TURKEY FLAT GROUND MOTION PREDICTION – INITIAL REVIEW

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Abstract

This paper describes an investigation of the ground motions recorded at the Turkey Flat test site, and of the predictions of those motions in the blind prediction symposium that took place in 2006. The subject investigation is currently in its early stages, so the current paper focuses on the site, measured subsurface conditions, and some of the characteristics of the recorded motions. A brief summary of the results of the ground motion predictions is also provided.

Introduction

The California Geological Survey Strong Motion Instrumentation Program (CSMIP) established an instrumented site effects array in a shallow valley at Turkey Flat, located 8 km southeast of the town of Parkfield about 5 km east of the San Andreas Fault in central California. The array was intended to provide data with which to investigate the accuracy and consistency of current methods for estimating the effects of site conditions on ground surface motions (Tucker and Real, 1986). The array became operational in 1987 and was subjected to numerous episodes of weak shaking; a weak-motion blind prediction exercise was conducted in 1989 (Real and Cramer, 1989; Cramer and Real, 1990a,b; Cramer, 1991). On September 28, 2004, the M6.0 Parkfield earthquake occurred producing much higher levels of ground shaking than the array had previously experienced. This event provided the ground motion records required to conduct the long-anticipated strong motion blind prediction test. In the two-phase test, recorded rock motions were provided to predictors in March, 2005 with predictions due in October, 2005, then additional motions were provided in October, 2005 with predictions due in February, 2006. A symposium was held in September, 2006 to reveal and discuss the measured and predicted surface motions.

Following the prediction symposium, a project was initiated to (a) investigate recorded ground response at the Turkey Flat array at different levels of shaking in multiple events, (b) evaluate equivalent linear and nonlinear blind predictions of site response in the September 28, 2004 Parkfield earthquake, (c) investigate differences between predicted and recorded motions at the various instrument locations, and (d) summarize lessons learned, recommended practices, and beneficial uses of strong motion records in site response prediction. Since the project was only recently begun, this paper provides a review of the Turkey Flat site, the recorded motions, and differences between the predicted and recorded ground motions from the prediction symposium.

Turkey Flat

The Turkey Flat site is located in a northwest-trending valley within the central California Coastal Range. The valley is filled with a relatively thin layer of stiff alluvial sediments with basement rock outcrops at the south and north ends of the valley (Figure 1). The valley is about 6.5 km long and 1.6 km wide, and is bounded on the north and east by the Maxim fault at the western flank of Table Mountain and on the south and west by a gentle topographic high (Real, 1988) near the Gold Hill fault. The valley is aligned with the southwest-plunging Parkfield syncline in which approximately 1 km of Upper Cretaceous and Tertiary strata overlying Franciscan basement are folded into a U-shape that dip at about 50^{o} and 70^{o} on the southwest and northwest flanks, respectively. The rock immediately underlying the valley sediments is sandstone of the Etchegoin formation.

Instrumentation Array

The Turkey Flat test site includes four recording sites – Rock South (labeled as R1 in Figure 1), Valley Center (V1), Valley North (V2), and Rock North (R2). Surface instruments were installed at each of these sites, and downhole instruments were also installed at the Rock South and Valley Center (Figure 2) sites. Downhole instrument D1 was located at a depth of approximately 24 m at the Rock South site, and downhole instruments D2 and D3 were located at depths of approximately 10 m and 24 m, respectively, at the Valley Center site. Instrument D3 was located about 1 m below the soil/rock boundary at the Valley Center site. Each instrument location included a three-component forced-balance accelerometer and a velocity transducer with 12-bit solid-state digital recording. CSMIP also established and maintained a 45-station wide-aperture strong-motion array across the Parkfield segment of the San Andreas fault several km from the Turkey Flat test site (McJunkin and Shakal, 1983).

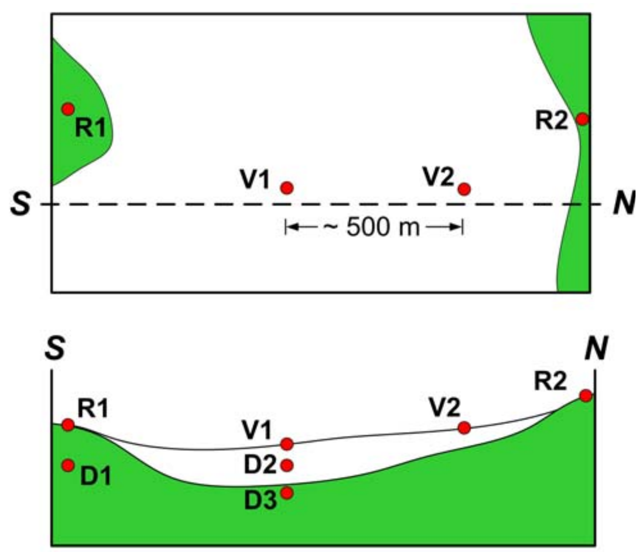

Figure 1. Schematic illustration of Turkey Flat instrumentation layout (after Tucker and Real, 1986).

Figure 2. Valley Center site looking west (after Real et al., 2006).

Subsurface Conditions

The Etchegoin sandstone formation underlies the alluvial sediments and outcrops at the borders of the valley. 25-m-deep boreholes at the southern outcrop showed medium brown to tan, highly friable sandstone with subangular to rounded, well-sorted grains composed of about 50% quartz (Real, 1988). The sandstone took on a bluish-gray color at a depth of about 14 m, which is believed to be the depth below which it remains saturated. Sandstone velocities (p- and s-wave) were measured by downhole, crosshole, and suspension logging tests; the results were interpreted as indicating two primary zones – an approximately 2.4-m-thick upper zone with V_s = 200 – 800 m/sec, and a lower zone with V_s = 700 – 1,500 m/sec. Review of individual logs indicates that the lower-velocity zone could extend to depths of approximately 6 m. Laboratory density measurements from samples in the upper 20 m showed relatively constant dry densities of 1.90 – 1.95 g/cm^3 and saturated densities of 2.20 – 2.23 g/cm^3.

The valley sediments were investigated by seismic reflection and refraction profiling, and by the installation of a dozen borings with sampling and insitu testing. The collective information was interpreted as indicating three primary soil units (Real, 1988). The upper unit consists of dark brown silty clay (at the Valley Center) to sandy clay (at Valley North). The middle unit consists predominantly of clayey sand that contains more gravel and sandy clay at the Valley North site than at the Valley Center. The lower unit fine to medium clayey sand with gravel. Shear wave velocities ranged from about 150 m/sec (Valley Center) to 135 m/sec (Valley North) in the upper unit, 460 m/sec (Valley Center) to 275 m/sec (Valley North) in the middle unit, and about 610 m/sec across the valley in the lower unit. The measured shear wave velocity data was used to construct "standard" profiles at the Rock South and Valley Center sites (Figure 3). Participants in the strong motion prediction exercise were required to make a prediction based on the standard profile, and encouraged to make another prediction using a "preferred" velocity profile based on their own interpretation of the field and laboratory velocity data.

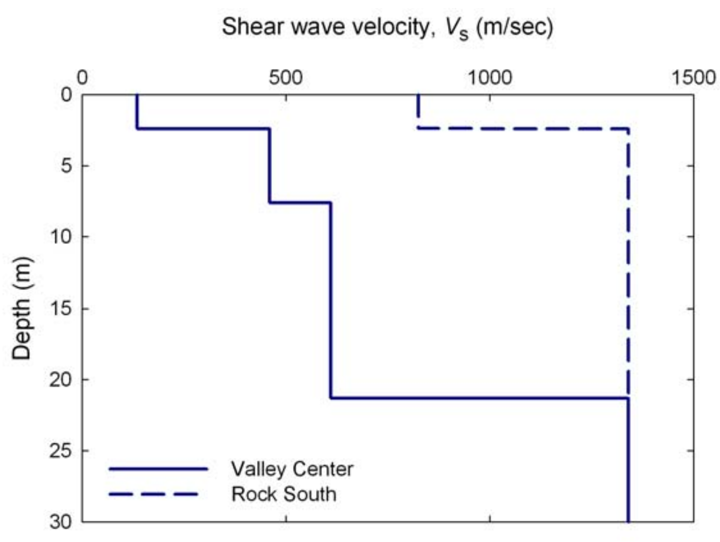

Figure 3. Standard shear wave velocity profiles for Valley Center and Rock South locations (after Real, 1988).

The September 28, 2004 Parkfield Earthquake

After some 17 years of operation, the Turkey Flat test site was subjected to strong ground shaking in the September 28, 2004 Parkfield earthquake. The earthquake was very well-documented and produced an extensive, dense set of near-fault strong motion records with measured peak accelerations of 2g or higher (Shakal et al., 2006a,b). The peak accelerations at the distance of the Turkey Flat test site were generally 0.3g or less.

Recorded Ground Motions

The acceleration time histories recorded at the Rock South and Valley Center arrays are shown in Figure 4. The time histories suggest a modest degree of amplification within the sandstone at the Rock South site; the NS component of the rock surface has a peak acceleration of 0.24g compared with a NS peak acceleration of 0.19g at the 24-m-deep R1 instrument. They also suggest a high degree of amplification at the Valley Center site; the NS peak accelerations at the ground surface (V1), mid-depth (D2), and rock (D3) instruments 0.29g, 0.12g, and 0.06g, respectively.

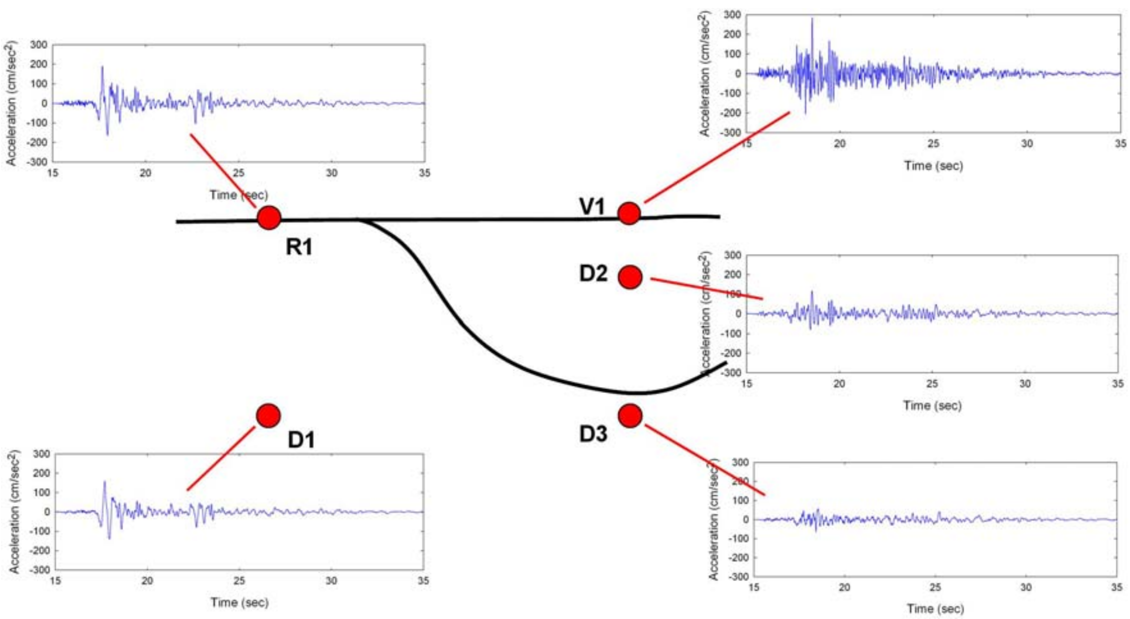

Figure 4. Time histories of North-South accelerations recorded at Rock South and Valley Center downhole arrays in September 28, 2004 Parkfield earthquake.

Response spectra for both components of the recorded motions are shown in Figure 5. At each instrument location, the NS and EW spectra are quite consistent, although the EW component of the D1 instrument was not recorded due to instrument malfunction. Nevertheless, the NS spectra at R1 and D1 are quite consistent, particularly at periods above about 0.3 sec where they are nearly identical. The R1 and D1 spectra are also nearly linear (in log-log space) over that range of periods. The NS response spectrum for the D3 instrument, which was located at the same depth below the Valley Center surface as the D1 instrument was below the Rock

South surface, is significantly weaker than the D1 spectrum at periods less than about 1.5 sec. The D3 spectrum also shows local peaks and valleys at periods above 0.3 sec, suggesting that some level of response not observed in the D1 record is occurring below a depth of 24 m at the Valley Center site.

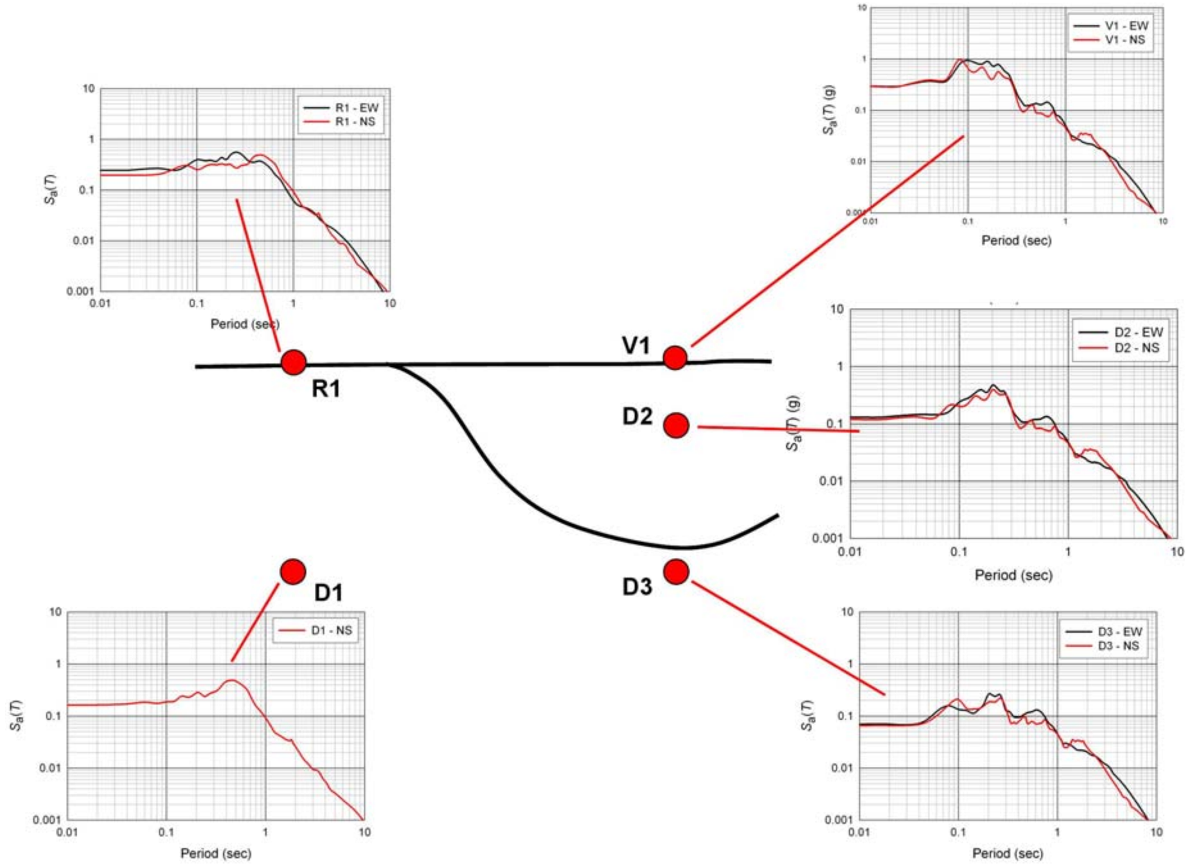

Figure 5. Response spectra from motions recorded at Rock South and Valley Center downhole arrays in September 28, 2004 Parkfield earthquake. EW component of D1 instrument was not recorded due to instrument malfunction.

Predicted Ground Motions

The strong motion prediction exercise was conducted in two phases. In the first phase, participants were provided with all available subsurface data and the recorded R1 motions, and asked to predict the response of the Valley Center profile. In the second phase, which was not initiated until all first-phase predictions had been received, participants were provided with the D3 motions and asked to predict the D2 and V1 motions. The first phase was therefore intended to represent the common situation in which recorded bedrock outcrop motions are used as input to ground response analyses, and the second to the much less common situation in which a downhole record is used excite a profile. Differences in the motions predicted by the two approaches depend on the extent to which the recorded downhole motion is similar to the “within profile” motion inferred from the rock outcrop motion and the assumed halfspace velocity.

Phase 1 Predictions

The range of predicted motions from equivalent linear analyses in the first phase are shown in Figure 6; the predictions of nonlinear analyses, though not shown here, were quite consistent with those of the equivalent linear analyses. The motions can be seen to agree with each other reasonably well, particularly at periods exceeding about 0.5 sec. The predicted spectra generally retain the linear nature of the R1 spectrum at periods greater than about 0.5-0.6 sec. Figure 7 shows the mean predicted spectrum along with the response spectrum for the recorded NS component at the Valley Center site (V1). The predicted spectra can be seen to greatly overpredict the recorded motions over a significant range of periods – approximately 0.3 – 1.5 sec.

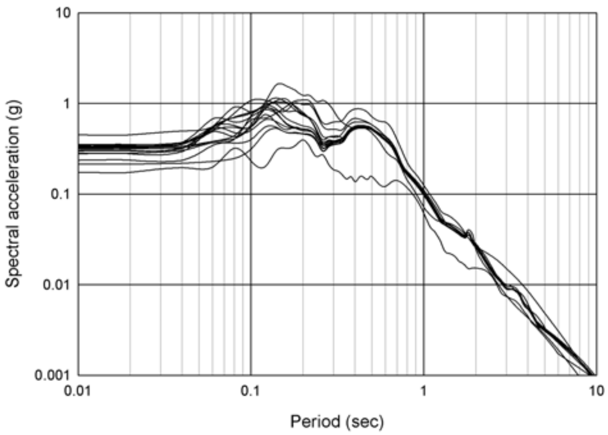

Figure 6. Equivalent linear predicted NS motions at surface of Valley Center site. Mean predicted spectrum indicated by bold line.

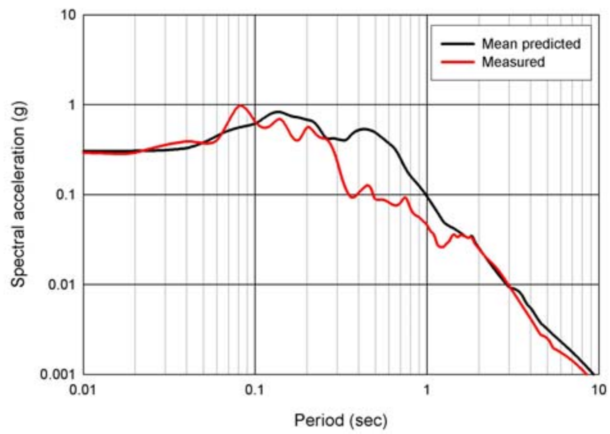

Figure 7. Recorded and mean equivalent linear predicted NS motions at surface of Valley Center site.

Phase 2 predictions

The second phase analyses were performed using the measured bedrock at the Valley Center site (D3) as the inputs to the Valley Center profile. The range of predicted motions from equivalent linear analyses in the second phase are shown in Figure 8; the predictions of nonlinear analyses were also quite consistent with those of the equivalent linear analyses. As in the case of the Phase 1 analyses, the predicted motions can be seen to agree with each other quite well over a wide range of frequencies. Figure 9 shows the mean predicted spectrum along with the response spectrum for the recorded NS component at the Valley Center site (V1). The predicted spectra can be seen to match the recorded motions very well over a broad range of periods. Due primarily to differences in the preferred velocity profiles selected by the predictors, the individual predicted spectra begin to differ from each other (and the mean, albeit modestly, from the actual) at periods less than about 0.2 sec.

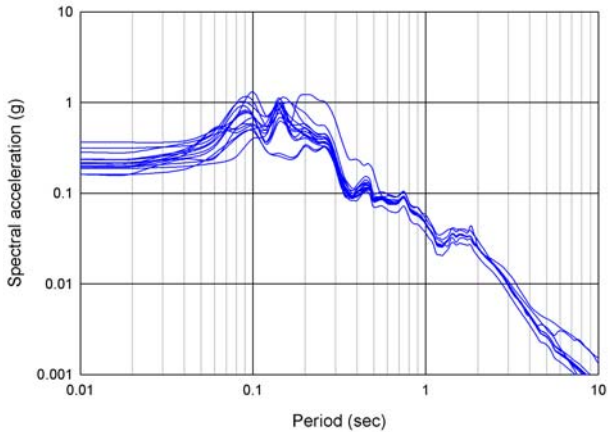

Figure 8. Equivalent linear predicted NS motions at surface of Valley Center site. Mean predicted spectrum indicated by bold line.

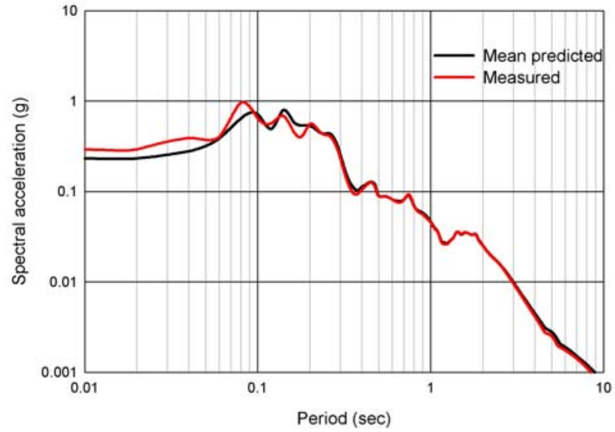

Figure 9. Recorded and mean equivalent linear predicted NS motions at surface of Valley Center site.

Comments

The high quality of the Phase 2 predictions (both equivalent linear and nonlinear), in which the Valley Center profiles selected by the participants were excited by the actual bedrock motions, indicates that (a) the site responded essentially one-dimensionally, as intended by the site developers, (b) the site responded essentially linearly in the 2004 Parkfield event, and (c) one-dimensional equivalent linear and nonlinear analyses were able to predict the measured surface response very well when the input motion was known accurately.

The low quality of the Phase 1 predictions, in which the Valley Center profiles were excited by modified versions of the Valley North rock outcrop motions, indicates that the common process of estimating within profile rock motions from nearby rock outcrop motions was not accurate, as applied by the predictors, in this particular case. This estimation process is affected by the characteristics of the rock at the rock outcrop, the characteristics of the rock and soil at the site to be analyzed, the characteristics of the measured rock outcrop motion, and the distance between the rock outcrop and the site at which the rock outcrop motion is to be used.

Preliminary Analyses

Of immediate interest is the reason for the difference in accuracy between the Phase 1 and Phase 2 predictions. Developing an understanding of the measured response requires a close look at the responses of both the Rock South and Valley Center profiles.

A sense of the response of the Rock South profile can be gained by examining at the R1 and D1 motions. The standard velocity profile for the Rock South site (Figure 3) shows a 2.4-m-thick layer of weathered sandstone with Vs = 825 m/sec. Using the familiar expression, $T = 4H/V_s$, implies that the shallow weathered sandstone layer would have a fundamental period of 8.6 Hz. As shown in Figures 4 and 5, the recorded R1 and D1 motions are quite similar in appearance (note that the EW component of the D1 motion was not recorded). Figure 10 shows the two motions plotted together, the variation with time of the difference between the two motions, and a spectrum of wavelet coefficients for the difference time history. The upper plot confirms that the motions are quite similar in amplitude and phasing, and shows that the largest difference occurs during the strongest part of the motion, i.e., from about 17.5 – 19 sec. The middle plot confirms that observation, and the lower plot shows that the difference between the motions has a predominant frequency of about 8 – 10 Hz during that period of time. The “extra” ground surface response, therefore, appears to be consistent with excitation of the surficial weathered sandstone layer as characterized by the standard model; of course, this result could be caused by many combinations of weathered layer thickness and velocity.

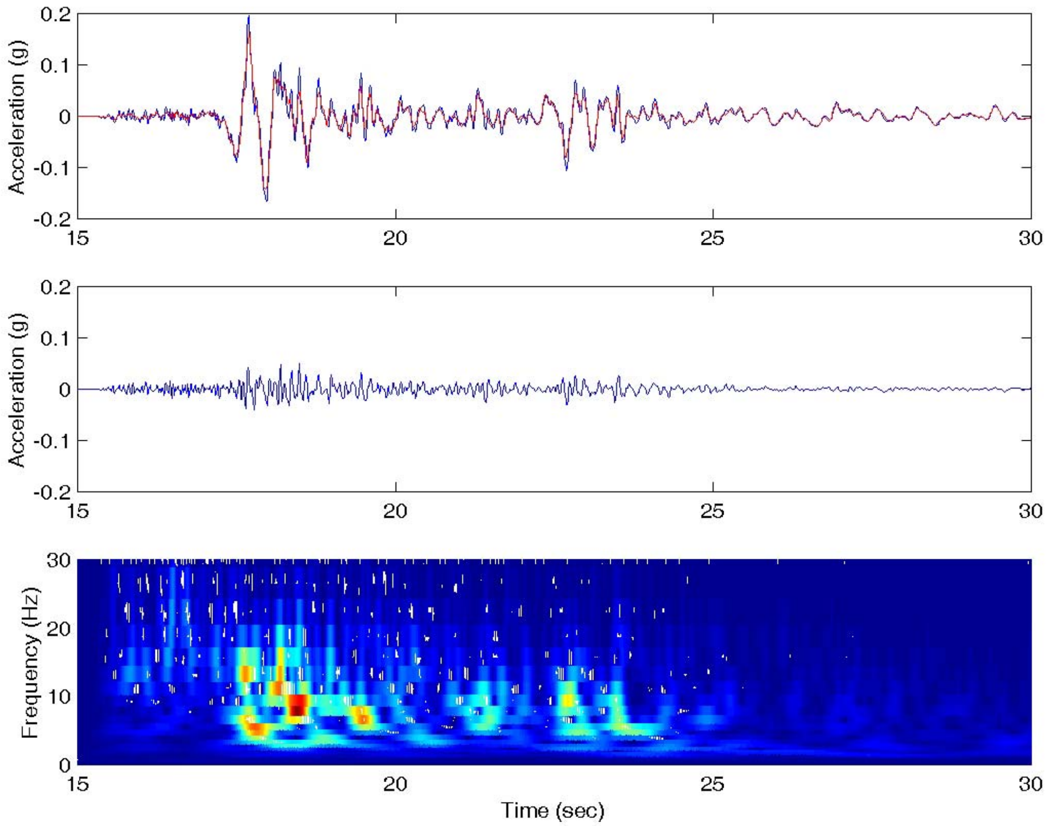

Figure 10. Rock South profile measurements: (upper) R1 (blue) and D1 (red) motions; (middle) R1 – D1 motion; and (lower) wavelet amplitudes vs. frequency and time for R1 – D1 motion.

The consistency of the R1 and D1 motions indicates that the Rock South profile behaved as expected and in a manner consistent with the standard Rock South velocity profile. The consistency of the V1 and D3 motions, and the accuracy with which the V1 motions could be predicted from the D3 motions, indicates that the upper 24 m of the Valley Center site behaved as expected. What is unexpected, therefore, is the relationship between the Rock South motions (at both R1 and D1) and the measured D3 motion. The expected D3 within-profile motion can be computed by using the preferred Valley Center profile with the measured R1 rock outcrop input motions. Figure 11 shows the measured and computed D3 motions corresponding to both components of the R1 record. Figure 12 shows the corresponding response spectra.

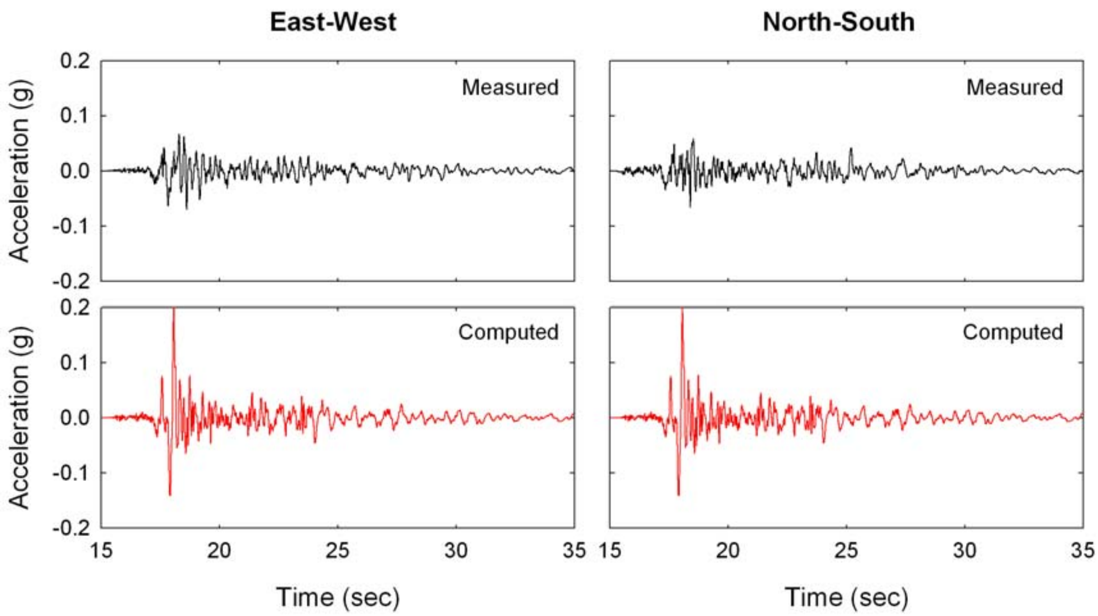

Figure 11. Measured and computed motions at location of D3 instrument. Computed motions are within-profile measurements based on measured R1 motions.

Using the standard Valley Center velocity profile, the computed D3 motions are much stronger than the measured motions in both the EW and NS directions, except at low frequencies (i.e., below about 0.5 Hz). The ratio of response spectra appears to have local maxima at periods of about 0.13 and 0.4 sec.

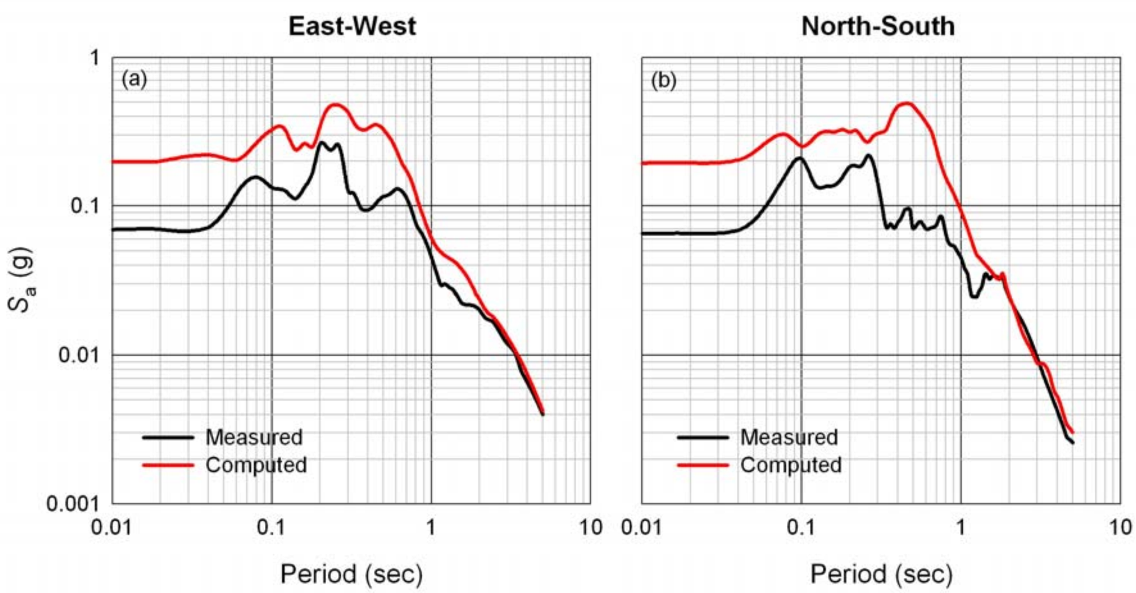

Figure 12. Measured and computed response spectra at location of D3 instrument. Computed motions are within-profile measurements based on measured R1 motions.

Figure 13 shows the computed and recorded NS components of the D3 record, and a plot of the ratio of the (natural logarithm of) wavelet coefficients of the two motions. The wavelet amplitude ratios indicate that the computed motion exceeds the recorded motion by the greatest amount at frequencies of about 2 and 6 Hz, and that those frequencies remain relatively stable over the duration of the motion.

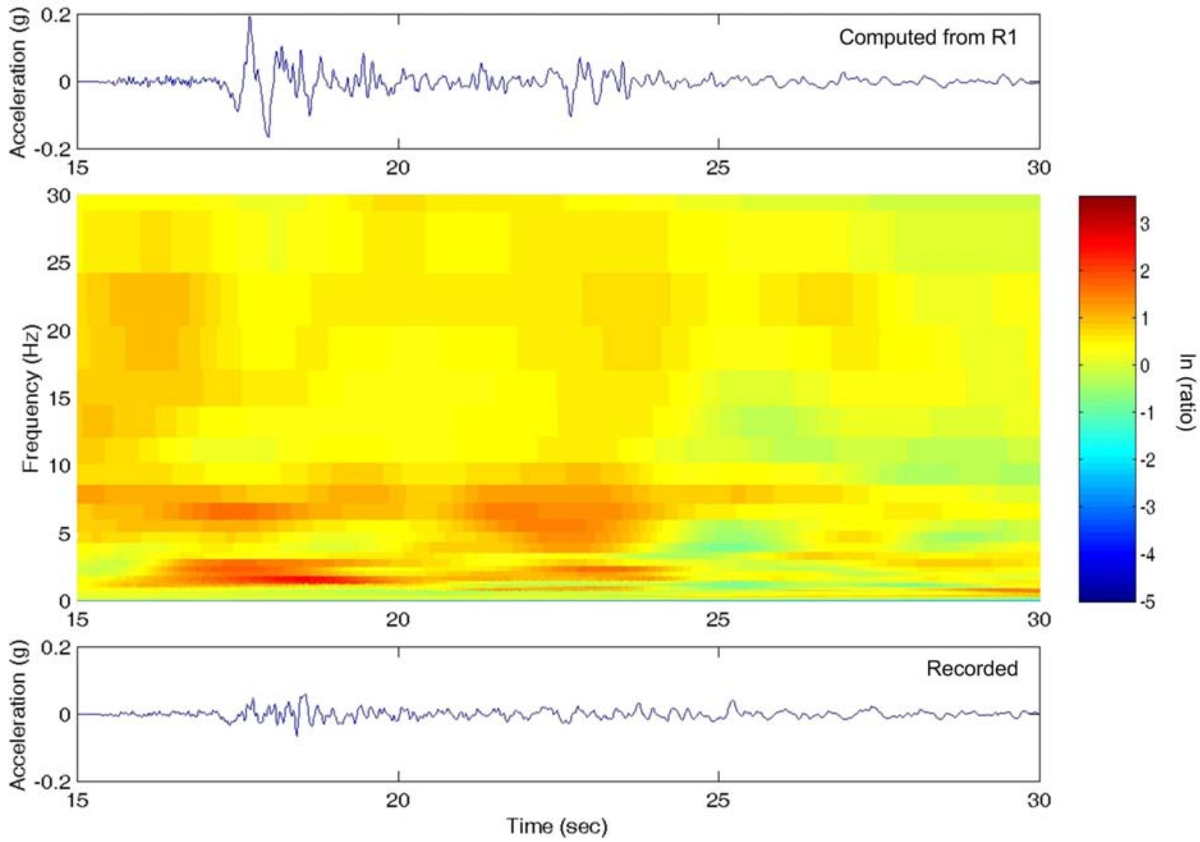

Figure 13. Time histories of NS component of D3 motion computed from R1 motion and recorded, and ratio of wavelet amplitudes (computed:recorded).

The Rock South array, at which the R1 motion was measured, is approximately 800 m from the Valley Center array. The Rock North station, at which the R2 motion was measured, is only about 300 m farther from the Valley Center array. If the Rock South motions were not available, it is likely that practicing geotechnical engineers would use the Rock North (R2) motions to predict the response at V1. Time histories from this type of analysis are shown in Figure 14. The V1 motions computed for the standard Valley Center velocity profile using both R2 components as inputs are significantly closer to the measured motions than those computed using the R1 motions as inputs. Figure 15 shows the response spectra from the motions in Figure 14; the computed spectra based on the R2 motions are much more consistent (though with some overprediction and underprediction in the 0.2 – 0.7 sec period range of the EW component, and overprediction from about 0.3 – 0.7 sec for the NS component) with the measured motions than those based on the R1 motions.

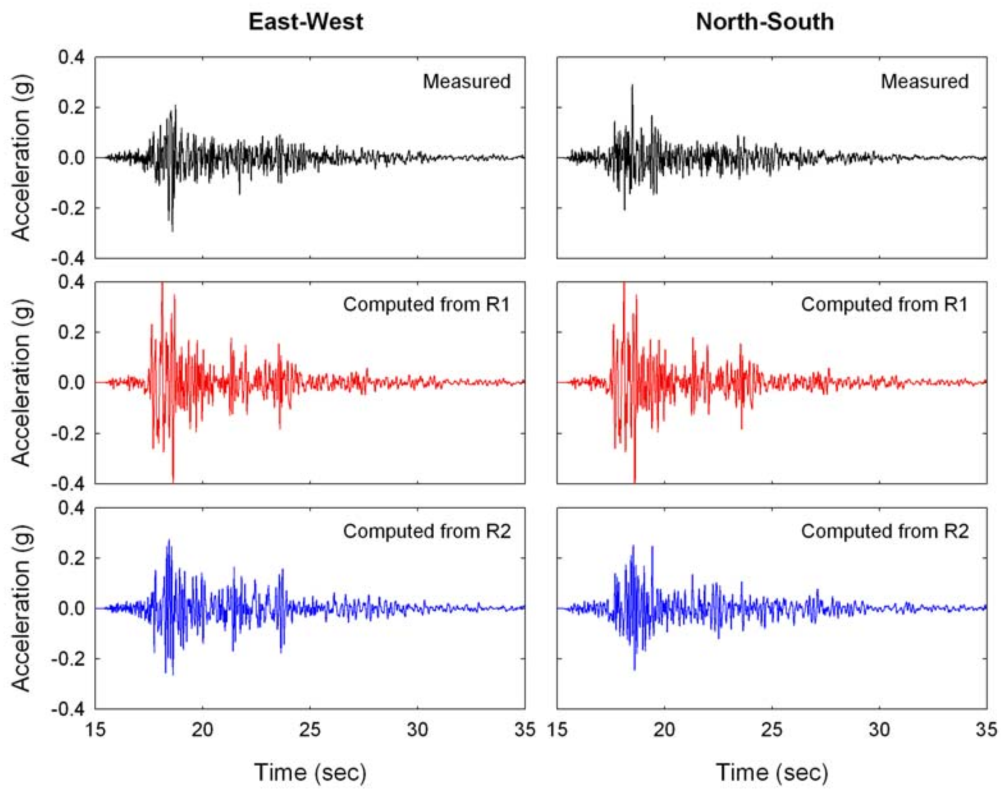

Figure 14. Measured and computed time histories for V1 instrument at Valley Center site.

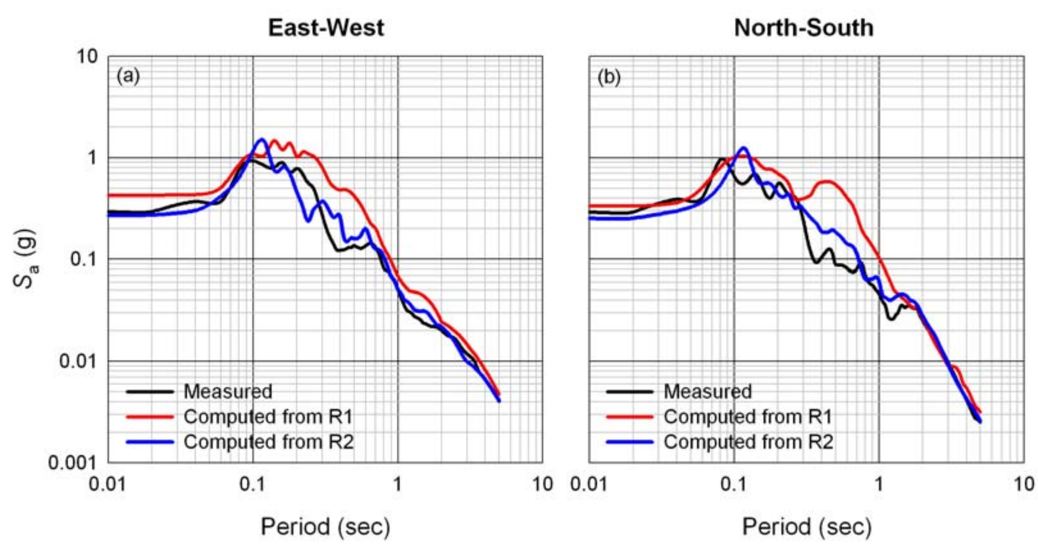

Figure 15. Measured and computed time histories for V1 instrument at Valley Center site.

Discussion

The strong motions recorded at the Turkey Flat instrumented site effects array raise some interesting questions about site characterization and response in both rock and soil materials. The response of the Rock South array appears to be consistent with one-dimensional response through the standard velocity model for that location, given the input motion recorded at 24 m depth. The response of the Valley Center array also appears to be consistent with one-dimensional response through its standard velocity profile, given the input motion recorded at 24 m depth below that site. Predictions of the Valley Center response using the Rock South input motions, however, are not consistent with the measured response. Similar predictions using the Rock North input motions are much closer to the measured response, even though the Rock North site is farther from the Valley Center array than the Rock South site.

As stated previously, an investigation of the Turkey Flat response and its prediction in the strong motion blind test was recently begun. The project will involve detailed comparison of the predicted and observed motions with consideration of different methodologies, velocity profiles, material models, and other considerations. The lessons learned from the Turkey Flat tests will be evaluated and recommendations for site response calculations presented.

References

Cramer, C.H. (1991). "Turkey Flat, USA Site Effects Test Area – Report 6, Observations and Modeling," California Division of Mines and Geology, ESAU Technical Report No. 91-1, 92 pp.

Real, C.R. and Cramer, C.H. (1989). "Turkey Flat, USA Site Effects Test Area – Report 3, Weak Motion Test: Prediction Criteria and Input Rock Motions," California Division of Mines and Geology, ESAU Technical Report No. 89-1, 48 pp.

Cramer, C.H. and Real, C.R. (1990a). "Turkey Flat, USA Site Effects Test Area – Report 4, Weak Motion Test: Observed Seismic Response," California Division of Mines and Geology, ESAU Technical Report No. 89-1, 28 pp.

Cramer, C.H. and Real, C.R. (1990b). "Turkey Flat, USA Site Effects Test Area – Report 5, Weak Motion Test: Statistical Analysis of Submitted Predictions and Comparison to Observations," California Division of Mines and Geology, ESAU Technical Report No. 90-2, 57 pp.

McJunkin, R.D. and Shakal, A.F. (1983). "The Parkfield Strong-Motion Array," *California Geology*, Vol. 36, No. 2, pp. 27-34.

Real, C.R. (1988). "Turkey Flat, USA Site Effects Test Area – Report 2: Site Characterization," California Division of Mines and Geology, ESAU Technical Report No. TR 88-2, 39 pp.

Real, C.R., Shakal, A.F., and Tucker, B.E. (2006). "Turkey Flat, U.S.A. Site Effects Test Area: Anatomy of a Blind Ground-Motion Prediction Test," Third International Symposium on the Effects of Surface Geology on Seismic Motion, Grenoble, France, Paper Number KN 3, pp. 1-19

Shakal, A., H. Haddadi, V. Graizer, K. Lin and M. Huang (2006a). Some key features of the strong motion data from the M6.0 Parkfield, California, earthquake of 28 September 2004, *Bulletin of the Seismological Society of America*, Vol. 96, No. 4B, S90-S118.

Shakal, A., H. Haddadi and M. Huang (2006b). Note on the very high-acceleration Fault Zone 16 record from the 2004 Parkfield earthquake, *Bulletin of the Seismological Society of America*, Vol. 96, No. 4B, S119-S142.

Tucker, B. and Real, C.R. (1986). "Turkey Flat, USA Site Effects Test Area – Report 1: Needs, Goals, and Objectives," TR 86-1, California Department of Conservation, Division of Mines and Geology, 16 pp.