Evaluation of Ground Response Uncertainty by Site Response Analysis at the Turkey Flat Geotechnical Array

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Abstract: Predicting the influence of local soil conditions on expected earthquake ground motions is a critical aspect of the seismic design process. In many situations, the effects of soils conditions on ground shaking are assessed through dynamic simulations of wave propagation called seismic site response analysis. Four basic sources of uncertainty are typically considered to influence the analysis, including (1) input rock motions; (2) shear-wave velocity (Vs) profile; (3) nonlinear soil properties; and (4) method of analysis (Idriss 2004). In this study, the Turkey Flat geotechnical array site is used to examine the effects of these uncertainties by performing 1D nonlinear and equivalent-linear ground response analyses and comparing the predictions to the measurements. The discrepancy between the measurements and predictions is minimized considering the aforementioned sources of variability. However, even if the best model is used, the predictions still cannot match the measurements perfectly because of the inherent randomness of seismic motion. The input motions significantly influence the prediction result, followed by the shear-wave velocity profiles, and the soil nonlinear curves present slight effects.

Keywords: Site response analysis; input rock motions; shear-wave velocity profile; nonlinear soil properties; Turkey Flat geotechnical array.

1 Introduction

Observations from earthquakes over the past 40 years have shown the importance of local site conditions on propagated ground motions. Strong motion records from many earthquakes show significant differences between soil site response and nearby rock site response. Site response analysis is typically performed to estimate the site effect on ground motion. Several factors can influence the result of site response analysis. The shear wave velocity (Vs) profile and soil nonlinearity curve (e.g., modulus reduction and damping curves) are two aleatory uncertainties of site characterization for producing different site responses (Kramer 1996). Vs profile represents the dynamic properties of soil at a very small strain and significantly influences the wave propagation under weak motion. Meanwhile, soil nonlinearity represents the large strain behavior under moderate to strong motions. In addition to the material variability, the uncertainty in ground motion characterization is a dominant source of aleatory uncertainty in the estimation of seismic site response (Rathje et al. 2010). The epistemic uncertainty, such as adopted site response analysis method (e.g., time domain or frequency domain, nonlinear (NL) or equivalent-linear (EQL)), can also change the prediction results (Tsai and Chen 2016; Stewart et al. 2008). Lastly, the ground motion characterization is one of the most dominant sources of uncertainty in seismic site response estimation (Rathje et al. 2010).

In this study, the Turkey Flat geotechnical array site is used to examine the effects of these uncertainties including (1) input rock motions; (2) shear-wave velocity (Vs) profile; (3) nonlinear soil properties; and (4) method of analysis. The predictions by 1D nonlinear and equivalent-linear ground response analyses are compared to the measurements. The discrepancy between the measurements and predictions is minimized considering the aforementioned sources of variability. Meanwhile, the relative influence of these variabilities on the predicted site response is also evaluated.

2 Turkey Flat Test Area

2.1 Instrumentation array

The Turkey Flat test area instrument array is composed of four recording sites: Rock South (R1), Valley Center (V1), Valley North (V2), and Rock North (R2), with downhole sensors at Rock South (D1) at 24m depth, and Valley Center at 10m depth in sediments (D2) and at 24m depth in bedrock (D3). A schematic representation of the instrument locations is shown in Figure 1. Each sensor location consists of 3-component forced-balance accelerometers. The strong-motion array was carefully maintained for 17 years by California Strong Motion Instrumentation Program (CSMIP).

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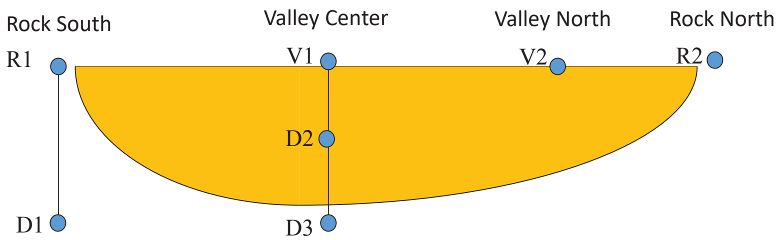

Figure 1. Instrument locations of Turkey Flat test site.

2.2 Subsurface conditions

Beginning in late 1987 and continuing through 1988, a comprehensive program of site characterization was carried out that included a broad range of field and laboratory geophysical and geotechnical tests (Real and Tucker 1988). The site-characterization program (Real and Tucker 1988) categorized the Turkey Flat test area as a shallow 25m deep stiff-soil site with depth to a half-width ratio of 1:40, consisting of unsaturated clayey sand and sandy clays. Repeated measurements during the wet and dry seasons show the water table generally remains below the sediment bedrock interface.

At the Rock South array, surficial materials consist of weathered sandstone that transitions to a lower degree of weathering at approximately 14 m. At the Valley Center array, the soil profile consists of dark-brown, silty clay near the surface (about 1.8–4.6 m), which is underlain by clayey sand to a depth of about 20 m. Underlying the soil materials is a sandstone bedrock profile similar to that at the Rock South. At the Valley North, the soil profile also consists of silty clay and clayey sand but the sandstone bedrock is shallow at a depth of about 10 m. Figure 2 shows the Vs data for the Valley Center site (V1–D3) and the Valley North site (V2) from a broad range of field geophysical and geotechnical tests along with mean ($\mp$ a standard deviation) profiles. The standard model profile provided by the Turkey Flat blind test program (Real and Shakal 2005) and the preferred model derived in this study (more detail described later) are also shown in Figure 2 for comparison. It can be seen that significant differences of Vs exhibit from different tests and the models.

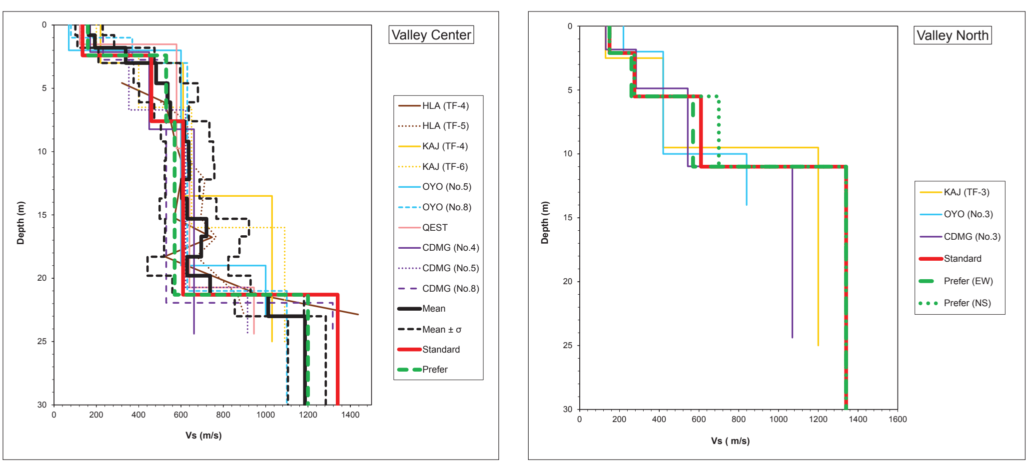

Figure 2. Vs profile at (a) the Valley Center and (b) Valley North.

2.3 Lab test data

In the site-characterization program (Real and Tucker 1988), cyclic laboratory testing was performed on specimens obtained from the Valley Center to measure nonlinear relationships between shear stress and shear strain and between the hysteretic-damping ratio and shear strain. The former is expressed in normalized form as modulus-reduction curves (G/Gmax curves), the later as damping ratio versus strain curves (D curves). Results obtained using resonant-column and cyclic-triaxial testing are plotted on the left-hand side of Figure 3 and the models used for analysis shown on the right hand side. The detail of these models and how the preferred models are derived will be described later. Generally, the different models generally show slight differences.

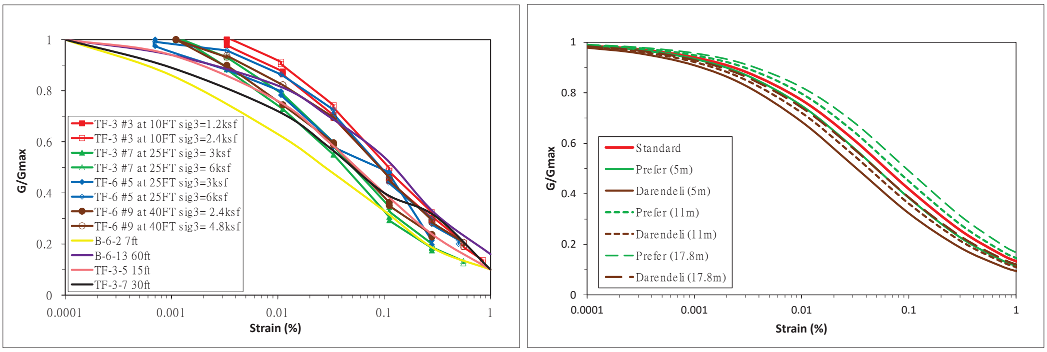

Figure 3. The G/Gmax curve of the soil.

2.4 Ground motion

A set of Turkey Flat ground motions produced by 11 earthquakes (Table 1) was collected by CSMIP. The 2004 Parkfield earthquake is part of this set, identified as Main in Table 1. Eight of the motions are aftershocks of the Parkfield mainshock with magnitudes ranging from 3.7 to 5.0. Other independent events include a 1993 Mw 4.2 event (Apr_93) located about 14 km from Turkey Flat, and the more distant Mw 6.5 San Simeon earthquake (San Simeon) from 2003.

Table 1. List of recorded motions.

Event	Date	Mw	PGA (g)													
			R1		D1		V1		D2		D3		V2		R2	
			EW	NS	EW	NS	EW	NS	EW	NS	EW	NS	EW	NS	EW	NS
Apr_93	1993/4/3	4.2	0.027	0.024	0.017	0.015	0.025	0.033	0.015	0.02	0.011	0.017	0.082	0.065	0.047	0.027
San Simeon	2003/12/22	6.5	0.032	0.035	-	0.034	0.032	0.036	0.025	0.027	0.021	0.019	0.03	0.031	0.022	0.023
Main	2004/ 9/28	6	0.244	0.195	-	0.163	0.293	0.294	0.132	0.119	0.07	0.065	0.255	0.256	0.105	0.108
As1	2004/ 9/28	4.2	0.052	0.05	-	0.041	0.173	0.094	0.08	0.056	0.041	0.022	0.072	0.052	0.034	0.024
As2	2004/ 9/28	4	0.02	0.045	-	0.039	0.071	0.074	0.021	0.023	0.012	0.011	0.04	0.054	0.011	0.013
As3	2004/ 9/28	3.7	0.009	0.016	-	0.015	0.024	0.026	0.01	0.013	0.005	0.006	0.024	0.026	0.003	0.006
As4	2004/ 9/28	3.6	-	-	-	-	0.007	0.006	0.005	0.004	0.003	0.003	-	-	-	-
As5	2004/ 9/28	3.1			-		0.019	0.013	0.008	0.005	0.004	0.003	-	-	-	-
As6	2004/ 9/28	4	0.012	0.01	-	0.006	0.049	0.03	0.025	0.01	0.009	0.006	0.024	0.022	0.007	0.008
As7	2004/ 9/29	5	0.016	0.013	-	0.012	0.042	0.031	0.026	0.023	0.017	0.015	0.037	0.036	0.03	0.023
As8	2004/ 9/29	3.8	-	-	-	-	0.006	0.007	0.004	0.004	0.003	0.003	-	-	-	-

3 Analysis Procedure

Because the Turkey Flat sedimentary valley is quite shallow with respect to its width (depth/width ≈ 0.02), wave propagation is approximated as a one-dimensional problem, with horizontal shear waves propagating vertically upwards through valley sediments. The predictions were made using DEEPSOIL site response analysis program to perform both one dimensional nonlinear and equivalent analysis.

The accuracy of prediction is assessed by residual as

$$R(T) = ln[S_a(T)]_{data} - ln[S_a(T)]_{pred} \quad (1)$$

$[S_a(T)]_{data}$ is the spectrum of recording and $[S_a(T)]_{pred}$ is the spectrum of prediction. Zero residuals indicate perfect prediction while the positive and negative residuals imply underestimation and overestimation of ground responses, respectively. The effects of the following uncertainties on the site response results are evaluated.

1. Input rock motions: R1, D3, or R2 where R1 and R2 are the outcrop motion and D3 is the within motion.
2. Shear-wave velocity profile: Standard model, preferred model, or mean profiles.
3. Nonlinear soil properties: Standard model, preferred model, or Darendeli generic curves (Darendeli 2001) that are widely used in engineering practice.
4. Analysis method: equivalent linear vs nonlinear method.

3.1 Preferred Vs profiles

Following the approach by Tsai and Hashash (2005), the preferred Vs profile was derived by adjusting the standard profiles until the best match of the theoretical spectral ratios and the empirical ones between V1, D2, and D3 was achieved. However, in addition to using spectral ratios in the Weak-Motion program (Cramer 1991), this study also adopted 7 additional weak motions (shown in Table 1, including 6 aftershocks of the Parkfield earthquake) to develop the preferred Vs profile. The anisotropic behavior of sediment in the valley (especially at the Valley North) is found through the matching process. Therefore, two Vs profiles, representing EW and NS direction, are proposed at the Valley North as indicated in Figure 2. Please note that the preferred Vs profiles yield to the best prediction under weak motions.

3.2 Preferred nonlinear curves

The preferred nonlinear curve is developed based on a review of the in-situ and laboratory test results from the Turkey Flat site characterization program (Real 1988). There are two sets of laboratory tests to measure the shear modulus reduction curve and damping curve in Turkey Flat site characterization program (Real 1988). One is performed by Dames and Moore and the other one is performed by OYO Corporation. The data shows an obvious difference between the nonlinear behavior of shallow (7 ft depth) sample and a deep (60 ft depth) sample as shown in Figure 3 (a). It implies that the nonlinear properties vary with depth (i.e. confining pressure). Therefore, pressure dependent parameters of DEEPSOIL are calibrated to represent these curves. Figure 3 (b) show the fit of pressure dependent curves from DEEPSOIL, which compare reasonably with the laboratory test results. The Darendeli curves based on the in-situ soil with PI=0 and OCR=1 (Kowk et al. 2008) is developed. As shown in Figure 3 (b), the standard curve exhibits a mean reduction of the pressure-dependent curves. In addition, the Darendeli generic curves exhibit more reduction (nonlinearity) compared to the preferred curve.

4 Analysis Result

4.1 Vs profile effect

Frequency domain linear analysis of weak motions was performed to evaluate the effect of Vs profile on the site response analysis. Figure 4 shows the average residuals of prediction of 7 weak motions (top) and the standard deviation (bottom). The residual by using the preferred profile is closer to zero compared to that of the standard profile and the mean profile, especially for the period less than 0.2 sec. In addition, the standard deviations are also reduced by using the preferred profile. The negative residual by using the standard model implies overestimation of site response for these period ranges, especially at the site period (~0.2 sec). The overestimation is because the standard model has a lower Vs at the depth from 3m to 8m than that of the preferred model that may be closer to the actual condition. The average residual of 7 weak motions by using the preferred model represents the baseline reference for the prediction of the strong event.

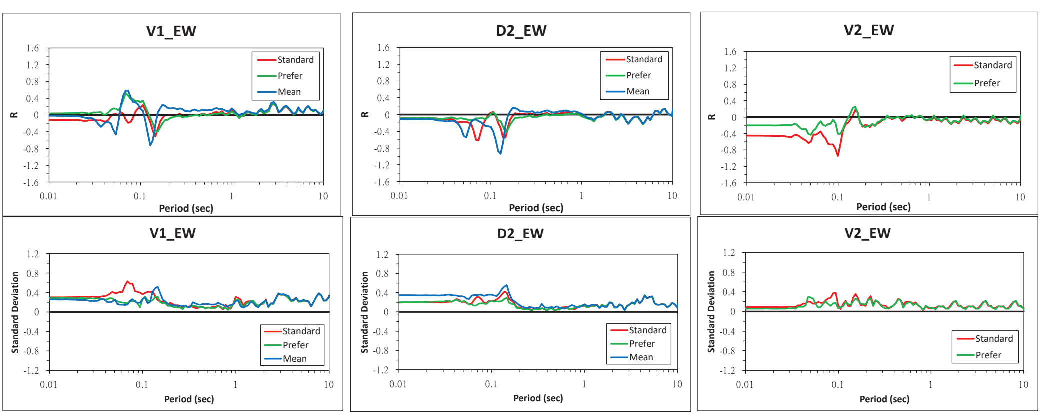

Figure 4. Average residual of prediction result of 7 weak motions.

4.2 Nonlinear curve effect

Figure 5 shows the residual of prediction of Parkfield main shake using the preferred Vs profile with different nonlinear curves. The results of the preferred nonlinear curve show very minor improvement compared to that of the standard curve. Meanwhile, the pressure-dependent generic curve also provided a good prediction as well. The result indicates that the influence of soil nonlinear curve is not significant.

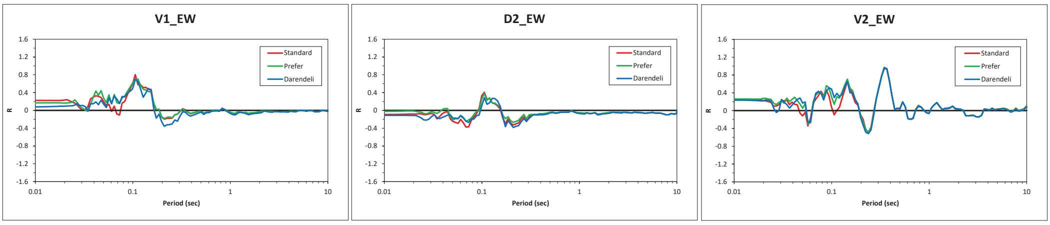

Figure 5. Residual of prediction using the different nonlinear curve.

4.3 Combining of Vs and nonlinear curve effect

The combing effect of Vs and nonlinear curve is evaluated using the standard model and the preferred model. Figure 6 shows that the prediction result using the preferred model is slightly worse (i.e. a little more residual) than that using the standard model. Compared to the residual shown in Figure 5, the residual is mostly attributed to the used Vs profile because the nonlinear curve does not cause much difference. The preferred Vs profile may be the best option for estimating the mean responses of 7 weak motions but it may induce more residual for a specific event (e.g. the main shake) compared to the standard profile.

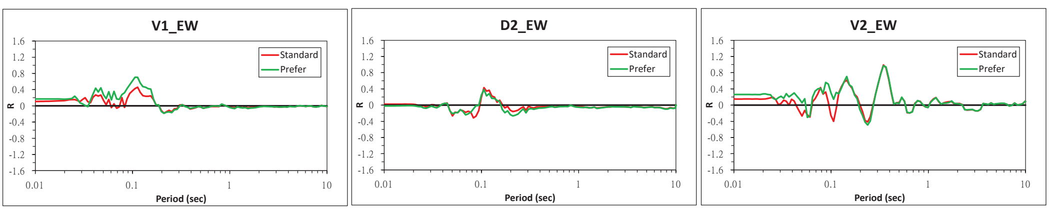

Figure 6. Residual of prediction using the standard model and the preferred model.

4.4 Analysis method effect

The range of predicted motions from equivalent linear and nonlinear analyses using the standard soil model using the D3 input motion are shown in Figure 7 for the EW components of the V1, D2, and V2 instruments (within the valley). The predicted motions can be seen to agree with each other quite well over a wide range of frequencies, although there were a number of outliers in different categories. In addition, the predicted spectra from both the equivalent linear and nonlinear analyses can be seen generally compatible. The analysis methods do not influence the prediction result of the stiff site excited by the moderate motion. Therefore, only the prediction by nonlinear analysis is presented in the later section.

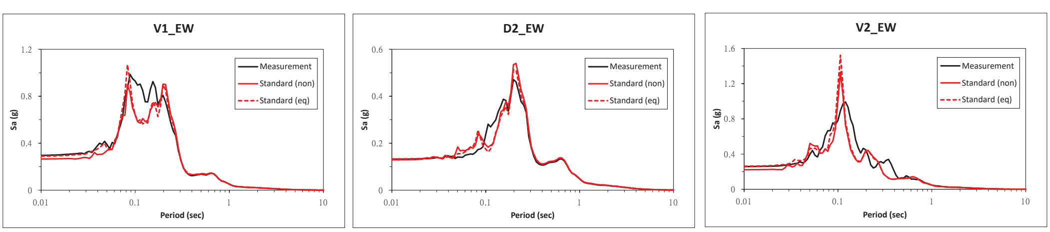

Figure 7. Predicted response by different methods using the standard model.

4.5 Input motion effect

Using R1 or R2 as input motion represents the common situation in which recorded bedrock outcrop motions are used as input to ground response analyses, and the Using R1 as input motion is a much less common situation in which a downhole record is used to excite a profile. Figure 8 shows the residual using 3 motions. The high variability indicates that input motions significantly affect the prediction result. Using R1 motion results in severe overprediction while using D3 provides the overall best results. However, it is interesting to see that the R2 motion results in the best prediction at the Valley North instead of the D3 motion. Characteristic of R1 is quite different from the other two records, especially for the NS component that exhibits high energy at the period of 0.5 sec. The similar features can be found in the San Simeon earthquake event. The R1 station could be located on different rock formation from the other two (Kramer 2009) or be contaminated due to the unknown reason. Therefore, selecting a rock input motion with special care is necessary to enhance the prediction results. On the other hand, the prediction of EW component is slightly better than that of NS component as indicated in Figure 8. This is may be due to that the valley is aligned in the EW direction that can be approximated as a 1D condition. As to the NS component, the south and north boundary of the valley may change the ground response within the valley due to the reflected waves.

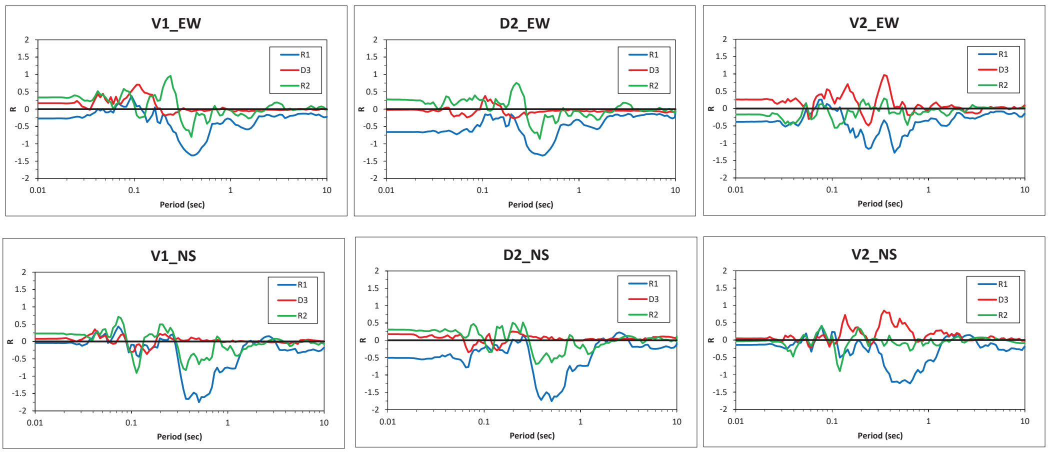

Figure 8. Residual of prediction using different input motions.

5 Conclusions

In this paper, we explore the different aspects/uncertainties that affect the accuracy of prediction at the Turkey Flat vertical array site during the 2004 Parkfield earthquake. The preferred Vs profile that was developed by the spectral ratio can improve the prediction results as compared to the standard profile provided by the program or the mean profiles typically used in the engineering practice. By contrast, the different nonlinear curves do not impact the result significantly for the moderate event. Moreover, the nonlinear and equivalent-linear ground-response analysis provide a similar result for this moderate event. However, the input motions mostly vary the prediction result significantly even though they are recorded in a close area. Therefore, selecting a rock input motion with special care is required to enhance the prediction results.

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