USGS AWARD NUMBER 03HQGR0061

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REFINING THE 3D VELOCITY MODEL OF THE SEATTLE BASIN BY 2DWAVEFORM INVERSION USING GROUND MOTION DATA FROM THE NISQUALLY EARTHQUAKE

PROGRAM ELEMENT I

Research supported by the U.S. Geological Survey (USGS), Department of the Interior, under USGS award number 03HQGR0061. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government"

REFINING THE 3D VELOCITY MODEL OF THE SEATTLE BASIN BY WAVEFORM INVERSION USING GROUND MOTION DATA FROM THE NISQUALLY EARTHQUAKE

USGS AWARD # 03HQGR0061

Final Technical Report

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Abstract

Recent earthquakes and seismic hazard investigations in the Seattle region have demonstrated the potential seismic hazard from earthquakes in this region and the implication of wave propagation and site effects on the amplification of strong ground motion. Analyses of ground motion from the June 1997 Bremerton and February 2001 Nisqually earthquakes reveal the significant effect of the Seattle basin structure in increasing the amplitude and duration of the ground motion in the Seattle basin. Some of these effects have been reproduced by two preliminary basin 3D velocity models at frequencies up to 0.5 Hz. With the newly available results from studies of the basin structure and ground motion waveform modeling the efficiency of the models can be improved also at higher frequencies. The efficiency of the waveform modeling approach to estimating basin structure and its effects on ground motion can be greatly enhanced by the use of inverse methods. This method can provide constraints that are essential in the process of model refinement in several parts of the Seattle basin.

Our goal is to provide constraints on the geometry of the shallow sedimentary layers of the Seattle basin along a N-S profile based on a 2D inversion of strong motion data (0.1-1 Hz) from the Nisqually earthquake. We used a 3D velocity model, seismic reflection profiles (Johnson et al.,1999; Brocher et al., 2001) and an available high resolution seismic tomography model (Calvert and Fisher,2001) to constraint the 2D initial velocity model of the Seattle basin. Our study was developed in two stages. First, we developed and tested an inversion technique that uses ground motion velocity waveforms from small earthquakes and a 2D finite-difference method. Second we obtained a 2D underground velocity structure of the basin by inverting ground motion waveforms from the Nisqually earthquake recorded at nine selected stations along a N-S line across the basin.

Introduction

Analyses of ground motion from the February 28, 2001 Nisqually earthquake reveal the significant effect of the shallow structure in increasing the amplitude and duration of the ground motion in the Seattle basin. Among the many results of such analyses, two have direct implications for the ongoing process of refinement and validation of the 3D velocity models of the Seattle basin. The first is that basin surface waves affected by the basement geometry dominated the recorded waveforms, especially at frequencies lower than 1Hz (Carver et al., 2002). The second is that there was a clear correlation between variations in the site response and Quaternary deposits (Troost et al.,2002). Similar properties were also observed during the June 1997 Bremerton and February 1997 South Seattle earthquakes (Hartzell et al., 2000).

Under a project funded by NEHRP external program (Pitarka et al.,2004) we have developed a preliminary 3D velocity model of the Seattle basin which here we refer to as the Pitarka et al. (2004) model. Another 3D velocity model of the Seattle basin has been developed by Frankel and Stephenson (2000). Both models are based on information from investigations of geological structure in the Puget Sound metropolitan regions (Johnson et al.,1999; Calvert and Fisher, 2001; Blakely et al.,2001) and data from passive and active source SHIPS data (Brocher et al., 2001; Pratt et al.,1997). Constraints on the shallow part of both models came solely from interpretations of limited geophysical information. The two models differ in the way the shallow sedimentary layers and basement geometry are represented. Validation analyses of both models based on waveform modeling have shown that their quality decreases significantly at periods shorter than 2 sec, where the models do a poor job at matching the amplitude of the surface waves. With the increasing amount of waveform data from earthquakes in the Seattle region and surrounding areas, it is essential that the procedures for improving the models should rely more on forward and inverse waveform modeling. Inverse methods based on waveform modeling are routinely used in studying the seismic source, but they have rarely been applied in basin structure estimation.

In this study we provide additional constraints that are consistent with ground motion data and can be used to guide the refinement of the existing 3D velocity models of the Seattle basin. We inverted ground motion data (0.1-1.0 Hz) from the Nisqually earthquake for the underground structure along one N-S cross-section that runs through the Seattle basin. The inverted cross-sections will be used to refine our preliminary 3D velocity model of the Seattle basin.

3D Velocity Models of the Seattle Basin

Figure 1 illustrates the main features of the Frankel and Stephenson (2000) and Pitarka et al.(2002) 3D velocity models of the Seattle basin. This figure shows basin sections that cross the central part of the basin along a N-S direction. Constraints on the structure of the two models came from several geophysical investigations as listed in Table 1. In our model the geometry of the south edge was derived from the DRY SHIPS deep (Miller and Snelson, 2001) and shallow (Calvert and Fisher, 2001) tomographic models which indicates that the southern edge of the basin dips to the south

(Figures 2,3). Note that the orientation of the profiles in Figure 3 are reversed from those in Figure 1. Although they share similar features the two models differ substantially in terms of basin edge geometry and lateral variations within the sediments. These features inherit inaccuracies that come from limitations in the geophysical models. For example, the gravity inversion is limited to vertical dips and cannot resolve structural overlap. This explains the lack of overthrust above the sediments along the Seattle fault in the Frankel and Stephenson model. Also the seismic profiles give good information about lateral variation in the sediments and, to some extent, the basement geometry, but they do not provide reliable information on the shear wave velocity within the layers.

Because of their limited resolution, the regional tomography models cannot be used to constrain small scale variations in the sedimentary layers or bedrock. In order to do so we inverted strong ground motion data (0.1-1.0 Hz) from the Nisqually earthquake to obtain the basin structure along the profile A-A` shown in Figure 4.

Full Waveform Inversion Method

The inversion technique we used is similar to the one proposed by Ji et al.(2000). Its basic idea is to start with an approximate model and make reasonable changes to the model parameterization (sedimentary layers and basement geometry) until it can explain the recorded motion.

In this technique the basin model parameters are represented by a vector **x**. The components of this vector are the positions of the layers interface control points. We also define an objective function E(**x**) which measures the difference between the data and synthetic seismograms using the shift time τ needed to fit the recorded and synthetic seismogram and $f(\tau)$.

$$f(\tau)= 1 -2*[\int p(t)_{obs}\, p(t+\tau)dt]/[\int (p(t)^2_{obs} + p(t+\tau)^2_{syn})dt]$$

where $p(t)_{obs}$and $p(t)_{syn}$ are the observed and synthetic seismograms, respectively.

The minimum of the E(**x**) which corresponds to the best basin model **x,** is found using the conjugate gradient algorithm. The speed of the convergence depends on the initial model and model complexity. Details of the inversion technique are given in the paper of Ji et al., 2000. In our inversions we used the transverse component of the velocity. The waveform calculations were performed using a 2D staggered grid finite-difference technique of 2nd order accuracy (Pitarka and Irikura, 1996). As in most inversion techniques of this type, the quality of the result depends on the station density and quality of the initial velocity model.

The performance of the technique using a simple one layer sedimentary basin is illustrated in Figure 6. In this figure we show the result of the inversion of synthetic ground motion velocity data (tangential component filtered at 0.1-1 Hz) calculated using a double-couple point source and a simple basin structure. The geometry of the starting basin model (green line) is very different from the actual model (red line) which is accurately reproduced by the inverted model (blue line).

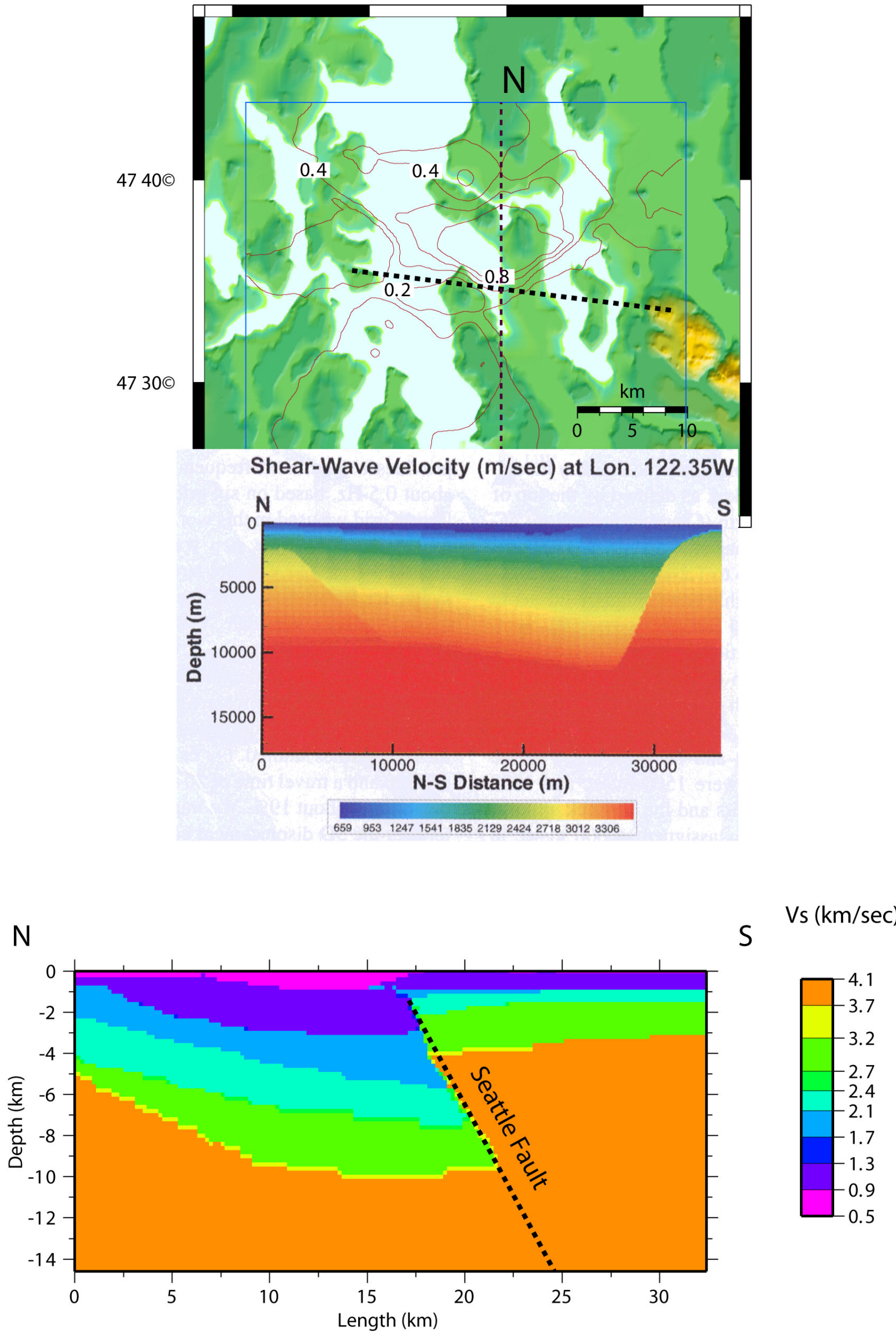

Figure 1. (top) Map showing depth to base of quaternary with locations of Seattle Fault and N-S cross-section. (middle bottom) Vertical N-S cros-sections of shear-wave velocity through Frankel et al. (2000) and Pitarka et al. (2002) 3D velocity models, respectively.

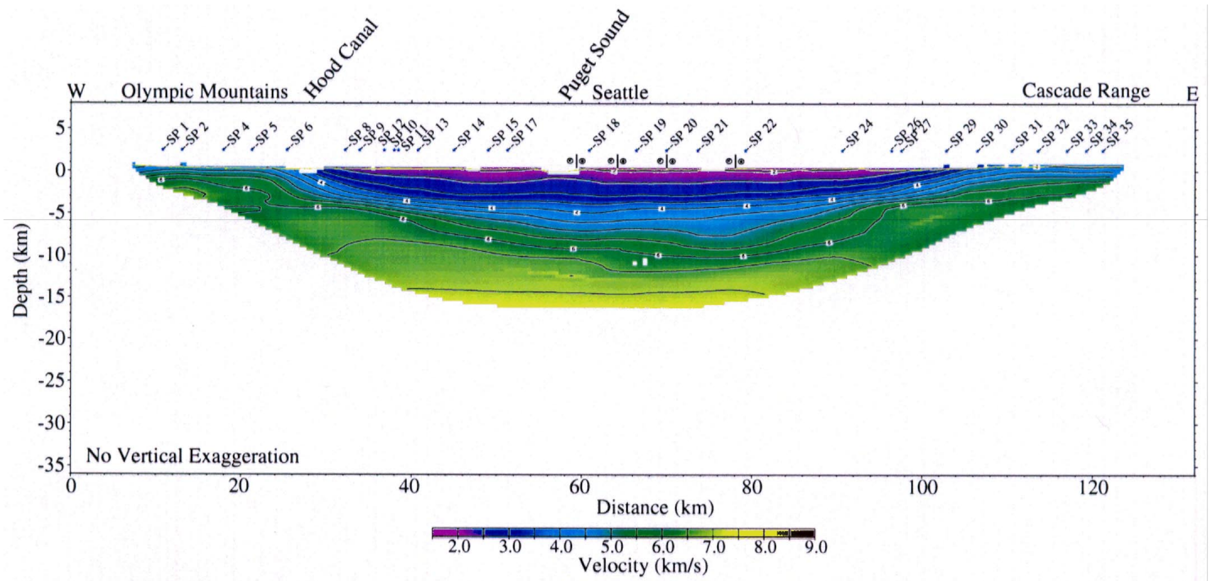

Figure 2. Velocity model for the DRY SHIPS E-W profile. Along this profile the basin is 7-8 km deep and about 70 km long (Miller and Snelson, 2001)

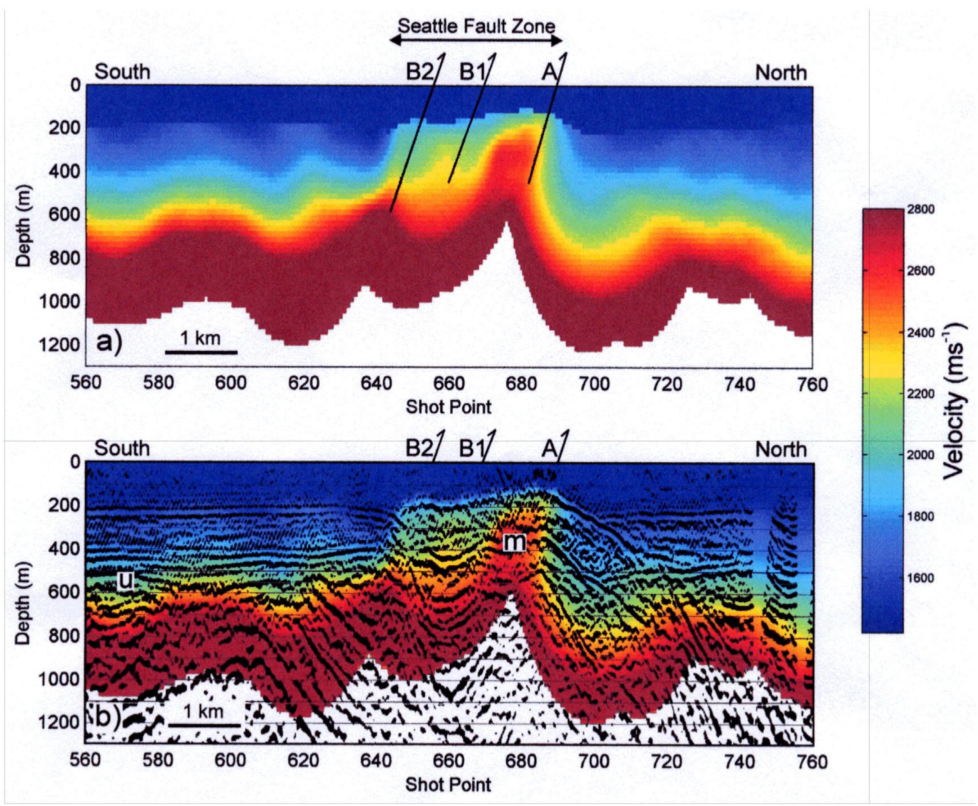

Figure 3. P wave velocity variation across the Seattle fault zone. Upper panel : velocity model derived from tomographic inversion with the position of the fault splays indicated. Lower panel: velocity model superimposed on the corresponding depth migrated N-S seismic reflection section (Calvert and Fisher,2001)

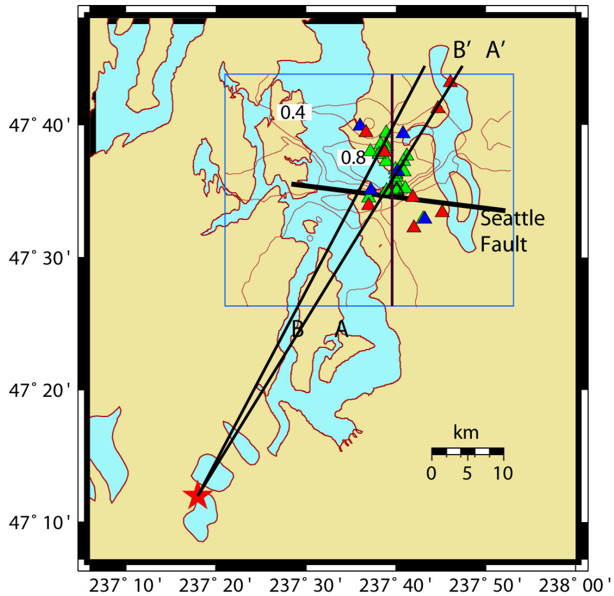

Figure 4 . Map of the Seattle region. A-A′ and B-B′ are cross-section locations. Also shown are strong motion recording sites (triangles).

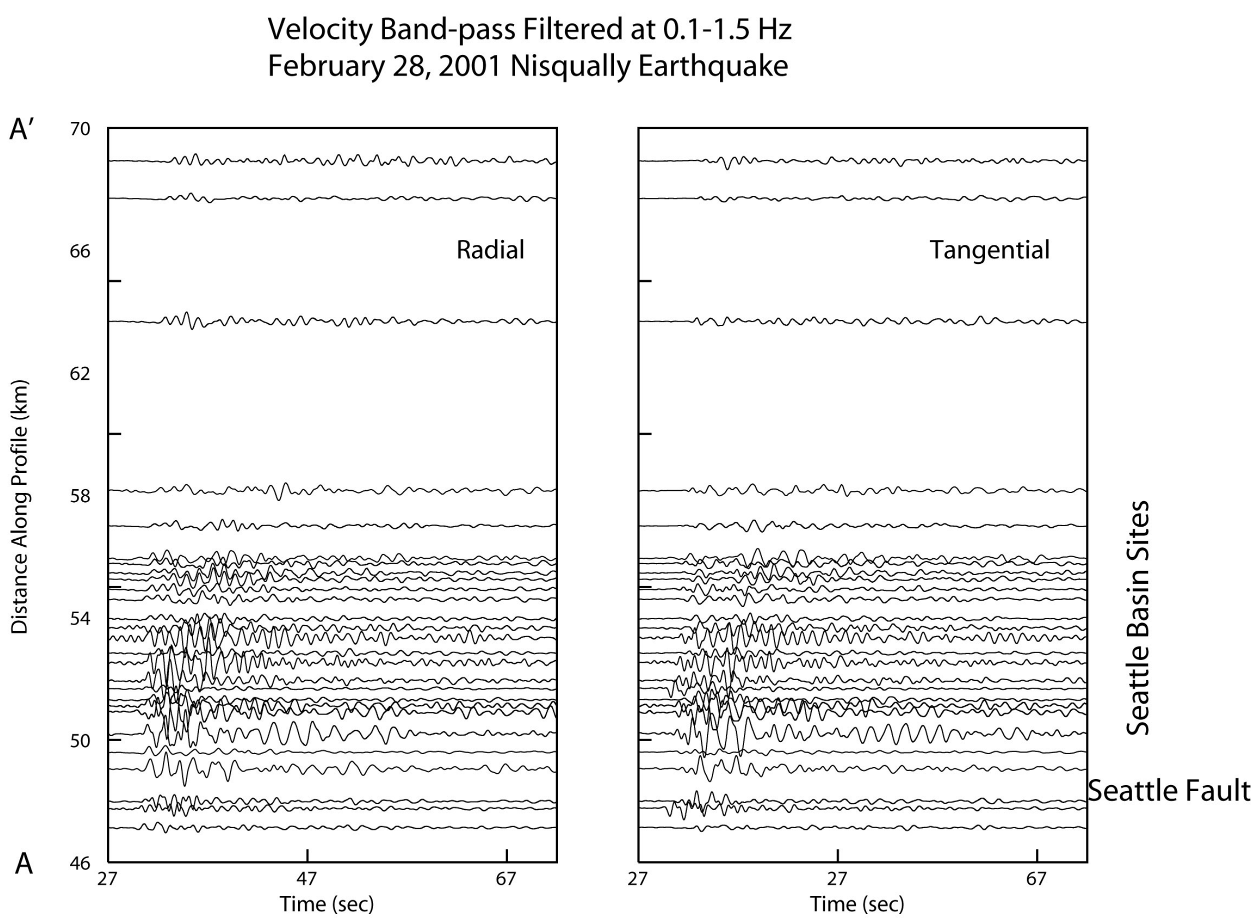

Figure 5 . Profiles of recorded velocity low pass filtered at 0.1-1.0 Hz from the February 28,2001 Nisqually earthquake.

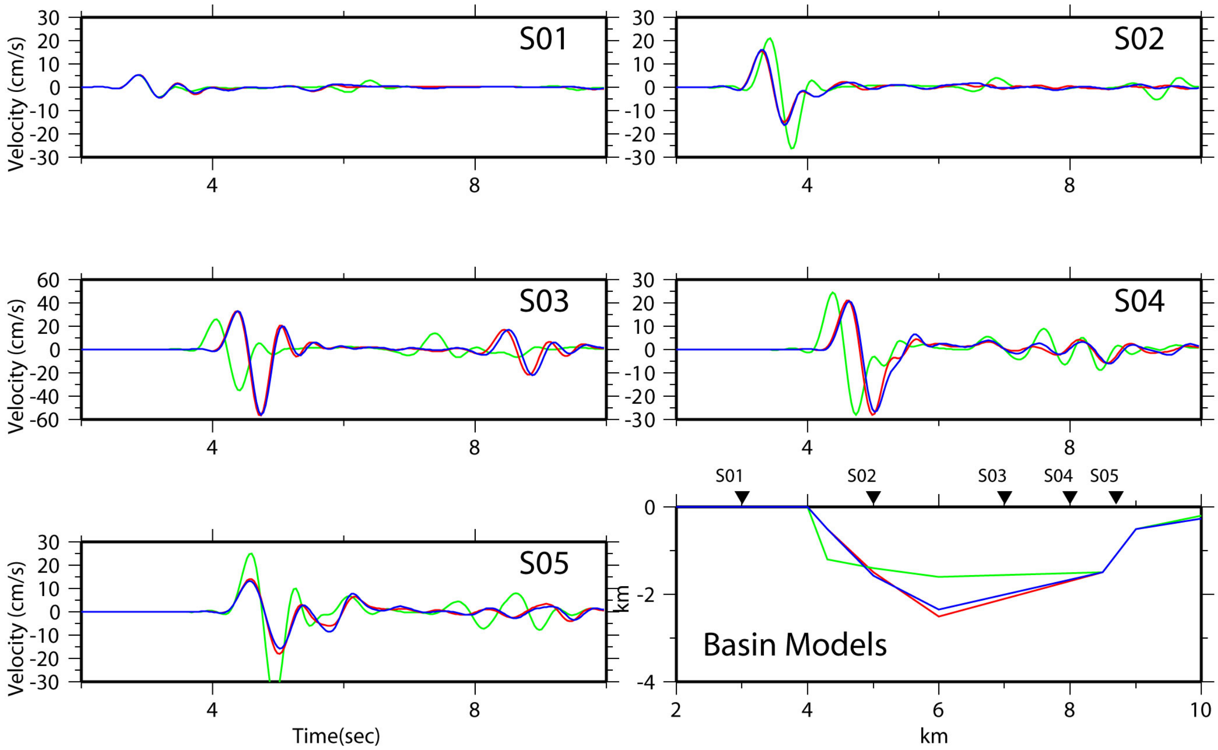

Figure 5. Comparison of tangential velocity component calculated using actual (red traces), inverted (blue traces), and the starting (green) velocity models.
The lower right panel shows the geometry of the target (red), starting(green), and inverted (blue) basins, and stations location.

Ground Motion Data

In our inversion we used available velocity waveform data filtered at 0.05-1.0 Hz from the M6.8 Nisqually earthquake of February 28, 2001. The earthquake was very well recorded by a dense network of stations in the Seattle region. Only stations that align along a N-S profile were considered. Figure 5 shows profiles of filtered (f< 1.5 Hz) velocity seismograms from the Nisqually earthquake recorded at selected stations near and along profile A-A`. The Seattle fault intersects this profile at a distance of 48 km. Sites to the north lie within the Seattle basin. The seismograms show clear basin induced waves that reflect complexities in the structure.

2D Inversion of the Seattle Basin Velocity Structure

We inverted the 2D underground structure of the Seattle basin along the line A-A' using ground motion from the Nisqually earthquake recorded at stations WEK, SDN, KDK, MAR, UNK, THO, ALO, SEA, and FINN. In our calculations we used the tangential component band-pass filtered at 0.05-1.0 Hz. Except for WEK, which is soft rock site, the others are soil sites. The initial velocity model used in the inversion was derived from the existing 3D model of the Seattle basin and constraints from the reflection section of Calvert and Fisher (2001) (see Figure 3 in this report). The basin sediments in the initial model are represented by 4 layers with constant velocity. Their parameters are shown in Table 2. In our modeling we only invert for the layers boundary geometry, and assume that the velocity in each layer is constant. The inverted 2D velocity model is shown in Figure 6. In this figure the inverted layers geometry is superposed to the corresponding 2D cross-section of the existing 3D model. The comparison between the observed and synthetic waveforms of the ground motion velocity is shown in figure 7.

Table 1. *Constraints used in the 3D Velocity Models of the Seattle Basin*

Velocity Model	Quaternary Deposits	Depth to bedrock	Velocity Structure in the Sediments
Frankel and Stephenson (2000)	Johnson et al. (1999)	Gravity and aeromagnetic data (Blakely et al., 1999) Yount et al, (1985)	Seismic reflections and borehole logs (Johnson et al.,1999)
Pitarka et al. (2002)	Johnson et al. (1999)	High resolution tomography (Calvert and Fisher,2001) Gravity and aeromagnetic data (Blakely et al., 1999) Yount et al, (1985)	Pratt et al, (1997) Johnson et al.,(1999)

Table 2. *2D Velocity Model Parameters*

Layer	Vs (km/s)	Density (g/cm^3)	Q
1	0.6	2.1	50
2	1.5	2.2	100.
3	2.1	2.5	200.
4	3.2	2.7	300.
Basement	3.65	2.8	1000.

Our inversion technique can not resolve very weak velocity contrasts. Therefore we could only determine the layers interface between basement and consolidated sediments of the basin. As mentioned before the stations density limits the resolution of the inversion, which is performed at rather low frequencies. The misfit between the recorded and simulated seismograms at several basin sites is a clear indication of the complexities in the shallow structure of the Seattle basin that are not yet represented in the velocity model .

Our inversion results suggests that the basin edge bounded by the Seatle fault is almost vertical and is characterized by a strong velocity contrast that causes complex interferences of basin induced

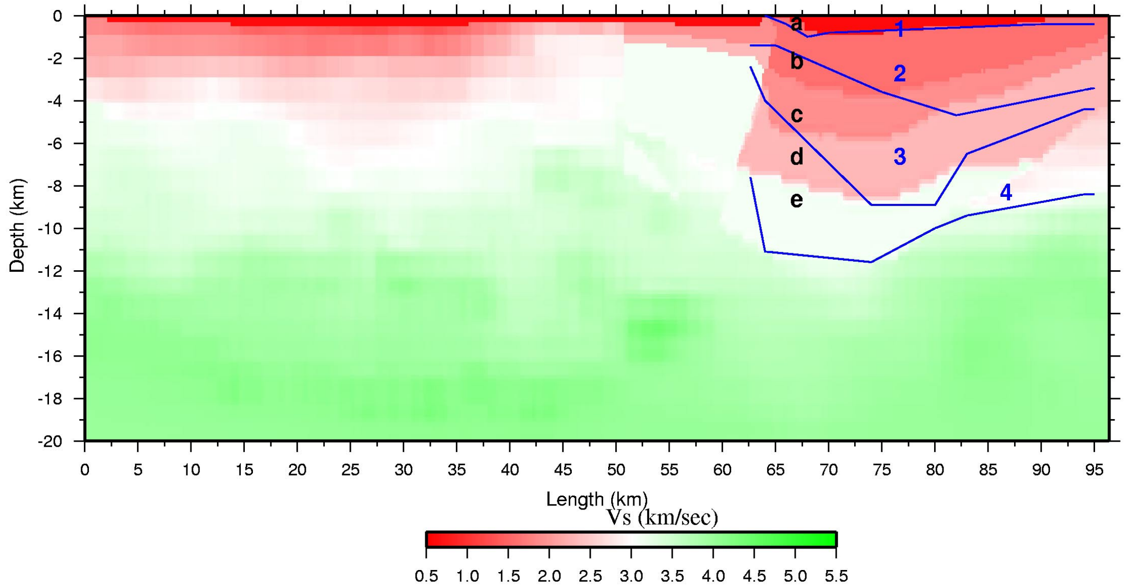

Figure 6. Vertical cross-section of the 3D velocity model (Pitarka,2004) along the A-A' profile. **a,b,c,d**, and **e** are labels of sedimentary layers of the Seattle basin with distinct velocity contrast. Blue lines represent the geometry of such basin layers obtained by the 2D inversion. Note that in the inversion layers **b** and **c** are represented by a single layer.

waves in the central part of the basin. It indicates that the thickness of the second basin layer at the center of the basin is probably larger than that in our 3D model. There is a good match between the 3D model and the inverted one in terms of basin basement geometry. The inversion also demonstrates that the existing 3D velocity model in the Seattle region is adequate for modeling long period waves.

Conclusions

1. Numerical tests of the inversion technique of Ji et al.(2000) presented in this study show that the performance of the inversion greatly depends on the quality of the initial model and the number of recordings. The convergence rate of the technique quickly deteriorates when the quality of the initial velocity model decreases. The technique works better for velocity models with strong velocity contrasts as it mostly relies on matching the waveform of the main phases in the recorded seismograms.
2. The 2D velocity model along a N-S profile across the Seattle basin derived from the inversion of strong ground motion from Nisqually earthquake recorded at a linear array of 9 stations suggests that the southern edge is almost vertical. The inverted 2D model shows that the thickness of the unconsolidated basin sediments in the central part of the basin is larger than that derived from the existing 3D velocity model of the Seattle area (Pitarka et al., 2004).

3. The installation of dense networks of ground motion stations in the Seattle basin will contribute to improvement of underground structure inversion techniques.

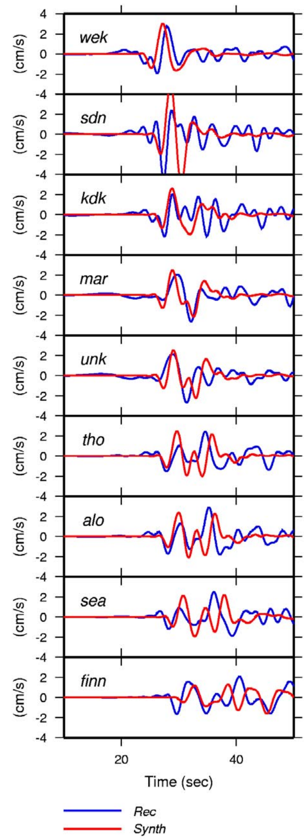

Figure 7. Comparison of FD synthetic (red) and recorded velocity seismograms (blue) that were used in the inversion.

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