A Rock Mass Approach to Assess Hydro-Mechanical Deformation in Tight Rock Reservoirs

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Summary

Natural fracture systems are ubiquitous in unconventional reservoirs and are inferred through direct core observations, microseismicity, rate transient analysis and outcrop observations. Furthermore, well production often does not match lab permeability results suggesting the need to invoke another permeability source such as natural fracture systems (Gale et al., 2014).

Naturally fractured tight reservoirs can be conceptualised as a group of blocks that interact with each other forming a rock mass. When fluid is injected into the rock block system, the pressure rises in the fractures and causes the rock mass to deform in two ways, either through the opening of the cracks or slip along the natural fractures and bedding planes. Many observations of rock block systems have been made in mines and tunnels which have led to the geological strength index classification scheme (Hoek and Brown, 1997). This classification scheme is simple and aims to identify poor or good strength rock block systems. An effective rock mass Biot's coefficient is derived from published empirical relationships in order to predict the fluid connectivity within the reservoir under various in-situ fluid pressure conditions. The fluid connectivity derived from the empirical relationships is then tested in an anisotropic framework using distinct element modelling for various cases of intact rock stiffness and geological strength index values. The results demonstrate that a highly fractured rock mass leads to more opening in the rock. Also, if the rock blocks are stiff, fluid is distributed evenly through the rock. Perhaps counter-intuitively, by injecting fluid into the rock mass, the matrix becomes stronger due to the confining stress on the matrix blocks from fluid pressure loading. Also, as the fluid pressures rises, the stresses become hydrostatic as a result of a loss in shear stress on natural fractures within the rock mass. By approaching the problem from a rock mass classification framework, an understanding of when the rock mass system undergoes active deformation has implications for treatment design and hydro-mechanical behaviour during stimulation.

Method

In the poro-elastic framework, introduced by Biot, (1941), the Biot effective stress coefficient for intact rock matrix describes how fluid pressure within the pore space of the matrix, counteracts total stresses, to create an effective stress condition. Using empirical relationships derived in the mining industry, a rock mass equivalent Biot's coefficient is derived which predicts how the natural fracture system behaves in a system with orthotropic anisotropy.

The empirical relationship is then tested through numerical simulation under a variety of effective stress conditions. A bilateral constraint boundary condition is applied where the rock cannot expand in all directions, thus representing a case in the centre of a hydraulic fracture stimulated volume.

Delaney et al., (1986) describe a ratio, R, between driving stress and mean stress to express the ability for joint and dikes to open in rock

$$R = \frac{P_f - \dfrac{\sigma_{11} + \sigma_{33}}{2}}{\dfrac{\sigma_{11} - \sigma_{33}}{2}}$$

Sanderson and Zhang, (2004) performed two dimensional numerical modelling and demonstrated that at a critical R value, fluid flow will localize into a connected flow plane. This generally occurs between a value of -2 and -1 depending on the rock mass properties.

Results

Figure 1 illustrates the stress perturbations after pressurisation and subsequent pressure draw down back to 10 kPa/m. It is observed that after stimulation, stresses change in both magnitudes and orientations with principal stresses reorienting orthogonal to surfaces that experience a drop in shear stress. Principal stress magnitudes also change as slip along natural fractures cause a redistribution of the stress field. Stresses also concentrate at the edges of matrix block and become uniform in the block centre. In heterogeneous rock, the stiff layers carry most of the stress and lead to larger stress contrast between subsequent beds.
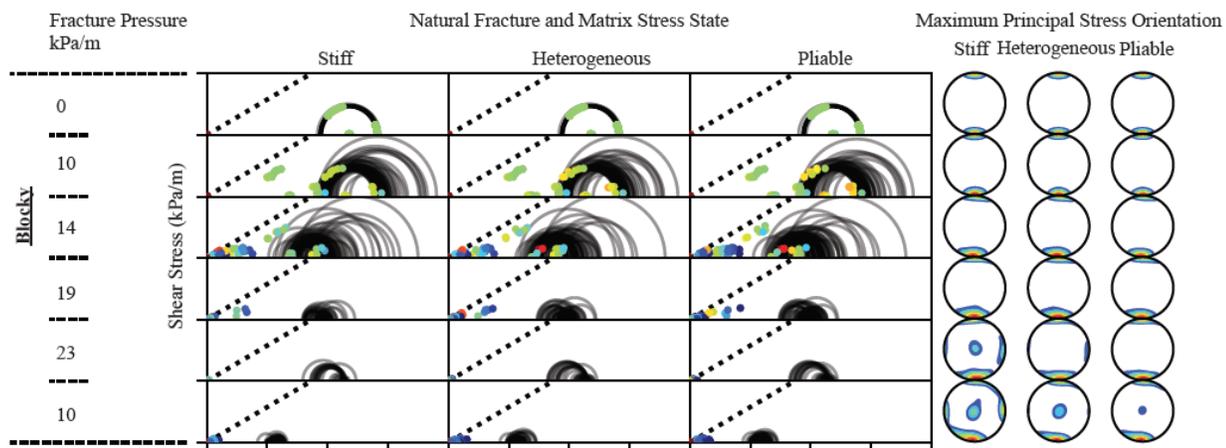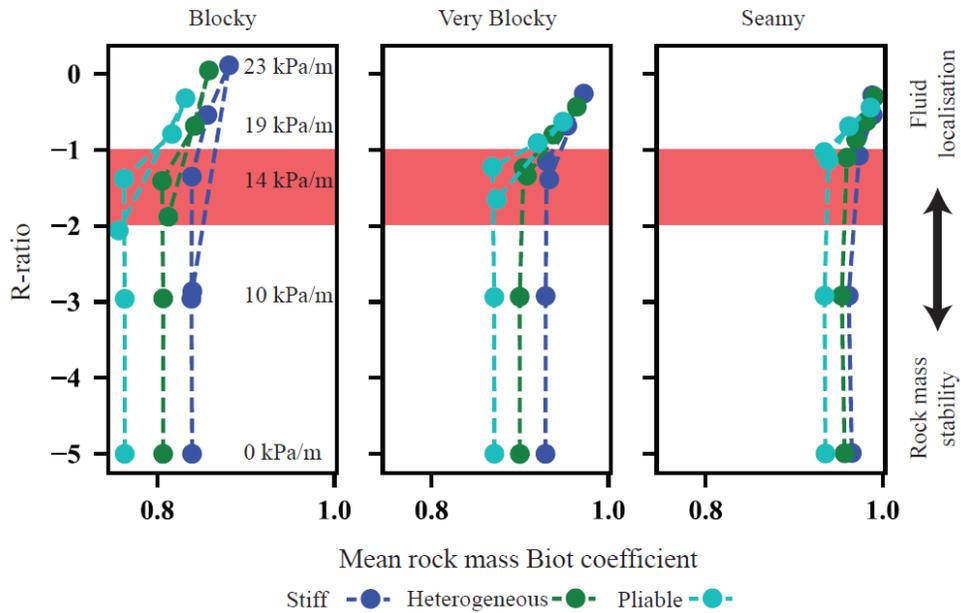

Figure 2 illustrates that when R is increased above -1 the rock mass Biot value begins to increase from the background value. At these elevated pressures, fluid concentrates into discrete flow channels, whereas at lower values, diffuse shear failure occurs throughout the rock mass.

Figure axes: Blocky, Very Blocky, Seamy (top labels). Y-axis: R-ratio. X-axis: Mean rock mass Biot coefficient. Legend: Stiff, Heterogeneous, Pliable. Fluid localisation / Rock mass stability. Pressure gradient labels: 23 kPa/m, 19 kPa/m, 14 kPa/m, 10 kPa/m, 0 kPa/m.

Conclusions

This study utilises the geologic strength index to classify different numerically modelled rock mass cases. Nine modelled cases were studied by varying the fracture density and matrix stiffness. Through modelling each case an understanding of how the rock mass behaves to changes in fluid pressure is observed at the sub-meter scale. This approach allows for up scaling of the rock mass parameters to predict larger scale reservoir behaviour during and after injection. A theory to predict a rock mass Biot's coefficient is derived which relates the deformability of the rock mass to creation and slip on natural fractures. The change in the rock mass Biot parameter infers an enhancement of permeability. Finally, through the use of constitutive relations, rock mass failure states are predicted and related to the observed increase in the rock mass Biot coefficient value. The primary conclusions drawn from this study are:

- The dynamic nature of hydro-mechanical interaction can be quantified through a rock mass characterisation approach. In this method, the natural fractures and the intact rock properties are quantified to characterise the rock mass continuum.
- Intact properties play a role in how deformation and fluid is distributed throughout the rock mass. A stiff rock mass distributes fluid more evenly, whereas a pliable matrix creates localised fluid pockets. A heterogeneous rock mass further segments fluid flow as stiff bed have smaller hydraulic apertures and greater stresses than the pliable beds.
- Rock mass exploration techniques can be used to quantify and target desirable rock mass conditions for ultimate recovery in fractured tight reservoirs.
- Different rock mass condition may have different optimal stimulation strategies. Stimulating the rock mass to achieve compressional mobilisation and extensional condition may allow for effective placement of proppant and maximising a self propping behaviour in the reservoir.
- The stress field does not stay consistent through the injection cycle, but the mean and deviatoric stresses exhibit an evolution depending on fluid pressure, matrix stiffness and fracture density. During pressurisation of the rock mass, increasing fluid connections lead to reduced shear stresses. When viewed in light of Mohr's circle analysis, a smaller circle is observed at greater fluid pressures. This results in a loss of deviatoric stresses as fluid planes become connected which are not able to support shear stresses.

Novel/Additive Information

This study presents a way to upscale natural fracture observations for quantitative use in reservoir simulators. It also suggests that there is a critical treating pressure window which will contribute to large-scale stress redistribution and permeability enhancement. Above this injection pressure, fluid tends to localize in discrete fracture planes, thus limiting stimulated reservoir volumes.

Acknowledgements

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