THE TURKEY-FLAT STRONG MOTION BLIND PREDICTION BY THE SOURCE MODELLING

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ABSTRACT - International experiment of strong motion prediction at the Turkey Flat test site near Parkfield, California (M6, Sep. 28, 2004 earthquake) was a two-phase experiment, where local site-specific structural data and two strong motion records were released to assist in the ground motion simulation. In our approach, record R1 (rock site) was firstly fit by finite-extent source modelling. Afterwards, using individual 1D crustal models and the same source model, complete numerical simulation was accomplished for sites R2, V1, V2, D1, D2, D3 in the 0 to 40 Hz band, comprising required acceleration time histories, Fourier spectral ratios, peak ground motion values and response spectra. In the second phase of the experiment the D3 (downhole) record was released to possibly modify the prediction. Since, however, we found the previous blind simulation of the D3 record (that from the 1st phase) acceptable up to 10 Hz, our 2nd phase prediction results remained unchanged compared to the 1st phase. This was the only technique among those applied by the participants in the present blind prediction experiment which focused on the finite-extent source effect.

1. Introduction

Philosophy of the strong motion blind prediction experiments (see Figure 1) is based on the pursuit to respond to a typical situation of many large earthquakes: Usually, good strong motion records are available at relatively few sites, while we attempt to explain the ground motion effects in a broader area. Surely, the ground motion prediction based on such limited information belongs to the most interesting and challenging tasks of both engineering and theoretical seismology. The records on rock outcrop, on sediments, or in boreholes are affected by local effects, like 3D heterogeneity (e.g., complex basin-edge effects at soft sediments beneath the heavily damaged part of the city; Iwata et al., 1995), 3D topography, and also by possibly non-linear rheology, thus physical parameters of the medium must be also known. However, the soil behaviour studied in the laboratory is not always the same as that in the field. For example, linear effects with high damping may still play a dominant role in the field, although laboratory measurements seem to indicate a significant non-linearity of the soil. Verification of new approaches and models is most straightforward at specific sites where a blind prediction is performed. As a rule, high quality measurements of ground motion, together with well-assessed geological data of the site, are available for such test sites.

Modelling methods to be used by the participants are not specified and even the computational model of the geological structure may be modified according to the simulation method used, practice of just an ‘educated guess, or feeling’ of the modeller. This might seem to be a very poorly defined problem ‘good just for a foreteller’, but this is
exactly the unanswered question of the day: to use a typical (sparse) data set, combine with a highly diversified modelling simplifications and approaches and to say how much the results differ from each other and from the observations. Efforts like this help to better understand differences in the individual simulations performed after large earthquakes (e.g., 1995 Hyogo-ken Nanbu earthquake, Japan; Irikura et al., 1999) and improve prediction of future events.

**“Blind” Test Reasoning**

**Typical situation:**

1. An earthquake appears
2. Heterogeneous damage distribution in a sedimentary basin
3. One rock-site strong motion recording close to the basin

   ![Diagram of Blind test reasoning](image)

   Engineering needs
   +
   seismological curiosity
   =
   predictions of strong motions in and around the basin
   based on the (single) rock-site recording
   using any means, model, information

**Figure 1. Blind test reasoning.**

Our participation in the international experiment at the Turkey Flat test site near Parkfield, California (Real et al., 2006) concerns strong motion prediction for the M6 earthquake of Sep. 28, 2004 (Report 7, 2005). Required complete numerical results consist from predicted acceleration time histories, Fourier spectral ratios, peak ground motion values and response spectra. The experiment has two phases (Figure 2). Phase I is based on disseminating strong motion record (R1 ‘Rock South station’) and consists of prediction of ground motion at a few other sites in and around a shallow stiff-soil sedimentary valley (R2, V1, V2, D1, D2, D3). Consequently, in phase II, the underlying bedrock (D3) record was released to assist/precise the ground motion prediction. A well-acquired local geology model is also distributed to the participants. We took the permission to modify this standard model into our preferred model, see below.

Initial plan to employ the 3D finite-difference hybrid method (Oprsal and Zahradnik, 2002; Oprsal et al., 2004) was rejected after careful analysis of the former weak-motion blind experiment at Turkey Flat (Report 5, 1990) because it had shown small 3D effects. Indeed, approximation of the site response with individual 1D models below the individual studied sites made by many participants was not worse than our 2D model (Zahradnik et al., 1991). On the other hand, we were strongly feeling that the present strong-motion experiment with M6 earthquake and the near-fault distance of the Turkey Flat site makes it hardly acceptable to adopt usual approximation of incident plane waves. For these
reasons, our leading idea is that the bedrock motion under the studied locations ought to be examined considering the given reference rock motion (R1/D3) in conjunction with a proper finite-extent fault model. Our predictions combine modelling of the fault rupture, crustal wave propagation and 1D local site effects for broad-band calculations, from 0 to 40 Hz.

Figure 2. Two phases of the experiment (modified from Real et al., 2006).

2. Modelling

Figure 3 shows that the Turkey Flat distance to the surface trace of the fault is approximately 5-6 km, while the source length is about 40 km (see also Table 1 for epicentral distances). Therefore, our modelling was based on the a priori guess that the extended-source effects rule the whole game (Figure 4).

In Phase I, R1 synthetics were produced by using the finite-extent source embedded in the crust (Table 2) and 1D individual model for the R1 station (Table 3), with the goal to fit the R1 recorded during the M6 event. The fit reached by tuning the source parameters taken form Ji (2005) was demanded for both horizontal components of the acceleration and the respective Fourier acceleration spectra (Figure 6). An advantage of such a procedure is that all remaining synthetics (R2, V1, V2, D1, D2, D3), based on their individual 1D receiver models, may then use the same source parameters.
2.1. Source and seismic radiation modelling

We use a non-uniform slip model taken (in digital form) from Ji (2005), see Figure 5. The reported strike, dip and rake are 137°, 83° and 180°. It basically consists of two main asperities, one near the hypocenter, with maximum slip of 0.42 m, the other centred some 15 km in the anti-strike direction. The hypocenter is at 35.8236° N and -120.3670° E at the depth of 8 km. The fault extends 7 km from hypocenter along strike (to south-east) and 33 km against strike. Its depth extent is from surface down to 14.4 km.
Seismic radiation from the fault is modelled with our combined deterministic-stochastic software PEXT (Zahradnik and Tselentis, 2002) extended here for a non-uniform slip. In the present study, the stochastic part of PEXT is switched off (see below). The method comprises full-wave propagation in 1D structures and a composite-source model (Irikura and Kamae, 1994; Hartzell et al., 1999). The source consists of 200 sub-events, 20 (along strike) x 10 (down dip), each one of 2.00 x 1.45 km, formally represented by all elements of the adopted slip model. However, based on slip values, the number of "effectively" contributing sub-events is considerably smaller (N^2=30). To properly scale the sub-event size and moment with respect to the whole fault, the sub-event slip is taken as u / N, where u is the true slip from Ji's model. Based on the same slip model we assume that the rupture front propagates radially from the hypocenter at a constant speed of 2.75 km/s, including low- or zero slip regions on the fault. Each sub-event is represented as a point source whose slip-velocity time history is causal Brune pulse with corner frequency of 2 Hz. (In other words, there are no effects of the super-shear rupture in our model although the rupture velocity 2.75 is higher than the lowest crustal velocity.) At localized places of the maximum fault slip, the model yields maximum slip velocity of 1.9 m/s. Smaller slip values provide the proportionally smaller slip-velocity values elsewhere on the fault. The wave-field contributions of sub-events sum up coherently at low frequencies and incoherently at higher frequencies. Incoherence is very significant due to heterogeneity of the slip distribution, relatively small fault distance and large size of the fault, and, due to relatively complex structural model, too. Just this allows us to calculate realistic high-frequency radiation (up to 40 Hz) without stochastic model features. We have tested also combined deterministic-stochastic calculations of the bedrock motion, to make sure that "on average" they agree with the deterministic result. Finally, for simplicity, we preferred to submit the deterministic prediction for it is easier to fit the observed R1 motion and include site effects.

To correctly simulate seismic radiation in entire frequency band, the above-mentioned slip adjustment (division by N) must be re-adjusted at the low frequencies. For that purpose we employ a causal filter with the amplitude spectrum of Frankel (1995), smoothly increasing from 1 (at 2 Hz) towards N (at 0 Hz). Then, with a crustal model described below, the total seismic moment of our fault model is 4.9 \times 10^{17} \text{Nm} (M_w = 5.9).
The full-wave seismic radiation and propagation is modelled using the discrete-wave number method and code of Bouchon (1981). The Turkey Flat sites were considered with their exact position; see Table 1, where also epicentral distance and azimuth of the sites are listed.

Table 1. Position of the studied sites

<table>
<thead>
<tr>
<th>Site</th>
<th>Lon. N (deg)</th>
<th>Lat. E (deg)</th>
<th>Epic. dist. (km)</th>
<th>Azimuth (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>35.878</td>
<td>-120.358</td>
<td>6.09</td>
<td>7.7</td>
</tr>
<tr>
<td>V1</td>
<td>35.882</td>
<td>-120.350</td>
<td>6.66</td>
<td>13.3</td>
</tr>
<tr>
<td>V2</td>
<td>35.886</td>
<td>-120.350</td>
<td>7.09</td>
<td>12.5</td>
</tr>
<tr>
<td>R2</td>
<td>35.892</td>
<td>-120.352</td>
<td>7.71</td>
<td>10.1</td>
</tr>
</tbody>
</table>

Advantage, compared to the often used simulation technique of Beresnev (1998), is: (i) broad frequency band, (ii) full wave field, including near-field terms, (iii) possibility to use complex crustal models, including multipathing, free-surface and near-surface effects, as well as faults passing through several crustal layers, (iv) full consideration of the double-couple radiation pattern. These features make the method attractive for applications where not only acceleration-, but also velocity and displacement time histories are demanded.

Preference, compared to kinematic source models, e.g. Bernard et al. (1996), based on representation theorem and integration over very densely sampled faults, is twofold: (i) an order of magnitude faster calculation speed, and, (ii) less severe (i.e. more realistic) high-frequency directivity. Therefore, the technique is efficient also for synthetic shake maps.

2.2. Structural models

Calculations are made separately for the individual locations at the Turkey Flat using the same source model and different 1D crustal models. Common part of the crustal model, reflecting the source-to-site path, is taken from GIL7 model of Baise et al. (2003), with the only modification made in the topmost 1-km thick layer, in which the original velocities were slightly changed to get proper values of the Turkey-Flat bedrock, see Table 2.

The individual 1D models, representing the top part of the crustal models for the studied sites, are listed in Table 3. In fact, they come from the Standard Geotechnical Model of the Turkey Flat, with two minor modifications: (i) Based on the weak-motion Turkey Flat experiment and subsequent modelling of the other weak-motion data (Report 6, 1991), the Vs value was increased in sediments by 5 percent at V1 and V2, and decreased by 20 percent at R1. (ii) The most problematic Q values have been chosen to reflect approximately the reported damping values measured at the site, to take into account larger shear strain due to near-fault strong motion, and also to keep Q larger at R1, R2 compared to the remaining sites. Besides the Q-effect, our modelling includes also the so-called "kappa-effect" ($\kappa = 0.05$ s) to account for the high-frequency spectral decay $\exp(-\pi \kappa f)$.
### Table 2. Common crustal model

<table>
<thead>
<tr>
<th>Thickness (m)</th>
<th>( V_p ) (m/s)</th>
<th>( V_s ) (m/s)</th>
<th>Density (kg/m(^3))</th>
<th>( Q_p )</th>
<th>( Q_s )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>2720</td>
<td>1350</td>
<td>2200</td>
<td>500</td>
<td>250</td>
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<tr>
<td>2000</td>
<td>4500</td>
<td>2400</td>
<td>2280</td>
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<td>4800</td>
<td>2780</td>
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<td>7830</td>
<td>4520</td>
<td>3260</td>
<td>1000</td>
<td>500</td>
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</table>

### Table 3. Local site models

<table>
<thead>
<tr>
<th>Site</th>
<th>Thickness (m)</th>
<th>( V_p ) (m/s)</th>
<th>( V_s ) (m/s)</th>
<th>Density (kg/m(^3))</th>
<th>( Q_p )</th>
<th>( Q_s )</th>
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<tr>
<td>R1</td>
<td>2.5</td>
<td>1980</td>
<td>660</td>
<td>2100</td>
<td>10</td>
<td>5</td>
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<tr>
<td></td>
<td>2.5</td>
<td>320</td>
<td>142</td>
<td>1500</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>5.2</td>
<td>975</td>
<td>483</td>
<td>1800</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>13.7</td>
<td>975</td>
<td>641</td>
<td>1900</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>V1</td>
<td>2.5</td>
<td>305</td>
<td>158</td>
<td>1550</td>
<td>4</td>
<td>2</td>
</tr>
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<td></td>
<td>3.4</td>
<td>915</td>
<td>289</td>
<td>1750</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>5.5</td>
<td>975</td>
<td>641</td>
<td>1900</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>R2</td>
<td>2.5</td>
<td>1980</td>
<td>825</td>
<td>2100</td>
<td>10</td>
<td>5</td>
</tr>
</tbody>
</table>

### 2.3. Ground motion modelling

First we did forward simulation of the observed R1 surface motion using slip model of Ji (2005). It appeared satisfactory in the spectral domain, but the main pulse dominating the R1 acceleration record was nearly absent. A trial and error procedure has shown that variation of most model parameters cannot improve the agreement, except some 10-degrees reduction of the fault dip. (More precisely, our final model has strike dip and rake of 141°, 72°, 178°.) Final agreement between synthetic and observed motion at R1 is good; Figure 6.

Next, we assumed that the adopted source model and the common source-to-site crustal model is representative not only for the tested R1 site, but for the whole Turkey Flat, and we simply repeated calculations separately for sites V1, V2, R2 with their specific 1D models. By a specific model we mean that the particular site model of Table 3 was placed on the top of the common crustal model of Table 2.

Acceleration time histories at receivers D1 and D3 (24 m below surface) were obtained by downward propagation of the surface motion calculated for R1 and V1, respectively, using matrix method for vertically propagating plane shear waves. Receiver D2 was calculated as an average from V1 and D3.

All simulations were made from 0 to 40 Hz (cosine tapered between 39 and 40), using FFT with 2048 points, time window length of 25.6 s, time step of 0.0125 s. Summation of the sub-event contributions is performed in the acceleration-time domain. Velocity and displacement is derived from the acceleration. Fourier spectral ratios were calculated from the amplitude spectra smoothed twice with a 27-point running average (1.016 Hz).
As already explained above in the introduction to section 2, in phase II of the experiment, the D3 record was released thus allowing comparison with our prediction (Figure 7). Based on satisfactory fit (to 10 Hz) we did not further modify the prediction results from phase I (Figure 8). Assessment of the prediction success for the remaining sites (R2, V1, V2, D1, D2) was not possible before the end of the blind experiment. Release of the whole set of records and collective comparison of the all submitted predictions was performed during the Turkey Flat Blind Prediction Workshop, September 21, 2006, Westin Hotel, San Francisco, USA (report under preparation). Specific implications related to this study, briefly made here without figures, just after the meeting and immediately before submission of this paper, are as follows.

Figure 6. Comparison of the observed and calculated acceleration at R1 site.

Figure 7. Comparison of the observed and calculated acceleration at D3 site.

We were the only group considering the finite-extent source effect and not trying to infer the ground motion at all locations solely from the R1 and D3 records. Consequently: (i) We fitted observed difference between and D3 (in terms of the typical amplitudes in the acceleration time histories) better than most of other participants. (iii) At V1, our predicted spectral accelerations are free of the strong overestimation in the 0.6 to 3 Hz band,
commonly seen throughout most of the participating teams in phase I. (iii) Our V1 prediction underestimated spectral amplitudes for frequencies above 10 Hz because we did not put enough attention to the same effect at D3 during phase II.

It is necessary to stress, that our preferred structural model remained both phases I and II, and, in fact, our whole prediction was based on R1. In particular, we did not make any modification of the source and/ or structural model after receiving D3 record. This may explain the above mentioned problem (iii).

![Figure 8. Synthetic acceleration at V, D, and R sites, vertical axes are in cm/s^2 (different scaling for different sites), horizontal axes are in seconds.](image)

**3. Conclusions**

It was found that, due to near fault distance, the calculated bedrock motion varies along the Turkey Flat quite considerably. It confirms the main assumption of this paper and proves that any reasonable simulation of the ground-motion variation at the Turkey Flat should not only consider the site effects, but also the source and path effect. Of course, a weak point of this approach was that the blind-prediction set up allowed us to check the calculated source and path effect at two sites (R1 and later also D3) only. This is also a reason why we cannot easily quantify the prediction error. Qualitatively, we assumed the acceleration to be possibly in error by a factor of 2. In practice, we would always prefer to do a site-specific prediction with checking synthetics against real ground motion at several observation sites. On the other hand, having at disposal only one record, or two, we believe that fitting it by the source and common path model (which is then used for predicting the other sites) is the only reasonable way how to employ such limited data. A small remark should be also made about linearity of our model. We believe that careful consideration of the source and path effect may, in some cases, explain data equally well as compared to purely site-specific predictions (sometimes only apparently) requiring a non-linear rheology in the shallow soil layers.
4. References


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