Guided waves from sources outside faults: an indication for shallow fault zone structure?

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Abstract

Using 3D numerical modeling of seismic wave propagation we investigate the possibility of generating fault zone (FZ) trapped wave energy from sources well outside the FZ. We find that in the low-velocity part of the FZ trapped waves can be excited from sources outside it if (1) the low-velocity structure ranges only to shallow depth and the source is located at greater depth or (2) the structure of the low-velocity zone is such that only the shallow part of the FZ traps energy. FZ trapped waves will not be excited from sources well outside a planar FZ continuous with depth. Together with evidence from observations of FZ trapped waves near the North-Anatolian fault this supports the concept of a shallow low-velocity FZ structure rather than a FZ structure continuous with depth. This may have implications for rupture dynamics as well as for aspects of shaking hazard near faults.

Introduction

In the last decade fault zone (FZ) guided head and trapped waves have been observed along several earthquake faults with receivers close to the FZ (see Jahnke et al., 2002, for a review). There is hope that analysis of such phases may be used to provide a higher resolution imaging of FZ structure at depth than is possible with standard ray tomographic methods. Such imaging can provide important input for mechanical models of faults before, during, and after earthquake ruptures. While attempts are being made to invert the observed trapped wave forms in terms of plane vertical fault zone structure (e.g. Michael and Ben-Zion, 1998) it is at present not clear how reliable the obtained structural information is, even when excellent data fitting is achieved. In previous studies (Igel et al., 2002; Jahnke et al., 2002) we were able to distinguish between important (e.g. structural discontinuities) and less important (e.g. vertical velocity gradients, small deviations from planar faults) effects on the trapping efficiency due to non-planar structures. However, we assumed that sources are located right in the fault or at the fault's side.

Several previous studies argued that FZ guided waves are only generated when the sources are close to or inside the low-velocity FZ layer. It is thought that only a small percentage of earthquakes in an active fault occurs inside this region. Here we discuss numerical simulations of 3D wave propagation which show that sources at considerable distance from the FZ are able to generate high amplitude trapped waves. We focus on a structure consisting of a shallow low velocity FZ layer (e.g., depth < 5 km) in a half space, and perform an extensive parameter study quantifying the amplification of ground motion for sources outside and below the FZ layer. In general, the trapping efficiency strongly depends on the source mechanism and orientation of the source with respect to the FZ layer.

The generation of guided waves by sources in a volume outside the FZ has implications for evaluation of seismic hazard close to faults. It further demonstrates that considerable care has to be taken when interpreting fault zone trapped waves in terms of low velocity zones that extend throughout the seismogenic crust.

Trapped waves from sources outside fault zones

To investigate the trapping efficiency we position various sources outside shallow and continuous faults and record seismograms at profiles across the fault at the surface. An example is shown in Figure 1. The snapshots show SH-type wave propagation from a strike slip source below a shallow low-velocity FZ structure.

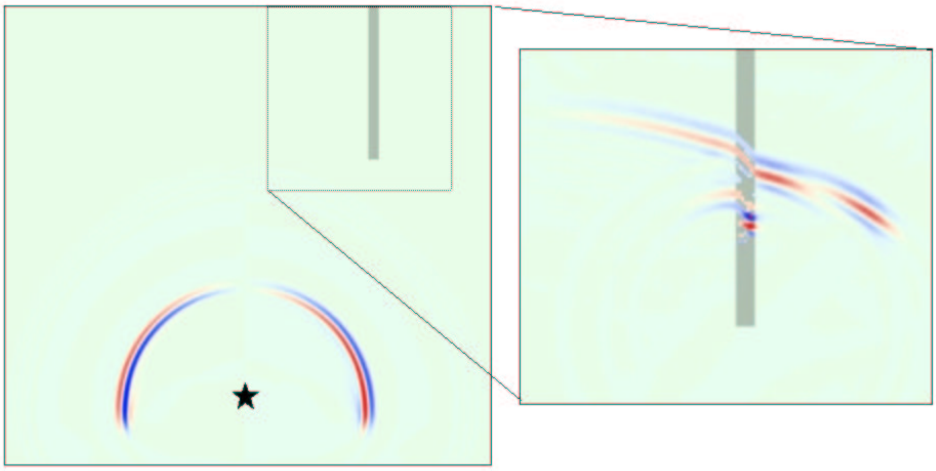

Figure 1: Transverse motion from a source (star) outside a low-velocity fault zone. At later time the trapping of wave energy inside the low-velocity structure (enlarged section) is visible.

The simulations indicate that if the FZ is continuous with depth, no trapped waves are generated from sources several FZ widths outside it. However - as can be seen from Figure 1 – as soon as the low-velocity structure is shallow, energy enters the FZ from below and is trapped. This is further highlighted looking at the horizontal ground motion recorded across the fault. In Figure 2 the seismograms clearly show amplified signals following the direct shear-wave arrivals. Note also the rapid decay of the amplitude of these signals when recorded just outside the fault.

We posed the question which source volume would be able to lead to trapped waves given a shallow fault zone structure. By defining time windows containing either the direct S-wave or the trapped waves we calculated the ratio of trapped wave to S-wave energy recorded at a particular receiver at the surface (see Figure 3) for a large number of source positions and source-receiver paths. This allowed us to estimate the source volume which will lead to a particular amplification at the surface location of the fault. In Figure 3 this relatively large volume (open to greater depth) is shown for an amplification factor of 2.

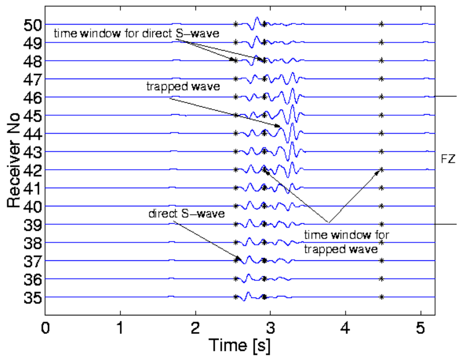

Figure 2: Horizontal ground velocity recorded above the fault for the model shown in Figure 1.

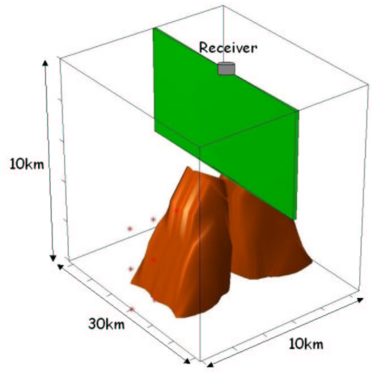

Figure 3: Surface of the volume in which amplification w.r.t. S-amplitude exceeds a factor of 2.

An extensive presentation of the simulation results will be reported elsewhere (Fohrmann et al., 2002).

Discussion

The (velocity-) structure of FZs at depth and near the surface is a crucial factor for the dynamic behavior of faults as well as the ground motion to be expected for earthquake scenarios in those regions. As ray-based methods are not capable of resolving the small scales involved there is hope that FZ guided waves are capable of providing this information. FZ guided waves are now commonly observed as soon as receivers are positioned directly above the FZ emerging at the surface. Over the past decade the main conclusions from either modeling or imaging of FZ trapped waves pointed towards planar low-velocity structures continuous with depth.

There is now substantial evidence from observations (Ben-Zion et al., 2002) that – at least in a typical large deformation-rate transform fault (North-Anatolian Fault) – almost all aftershocks recorded above the active fault from a large source volume contain trapped wave motion. This indicates that a shallow (vertical) low-velocity structure below the receivers on the fault is responsible for the observed ground motion. This is supported by the numerical simulations presented here and further detailed in Fohrmann et al. (2002).

In addition to the implications for the dynamic behavior of faults at depth these findings suggest that amplification of ground motion near FZs at the surface may occur for sources originating in a large volume. Such structures may have to be included in the evaluation of shaking hazard based on earthquake simulations, as previously suggested by Spudich and Olsen (2001).

Acknowledgments

We acknowledge support for a visit of YBZ to Munich by the German Academic Exchange Service through the IQN-Georisk (www.iqn-georisk.de).

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