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ON THE APPLICABILITY OF ONE-DIMENSIONAL CRUSTAL STRUCTURES FOR GROUND-MOTION SIMULATION

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SUMMARY

Ground motion simulation methods, such as the finite-difference method (FDM) or the modal summation technique, require a model of the crustal structure through which the seismic waves pass in terms of density, velocity and attenuation parameters, such as Q. The use of such structural models within simulations means that travel path effects, such as the constructive interference of different phases, can be modelled. Currently one-, two- or three-dimensional models are used without much description of the benefits of using a particular dimension of model. Within FDMs, a 2D or 3D structure can be assumed without a significant increase in computational time. One-dimensional models have the advantage of yielding results that are easier to interpret in terms of phases and also they require only one set of simulations for all considered horizontal source and site locations. In addition, the method introduced by Douglas et al. (2004) for the incorporation of the effect of crustal structure into empirical ground motion estimation equations is only practical for one-dimensional structures.

The purpose of this article is to investigate when two-dimensional structures provide significantly different results than using an average one-dimensional model. The difference between the 2D and the derived 1D structure is quantified by a single parameter that seeks to characterise how two-dimensional the structure is. The maximum size this parameter can be before a 2D structure is required for accurate modelling of ground motions is assessed based on a series of FDM simulations. The purpose of this proposed technique is to provide guidance as to when 2D structures should be used or when 1D structures are sufficient, without the requirement to performing many simulations.

1. INTRODUCTION

Ground motion simulation methods, such as the finite-difference method (FDM) or the modal summation technique, require a model of the crustal structure through which the seismic waves pass in terms of density, velocity and attenuation parameters, such as Q. The use of such structural models within simulations means that travel path effects, such as the constructive interference of different phases, can be modelled. Currently one-, two- or three-dimensional models are used without much description of the benefits of using a particular dimension of model. Within FDMs, a 2D or 3D structure can be assumed without a significant increase in computational time. One-dimensional models have the advantage of yielding results that are easier to interpret in terms of phases and also they require only one set of simulations for all considered horizontal source and site locations. In addition, the

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2. PREVIOUS STUDIES

There are few published studies that examine the difference in simulated ground motions from using a 3D or 2D model as opposed to a 1D model (sometimes referred to as a plane layer model) except for examining near-surface effects such as basin effects (e.g. Bard and Gariel, 1986).

Heaton and Helmberger (1977) model the strong-motion displacements recorded at El Centro from the 1968 Borrego Mountain earthquake. They note that the thick sediments under the receiver are not present in the source region and therefore the crustal structure along the travel-path is 2D. However, since the basin structure near El Centro is relatively flat and homogeneous and because the major effect of sediments is to allow post-critical angle multiple reflections to occur near the receiver Heaton and Helmberger (1977) are able to model the displacements (dominated by SH type motion) reasonably accurately by adopting a simple plane layer over a half-space model of the receiver region. They find that it is not necessary to include intermediate and lower crustal structure to model the El Centro strong-motion record. Heaton and Helmberger (1978) conduct a similar study to model displacements from a smaller earthquake in the same region and find that a 1D model is sufficient. This paper is also important since the authors find that wave propagation effects (due to the crustal structure) should be included in studies of source spectra and seismic wave attenuation.

To model the same strong-motion displacements as Heaton and Helmberger (1977), Swanger and Boore (1978) overcome the problem of a slight change in crustal structure at the source and at the site by using a 1D from a point allow the travel path from source to site. However, they do not provide a objective method for choosing this model. They believe that they are able to accurately model the displacements at El Centro since the crustal between the source and the site is uniform laterally.

Dreger and Helmberger (1990) investigate the difference in ground motions using a simple 1D structure and a series of relatively simple 2D structures representing the Los Angeles area. They find that: a ridge structure beneath the recording station acts as a low-pass filter; a ridge structure between the source and receiver dramatically alters the motions; and that a basin structure leads to the trapping of energy in the basin which escapes leading to much higher ground motions.

Campillo et al. (1993) model the propagation of waves across the Alps using both a flat layer model and a 2D model and find considerable differences with ground motions from the 2D model being much less than those from the 1D simulation. However, they find that the observed Lg decay is much stronger than that predicted by the simulations.

Similarly Gibson and Campillo (1994) model the propagation of Lg waves within a flat layer structure, across the Pyrenees and also within a structure with a Moho step. Again significant differences in ground motions are found between the different simulations but they do not closely match the strong Lg attenuation observed within recorded seismograms.

Stidham et al. (1999) compute synthetics for a 1D and 3D velocity model of the San Francisco Bay region where 3D effects are particularly important. They find that there is significant difference in the simulated ground motions and that the ground motions from the 3D model match the observed ground motions from the Loma Prieta earthquake better than those from the 1D model.

Kennett and Furumura (2002) use a 3D model to simulate ground motions ground motions from two Japanese earthquakes (the 1946 Nankai and the 2000 Tottori-ken Seibu earthquakes) and find that it helps the match between the simulated and observed ground motions.

Komatitsch et al. (2004) find that for the Los Angeles basin 1D structures are not appropriate and lead to underestimations of the ground motions by up to 20 times because the effect of basin resonance is not able to be modelled. A detailed 3D model of the basin, however, leads to good estimations of the ground motions.

Laurenzano and Priolo (2005) modelled the recorded ground motions at the Catania station from the 13th December 1990 M5.8 east Sicily earthquake using a detailed 2D and a variety of 1D structures and find that the 2D structure leads to time-histories that match the recorded motions much better than those computed using the 1D structures.

3. UTILITY OF 2D SIMULATIONS

The purpose of this article is to propose criteria that can be used to decide whether the crustal structure in a region is sufficiently one-dimensional that simulations using a one-dimensional model of the crustal structure in the region provide accurate ground motion estimates. The following method is proposed to define such a criterion that allows the utility of 2D simulations to be known by just examining the crustal structure model.

The first step of the proposed method is to consider an earthquake located within a two-dimensional crustal structure and a series of stations located at given distances from the earthquake. Next compute two simulations for each station: one using the 2D structure and the second using a velocity-averaged 1D structure (where velocity-averaged means that at each depth the velocities within the 2D structure are averaged from the horizontal location of the source to the horizontal location of the site). During the velocity-averaging process calculate the standard deviations of the velocities within each layer. Average these standard deviations in some way to compute a number that characterises the 1D-ness of the structure between the source and the site. Repeat these last two steps for different receiver points. Plot the decay curves derived from the 1D and 2D simulations and underneath the computed standard deviations of the averaging process. Examine the decay curves from the 1D and 2D simulations to see where they deviate from one another ad at which value of the standard deviation this occurs. The limit defines the criterion for assessing when 1D simulations are sufficient.

4. SIMULATION SCHEME

For the simulations here the following simulation scheme was used, which is a similar scheme to that used by Douglas et al. (2006) to model ground motions in three French regions. A standard staggered finite difference method (FDM), which is fourth order in space and second order in time (Levander, 1988, Olsen, 1994), is used. A time-variable double-couple point source with a strike of 0° is introduced, using the technique of Olsen (1994) and Graves (1996), at the origin of the model region. The mechanism-independent equation of Wells and Coppersmith (1994) for subsurface fault length was used to estimate the source duration assuming a rupture velocity of 2.5km/s, giving durations of 1.30 s for the source-time functions of the simulated earthquakes of M_w 5.0. The source time function is described by a locally supported B-spline function of order 4 (degree 3).

Ground motions are calculated within a halfspace (-10–150 km by -5–25 km by −40–0 km) at spatial grid points with 500 m spacing using a time step of 0.02 s, which is sufficient for the assumed source-time function and the wave velocities in the crustal models. Synthetic seismograms are obtained at different epicentral distances from 0 to 145 km every 5 km in the x direction, perpendicular to the fault strike.

Because the assumed source model (point source with a simple smooth time function) poorly simulates the high frequency content of the motions it was decided to study the decay of peak ground velocity (PGV).

5. CONSIDERED CRUSTAL STRUCTURE

For this preliminary investigation of the importance of 2D structure, the model for the Pyrenees by Souriau and Granet (1995) was used for a source at 42.25N-0.25E and stations at regular distances up to 43.25N-1.5E (about 140 km). Figure 1 displays the 2D shear-wave velocity crustal structure considered. The 2D cross section along this path features a high velocity zone that is coincident with the Pyrenees mountains. The model of Souriau and Granet (1995) is not constrained for depths less than 3km therefore the velocity at 3km is assumed to be constant until the surface. This will probably lead to lower amplitude ground motions that occur in practice in the Pyrenees but this is not important for the purpose of this article.

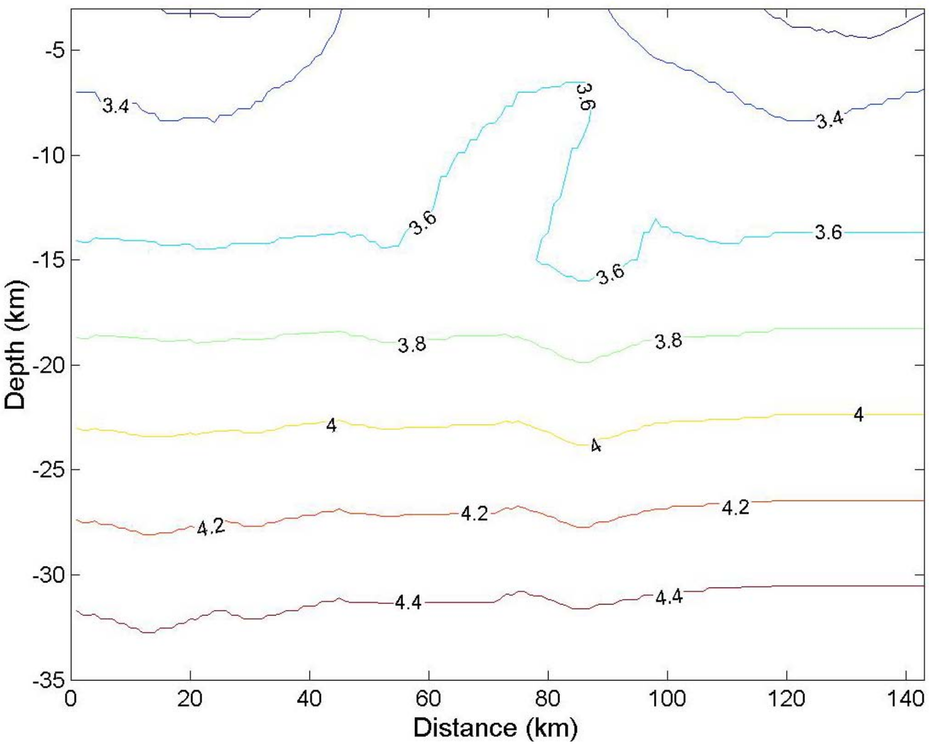

Figure 1: Two-dimensional crustal structure for shear-wave velocities (see labels on contour lines) used for simulations. Velocities extracted from the model of Souriau and Granet (1995) along a path 42.25N-0.25E to 43.25N-1.5E.

As discussed above the 2D structure between the source and the series of receivers at different distances was velocity-averaged to obtain a series of 1D structures for which to use for the simulations. This averaging was conducted from the source (left-hand side) to the site (right-hand side).

Published density estimates for the Pyrenees are not common. Therefore the commonly adopted relation of Gardner et al. (1974): $\rho = 1.741 V_p^{0.25}$, where V_p is P-wave velocity in km/s and ρ is density in g/cm^3, was adopted. Minor changes in the density values will not significantly affect the results. $Q = 300$ is assumed for the entire medium, but, in fact, this leads to no significant anelastic attenuation in the simulations.

6. RESULTS

Figure 2 shows the simulated PGVs with respect to distance using a 1D structure that was computed by averaging the 2D structure between 0 and 140km and the true 2D model. As can be seen the simulated PGV values from the two simulations do not match after a distance of about 60km where the 2D structure features significant variations in velocity.

Figure 3 shows the PGVs simulated using a series of 1D structures with velocities equal to the average from the epicentre to the station (as described above) and also the PGVs from the full 2D simulations. On the same figure the standard deviations (σ) from the velocity averaging process are displayed. The standard deviation seeks to measure how two-dimensional the structure is. This figure shows that the results obtained using the two structures are similar until the averaging process means that the 1D and 2D structures are no longer comparable (measured by σ for the first layer higher than about 0.05) at a distance of about 60km corresponding to the high velocity zone in the 2D structure shown in Figure 1. After this threshold is passed the simulated PGVs begin to diverge although since the 2D structure does not feature large lateral variations in velocity (see Figure 1) the results from the 1D and 2D simulations do not differ by much (the maximum difference is about 40%). One interesting result is that the results from the 1D simulations using the velocities averaged up until the station better match those computed using the 2D structure compared with those computed using the velocities averaged up until the end of the grid at 140km. This shows that for lightly 2D structures like examined here the utility of conducting fully 2D simulations is limited and good results can be obtained using correctly averaged 1D structures.

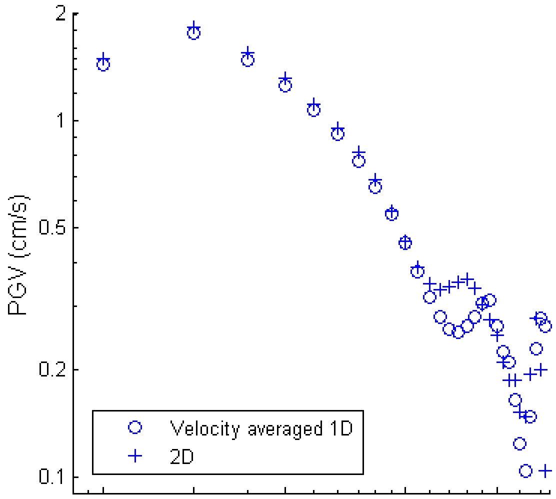

Figure 2: Simulated peak ground velocity using the uniform (averaged up to 140km) velocity-averaged 1D structure and the true 2D structure.

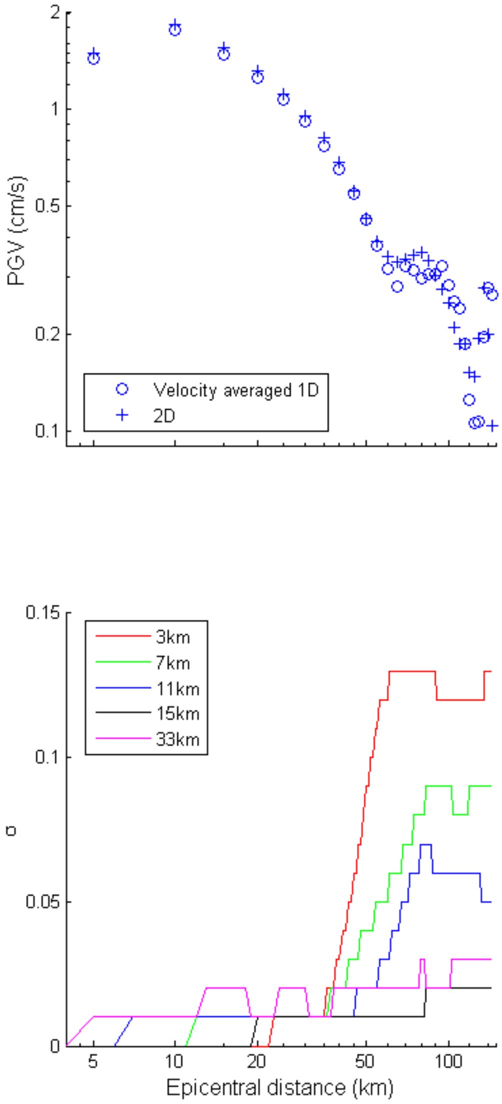

Figure 3: Simulated peak ground velocity using the velocity-averaged (averaged every 10km) 1D structure and the true 2D structure (top figure) and the standard deviation (σ) from the velocity averaging process for the five layers.

7. DISCUSSION

The results obtained above suggest a criterion for assessing the need to conduct two-dimensional as opposed one-dimensional wave propagation simulations by simply examining the crustal structure model for the region. However, it should be noted that this criterion is based on the results of simulations using only one crustal structure model and hence they must be verified using a variety of different structures to assess how universal the criterion is. A couple of other open questions are the following.

- Is the standard deviation of the velocities along layers at constant depth a good way to characterise the error in averaging 2D structures?
- How can the standard deviation of each layer be averaged to take into account that certain layers are more important than others in modifying ground motions (e.g. for short distances layers below the hypocentre are not important)?

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