ANALYSIS OF TURKEY FLAT GROUND MOTION PREDICTION EXPERIMENT – LESSONS LEARNED AND IMPLICATIONS FOR PRACTICE

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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 two-phase prediction experiment attracted numerous participants using several approaches to ground motion modeling and site data interpretation. The results of the Phase 1 predictions showed strong consistency in the predicted motions, but significant differences between the predicted and recorded motions. The Phase 2 predictions were also consistent and were also quite accurate. The paper reviews the basic experiment, summarizes the results of the Phase 1 and 2 predictions, examines potential explanations for the differences between the predicted and observed motions, and comments on lessons learned and implications for site response practice.

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. This paper summarizes the results of that project.

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 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).

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). 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.

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 is 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 2). 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.

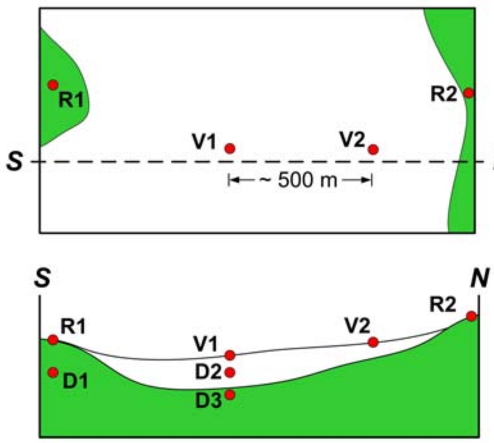

Figure 1. Schematic illustration of Turkey Flat instrumentation layout (after Tucker and Real, 1986).

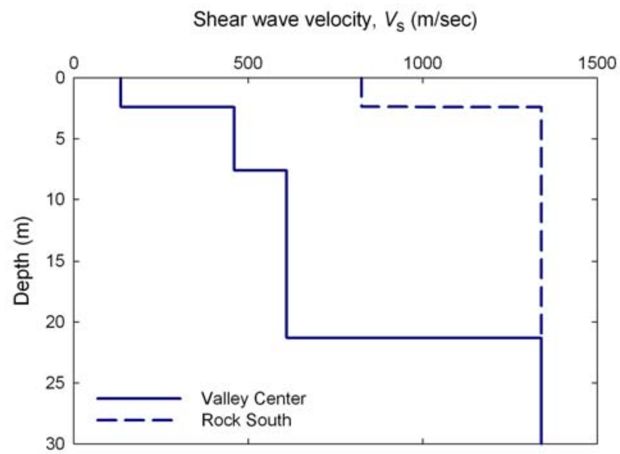

Figure 2. Standard shear wave velocity profiles for Valley Center and Rock South locations (after Real, 1988).

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 3. 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. Response spectra for the EW and NS components of the motions were consistent with each other.

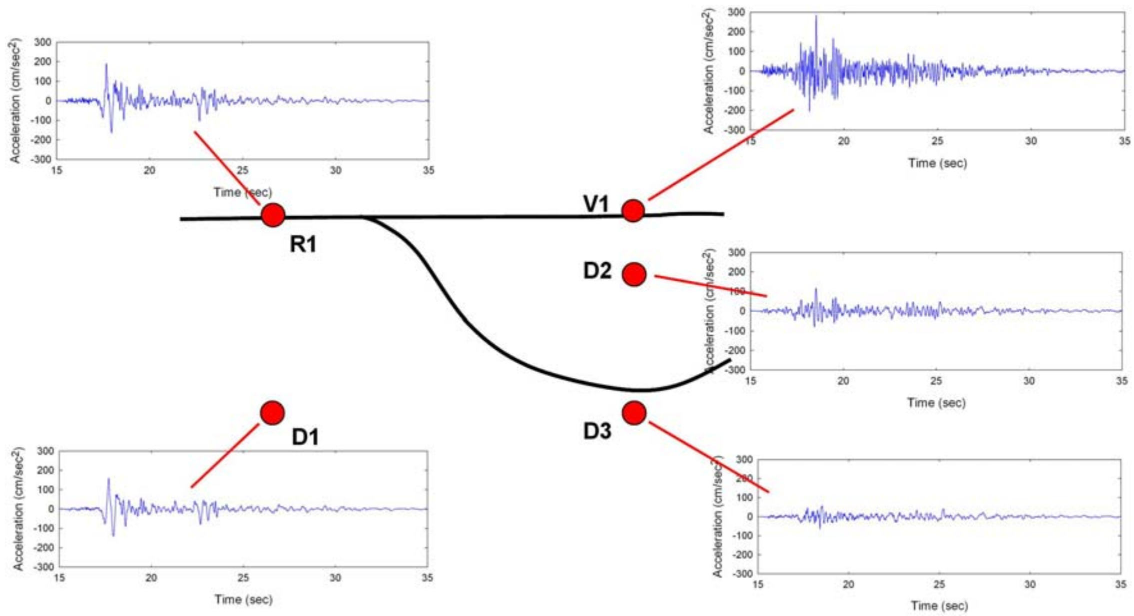

Figure 3. Time histories of North-South accelerations recorded at Rock South and Valley Center downhole arrays in September 28, 2004 Parkfield earthquake.

Other Events

A set of Turkey Flat ground motions produced by eight earthquakes (Table 1) was collected and provided to the earth science community by CSMIP. The 2004 Parkfield earthquake is part of this set, identified as Event 3 in Table 1. Five of the motions are aftershocks of the Parkfield mainshock with magnitudes ranging from 3.7 to 5.0. Other independent events include a 1993 M_w 4.2 event (Event 1) located about 14 km from Turkey Flat, and the more distant M_w 6.5 San Simeon earthquake from 2003.

Table 1 Events producing moderate to strong motion at Turkey Flat (after Haddadi et al., 2008).

Event No.	Event Name	Date	Time	M_w	Epicenter		Distance from Epicenter to:				PGA @ Surface			
					Lat	Lon	RS	VC	VN	RN	RS	VC	VN	RN
1	Apr-93	4/3/1993	21:21:24	4.2	35.942	120.493	14.1	14.5	14.3	13.9	0.026	0.033	0.081	0.047
2	San Simeon	12/22/2003	11:15:56	6.5	35.710	121.100	69.6	70.4	70.6	70.6	0.035	0.036	0.031	0.023
3	Parkfield	9/28/2004	10:15:24	6.0	35.810	120.370	7.6	8.2	8.6	9.2	0.245	0.300	0.260	0.110
4	Aftershock	9/28/2004	10:19:24	4.2	35.844	120.402	5.5	6.3	6.6	7.0	0.052	0.170	0.072	0.034
5	Aftershock	9/28/2004	10:24:15	4.7	35.810	120.350	7.6	8.0	8.4	9.1	0.046	0.074	0.053	0.013
6	Aftershock	9/28/2004	10:33:56	3.7	35.815	120.363	7.0	7.5	8.0	8.6	0.016	0.026	0.026	0.006
7	Aftershock	9/28/2004	12:31:27	4.0	35.840	120.390	5.1	5.9	6.3	6.7	0.012	0.049	0.024	0.008
8	Aftershock	9/29/2004	10:10:04	5.0	35.954	120.502	15.5	15.9	15.7	15.2	0.016	0.042	0.037	0.030

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 (i.e., the D3, D2, and V1 motions). 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

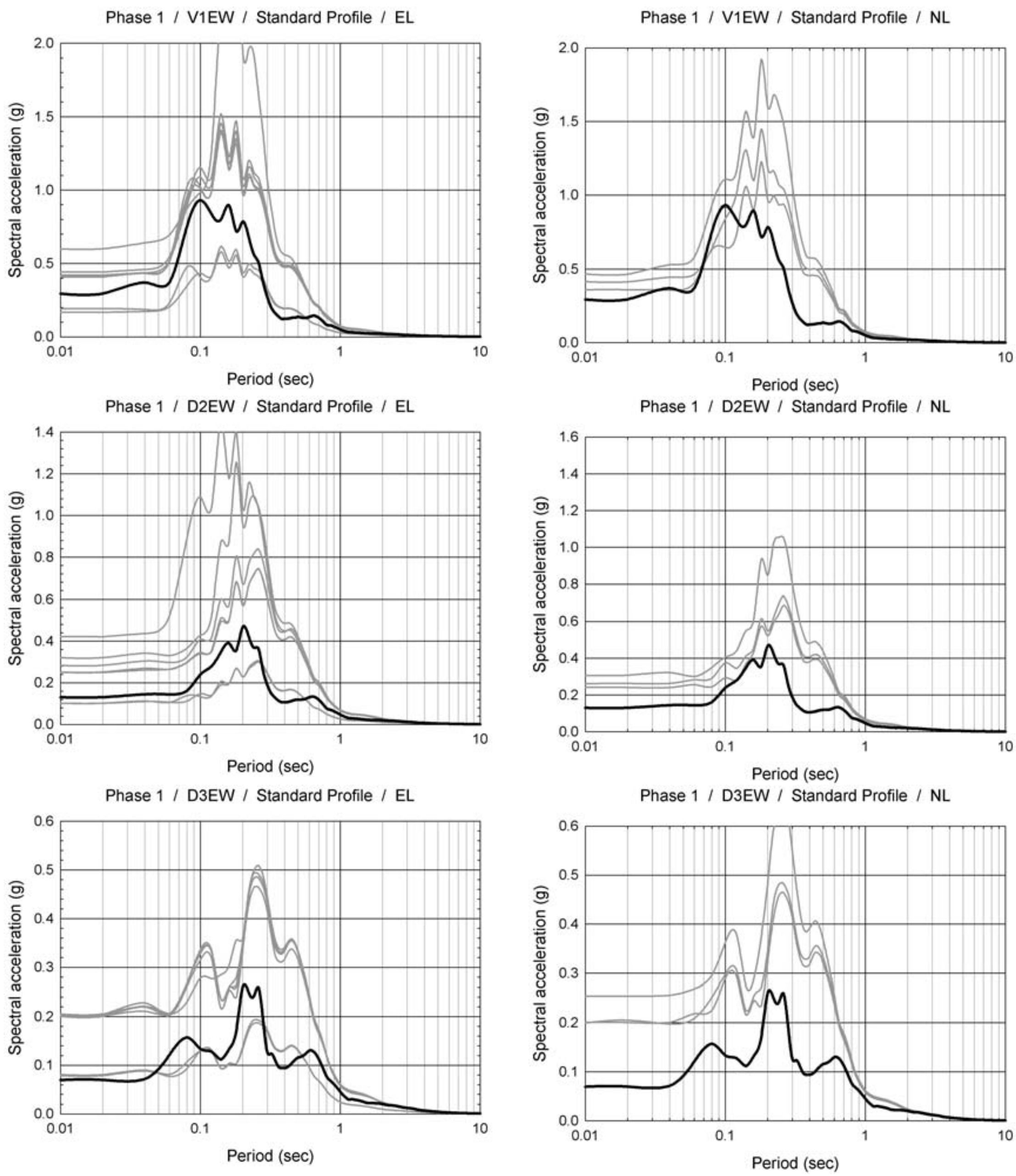

Figure 4. EW response spectra from Phase 1 predicted (gray) and recorded (black) motions.

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.

Phase 1 Predictions

The range of predicted motions from equivalent linear and nonlinear analyses using the standard soil model in the first phase are shown for the EW components of the V1, D2, and D3 instruments in Figure 4. The motions can be seen to agree with each other reasonably well, particularly at periods exceeding about 0.3 sec, although there were a number of outliers in different categories. The predicted spectra from both the equivalent linear and nonlinear analyses can be seen to greatly overpredict the recorded motions over a significant range of periods. This overprediction occurs at all three depths within the Valley Center profile.

Phase 2 Predictions

The second phase analyses were performed using the measured bedrock motions at the Valley Center site (D3) as the inputs to the Valley Center profile. The range of predicted EW motions from equivalent linear and nonlinear analyses in the second phase are shown in Figure 5. 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. The Phase 2 predicted spectra can be seen to match the recorded motions well over a much broader range of periods than the Phase 1 predictions.

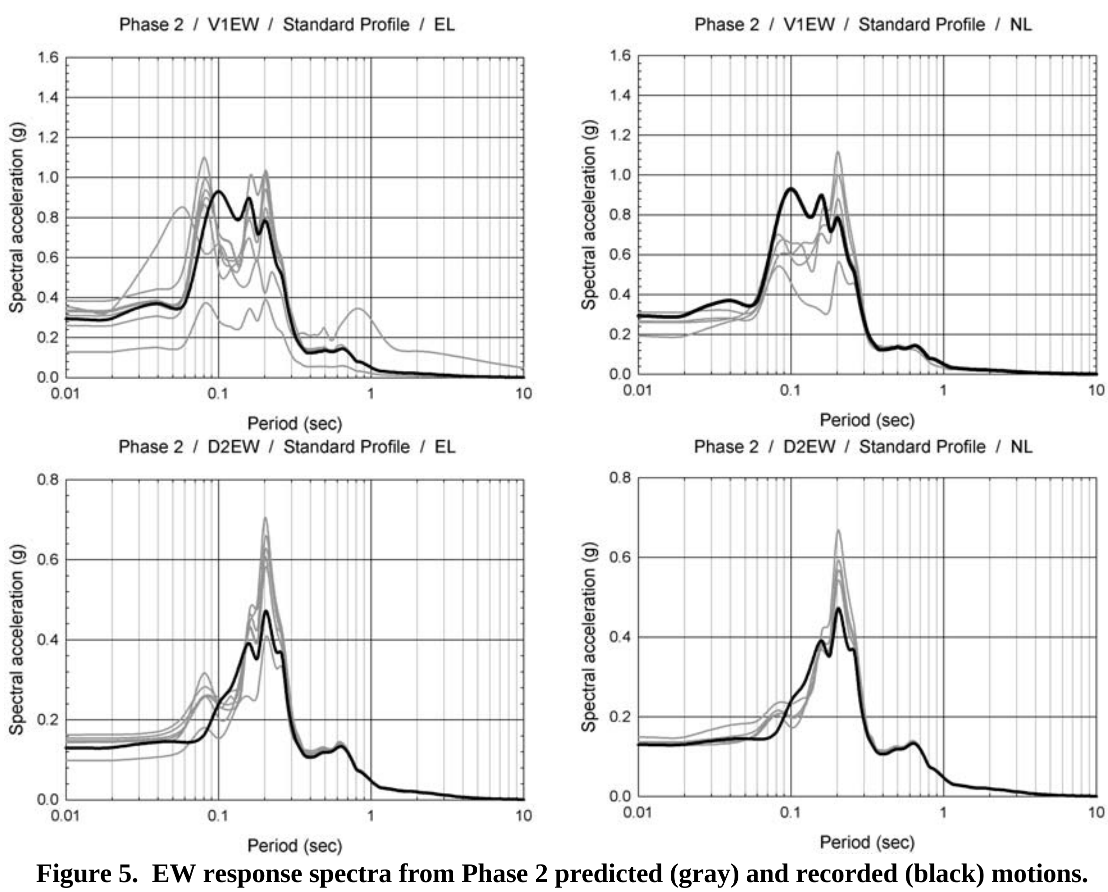

Figure 5. EW response spectra from Phase 2 predicted (gray) and recorded (black) motions.

Comparison of Phase 1 and Phase 2 Predictions

Both the equivalent linear and nonlinear standard analyses with the standard soil model tended to overpredict the response spectra computed from the recorded motions in Phase 1 of the Turkey Flat blind prediction exercise. The overprediction was consistent and systematic. To quantify the prediction errors, residuals defined as

$$R(T) = \ln S_a^{recorded}(T) - \ln S_a^{predicted}(T) \tag{1}$$

were computed for all predictions. Note that the residuals are defined in terms of the logarithm of spectral acceleration, and that a high value of $R(T)$ corresponds to an underprediction and a low value of $R(T)$ to an overprediction of the recorded spectral acceleration.

Residuals were computed for all of the Phase 1and 2 predictions. Figure 6 presents the residuals for the EW components of the equivalent linear and nonlinear standard model predictions of the V1 instrument response. The residuals can be seen to be small at periods greater than about 0.7 sec in the EW direction (and were small below 1.3 sec in the NS direction). At lower periods, however, the residuals are strongly negative, indicating systematic overprediction of spectral accelerations at the Valley Center rock level. The residuals are particularly low, in all cases, for periods of about 0.3-0.7 sec. This overprediction was more pronounced in the NS direction than the EW direction. It should be noted that, due to their logarithmic definition, a mean residual of α corresponds to a median overprediction ratio of $e^{-\alpha}$.

The results point to a fundamental issue with the Phase 1 predictions – the recorded D3 motions are inconsistent with those inferred from the recorded R1 (and, as discussed subsequently, D1) motions, as interpreted in the context of one-dimensional site response. The mean residuals are generally smaller for the equivalent linear predictions than for the nonlinear predictions, but the nature of the prediction errors, as evidenced by the shapes of the residual curves, are quite similar. The value of $\sigma_{\ln R}$ provides an indication of the variability within a given class of predictions. For the standard model predictions, $\sigma_{\ln R}$ essentially represents the model uncertainty since the other most significant variables (i.e., the velocity profile and soil models) are held constant. For preferred profile predictions, $\sigma_{\ln R}$ also includes variability associated with different shear wave velocity profiles and soil models. The variability in the equivalent linear predictions can be seen to be significantly greater than that in the nonlinear predictions. The values of $\sigma_{\ln R}$ for the equivalent linear case, however, are strongly affected by the long-period outliers shown in Figure 5.

In order to quantify the level of overall error in a given prediction using a single, scalar parameter, a “misfit index” for a given prediction was defined as a root-mean-square residual, i.e.,

$$M = \sqrt{\frac{1}{\log(T_{\max}) - \log(T_{\min})} \int_{T_{\min}}^{T_{\max}} \left[R(T)\right]^2 d(\log T)} \tag{2}$$

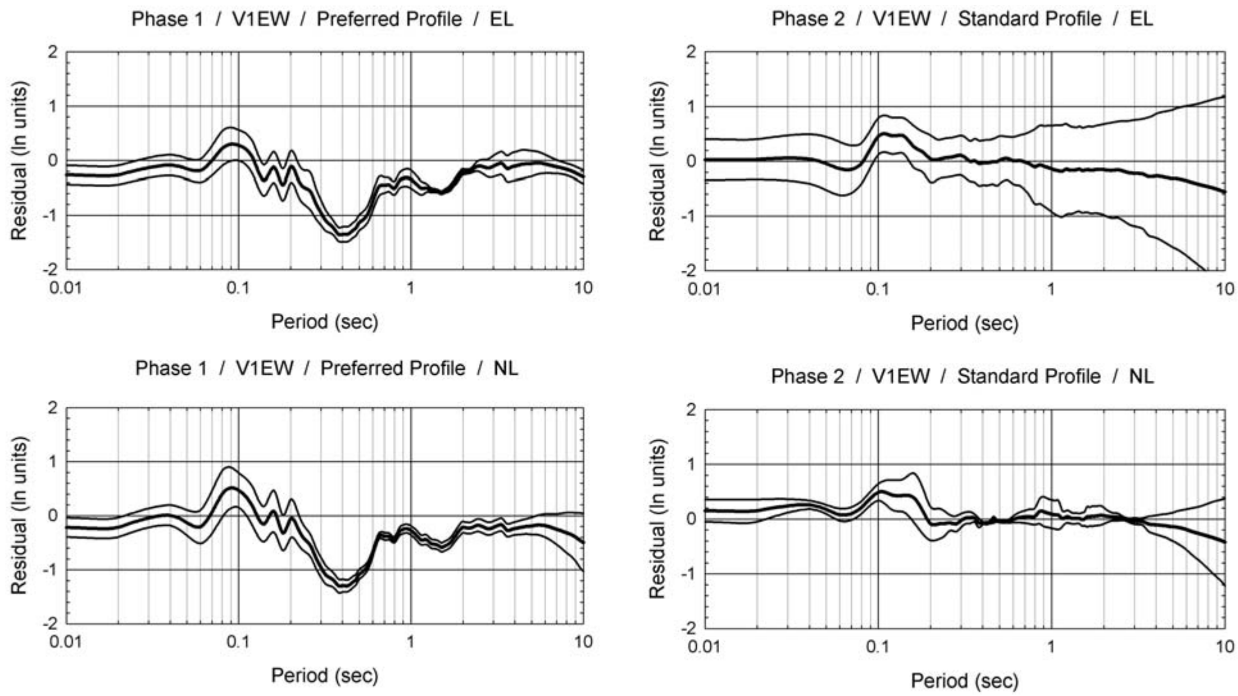

Figure 6. Residuals for Phase 1 and 2 equivalent linear and nonlinear analyses of V1 ground motions using preferred soil models. Bold line indicates mean and lighter lines indicate mean +/- $\sigma_{\ln R}$.

which was computed numerically using $T_{\min}$ = 0.01 sec and $T_{\max}$ = 2.0 sec as

$$M = \sqrt{\frac{1}{2.301}\sum_{j=1}^{N-1}\frac{1}{2}\left[R(T_j)+R(T_{j+1})\right]^2\cdot\left(\log T_{j+1}-\log T_j\right)} \tag{3}$$

where N is the number of periods (57 for the results presented herein) at which spectral accelerations are computed. The upper bound of 2.0 sec in the misfit index definition was selected to focus the index on the period range of greatest interest for Valley Center site response, and to eliminate the effects of prediction errors for long periods at which amplitudes are low and essentially rigid body motion is occurring.

The computed misfit indices are much higher for the Phase 1 predictions (Table 2) than for the Phase 2 predictions (Table 3). Because of the presence of outlier predictions in many cases, the median misfit indices give a better indication of central tendency than the mean values. The misfit indices show that the equivalent linear and nonlinear analyses produced results of similar accuracy, and that the results of analyses based on the standard soil model were generally more accurate, and less variable, than those based on the preferred models.

Table 2 Misfit index statistics for Phase 1 predictions.

Group	Standard Model			Preferred Model		
	Median	Mean	St. Dev.	Median	Mean	St. Dev.
Equivalent linear	1.158	1.070	0.201	1.117	1.190	0.147
Linear	--	--	--	0.916	0.916	0.562
Nonlinear	1.174	1.217	0.207	1.127	1.110	0.134

Table 3 Misfit index statistics for Phase 2 predictions.

Group	Standard Model			Preferred Model		
	Median	Mean	St. Dev.	Median	Mean	St. Dev.
Equivalent linear	0.025	0.432	0.776	0.032	0.044	0.030
Linear	--	--	--	0.250	0.250	0.180
Nonlinear	0.023	0.037	0.031	0.075	0.165	0.254

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. Nevertheless, uncertainty in the predicted motions still existed. The nature of the predictions were not such that these uncertainties could be estimated in the optimal manner. However, one predictor used a set of five nonlinear analyses for Phase 2 predictions and the Phase 2 equivalent linear predictions were made predominantly using programs that were derivatives of SHAKE (Schnabel et al., 1972). Uncertainties in the Phase 2 standard model predictions (leaving out two equivalent linear predictions with obvious errors) are shown in Figure 7.

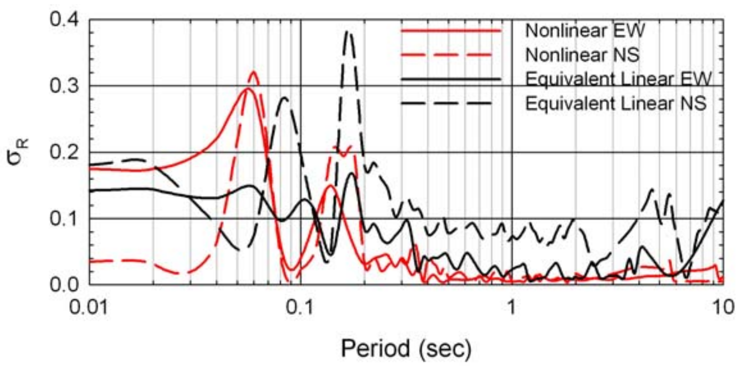

Figure 7. Estimated model-to-model uncertainty for equivalent linear and nonlinear predictions of ground surface motions.

Investigation of Site Response Inconsistencies

Of significant 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. Equivalent linear analyses of the Rock South site response showed a high level of consistency between the R1 and D1 motions, i.e., the recorded R1 motion could be predicted accurately in a one-dimensional analysis of the Rock South profile using the recorded D1 motion as input. The Phase 2 analyses showed that the recorded V1 motion could be predicted accurately using the standard soil model with the recorded D3 motion used as input. These results show that the poor performance of the Phase 1 predictions was due to the inconsistency between the D1 (and R1) and D3 rock motions.

In order to determine the consistency of the Rock South and Valley Center rock motions with the motions measured or inferred at other sites, rock outcrop motions for all four sites were developed. For the Rock South and Rock North sites, the recorded rock outcrop motions were used. For the Valley Center site, the recorded motion at the D3 instrument was corrected to obtain a consistent rock outcrop motion. The inferred rock outcrop motion at the Valley North site was obtained by deconvolving the recorded Valley North surface motion down to bedrock level. The resulting motions are shown in Figure 8.

The degree to which any of the rock outcrop motions could be considered unusual with respect to ground motions at similar distances in similar earthquake can be evaluated using the parameter "epsilon." To account for both components of ground motion, a value of epsilon was computed using the SRSS spectral accelerations, i.e., as

$$\varepsilon = \frac{\ln S_a^{SRSS}(T) - \ln \hat{S}_a(T)}{\sigma_{\ln S_a}} \tag{4}$$

where $\ln S_a^{SRSS}(T) = \sqrt{\left(\ln S_a^{EW}(T)\right)^2 + \left(\ln S_a^{NS}(T)\right)^2}$ and $\hat{S}_a(T)$ is the median spectral acceleration predicted by the Campbell and Bozorgnia (2008) attenuation relationship. The epsilon value indicates the number of (logarithmic) standard deviations above or below the median value of a ground motion parameter. Figure 9 shows the epsilon values for the four rock outcrop motions. The epsilon values indicate that the spectral accelerations in the period range of 0.3 – 0.8 sec at the Rock South site were well above the median values and that the Valley Center rock spectral accelerations in the 0.3 – 0.5 sec period range were well below the median values. These results are consistent with the very large apparent differences in the Rock South and Valley Center rock motions at periods of about 0.3 – 0.5 sec.

Shallow Rock Weathering Effects

At the 2006 Blind Prediction Symposium, considerable discussion centered on the potential for weathering of the upper portion of the rock to cause the discrepancy between the Rock South and Valley Center rock motions. This potential was investigated by an extensive series of one-dimensional, equivalent linear analyses which found no remotely feasible weathering-related velocity profile that would produce the observed inconsistency. As a result, shallow weathering effects were ruled out as a significant cause of the inconsistency.

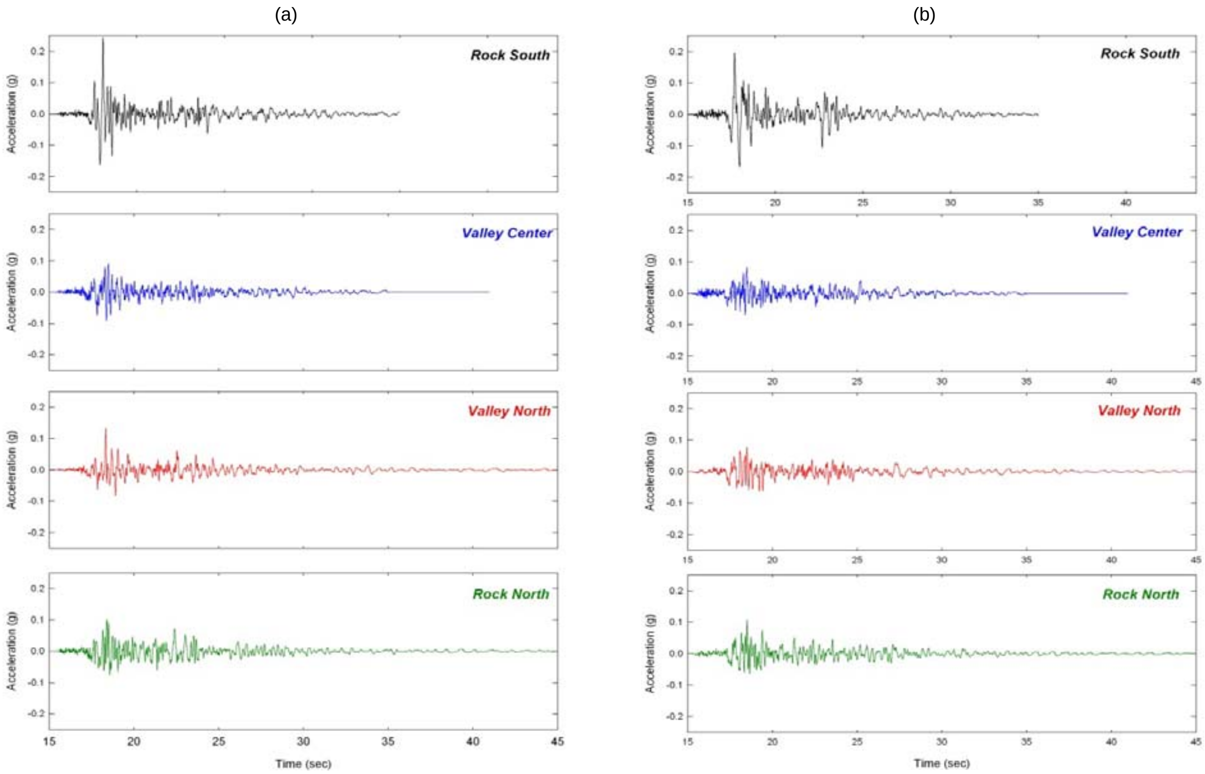

Figure 8. Rock outcrop time histories at all four Turkey Flat sites (a) EW components, and (b) NS components.

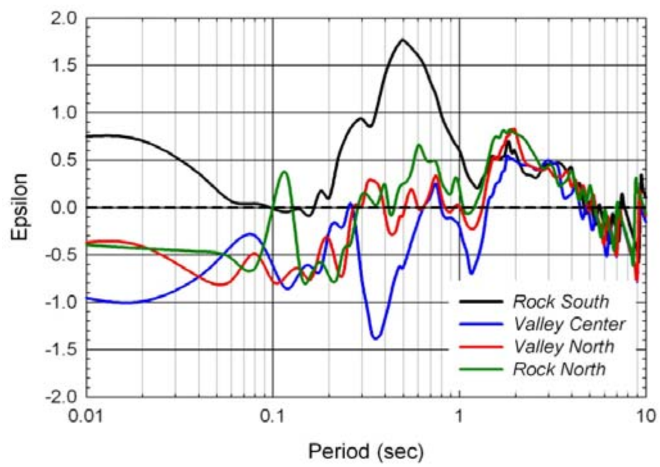

Figure 9. Epsilon values for four Turkey Flat rock outcrop motions. Median spectral accelerations calculated using Campbell and Bozorgnia (2009) with $V_{s,30}$ = 1,276 m/sec, $Z_{2.5}$ = 0.27 km, M_w = 6.0, and R = 7.6, 8.2, 8.6, and 9.2 km.

Deep Velocity Anomaly Effects

Another potential explanation of the inconsistency between the D1 and D3 motions is the presence of an anomalous velocity zone at depths greater than those explored in the Turkey Flat subsurface investigation. The potential existence of such an anomaly is suggested by data from downhole studies in the Varian No. 1 well, a 1,500-m deep well located north of the Turkey Flat test. Sonic logging data (Real, 1988) from the well showed a zone of reduced shear wave velocity at a depth of approximately 600 – 720 m. Furthermore, a series of seismic refraction tests performed at the Turkey Flat test array site showed evidence of a low-velocity layer at about the mid-depth (900 – 1100 m deep) of the Etchegoin formation. The persistence of this layer suggests that it also exists beneath the Turkey Flat test array. The potential for such an anomaly to cause differences consistent with those observed in the 2004 Parkfield earthquake were investigated in a series of equivalent linear analyses.

To investigate the potential effects of a deeper velocity anomaly, deep one-dimensional profiles were developed for both the Rock South and Valley Center sites. The deep profiles extended to depths of 1 km. The goal of this investigation was to determine whether a single anomaly located at the same depth below the top of bedrock could produce the observed D1 and D3 motions when subjected to the same motion at a depth of 1 km. A velocity multiplier function was used to modify the standard velocity profile at large depths. The multiplier function could describe a depth-dependent anomaly of variable depth, amplitude, and shape. Site response analyses using the computer program SHAKE91 were implemented into a numerical optimization analysis. The parameters defining the velocity multiplier function were then optimized to identify the characteristics of the deep velocity anomaly that produced rock motions that were most consistent with both components of the recorded Rock South and Valley Center rock motions.

The first optimization analyses were performed with a velocity anomaly equivalent to that suggested in previous subsurface investigations, and were repeated many times with different initial velocity anomaly profiles. The lowest value of the objective function in numerous optimization analyses was obtained for a profile with the velocity multiplier function that had values greater than 1.0, indicating that a zone of increased velocity between depths of approximately 450 m and 800 m provided the best fit between the Rock South and Valley Center rock motions. The level of agreement with the optimized function was poor, and the inferred spectra had amplitudes that could not realistically be expected at a depth of 1 km. As a result, a deep velocity anomaly was ruled out as a significant cause of the observed inconsistency in the Rock South and Valley Center rock motions.

Higher Dimensional Effects

Local multi-dimensional subsurface and topographic features can also cause focusing, or amplified shaking, at some orientations and frequencies. Seismic refraction surveys in the vicinity of the Rock South site produced the inferred subsurface velocity profile shown in Figure 10. The nature of the contact between the materials with shear wave velocities of 1,520 m/sec and 3,350 m/sec could potentially lead to some focusing of vertically propagating shear waves that would cause locally increased motions at some frequencies at the Rock South site.

Depending on the three-dimensional nature of that contact, which is not known, this local amplification could be stronger in some directions than others.

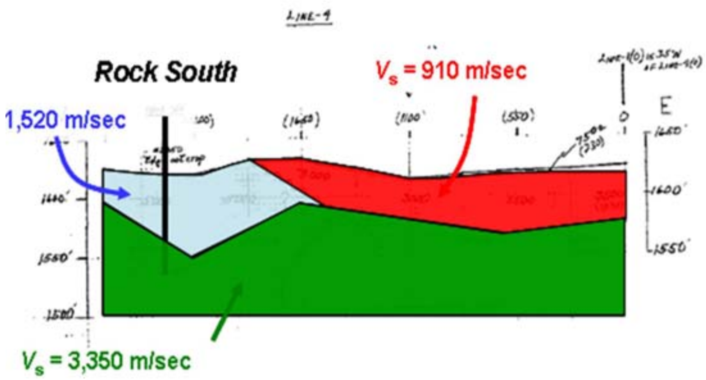

Figure 10. Inferred velocity profile in vicinity of Rock South recording instrument (after Real, 1988).

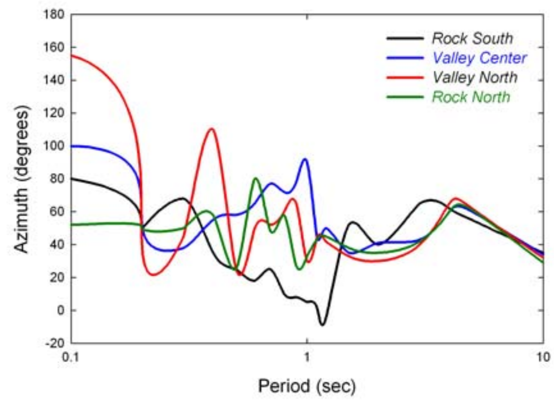

Figure 11. Azimuthal orientation of maximum spectral acceleration. Azimuthal angle is measured clockwise from north-south direction.

The orientation of the maximum response of all of the rock motions was also examined. Figure 11 shows the azimuthal orientation of the maximum spectral acceleration at different periods for all four sets of rock motions. Since the Turkey Flat array is located near the epicenter of the 2004 Parkfield earthquake, the maximum response would be expected in the fault-normal direction, which would be at about 48 degrees in Figure 10, and most of the maximum response is oriented in that general direction. The azimuthal directions at all four locations are quite consistent at periods greater than 2 sec, and much more variable at shorter periods. The Rock South and Valley Center rock motions show relatively consistent orientations at periods lower than about 0.3 sec, but have substantially different orientations at periods of about 0.5 – 1.2 sec. In this period range, the strongest Rock South motions tend to be in the NS direction and the strongest Valley Center motions are aligned in a more EW direction. Such differences could potentially be associated with three-dimensional subsurface geometry, and possibly associated with the geometry of the rock surface at the location of the Rock South instrument. Hence, higher dimensional effects could be a potential contributor to the inconsistency between the Rock South and Valley Center rock motions.

Path Effects

In order to investigate the extent to which path effects may have affected the inconsistency between the Rock South and Valley Center rock motions, the average ln $S_a(T)$ values for both recorded components of all four rock outcrop motions between T = 0.4 sec and T = 0.5 sec were computed. These values were then used to compute a relative rock motion parameter defined as the difference between the value computed from the RS motion and the average of the values computed for all four motions, i.e.

$$R_{RS} = \ln\left[\bar{S}_{a,RS}(0.4-0.5)\right] - \overline{\ln[\bar{S}_{a,all}(0.4-0.5)]} \qquad (5)$$

where $\overline{\ln[\bar{S}_{a,all}(0.4-0.5)]}$ is the average of the average (natural) logarithmic spectral acceleration for all four pairs of rock outcrop motions. Positive values of R_{RS}, therefore, indicate cases where the Rock South motion is stronger than average and negative values indicate cases in which it is weaker.

The values of R_{RS} for each of the eight events are listed and shown graphically in Figure 12. The azimuthal variation of the relative degree to which the Rock South motion exceeds the other rock outcrop motions is notable. The R_{RS} value for Event 3 is the highest, but the values for the other events initiating nearly due south of the Turkey Flat array are the next highest. The three events located west and southwest of the array have intermediate values, and the R_{RS} values for the two events located northwest of the Turkey Flat array have very low and even negative values, indicating that the 0.4 – 0.5 sec spectral accelerations at Rock South for these events ranged from about 2% weaker to only 5% stronger than the average at all four sites. The exponentials of the R_{RS} values, which represent ratios of the Rock South value to the mean value, are shown with azimuth (measured clockwise from due north) in Figure 13.

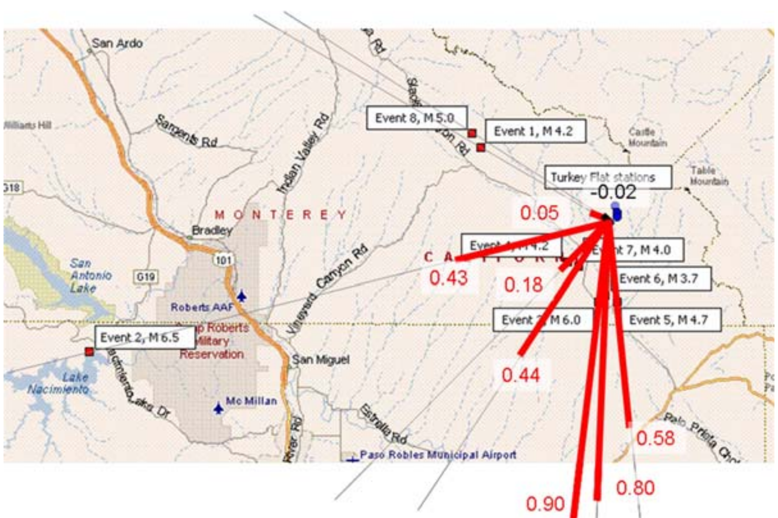

Figure 12. Variation of RRS with azimuthal direction for each of eight events producing strong ground motion at Turkey Flat.

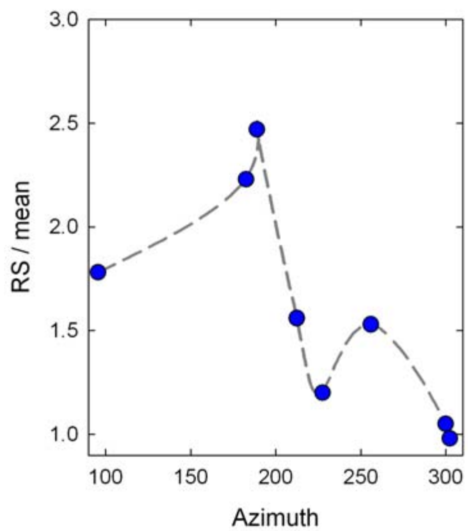

Figure 13. Variation of ground motion intensity (exp(R_{RS})) with azimuth (clockwise from due north).

Thus, this relatively small dataset suggests strong variability of ground motion intensity in the 0.4 – 0.5 sec period range at Turkey Flat. Such variability has been observed in previous earthquakes. The Northridge earthquake, for example, produced localized areas of higher damage in certain areas. Studies of aftershock data (e.g., Gao et al., 1996; Davis et al., 2000) showed that amplification factors were quite sensitive to the path between the epicenter and the recording instrument (Boore, 2004), a result attributed to critical refractions. Of interest for Turkey Flat is the fact that the path for all but Events 1 and 8 crossed the Gold Hill fault, located just northeast of the San Andreas fault near Turkey Flat, before reaching the Turkey Flat array. The fact that these motions exhibited significantly stronger Rock South response than those that did not cross the Gold Hill fault suggests that path effects may have played a significant role in the inconsistency between the Rock South and Valley Center rock motions.

Observations

A number of observations relevant to the estimation of ground motion hazards can be made from the ground motions that have been recorded by the Turkey Flat strong motion array and from the attempts at predicting those motions. These observations are made from the perspective of site response analyst charged with making the types of predictions that form the basis for seismic design of various infrastructure elements.

Observations of Site Response

Observations about site response, which are based on interpretation of recordings from multiple events, are divided into those associated with source, path, and site effects.

Source Effects

Source effects can have important effects on the motions recorded by a spatially distributed array, particularly when rupture occurs over a length of fault that is large with respect to the distances of the array stations from the fault and from each other. In the case of the 2004 Parkfield earthquake, rupture occurred over a length of approximately 20 km located mostly northwest of the hypocenter. As discussed previously, the earthquake produced spatially variable ground motions in the near-fault region. Some of this variability is attributable to source effects, such as the slip distribution and locations of asperities on the rupture surface. Other aspects of the variability could be due to three-dimensional fault zone effects such as lateral refraction, fault zone guided waves (Jongmans and Malin, 1995), and other three-dimensional multipathing effects (Kim and Dreger, 2008). In a source inversion investigation, Kim and Dreger (2008) excluded a number of recorded motions from a zone generally within about 4-5 km northeast of the rupture surface due to complexity associated with fault structure. That zone extended to the location of the Turkey Flat array, and suggests that the motions recorded by the array could potentially have been influenced by such effects.

Path Effects

The path from the source of the 2004 Parkfield earthquake to the Turkey Flat strong motions stations is complicated. The geology shows a significant syncline beneath Turkey Flat (between the Gold Hill and Maxim faults), and a steeply dipping boundary between the granitic Salinian block (on the west) and the softer Franciscan rock (on the east) of the Gold Hill fault. Deep explorations to the north of Turkey Flat revealed three flower structures, i.e., groups of nested rupture surfaces along the San Andreas fault (Rymer et al., 2004; Thayer and Arrowsmith, 1995a,b). Given the reduced stiffnesses of materials encountered along such rupture surfaces and along the Gold Hill fault, waves crossing portions of the flower structure could be refracted or otherwise affected by those structures. Also, the distances from the rupture surface to the Turkey Flat instruments were relatively short compared with the distances between the instruments, so waves traveled to the instruments along different paths. As a result, path effects could have led to significant differences between the rock motions at the four Turkey Flat sites.

The Turkey Flat array has also recorded motions from other earthquakes and from aftershocks of the 2004 Parkfield earthquake. These events occurred at a number of locations, some of which were near that of the 2004 Parkfield event and some of which were at different locations. Analyses of the recorded motions from these other events showed that the relationship between the rock motions at the Rock South and Valley Center sites was similar to that of the 2004 Parkfield earthquake for the events located at about the same azimuthal angle from that earthquake, but were considerably different for those at different azimuthal angles. The events located to the north of the Turkey Flat array, for which waves did not have to cross the Gold Hill fault, produced rock motions at the Rock South and Valley Center sites that were quite consistent with each other. Events for which waves did have to cross the Gold Hill fault to reach Turkey Flat produced significantly inconsistent Rock South and Valley Center rock motions. These observations help illustrate the important influence of path effects on motions at the Turkey Flat array.

Site Effects

The Turkey Flat test site (specifically, the Valley Center site) was selected so that the common one-dimensional idealization would be as appropriate as possible. The edges of the valley, however, may have been more susceptible to two- or three-dimensional effects. Topographic contours and subsurface conditions in the vicinity of the Rock South station indicate some potential three-dimensional effects, although the flat nature of the ground suggests that they should be relatively subtle.

The measured site response at the Valley Center profile was consistent with expectations given the recorded rock motions beneath the valley sediments. The ground motion amplitudes increased from the rock level through the soil profile and up to the ground surface. Because the Turkey Flat region was between the lobes of strongest shaking closer to the ends of the fault rupture, the ground motions did not induce high strains, and consequent significant nonlinearity, in the relatively stiff, unsaturated Valley Center sediments.

Observations of Predicted Response

The Turkey Flat Blind Prediction test provided an opportunity to evaluate the predictive capabilities of both computer programs and people. The predictors were generally quite experienced engineers and earth scientists who were very familiar with, and in quite a few cases developers of, the site response codes used to make their predictions. Nevertheless, there was still a significant degree of variability in the predicted ground motions.

The predictors used a range of analytical techniques, and a range of specific computer programs, to make their predictions. Most prediction groups used one or possibly two site response models within a given model category, but one group used five nonlinear models with consistent application protocols. Analysis of that group’s predictions offers insight into the model-to-model component of prediction variability. Unfortunately, no single specific model was used by a sufficient number of predictors to allow direct evaluation of predictor-to-predictor variability.

Phase 1 Predictions

The Phase 1 predictions tested, in addition to the ability to predict soil profile response given a rock input motion, the ability to predict the rock motion beneath the soil profile from a rock outcrop motion recorded some 800 m away. These predictions were made using both standard and preferred soil models.

The primary observation in all of the Phase 1 predictions is the strong and consistent overprediction of site response, particularly in the period range of 0.3 - 0.6 sec. This prediction error, which was consistently produced by virtually all of the Phase 1 predictors, dominated the Phase 1 results. The error was so large as to reduce the significance of some of the observations and conclusions that could be drawn from the Phase 1 predictions.

Phase 2 Predictions

The Phase 2 predictions were based on the recorded rock (D3) motions beneath the Valley Center soil profile; as a result, the error in predicting the D3 motion from the R1 motion was eliminated. The predictions in the Phase 2 analyses, using both standard and preferred soil models, were much better than those from the Phase 1 analyses. The recorded response was generally predicted quite accurately at periods as low as 0.2-0.3 sec, which was much closer to the extended characteristic site period and helps validate the one-dimensional assumption inherent in the great majority of the predictions.

Lessons Learned from Observations

The Turkey Flat Blind Prediction test required a tremendous effort by many people, ranging from the planning, design, installation, and monitoring of the array itself to the performance of the ground motion predictions. A number of lessons can be learned from the observed site response and efforts at its prediction. Those lessons are tabulated below:

1. While Turkey Flat itself is relatively simple and was a good choice for testing the earth science and geotechnical professions' ability to predict one-dimensional response, the area between Turkey Flat and the source of the 2004 Parkfield earthquake (i.e., the San Andreas fault) is quite complicated. This type of complexity can lead to significant variability in rock motions.

2. The extent to which nearby rock motions can be used to predict site response is affected by proximity of the site to the rock motion and on source-site distance. In Phase 1 of the Turkey Flat Blind Prediction test, as-yet-unexplained inconsistencies between rock motions at sites located 800 m apart caused poor predictions of soil profile response.

3. Path effects can be important, particularly in areas with complicated geologic conditions and in the presence of intermediate faults or fault zones. Fault zones can give rise to waveguide effects and can refract waves in a complicated manner that can lead to spatial variability of rock motions. At Turkey Flat, motions from events in which waves did not have to cross the Gold Hill fault appeared to produce much more consistent rock motions than events located on the other side of that fault.

4. The extensive site characterization program undertaken at Turkey Flat involved several different types of tests and produced a number of different subsurface velocity profiles.

Analyses based on individual velocity profiles were not, in general, as accurate as those based on the standard profile, which approximated the average velocities from all of the tests.

5. Site response is most sensitive to the shear wave velocity profile. Shear wave velocities at shallow depths, while difficult to measure accurately, can have a strong effect on spectral response, particularly at low periods.
6. Even for cases in which substantial consistency in ground motion predictions were expected (e.g., standard model predictions using equivalent linear analyses), outlier predictions were found.
7. The availability of downhole soil records is extremely useful for validation of site response analyses. Some predictions produced reasonably good fits to the recorded ground surface spectra while making relatively poor predictions of the recorded motion at 10 m depth. Ideally, a good prediction would be good at all depths.
8. The general consistency of the predictions suggest that differences in predictions have more to do with different interpretations of site characteristics than with differences in methods of analysis. There are many available software packages that, when used with appropriate site characterization, can produce accurate ground motion predictions.
9. Both average prediction error (bias) and dispersion of a group of ground motion predictions were observed to vary with depth. In Phase 2, where the input motion was known much more accurately than in Phase 1, the average error and dispersion both decreased with depth, although the variability in Phase 2 standard model predictions was unexpectedly (and inexplicably, given the available information) high.
10. Some predictors made use of the results of available weak-motion data to "tune" their preferred models prior to making their predictions. The most common approach was to adjust the shear wave velocity profile until the periods of computed local spectral peaks matched those of the recorded motions, and then to adjust the low-strain damping until the amplitudes agreed. The use of this data did appear to produce some benefits with respect to prediction accuracy.
11. For the previously discussed reasons, the Phase 1 predictions were all inaccurate at periods below about 0.6 – 1.5 sec in the EW and NS directions. The Phase 2 predictions, which were not affected by the inconsistency between the R1 and D3 motions, showed good accuracy in an average sense. The level and patterns of the errors in average equivalent linear and nonlinear predictions were similar, indicating that nonlinear analyses can predict response consistent with equivalent linear analyses when nonlinearity is modest.
12. The nonlinear analyses had a tendency to underpredict both the recorded response and the equivalent linear predictions at low periods. While some of the difference between the predicted and recorded response could be due to errors in assumed shallow shear wave velocities, the differences between the mean nonlinear and equivalent linear predictions suggest that other factors may also have contributed. The nonlinear models are not able to independently control stiffness and damping behavior, so attempts at matching both usually result in damping ratios that are higher than would be expected for the modeled stiffness behavior. Also, most of the nonlinear codes use Rayleigh damping, which is inherently frequency-dependent. Modified Rayleigh damping formulations render the effective

damping ratio relatively constant over a certain frequency range, but frequencies above that range are still highly damped.

13. Interpretation of the results of the Turkey Flat Blind Prediction test showed that better (i.e., more accurate) average predictions were made using the standard soil model than the preferred models. While some preferred models produced predictions that were superior to the standard model predictions, on average they did not. The standard model was developed by consensus of a group of experts who were quite familiar with the site and the results of the extensive site characterization work. As a consensus-based profile, it was relatively simple in comparison to most of the referred profiles; nevertheless, it worked quite well.

Recommended Practices

The lessons learned from the Turkey Flat Blind Prediction test can be used to formulate some recommendations for site response analysis practice. The following paragraphs describe recommendations related to the results of the Turkey Flat Blind Prediction test, and should not be considered an exhaustive set of recommendations for site response practice.

1. Site response analysts should recognize that accurate site characterization is required for accurate prediction of site response. More attention should, in nearly all cases, be paid to the manner in which subsurface data is obtained and interpreted than to which particular method of site response analysis is utilized. For sites softer than that at Turkey Flat and/or for stronger levels of shaking, larger differences between different classes of analysis (e.g., equivalent linear or nonlinear) and different site response computer programs will be observed, but differences in site characterization will usually dominate differences in computational methods.
2. Different insitu and laboratory tests provide different types and levels of information on subsurface conditions. The acquisition of extensive amounts of subsurface data, and of different types of subsurface data, is recommended whenever possible.
3. Evaluation and interpretation of subsurface data for the purpose of developing a standard site model proved to be beneficial for estimation of site response at Turkey Flat. When possible, collaborative development of a site model by a panel of experts should be used. In some cases, the site model may include more than one soil profile for analysis.
4. Development of a standard site model should include consideration of the level of nonlinearity expected to be induced in the soils by the ground motions of interest. For the ground motions produced at Turkey Flat by the 2004 Parkfield earthquake, nonlinearity in the Valley Center soil profile was modest. Under such conditions, analysis of a single, consensus-based average soil profile can produce results that are consistent with the average of analyses of profiles that span the range of potential input parameter values. For sites or ground motions where greater levels of nonlinearity are expected, however, consideration of the range of results may require analyses of multiple soil profiles that span the range of input parameter values. Averaging the results of the multiple analyses will produce a better indication of the expected response than the results of a single analysis of an average profile.
5. When available, the use of recorded weak motion response can help confirm or improve a standard site model. Measurement of ground motions from small earthquakes or ambient

vibration, interpreted in terms of H/V ratios if only surface motions are possible, can be used to estimate the fundamental period of a soil profile; that information can be used to tune a shear wave velocity profile used in a site response analysis for design-level ground motions.

6. The method of site response analysis should be appropriate for the problem at hand. For cases involving stiff sites and/or weak motions, soil strains will be small, hence nonlinear effects will be modest. In such cases, both equivalent linear and nonlinear analyses can produce very similar response. Attention must be paid to the manner in which nonlinear analyses treat stiffness and damping when nonlinear response occurs. The inability of nonlinear models to independently control stiffness and damping behavior means that one or both will generally be modeled inaccurately. Given the sensitivity of site response to stiffness, modeling the stiffness correctly is more important than modeling the damping behavior correctly. With most nonlinear models, matching the stiffness behavior will lead to overpredicted damping.

7. Many nonlinear models, particularly those based on lumped-mass models of the soil profile, use some form of Rayleigh damping. The basic form of Rayleigh damping has a strong tendency to overdamp high frequency motions; extended Rayleigh damping formulations have been shown to be effective in controlling damping over a desired range of frequencies and to provide improved predictive capabilities.

8. The expected results of a site response analysis should be estimated before performing the analysis. The analyst should recognize the range of periods expected to be influenced by the local soil conditions. Site response will be low at periods beyond the characteristic (fundamental) site period, so analyses with multiple motions should produce very similar amplification behavior at periods longer than the characteristic site period – if they don't, an error may be the cause. By the same token, consistent results at periods beyond the characteristic site period should not be taken as evidence that the site profile has been modeled correctly. After performing the site response analysis, the results should be checked against the expected results to confirm their general validity or to expose potential modeling problems. Discrepancies should be resolved or rationalized before the analytical results are used for design or evaluation purposes.

9. Site response analysts should strive to understand the relationship between the various soil units in a particular profile and the different regions of a response spectrum. Shallow zones will be excited by short wavelengths, which generally correspond to higher frequencies. Similarly, deeper zones will respond most strongly to longer wavelengths which depend on the characteristics of a deeper zone of soil. If high frequencies are of particular interest at a given site, more attention may need to be paid to accurate measurement of shear wave velocities of shallow soils.

10. Uncertainty exists and design site response studies should explore and accommodate it. Studies at numerous sites, including Turkey Flat, have shown that uncertainty in the shear wave velocity profile contributes much more strongly to total uncertainty than other significant sources. With the availability of convenient, Windows-based site response programs, sensitivity analyses can be performed quickly and conveniently, and should nearly always be performed. When possible, response analyses with randomized velocity profiles should be performed to allow the analyst to understand and accommodate, as necessary, the uncertainty in site response.

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