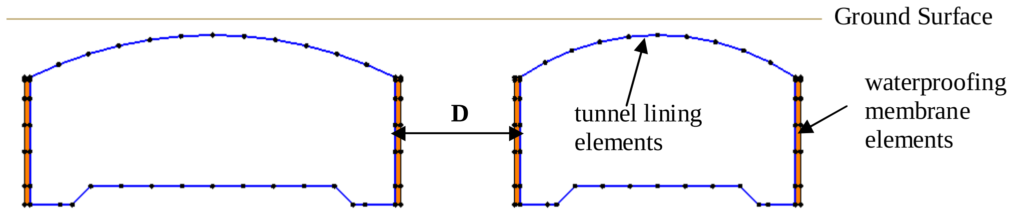


Figure 3.1. SASSI Model of double tunnel lingings with waterproofing membrane boundaries

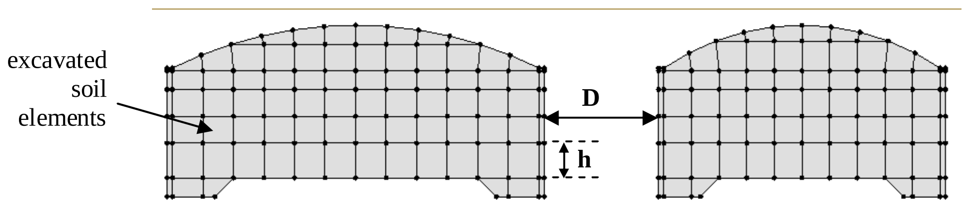


Figure 3.2. SASSI Model of excavated soil

The transverse loading 'control motions' that represent the seismic excitation due to vertically propagating S-waves were obtained from the depth-variable free-field motions developed by the site response analyses (Figure 2.3 shows the Manjil-based SEE). For each load case, the 'interface' acceleration time-history corresponding to the top-of-rock elevation in the profile was used for the analyses. The frequency-domain based formulation in SASSI2000 uses Transfer Functions that relate response quantities to the acceleration 'control motion'. The transfer functions for acceleration at the free-field (monitored by a vertical string of interaction nodes placed 500-ft away from tunnel structure) and the tunnel structure cross-section for the model depicted in Figures 3.1 and 3.2 are shown in Figure 3.3.

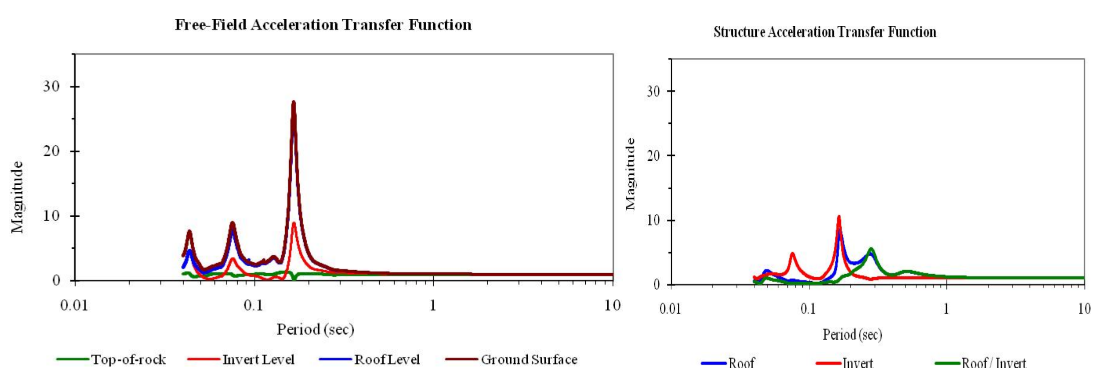


Figure 3.3. Acceleration transfer functions with respect to acceleration control motion at depth

As shown, the soil column exhibits a fundamental vibration period of about 0.17 seconds and a much stiffer 2nd mode of 0.075 seconds, and the soil-structure system introduces vibration periods in the 0.2 to 0.3 second range.

The critical mechanism of 'racking drift deformation' causing structural damage for underground structures with box-shaped cross-sections is induced by distortion of the tunnel cross-section under lateral seismic loading. In these studies, the transverse drift is computed as the relative displacement between the top and bottom extremities of the walls, corrected for the effect of rigid body rotation of the cross-section. A representative sample of tunnel transverse racking response time history and its corresponding frequency content (Fourier Transform) are presented in Figure 3.4.

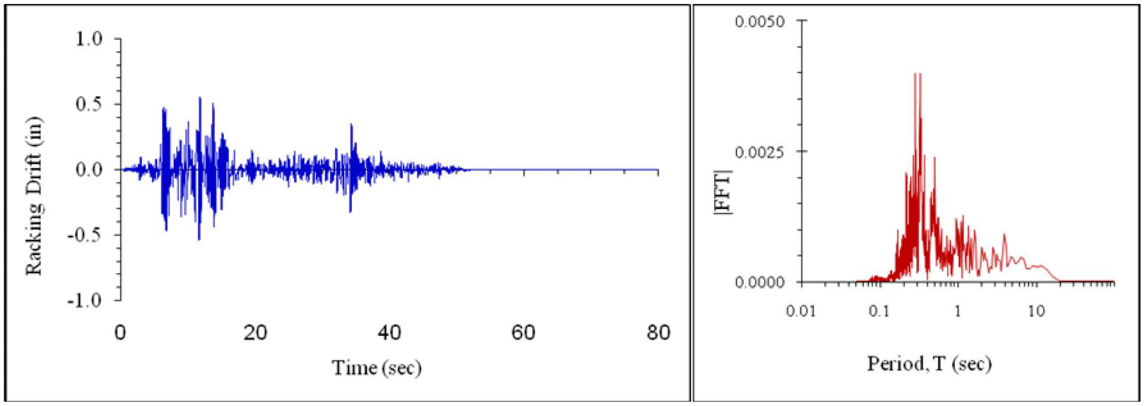


Figure 3.4. Racking time history and corresponding frequency content under Manjil-based SEE motion

For the purpose of comparison and validation, calculations of drift responses were also performed based on time-domain solution using a nonlinear model for the applicable soil profile with the FLAC computer analysis code. The results obtained by the FLAC model validated the results obtained by the SASSI2000 parametric analyses. This exercise confirmed the validity of the modeling approach and the parameters developed in generating the SASSI2000 models for the purposes of this study.

3.2. Parametric Studies

The set of parametric studies presented in this paper were intended to investigate the sensitivity of the seismic design of the tunnel structure in the Phase 1 stage of the project (southbound Battery Tunnel) to variations in design and analysis model parameters. The parameters investigated in this study include: (a) model mesh size; (b) effect of tunnel waterproofing membranes; (c) the presence and proximity of a future adjacent tunnel.

3.2.1 Model Mesh Size

Mesh size is a parameter that affects modeling accuracy in numerical dynamic SSI analyses involving wave propagation, and it is a requirement that element dimensions be limited to $h_o = Vs/5f_{NF}$ (Ostadan, 2006), where Vs is the soil layer-specific shear wave velocity, and f_{NF} is the highest frequency of analysis. Three sets of models with different mesh sizes (h ≈ 2, 5, and 10 feet) were analyzed for this purpose. The results obtained from these showed that the coarser mesh size of h=10 ft will not cause any loss in accuracy of results obtained in these case studied. This aspect is important for deciding the element size of complex models, such as the three-dimensional model with extensive excavated soil and tunnel structure elements developed for the project (Donikian et al, 2012), since mesh size affects numerical computation time exponentially.

3.2.2 Waterproofing Membrane Effect

The effect of waterproofing membranes placed between the soil medium and the tunnel walls was investigated by modeling the effect of the membranes with zero-shear resistance 2D Plane Strain elements, as shown in Figure 3.1. The results showed that the existence of waterproofing membranes increases the dynamic soil-structure interaction effect, with up to a 30% increase in the racking drift displacement in "soft" soil media.

3.2.3 Proximity of Adjacent Tunnels

Tunnel-soil-tunnel interaction was also investigated by varying the distance between adjacent tunnel bores. The studies showed that a significant increase in the racking drifts (in terms of racking ratios discussed below) are possible as a result of small separation distances between adjacent tunnel linings. Single tunnel linings were also analyzed to establish the baseline racking ratios, R, defined in Penzien

(2000) as the ratio of the 'structure drift response to the free-field drift response', i.e, Δ_{SSI}/Δ_{FF}. It was found that for the single tunnel case the values for R varied from 2.1 to 2.5, which are consistent with the traditional curves presented by Penzien (2000). It was found that racking ratios of tunnel structures with two linings close to each other can be as much as 2.5 times larger than that of a single lining. These results indicate that racking ratios obtained by simplified manual analysis method based on single tunnel bores, such as the one presented in Penzien (2000), may vary by factors ranging from 1.7 (for "stiff" soil media) to 2.5 (for "soft" soil media) for double tunnel designs.

Furthermore, the acceleration transfer function ratios between roof and invert shown in Figure 3.5 indicate that the presence of a waterproofing membrane amplifies the magnitude and increases the soil-structure system fundamental period of the transfer function, and the double tunnel lining system further increases the system period and introduces a second vibration mode. The implications of these observations are further discussed below.

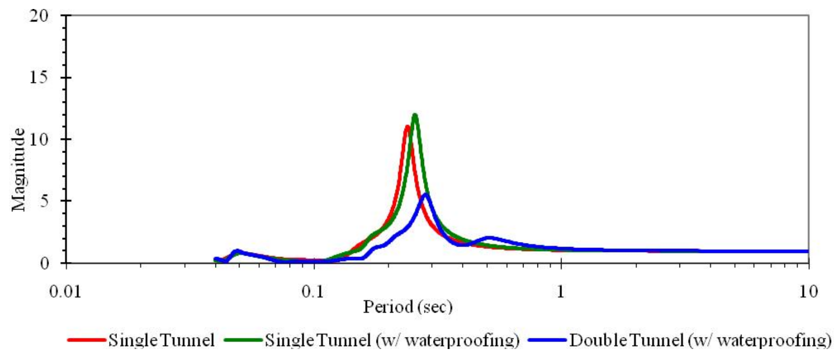


Figure 3.5. Acceleration transfer functions and ratios between roof and invert

Table 3.1 summarizes the tunnel maximum racking drifts (Δ_{SSI}) and the free-field racking drifts (Δ_{FF}) between the levels of tunnel roof and invert in the transverse direction at four locations along the tunnel alignment, for three sets of ground motions. The table also shows the racking ratios ($R=\Delta_{SSI}/\Delta_{FF}$) vary from 2.9 to 5.8, which indicates the significance of SSI effects on the various configurations studied.

Table 3.2 summarizes the effects of SSI on the racking ratios of the various configurations studied. It is clear from these results that significant increases in racking displacements can occur due to SSI effects on system with waterproofing membranes and twin-tunnel configurations, and need to be evaluated for their impact on design decisions.

Table 3.1. Tunnel Cross-Section Racking Drift Displacement Summary

Location	Manjil-based Motions			Kocaeli-based Motions			Chi-Chi-based Motions		
	Δ_{SSI} (in)	Δ_{FF} (in)	Δ_{SSI}/Δ_{FF}	Δ_{SSI} (in)	Δ_{FF} (in)	Δ_{SSI}/Δ_{FF}	Δ_{SSI} (in)	Δ_{FF} (in)	Δ_{SSI}/Δ_{FF}
1*	0.84	0.134	6.3	0.93	0.172	5.4	0.83	0.157	5.3
2**	0.20	0.056	3.6	0.25	0.085	2.9	0.23	0.050	4.6
3**	0.22	0.056	3.9	0.31	0.085	3.6	0.29	0.050	5.8
4**	0.20	0.056	3.6	0.28	0.085	3.3	0.27	0.050	5.4

* "deep" soil profile (soft); ** "shallow" soil profile (stiff)

Table 3.2. Racking Drift Displacement of Different Tunnel Systems under Manjil-based Motions

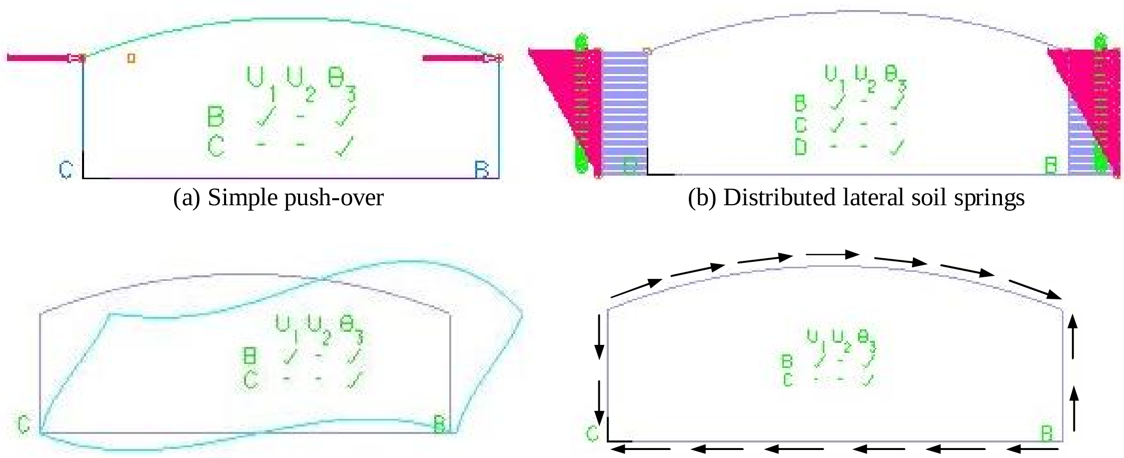
Location	Single Bore Tunnel (no waterproofing)			Single Bore Tunnel (with waterproofing)			Double Bore Tunnel (with waterproofing)		
	Δ_{SSI} (in)	Δ_{FF} (in)	Δ_{SSI}/Δ_{FF}	Δ_{SSI} (in)	Δ_{FF} (in)	Δ_{SSI}/Δ_{FF}	Δ_{SSI} (in)	Δ_{FF} (in)	Δ_{SSI}/Δ_{FF}
1	0.34	0.134	2.5	0.43	0.134	3.2	0.84	0.134	6.3
2	0.12	0.056	2.1	0.13	0.056	2.3	0.20	0.056	3.6

4. STRUCTURE PERFORMANCE EVALUATION

The performance evaluation of the various configurations studied are based on seismic demand estimation obtained by SSI analyses and structural deformation racking capacity assessment based on push-over analyses by using finite element computer software ADINA (ADINA R & D, Inc., 2005).

4.1. Push-over Racking Analyses

Due to the complex nature in the seismic racking mechanism in soil-structure systems, especially for shallow embedded underground structures, several approaches were applied to obtain force-deflection curves for these studies. Four push-over methods depicted in Figure 4.1 were used: (a) "Simple Push-over", by applying point displacement loading at the top of the walls; (b) "Distributed Load Push-over", by applying a triangular displacement field to the soil profile modeled by nonlinear springs; (c) "Superposed Mode Shape" , by applying the first racking mode shape obtained from modal analyses of the structure only; and (d) "Shear Distortion", by applying a constant shear flow to the liner. All four of these methods were used to simulate racking deformation of tunnel structures, and yield limit state drift displacements and load-deflection curves generated resulted in the four methods producing relatively close results. Note that the boundary conditions at the invert consist of pin and roller supports.



(a) Simple push-over

(b) Distributed lateral soil springs

(c) Superimposed mode shape

(d) Shear flow

Figure 4.1. Racking deformation kinematics models

4.2. Performance Assessment

As fundamental measures of structural seismic performance, FEE ductility and SEE ductility are defined as $\mu_{FEE} = \delta_{FEE}/\delta_y$, and $\mu_{SEE} = \delta_{SEE}/\delta_y$, respectively, where δ_y is the racking drift at the point of yielding initiation, and δ_{FEE} and δ_{SEE} are the racking drifts where the concrete reaches its ultimate strength, for the FEE and SEE performance limit states, respectively. For these studies, the ADINA inelastic push-over model was used to track the bending moments, shears, axial forces, plastic curvatures, plastic hinges and lengths, and concrete & rebar strains during the racking displacement progress, from which the ductilities capacities of the tunnel lining were evaluated.

Performance measures established to ensure that the tunnel structure has sufficient capacity to resist demand racking drift in a ductile manner, target ducitilities for racking of 2.0 and 4.0 were specified for the FEE and SEE performance levels, respectively. The FEE and SEE ductility capacities of the actual structural configurations were determined by the ADINA push-over analyses, where minimum ductility capacity values of 3.0 and 6.0 were achieved, respectively. The seismic performance of the tunnel structural system was then evaluated based on "demand/capacity" ratios. It was found that the seismic demand ductility levels obtained from the parametric SSI analyses were less than 1.0 for the FEE, and between 2 and 3 for the SEE.

5. CONCLUSIONS

The findings of the parametric studies based on SSI analyses and the essential aspects of PBEE design of cut-and-cover tunnel structures are summarized below:

a) SSI effects on the response of shallow embedded tunnel structures were shown to be important, especially in the presence of a twin companion tunnel. Racking ratios for twin-tunnel configurations were found to be higher than those for single bore configurations by factors of 1.7 and 2.5, for tunnels in stiff and soft soil media, respectively.

b) The presence of waterproofing membranes surrounding tunnel linings, which tends to reduce shear resistance, amplifies the SSI effect where racking ratios can increase by up to 50%.

c) The parametric case study demonstrates that SSI effect in determining seismic demand on shallow tunnel linings is essential for the PBEE design approach.

d) Effects of soil nonlinearities on the racking drift response of shallow tunnels is sensitive to model parameters, especially with sloping layers which may cause permanent deformation. This aspect requires caution in using strong nonlinearities in soil models that may be unrealistic.

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