Physical seismic modeling of a vertical fault

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Summary

This study shows seismic physical modeling results of a shallow vertical fault zone with slight vertical throw. Several model prototypes are created with materials which range in velocity and density, and 2D marine seismic data is acquired and processed. The post-stack imaged results are compared and it can be seen that the fault zone is resolved in both common offset and common source data. The modeled fault zone images show a likeness to real 2D seismic data collected over a recent ruptured surface fault.

Introduction

Detecting shallow fault zones are significant in geotechnical engineering applications and seismic hazard assessment in earthquake studies. The Greendale fault in the Canterbury region of New Zealand was previously undetected when it ruptured the ground surface during the Mw 7.1 Darfield earthquake in 2010. Shallow fault zones can be determined by high resolution seismic reflection profiling (Kaiser et al., 2011), as the deformation of rocks near the fault zone causes changes in lithology, pore pressure, and seismic velocity (Mooney and Ginzburg, 1986).

Seismic physical modeling provides scaled simulations of real-world scenarios with the benefit of controlled acquisition geometry and physical model properties (Lawton et al., 1998). Modeling of simple faults and geometries are beneficial to understand seismic sections with faults and structure (Angona, 1960). Hilterman (1970) used wood and paper to model synclines, anticlines, and vertical and low angle faults. An electric spark and a condenser microphone served as a source and receiver in this early experiment. Modeled seismic data collected in a water tank has shown success in comparing data processing and imaging between 2D and 3D datasets of ridge and fault models (French, 1974).

Several physical model prototypes of a simple vertical fault which ruptures a geologic surface were created to image a fault deformation zone using 2D marine seismic measurements. The seismic data were acquired at the University of Calgary Seismic Physical modeling Facility which is maintained by the Consortium for Research in Elastic Wave Exploration Seismology (CREWES). The modeling laboratory supports both acoustic and elastic modeling. The modeling systems are described in detail by Cheadle et al. (1985), Lawton et al. (1989), and Wong et al. (2009).

Fault resolution and the Fresnel zone

The quality of seismic imaging over a fault zone is constrained by seismic resolution. Both vertical and lateral resolution are controlled by spectral bandwidth, and describe the ability to distinguish separate features (Yilmaz, 1987, p. 468). Dominant wavelength varies with velocity and dominant seismic frequency, and is given by:

\[ \lambda = \frac{v}{f}, \]  

Vertical seismic resolution is defined by Widess (1973) as the thickness equal to one eighth of the seismic dominant seismic wavelength. However, one quarter of the predominant wavelength is taken as an industry standard for thin bed vertical resolution as the Widess threshold does not account for noise and wavelet broadening. Vertical resolution is important in imaging the vertical throw of a fault.

Lateral resolution threshold is determined by the Fresnel zone (Figure 1), an area of constructive reflection accumulation surrounding a reflection point (Lindsey, 1989). The radius of the Fresnel zone is given by:

\[ r = \left( \frac{v}{2} \right) \left( \frac{t}{f} \right)^{1/2} \]  

Two reflecting points that fall within the Fresnel zone are considered irresolvable, therefore lateral resolution improves as the Fresnel zone narrows. The deformation zone of shallower faults is more resolvable than deeper faults, as the Fresnel zone increases in area with depth.

Figure 1. The Fresnel zone radius (r) for a coincident source and receiver, adapted from Yilmaz (1987).
Modeling of a vertical fault

Physical models

The displacement and deformation zone of the Greendale fault, which was ruptured during the 2010 Darfield earthquake, served as a general guide to creating the fault models. The Greendale fault surface rupture was mainly dextral strike-slip with 2.5 m average displacement, vertical displacement less than 0.75 m, and a 30 to 300 m wide deformation zone (Van Dissen et al., 2011). Pure strike slip faults are difficult to detect in seismic imaging due to lack of significant vertical displacement (Fossen, 2010, p.356). However, deformed bends associated with strike-slip faults may split and widen upward into flower structures, which may be more detectable in seismic imaging as there is a wider fault zone in the near surface. Fault zones also show reduced seismic velocities which are associated with densely cracked and fractured rocks, altered rock composition, and near-surface fault gouge material (Mooney and Ginzburg, 1986).

Given these considerations, several physical model prototypes were constructed to best represent a vertical fault that ruptures the surface. A fault zone was created, closed at one end of the model, and widens with fault length distance. Several types of materials used to create the models and are summarized in Table 1. The velocity of the materials were measured with a Tektronix TDS 420A 200 MHz 4 Channel Digital Real-Time Oscilloscope. All of the models had zero-offset seismic reflection surveys acquired as a quality check. Survey parameters are discussed in greater detail in the next section.

The model and seismic acquisition measurements are scaled, where 1 mm in the physical modeling world is equivalent to 10 m in field equivalents. All referred measurements are scaled to represent field values and measurements have an approximate error of 5%. The Plaster of Paris - Lard model (model 1) has an average thickness of 285 m. Issues arose with this model due to air bubbles setting in the plaster as it dried, and the lifespan of the model was limited as the seismic surveys were acquired in water. The Sandstone – Epoxy model (model 2) had an average thickness of 248 m. The model was sturdy; however scaled grain sizes of the rock would be equivalent to 5 m. These unrealistic grain sizes contribute to point scattering in a seismic reflection survey. The limestone model (average thickness of 300 m) showed greatest promise as potential modeling material.

Different fault-zone infill materials were tested: water, vegetable shortening, wax, and finally acrylic plastic. The model was uplifted on one side by 10 m to illustrate a fault in the imaging. Models 4 and 5 were considered optimal and the results are compared in further analysis. Figure 2a shows Model 1 in the physical modeling water tank system, and Figure 2b shows the limestone model with an empty fault zone.

Table 1. Summary of physical model prototypes

<table>
<thead>
<tr>
<th>Model 1</th>
<th>Model 2</th>
<th>Model 3</th>
<th>Model 4</th>
<th>Model 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model material</td>
<td>Fault zone infill</td>
<td>Model material</td>
<td>Fault zone infill</td>
<td>Model material</td>
</tr>
<tr>
<td>Plaster of Paris</td>
<td>Lard</td>
<td>Sandstone</td>
<td>Epoxy</td>
<td>Limestone</td>
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<tr>
<td>Density (g/cm³)</td>
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<td>0.98</td>
<td>2.6</td>
<td>1.7</td>
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<tr>
<td>Measured Velocity (m/s)</td>
<td>3035</td>
<td>1490</td>
<td>2965</td>
<td>2680</td>
</tr>
</tbody>
</table>

Figure 2. a) The Plaster of Paris – Lard model in the physical modeling water tank. b) The limestone model help in place by putty, prior to fault zone infill.
The physical models were immersed in the modeling water tank for seismic acquisition. The model was placed on top of an aluminum plate, which rested on a phenolic resin block. A schematic of model 5 is shown in Figure 3. Panametrics V103 transducers acted as the source and receiver. Model V103 transducers produce and detect vibrations with particle motion in the vertical direction (Wong et al., 2011).

Common-offset gathers were acquired for all the models for quality control to determine if the model was suitable for further investigation. The common offset profiles ran perpendicular to the fault length, with the transmitter-receiver pair moving in 50 m increments with a 50-m offset along the line. The data were processed assuming a coincident source and receiver. Three profiles were collected over each model at varying fault zone thicknesses. For the final limestone models, the surveys crossed fault zone widths of 50, 100, and 150 metres.

Common-source gathers were acquired for the limestone–water model (model 4) and the limestone–acrylic model (model 5) over the 50 m fault width. The source increment spacing was 10 m and the receiver spacing was 5 m. The maximum fold was 200. A sample rate of 1 ms (scaled units) was used during all acquisition.

Data processing

The initial processing flow for the common shot gathers is shown in Figure 4. Further work is needed in developing a processing flow that eliminates multiples from the primary reflection data and enhances the fault zone. In addition, a processing flow to preserve and image the multiples is being investigated.

We performed ray tracing in order to help identify events on the seismic records. A raw record of the Limestone-Water model is shown in Figure 5.
The multiple reflections identified are interesting as they do not interfere with the primary data, and may be useful in further imaging focused only on the multiple data.

The initial post-stack migrated section of the Limestone-Water model is shown in Figure 6. The deeper section containing multiples has been cropped to focus only on the primary reflections of the fault zone. The fault zone of 50 m and the fault throw of 10 m are resolved at the near surface.

Figure 6. Initial post-migrated results of the Limestone – Water model with a 50 m fault zone. The zone of deformation is outlined. The bottom of the water filled fault is observed near 720 ms.

The migrated seismic section for the Greendale Greendale fault zone which ruptured the surface in New Zealand is shown in Figure 7. The 2D seismic land data was collected by CREWES in 2011. A similar fault throw is observed in both the physical modeled and field seismic sections, as well as the wide fault zone.

Figure 7. Post-stack migrated seismic section for the Greendale fault zone, New Zealand. The deformed fault zone is outlined.

Conclusions

Physical modeling provides a method to test seismic acquisition parameters for detecting fault resolvability. A great deal of consideration must be taken when designing a physical model to best represent a realistic geologic model. Selection of materials is important especially when considering attenuation, scaled geologic properties, the ability to withstand long durations in water.

Processed model data yielded images that resolved a shallow fault with a small vertical throw, and the width of the fault zone. The image shows similarities in fault zone deformation observed in a field survey across a recent fault in New Zealand. Further comparisons between all the models and additional data processing are planned.

Acknowledgements

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