OVERVIEW OF THE TURKEY FLAT GROUND MOTION PREDICTION EXPERIMENT

Charles R. Real[1], Anthony F. Shakal[1], Brian E. Tucker[2]

[1] California Geological Survey, Sacramento, CA
[2] GeoHazards International, Palo Alto, CA

Abstract

Recognizing the wide variability of methods and often conflicting results of seismic response analyses used for design and construction in the early 1980's, the California Geological Survey (CGS) established the Turkey Flat Site Effects Test Area in 1987, and within two years a *blind* test was conducted to predict the test area's low-strain seismic response. Test results focused on the need to reduce uncertainties in the geotechnical parameters that drive site response codes. Fifteen years later, the array recorded the September 28, 2004 M6.0 Parkfield Earthquake at a fault-rupture distance of only 5 km. A blind test has been conducted to evaluate the ability of current practice to determine the test area's moderate-strain seismic response. This paper provides an overview of the Turkey Flat test site, and describes the rationale for what has become an evolving blind test experiment.

Introduction

The Turkey Flat test area was established to help determine the *state-of practice* in estimating the effects of surface geology on earthquake ground motion (Tucker and Real, 1986, 1988). The California Geological Survey (CGS) joined formation of the IASPEI/IAEE working group on ESG to promote installation of strong-motion arrays specifically designed to study the site-effects phenomenon (Kudo, 2003). CGS's Strong-Motion instrumentation Program (CSMIP) established the Turkey Flat test area in 1987 near the town of Parkfield in the central California Coast Ranges (figure 1).

A clear lack of consensus prevailed in the early 1980's on how soils behave under strong earthquake shaking and their potential to amplify ground motions. The unexpected high level of ground shaking in Mexico City, well above that predicted by contemporary attenuation models, underscored the importance of amplified ground motions caused by linear behavior of high-plasticity clays (Bielak and Romo, 1989).

At the same time advances in soil mechanics began illuminating the importance of non-linear soil behavior at high cyclic strains, and the accompanying de-amplification of ground motions that should be considered when estimating site response in engineering practice (Idriss, 1990). Increasingly complex 2-D and 3-D computer codes were developed to model dynamic soil behavior, providing more opportunity for a wider range of predicted ground motions depending on the constitutive model chosen to represent the soil column on a particular project. There became a clear need to judge the validity of the new models based on a comparison of model results with actual measurements of ground motion in an objective but decisive manner. This paper provides an overview of the Turkey Flat Experiment and its approach to this challenge, and focuses on what has been learned regarding the design and operation of a site-effects test area over the past 2 decades. A companion paper in these proceedings describes preliminary results of the Strong-Motion Test (Shakal, et al., 2006a).

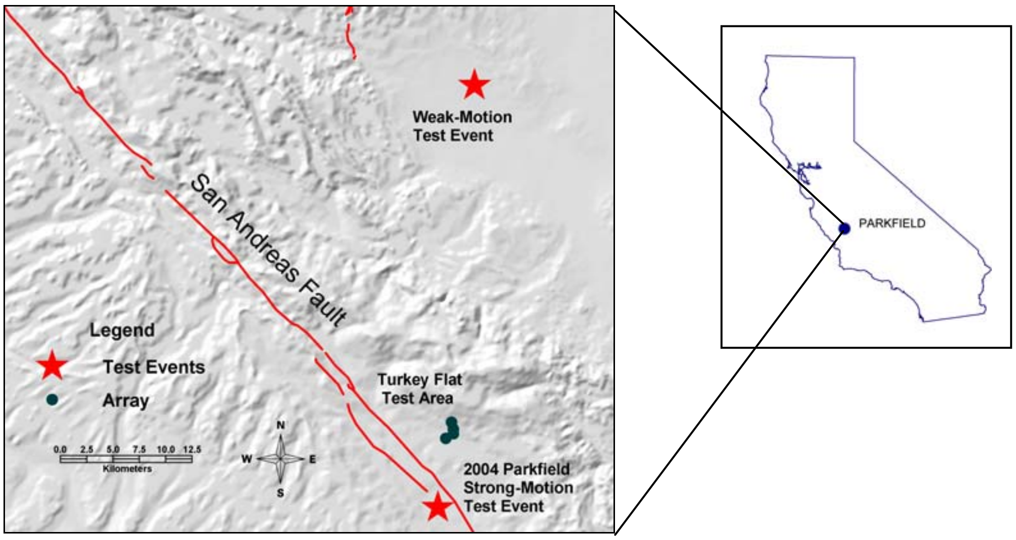


Figure 1. Turkey Flat Site Effects Test Area

Experiment Design

Design of the Turkey Flat experiment was driven by a need to emulate a site response analysis as conducted for a large construction project. The site should be representative of that typically chosen for development, and data provided that are normally attainable in practice. The design was also driven by secondary goals to identify weaknesses and limitations of contemporary site response analyses and to provide a comprehensive database of high-quality geotechnical and seismological data that will continue to facilitate future site-response earthquake engineering research. With these goals in mind it was recognized that although the test site represents only one of an endless variety of site conditions, it is important that the results of the experiment be definitive.

Being among the first international test areas to be established, and knowing that there would be more to follow, it was decided that a site be selected where there is a reasonable likelihood of predicting the correct site response. The rationale being to begin with a simple site before moving to more complicated sites that require complex models and extensive field investigations in order to define the model parameters. If the state-of-practice performs poorly at a geologically simple site, then it is unlikely that it can do better in a more complex site, where the results of a validation test would most likely be less definitive.

Another consideration that bears on experiment design is the site response modeling process. In contrast to an approach where the model is adjusted *a priori* to yield a known site response, a true test of the state-of-practice demands the construct of forward modeling. While valuable for research, inverse modeling is not representative of site response in earthquake engineering practice. Consequently, a blind ground motion prediction test forms the basic framework of the Turkey Flat site response prediction experiment. Assessing the state-of-practice should also include an assessment of the confidence practitioners place on their results, which is incorporated into the blind test process with appropriate consideration in experiment design.

The nature of the experiment requires a broad range of participation, with industry a crucial player. The more sophisticated *state-of-the-art* models reside in the research sector, but these models are not representative of those typically employed in practice. To achieve the goals of the Turkey Flat experiment requires the participation of reputable earthquake engineering firms. Finally, expertise in ground motion estimation is international, so results of the experiment benefit from foreign participation. As the experiment takes on a more serious nature, assuring the desired level of participation requires complete anonymity throughout the experiment; especially in the industrial sector where company reputations may otherwise be affected.

Another requirement for definitive results is the acquisition of high-quality data from which to derive reliable model parameters, and which forms the basis for *ground truth* observations of site response against which prediction results are to be judged. This called for a comprehensive program of geotechnical site characterization and a well-planned high-performance seismic instrument array that must be maintained throughout the operational life of the test site. The scope of the experiment is costly, so a reasonable return on the investment required locating the test site in a seismically active area where a moderate or larger earthquake is imminent.

The secondary goal of identifying the limitations and weaknesses of the various site response estimation processes requires an understanding of uncertainties. To help isolate uncertainties the experiment is conducted in multiple phases, with multiple investigation teams in each phase (figure 2). Three principal phases were identified: 1) *site characterization* to help select an appropriate site response model, and to estimate appropriate model parameters and their uncertainties, 2) a *weak-motion test* to predict the low-strain response of the test site, evaluate the adequacy of the site characterization, provide a preliminary assessment of the state-of- practice, and exercise the entire testing procedure, and 3) a *strong-motion test*, to predict the high-strain response of the test site, quantify nonlinearity of site response, and provide the results necessary to gauge the state-of-practice in site response estimation. Each blind test is conducted in two parts: 1) predictions based on surface rock motions and 2) predictions based on rock motions beneath the sediments. This multi-phase approach allows for tracking the propagation of errors, and helps to distinguish aleatory and epistemic uncertainties. To further isolate uncertainties and assist in the comparison of prediction models, site response predictions were made using a *standard* geotechnical model and a *preferred* geotechnical model derived by each prediction team from the basic field and laboratory measurements.

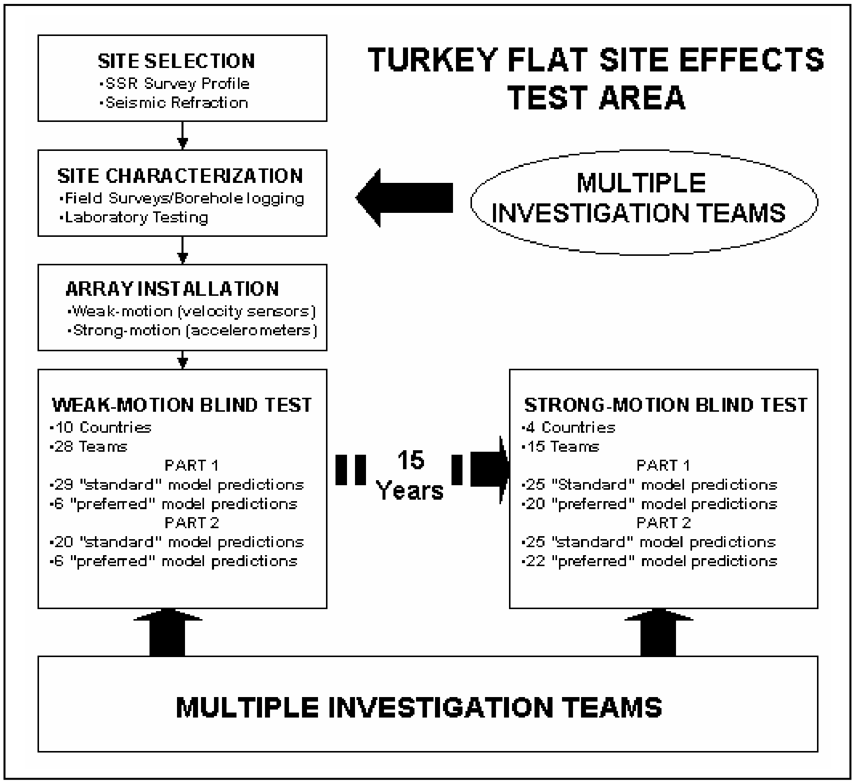


Figure 2. Principal Phases of the Turkey Flat Experiment.

Finally, the highly structured nature and broad scope of the experiment has benefited from expert advice. The Turkey Flat experiment receives oversight from two different advisory groups: an *ad hoc* project steering committee and the Strong-Motion Instrumentation Advisory Subcommittee on Ground Response, both consisting of experts representing practitioners in industry, government, and academia. Having several members who have served since the inception of the Turkey Flat experiment, these groups have provided advice on all aspects of the project including site characterization and the structure of the blind tests.

Site selection

Given the constraints of a geologically-simple site where a moderate event is expected soon and is close enough to experience strong motion, but not too close to be dominated by source effects led to the selection of Turkey Flat (figure 1). The site lies about 5km east of the San Andreas fault, where a characteristic ~M6.0 Parkfield Earthquake was predicted to occur sometime between 1988 and 1992 based on an average historical recurrence interval of 22 years ± 7 (Bakun and Lindh, 1985). Turkey flat is a shallow elongated valley composed of unsaturated Holocene and late Quaternary stiff alluvial terrace sediments overlying basement rocks consisting of Upper Cretaceous and Tertiary sedimentary rocks folded into a southwest plunging syncline (Hanna et al., 1972). Basement rocks outcrop along the western edge of the valley with practically no topographic relief, providing an excellent location for a ground motion reference site. Elevated basement rocks outcrop to the east, where the valley sediments pinch out along the western foot of the southern Diablo range (figure 3).

Beginning in the Fall of 1987 and continuing through Fall 1988, a comprehensive program of site characterization was carried out that included multiple investigation teams, both domestic and abroad, that conducted a broad range of field and laboratory geophysical and geotechnical tests (table 1) (Real and Tucker, 1987; Real and Tucker, 1988c; Tucker et al., 1988). Participants from industry, government, and academia, provided the redundancy of measurements necessary for estimates of uncertainty in site characterization (table 2).

Eight boreholes were drilled through valley sediments into the underlying basement rocks, in which *in situ* testing was performed and rock and sediment samples were acquired for laboratory analysis. All boreholes were cased except one, which provided for improved *in situ* testing of native materials. The cased boreholes were later used for installation of temporary downhole weak-motion sensors and permanent downhole strong-motion sensors. The site-characterization program categorized the Turkey Flat test area as a shallow 25m deep stiff-soil site with a depth to half-width ratio of 1:40, consisting of unsaturated clayey sand and sandy clays derived from the mountain slopes along the eastern edge of the valley (figure 4). Repeated measurements during the wet and dry seasons show the water table remains below the sediment bedrock interface. The interface slopes from the edges toward the valley center with little intervening relief, and is marked by a shear-wave impedance contrast of about 3. Although simple, the site is one where surface geology has a measurable site response, and where 1-D equivalent-linear ground motion models would be expected to perform well. Details of the site-characterization program have been reported (Real, 1988; Real and Tucker, 1988a, 1988b; Real and Cramer, 1992).

Table 1. Participants in Site-Characterization

- Leroy Crandall Associates
- Dames and Moore
- Woodward Clyde Consultants
- Qest Consultants
- Harding Lawson Associates
- Pitcher Drilling Company
- Lawrence Livermore National Laboratory
- California Geological Survey
- Oyo Corporation
- Kajima Corporation

Table 2. Site Characterization Tests

Geophysical/Geotechnical Field	Laboratory
Seismic Refraction (weight drop/explosives)	Unit weight
Seismic Reflection (large air gun)	Liquid limit
Resistivity log	Plastic limit
Spontaneous-Potential Log	Plasticity index
Density log (gamma-gamma)	Sieve analysis
Natural gamma	Moisture content
Downhole velocity (Vp & Vs)	Soil classification
Cross-hole velocity (Vp & Vs)	Consolidation test
Suspension velocity log (Vp & Vs)	Direct shear test
Vertical seismic profile (Vs)	Cyclic triaxial test
Caliper log	Resonance column test
Borehole deviation log	Dynamic torsion test
Pressuremeter test	Triaxial ultrasonic wave velocity
Standard penetration test	
Downhole Q (P & S-wave)	

The Turkey Flat test area instrument array is composed of four recording sites: Rock South (R1), Valley Center (V1), Valley North (V2), and Rock North (R2), with downhole sensors at Rock South (D1), and mid-way (D2) and in the underlying bedrock (D3) at Valley

Center (figures 3-5). Each sensor location consists of 3-component forced-balance accelerometers (details of the instrumentation are provided in figure 5). The strong-motion array was carefully maintained for 17 years by CSMIP. In 2001, 3 years prior to the occurrence of the 2004 Parkfield Earthquake, instrumentation was upgraded to12-bit solid-state digital recorders, which resulted in high-quality records of the Parkfield event. Details of the standard record processing are available (e.g. Shakal et al., 2003).

The CSMIP also established and maintains a 45-station wide-aperture strong-motion array across the Parkfield segment of the San Andreas Fault a few kilometers from the Turkey Flat array (McJunkin and Shakal, 1983). The Parkfield array consists mostly of analog accelerographs and is designed to provide near-fault ground motion data for researching the fault rupture process. The array recorded the 2004 event and has produced an abundance of records that uniquely document a complex rupture process and highly variable near-fault ground motions. These data can provide important insights into the source characteristics of the test event that may be of value in the analysis of Turkey Flat site response. A description of the Parkfield array and a preliminary analysis of records from the 2004 Parkfield event are available (Shakal et al., 2006b).

During Spring 1988, a weak-motion survey of local and regional earthquakes was conducted in order to determine weak-motion empirical transfer functions for each recording site of the strong-motion test area array, and to acquire data to conduct the weak-motion blind test (Cramer, 1990a, 1992, 1995). Velocity sensors were installed at all accelerometer locations on the ground surface and in adjacent boreholes across the test site array (figures 3-5). During the 2 1/2 months of operation 33 local and regional earthquakes were recorded in the magnitude 2-4 range, at distances of 20-230 Km, and azimuths ranging 4°-350°. The SSR technique was used with these data to compute average site transfer functions, which are being used to test the utility of the technique for predicting moderate and high-strain site response in the strong-motion blind prediction test (Cramer, 1995).

In addition to the strong-motion arrays near Parkfield, regional seismograph network coverage by the California Integrated Seismic Network provides accurate locations of local and regional earthquakes.

The Blind Tests

In a blind test high-quality geotechnical data and bedrock motions from a test event recorded at a reference station are distributed to participants as input to the site response estimation process. Participants are then asked to predict bedrock motions beneath the valley (Part 1) and at all other recording sites within and across the valley using the standard geotechnical model, and, if desired, a second set using their preferred geotechnical model. After receiving all predictions from Part 1, the procedure is repeated only this time using the actual recorded ground motions beneath the valley as input (Part 2). With the exception of those recordings used as input motions, all other recorded ground motions across the array are held confidential until all site response predictions are completed. Comparisons are then made between predicted response and observed response.

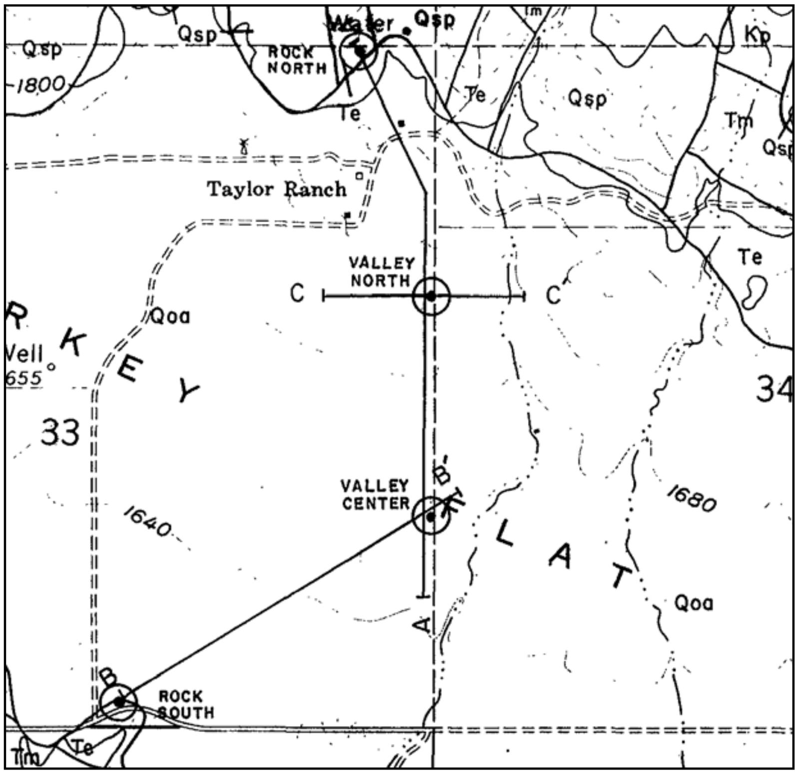


Figure 3. Plan view of Turkey Flat test area showing cross-section lines and location of instrument recording sites.

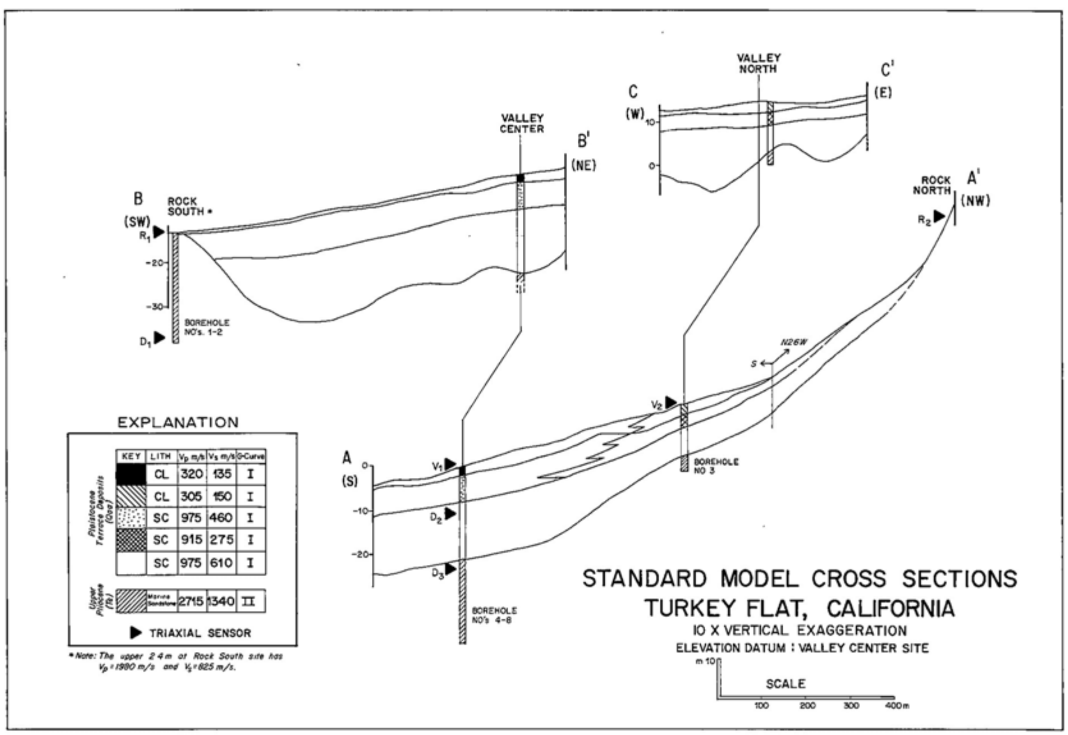
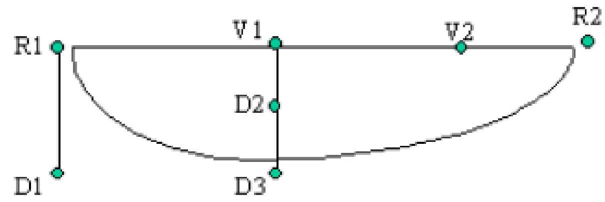


Figure 4. Cross-sections of Turkey Flat Test Area.

Turkey Flat Instrument Array Configuration



Cross-section schematic

Array Sensor Locations and Coordinates*

Location Code	Lat	Long	Depth (m)	Station Number	SMIP Station Name
R1	35.878	-120.358	0	36529	Parkfield - Turkey Flat #1
D1	35.878	-120.358	24		
V1	35.882	-120.350	0	36520	Parkfield - Turkey Flat #2
D2	35.882	-120.350	10		
D3	35.882	-120.350	24		
V2	35.886	-120.350	0	36519	Parkfield - Turkey Flat #3
R2	35.892	-120.352	0	36518	Parkfield - Turkey Flat #4

*Instruments at each location are oriented West, Up, North.

Accelerometers:
- FBA 3-component (Kinemeterics)
- Digital Recording – 12-bit (solid state system since 2001)

Velocity Sensors:
- Surface – 3-component 2Hz (Springnether S-6000)
- Downhole – 3-component 4.5Hz (Mark Products L10-SWC)
- Digital Recording – 12-bit

Figure 5. Turkey Flat array instrument types and locations.

Prediction of earthquake ground motions can be categorized as Class A (considering source, path, and site effects) and Class B (considering only site effects). Because the focus of the experiment is on site effects, the initial blind test predictions are of type Class B, which further constrained the site selection process. Confidentiality of observed site response throughout the blind test process is important because upon completion, should the accuracy of predictions fall short of observations because of suspected path or source effects, a Class A prediction blind test could still be performed at a subsequent stage.

Predicted site response is requested at specific sensor locations, and are in four prescribed forms: 1) acceleration time histories, 2) pseudovelocity response spectra, 3) Fourier amplitude spectral ratios relative to a rock reference site, and 4) peak values of acceleration, velocity, and displacement. Each form is to include an estimate of uncertainty (standard errors), and is requested to be submitted as digital files and printed plots, both in a prescribed format.

Weak-Motion Blind Test

A M2 event located about 32 km north of the Turkey Flat test site (figure 1) was recorded on 04/27/1988 at the bedrock reference site (Rock South on figure 4). The record was processed and distributed as input motions to the weak-motion blind test (Cramer et al., 1989; Real and Cramer, 1989,1990).

The Turkey Flat weak-motion blind test began Spring 1989 and concluded 16 months later (Cramer and Real, 1990c). There were 28 participants from 10 countries that submitted a total of 29 predictions for Part 1 and 20 predictions for Part 2 based on the standard geotechnical model (tables 3- 4). Eight categories of site response methods were tested in Part 1, and 6 categories in Part 2 (table 4).

Table 3. Participation

Country	No.
Canada	1
China	3
Czechoslovakia	2
France	3
Germany	1
Italy	1
Japan	7
Mexico	1
New Zealand	1
United States	8

Table 4. Categories of site response models tested

Site Response Category		Part 1 (R1-based)	Part 2 (D3-based)
1-D	Equivalent linear	8	5
	Spectral	3	2
	Haskell-like	3	2
	Wave propagation	3	2
2-D	Finite element	5	2
	Wave propagation	3	7
	Boundary element	1	-
3-D	Wave propagation	1	-

Participants were encouraged to submit a second set of predictions based on their preferred geotechnical model which they derived from the basic field and laboratory data. There were 6 submissions for Part 1 and 6 for Part 2.

Each set of predictions was grouped according to their input ground motions, the geotechnical model used, site response model dimensionality, and whether the prediction is optional. They were then statistically compared with observations in all four prescribed forms by computing means, standard deviations, medians, quartiles, and average deviations from observations (Cramer and Real, 1990b,1992). This comparative analysis provided the following results:

- The inter-quartile range of predictions cluster within 10% of their median response, regardless of the geotechnical and site response model used;
- Similarity of shape and frequency of resonant peaks between predicted and observed spectral ratios suggest that layer thicknesses and velocities of the standard geotechnical model are generally reasonable;
- Predictions tend to over estimate the amplitude of the observed ground motions (e.g. figure 6), suggesting that damping in the standard geotechnical model is too low; and,
- Predictors tend to significantly underestimate the uncertainty of their results.

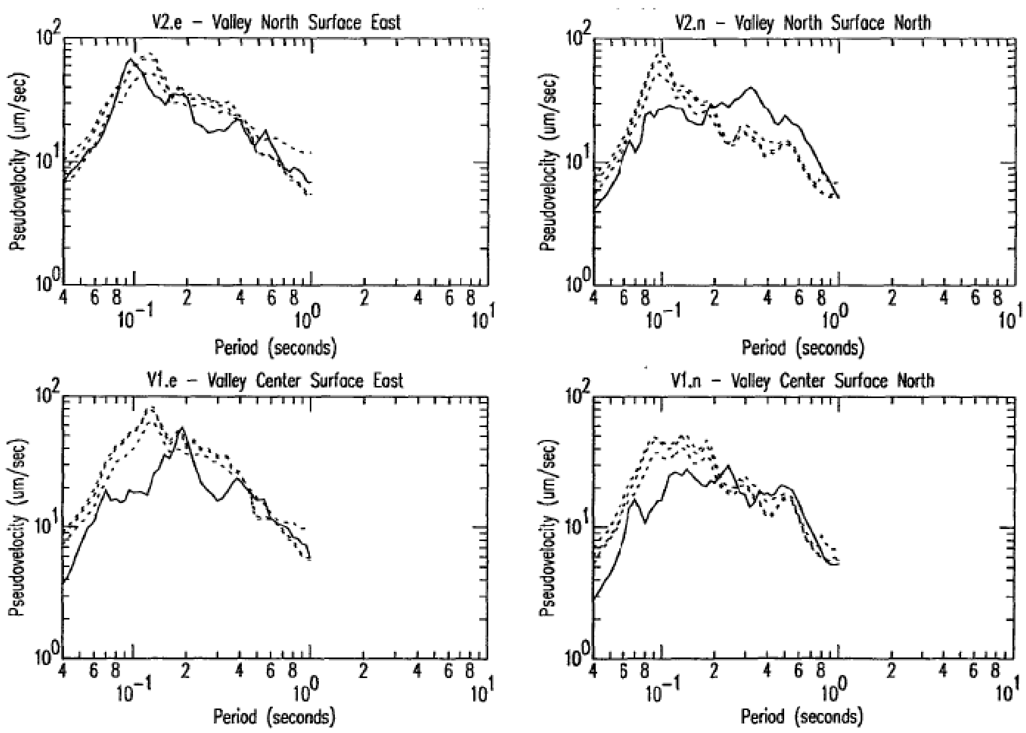


Figure 6. Predicted horizontal pseudovelocity response spectra (dotted lines quartiles) for Valley North (top pair) and Valley Center (bottom pair) surface sites compared with observations (solid lines) (Cramer and Real, 1990b).

Although the level of participation in the weak-motion test was high, the number of submitted predictions is too small to statistically evaluate performance of the individual site response methods used. However, a comparison of the performance of 1-D methods with that of 2-D and 3-D methods combined indicates no significant improvement using site response methods of higher dimensionality. This might be expected given the relative geologic simplicity of the Turkey Flat test site. Despite the simplicity, however, results indicate that improvements are necessary in site characterization; particularly in reducing the uncertainties in damping and velocity structure. It is worth noting that damping in the standard geotechnical model is biased toward laboratory measurements, which were significantly lower (up to a factor of 10) than damping values obtained by field methods. The results of the blind test suggest the latter may be more reliable. Too few participants submitted predictions based on a preferred model to draw significant conclusions, but of the 6 on hand the one preferred geotechnical model that significantly improved the prediction had increased damping.

Field and Jacob (1993) analyzed the sensitivity of theoretical site response predictions at Turkey Flat to uncertainties in the standard geotechnical model using Monte Carlo simulation. Based on data from the site characterization, they modeled uncertainty distributions for velocity, damping, and layer thicknesses, using a 1-D linear-viscoelastic model to calculate site response for thousands of iterations randomly varying the model parameters according to their uncertainty distributions. The result shows that uncertainties in input parameters produce a large variability in computed site response (e.g. inter-quartile range is 82% of the median response at valley center site). Two important conclusions were drawn from their results: 1) nearly all of the weak-motion predictions can be considered a success since their average deviations from observations fall within the expected range of uncertainty, and 2) considering the geologic simplicity of the Turkey Flat test site and the comprehensive site characterization program, site response estimates based on a single contemporary geotechnical study elsewhere are likely to be unreliable.

The principal conclusion drawn from these findings is that when estimating the response of a geologically simple, shallow stiff-soil site the geotechnical model may be more important than the method used to calculate response, underscoring the importance of obtaining more accurate estimates of seismic velocity structure and damping during site characterization.

Strong-Motion Blind Test

The M6.0 Parkfield earthquake occurred on September 28, 2004, rupturing the ground surface for a distance of 25 km along the San Andreas Fault, which passed within about 4 km southwest of the Rock South recording site. The main shock was well recorded by the dense Parkfield array, revealing a complex pattern of highly variable ground motions (figure 7).

Near-fault peak accelerations range from .13g to more than 2.5g, while stations separated by only 2-3 km differed by nearly an order of magnitude (Shakal et al, 2006b). Possibly due to source and/or site effects, the high degree of ground shaking variability over short distance is under investigation. No significant directivity is evident from the dense near-field array data, which may be due to bilateral rupture along the San Andreas Fault during the 2004 event (Shakal et al., 2006b).

Turkey Flat lies between the two high acceleration lobes at each end of the fault rupture as shown on figure 7. The main shock produced a peak rock acceleration of 0.245g at station Rock South (surface), and 0.07g at station D3 (rock beneath valley) of the Turkey Flat array (figure 8). The Rock South records were processed and distributed March 2005 for the beginning of the strong-motion blind test (Real and Shakal, 2005; Real et al., 2005), and the D3 records were distributed 7 months later. The deadline for Part 1 predictions was October 2005, and for Part 2 February 2006. Analysis of the submitted predictions is still underway at the writing of this paper, and final results will be available by Fall 2006.

The Turkey Flat strong-motion blind test began March 2005 and is expected to conclude Fall of 2006. There are 15 participating teams from 4 countries that have submitted a total of 92 sets of blind predictions, 45 for Part 1 and 47 for Part 2 of the test. Of the 92 sets of predictions, 18 are from industry, 54 are from academia, and 20 are from government sectors (Table 5). Each *prediction set* corresponds to various sensor locations depending on the level of participation, and varies for Part 1 and Part 2.

Table 6 identifies the various computer codes and model categories being tested. All prediction sets are 1-D analyses except 3 that are 2-D. Also indicated for each code/model being tested are the numbers of prediction sets as described previously that have been submitted for the array, and the number of site response predictions tallied by individual sensor locations (horizontal component pairs) for Part 1 and Part 2, all subtotaled by model category.

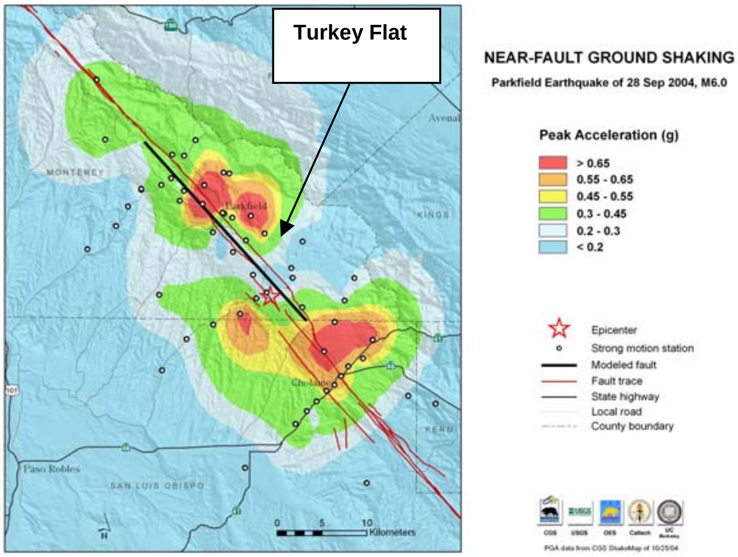


Figure 7. Near-field peak acceleration map of M6.0 2004 Parkfield Earthquake (Shakal et al., 2005)

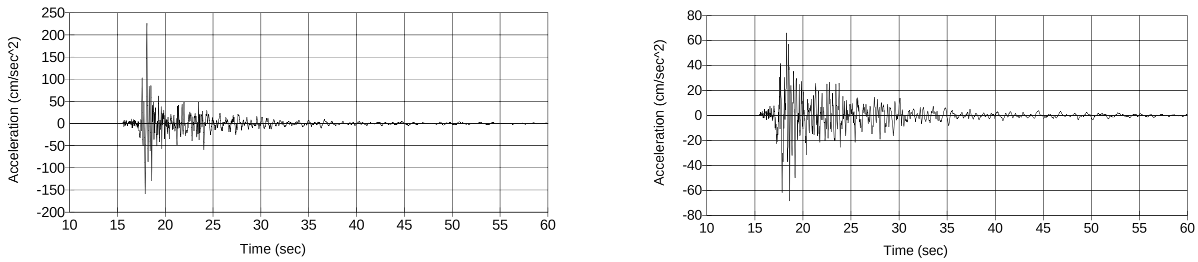


Figure 8. 2004 Parkfield mainshock recorded at (left) Rock South and (right) D3 (rock beneath Valley Center) of the Turkey Flat array.

Table 5. Number of site response prediction sets for Turkey Flat strong-motion test.

Sector	Part 1		Part 2		Total
	Preferred	Standard	Preferred	Standard	
Industry	5	4	5	4	18
Academia	15	11	17	11	54
Government	5	5	5	5	20

The grand total of individual predictions, most provided in the 4 basic forms described previously, exceeds 250 (or more than 500 for individual horizontal components). Thus, the level of participation is believed to be sufficient to draw meaningful conclusions regarding the state-of-practice in site response analysis.

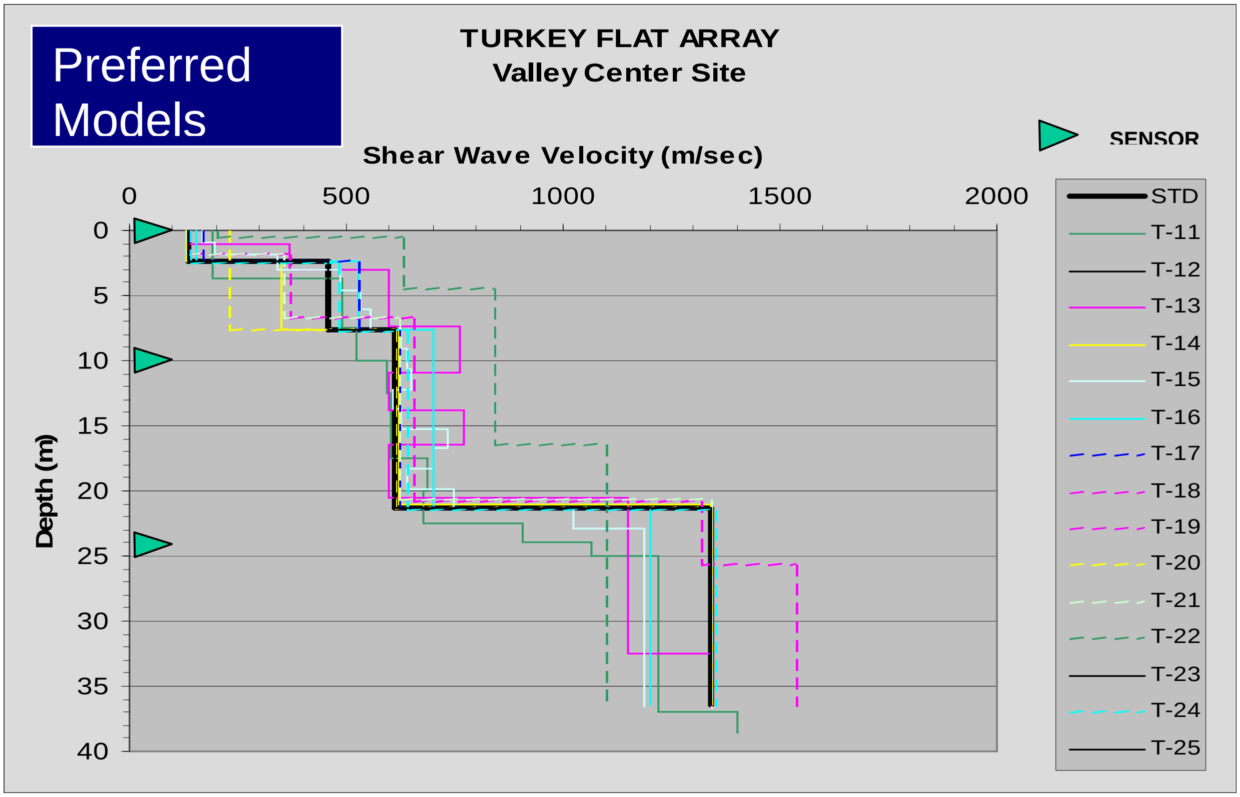
Table 6. Site response codes tested and number of predictions.

Category	Method/Code	No. Sets	Analysis Performed	No. Predictions[2]	
				Part 1	Part 2
Equivalent Linear	SHAKE04	2	1-D	0	4
	SHAKE96B	4	1-D	12	4
	SHAKE91	18	1-D	29	16
	SHAKE72	4	1-D	12	10
	TremorKA	2	1-D	6	2
	TremorN2	2	1-D	6	2
	DeepSoil	6	1-D	12	6
	FDM	4	1-D	12	6
	BESOIL	2	1-D	6	2
	RASCAL	4	1-D	12	4
	SuperFLUSH[1]	2	2-D	6	2
	DYNEQ	5	1-D	15	4
	Subtotal	(55)	Subtotal	(128)	(62)
Nonlinear	DMOD-2[1]	6	1-D	4	10
	DeepSoil	6	1-D	12	6
	TESS	4	1-D	7	4
	FLAC[1]	4	1-D	4	4
	FLAC[1]	1	2-D	0	2
	OpenSees[1]	4	1-D	5	4
	SUMDES[1]	4	1-D	4	4
	NOAHW[1]	2	1-D	6	2
	Subtotal	(31)	Subtotal	(42)	(36)
Other	SSR	2	Empirical transfer function	6	5
	PEXT	2	1-D Source, path, site	6	6
	Subtotal	(4)	Subtotal	(12)	(11)
	Total	90[3]	Total	182	109

[1] Also capable of 2- and/or 3-D analyses. [2] Count is for horizontal component pairs. [3] Two additional sets were submitted that averaged the results from several different codes.

Preferred Soil Models

One major difference between the weak- and strong-motion tests is that the latter required submittal of predictions based on a user-preferred soil model. While only 6 predictions based on a preferred model were submitted for the weak-motion test, 22 were submitted for the strong-motion test. Figure 9 shows preferred velocity and slowness profiles derived from the field measurements by the participants, and indicates substantial variability in judgment among predictors. Slowness is the inverse of velocity, which is linearly related to the time seismic waves spend traveling through each layer. The importance of the near-surface layers is of physical significance as clearly indicated by their longer travel times.



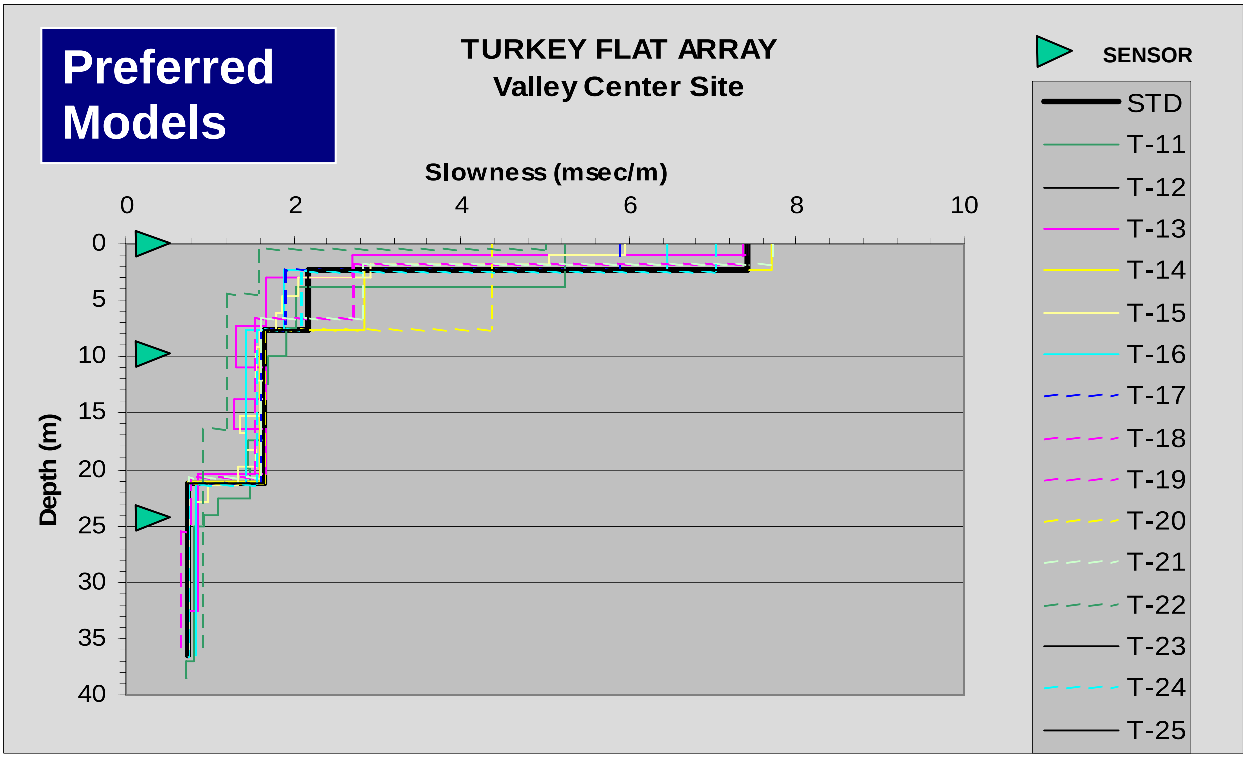
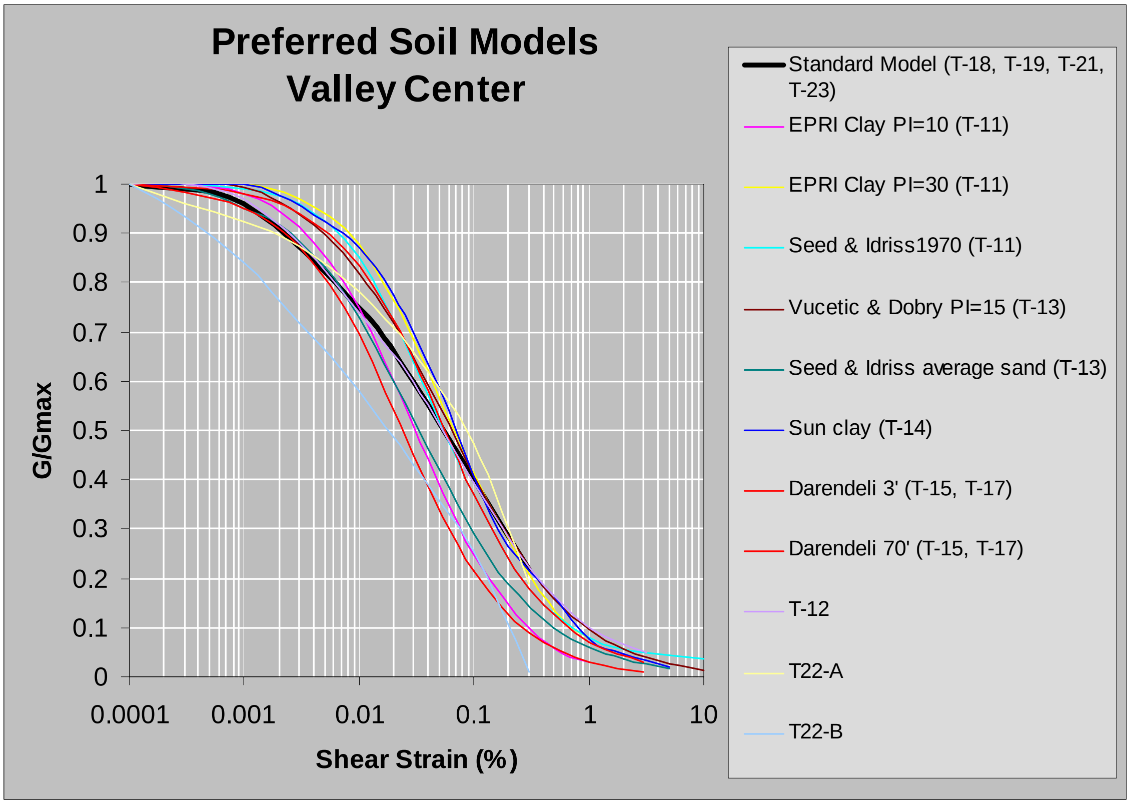


Figure 9. Preferred velocity models used by various predictor teams (indicated by team number).



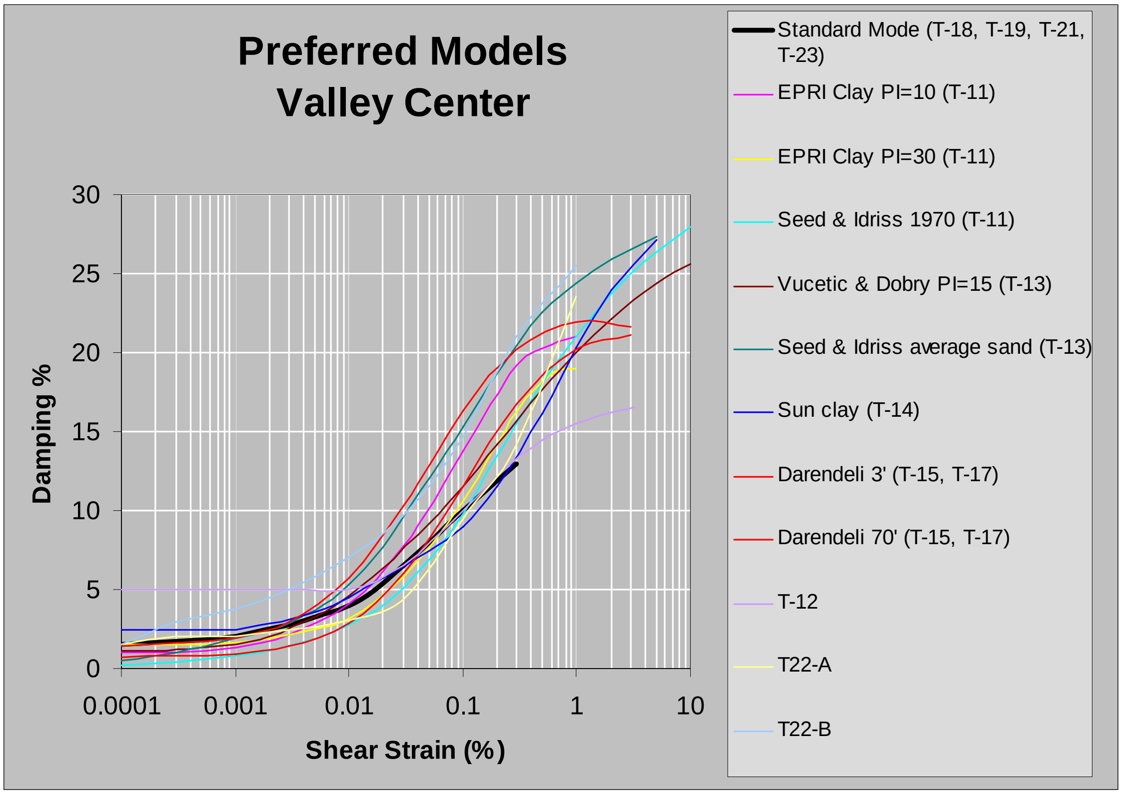


Figure 10. Preferred dynamic soil properties used by the various prediction teams.

Significant advances in site response research have occurred during the 15 years since the weak-motion blind test. Improvements in field and laboratory soil testing and numerous dynamic soil tests made for a variety of soils and representative site conditions have led to a greater understanding of the physics of soil behavior at large strains. The result is a more comprehensive theory of critical state soil mechanics, which has prompted the development of more sophisticated fully nonlinear computer codes and more realistic rheologies to better represent the dynamic behavior of various soil types (Lo Pristi et al., 2004). As a consequence, practice has advanced since the weak-motion test was conducted, which has implications on the soil models chosen for use in the various equivalent-linear and nonlinear codes used in the strong-motion blind test. Variability of the preferred modulus reduction and damping curves used by predictors is shown in figure 10. In addition to these parameters, other parameters not shown that are used in the nonlinear computational models include those used to define the hysteretic behavior of soils under cyclic loading, which are code specific.

Discussion

There are at least two principal issues that are being closely examined that could compromise the integrity of the experiment at Turkey Flat in regards to the strong-motion blind test and its effectiveness in addressing the primary goal of helping to determine the current state-of-practice in estimating site response: 1) improvements in the state-of-practice of site characterization since establishment of the Turkey Flat test site, and 2) potential effects of the source and/or path on ground motions recorded across the array due to the close proximity to the test event surface fault rupture.

The principal issue concerning site characterization is that the uncertainty of site response parameters derived in the late 1980’s may be greater than what would result from the current state-of-practice because of interim improvements in field and laboratory testing. If true, this questions the validity of combining circa 1990 practice in site characterization with 2005 practice in site response modeling in order to draw conclusions about the overall reliability of current practice in site response analysis. If today’s methods of site characterization are indeed better, then consideration should be given to a supplementary site characterization program at Turkey Flat to perform those tests where improvements have significantly reduced parameter uncertainties in order to obtain improved parameter estimates that would be more representative of the current state-of-practice.

Of the 15 participating teams, one team submitted a Class-A prediction that explicitly considers non-uniform source rupture and full wave propagation through a 1-D linear rheology. Analyses of data from the Parkfield array may further validate whether there are significant source effects at sources distances comparable to Turkey Flat. Consideration might be given to conducting a Class-A prediction blind test if differences between site response predictions and observations cannot be adequately explained by errors in site-effects modeling; particularly if analyses of the Parkfield strong-motion array test event records indicate the likelihood of near-field source effects.

Although the strong-motion blind test is still in progress, experience gained thus far suggest several ways to improve similar blind tests that may be conducted elsewhere in the future. The following is a summary of recommendations:

- To better quantify the performance of current site response estimation analyses will require more redundancy of parameter measurements obtained during site characterization. Multiple measurements of a given parameter by each investigator for each method employed would permit a better estimate of the error distributions, improving the statistical significance of performance results;
- Performing site characterization well in advance of array instrumentation allows for more optimal placement of recording sites and sensors;
- The long wait for significant strong-motion recordings requires a robust program and long-term funding for instrument maintenance for calibration, repairs, upgrades, and constant readiness;
- Statistical robustness in the analysis of prediction results and site response estimation methods requires a high level of participation. Evaluating state-of-practice demands participation by industry, which requires anonymity. Achieving a suitable number of participants may require funding support for their time and effort; particularly for industry participants who work for profit and have less discretionary funding available for research.

Finally, we recommend allowing more flexibility in the format for exchange of prediction results. We chose to adhere to a rigid format that was established 15 years ago for the weak-motion blind test. At that time it was prescribed to be the format that would be used for the strong-motion blind test results as well. Experience showed that this was an obstacle to timely submission and exchange of results. With today's computing technology, the format of results has several alternatives such as spreadsheets, text files, or xml files. Use of more conventional formats would have made the task of transferring site response prediction results much easier.

.

A website has been established to provide updates and disseminate information regarding the Turkey Flat Site Effects Test Area and the blind site response tests:
http://www.quake.ca.gov/turkeyflat.htm.

Acknowledgments

Much of the geophysical field work accomplished in this project has been voluntary, and the project would otherwise not have been possible. We thank the following companies for their contributions: LeRoy Crandall Associates (now MACTEC, Inc.), Dames & Moore (now URS Corporation), Geomatrix Consultants, Harding Lawson Associates, Lawrence Livermore National Laboratory, Pitcher Drilling company, and Qest Consultants. We are especially indebted to OYO Corporation and Kajima Corporation of Japan, who traveled great distances at great expense to contribute to the site characterization effort and to share their technologies. We also wish to thank the California Department of Transportation for their assistance in field operations.

We especially wish to thank all participants in both the weak-motion and strong-motion blind tests, for without their participation this experiment would not be possible. We also thank members of the original Turkey Flat Steering Committee. Most of all we are grateful for the generosity and kindness of the land owners, Donald and Nila McCornack, and adjacent residents

Melvin and Ruth Taylor, who understood the value of this project and who made their land available for the Turkey Flat, USA Site Effects Test Area.

References

Bakun, W.H., and A.G. Lindh (1985). The Parkfield, California, Earthquake Prediction Experiment. *Science 22 (4714)*, 619-624.

Bielak, J. and M. Romo (1989). Working Group Conclusions on Geotechnical Engineering and Foundations, in, Bertero, V.V. ed., Lessons Learned from the 1985 Mexico Earthquake: *Earthquake Engineering Research Institute Report 89-02*, 56-58.

Cramer, C.H. (1995). Weak-Motion Observations and Modeling for the Turkey Flat, U.S., Site Effects Test Area near Parkfield, California. *Bulletin of the Seismological Society of America 85,* (2), 440-451.

Cramer, C.H (1992). Weak motion observations and modeling for the Turkey Flat, USA, site effects test area near Parkfield, California. *Proceedings of the International Symposium on the Effects of Surface Geology on Seismic Motion, March, 1992, Odawara, Japan 2*. Association for Earthquake Disaster Prevention, Tokyo, Japan, 21-26.

Cramer, C.H., and C.R. Real (1992). A statistical analysis of submitted site-effects predictions for the weak-motion blind prediction test conducted at the Turkey Flat, USA, site effects test area near Parkfield, California. *Proceedings of the International Symposium on the Effects of Surface Geology on Seismic Motion, March, 1992, Odawara, Japan 2*. Association for Earthquake Disaster Prevention, Tokyo, Japan, 15-20.

Cramer, C.H.. *Turkey Flat, USA Site Effects Test Area – Report 6: Weak-Motion Test: Observations and Modeling*. California, Division of Mines and Geology, TR 91-1(1991).

Cramer, C.H. and C.R. Real (1990a). Ground Response to Weak Motions From Local and Regional Earthquakes at The Turkey Flat Site-Effects Test Area Near Parkfield, CA: Observations, Modeling, and Implications for Ground Motion Prediction. *Seismological Research Letters 61*(1), 51.

Cramer, C.H. and C.R. Real. *Turkey Flat, USA Site Effects Test Area – Report 5: Weak Motion Test: Statistical Analysis of Submitted Predictions and comparisons to Observations.* California Division of Mines and Geology, TR 90-2 (1990b).

Cramer, C.H. and C.R. Real. *Turkey Flat, USA Site Effects Test Area – Report 4: Weak-Motion Test: Observed Seismic Response*. California Division of Mines and Geology, TR 90-1 (1990c).

Cramer, C.H., C.R. Real, and B.E. Tucker (1989). The Weak-Motion Test of The Ground-Motion Prediction Phase of The Turkey Flat, USA, Site Effects Test Area Experiment. *Seismological Research Letters 60* (1), 8.

Field, E.H. and K.H. Jacob (1993). Monte-Carlo Simulation of the Theoretical Site Response Variability at Turkey Flat, California, Given the Uncertainty in the Geotechnically Derived Input Parameters. *Earthquake Spectra 9* (4) 669-702.

Hanna, W.F., Burch, S.H., and T.W. Dibblee, Jr. (1972). Gravity, Magnetics, and Geology of the San Andreas Fault Area Near Cholame, California. *U.S. Geological Survey Professional Paper 646-C*.

Idriss, I.M. (1990) Response of Soft Soil Sites during Earthquakes. *Proceedings, Memorial Symposium to honor Professor Harry Bolton Seed 2*, Berkeley, California, 273-289.

Jarpe, S.P., Cramer, C.H., Tucker, B.E., and A.F. Shakal (1988). A Comparison of Observations of Ground Response to Weak and Strong Motion at Coalinga, California. *Bulletin of Seismological Society of America 78* (2), 421-435.

Kudo, K. (2003). IASPEI/IAEE Joint Working Group on the Effects of Surface Geology on Seismic Motion. *International Handbook of Earthquake Engineering and Engineering Seismology 81.7* CD-ROM #2.

Lo Pristi, D. Lai, C., and S. Foti. Geophysical and Geotechnical Investigations for Ground Response Analyses, in, Ansal, A., ed., *Recent Advances in Earthquake Geotechnical Engineering and Microzonation*. Kluwer Academic Publishers, Dordrecht, Netherlands, (2004).

McJunkin, R.D., and A.F. Shakal (1983). The Parkfield Strong-Motion Array. *California Geology 36* (2), 27-34.

Real, C.R., Shakal, A.F., and V. Graizer (2005). Blind prediction test of the response of Turkey Flat Site Effects Test Area to the September 28, 2004 Parkfield Earthquake. *Proceedings of the IASPEI General Assembly, October 2-8, 2005, Santiago, Chile*.

Real, C.R. and A.F. Shakal. *Turkey Flat, USA Site Effects Test Area – Report 7: Strong-Motion Test: : Prediction Criteria and Input Rock Motions*. California Geological Survey, OSMS 05-1 (2005).

Real, C.R., and C.H. Cramer (1992). Site characterization and standard geotechnical model for the Turkey Flat, USA, site effects test area near Parkfield, California*. Proceedings of the International Symposium in the Effects of Surface Geology on Seismic Motion, March 25-27, 1992, Odawara, Japan 2*. Association for Earthquake Disaster Prevention, Tokyo, Japan, 9-14.

Real, C.R. and C.H. Cramer (1990). Turkey Flat, USA, Site Effects Test Area: "Blind" Test of Weak-Motion Soil Response Prediction. *Proceedings of the Fourth U.S. National Conference on Earthquake Engineering 1*, 535-544.

Real, C.R. and C.H. Cramer. *Turkey Flat, USA Site Effects Test Area – Report 3: Weak-Motion Test: Prediction Criteria and Input Rock Motions*. California Division of Mines and Geology TR 89-1 (1989).

Real, C.R. *Turkey Flat, USA Site Effects Test Area – Report 2: Site Characterization*. California Division of Mines and Geology, TR 88-2 (1988).

Real, C.R. and B.E. Tucker (1988a). Ground Motion Site Effects Test Area Near Parkfield, California. *Proceedings of the Sino-American Workshop on Strong-Motion Measurement*, 140-147.

Real, C.R. and B.E. Tucker (1988b). Turkey Flat, USA Site Effects Test Area site characteristics. *Proceedings of the IASPEI/IAEE Joint Working Group on Effects of Surface Geology on Seismic Motion Second Workshop, Tokyo Japan*, 1-22.

Real, C.R. and B.E. Tucker (1988c). Ground Motion Site Effects Test Area Near Parkfield, California. *Proceedings Ninth World Conference on Earthquake Engineering, Tokyo, Japan VIII*, 187-191.

Real, C.R. and B.E. Tucker (1987). Ground Motion Site Effects Test Area at Turkey Flat, California. *EOS, Transactions American Geophysical Union 68*, 1350.

Shakal, A.F., Huang, M.J., and V.M. Graizer (2003). Strong-Motion Data Processing. *International Handbook of Earthquake Engineering and Engineering Seismology Part B*, 967-981.

Shakal, A., H. Haddadi and C. Real (2006a). Recorded data and preliminary review of predictions in the Turkey Flat blind prediction experiment for the September 28, 2004 Parkfield earthquake, *Proceedings of SMIP06 Seminar on Utilization of Strong-Motion Data, September 28, 2006, Oakland, California*, 137-152.

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

Shakal, A., Graizer, V., Huang, M., Borcherdt, R., Haddadi, H., Lin, K., Stephens, C., and P. Roffers (2005). Preliminary Analysis of Strong-motion Recordings form the 28 September 2004 Parkfield, California Earthquake. *Seismological Research Letters 76* (1), 27-39.

Tucker, B.E., C.R. Real, and P.Y. Bard (1988). Validation Des Methodes De Prediction Des Effets De Site: L'Experience De Turkey Flat En Californie Centrale. Les Mouvements Sismiques , Reunion de l'AFPS, 16-03-88, Saint Remy les Chevreuse. 344-351.

Tucker, B.E. and C.R. Real (1988). The Design and Operation of a Test Site Near Parkfield, California to Compare and Test Methods of Estimating the Effect of Surface Geology on Seismic Motion. *Proceedings of Workshop on Earthquake Ground-Motion Estimation in Eastern North America*. Electric Power Research Institute EPRI NP 5875, Chapter 15, 1-15.

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