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Coal failure during primary and enhanced coalbed methane production — Theory and approximate analyses

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ABSTRACT

This paper presents a study on reservoir-scale failure in coal seams during primary and enhanced coalbed methane production. Two sets of formulations for reservoir-scale coal failure analysis are presented: one is based on the routine effective stress definition, while the other is based on an extended definition. Two application examples – the Fruitland reservoir in San Juan Basin and a reservoir in the Sydney Basin – are investigated in terms of the approximate treatment proposed, which employs the common uniaxial strain and constant vertical total stress assumptions. The Fruitland case study found that the (reservoir-scale) friction angles fitted with the routine effective stress, at a failure pressure equal to 1.9 MPa (observed) and with the assumed weakest low-volatile–medium volatile coal, would be 22–24°. If the extended effective stress definition is used, the friction angle would be 12–15°. The former results are apparently closer to some core-scale laboratory results (usually above 30°) than the latter. However, as discussed in this paper, using the routine effective stress for coal may result in some theoretical anomalies that seem to be fundamentally against the concept of the 'effective stress' in a porous rock: i.e., the pore fluid pressure reduces the effective stress in the rock. In contrast, the extended effective stress invoked in this text is theoretically more plausible for coal.

1. Introduction

Coal fails when a load exceeds its strength. Local coal failure can cause major problems in mining and coalbed methane production, such as gas outbursts (e.g., Hyman, 1987; Beamish and Crosdale, 1998) and failure in coalbed methane wells (e.g., Gentzis, 2009; Gentzis et al., 2009).

A related issue is the potential for large-scale failure behaviour in coalbed methane reservoirs during production. Based on their analysis of observed gas production from several wells in the San Juan Basin, Moore et al. (2011) identified a sudden drop in permeability after several years of production, as the reservoir pressure decreased to 1.7–2.1 MPa. Prior to this sudden decrease, the coal's permeability demonstrated an exponential increase with decreasing pore pressure, consistent with that described by common coal permeability models in response to matrix shrinkage under elastic geomechanical conditions (e.g., Shi and Durucan, 2009, 2010). The trend of increasing permeability was interrupted by the sudden decrease, but was subsequently followed by another increase for some wells, with others either flat or even slightly decreasing. Moore et al. proposed that this sudden decrease was a result of coal failure within the reservoir, associated with matrix shrinkage caused by gas desorption.

Extensive failure zones have been observed in conventional petroleum reservoirs that do not undergo matrix shrinkage. For example, Teufel et al. (1991) report such a case in the Ekofisk Field, North Sea. Through a laboratory simulation, they showed that the change in effective stress from pressure drawdown increased the shear stress, leading to shear failure. The authors believe this failure would increase the fracture density and thus maintain the reservoir's permeability, accounting for its continued good productivity.

In contrast to the Ekofisk reservoir, where permeability decreased with depletion, permeability in the Fruitland reservoir increased before the point of proposed failure (Moore et al., 2011). This behaviour emphasises a unique aspect of coal; the impact of pore pressure changes on permeability, which acts in two competing processes (e.g., Gray, 1987; Palmer and Mansoori, 1998; Shi and Durucan, 2004, 2005; Connell et al., 2010). On one hand, decreasing pore pressure tends to reduce the aperture of coal cleats, and thus lower permeability; on the other hand, it also results in gas desorption and matrix shrinkage, which tends to increase cleat aperture and thus also permeability.

Consequently, a turning point, called rebound pressure, is generally present in the behaviour of reservoir permeability versus pore pressure. The pre-failure trend of increasing permeability in the Fruitland coalbed methane reservoir implies that the reservoir pressure range was below the relevant rebound pressure of the coal, where the matrix shrinkage effect dominated the trend. After failure, the permeability in the Fruitland and Ekofisk reservoirs also behaved in an opposing fashion.

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For many rocks, failure often leads to irreversible extension of fractures or creation of new fractures (e.g., Brace et al., 1966; Bieniawski, 1967), even though crack closure, which often plays a secondary role, may also take place. Therefore, failure would often tend to increase the permeability of the formation, as observed in the Ekofisk petroleum reservoir (Teufel et al., 1991). However, for coal, Moore et al. (2011) proposed that the failure occurring in the Fruitland coal led to the creation of coal fines, which migrated within the coal cleat system and clogged cleats in the coal, thereby reducing permeability.

To simulate the potential failure in coal seams during depletion and gas desorption, Epinoza et al. (2015) recently simulated the desorption-induced lateral stress changes in coal seams. Their test replicated the depletion pressure–stress path and the zero-lateral strain and constant vertical total stress condition, which is routinely assumed to apply to coal seams. The authors observed that the reduction of lateral stress can be several megaPascals or more, due to the shrinkage effect of gas desorption, and that the steep slope of the desorption-induced stress path can reach the failure envelope and promote shearing sooner than for a conventional, non-adsorptive reservoir rock.

This paper presents a further field-scale failure analysis of coal. It includes an in-depth discussion on the use of two different effective stresses, and several important new and field aspects that are not considered in laboratory observations, such as the in-situ reference stress and the scale effect in a coal seam. The results obtained in this study may also help in conceptual understanding of the following questions:

i. What is the potential for failure in a coal seam undergoing reservoir pore pressure depletion during primary methane production?
ii. Can failure occur during enhanced coalbed methane production, where the reservoir pressure increases due to injection-induced pressure build-up?
iii. If failure is found to occur, what are the critical conditions, and can a window be identified for safe operation?
iv. How is the permeability influenced by failure?

This text presents a study of the first three questions above, and considers the fourth in a preliminary analysis. This is because the fourth question actually involves two issues: one is the effect of post-failure stresses on coal permeability, and the other is how the failure could lead to open or closure and creation or blockage of pores and fractures in coals. The latter issue is not considered here, because it would require observations that are outside the current scope of work.

This work introduces the theoretical development and discusses definitions of the effective stress. Two sets of approximate, analytical relationships for failure in coal reservoirs are formulated, where the averaged geological conditions and reservoir-scale coal properties are invoked. This work also presents two application examples: one for the Fruitland coalbed methane reservoir in the San Juan Basin, United States, and the other for a Sydney Basin reservoir, Australia. In another work (Connell and Lu, submitted for publication) we shall conduct a further numerical simulation with a coupled flow-geomechanical procedure (Connell, 2009; Connell and Detournay, 2009) in which the general poro-elastoplastic constitutive law presented here will be used but many of the major simplifying approximations are no longer needed, allowing more accurate insights into the relevant failure mechanisms. For example, we find that in the presence of wells, the uniaxial strain assumption may cause noticeable deviations in failure prediction.

2. Geological characteristics of coal seams

To simplify the problem and render it tractable for analytical treatment, we introduced several approximations. In terms of the problem geometry, coal seams have two significantly distinct dimensions: horizontally, a coal seam is laterally extensive in the order of kilometres, while vertically, the seam thickness is much smaller, in the order of metres. Therefore, one approximation used here is to treat the coal seam as a two-dimensional problem and neglect vertical gradients within the seam. The following assumptions are also made:

i. While coal is often anisotropic and highly heterogeneous, and these properties could play a role in detailed failure behaviour, it is assumed that the coal is isotropic and homogenous on average.
ii. While coal seams often dip, it is assumed that the seams are horizontal.
iii. The seam undergoes uniaxial strain and the vertical stress (overburden pressure) is constant.
iv. The shear stresses exerted on the boundaries and surfaces of the coal seams are ignored.

These assumptions are the basis for many of the analytical models of coal reservoir permeability behaviour (e.g., Palmer and Mansoori, 1998; Shi and Durucan, 2004; Cui and Bustin, 2005). They are used here to conduct the approximate, analytical analysis for reservoir-scale coal failure.

3. Geomechanical properties of coal

3.1. Poro-elasticity of coal — before failure

When a stressed coal has not reached its elastic limit, its behaviour can be described by the linear poro-elastic constitutive law (e.g., Rice and Cleary, 1976), plus a term associated with the matrix swelling/shrinkage due to gas adsorption/desorption. That is (e.g., Shi and Durucan, 2004):

$$\Delta\sigma_{ij} = 2G\Delta\varepsilon_{ij} + \lambda\Delta\varepsilon_V\delta_{ij} - \alpha\Delta p_\alpha\delta_{ij} - K\Delta\varepsilon_b^S(p_\alpha)\delta_{ij}, (i, j = 1, 2, 3). \tag{1}$$

Here, compression is defined as negative. σ_{ij} is the current total stress tensor, G the shear modulus, λ the Lame coefficient, α the Biot coefficient, K the bulk modulus of the coal, ε_{ij} the current linear strain tensor, $\varepsilon_V = (\varepsilon_{11} + \varepsilon_{22} + \varepsilon_{33})$ the total current volumetric strain, p_α the current pore pressure, and ε_b^S the bulk or volumetric sorption strain; this is a function of pore pressure and will be addressed in further detail in Section 3.3. The sign Δ in Eq. (1) indicates the incremental value of a quantity from its reference state. Namely, $\Delta\sigma_{ij} = \sigma_{ij} - \sigma_{ij}^0$, $\Delta\varepsilon_{ij} = \varepsilon_{ij} - \varepsilon_{ij}^0 \Delta p_\alpha = p_\alpha - p_\alpha^0$, and $\Delta\varepsilon_b^S(p_\alpha) = \varepsilon_b^S(p_\alpha) - \varepsilon_b^{S,0}(p_\alpha^0)$, where σ_{ij}^0, ε_{ij}^0, p_α^0 and $\varepsilon_b^{S,0}$ stand for respectively their initial counterparts of σ_{ij}, ε_{ij}, p_α, and ε_b^S at a reference state.

3.2. Reference state and in-situ reference stress

The constitutive law (1) is expressed on an incremental basis. However, to carry out stress and failure analyses, one has to use the current magnitudes of stresses, rather than their increments. Thus, we need first to know their relevant initial and current values at a given reference state. For reservoir analysis, the reference state should be defined in an in-situ reservoir condition. Then, Eq. (1) can be expressed by:

$$\sigma_{ij} = \sigma_{ij}^0 + 2G\varepsilon_{ij} + \lambda\varepsilon_V\delta_{ij} - \alpha(p_\alpha - p_\alpha^0)\delta_{ij} - K\left[\varepsilon_b^S(p_\alpha) - \varepsilon_b^{S,0}(p_\alpha^0)\right]\delta_{ij} \tag{2}$$

where σ_{ij}^0 is the in-situ reference stress at the initial reservoir condition, which includes the contributions from the tectonic stress, and p_α^0 is the in-situ reservoir pressure. We will discuss how to evaluate σ_{ij}^0 in Section 4.

3.3. Sorption strain and sorption stress

The sorption strain in Eq. (1) stems from the gas sorption behaviour, and introduces a sorption-induced stress (e.g., Sawyer et al., 1990; Gu and Chalaturnyk, 2005a, 2005b, 2006). Coal is a dual-porosity medium