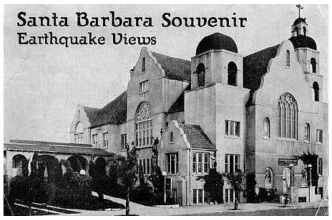

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NEAR SURFACE GEOLOGY AND THE TURKEY FLAT GROUND MOTION PREDICTION EXPERIMENT – LESSONS LEARNED AND IMPLICATIONS FOR PRACTICE

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ABSTRACT

A long-term experiment was planned and performed to assess the contemporary ability to predict the effects of near surface geology on strong ground motion. The experiment was established at an alluvial valley called Turkey Flat, about 5 km from the eventual M6.0 2004 Parkfield earthquake in central California. This paper summarizes the ground motions recorded at the site and the prediction of those motions in a blind prediction experiment. The two-phase prediction experiment attracted numerous participants using a number of approaches to ground motion modeling and site data interpretation. The results of the first phase, the prediction of the valley surface motion based on the rock outcrop motion at the valley edge, showed clear consistency in the predicted motions, but significant differences between the predicted and recorded motions. The results of the second phase, the prediction of the valley surface motion based on the subsurface rock motion, were also consistent, and were also quite accurate. This paper reviews the basic experiment, summarizes the results of the predictions, and examines potential explanations for the difference between the observations and predictions. Finally, lessons learned from the observations and predictions, and implications for site response analysis practice are reviewed.

INTRODUCTION

In order to assess the current ability to predict strong motion at a shallow alluvial site, the California Geological Survey (CGS) (then the Div. of Mines & Geology) established a site effects experiment in a shallow valley at Turkey Flat, located 8 km southeast of the town of Parkfield and about 5 km east of the San Andreas Fault in central California (Tucker and Real, 1986). The CGS California Strong Motion Instrumentation Program (CSMIP) installed a surface and downhole array as part of the experiment, intended to provide data with which to investigate the accuracy and consistency of methods for estimating the effects of site conditions on ground surface motions. 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 (e.g., Real and Cramer, 1989; Cramer and Real, 1990a,b). On September 28, 2004, the M6.0 Parkfield earthquake occurred and produced much higher levels of ground shaking than the array had previously experienced, providing the ground motion records required to conduct the long-planned 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, then additional motions were provided in October with predictions due in February, 2006. CGS held a symposium in September 2006 to reveal and discuss the measured and predicted surface motions. Summaries of the prediction methods are included in Real et al. (2006a), and the predictions are summarized in Shakal et al. (2006a).

Subsequently 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 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. The results of that project are summarized here, and were more fully treated in Kramer (2009).

TURKEY FLAT

The Turkey Flat site is located in a northwest-trending valley within the central California Coastal Range, about 5 km from the San Andreas fault at its closest point. 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 (Fig. 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 dips at about 50^o and 70^o on the southwest and northwest flanks, respectively.

Instrumentation Array

Four recording sites spanning the valley were installed at the Turkey Flat Test Site by CSMIP – Rock South (labeled as R1 in Fig. 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. At the Rock South site downhole instrument D1 was located at a depth of approximately 24 m. At the Valley Center site downhole instruments D2 and D3 were located at depths of approximately 10 m and 24 m, respectively; D3 was located about 1 m below the soil/rock boundary. Each instrument location included a three-component forced-balance accelerometer 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 outcrops at the borders of the valley and underlies the alluvial sediments 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 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, refraction profiling, and 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 at Valley Center consists of dark brown silty clay, the middle unit consists predominantly of clayey sand, and the lower unit consists of fine to medium clayey sand with gravel. Shear wave velocities in the upper unit range from about 150 m/sec (at Valley Center) to 135 m/sec (at Valley North). Velocities in the middle unit range from 460 m/sec (at Valley Center) to 275 m/sec (at Valley North), and are about 610 m/sec across the valley in the lower unit. The shear wave velocity data were used to construct "standard"

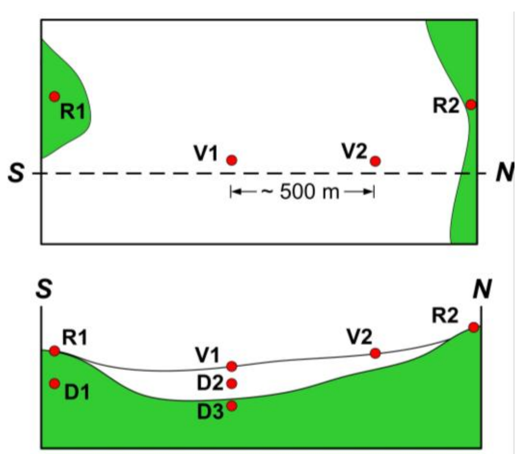

Fig. 1. Schematic illustration of Turkey Flat and instrumentation layout (after Tucker and Real, 1986).

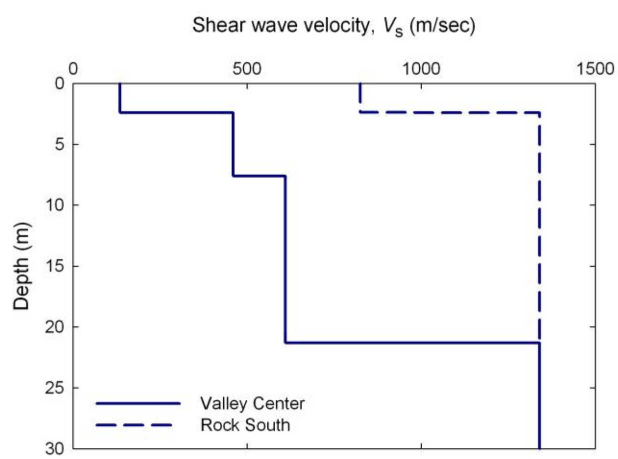

Fig. 2. Standard shear wave velocity profiles for Valley Center and Rock South locations (after Real, 1988).

profiles at the Rock South and Valley Center sites (Fig. 2). Participants in the strong motion prediction exercise were required to make a prediction based on this 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.

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 M6.0 Parkfield earthquake of September 28, 2004. 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., 2006b,c). 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 Fig. 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 an acceleration of 0.19g at 24 m. The time histories 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 are 0.29g, 0.12g, and 0.06g, respectively. Response spectra for the EW and NS components of the motions were consistent with each other.

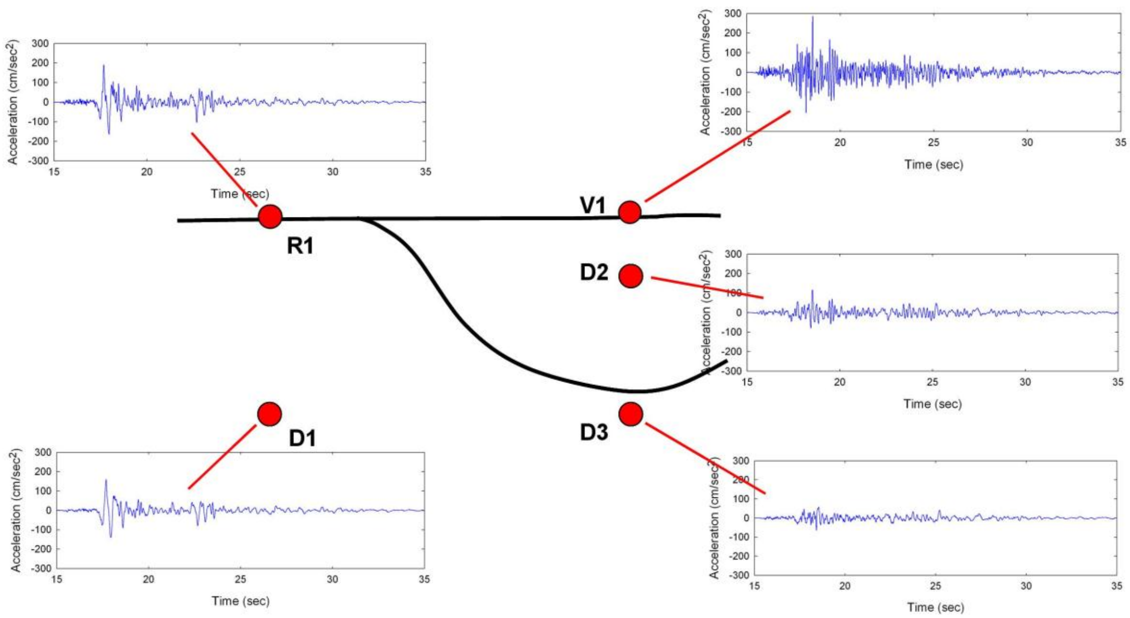

Fig. 3. Time histories of North-South accelerations recorded at the Rock South and Valley Center surface and downhole instruments in the M6.0 September 28, 2004 Parkfield earthquake.

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 valley edge rock outcrop (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 bedrock motions under the valley (D3) 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 to excite a profile.

Phase 1 Predictions – Valley Center Motion Based on Valley Edge Motion. 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 at V1, D2, and D3 in the spectra of Fig. 4. The specific methods used are summarized in Real et al. (2006a,b). The predicted 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. However, the predicted spectra, from both the equivalent linear and nonlinear analyses, are 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.

<u>Phase 2 Predictions – Valley Center Motion Based on Valley Bedrock Motion</u>. The second phase analyses were performed using the measured Valley Center bedrock motions (D3) as the input to the Valley Center profile. The range of predicted EW motions from equivalent linear and nonlinear analyses in the second phase is shown in Fig. 5. As in the first phase, the predicted motions can be seen to agree with each other quite well over a wide range of frequencies. However, the Phase 2 predicted spectra can be seen to match the recorded motions quite well over a broad range of periods.

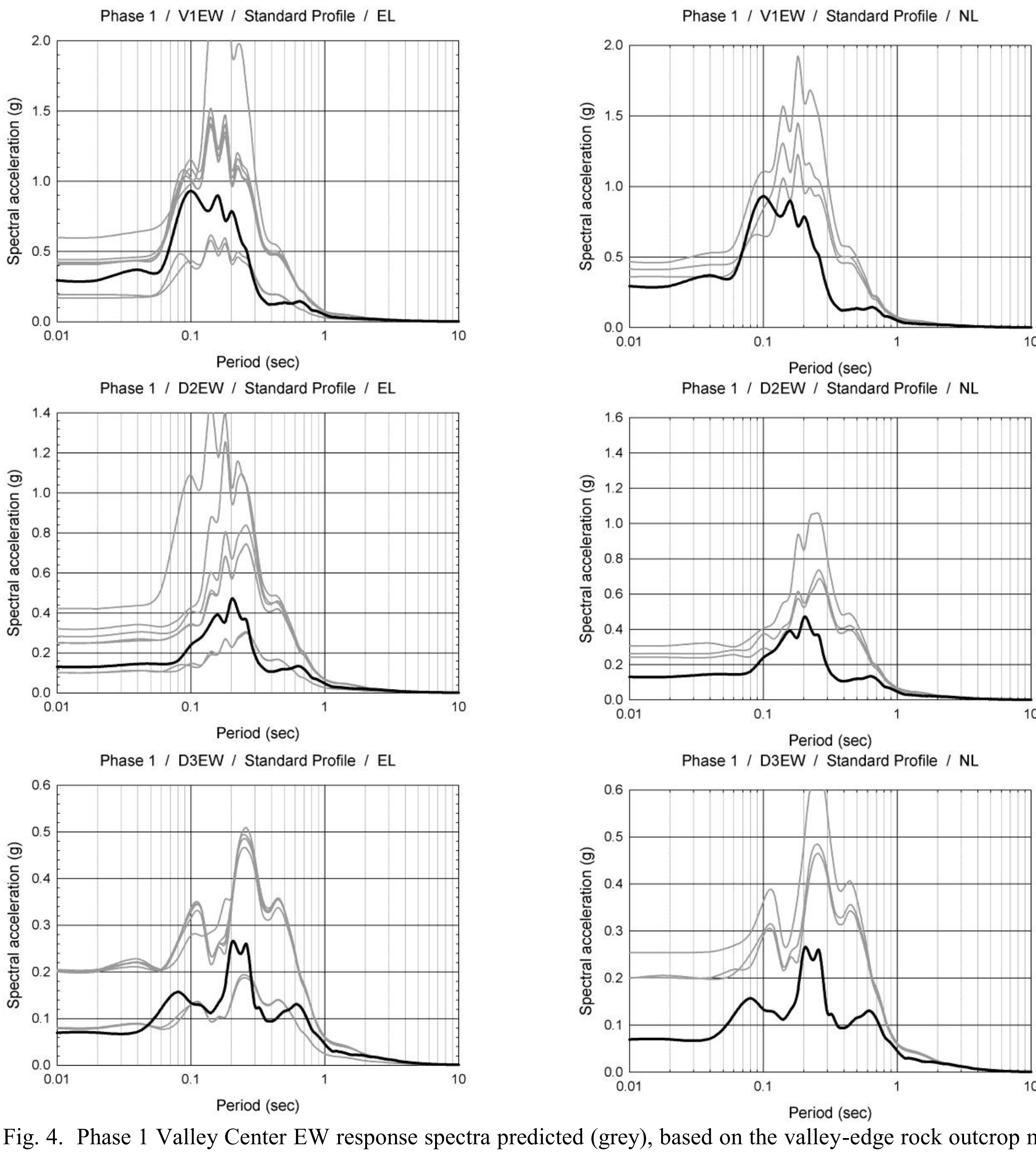

Fig. 4. Phase 1 Valley Center EW response spectra predicted (grey), based on the valley-edge rock outcrop motion, and the observed (black), at the surface, at 10 m, and at 24 m (top to bottom). Equivalent linear methods on the left, non-linear on the right.

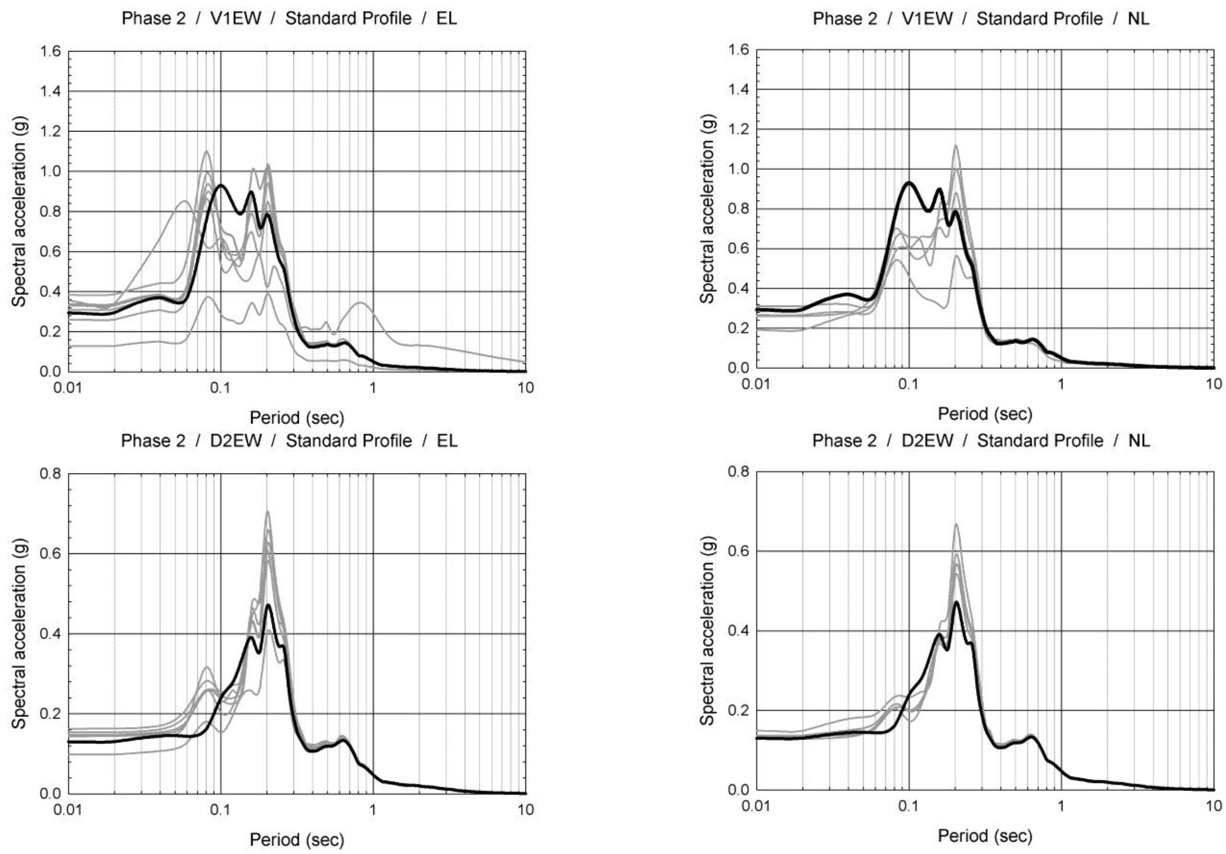

Fig. 5. Phase 2 EW Valley Center response spectra predicted (grey), based on the bedrock motion under the valley (gray) and observed (black), at the surface (upper) and 10 m depth (lower). Equivalent linear methods on the left, non-linear on the right.

Comparison of Phase 1 and Phase 2 Predictions. Both the equivalent linear and nonlinear standard analyses using 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

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

were computed for all predictions. Fig. 6 presents the residuals for the EW components of the equivalent linear and nonlinear standard model predictions of the Valley Center surface motion (V1). The residuals are small at periods above about 0.7 sec. At lower periods the residuals are strongly negative and indicate systematic overprediction of spectral accelerations at the Valley Center rock level (D3). The residuals are particularly large for periods of about 0.3-0.7 sec.

The results point to a fundamental issue with the Phase 1 predictions – the recorded Valley Center bedrock motions (D3) are inconsistent with those inferred from the valley edge rock outcrop motions (R1), 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 variability in the equivalent linear predictions is significantly greater than for the nonlinear predictions.

Comments

The high quality of the Phase 2 predictions (both equivalent linear and nonlinear; see Fig. 5), in which the Valley Center profile was excited by the actual rock motions below the alluvium, indicates that (a) the site responded essentially one-dimensionally, as intended in the original experiment design, (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 well when the input motion was known accurately.

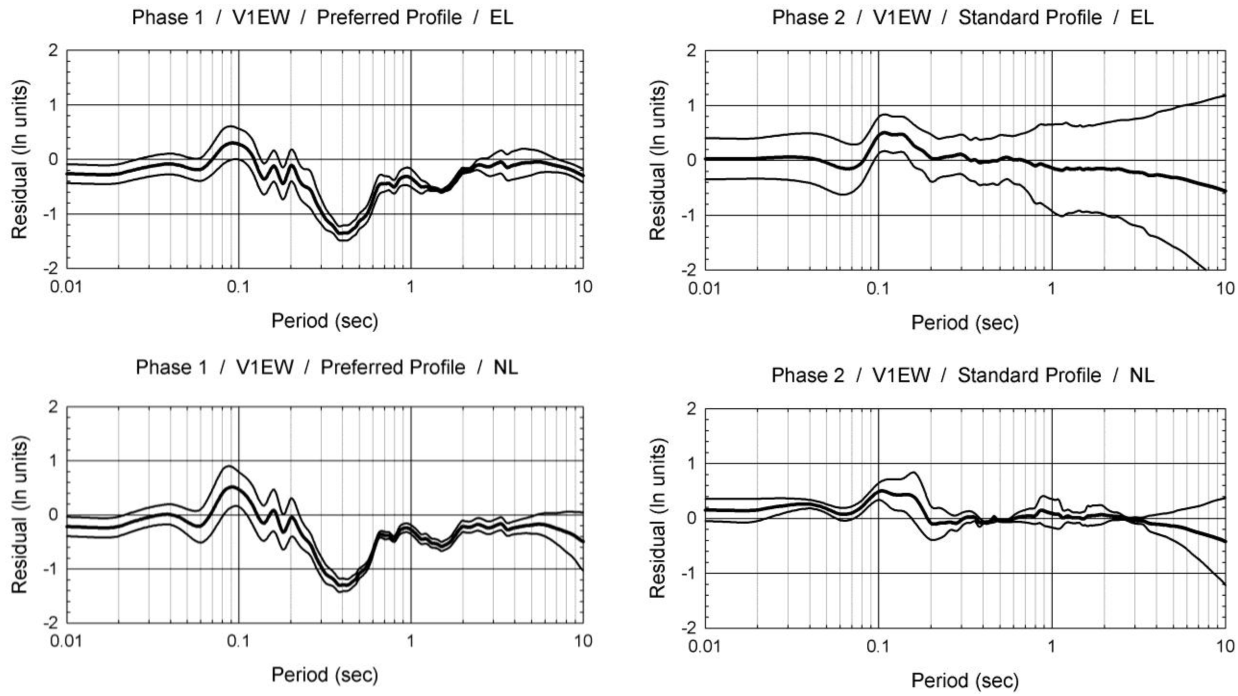

Fig. 6. Residuals for Phase 1 and 2 equivalent linear (left) and nonlinear (right) predictions of Valley Center surface motions (V1) using preferred soil models. Bold line indicates mean and lighter lines indicate mean +/- sigma.

POSSIBLE CAUSES OF SITE RESPONSE INCONSISTENCIES

The difference in accuracy of the results for the Phase 1 and Phase 2 predictions is important to study. Developing an understanding of the observed data 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 surface (R1) motion could be predicted accurately in one-dimensional modeling of the Rock South profile using the recorded subsurface (D1) motion as input. The Phase 2 analyses showed that the recorded Valley Center surface motion (V1) could be predicted accurately using the standard soil model with the recorded valley bedrock (D3) motion used as input. These results show that the poor performance of the Phase 1 predictions is due to the inconsistency between the D1 (and R1) and D3 rock motions, and it is important to consider the possible causes of this inconsistency.

<u>Shallow Rock Weathering Effects</u>. 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 that found no remotely feasible weathering-related velocity profile that would produce the observed inconsistency.

<u>Deep Velocity Anomaly Effects</u>. 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 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. A series of analyses were performed in which the deep velocity profiles for the Rock South and Valley Center sites were both multiplied by a function that described a velocity anomaly of arbitrary thickness at some arbitrary depth. Optimization analyses found that only a poor fit to both surface motions could be obtained using the optimized anomaly, and that the resulting motions were unrealistic. 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 cause focusing, or amplified shaking, at some orientations and frequencies. The nature of the contact between materials with lower and higher shear wave velocities could potentially lead to some focusing of vertically propagating shear waves, which could in turn cause locally increased motions at some frequencies at the Rock South site. Depending on the three-dimensional nature of this contact, which is not known, this local amplification could be stronger in some directions than others. 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.

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 relative to the distance 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 such effects could potentially have influenced the motions recorded by the array.

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 of the Gold Hill fault) and the softer Franciscan rock (on the east). 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, 2005a,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 somewhat different paths. As a result, path effects could have led to significant differences between the rock motions at the four Turkey Flat sites.

The CSMIP Turkey Flat array has also recorded lower level motions from earlier earthquakes and from aftershocks of the 2004 Parkfield earthquake. Haddadi et al. (2008) compiled the set of all events recorded at the array, even though of small amplitude. These events occurred at a number of locations, some of which were near that of the 2004 Parkfield event and some 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 (Fig. 7). 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

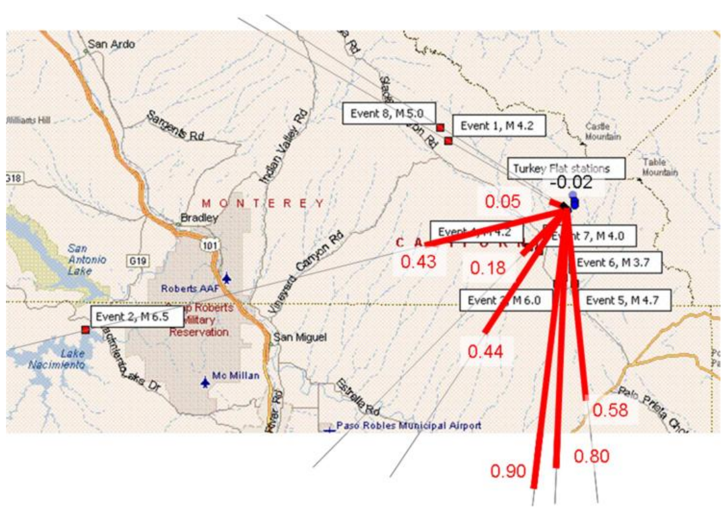

Fig. 7. Variation of relative amplitude of subsurface rock motion spectral accelerations in T = 0.4-0.5 sec range, at Rock South relative to Valley Center, with azimuthal direction for the eight events (in addition to the 2006 Parkfield earthquake, from Haddadi et al. 2008), that produced strong motion at Turkey Flat, though of low amplitude.

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 and suggest that path effects may have played a significant role in the inconsistency between the Rock South and Valley Center rock motions.

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 on Predictions – General. 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. The Phase 1 predictions of Valley Center motions based on Rock South 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. 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 Rock South (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 AND PREDICTIONS

The Turkey Flat Blind Prediction test required a tremendous effort by many people over nearly 20 years, ranging from the initial planning, the extensive site characterization measurements, the design, installation, monitoring and maintenance of the strong motion array itself, and finally the execution of the ground motion predictions. A number of lessons can be learned from the observed site response and efforts at its prediction.

1. Source Distance and Complex Geology. 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. Inconsistencies Between Rock Motions at Depth. 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 and surface motions.

3. Path Effects. 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, events for which waves did not have to cross the Gold Hill fault appeared to produce much more consistent rock motions than did events located on the other side of that fault.

4. Standard Model Profile. 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 a composite, or standard profile, which approximated the average velocities from all of the tests.

5. Shear Velocity Near Surface. 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. Outlier Predictions. Even for cases in which substantial consistency in ground motion predictions were expected (e.g., standard model predictions using equivalent linear analyses), outlier predictions occurred.

7. Downhole Soil Records. 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. Effects of Methods. The general consistency of the predictions suggests 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 relatively accurate ground motion predictions.

9. Prediction Error vs. Depth. 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. Use of Weak-Motion Data. 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. Nonlinear and Equivalent Linear When Nonlinearity Small. 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. Nonlinear Methods. 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. Standard Consensus Model. 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 SITE RESPONSE ANALYSIS 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. Accurate Site Characterization. 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 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. Subsurface Data. 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. Collaborative Site Model. 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. Nonlinearity. 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. Weak Motion Response. 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. Choice of Analysis Method. 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. Rayleigh Damping. 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. Planning Site Response Analyses. 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. Effects of Soil Units on Response. 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. Accommodation of Uncertainty. 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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