

C009

Shear Waves in Streamer Data via Non-geometrical Conversions

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SUMMARY

In this paper we show that when an airgun source and a hydrophone streamer are situated in the vicinity of the water bottom, shear-related events are generated via the evanescent part of the P-wave in the water. The shear-related events are not only the often-used surface/Scholte waves but also body S-waves which can be reflected/refracted in the subsurface. The gain of this approach that neither source nor receiver is making any contact with the water bottom itself, making it possible to do shear-wave surveys on water in an efficient manner. We show that such shear-wave events are observed in real data, and can be reproduced by modelling. The results are further validated via real measurements in a borehole.

Introduction

Non-geometric waves are arrivals for which a conventional ray path cannot be drawn from the source to the receiver. Its reason lies in the fact that the arrival includes an evanescent exponentially-decaying part for which this ray path cannot be drawn. Examples of such waves have been reported in the past, like on land in global seismology (Daley & Hron, 1983) and in shallow land seismic (Roth & Holliger, 2000), called S^* and a \overline{P} S-wave respectively. Recently, such a non-geometric wave has also been discovered in a marine environment by Allouche *et al.* (2011), where an evanescent P-wave in the water converts to a propagating S-wave in the water bottom. Its existence was shown by the use of OBC data and the modelling thereof. In this abstract we want to show that such arrivals also exist in streamer data, i.e., data where both the source (airgun) and the receivers (hydrophones) do not make any contact with the water bottom.

Before going into the theoretical background of these arrivals, let us show a record in a marine environment that we refer to; it was shot with a 10 cu-inch airgun and recorded with a hydrophone streamer with 3.125m group spacing (4 hydrophones per group). This is shown in Figure 1. On the left (Fig. 1(a)) the raw record is shown. A low-pass filter has been applied to this raw record to highlight shear-related arrivals (Fig. 1(b)). The main arrival in Figure 1(b) is the Scholte wave, well known since it has been used the last decade for obtaining shear-velocity profiles by inversion (see, e.g., Kaufman *et al.*, 2005). The next in prominence in Figure 1(b) is another faster arrival. We shall show in this paper that this arrival is a body-wave arrival, in particular a shear-wave refraction of a deeper layer. The fact that both surface waves and refracted shear waves are excited indicates that, in more general terms, shear-wave motion in the subsurface is excited and recorded, and that this information can be used for further analysis, processing and interpretation.

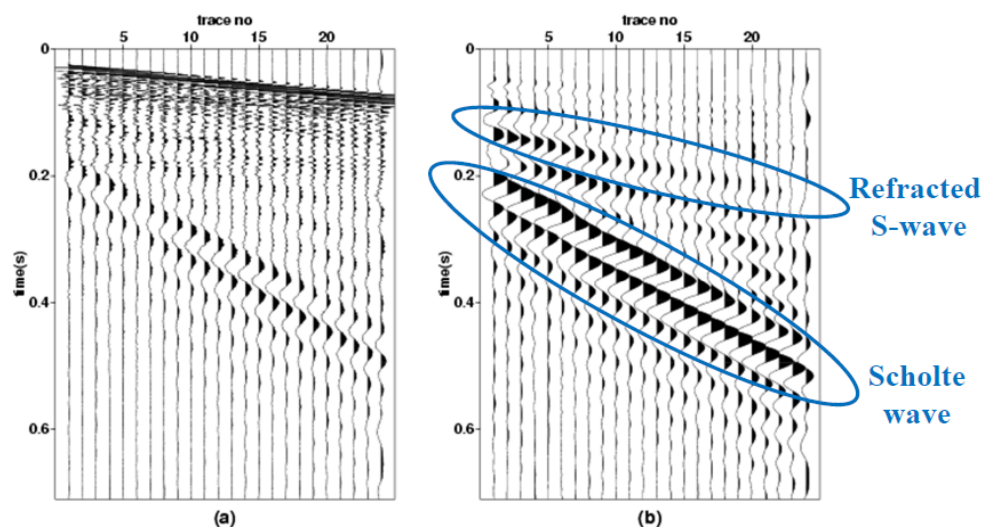


Figure 1 (a) Streamer record and (b) low-pass filtered version.

These non-geometric shear-wave arrivals have great potential for shallow marine investigations. For “soft” water bottoms like in deltaic areas, shear waves are good indicators for loams, clays and sands. The detection of thick layers of loam is important for avoiding clogging of the cutters in dredges. The detection of sand is very important for building activities in general.

Theoretical background

Theoretically, evanescent waves have been studied abundantly in the past, such as already in Brekhovskik (1960). Often in seismic exploration, the evanescent part is neglected. However, here we are looking at cases that it cannot be neglected. Such cases can happen when a source and/or receiver is near an interface where the wave has not damped enough and is therefore still observable.

Since evanescence already happens in very simple configurations, exact-solution methods can be used to simulate these waves, such as the Cagniard-de Hoop method. Without going into detail in the Cagniard-de Hoop method, the crucial point is the following. The complex path of integration over the horizontal slowness for this non-geometrical arrival passes very near the point associated with a real geometrical arrival. This real geometrical arrival is the arrival when the source and/or receiver is actually situated *on* the interface. It can be shown (Drijkoningen & Chapman, 1988) that expanding about this real point gives an arrival with an exponentially decaying part (in the frequency domain). This very well approximates the exact response, thereby explaining this arrival. Here we shall not use the Cagniard-de Hoop method since it has been worked out sufficiently in the literature, but we shall employ the elastic finite-difference method as given in Virieux (1986) since it includes multiples and the snapshot feature.

There remains one important item to mention, and that is the question when the evanescent part becomes important. In Allouche *et al.* (2011) this is worked out theoretically; as a rule of thumb it can be said that a source and/or receiver must be within some quarter of a wavelength to the interface such that the exponentially decaying (evanescent) part of the arrival makes the amplitude not too small.

Modelling the non-geometric arrival (with the FD method)

Here we will start with showing the response of a very simple configuration, with both the source (simulating an airgun) and the pressure receivers (simulating a hydrophone streamer) in the water. As model, a water-layer of 4 m is taken. At 4 m the model becomes a solid: the P-wave velocity increases from 1500 to 1600 m/s, the S-wave velocity from 0 to 300 m/s and the mass density from 1000 to 1500 kg/m³. With the elastic finite-difference method, we simulate the τ_{zz} wave field in the solid and the fluid, noting that in the fluid τ_{zz} reduces to the negative pressure ($\tau_{zz} = -p$). The wavelet has a dominant frequency of around 26 Hz. The feature of generating snapshots with the finite-difference method us in interpreting the non-geometrical arrivals. In Figure 2, we show 3 of such snapshots of the wave field for the model described above.

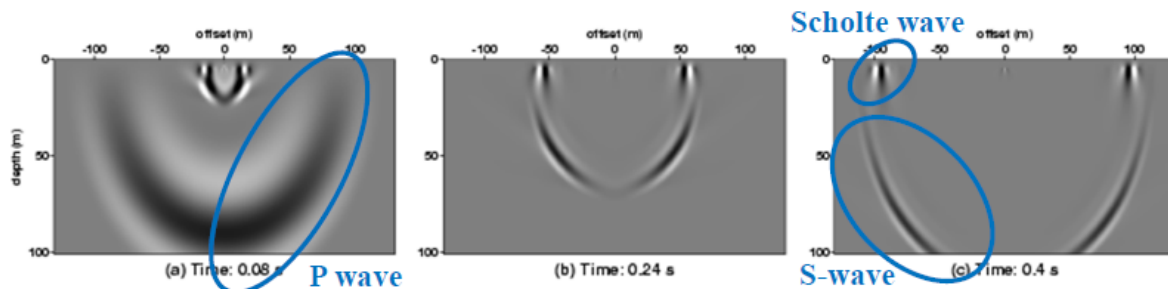


Figure 2 Snapshots of the τ_{zz} wavefield for a water layer on top of a solid half-space. P-wave, S-wave and Scholte wave indicated.

What can be seen on the first snapshot (Fig.2(a)) is the fast “low-frequency” P-wave. The 4 m-water layer is much smaller than the wavelength of this P-wave so therefore the “path” of the exponentially decaying part is small enough that the slower “higher-frequency” shear- and surface-wave events are generated (Fig. 2(b)). The separation between the shear-body-wave and the surface (Scholte) wave becomes more obvious at larger snapshot time (Fig.2(c)), where the obvious behaviour of a surface wave remaining near the surface can be observed. Totally, a pressure recording in the water will show only a direct P-wave and a direct surface/Scholte wave (not shown).

The above simple model shows the generation of shear waves in the subsurface but the model did not include an extra contrast in the subsurface which would bounce back as a reflection or refraction. Therefore a model with an extra layer is considered next.

An extra layer is added to mimic approximately the arrivals as seen in Figure 1 in the introduction. To that end, an extra contrast is added at 12 m depth: the shear-wave velocity has been increased to 700 m/s, the P-wave velocity to 1800 m/s and the mass density to 1800 kg/m³. The snapshots and a recording with distances similar to Figure 1 are shown in Figure 3. The first snapshot (Fig.3(a)) shows again the faster “low-frequency” P-wave and the first generation of shear-related waves like the body

shear wave and the surface wave. They are more obvious in the second snapshot (Fig.3(b)), where it can be seen that some S-wave energy is trapped in the solid layer. However, a faster refracted event can also be seen (fainter, but linking up to the fast S-wave wavefront below 12 m), which comes back at the surface. Especially in the last snapshot (Fig.3(c)) the separation of this refracted event and the surface/Scholte wave is obvious. When looking then at pressure recordings in the water (Fig.3(d)), the different events can be very well observed. An important observation of this latter figure is that the faster event (the one starting at ~ 0.14 s at 40 m offset and ~ 0.2 s at 110 m offset) is very similar to the one seen in the real data in Figure 1, and that event in the real data can therefore be interpreted as a *shear-wave* refraction.

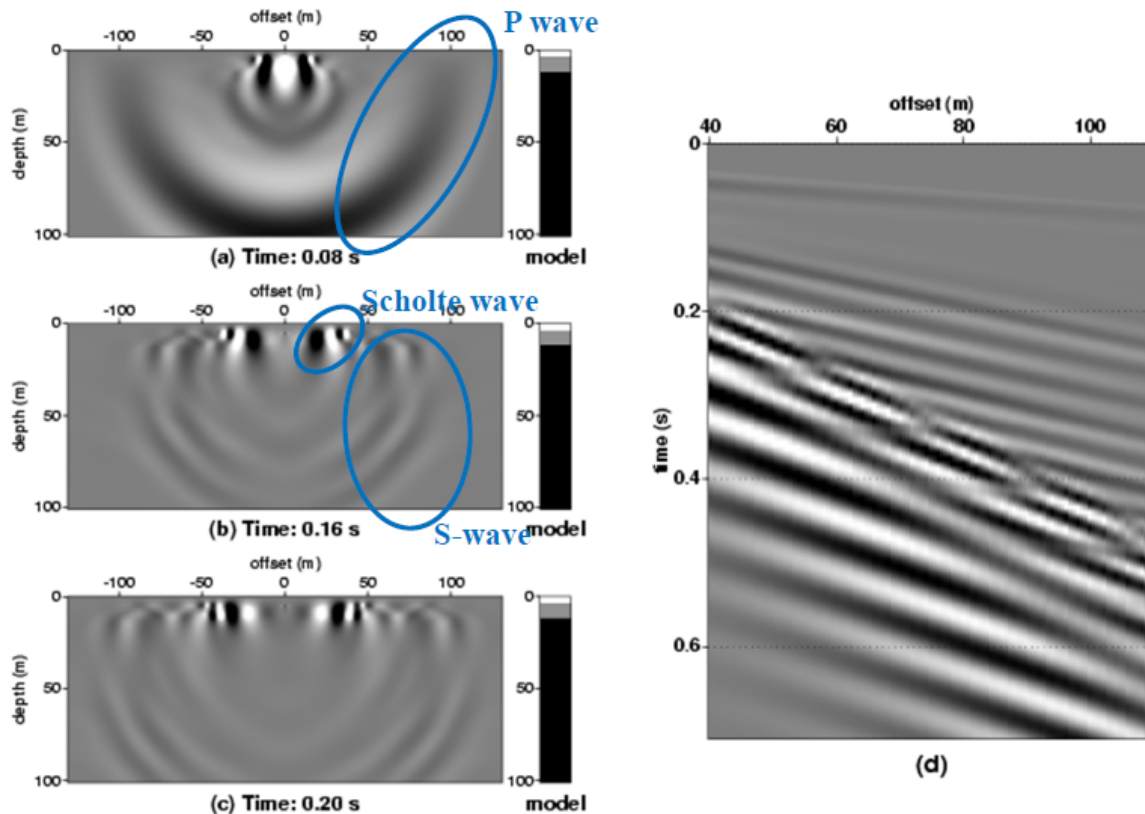


Figure 3 Modelled streamer: snapshots((a)-(c))showing the fast low-frequency P-wave event and the slower S-events. (d) Streamer record showing refracted S-wave event (including multiples).

Validation via borehole recordings

In order to really make sure that a shear body wave is generated in the subsurface, a borehole was used for recording the wavefield at depth. Such a recording would unequivocally establish that the event is a body wave and not a (possibly) different surface wave. In our case, the borehole was situated in the river. We employed both 3C geophones and hydrophones in the borehole, and we sailed with the airgun along the borehole (with some cross-line offset). Two common-receiver gathers obtained this way, are shown in Figure 4.

In Figure 4(a), a recording of the vertical component of the geophone (particle velocity) is shown at shallow depth. There, the surface/Scholte wave is dominant. Looking at a deeper level (Fig.4(b)), a faster event has appeared, and the surface/Scholte wave has as good as disappeared. This faster arrival is mainly linear; it has some slight hyperbolic behaviour at near offset which is entirely due to the cross-line offset. This is clearly a refracted shear wave, based on this time-space behaviour and on its velocity. And this behaviour is very similar to the event as seen in the real streamer record.

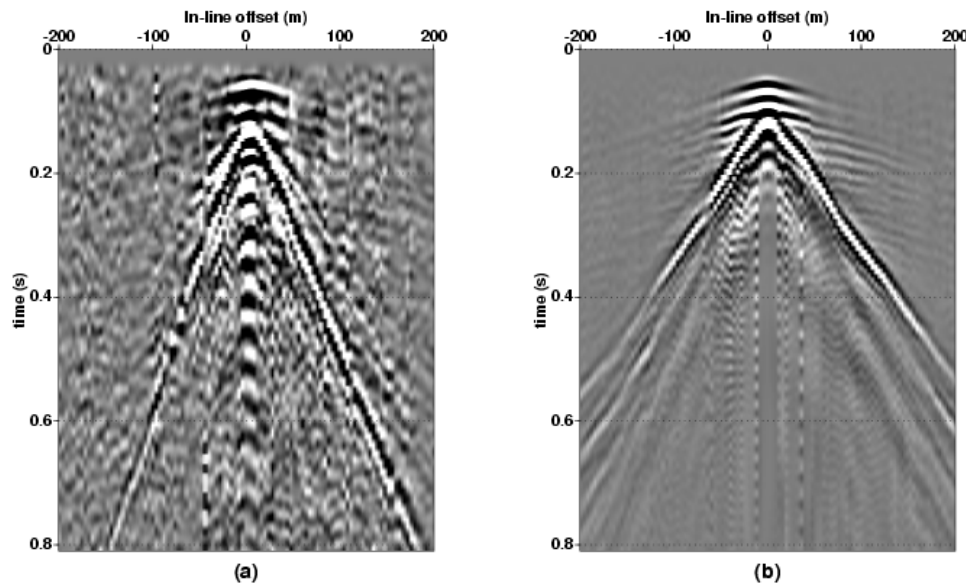


Figure 4 Two common-receiver gathers, obtained with geophones at depth in borehole and airgun in water: (a) vertical component at depth 12 m, (b) 33 m.

Conclusions

In this paper we have shown that when an airgun source and a hydrophone streamer are situated in the vicinity of the water bottom, shear-related events are generated via the evanescent part of the P-wave in the water. The shear-related events are not only the often-used surface/Scholte waves but also body S-waves which can be reflected/refracted in the subsurface. The gain of this approach is that neither source nor receiver is making any contact with the water bottom itself. We have shown that refracted shear-wave events are observed in real streamer data, and can be modelled well with the (elastic) finite-difference method. The results are further validated via measurements in a borehole. Our approach allows a much more efficient way of generating shear waves than before.

Acknowledgements

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