

**RECORDED DATA AND
PRELIMINARY REVIEW OF PREDICTIONS IN THE
TURKEY FLAT BLIND PREDICTION EXPERIMENT
FOR THE SEPTEMBER 28, 2004 PARKFIELD EARTHQUAKE**

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Abstract

A blind prediction experiment was conducted for the strong-motion data recorded at the Turkey Flat test area during the September 28, 2004 M6.0 earthquake. The motion was predicted at several sites by 15 prediction teams, first based on the observed motion at the edge of the valley, and secondly, based on the observed motion in the rock underlying the valley. Predictions were received from geotechnical firms and researchers, both in the US and internationally. A workshop was held to preliminarily review and compare the predictions to each other and the recorded data. In general, the predictions based on the valley-edge motion exceeded the observed data. Predicted peak ground acceleration at the center of the valley exceeded the observed by about 50% and predicted response spectra exceeded the observed by as much as 3–5 times at periods near 0.5 sec. In the second phase, involving predictions based on the recorded motion beneath the valley sediments, much closer results were obtained. In both phases, the predictions by different investigators were quite similar to each other. The use of nonlinear vs. equivalent-linear models did not significantly improve the predictions for this stiff-soil, relatively low strain motion.

Introduction

In anticipation of an earthquake near Parkfield, the California Geological Survey established a site effects test area across a sedimentary valley at Turkey Flat, east of Parkfield, California in the late 1980s (Tucker and Real, 1986). The geophysical properties of the site were thoroughly characterized in a cooperative effort by CGS, firms in the geotechnical community, and the IASPEI/IAEE Joint Working Group on Effects of Surface Geology on Seismic Motion. The test site was instrumented with a strong motion array by consisting of surface and downhole accelerometers by the California Strong Motion Instrumentation Program of CGS. The array includes surface instruments at the two valley edges, at one quarter the valley width, and at the center of the small, shallow 23 m stiff-soil sedimentary valley. The instrumentation at the valley center also includes a downhole array, with an instrument at mid-height in the sediments and another just below the rock interface. The instrumentation at one valley edge also includes a downhole accelerometer at the same depth as the deep accelerometer at valley center.

The Parkfield earthquake was well recorded throughout the Turkey Flat array, providing the records necessary to conduct the long awaited blind prediction test. In this prediction experiment, acceleration time histories recorded on bedrock near one valley edge were provided

to participants, along with a “Standard” model of the subsurface geotechnical properties defined following measurements made in the 1980s (e.g., Real et al., 2006a,b). Participants were asked to make predictions of the ground motions at the valley center and other recording locations for which, as part of a long-term plan, records were not made public. A workshop at which predictions were compared to each other and the recorded motions was held on September 21, 2006.

The M6.0 Parkfield earthquake of September 28, 2004 was a well-documented event (e.g., Harris and Arrowsmith, 2006) and produced a very extensive, dense set of near-fault strong motion recordings. The strong-motion measurements included unprecedented near-fault coverage, and the measured strong motion includes high variability in the near fault motion, with accelerations as high as 2g or larger (e.g., Shakal et al., 2006a,b). At the distance of the Turkey Flat array, peak acceleration was generally 0.3 g or less.

The Turkey Flat Blind prediction experiment is based on the recordings at the Turkey Flat strong-motion array, shown schematically in Figure 1. The array has a surface site, R1, at the south side of the valley, a downhole array (V1, D2 and D3) at the center of the valley, a surface site farther north in the valley (V2), and a rock site at the north side of the valley (R2). Each location has a triaxial set of force-balance accelerometers, recorded by a digital solid-state recorder (SSA-1).

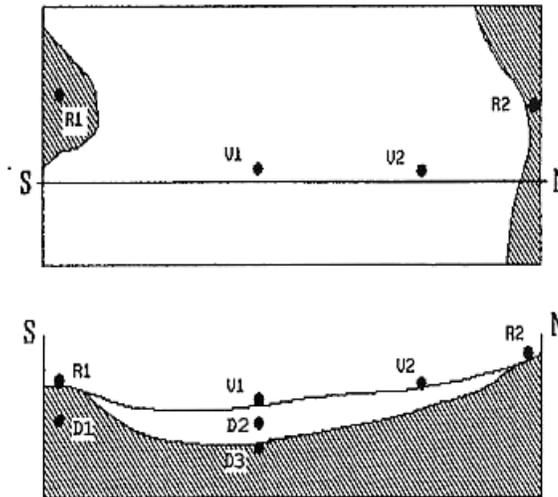


Figure 1. Schematic illustration of the Turkey Flat site effects test area and the strong-motion array stations (after Tucker and Real, 1986). Downhole sensor D3 is about 1 m below the rock interface at valley center. D1 is at a similar depth (24 m, 80 ft) below rock site R1. D2 is at mid-height in the sediments (11 m, or 35 ft). For reference, the distance from V1 to V2 is about 500 m, and from V1 to R1 is about 800 m.

In the first phase of the experiment, the R1 record was released and predictions were to be made for all other sites, though V2 and R2 were optional. In the second phase of the

experiment, starting about 6 months later, the D3 record was released, and the other sites were to be predicted again.

The purpose of the prediction experiment is to assess the state of the practice for predicting site response at a site in California, not to establish winners or losers. The site is of a particular type, thin, stiff alluvium over rock. The site was chosen as a highly likely site to experience strong shaking, being near the Parkfield segment of the San Andreas fault on which an earthquake was predicted to occur soon. The site is about 5 km from the San Andreas fault and ideally should be more distant to be confident of avoiding finite fault effects at the different sites of the array. However, given the moderate magnitude event expected at Parkfield, strong shaking could not be expected at great distances from the event. Clear tradeoffs were necessary for this experiment, but as a result, the first successful blind prediction has been made, described in greater detail in Real et al. (2006a, b).

Recorded Data

The Turkey Flat array, at its closest point, is located approximately 5 km from the fault and approximately 7 km from the epicenter of the Parkfield earthquake. The peak acceleration at the valley center site (Turkey Flat #2) was 0.29g. The acceleration records are shown in Figure 2, which also shows the records at 11 m depth (D2) and 34 m, in the bedrock (D3). The records at the rock site at the south edge of the valley, Rock South, are shown in Figure 3.

A striking difference between Rock South and Valley Center is that the EW record from 23 m depth at Valley Center (D3) is only 0.07g, in contrast with a value of 0.16g at the same depth at Rock South (D1). The rock at D1 and D3 has the same S-wave velocity according to the field measurements performed in 1988 (Real et al., 2006b). As shown in Figure 3, the NS record at D1 looks very similar to that at the surface (R1), but reduced from the 0.19g at the surface to 0.16g. The surface records from Valley North (Turkey Flat 3) and Rock North (Turkey Flat 4) are shown in Figure 4.

The low amplitude of the record at D3 compared to D1 and V1 may raise a question about possible errors in the recording at D3. To confirm the D3 record, in Figure 5 the computed horizontal displacements at Valley Center are shown. The displacements are nearly identical at all depths, with a peak value less than 1.5 cm. Though not shown, the NS displacement at V1 appears very similar to that at R1. The EW displacements at R1 and D1 have amplitudes very similar to that at V1, but they have an additional arrival or reflection in the middle of the simple displacement wavelet. The displacements at the V2 and R2 surface sites look very similar to those at V1. This comparison indicates that at long period the sensors have the same waveform and that there is not an error in gain, etc. At high frequency, on the other hand, the routine sensor tests done at record recovery look very ordinary and nominal. Thus, there is no reason to doubt the D3 recordings.

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Parkfield - Turkey Flat #2 (0, 10 & 24m) CGS Sta 36520
 Record of Tue Sep 28, 2004 10: 15: 11.4 PDT
 Frequency Band Processed: 8.0 secs to 40.0 Hz
 CSMIP Automated Strong Motion Processing - Preliminary and Subject to Revision

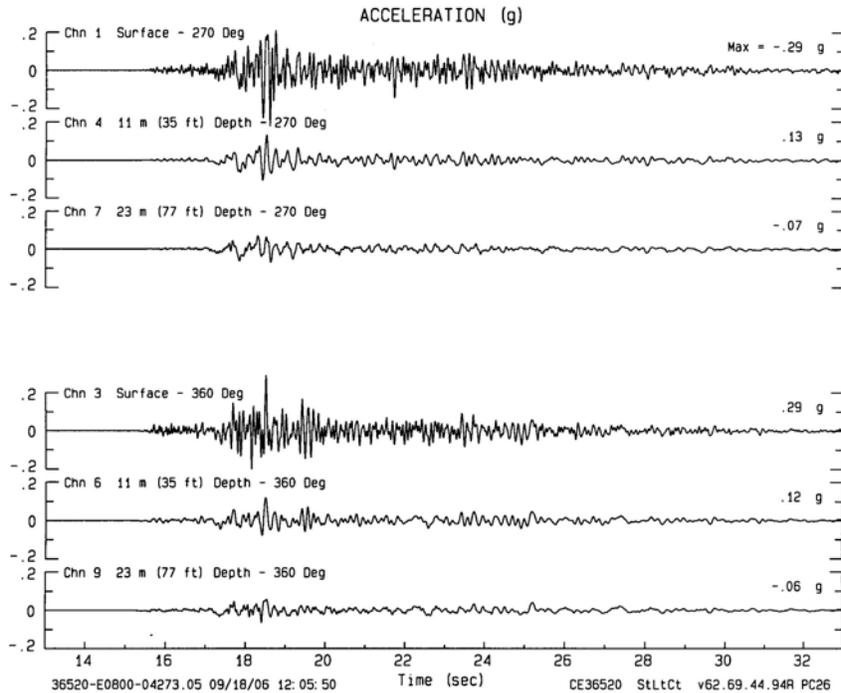


Figure 2. Horizontal accelerations recorded by the downhole array at valley center (station Turkey Flat #2), at the surface, 11 m and 23 m. These are locations V1, D2 and D3, respectively, of the Turkey Flat array.

Parkfield - Turkey Flat #1 (0 & 24m) CGS Sta 36529
 Record of Tue Sep 28, 2004 10: 15: 11.4 PDT
 Frequency Band Processed: 8.0 secs to 40.0 Hz
 CSMIP Automated Strong Motion Processing - Preliminary and Subject to Revision

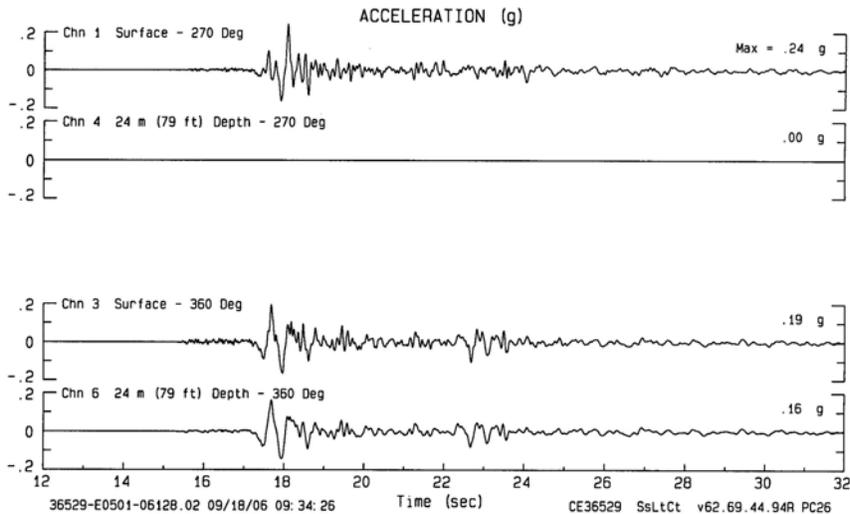


Figure 3. Horizontal accelerations recorded by the downhole array at Rock South, at the south edge of the valley, at the surface and at 24 m depth (locations R1 and D1, respectively). The EW sensor at D1 did not record.

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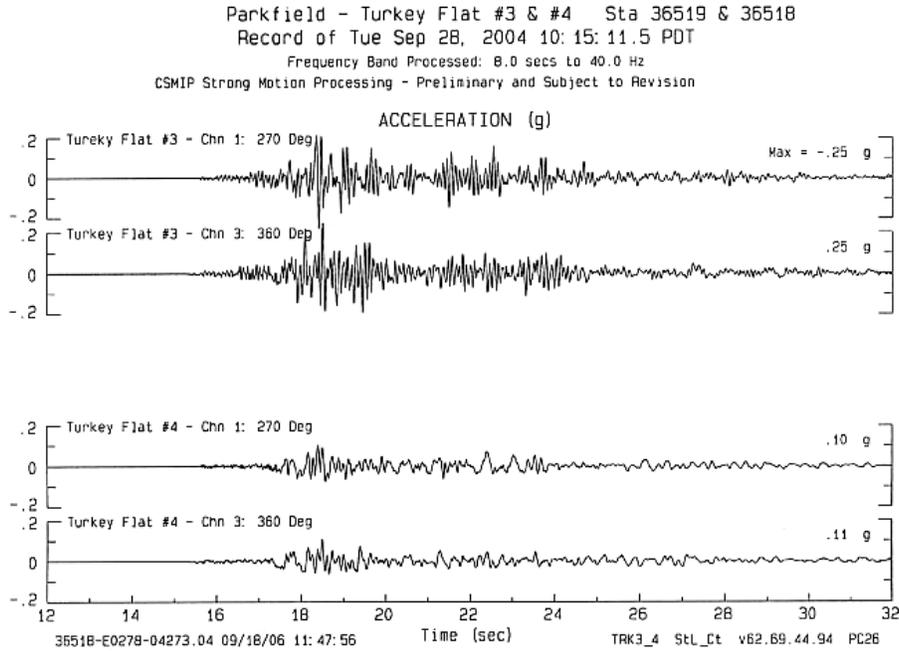


Figure 4. Horizontal accelerations recorded at the surface installations at Valley North (Turkey Flat #3) and Rock North (Turkey Flat #4).

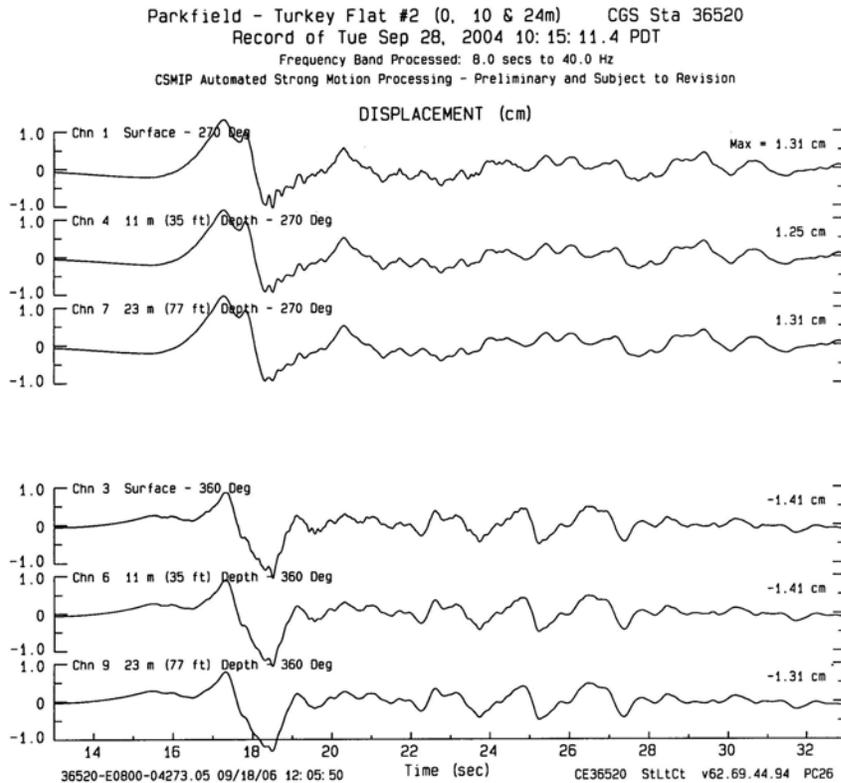


Figure 5. Horizontal displacements at the downhole array at Valley Center (V1, D2, D3).

Phase 1 Predictions – Based on R1

In Phase 1 of the blind prediction test, predictions teams were asked to predict the motion at all sites given the record at Rock South, R1. Fifteen different prediction teams submitted predictions, using one or more methods and soil models. The predictors were asked to submit, for the same computational method, a run made using a Standard soil model provided by CGS as well as a modified soil model, for which they altered parameters as they saw appropriate, and which was called a Preferred soils model. Some predictors used more than one computation method. The methods were divided into the categories of Equivalent-Linear (Shake-like), Nonlinear, and Linear. There were 23 computational methods used, of which 13 were of equivalent-linear type, eight nonlinear, and two linear. The predictors were kept anonymous, and are not identified except by an assigned number.

The predicted peak accelerations (EW component) at center of the valley are shown in Figure 6, along with the observed peak accelerations, for the surface, 11 m and 23 m depths, respectively. Nearly all predictions were high, with most predictions in the 0.40-0.45g range – compared to the observed peak of 0.29g, approximately 50% high. In general, predictions obtained by an investigator when using a Preferred model were lower than for the Standard model (both are shown, in different symbols, where given, in Figure 6). Thus, the use of a modified or Preferred soil model improved investigator predictions slightly.

The over prediction at the surface also occurs at 11 m depth (D2), with many predictions around 0.25g, approximately double the 0.13g value observed. The over prediction is greater at 23 m depth (D3), where most of the predictions are near 0.20g, approximately 3 times the observed value of 0.07g.

The over prediction also occurs for the two other surface sites of the arrays. Figure 7 shows the prediction at Valley North (V2), which is similar, in the difference between the predicted and observed values, to those at Valley Center (V1). Finally, the predicted accelerations for Rock North (R2) are near 0.25g, over double the observed peak of 0.11g.

The over prediction also occurs at D1, at 24 m depth in the rock immediately below the released R1 record as shown in Figure 8. Most of the predictions are near 0.20g, 25% larger than the observed value of 0.16 g.

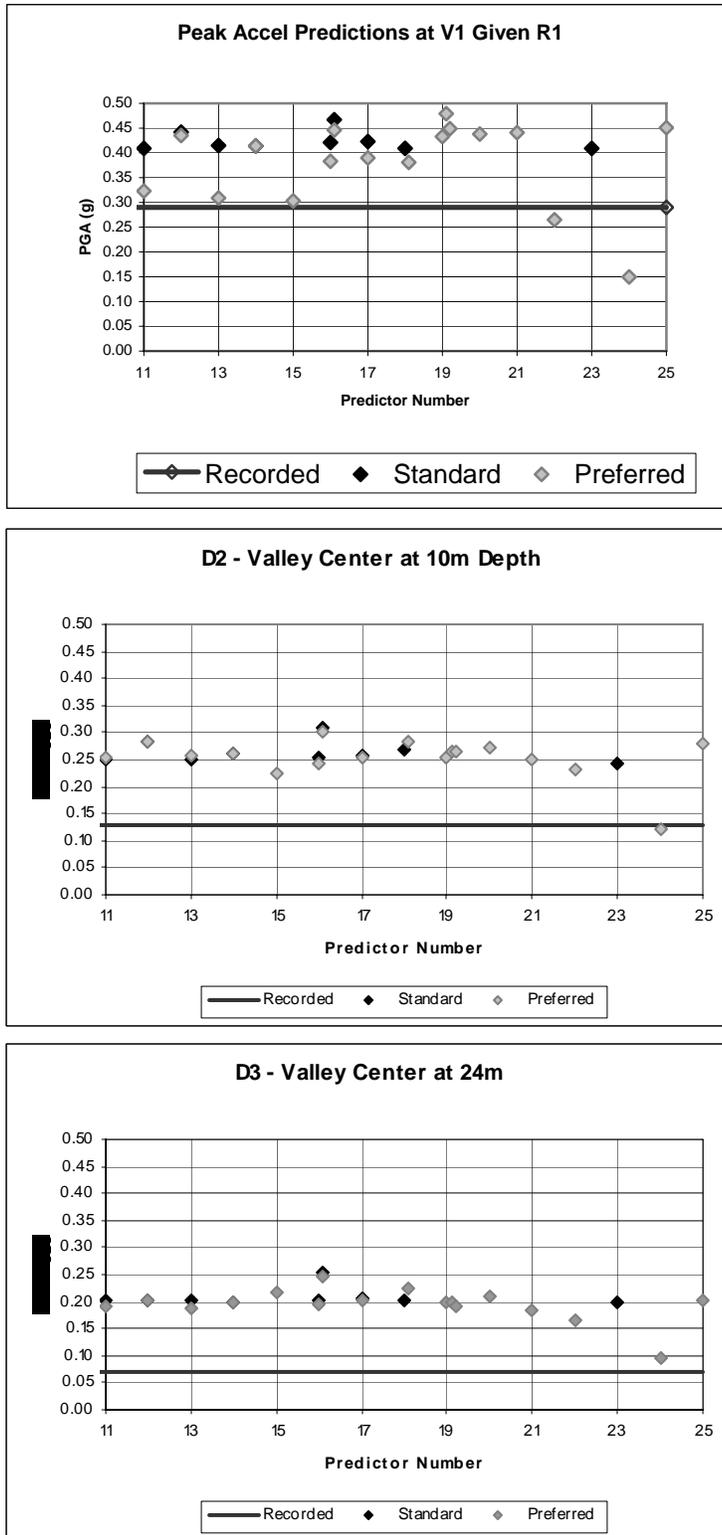


Figure 6. Peak accelerations (EW) predicted at V1, D2 and D3, given the record at R1, by numbered predictor teams compared to the observed values (line), for predictions using the Standard soil model (black), and Preferred models (gray).

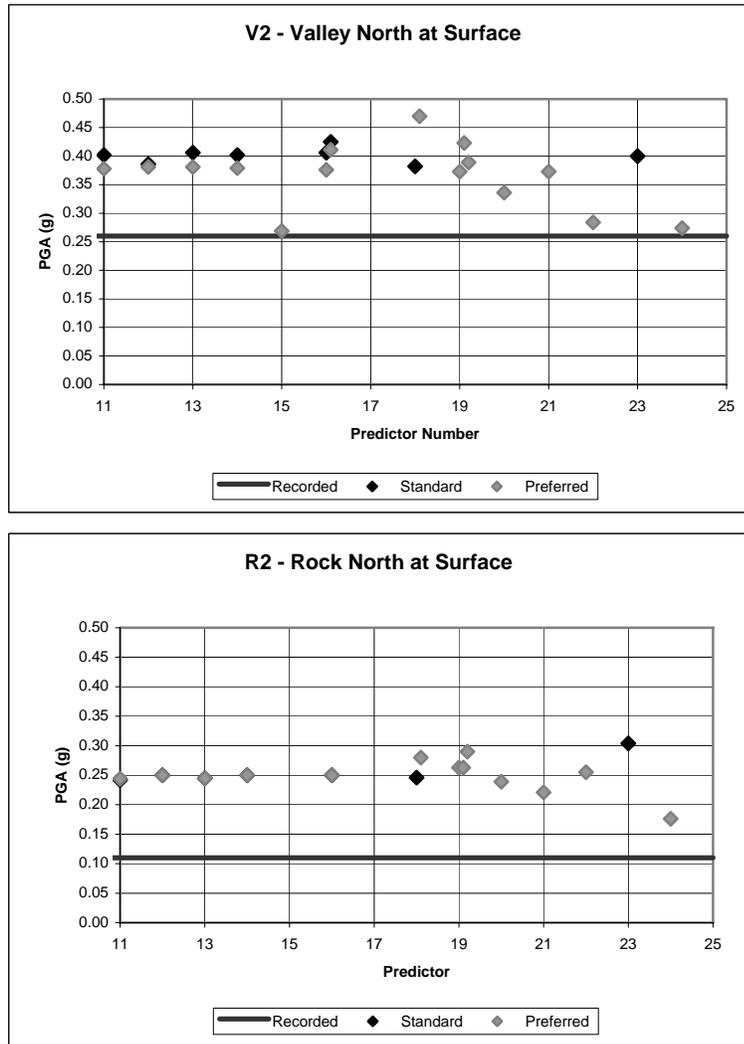


Figure 7. Peak accelerations predicted by numbered prediction teams for the motion at V2 and R2, given the record at R1, compared to the observed values (line). Black symbols are for predictions using the Standard soil model, gray are for Preferred models.

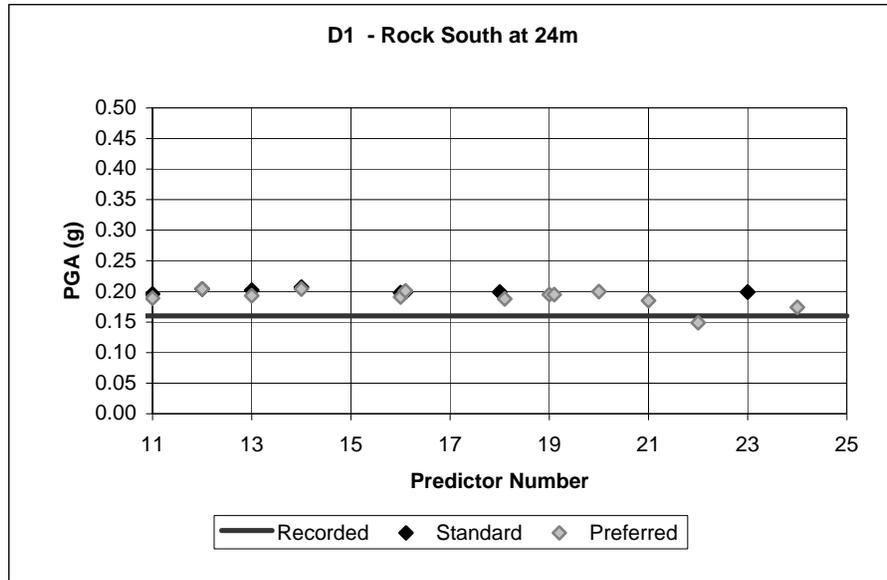


Figure 8. Peak accelerations predicted by numbered predictor teams for the motion at D1, given the record at R1, compared to the observed value (line). Black symbols are for predictions using the Standard soil model, gray for Preferred models.

Time Series Comparisons

Acceleration time series predicted for the valley center site, V1, are compared with the observed in Figure 9, for the Standard soil model. Only a subset is shown, as many of the predicted waveforms look similar. Peak accelerations greater than the observed, noted in Figure 6, are apparent, as well as some increase in apparent duration. Time series generated using Preferred models are somewhat lower in amplitude but the improvement is modest.

The observed record and a subset of the predicted records at D3, at 23 m, is shown in Figure 10. The waveforms are all substantially larger than the observed, which was reflected in the peak acceleration amplitudes in Figure 6.

In general, predicted waveforms in the Phase 1 part experiment are substantially higher than the observed. In addition, they share a high degree of similarity, and are more similar to each other than to the data.

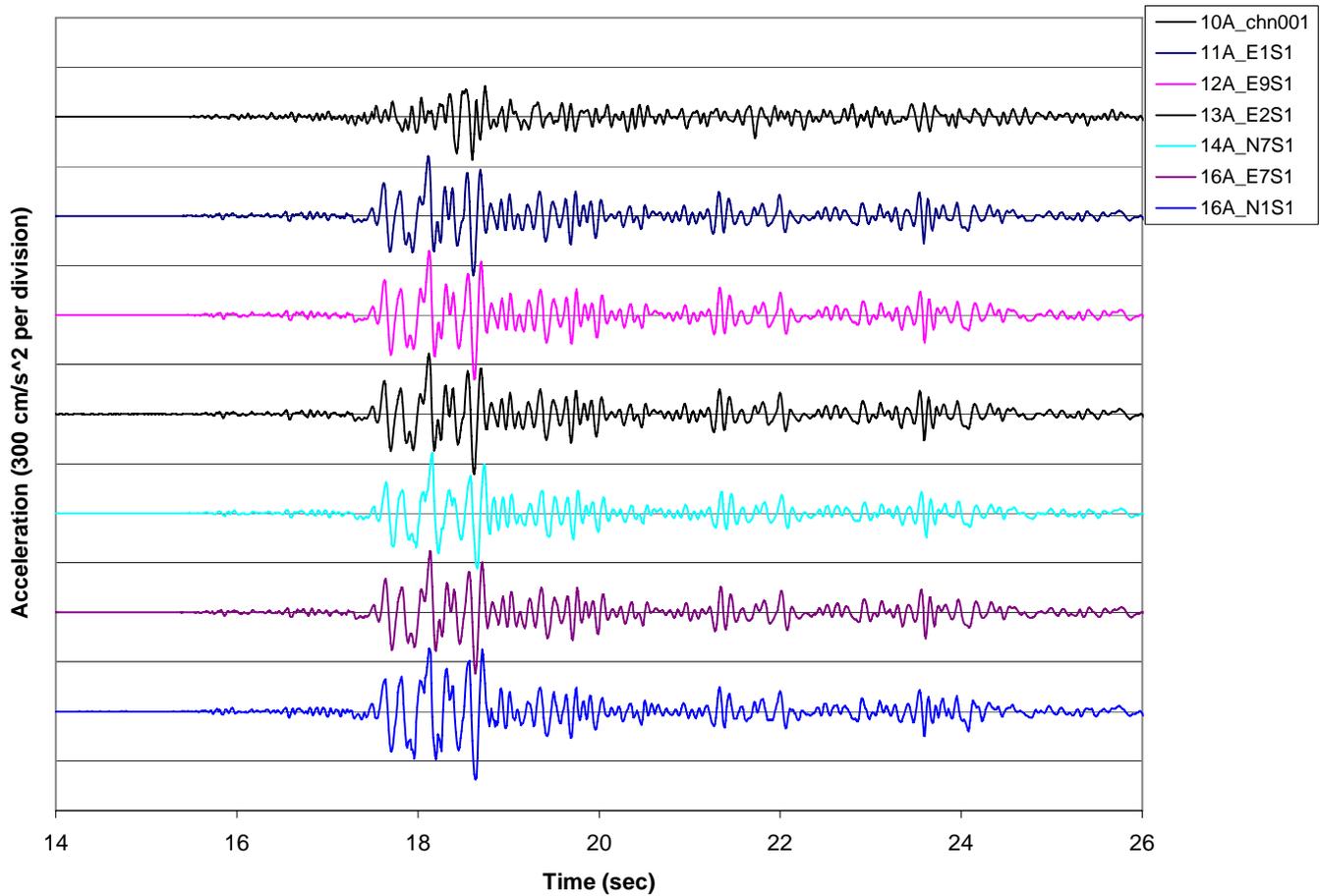


Figure 9. Observed (top) and predicted time series, EW component, for the valley center surface site, V1, based on the valley-edge rock record (R1), generated using the Standard soil model and a variety of computational methods. Only a subset of the predicted waveforms is shown as they look quite similar.

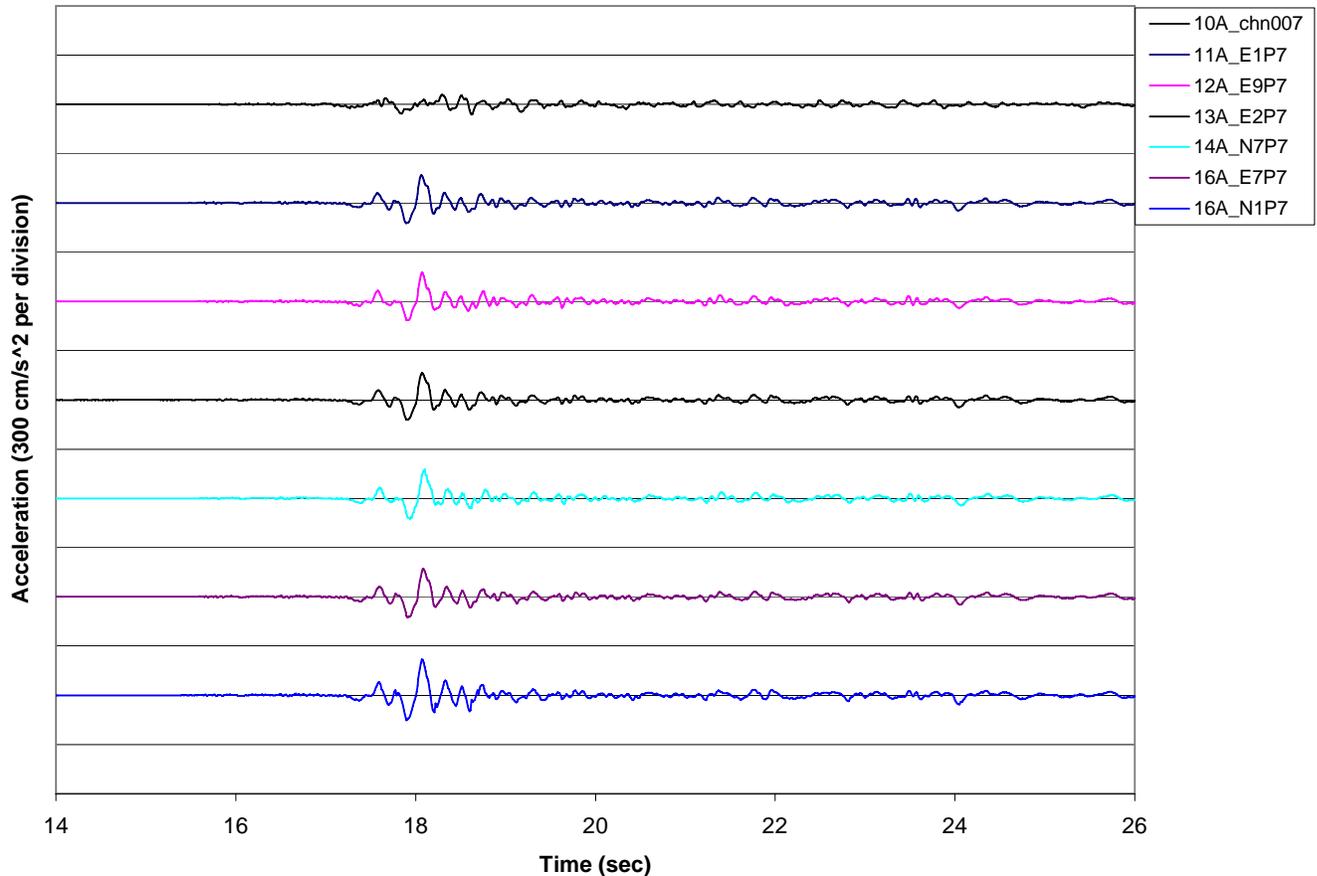


Figure 10. Observed (top) and predicted time series, EW component, at site D3, in the rock at the base of the sediments in the valley, based on the valley-edge rock record (R1), generated using the Standard soil model and a variety of computational methods.

Response Spectra Comparisons

To more completely compare the predictions and the recorded motion, response spectra are compared. Figure 11 shows the response spectra of the EW component for the observed record, and for all predictions obtained using the Standard soil model. In general, the predicted spectra cluster together, and are quite similar to each other, while the observed spectrum is significantly lower over most periods. At high frequencies (short period **less than .2sec?**), the predicted and observed are quite close (reflecting the difference of 50% or less in the peak values in Figure 6). However, at longer periods, between 0.25 and 0.75 sec, the predictions are several times higher than the observed. The spectra for the predictions based on Preferred soils models are lower, but still well above the observed. Very similar character is shown in the NS component.

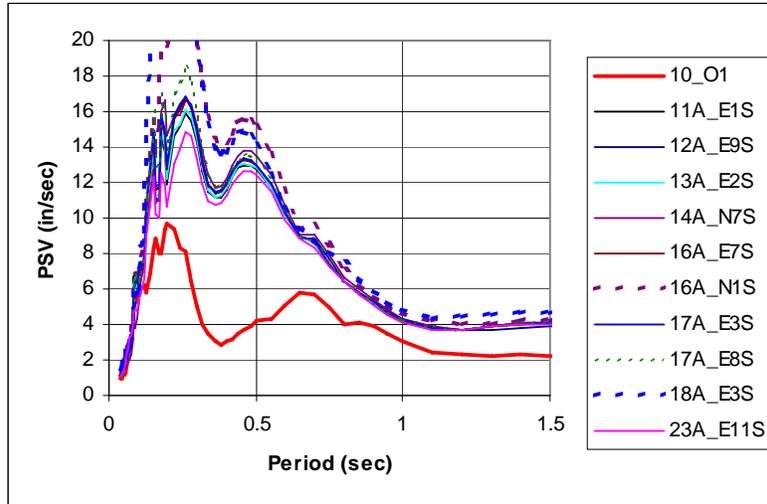


Figure 11. Response spectra of the EW component (5% damping) for the observed record and all predictions, obtained using the R1 valley-edge record and the Standard soil model. The lowest thick line is the observed spectra. The predicted spectra are quite similar to each other and well above the observed spectra at most periods.

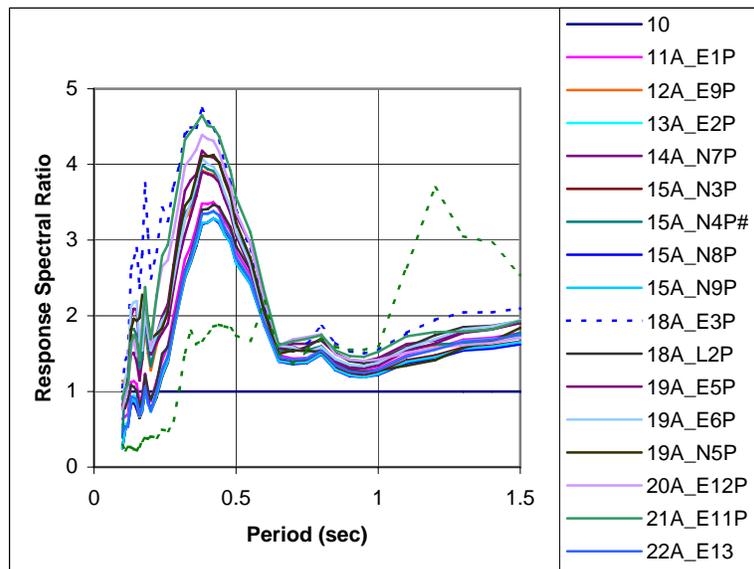


Figure 12. Ratios of the predicted response spectra (EW component, PSV, 5% damping) to the observed at V1, using the R1 valley-edge record and Preferred soil models, for all computational methods. The ratio spectra are quite similar to one another, expect for a few outliers. At periods between about 0.3 to 0.5 second, the predicted spectra are 3 to 4 times larger than the observed.

The difference is clear in the ratios of the predicted to the observed response spectra at V1, shown for the EW component in Figure 12. The ratio spectra are quite similar to one another, expect for a few outliers. At periods from 0.3 to 0.5 second, the spectra are 3 to 4 times

the observed. All methods are shown in Figure 12. There is not a clear difference between the predictions obtained using equivalent linear, nonlinear or linear methods. At long periods, the ratios are somewhat high as well, clustering at a ratio near 2 at 1.5 seconds and increasing slowly for longer periods. For the NS component the ratios are similar, but higher, with the ratios generally being between 5 and 6 in approximately the same period band where the EW component is high.

Phase 2 Predictions – Based on D3

In the second phase of the blind prediction experiment, the predictors were provided with the record from D3, in the rock under the sedimentary valley. The difference between the recording at D1 and D3 is significant, and unexpected by the predictors; this Phase of the experiment avoids this problem.

Peak Accelerations

A comparison of the peak accelerations with each other and the observed, for the EW component, is shown in Figure 13. The predictions cluster around the observed values much better than for the Phase 1 results. Most peak values are somewhat low, surprisingly. For comparison purposes, the Phase 1 predictions are also shown in Figure 13. The spread of predictions is not reduced in Phase 2, though the given record is only 23 meters below the predicted site. It is also clear that some of the predictions which were close to the observed in Phase 1 (e.g., Nos. 13 and 15) are now low.

Response Spectra

The predicted response spectra for the EW component are compared to the observed in Figure 14 and they are quite close to the observed. Beyond about 0.5 second, the predicted and observed spectra are very close to each other, though they drift apart at longer periods. At the spectral peak, around 0.25 second, many of the predicted spectra are smaller than the observed. In the NS direction, the predictions are again quite close to the observed, though at the spectra peak most of the predicted spectra are above the observed.

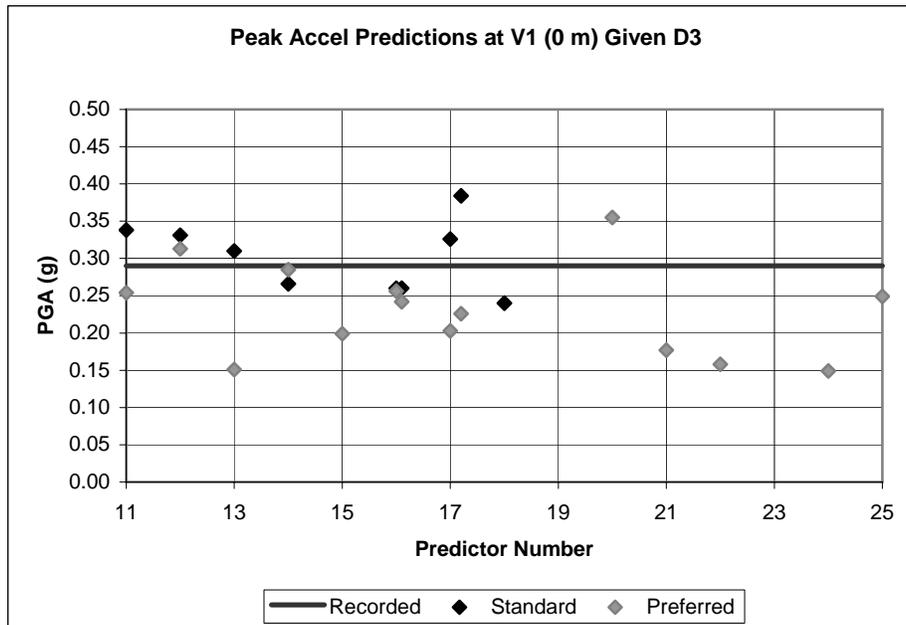
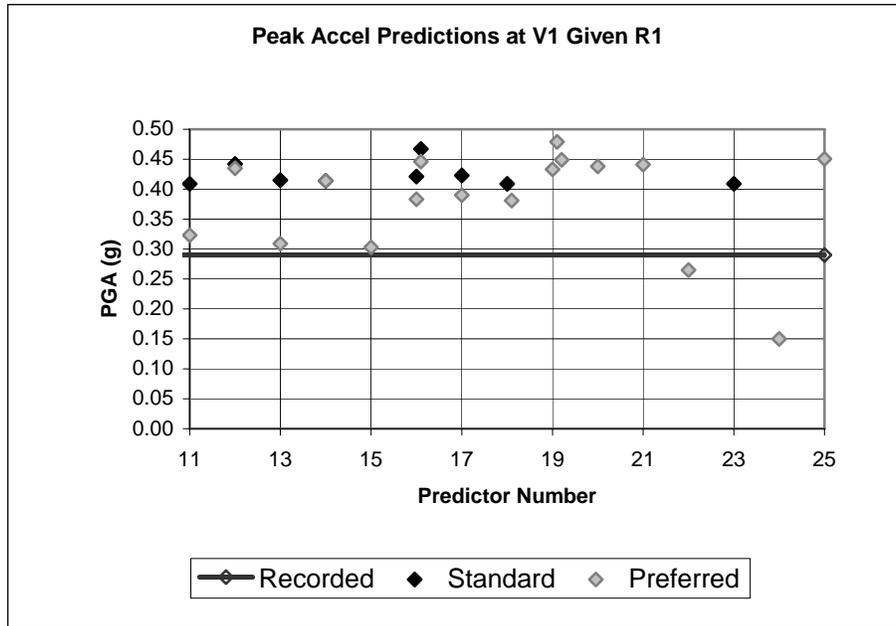


Figure 13. Peak accelerations (EW), observed and predicted, at valley center, V1. Upper: Peak acceleration predictions given the valley-edge record, R1. Lower: Peak acceleration predictions given the record from the rock under the sediments, D3. Predictions were made based on the Standard soil model (black) and Preferred soil models (gray).

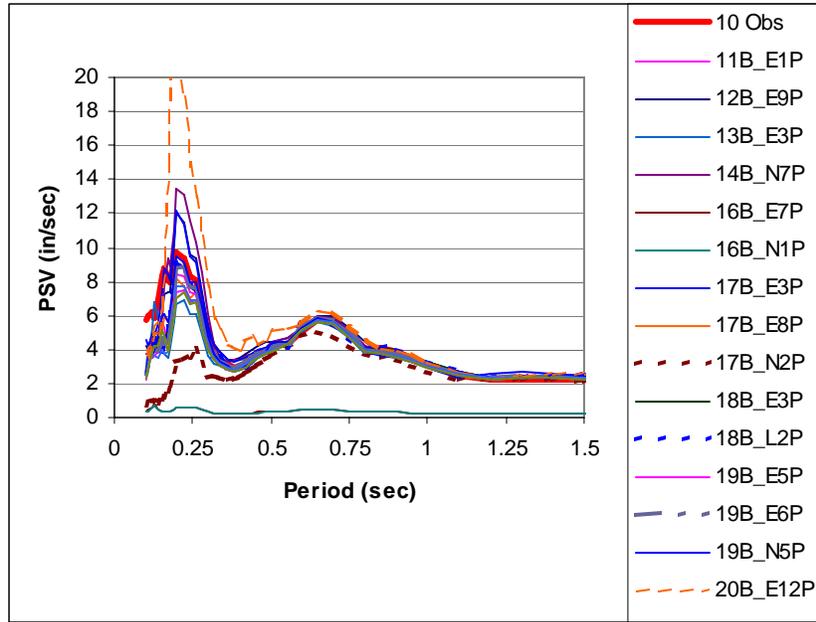


Figure 14. Predicted response spectra (5% damping), given the D3 record, compared to the observed spectra (EW component). Around 0.25 second the observed spectra (at about 9 in/sec) is above most of the predicted spectra (7 to 9 in/sec), but in general the predicted spectra are close to the observed, with some outliers.

Summary

As a result of preparations made two decades ago, continued careful maintenance of the deployed array and the occurrence of the 2004 Parkfield earthquake, an important blind prediction experiment was possible. Fifteen teams participated in the blind prediction; the other key element of the experiment, and in so doing made an important contribution to the community and to the advancement of the science and practice. Analyses of the experiment results have only begun and important advances should result.

Some preliminary assessments can be made. The use of Preferred soil models by the predictors yielded, in general, only limited improvement over the results for the Standard model. The predictions were much more similar to each other than to the observations. The use of nonlinear versus equivalent linear computational methods did not yield dramatic differences for this motion at this site. An experiment with stronger shaking, and/or a softer soil site, may be necessary for the benefit of nonlinear methods to be observed.

The results for the Phase 1 predictions (based on the rock record at the valley edge) showed over prediction of peak accelerations around 50% and of peak response spectra by as much as 3 - 5 times the observed.

The results of the Phase 2 predictions (based on the rock record at the base of the valley sediments) are much closer to the observations. The results show over and under prediction of the peak acceleration and the spectra. The spectra beyond about 0.4 second (frequencies below

2.5 Hz) cluster around each other and the observed spectra well. An important conclusion is that the present ability to predict the motion traveling up through a sedimentary layering is much better than the ability to predict the same motion using an observed surface rock record from about 800 m away, in the Turkey Flat environment.

Data Access

All of the data discussed here is available through the California Integrated Seismic Network's (CISN) Engineering Data Center (EDC), a joint effort of the CGS California Strong Motion Instrumentation Program and the USGS National Strong Motion Program, at <http://www.cisn-edc.org>. Both the processed and raw data are available for download.

Acknowledgements

The success of a blind experiment like this depends on several key elements. With the initial impetus of B. Tucker in 1986, the Strong Motion Instrumentation Advisory Committee reviewed and recommended the deployment of an array in 1987. Key individuals included C. Stepp, L. Crandall, M. Power, N. Donovan, I. Idriss and W. Joyner. Current members of SMIAC or its subcommittees, including W. Iwan, M. Lew, G. Martin, B. Chiou, B. Tsai, Y. Borzorgnia and A. Abghari, none of whom were involved in any of the prediction teams, helped plan the prediction workshop. Geotechnical properties of the site were measured in the 1980s by Crandall & Assoc., Dames and Moore, Geomatrix, Woodward Clyde, Oyo Corp. and others. Drilling was provided by Pitcher Drilling. W. Thomson of CSMIP maintained the array for the last 10 years, originally installed by C. Petersen and others. The success of the experiment was crucially dependent on the efforts of the predictor teams, whose involvement was critical to real benefit being obtained from the experiment, and the geotechnical community is indebted to their public-spirited participation in the experiment.

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