Elastic modeling of seismic wave propagation in partially saturated rocks

James Deeks
CPGCO2
The University of Western Australia
M004, 35 Stirling Hwy
Crawley WA 6009
Australia
deeksj01@student.uwa.edu.au

David Lumley
CPGCO2
The University of Western Australia
M004, 35 Stirling Hwy
Crawley WA 6009
Australia
david.lumley@uwa.edu.au

SUMMARY

The effect of single-phase fluid saturation on a rock's bulk modulus is well understood using Gassmann's equation. However when multiple fluids are involved the behaviour is not as well understood. Several fluid mixing averages have been suggested (Voigt, Reuss, Hill), and each apply in certain situations, however it is often not clear which model to select in a specific scenario and in some scenarios none of the models are accurate. The critical factor in deciding which average to use depends on the way the fluids are spatially distributed within the rock. We have applied elastic finite difference computational modelling to many different fluid distribution scenarios and have replicated behaviour described by various theoretical, empirical and lab data results, as well as generating results that span the space between these models. Importantly, our results compare well with observations in lab experiments, without relying on poroelastic or squirt-flow models which require parameters that are difficult to estimate for real reservoirs. Our elastic scattering approach is less computationally expensive than poroelastic modelling and can be more easily applied to actual reservoir rock and fluid distributions. Our results provide us with a powerful new method to analyse and predict the effects of multiple fluids and 'patchy' saturation on saturated rock bulk moduli and velocity. They also challenge traditional assumptions about the controlling factors on saturated bulk moduli suggesting it is more dominantly affected by the spatial fluid distribution properties rather than pore-scale fluid flow effects.

Key words: partial saturation, elastic modelling, patchy.

INTRODUCTION

Characterizing seismic velocities in reservoirs with heterogeneous ('patchy') fluid distributions is difficult and the effect of changing saturation is not well understood. The effects of patchy saturation can be a significant issue when encountered during reservoir monitoring or exploration, because not knowing the velocity – saturation relationship can potentially lead to false assumptions about the contents of the reservoir.

Gassmann (1951) developed an equation describing the seismic velocity of a rock saturated with a single fluid. Reuss (1929) and Voigt (1910) averages have been used (White 1975) to define bounds on the relationship and the Reuss average has been thought to apply to most low frequency seismic, cases. Domenico (1976) was the first to suggest that the heterogeneity of the fluid distribution in a rock might affect its seismic velocity and suggested the Voigt average effective fluid. Mavko and Mukerji (1998) suggested the Hill (1963) average could apply to saturation patches for sufficiently low frequencies; this is known as the patchy curve. Velocity trends at higher frequencies have been observed to transition between bounds and sometimes follow the upper bounds (Lebedev, et al. 2009, Mavko and Mukerji 1998). These examples highlight the uncertainty involved in characterising and predicting the velocity-saturation trend for a given scenario. Various authors (Akbar, et al. 1994, Mavko and Mukerji 1998, White 1975) have suggested critical heterogeneity scales based on pore scale flow. They suggest this patch scale is the critical factor in determining whether the velocities tend to follow the patchy bound or the lower (uniform) bound. Some authors have discussed possible intermediate curves to span the space (e.g. Brie, et al. (1995)), but they have not had great success as they are empirical, qualitative and thus have limited predictive capability.

At higher frequencies faster velocities are observed (Cadoret, et al. 1995) including velocities above the patchy bound at low gas saturations (Mavko and Mukerji 1998). These velocities are attributed to Biot (1956) and squirt dispersion (O'Connell and Budiansky 1977); mechanisms that involve wave-coupled fluid flow at the pore scale. However, we show that these effects can be explained by complex elastic wave multi-pathing.

Recent simulations have focused on poroelastic models. These models include pore fluid flow which makes them more computationally expensive and has limited them to smaller, less complex scenarios. The parameters for poroelastic flow (such as pore-space tortuosity,) are often difficult to obtain in practice, which limits the usefulness of this type of modelling.

In this project we modelled heterogeneous spatial fluid distributions using elastic models with no pore fluid flow to determine the extent to which this type of modelling can accurately reproduce experimentally observed behaviour. We have modelled plane waves with three different frequencies to examine the interaction between the fluid heterogeneity and wavelength spatial scales.

During the project we found that elastic modelling was able qualitatively reproduce the expected behaviour, without the need to include pore fluid flow effects. We also found that to fully describe the range of behaviour observed experimentally, in addition to saturation, frequency and patch size we required a new parameter to describe the smoothness of the patches.

We found elastic modelling is sufficient to model the effect of partial fluid saturation, but it requires two parameters to describe the heterogeneity of the fluid distribution. The two parameters are the scale of the heterogeneity, (i.e. the patch size,) and the scale of the smoothness (a measure of the amount of mixing).

INITIAL MODELLING RESULTS

The initial modelling process consisted of generating two dimensional velocity and density maps of a rock cross-section, simulating the propagation of an elastic plane wave using a finite difference approximation and calculating the travel times from the output signal. Binary maps of the cross-section were generated with every point being either water or gas saturated. The points formed patches saturated with each type of fluid and a known average radius. Properties were then assigned to each point from a distribution based on whether it was water or gas saturated. P-wave velocity, S-wave velocity and density models were then calculated based on these maps, using Gassmann's equation. An example of a P-wave velocity model is shown in Figure 1, the red regions are gas saturated and the blue regions are water saturated. We then computationally simulated the propagation of a plane wave through these models using the finite difference approximation. The output traces along the central 80% of the model were stacked to simulate the lab experiment and avoid edge effects, and the arrival times were picked from these traces.

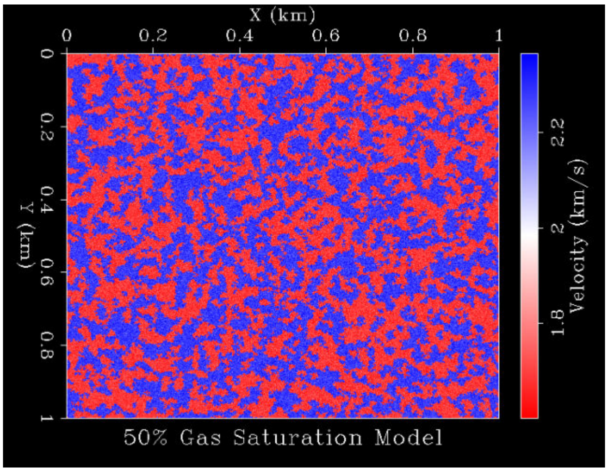

Figure 1. One of the velocity models used in the initial modelling. This model represents a cross-section of a reservoir rock 50% gas saturated and 50% water saturated.

From these arrival times the velocities were calculated and the results are shown in Figure 2. The top curve is the Voigt bound, the bottom curve is the Reuss bound and the middle curve is the patchy curve. The three different symbols represent the three different frequencies of the plane waves that were modelled. The results from this set of models are the dark blue points labelled as '0 –' on the legend. The decreasing frequency did decrease the velocities from the Voigt bound to the patchy bound, but they did not drop below the patchy bound, no matter how low the frequency. These models are very discrete so to try and extend the behaviour to simulate further mixing of the fluids we smoothed the saturation models.

FLUID MIXING RESULTS

We smoothed the models over three different scales, one where the smoothing scale was smaller than the average patch size, one where it was slightly larger and one where it was much larger. Two of the smoothed 50% gas saturation maps are shown in Figure 3 and Figure 4 with the red regions gas saturated and the blue regions water saturated. The model in Figure 3 is smoothed over a scale smaller than the patch size and the model in Figure 4 is smoothed over a scale significantly larger than the patches. For each of these models the properties and velocities were calculated at each point, at points with partial saturations the fluid bulk modulus was calculated as a harmonic average and the density as an arithmetic average. We simulated plane wave propagation through the velocity and density models for these three new distributions and picked the arrival times.

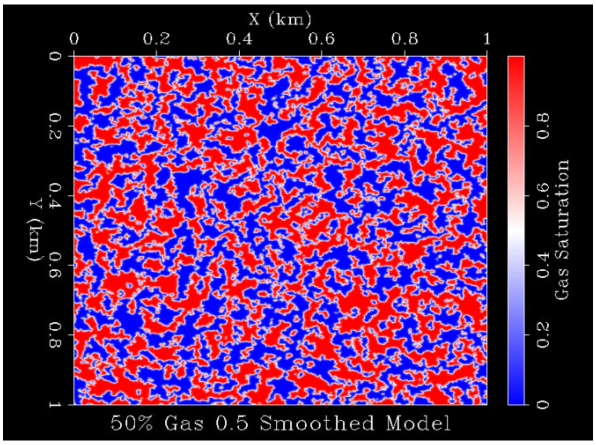

Figure 3. A smoothed version of 50% gas saturation map with the smoothing range smaller than the patch size.

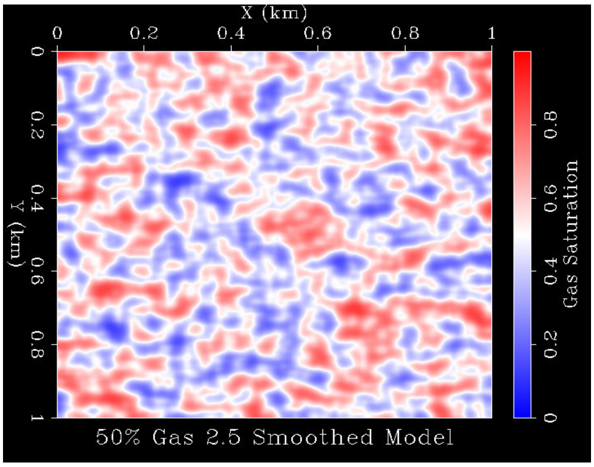

Figure 4. A smoothed version of 50% gas saturation map with the smoothing range significantly larger than the patch size.

These results are also shown in Figure 2 with the colours progressing from blue to red represent increasing amounts of smoothing. In the legend the first number for each series is the half width of the smoothing triangle and the second number is the frequency of the input plane wave. The arrivals were picked when the signals reached 0.2% of the maximum amplitude and these arrivals were calibrated using the 0% and 100% gas saturated models. The results from the smoothed models quickly dropped below the patchy bound.

ANALYSIS

The first observation we made is that regardless of whether the distribution of fluids is 'patchy' or not, if the fluids are modelled as a set of discrete, 100% gas saturated and 100% water saturated points then the velocity never drops below the patchy curve. Decreasing the frequency of the input wave for these models moved the velocity from the Voigt bound down toward the patchy curve.

By implementing increased amounts of smoothing we generated three sets of data points for each frequency that seem to describe curves that move towards the Reuss bound. Changing the wave frequency still had an effect on the smoothed models, but the magnitude of the effect decreased as the smoothing range increased. This behaviour is consistent with an increasingly smoothed model limiting to a constant model in which frequency would have no effect.

By varying the two ratios of wavelength to patch size and smoothing scale to patch size we could generate velocity-saturation curves that span the space between the Voigt and Reusss curves. This suggests method we have developed could be used to predict the velocity-saturation curve for any reservoir (containing a heterogeneous fluid mixture) based on its smoothing scale and input wavelength as a fraction of the average fluid patch size.

CONCLUSIONS

Previous modelling of patchy saturation has concentrated on full poroelastic modelling. However by using elastic scattering modelling we were able to reproduce the Voigt and patchy curves by varying the ratio of the input wavelength to the discrete fluid patch sizes. Using smooth fluid saturation models to model mixing we were able to produce a family of curves that trend from the Voigt bound towards the Reuss bound. This suggests that pure elastic scattering (not poroelastic squirt flow) is the dominant cause of the behaviour observed in laboratory experiments.

We also found the discreteness or smoothness of the fluid patches was a critical factor in determining the measured velocity; this is a result that we have not yet seen discussed in the literature. It suggests the extent to which two fluids mix in a patchy distribution is a very important factor in determining seismic velocities, with the smoothing scale measured as a fraction of the patch size.

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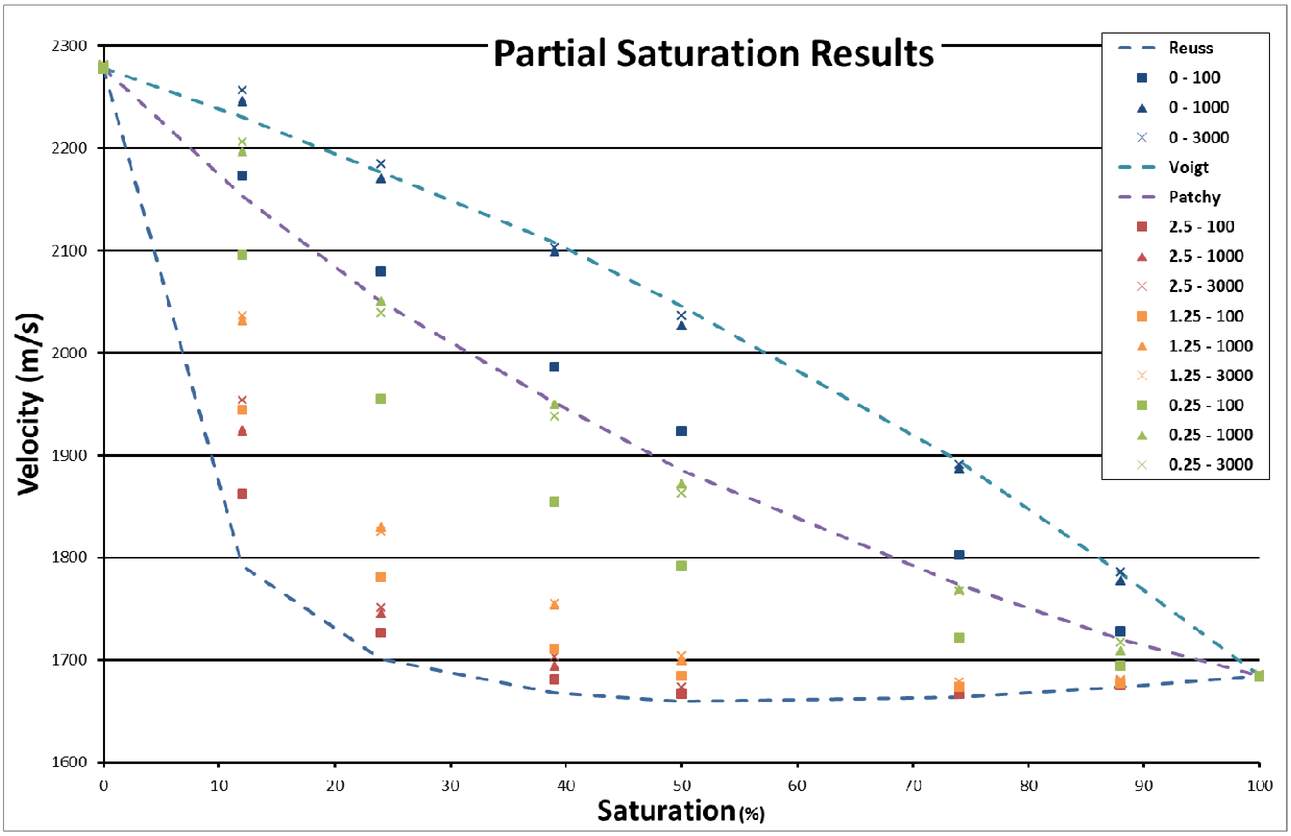

Figure 2. The velocities measured in this study. The first number for each series in the legend describes the amount of smoothing that was applied to the velocity model; the second number is the central frequency of the input plane wave. The dashed lines are the three theoretical bounds.