AVO effect of elastic wave modelling

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ABSTRACT

Reflection coefficients are studied from 2D P-SV cases of wave-equation based elastic wave modelling. The modelled results are compared to analytical results obtained from Zoeppritz equations.

INTRODUCTION

Two common categories of amplitude versus offset (AVO) modelling methods are 1) Zoeppritz modeling with ray-tracing, and 2) full wave elastic wave equation (Li et al., 2003, 2004).

Among most typical modelling methods, including normal-incidence reflectivity, amplitude variation with offset, ray tracing, wave-equation finite-difference (FD) or finite-element (FE) solutions, and physical modelling, wave-equation finite-difference (FD) methods are regarded as a more expensive category, but they can offer more general and complete seismic models than other methods (Lines and Newrick, 2004, chap. 15). It has been found that elastic wave FD modelling is accurate in terms of wave velocity, wave length, and geometrical spreading in 1D and 2D cases, and in terms of normal incident reflection and transmission coefficients in 1D cases (Jiang et al., 2011; Jiang, 2012) .

This report focuses on AVO effect of full wave elastic wave modelling. P-P reflection coefficients with different incident angles are extracted from wave modelling experiments, and the numerical results are compared to analytical results obtained from Zoeppritz equations. Discrepancy between the Zoeppritz solutions and the finite-difference modelling results is found. Analyzing suggests that the discrepancy is resulted from the modelling method.

EXTRACT REFLECTION COEFFICIENTS FROM WAVE MODELLING

Wave modelling upon a two-layer elastic model

A two-layer subsurface model was built, as shown in Figure 1. The media includes a flat geological interface separating two rock layers. The rock interface is at the depth of $500m$. The finite-difference node spacing in the model is $1m$. The wave velocities and densities are shown in Table 1.

A modelling experiment was done with a time step of $0.0001s$ and with a P-wave source

Table 1: Wave velocities and densities in the model shown in Figure 1

Layer	P-wave vel.(m/s)	S-wave vel.(m/s)	Density (kg/m^3)
Surface layer	3000	1732.05	2290.89
Deeper layer	1000	577.35	1740.7

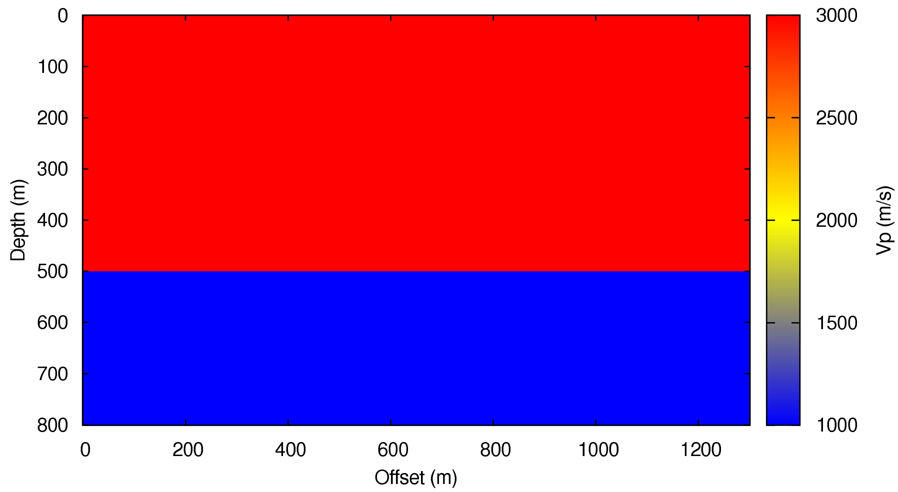


FIG. 1: A two-layer subsurface model.

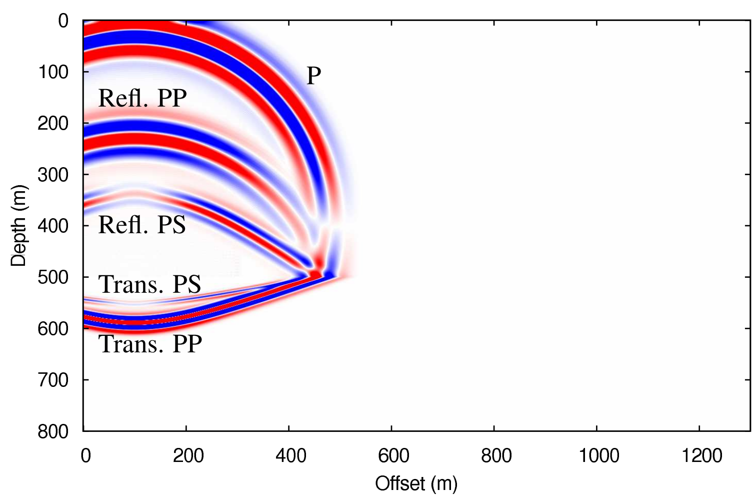


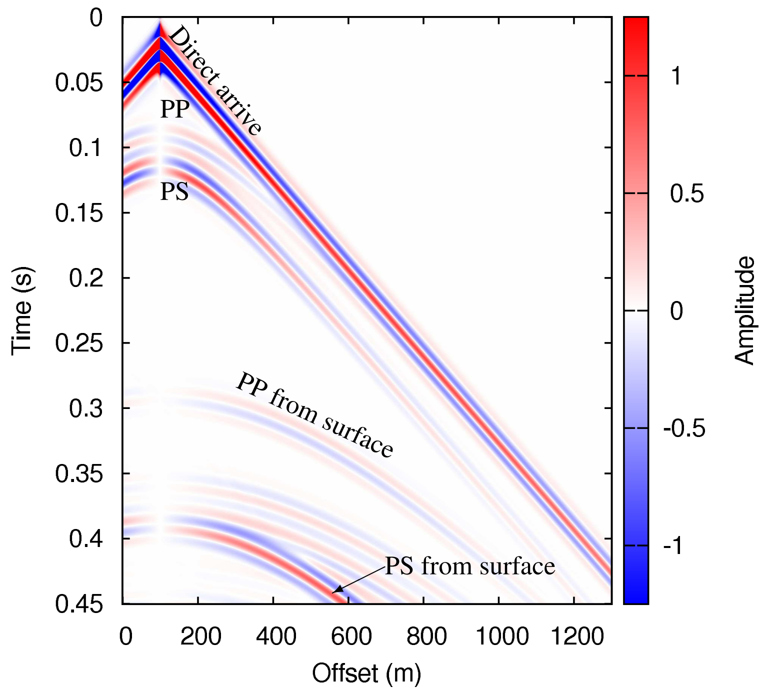
FIG. 2: A snapshot of vertical component at time 0.15s.

at $(100m, 400m)$ and receivers at $400m$. Wavefields are generated and a vertical component snapshot is shown in Figure 2. The five wavefronts are a direct P wave generated from the energy source, a PP reflection and a PS reflection upon the rock interface at $500m$, a PS transmission and a PP transmission under the rock interface.

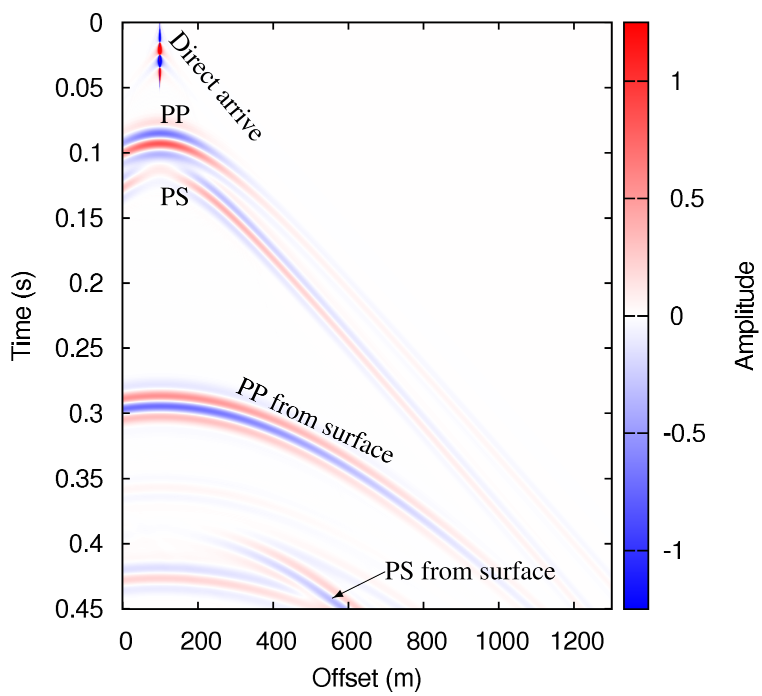
Seismic data recorded at the depth of $400m$ are shown in Figure 3. The recorded events include direct P-wave arrival, PP and PS reflections from the rock interface, and some other events. The studied reflection coefficients R_{PP} is based on the PP event.

Measuring modelled PP reflection coefficients

There are two obstacles for one to study the rock interface PP reflection coefficients (R_{PP}) from the records shown in Figure 3. First, the PP event is merged into the direct P-wave arrival with large offsets. Second, from the wave energy source to the receivers, the amplitude attenuation includes both geometrical spreading and transmission losses.



(a) Horizontal component



(b) Vertical component

FIG. 3: Records received at a depth of $400m$. The wavefield is generated from the subsurface model shown in Figure 1.

To calculate the reflection coefficients R_{PP}, another subsurface model, referred to as the homegeneous model, was built. The demensions of the model are the same as the two-layer model shown Figure 1. However, the new model contains only a homogenerous medium, which has the same rock properties as the surface layer in the two-layer model.

Two wave modelling experiments are done using the homogeneous model.

The first experiment is designed to help remove the direct arrival in records from the two-layer model: a same acquisition geometry is employed, and only direct P wave and its surface reflections are generated. Thus, recorded events are the same P-wave arrival and its surface reflections as those obtained in the two-layer model experiment. Substraction of the homogeneous model records from the two-layer model records removes the direct arrival and its surface reflections in the two-layer-model records. Using this method, the PP event in the two-layer experiment is separated from the direct P-wave arrival. The records after removing the direct P-wave arrival are shown in Figure 4.

The second experiment on the homogeneous medium is done with an energy source at ($100m$, $600m$). Recorded data are the P-wave arrival and its surface PP reflection (Figure 5). Suppose A is a point on the event on a certain trace, and A' is a corresponding point on the PP event on a corresponding trace from the two-layer model. Because the raypath length of A is the same as that of A', geometrical spreading of A is the same as A'. Thus, the ratio of the amplitudes between A' and A should be equal to the reflection coefficient on the raypath of A'.

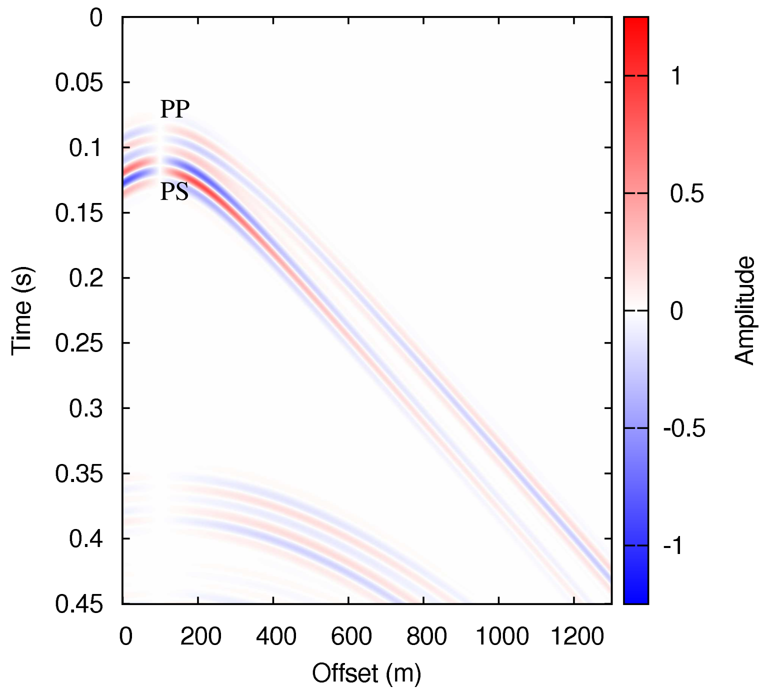
In the calculation of reflection coefficients, two adjustments have to be done. First, the ratios are negative because of the change of wave propagation direction upon the rock interface. Second, one needs to find A' as the local maximum in a trace according to the position of A (i.e., the time of A), since there is a slight position difference between A and A', which is caused by the phase change accompanying with wave reflection. Calculated reflection coefficients are shown in Figure 6. The measurement of the amplitudes and the calculation of incident angle are limited to $85°$ because of the limited width of the subsurface model.

MODELLED VERSUS ANALYTICAL REFLECTION COEFFICIENTS

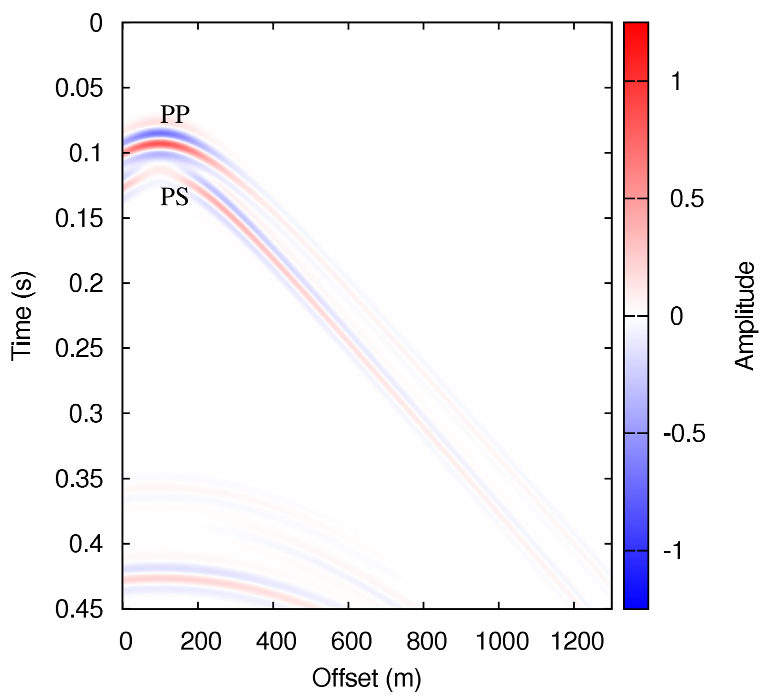
Reflection and transmission of plane P-SV waves at non-normal incidence are governed by Zoeppritz equations and the analytical solutions are given by Aki and Richards (2002, chap. 5). For the given rock interface shown in Figure 1 and Table 1, the analytical results are also plotted in Figure 6.

There are differences between the modelled and analytical reflection coefficients. There might be three causes of discrepancy: the seismic energy source, inaccuracy of the modelling method, and/or inaccuracy of the reflection coefficient measuring method. However, only the first one is discussed here.

A first guess is that the differences are mainly caused by the seismic energy sources: the modelling results are obtained with a circular source, while the analytical results are based on a plane wave source.

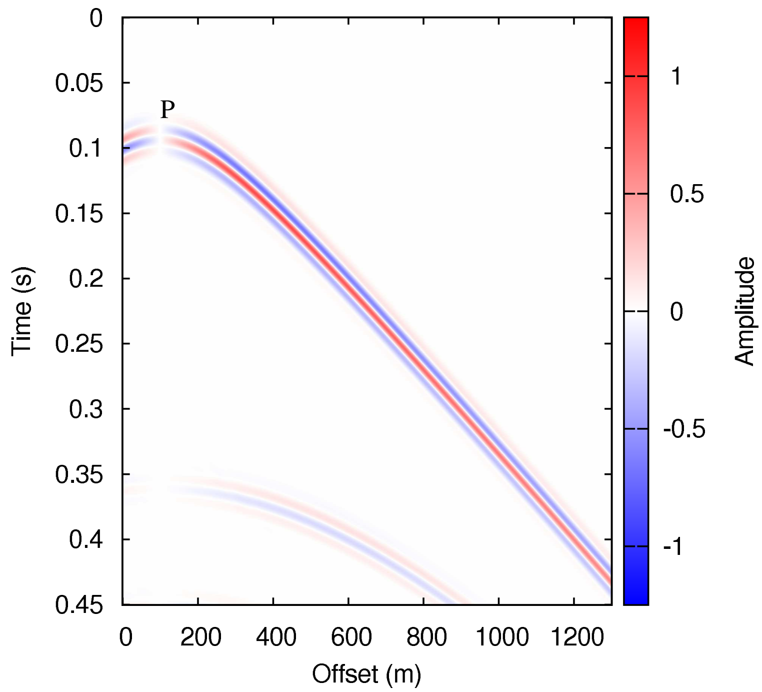


(a) Horizontal component

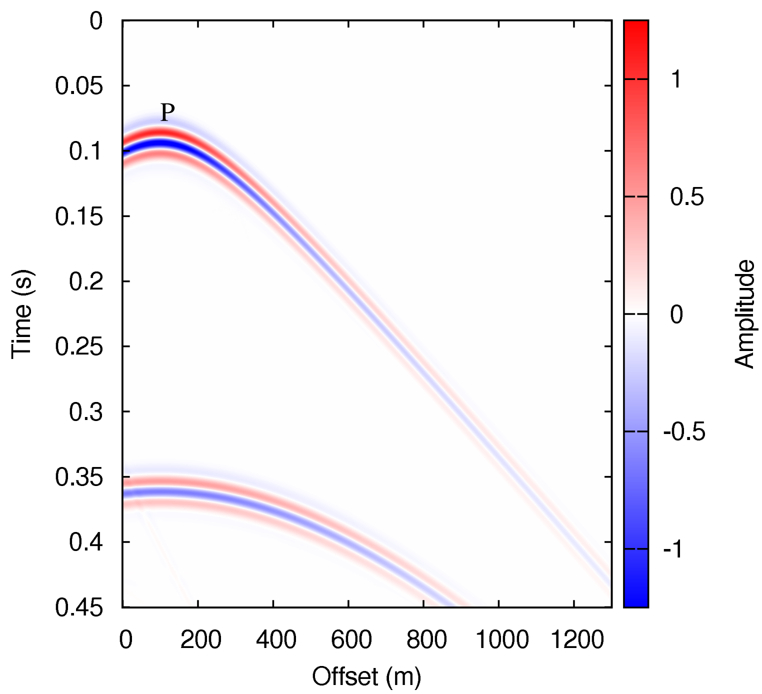


(b) Vertical component

FIG. 4: Records resulted from removing direct arrival and its surface reflections in Figure 3.



(a) Horizontal component



(b) Vertical component

FIG. 5: Records at a depth of $400m$, with the source at $(100m, 600m)$ and a homogeneous medium subsurface model. The medium has the same rock properties as those of the surface layer in the two-layer model shown in Figure 1.

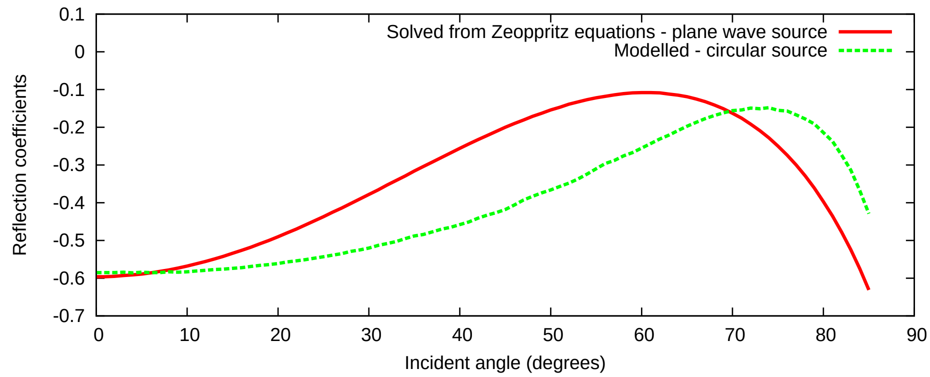


FIG. 6: Reflection coefficients calculated from Zoeppritz equations versus those measured from modelling results.

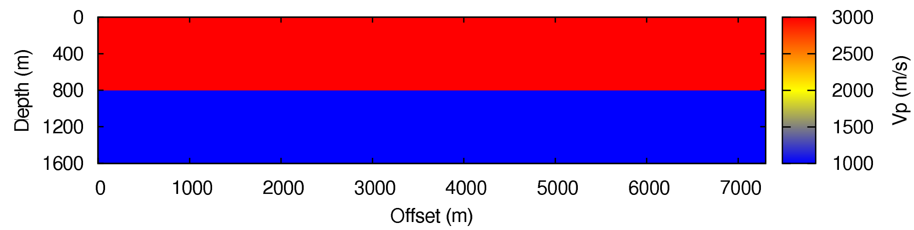


FIG. 7: A two-layer subsurface model, larger than the one shown in Figure 1.

If the discrepancy is due to circular waves, then it should become less if one increased the distance between the point envergy source and reflectors. This causes the incident wavefront to have a larger radius of curvature and hence be more locally planar.

In order to verify the guess about the source, another set of experiments are carried out. First, another two-layer subsurface model was built, as shown in Figure 7. The rock interface is at the depth of $800m$. The finite-difference node spacing in the model is $1m$. The wave velocities and densities are the same as shown in Table 1. Second, modelling and calculation on the larger two-layer model are done similar to those on the smaller model, but the energy source and receivers are put at a depth of $200m$. The result is plotted in Figure 8.

It was observed that the distance between the circular energy source and the reflector has very limited affections on the modelling result, although at small angles the large distance modelling agrees with Zoeppritz solution more.

Thus, it seems that the reflection coefficient discrepancy between the Zoeppritz solution and the finite-difference modelling result is mainly caused by inaccuracy of the modelling method.

CONCLUSIONS

The AVO effect from numerical wave modelling is different from theoritical Zoeppritz solution, although in normal or nearly normal incident cases the modelled results are close to analytical solutions.

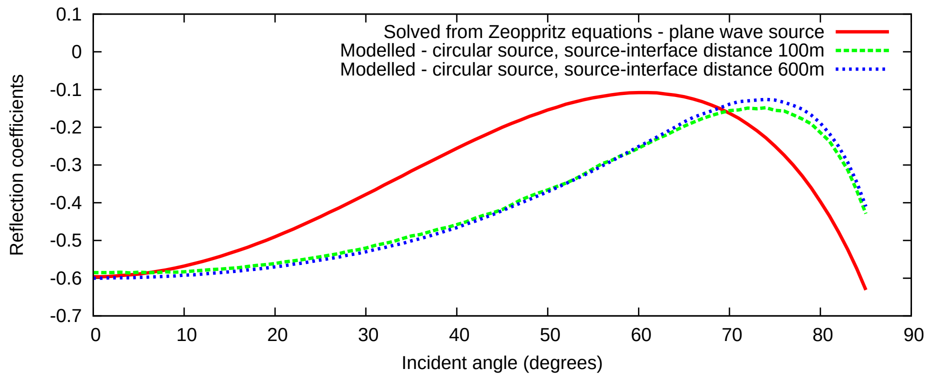


FIG. 8: Reflection coefficients calculated from Zoeppritz equations versus those measured from modelling results.

The reflection coefficient discrepancy between the Zoeppritz solution and the finite-difference modelling result is mainly caused by the modelling method itself, instead of by the circular seismic source of the modelling experiments.

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