A physical modelling study of time-lapse AVO signatures

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ABSTRACT

Physical modeling can be used to validate the reflectivity predicted with different theoretical methods. We acquired a physical model experiment simulating a time lapse problem to investigate our theoretical results. The baseline survey has been modeled with plexiglass and PVC slabs resembling the cap rock and reservoir. The PVC slab has been replaced with a phenolic slab to resemble the monitor survey in which the reservoir had been gone under geological-geophysical changes during the time. Picked amplitudes from plexiglass-PVC and plexiglass-phenolic interfaces are corrected for geometrical spreading, emergence angle, free surface, transmission loss, and radiation patterns. The results for baseline survey, monitor survey, and their difference representing the difference data in time-lapse are analyzed. The linear and higher order approximations for difference data derived theoretically using perturbation theory and Zoeppritz equations were provided from the companion paper (Jabbari and Innanen 2012). These approximations are compared with the model data for validation. Results showed that the higher order approximations are more comparable with the model data which emphasize on including higher order terms for difference data calculations in time-lapse.

INTRODUCTION

Time-lapse monitoring facilitates management of a reservoir and extends the useful life of an oilfield. Comparison of repeated seismic surveys over months, years, or decades adds the fourth dimension calendar, time, to the seismic data (Greaves and Fulp, 1987; Lumley, 2001). Amplitude variation with offset (AVO) methods can be applied to analyze the changes from a baseline survey to monitor survey which indicates a none linear relationship between the pressure and saturation changes and P wave velocity change. Indeed, there is a highly non-linear relationship between P wave velocity change and the pressure change in a reservoir, demanding of providing higher order terms (Tura and Lumley, 1998; M. Landrø and Strønen, 1999; Landrø, 2001).

The perturbation theory is applied in time-lapse AVO method and a framework for linear and higher order terms is modeled to describe the difference data from a baseline survey to monitor survey in a reservoir (Jabbari and Innanen, 2012).

This study investigates the validation of the linear and higher order terms calculated for difference time lapse data which described in companion paper (Jabbari and Innanen, 2012), on a physical model. Physical modelling of geophysical data provides physical property distributions of the earth which are invariably simpler than the real Earth, and the degree of simplification depends upon the geometry used for the data acquisition. In 1D models, the physical property is assumed to be varied only in depth. In 2D models, they vary in depth and the direction parallel to a survey line. In 3D modeling, the physical property varies in all three directions. 3D seismic surveys resembling baseline and monitor surveys are modeled with The University of Calgary Seismic Physical Modelling Facility.

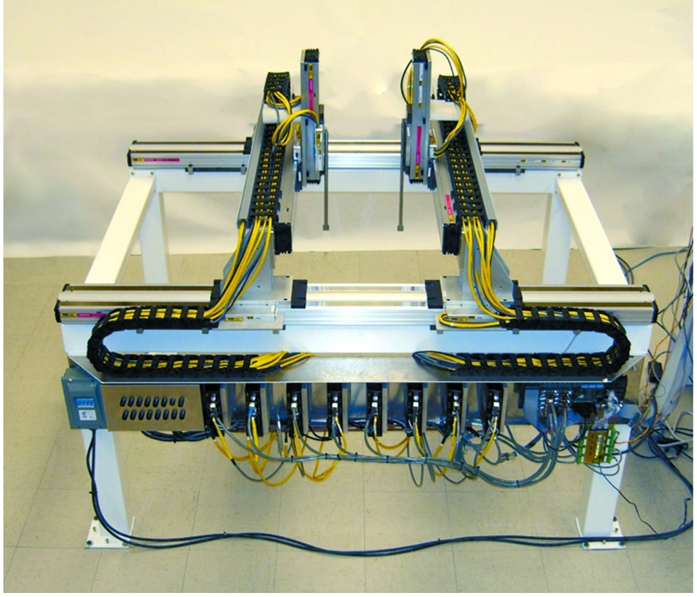

FIG. 1. The six-axes 3D positioning system (-/+ X is left/right, -/+ Y is towards/away, -/+ Z is up/down). Gantry A is to the left; Gantry B is to the right (J. Wong and Lawton, 2009)

DATA ACQUISITIONS

The University of Calgary Seismic Physical Modelling Facility has been used to conduct the experiment (Figure 1). Elastic wave were generated and detected by arrays of small transducers which were mounted on a Gantry. These transducers were moved with a six-axes positioning system using linear electric motors to accomplish a 2D seismic survey over a model with a volume of $1000 \times 800 \times 600 mm^3$ which is scaled up to a real-world survey with a volume of $10 \times 8 \times 6 km^3$. The model contains water and different material blocks resembling the Earth model. The acquisition software is running in Java on a MS Windows PC. V103 transducers were used as sources and detectors to emit and detect P wave. Common midpoint (CMP) gathers are recorded on SEG-Y files.

In this model the scale factor is 10^4. Each 1 mm in the physical model represents 10 m in the real world, and each 1 MHz in the physical model represents 100 Hz in the real world. Material velocities are unscaled.

Figure 2 shows the experimental setup for our measurements. Two seismic experiments which are involved in a time-lapse survey, the baseline survey, followed by a monitoring survey were modeled. Baseline survey was simulated as an plexiglass (acrylic) block on a PVC (Polyvinyl chloride) block both were immersed in the water. Another experiment was repeated with the same physical properties except the PVC block was replaced by a phenolic block to resemble the monitor survey. The plexiglass block is representing the cap rock and the PVC and phenolic are representing the reservoir in the baseline and monitor survey. The thickness of water, plexiglass, PVC, and Phenolic are 700, 500, 245, and 700 meters respectively. Several common-mid-point (CMP) reflection gathers were acquired for several offsets. The PP amplitudes were picked at plexiglass-PVC interface for baseline survey and plexiglass-phenolic interface for monitor survey. To avoid surface waves, the

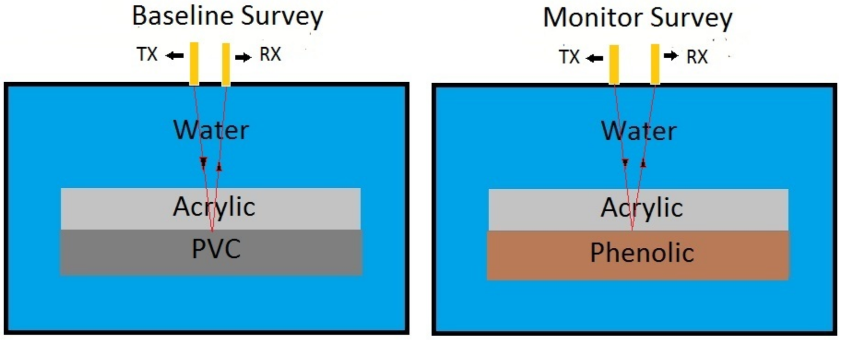

FIG. 2. Acquiring CMP data over an acrylic, PVC, and phenolic slabs for baseline and monitor surveys. Elastic incidence parameters; Acrylic (Plexiglass): $V_P = 2745m/s$, $V_S = 1380m/s$ and $\rho = 1.19gm/cc$; PVC: $V_P = 2370m/s$, $V_S = 1122m/s$ and $\rho = 1.13gm/cc$; Phenolic: $V_P = 3500m/s$, $V_S = 1700m/s$ and $\rho = 1.39gm/cc$.

measurement has been done in water.

Corrections

Prior to do any AVO analysis, amplitude information acquired by physical modeling must be corrected to compensate for various effects that can mask the AVO information. These effects can be geometrical spreading, transmission loss and overburden effect, multiple reflections, ground roll, source radiation pattern, and geophone response and can be accounted for (R. S. Spratt and Fitch, 2009; F. Mahmoudian and Wong, 2012). The reflected amplitude data were corrected for geometrical spreading, emergence angle, free surface, and transmission loss, applying the method explained in Mahmoudian et al. (2012).

Also source-receiver directivity correction due to the piezoelectric transducers used in the physical modeling were applied. The size of disc-shaped transducers causes an effect called directivity which should be corrected for the reflection amplitude. With a scale factor of 10^4, a transducer with 1 mm diameters mimics a source/receiver with 10 mm diameters in the real-world. Taking into account the dominant frequencies of 500 kHz, the transducers diameters to the wavelength are significant. As transducers are not acting as point sources/detectors, the radiation patterns in the far field, will have directivities due to wave interference (Wong and Mahmoudian, 2011; M. L. Buddensiek and Oncken, 2009). The correction for radiation patterns has been done using Mahmoudian and et al. (2012) method. Figure 4 shows the corrected CMP gather for one of our experiments, the monitor survey.

Difference data reflection coefficient in time lapse survey based on perturbation theory

The perturbation (scattering) theory can be used as a framework to model the difference data in a time lapse survey and first suggested by Zhang (2006). The baseline survey is set to be the background medium which goes under perturbation by the time of the monitor survey. The perturbation is presented here such that it quantifies the changes in P wave

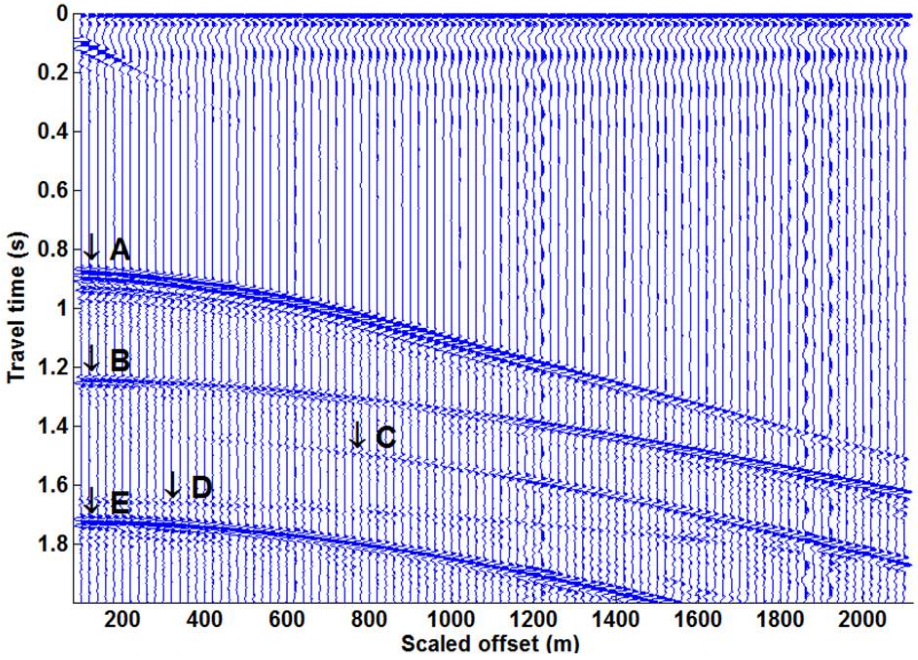

FIG. 3. CMP gather along isotropic plane direction with a long gate automatic gain control applied. In the display, event "A" is the PP reflection from the top of the plexiglas layer, event "B" is the PP reflection from the top of the fractured layer (our target), event "C" is the PS reflection from the top of the fractured layer, event "D" is the PP reflection from the bottom of the fractured layer, and event "E" is the PP reflection from the base layer.

and S wave velocities and density form the time of the baseline to monitor survey (Zhang, 2006; Innanen and Naghizadeh, 2010).

$$a_{VP} = 1 - \frac{V_{P_0}^2}{V_{P_{BL}}^2}, \;\; a_{VS} = 1 - \frac{V_{S_0}^2}{V_{S_{BL}}^2}, \;\; a_\rho = 1 - \frac{\rho_0}{\rho_{BL}}, \tag{1}$$

To account for the perturbation from baseline to monitor survey we define:

$$b_{VP} = 1 - \frac{V_{P_{BL}}^2}{V_{P_M}^2}, \;\; b_{VS} = 1 - \frac{V_{S_{BL}}^2}{V_{S_M}^2}, \;\; b_\rho = 1 - \frac{\rho_{BL}}{\rho_M}, \tag{2}$$

A framework formulated for linear and higher order approximation of difference reflection data from baseline to monitor survey in a time-lapse problem using amplitude variation with offset (Time-lapse AVO) analysis and perturbation theory described in a companion paper (Jabbari and Innanen, 2012). Reflection coefficients were derived for the baseline and monitor survey to calculate the reflection coefficient for difference data. The results were also presented in terms of relative changes:

$$\begin{aligned} \frac{\Delta V_P}{V_P} &= 2 \times \frac{V_{Pb} - V_{P0}}{V_{Pb} + V_{P0}} \\ \frac{\Delta V_S}{V_S} &= 2 \times \frac{V_{Sb} - V_{S0}}{V_{Sb} + V_{S0}} \\ \frac{\Delta \rho}{\rho} &= 2 \times \frac{\rho_b - \rho_0}{\rho_b + \rho_0} \end{aligned} \tag{3}$$

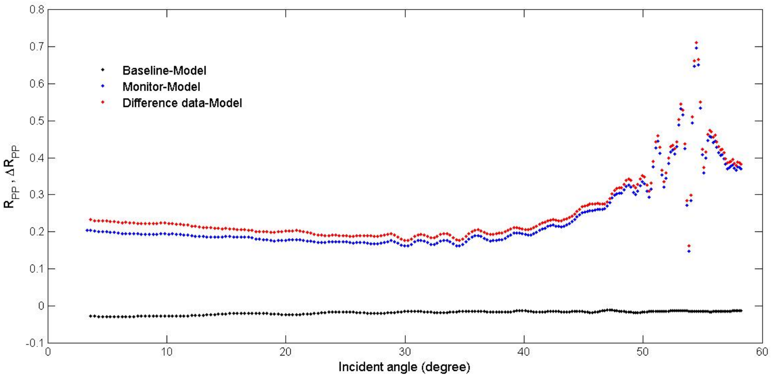

FIG. 4. $R_{PP}and\Delta R_{PP}$ for the baseline, monitor, and difference data for physical model. Elastic incidence parameters: $V_{P0} = 2745m/s$, $V_{S0} = 1380m/s$ and $\rho_0 = 1.19gm/cc$; Baseline parameters:$V_{P_{BL}} = 2370m/s$, $V_{S_{BL}} = 1122m/s$ and $\rho_{BL} = 1.13gm/cc$; Monitor parameters:$V_{P_M} = 3500m/s$, $V_{S_M} = 1700m/s$ and $\rho_M = 1.39gm/cc$.

for baseline perturbations and

$$\begin{aligned}\frac{\delta V_P}{V_P} =& 2 \times \frac{V_{Pm} - V_{Pb}}{V_{Pm} + V_{Pb}}\\ \frac{\delta V_S}{V_S} =& 2 \times \frac{V_{Sm} - V_{Sb}}{V_{Sm} + V_{Sb}}\\ \frac{\delta \rho}{\rho} =& 2 \times \frac{\rho_m - \rho_b}{\rho_m + \rho_b}\end{aligned} \tag{4}$$

for time-lapse perturbations.

The linear, second, and third order were calculated in terms of perturbation parameters and relative changes and can be found in more details in the reference (Jabbari and Innanen, 2012).

Comparison of the formulated linear and higher order approximation difference data with physical model results

Figure 5 shows the reflection data for the baseline survey, monitor survey and their difference provided from the data acquired by physical model and corrected for geometrical spreading, emergence angle, free surface, and transmission loss. These data are in agreement with the exact reflection data for baseline, monitor, and difference data calculated using Zoeppritz equations for angles smaller than critical angle. As it's seen in Fighure 5, the third order approximation is in a better agreement with the physical model data.

The linear, second order, and third order difference data are calculated using Equations (16), (17), and (27) by Jabbari and Innanen(2012). The linear and third order approximation derived from our results also compared with the model data from the physical experiment (Figure 5).

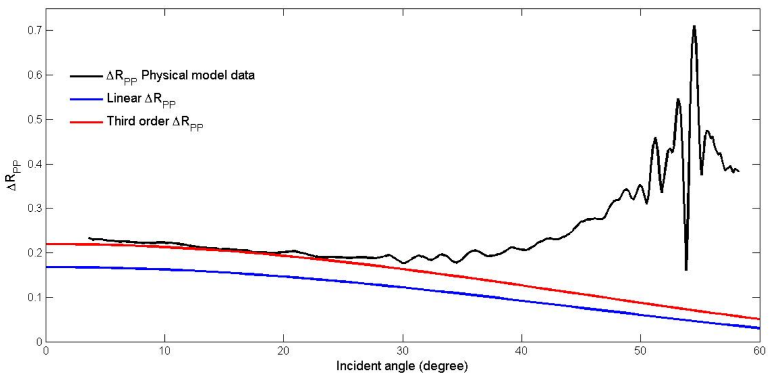

FIG. 5. ΔR_{PP} for the physical model, linear, and third order approximation. Elastic incidence parameters: $V_{P0} = 2745 m/s$, $V_{S0} = 1380 m/s$ and $\rho_0 = 1.19 gm/cc$; Baseline parameters:$V_{P_{BL}} = 2370 m/s$, $V_{S_{BL}} = 1122 m/s$ and $\rho_{BL} = 1.13 gm/cc$; Monitor parameters:$V_{P_M} = 3500 m/s$, $V_{S_M} = 1700 m/s$ and $\rho_M = 1.39 gm/cc$.

CONCLUSION

Changes in elastic parameters such as P wave, S wave, and density of the reservoir in a time lapse problem are caused by changes in geological-geophysical properties of a reservoir properties during the time due to production or applying enhanced oil recovery techniques (EOR). These changes from baseline survey to monitor survey, difference data, are derived for linear and higher order approximations in a companion paper (Jabbari and Innanen, 2012). Here, we applied a physical model experiment to validate our formulation. The comparison of the theoretical results for linear and higher order approximation with the physical model data showed that including higher order terms in approximating the difference data is definitely necessary.

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