A Case Study on Simulation of Seismic Reflections for 4C Ocean Bottom Seismometer Data in Anisotropic Media Using Gas Hydrate Model

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Summary

Converted mode (P-S) exploration is more complex in nature and may probably contain more information. Wave equation simulations are carried out and synthetic seismograms of reflection profile have been constructed for hydraulic pressure and three-component (3C) records on seafloor. The results show that a typical impedance contrast across the medium is the strong conversion boundary through which wave conversion of P-wave and shear-wave takes place. The frequency of the incident P mode is conserved during conversion. The dominant reflections on P-wave profile (pressure and vertical component) may include the contribution of converted share-wave. P-S waves from different mode-conversions underneath water layer can be recorded by 4C ocean bottom seismometer (OBS) operations at seafloor. The characteristics of multiples, on reflection profiles, have close relation to mode conversions and vertical transverse isotropy (VTI). The shear wave splitting with different travel time occurs at the bottom simulating reflector's (BSR) interface. Amplitude variation with offset (AVO) analyses is performed on synthetic data and two important attributes, intercept and gradient have been calculated which provide the high-resolution estimates of change in shear-wave splitting and the fractional change in shear-wave velocity. Modeling in anisotropic media signifies that BSR has dependence on the incidence angle with maximum value in near offset data (-6^{o} to $+6^{o}$) and the maximum correlation (0.7) is observed.

Introduction

Increased information about subsurface earth from the seismic data can be achieved using recently developed tools for multicomponent seismic acquisition such as Ocean Bottom Cables (OBC) or Ocean Bottom Seismometer (OBS). Seismic wave propagating as elastic wave below the surface undergoes the transmission, reflection and conversion on each interface of layered media. Model studies are of prime importance to know about the various aspects of reflections with hydrophones placed at seafloor.

Since four component (4C) sea bottom surveys use conventional air gun sources, which generate P waves only therefore the shear waves recorded by these 4C sensors on the ocean bottom, are mode-converted shear waves. The 4C OBS includes one hydrophone, one vertical geophone, one in-line horizontal geophone and one cross-line horizontal geophone. The P- waves generated by the air-gun sources are converted to shear waves (PS) at the sea floor, then reflected back at the reflectors and converted to P-waves again at the seafloor, and finally recorded by the sensors near the sea surface. This kind of converted shear wave has a symmetric ray path and can be processed using conventional techniques.

From 4C OBS data, both P-P and P-S sections can be obtained. The OBS generally record four components, two horizontal (X & Y), one vertical (Z) and pressure (H) components. Out of these four components the converted shear waves are recorded by X and Y component and the P-waves are recorded by Z and H components respectively. The P-S waves recorded by the sensor carry different information about the target horizons and may provide the better estimate of petrophysical properties, which cannot be determined with P-wave data alone. The objectives for exploitation of conventional and non-conventional energy resources cannot be fulfilled without considering anisotropy, which plays a vital role in multicomponent seismic surveys. The most diagnostic effect of anisotropy is shear-wave splitting, where a shear wave, with transverse motion, splits into two or more components of different polarization with different velocities. The effect of anisotropy examined from numerical simulations (Rajput et al., 2005, a) and a fundamental review of wave propagation in anisotropic media is available (Crampin, 1981). These analytic solutions within the context of geophysical exploration are studied and some logical formulations of these effects are presented under the assumption of weak elastic anisotropy (Thomsen, 1986, 1988, 2001). Recently the effects of compressional wave propagation in an elastic anisotropic medium with a vertical symmetry axis are studied and illustrated from analytical solutions (Tsvankin, 1996).

Wave equation technique and ocean floor model

Since we are concentrating on PS waves (converted from P to S), the recording of SP waves (from S to P) requires extra efforts and not being considered here. This paper is divided into two parts; in first the reflections on each component of 4C are calculated by wave equation technique for the case of a complex gas hydrate model, secondly we focus to find the ways to better understand mode-converted shear waves in the presence of seismic anisotropy, which is common in aquatic deposits. To meet this end, we examine and model the characteristics of 4C seismic data, evaluate the basic theory of converted wave processing, develop new kinematics theories for converted waves propagation in transverse isotropic media.

The seismic wave generated by a point source in seawater propagates first as compressional wave (P-wave), then transmitted wave, reflected wave, and mode conversion (P-S waves) with the curved wave fronts in layered anisotropic media, finally recorded by the receivers which are deployed on sea floor. In order to get the full waveform synthetics, the anisotropic wave equation technique has been used to study enigmatic behavior of Bottom Simulating Reflector (BSR) in marine sediments (Rajput et al., 2005, a and b). The detailed description of anisotropic modeling

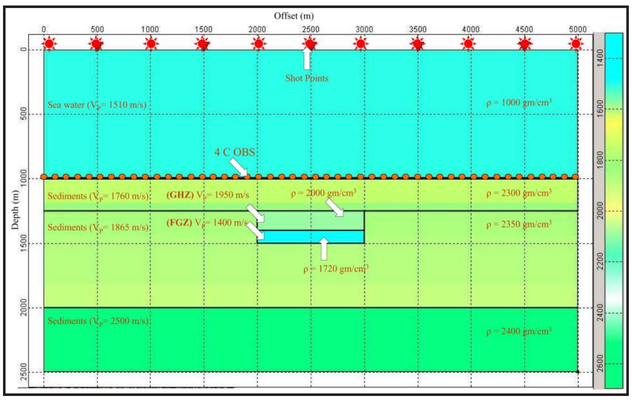

Fig.1: Key Model used for anisotropic simulations, Gas Hydrate Zone (GHZ) & Free Gas Zone (FGZ) are located at 1250-m and 1400-m depth respectively. 4C Ocean Bottom Seismometers are deployed on the ocean surface. 20 kHz shot are located at 10-meter depth.

technique by elastic wave equation is presented in Rajput et al. (2005, c). This technique is now applied for modeling 4-component (4C) reflection seismic survey. It is not easy to identify all the seismic reflections on profile even for a simple sea floor model. Generally for anisotropic multi-layered complex media the technique of elastic wave equation calculates the time-offset (X-T) for different kind of seismic reflections and these features in synthetics have to be interpreted.

In low frequency seismic prospecting the effect of quasi-anisotropy is one of the most common phenomena and is very important in understanding the geological configuration of the region. The sea floor model used here is listed in Table-1, which has a thick sea water layer, thinner and thicker sedimentary layers with variation in velocities, high velocity layer and sandwiched anomalous layers of gas hydrates and free gas deposits as a part of real model (Fig.1). The source is located at a depth of 10m below the sea surface with 20kz peak frequency. The hydrophones and three-component geophones are deployed at depth of 1000 meter on ocean bottom. The record length varies within 0.6-3.2 s. The positive (maximum amplitude in positive direction) and negative amplitude (maximum amplitude in negative direction) can be observed from the seismogram. Propagating wave front in time field of the first arrival of seismic wave for the complex anisotropic media can be visualized as snapshot during runtime of model.

Results and Discussion

Some assumptions have to be taken into account: that P-waves are mainly recorded by the hydrophone and vertical geophone (Z-component) and converted-waves are recorded by two horizontal geophones (X & Y components). It is also assumed that P-S conversions occur at the reflectors. These assumptions are valid for most of the cases (Caldwell, 1999). Following the converted mode geometry, the synthetic seismograms have been calculated for all the four components (X, Y, Z, and H) and will be elaborately discussed with wave equation technique during oral/poster presentation. In this article, the description of synthetic seismograms has been restricted only to hydrophone component and AVO analysis on PS-wave.

Hydrophone Recording

Converted ray geometry for the key model for a number of point sources located 10-meter depth in the sea water with different receivers deployed at ocean floor is calculated. Reflection recorded by the hydrophone component for the single point source located in the middle of the seismic profile above the seafloor is shown in Fig.-2. The strong direct wave, reflected waves from the sea bottom are clearly visible on the seismic section. By the order of the arrival time on the profile of seismic reflections with the obvious amplitudes are PPP, PPPPP, PPPPPPP, PPPPPPPPP, PPS, PPPSS, PPPPSSS, and PPPPPSSSS. The letter P and

S represent P-wave and shear-wave propagating in each layer respectively. PPP represents down-going P-wave in water, then down-going P-wave in layer-1, and then up-going P-wave recorded by receivers, which are placed at ocean bottom. Most of the reflections (e.g. PPS, PPPSS etc.) have component of shear wave ray paths, which are due to multi conversions at the reflectors except some of the reflections (e.g. PPP etc). Some of the seismic reflections are due to transmitted mode-conversion on the hydrate-gas interface. These reflections may have larger amplitudes than that of the P-wave path reflections from the other inter phases. These aspects should be paid more attention for seismic data processing and interpretations. Two sections (Fig.-2 a & b) from H components illustrate the synthetics shot gather calculated by wave equation technique. From dominant reflections and wave type numbers (PPP and PPS etc.) the reflection characteristics on the seismic section can be easily identified. Multi-converted diffractions with multiples are also identified. Fig.-2b show the processing of the wavelets which are propagating inside the earth structures; transmission of seismic energy inside the earth as well as in the sea water, diffracted wavelets while propagation through a typical acoustic impedance contrast zone and converted wavelets are easily identified and demarcated on the profile.

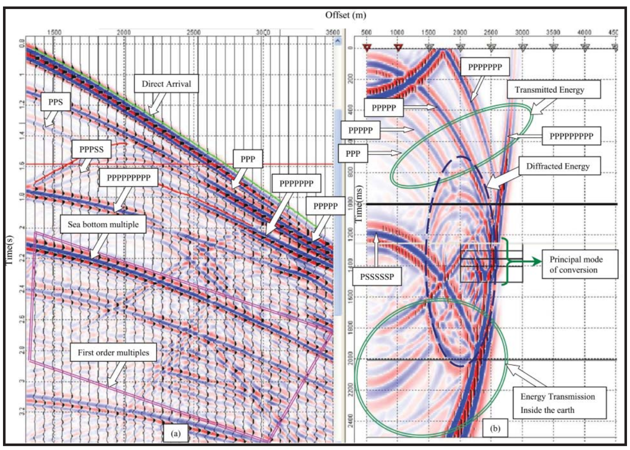

Fig.2: Hydraulic pressure (H component) recorded by hydrophone with some observed multiples and energy propagation inside the earth. (a); Pressure wave field including reflections with obvious amplitudes PPP, PPPPP, PPPPPPP, PPPPPPPPP, PPS, PPPSS, Green line indicates direct arrival and the red line indicates some reflected arrivals.

PS wave AVO analysis

Amplitude variation with offset is closely related to the energy partitioning. Impinging of seismic waves at a boundary experiences reflection and transmission and parts depends upon the angle of incidence. If the angle of incidence is not zero, P wave energy is partitioned further into reflected and transmitted P and S components. The amplitudes of the reflected and transmitted energy depend on the contrast in physical properties across the boundary. Compressional wave velocity (Vp), shear wave velocity (Vs) and density (ñ) are the important physical properties for determining the wave motion behavior. The reflection amplitudes depend on the angle-of-incidence of the incident ray. Therefore by knowing the amplitude of a reflector with angle of incidence/offset (AVO), the changes in physical properties of the rocks can be estimated and is described by the 'Zoeppritz equations', as well as with some higher level of approximations by Aki and Richard, (1979). Shuey (1985) simplifies the AVO Zoeppritz Equation by using the Aki and Richard approximation. The amplitudes at every time sample are plotted against the squared time of the angle of incidence. The intercept describes the normal-incidence P-reflectivity, while the slope is the gradient, which explains the behavior of amplitude with incidence angle. The PS ray path is asymmetric, usually with reflection point toward the receiver, so survey design must be altered to accommodate this peculiarity. Travel times are increased and AVO effects are important in PS recording. Amplitude changes are fit to a two term linear AVO approximation from which two attributes can be extracted. These two attributes describe the AVO character. AVO analysis provides high-resolution estimates of both the change in shear wave splitting and the fractional change in shear-wave velocity. The amplitude of the source waves as well as of the reflected wave from the hydrate boundary as marked on the seismic profile (Fig.3 a) is calculated and correlated with a sample length of 0.95. A graph of source wave amplitude verses incidence angle is plotted and proportion of decreasing the amplitude with increasing the incidence angle is observed and demarcated in Fig.-3b. The amplitude of the BSR shows its maximum value at the near offset, which observes a decrease on far offset data and illustrated in Fig.3c. The reflection coefficient of the simulating reflector is calculated and correlated with the reflected wave from the same reflector (Fig.3d), which varies from – 0.07 to -0.23 with a maximum correlation of 0.7.

Table 1: The model parameters

Layers	Velocities (m/s)	ρ (Density in gm/cm³)	Gradient
Water (Layer-1)	1510	1000	0
Sediments ((Layer-2)	1760	2300	0.4
Sediments (Layer-3)	1865	2350	0.4
Gas Hydrate (Layer-4)	1950	2000	0.4
Free Gas (Layer-5)	1400	1720	0.4
Sediments (Layer- 6)	2500	2400	0.4

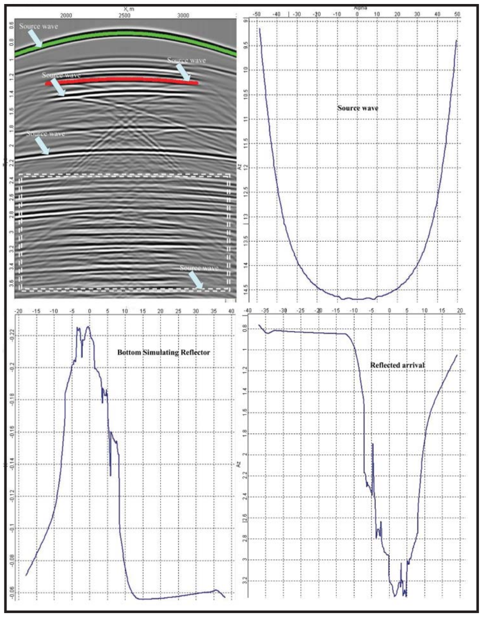

Fig.3: AVO response for the gas hydrate model. (a) Seismic source wave (green lines), reflected arrival from the BSR (red line) and multiples of the reflectors; (b) A graph of the amplitude of the source wave versed incidence angle; (c) Response of the amplitude of the reflected wave from the simulating reflector verses incidence angle; (d) Reflection coefficient of the BSR verses incidence angle.

Conclusion

Simulation of seismic reflections for 4C OBS data in anisotropic media with a vertical symmetry axis are carried out and some significant aspects of converted waves have examined. The seismic wave propagation in water layer could be simplified as scalar wave field but has to be treated as vector wave field in the sedimentary layer underneath. P-wave impressions occur with wide azimuth while in contrast PS wave effects occurs at near vertical propagations. The strong acoustic impedance contrast boundary where the BSR identifiable in the complex gas hydrate model (Fig.-4) is the principal conversion boundary between scalar field and the vector field. Even the pressure record shall include the effect of vector wave field in the sedimentary, which could be considerably diverse from that of scalar wave field.

The ocean bottom boundary may be treated as the natural shear-wave source in seismic prospecting. The reflection, received in water layer on the top of the sedimentary layer, has the attribute necessarily depending on the structure of the shear-wave velocity. The anisotropy with vertical symmetry axis induce the coupling wave motion on the incidence and transverse. The shear wave splitting could be dominant mark for identifying the existence anisotropy in the medium. If we are able to split the fast and

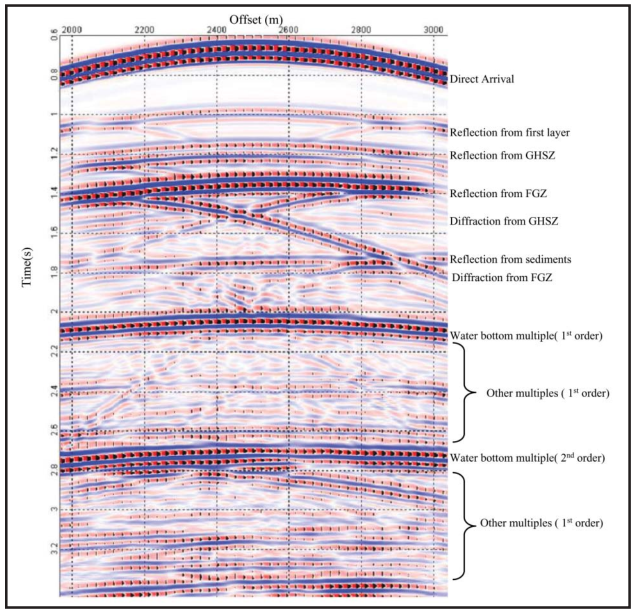

Fig.4: Vertical component synthetic section of a complex gas hydrate model, which includes multiple reflections including the motion of both compressional and converted wave above the half space.

slow shear-waves then the time delay can be predictable from the horizontal partial velocity component. Even if simple and isotropic layered structure could introduce multifaceted multiples, which usually predisposed by the shear wave velocity on the seismic sections. As the AVO phenomena translate the sharing of the energy of the incident compressional wave between the compressional and converted reflections so it's relationship can be measured from a theoretical or practical standpoint. AVO analysis generalizes converted-wave amplitude to include two important attributes (intercept and gradient) and consequently provide the high-resolution estimates of shear-wave bi-refringence and the fractional change in shear-wave velocity to aid interpretation and make the PS dimension more consistent. Synthetic developed and suggested here could be used for further study to develop the relationship between reflected, refracted, diffracted waves and multiples, phase change phenomenon, to recover the anisotropic parameters for PS waves, and to authenticate the technique of processing 4C OBS seismic data. The development of 4C ocean bottom technology resulted in acquiring high quality seismic data put and additional emphasis on the anisotropy. The velocity anisotropy of the PS ray trajectories is grater than that of compressional mode.

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