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MODELING THE 2006 KOCHKOR, KYRGYZSTAN EARTHQUAKE AND WAVERFORM PROPAGATION IN THE NORTHERN TIEN SHAN

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Summary. On 26 December 2006 an M_w 5.8 earthquake occurred in the northern Tien Shan, Kyrgyzstan. The earthquake caused significant damage to several hundred buildings (including 9 schools) in the Kochkor valley. An area of approximately 3700 square km was affected. Aftershocks were recorded by a local broadband network and located using both relative (double difference) and absolute algorithms. The area of the earthquake was also imaged by the ALOS L band radar satellite but a clear deformation signal was not observed suggesting that the majority of the rupture was at depths greater than 5 km. A model of the fault rupture was developed using the aftershock hypocenters, InSAR data, and main shock focal mechanism. This rupture model is then used as a basis for waveform modeling and compared with data from the observed broadband stations. The use of a 3D finite difference code is tested and preliminary results presented. The objectives are twofold: to investigate whether realistic 3D waveform propagation of the Tien Shan is possible with moderate computational resources and to assess the potential effects of basin sediments in the Chu, Kochkor, and Issykul valleys. The finite difference code produces waveforms that match semi-analytic 1D synthetics well and a reasonable approximation to the observed seismograms in terms of duration and amplitude. Indications of exceptionally high amplitude I the Kochkor valley, which might explain the widespread damage in that region, appear.

Key words: earthquake, 3D finite difference, waveforms, Kochkor

Introduction. The northern Tien Shan of Central Asia is an area of active mid-continent deformation. Although far from a plate boundary, this region has experienced 5 earthquakes larger than magnitude 7 in the past century and includes one event that may as be as large as Mw 8.0. Studies based on GPS measurements indicate on the order of 23 mm/yr of shortening across the entire Tien Shan and up to 15 mm/year in the northern Tien Shan (Figure 1) [1,2]. The strain measured by geodesy matches the expected seismic moment release rate [3], at least to first order, suggesting that the earthquake activity in the past century is not exceptionally anomalous and that large earthquakes may be expected to strike the region in the future. This seismic activity, when combined with the significant population exposure, creates a significant seismic risk in the region. This is critical for assessing risk along the northern boundary faults near the major population centers of Bishkek and Alamaty. As an example, one study [4] indicates that the expected slip rate at the Issyk Ata fault next to the city of Bishkek (a population of over 1 million) might be as high as 5 mm/year, which could lead to a significant earthquake with an recurrence time of several hundred years. Since a large earthquake has not occurred along that particular fault in the last few hundred years, the risk is substantial.

An important aspect of earthquake hazard reduction is prediction of potential seismic motion from future earthquakes. This requires two basic elements: knowledge of the potentially active faults, the likelihood of earthquakes on these faults, and the expected ground motion resulting from these potential earthquakes. This work seeks to increase understanding of seismic wave propagation in the Tien Shan and expected ground motion from earthquake along known faults.

Previous work [5] modeled waveforms using 1D semi-analytic methods to infer source properties. This type of method, which assumes a velocity structure that varies only with depth, is fast and works reasonably well at longer period wavelength but poorly at shorter wavelengths. In areas with laterally varying velocity heterogeneities, shorter period waves are more strongly affected than longer wavelengths. This is especially true of the Tien Shan which possesses complex structure and rapid changes in seismic wave velocity over short distances [6]. If a 1D method is used in areas with complex velocity structure, the errors in the propagation typically get folded back into the source, which leads to inaccurate results. 3D effects are particularly important in estimating seismic hazard, as focusing effects and resonances can produce expectedly high amplitudes causing damage even at long distance. This type of effect caused considerable damage in the Mexico City earthquake of 1985, event though the epicenter was hundreds of kilometers from Mexico City. Sedimentary basins are particularly prone to this effect.

As the North Tien Shan is both complex and the major urban areas of Bishkek and Almaty lie on top of sedimentary basins, a 3D code is essential for a proper understanding of the seismic hazard. Similar efforts using 3D waveform modeling are underway in other areas such as Los Angeles [6]. Typically, a number of numerical approaches can be used to conduct 3D waveform modeling. The major categories include finite difference, finite element, and spectral methods. Of these methods, finite difference methods have been applied most frequently to waveform modeling. These methods differ from 1D methods in that the full wavefield is calculated at every point ona 3D volume, which requires considerable computation effort. In the past, full 3D methods have required parallel computers or clusters but recent advances in computational technology mean that small 3D models are now possible with moderate size computers. In order to evaluate the use of these methods, we model the Dec 26, Kochkorka earthquake.

Method. We chose the Dec. 26, 2006, Kochkorka earthquake as a test case. The Kochkorka (Mw 5.8) earthquake destroyed or severely damaged 400 houses as well as power and communication lines in the region [7]. The earthquake was well recorded by a local broadband seismic network as well as global stations. The local network also recorded numerous aftershocks, which we relocated using the algorithm of [8]. A global focal mechanism [9] indicated a thrust mechanism with a component of strike-slip. The aftershocks suggest a south-dipping thrust fault striking NNE and dipping at an angle of 35-45° (Figure 2) although imaging radar did not show a clear signal [10]. Well-constrained aftershocks ranged from about 6 km to 26 km in depth. A previous large earthquake in the region possessed a similar mechanism and aftershock depth distribution [11]. No known surface rupture has been mapped as far as we know but this fault orientation is consistent with a continuation of the South Kochkorka thrust fault [4].

The earthquake is well suited as a test example because the focal mechanism is well-constrained but it is small enough so that a point source is a reasonable assumption, which eliminates the additional complexity of an extended finite rupture with uncertain slip distribution. The code of [12] is used. It is a partly staggered grid 3D finite difference code capable of including elastic or viscoelastic effects. For these runs the approximation was 2nd order in time and 4th order in space. PML (perfectly matched layers) boundary conditions were used. The code written in C and is highly modular. This makes it highly portable and relatively easy to understand.

The initial model is based on the North Tien velocity structure of [13]. The model is parameterized as a 766 by 566 by 362 rectangular volume with a grid spacing of 300m. The grid is sufficiently large to include the epicenter and all nearby broadband stations. With this grid spacing and the lower velocity being 3.0 km/s, simulations resolve up to a frequency of 0.6 Hz.

Initially, we use a 2D model in order to compare the results with a semi-analytic method (Figure 3). Figure 3 shows the comparison between the finite difference and semi-analytic wavenumber synthetic at station USP, which is the farthest stations from the epicenter and consequently should incur the maximum error. The body waves are matched well but slight difference are observed in the surface waves, which can be explained by an under-sampling of these waves in the numerical grid due to the very short wavelengths. Note that this represents the largest possible numerical error.

Results. Next, the finite difference synthetics were compared to observed data from the Kochkorka earthquake as recorded by the KNET seismic network. The observed data was demeaned and filtered to match the frequency content of the synthetics (Figure 3). The synthetic matches the amplitude and duration of the observed data except at station KZA, which showed a longer duration of higher amplitude waves. Interesting, KZA is nearest the area of most damage. Given the preliminary nature of this investigation, we hesitate to draw any conclusions as the anomalous waveforms as they could be due to rupture effects but it offers an intriguing possibility that may be useful for future hazard studies.

A powerful use of the 3D studies is the capability to reconstruct the wavefield at any point or time. Figure 4 shows snapshots of the Z component of the wavefield at intervals of after the earthquakes. The red color shows motion upwards while the blue shows motions downward. The seismic waves can clearly be seen propagating out away from the epicenter. It is also possible to create animations of the seismic waves which are useful for visualizations.

Conclusions and recommendations. This work, although preliminary in nature, has shown that 3D finite difference methods are suitable for modeling waveforms in the Northern Tien Shan. These simulations are possible using moderate computer resources and are useful for assessing seismic hazard. The next step is to develop a more realistic 3D velocity model and test wave propagation through the model. This offers a way to validate the models and to investigate the potential effects of sedimentary basins on seismic wave amplitudes in the Chu Valley and surrounding regions. A useful step would be the creation of a working group consisting of seismologists and geologists to construct the next generation of velocity models in the region. This would greatly aid understanding of seismic hazard in the area and provide state-of-the-art training for students in these methods.

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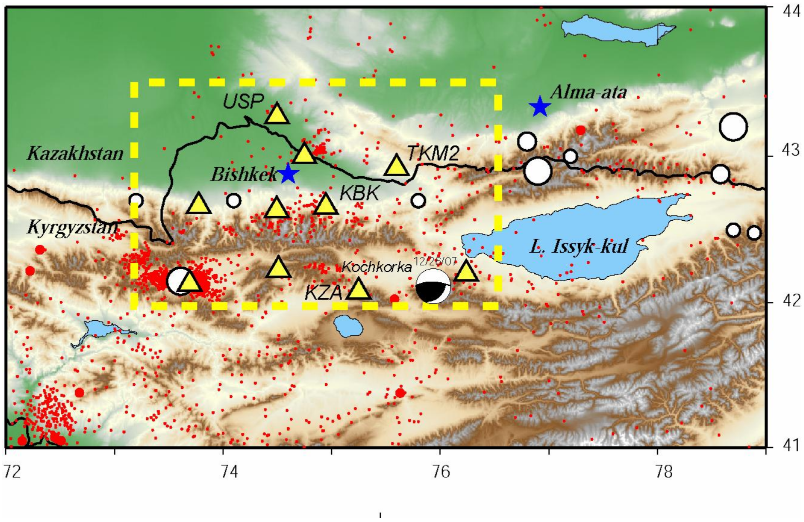

Figure 1. Map of region showing focal mechanism and location of the 2004 Kochkorka earthquake, outline of grid (dashed box), seismic stations (triangles), major cities (stars), large historical earthquakes (circles) and seismicity (dots).

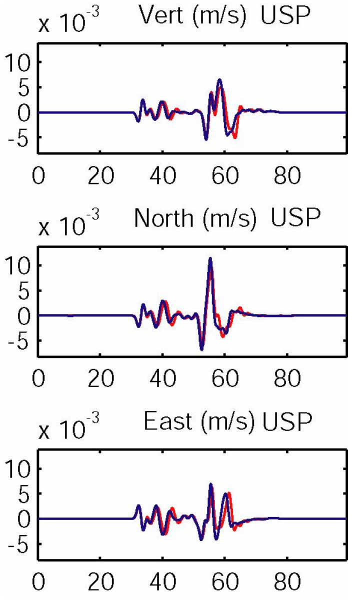

Figure 2. Comparison of 3D finite difference synthetics (red) with 1D semi-analytic wavenumber (blue) synthetics at station USP. This station is the farthest from the source and should contain maximum error. The two sets of synthetics are in good agreement.

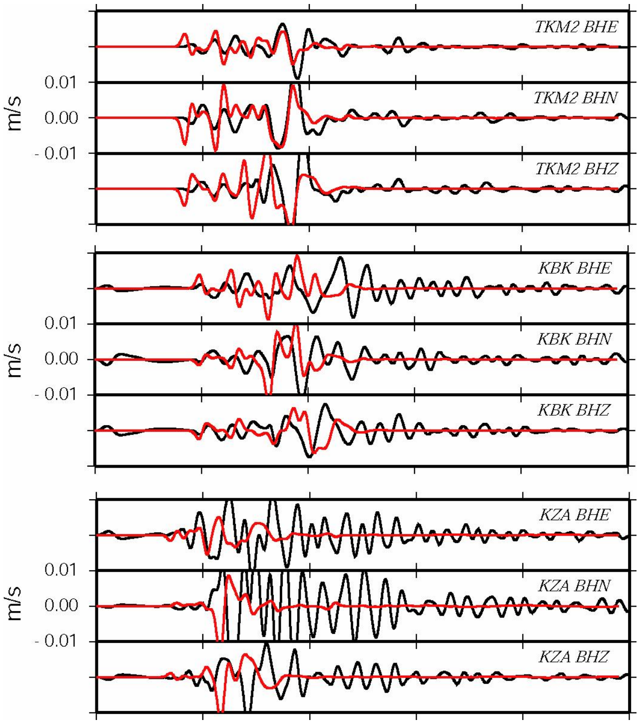

Figure 3. Comparison between observed data (black) and finite difference synthetics (red) for selected KNET stations (KZA, KBK, and TKM2). The channels are indicated by the BHZ (vertical), BHE (east-west), and BHN (north-south). The synthetic matches the amplitude and duration of the observed data except at station KZA, near the site of most damage.

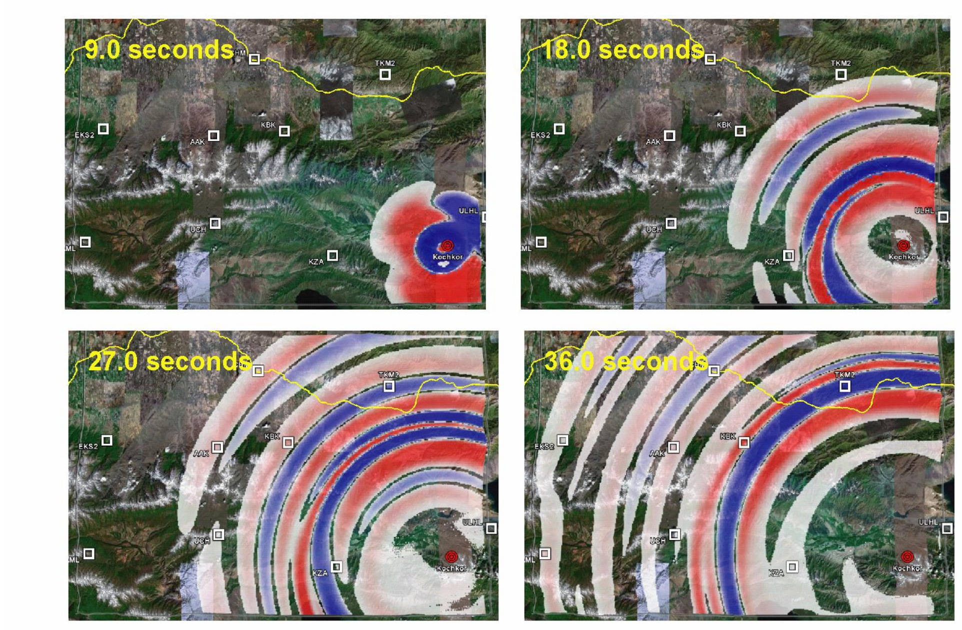

Figure 4. Map view of the wavefield propagation at intervals after the origin time superimposed over a satellite image the northern Tien Shan. Red represents upward movement and blue downward. Boxes represent seismic stations as shown on Figure 1.