Modeling of effective pressure effect on porous reservoir rocks

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Summary

Effective pressure effect on porous reservoir formation is one of the most important factors contributing to time-lapse seismic attribute changes. Our research shows that the existing commonly used models tend to overestimate effective pressure effect at high effective pressure, which might cause significant misinterpretation of 4D seismic data. Based on analysis of a large quantity of lab data, a new model that is simpler and has clearer physical meaning was brought up in this study. This new model should be sufficient to describe the effective pressure effect on various porous reservoir rocks.

Introduction

Effective pressure, also called differential pressure, is the difference between the confining pressure and pore pressure. Usually the confining pressure of a reservoir is assumed constant while the pore pressure will vary with reservoir productivity. In certain condition, the seismic attribute changes caused by differential pressure might be more significant than those caused by saturation change. So accurately modeling the effective pressure effect on seismic attribute changes of porous media is very important for 4D seismic modeling and interpretation.

Based on Han's (1986) data and study, Eberhart-Phillips (referred as E-P in this paper) et al, (1989) brought up a set of empirical formulas to predict pressure effect on velocities of dry or wet rocks. Shapiro (2003) summarized these empirical formulas as

$$V = A + KP - B\exp(-PD) \qquad (1)$$

Where P is the effective pressure, A, K, B and D are fitting parameters for a given set of measurements. In his paper, he theoretically proved that equation (1) is the correct form to predict effective pressure effect on velocities. But most of his derivation steps are based on assumption or approximation which might not stand in real conditions and too many approximations might lead to uncontrollable error propagation.

Vernick and Hamman (2009) treat equation (1) as a theoretically based model and rearrange equation (1) in a different form to give physical interpretation of the fitting parameters. They noticed that there are strong correlations between certain fitting parameters, which basically mean that equation (1) used more fitting parameters than necessary.

Compared with our new model to be brought up in this study, Figure 1 shows the typical performance of E-P and Shapiro model. This model fits the data fairly well in the measured data range, but when it is extrapolated from both data ends, it begins to be out of trend with the measured data. At high pressure, it predicts that the velocity has a linear relationship with the pressure because the exponential pressure term in equation (1) becomes negligible. From observation of large quantity of lab data we think this linear relation is problematic. If we separate the total porosity into two parts: compliant porosity and stiff porosity, with increasing differential pressure the compliant porosity will gradually decreases and completely closes up by effective pressure of about a few hundred MPa (Shapiro, 2003). The stiff porosity will also stop decreasing. Therefore with increasing pressure, the rock will become almost incompressible and thus the velocity will stop increasing.

From observation of lab measured data, for some rocks samples, the velocity increase is almost unnoticeable at differential pressure higher than 40 MPa. Thus using the E-P and Shapiro model might cause significant error in 4D time seismic modeling and interpretation.

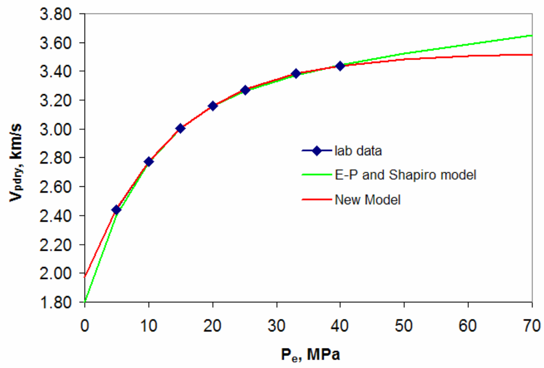

Figure 1: Typical difference between the E-P and Shapiro model and the new model

Establish of the new model

As discussed above, instead of assumption of linear relation between effective pressure and velocity at high effective pressure, from observance of lab data we believe the effective pressure will gradually have less effect on rock velocities with increasing effective pressure, and finally the velocities will stop increasing with increasing effective pressure. We denote these limitation velocities as $V_{P\infty}$ and $V_{S\infty}$ respectively for dry P-wave and shear wave velocities. At effective pressure $P_e = 0$, all the compliant pore spaces are open and the stiff pore spaces are at maximum volume, thus the corresponding velocities are at minimum values and are denoted as V_{P0} and V_{S0} for dry P-wave and shear wave respectively. After regression analysis of a large quantity of lab data, we propose the following formulas to model the effective pressure effect on dry velocities of porous rock:

$$V_P = V_{P\infty}\left(1 - c_P \cdot \exp\left(-\frac{P_e}{b_P}\right)\right) \tag{2}$$

$$V_S = V_{S\infty}\left(1 - c_S \cdot \exp\left(-\frac{P_e}{b_S}\right)\right) \tag{3}$$

where c_P and c_S are maximum relative velocity changes that can be expressed by:

$$c_P = \frac{V_{P\infty} - V_{P0}}{V_{P\infty}}, \qquad c_S = \frac{V_{S\infty} - V_{S0}}{V_{S\infty}} \tag{4}$$

b_P and b_S are shape factors determining the pattern of velocity change for P-wave and S-wave velocity respectively(Figure 2). Our study shows that b_P and b_S have good correlation and are distributed in a narrow range (10 to 20) for most of the reservoir rocks.

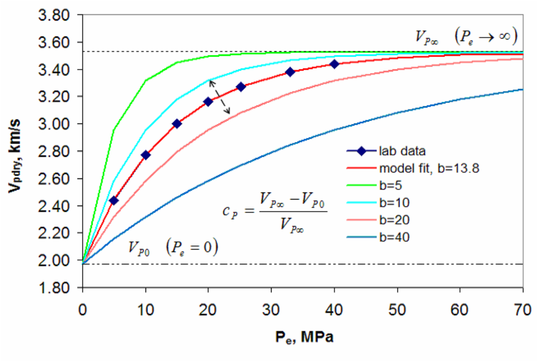

Figure 2: Schematic interpretation of the new model using one rock sample data.

Compared to the E-P and Shapiro model, our new model is simpler with one less fitting coefficients. One big advantage of our model is that an explicit expression of P_e as function of velocity can be derived, which is impossible for the old model. This is important because as Yan and Han's study (2007) shown that the time lapse seismic changes can be linearly decomposed into the changes caused by dry rock and fluid separately. If we know the saturation, it is possible to directly estimate pore pressure by inversion of time lapse seismic data.

Performance of the new model

We have applied the new model to 69 samples from Han's data (1986) and 42 samples from a North Sea gas field data recently measured by our lab. All the velocities in this paper are dry rock velocities, although our model might also apply to wet rock velocities. Figure 3 shows the dry P-wave velocity modeling of Han's data. Han's data represents a wide a variation of different porous rocks. From the figure we can see that the velocity change trend with differential is quite different for different groups of rocks, but our model can have good match with almost all the samples. 94% percent of the samples with regression coefficient R^2 is higher than 0.98. The match is similar for dry shear wave velocities. For the recently measured North Sea gas field, the matches for both V_p and Vs are almost perfect, the regression coefficient R^2 is higher than 0.99 for all the samples. Thus the new model should be sufficient to describe the effective pressure effect on dry rock velocities of various porous reservoir rocks.

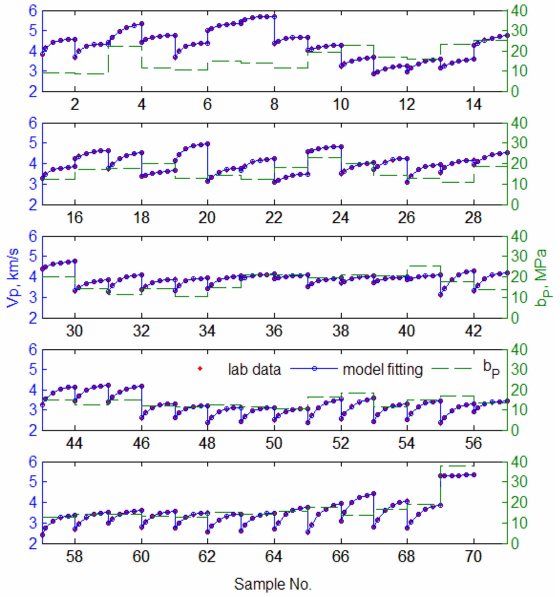

Figure 3: Dry rock P-wave velocity modeling using equation (2) (Han's data, 1986)

Shape factor *b*

Shape factor determines the pattern of velocity approaching limitation velocity with increasing effective pressure. It is controlled by deposition environment and digenesis of individual rocks. The complicated geological factors, like sorting, cementation, and how clay is distributed in the rock matrix and et cetera, are difficult to be represented parametrically. We believe the proportion of soft pores are an important factor: the higher the proportion of soft pores, the bigger is the shape factor, which means the velocity change more slowly with increasing effective pressure.

Most of the pure sandstone samples in Han’s data (1986) have *b* value around 10. The shaly sandstone tends to have higher *b* value if cementation is not very good. Unfortunately we don’t have detailed geological information regarding individual rock to make definite interpretation. But from our analysis of a large number of rock samples we found that the shape factor for porous reservoir rock are usually lied in a narrow range of values from 10 to 20 (Figure 4). For rock samples with b value far away from this range, they are usually not from economical petroleum-bearing formation, and rock samples from same area tend to have similar shape factor values.

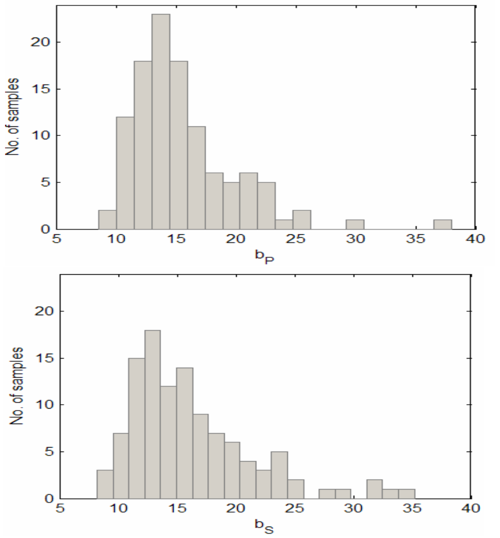

Figure 4: Distribution of shape factor b_P and b_S

Maximum velocity

Maximum velocity is the limitation velocity when porous rock is almost incompressible and the effective pressure has no effect on rock velocity. The maximum velocities for each rock sample can be estimated by modeling the lab data with equation (2) and (3). Han (1986) proposed empirical relationships between velocity, porosity and clay content and found that the relationships improve with increasing effective pressure. As shown in Figure 5, our modeling results agree and further verified this conclusion. Using same porosity data measured at lowest pressure, the maximum velocities have much better correlation with porosity and clay content. One possible explanation is that with increasing effective pressure, larger portion of clay take burden of the stress and thus is more related to rock velocities. So it is advantageous to use the maximum velocities as fitting coefficients and heterogeneity can be included by substituting the improved velocity, porosity and clay content relations into equation (2) and (3).

Figure 6 is used for clarification that reaching of limitation velocities does not mean that the Voigt bonds are reached. Voigt bond is an ideal state that rarely reached by real reservoir rocks. Poor sorting and clay content make it more difficult to reach Voigt bound, while cementation makes it closer.

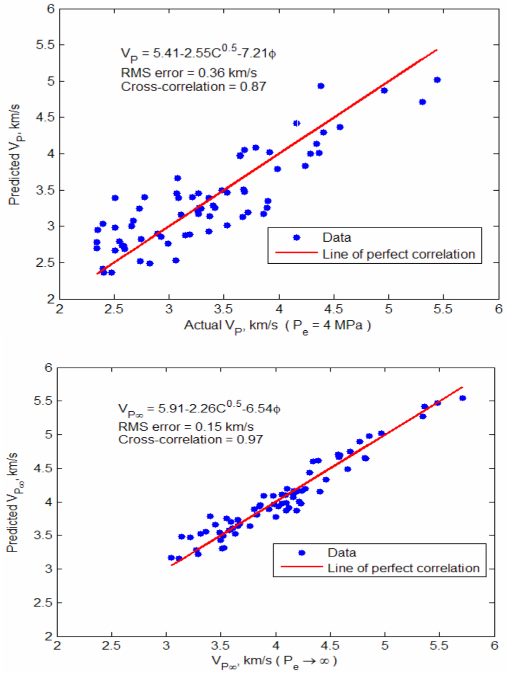

Figure 5: Effective pressure effect on relationship between velocity, porosity and clay content

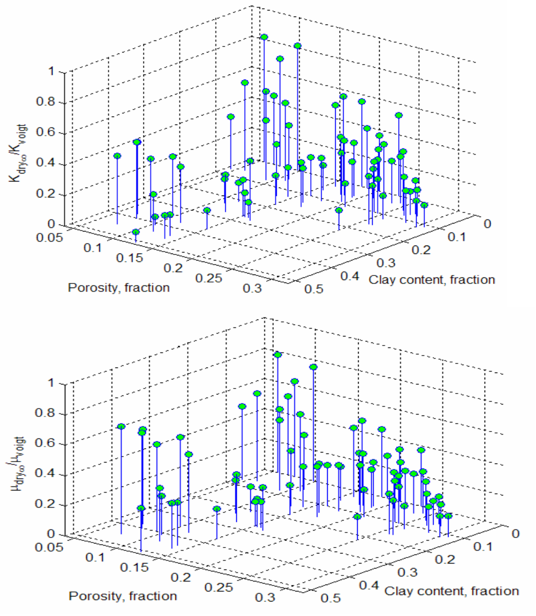

Figure 6: Maximum moduli and Voigt bounds

Maximum relative velocity change

Maximum relative velocity changes (c_P for P-wave and c_S for S-wave) are defined by equation (4). They are indicators of significance of effective pressure effect. We found that c_P and c_S are closely related to the "hardness" of the individual rock under zero effective pressure.

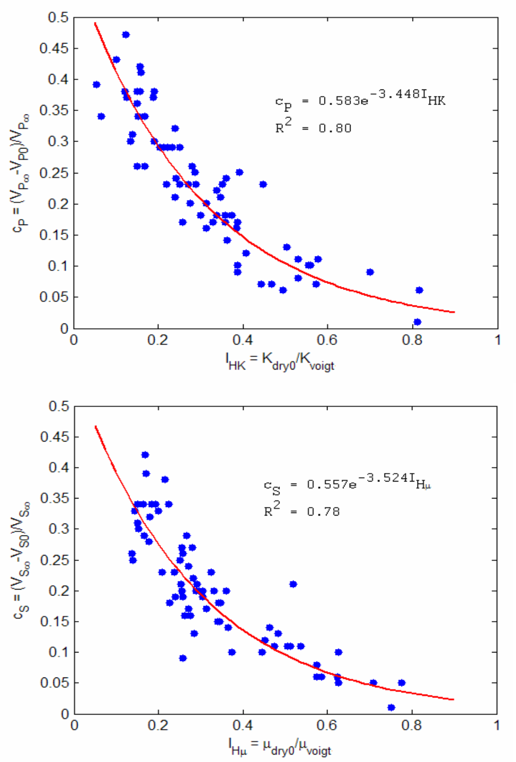

Figure 7: Relation between maximum relative velocity change and hardness of the rock

If we define the "compressive hardness" and "shear hardness" of porous rock of certain composition respectively as:

$$I_{HK} = \frac{K_{dry0}}{K_{voigt}}, \qquad I_{H\mu} = \frac{\mu_{dry0}}{\mu_{voigt}} \tag{5}$$

Where K_{dry0} and μ_{dry0} are bulk modulus and shear modulus when effective pressure is zero. They are calculated from the modeling results by application of our new model to Han's data (1986). K_{voigt} and μ_{voigt} are the Voigt bounds calculated by using porosity data measured at lowest effect pressure and assuming bulk modulus and shear modulus of quartz are 37 GPa and 44 GPa respectively, and bulk modulus and shear modulus of clay are 25 GPa and 9 GPa respectively for all the rock samples.

As shown in Figure 7, the maximum relative velocity changes have good correlation with the "hardness" of rock of certain composition at zero differential pressure. These relationships might be improved with more information of mineral composition and their moduli of individual rock samples. The results agree very well with our common sense that the softer is the rock, and more compressible is it and thus more significant is the effective pressure effect. The hardness indexes we defined are very useful parameters to predict maximum effective pressure effect if we know the composition of the rock and the velocities measured at low effective pressure.

Conclusions

Compared to the commonly used E-P and Shapiro model (equation (1)), our new model is simpler with one less fitting coefficient, and clearer physical meaning of the fitting coefficients as discussed above. Also, our new model has better performance in fitting the data and predicting the velocity trend beyond measured data range. The E-P and Shapiro model was first brought up as an empirical formula and it should not be treated as a theoretically based model. Detailed analyzing of the three fitting parameters (shape factor, maximum velocity and maximum relative velocity change) of the new model gives us more insights to understand effective pressure effect and predict effective pressure effect on reservoir rocks when routine lab measurement data are not available.

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EDITED REFERENCES

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