Stress Induced Permeability Changes due to Production from a Coal Seam

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Abstract

Gas production from coal seams has attracted a great deal of attention around the world and in particular in Australia with its rich resources of coal. In general the coal bed methane (CBM) resources are located at lower depths (i.e. less than 1000 m) compared to conventional gas reservoirs. This increases the chance of a horizontal fracture to be developed if hydraulic fracturing is used to enhance gas production from a coal seam by connecting the cleates more effectively to each other and to the wellbore. During gas production, due to changes in stress fields, fractures, from the very small scale of coal cleates to those extending a few meters and large scale fault planes may get highly stressed and slide to some extent and experience changes in their apertures. The potential for this depends on the magnitude of in-situ stresses and also the geometry of the fracture plane with respect to the direction of principal stresses. This is a dynamic process which results in continuous changes in productivity of a CBM reservoir.

This paper aims at studying the potential for fracture reactivation during the production life of a CBM reservoir and how this may result in changing the permeability of the coalbed by communicating small fracture planes to each other. The Mohr-Coloumb criteria was used to investigate the sliding potential.

Also, to demonstrate the significance of stress changes due to gas production from coal seams on changing the sliding status of small fracture planes (here the coal cleats) a number of fracture planes were generated randomly and the sliding potential was assessed for these planes with respect to depletion rate. It is seen that increased production will change the results to a large extent: this shows how the secondary porosity and permeability may change significantly as a result of communication of cleates on a random basis during the production life of the coal seam. Changing the stress regime in the field, e.g. from normal to strike-slip, also changes the results significantly. The results are presented in this paper and conclusions will be made.

1. Introduction

Production of methane, as a major source for natural gas, from Coal seams is gorwing rapidly [Pu *et al.*, 2008 and Morad *et al.*, 2008]. Coalbed Methane (CBM) are classified as unconventional resources which differ from conventional sandstone and carbonate reservoirs in different aspects. Permeability of a coal seam is dominated by cleats, which are two sets of orthogonally spaced natural fractures. Due to significant difference in conductivity of these two fracture sets, the permeability in coal layers are therefore highly anisotropic. The cleats, extended from few milimiters to few centimeters, are very narrow and have a very low permeability. [Gilman A., and Beckie, 2000]. Initially, most methane exist in the coal matrix (i.e. micropores) rather than the fractures (i.e. macropores). Therefore a large prerssure drop is needed to mobilise the gas in place. The dewatering process forces the gas molecules to desorb from the coal and transport from the matrix to the cleats.

The major cleat system, known as face cleats, is formed parallel to the direction of maximum stress, whereas the second cleat part, is aligned with minimum stress direction [Morad *et al.*, 2008]. The fracture network structure formed by cleats governs the permeability from a coal seam. The cleats spacing, effective porosity and water saturation are some of the important properties defined for a cleat system [Morad *et al.*, 2008]. While, in general, it is expected that the cleat are arranged in an orthogonal network system, there are many cases where this is not the case and the natural fractures may develop in other directions [Xianbo *et al.*, 2001].

Besides the cleat systems in a coal seam, it is very likely that larger scale fracture planes and faults present in the field. These planes may have been formed at different geological time and therefore may have any orientation with respect to the current in-situ stresses in the field. These fracture planes, depending on their extension, may be limited within the coal seam, overburden layers or cross both formations. For production purposes having a good knowledge about the relative geometry of these fracture planes with respect to the in-situ stresses is important.

During production phase the change in pore pressure will change the magnitude of induced stresses within the reservoir and in the overburden [Palmer and Mansoori, 2008]. The resultant stresses acting parallel and perpendicular to a fracture plane can be used to assess the sliding potential. A common approach for such an analysis is to use the Mohr-Coloumb failure criteria, for which fracture surface mechanical properties, fracture plane orientation data and the status of in-situ stresses are required as the input data [Hudson and Harrison, 1997]. The critically stressed fractures are those which potentially contribute into larger permeability of the formation and this concept has been addressed in the past [Barton *et al.*, 1995(a), Barton *et al.*, 1995(b), Rogers, 2003, and Hudya *et al.*, 2007].

In this paper the objective is to investigate the potential for fracture reactivation in a CBM field. Firstly, the potential for large scale fracture slippage will be assessed considering the data corresponding to a typical CBM. Sensitivity analyses was performed to indicate the importance of different parameters on enhacing the fracture slippage potential. Secondly, the effect of production induced stresses on reactivation of cleat planes in a coal seam was investigated. A generated model with several randomly distributed natural fracture planes will be presented and it is shown how depletion causes fractures change their sliding potential status. Also, the results indicate that even small changes from an orthogonal network, as is ideally assumed for cleat systems, could result in a change in fracture sliding potential.

The results are presented in the subsequent sections after reviewing some general aspects related to fracture systems in coal seams and fracture sliding mechanisms.

2. Fracture systems in coal seams

Figure 1 shows schematically the system of natural fractures in a coal seam and different terminologies used in coal industries [Tonnsen and Miskimins, 2010]. As is seen from this figure the face cleats are typically continuous fractures that go across the reservoir and are considered as the main pathway for gas production. Butt cleats refer to discontinuities which are perpendicular to the face cleats and the gas passes through them to enter to the face cleats [Morad *et al.*, 2008].

The trace of both face and butt cleats can be observed in the image logs, an example of which is shown in Figure 2. This image belongs to the Alberta Plains coal [Oilfield review, 2003].

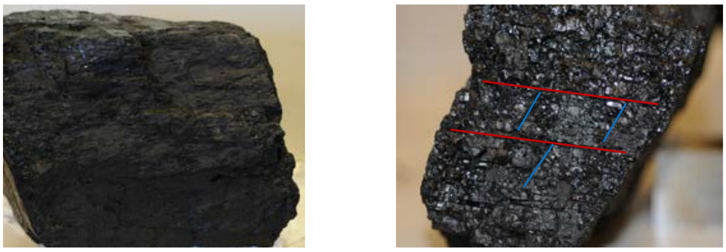

Figure 1: A coal block from an open pit mine in Queensland, with face (red) and butt cleats (blue)

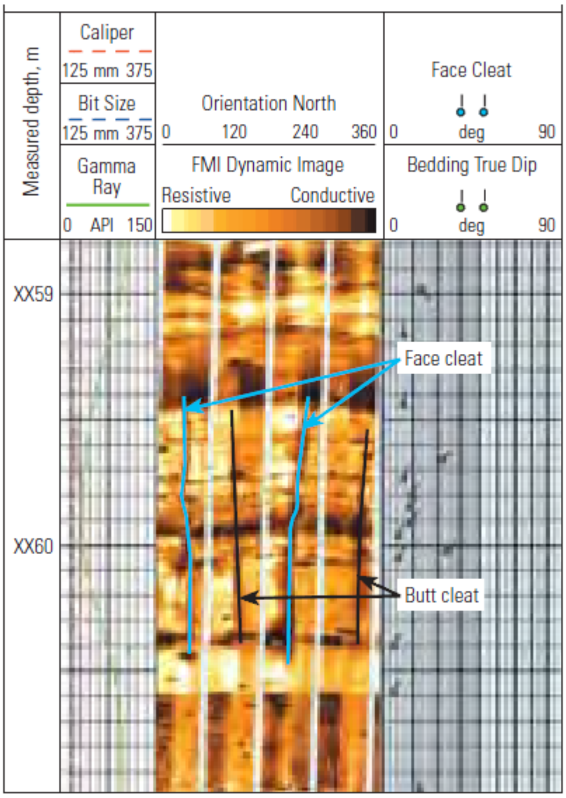

Figure 2: The FMI log of the Alberta Plains coal show face and butt cleats [Oilfield review, 2003].

Figure 3 shows various network pattern for cleats. In general, an orthogonal network with major fractures being face cleats aligned in the direction of maximum stress and minor discontinuities, i.e. butt cleats oriented along minimum stress direction is expected (see Figure 3.a). However, Figures 3.b to 3.e shows other possible network structures for cleats which is very different from general expectation [Xianbo *et al.*, 2001].

The cleat structures shown in Figure 3 implies the complex nature of flow path and also the anisotropic nature of flow properties in production from a coal seam. It is apparent that the coal permeability is influenced by the structure and characteristics of the cleat network, e.g., the dominant fracture orientation, Fracture continuity, frequency, and width. Similarly, the cleat system is affected by the contrast between face and butt cleat permeability [Morad *et al.*, 2008].

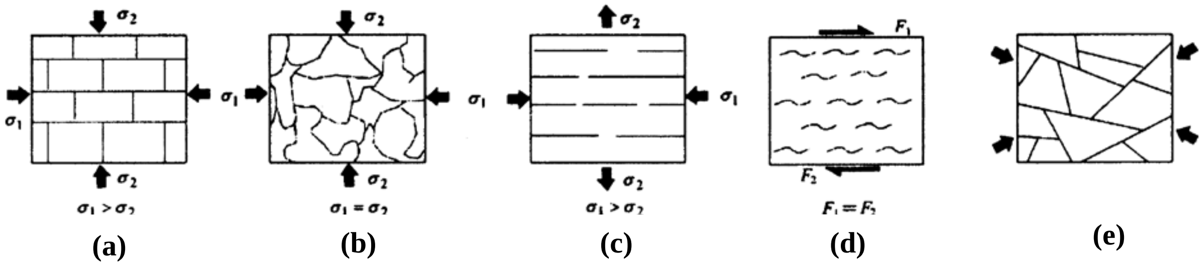

Figure 3: The network patterns of cleats [Xianbo et al., 2001].

From practical point of view, if the cleat planes are critically stressed depending on the status of in-situ stresses and are connected to each other they would provide an effective path for the gas to be desorbed from the coal. This is the concept which is modelled in this study and its response due to production from the coal seam is investigated. It is to be noted that while the most common network patterns for cleats is the orthogonal system, in this study cleat planes are generated randomly to show the improtance of stress orientation with respect to the geometry of cleats.

3. Fracture sliding mechanisms

Fracture reactivation may occur either during drilling operation (Maury, 1994) or production phase [Dusseault et al., 2001]. The latter is the mechanism that we are discussing in this paper. We use the Mohr-Coulomb failure criterion to analyse the sliding mechanism. According to this criterion sliding failure is initiated as the induced shear stress exceeds the shear strength of the plane.

The Mohr-Coulomb criterion, represented graphically in Figure 4 is expressed mathematically as:

$$\tau = C_d + \sigma_n' \tan \phi_d \tag{1}$$

where

$\tau =$ induced shear stress applied on the weak plane (MPa)

$C_d =$ cohesion of the discontinuity (MPa).

$\sigma_n' =$ induced normal effective stress applied on the discontinuity (MPa).

$\phi_d =$ internal friction angle of the discontinuity (deg).

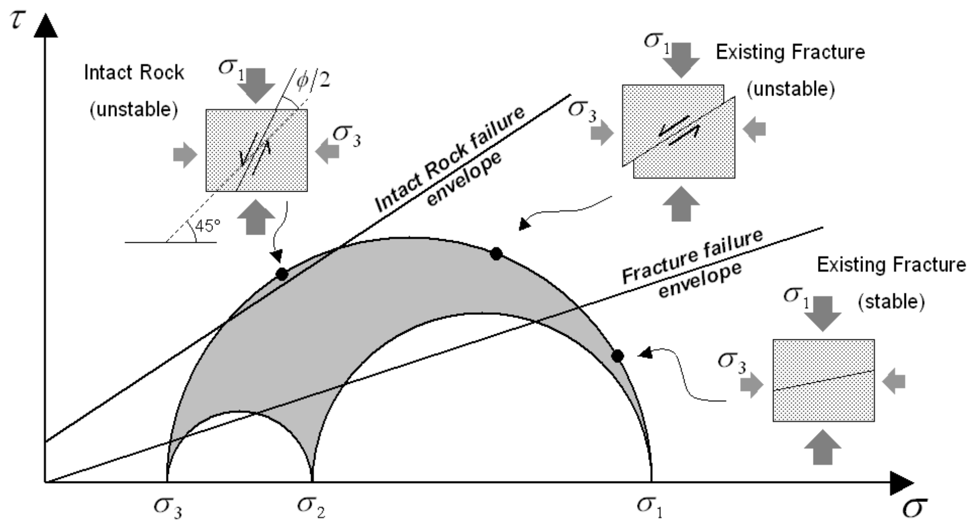

Figure 4: The state of stress is demonstrated by Mohr's circle. The envelopes are the intersections between the stable and unstable conditions [Younessi and Rasouli, 2008].

Production of gas from coal seam causes a reduction in pressure, which means an increase in the effective stress.This results in volumetric changes of the coal seam and therefore formation compaction [Dusseault et al., 2001].

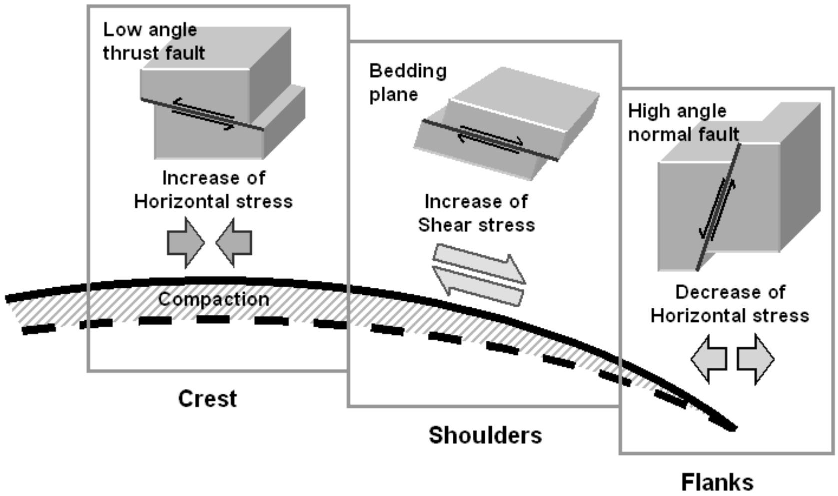

Figure 5: Faults and other discontinuities may fail in different section of the overburden due to reservoir compaction [Younessi and Rasouli, 2008].

As a result of compaction, as is shown in Figure 5 for non-flat overburden layers the crestal section experiences an increase in horizontal stress; whereas a reduction in the remote flank is expceted. The rocks above the shoulders would undergo a shear stress. More production from the coal seam means further stress redistribution in the overburden layers and therefore if the induced shear (mostly above the coal seam shoulders) exceeds the shear strength of the existing fracture (or the bedding planes) sliding of fracture plane (or interbeds) may happen. Looking at Figure 5, and considering the change of stresses in different zones above the coal layer it is seen that at the crestal section it is likely for a low-angle thrust fault to slide whereas in flank zone a high-angle normal fault stands a more likelihood to slide [Younessi and Rasouli, 2008].

The above discussion shows how the geometry of the fracture and layers with respect to the in-situ stresses could significantly dominate the likelihood of shear slippage. Of course the mechanical properties of the fracture plane needs to be considered when sliding analysis is carried out.

4. Fracture sliding analyis in a coal seam

Younessi and Rasouli (2010), carried out a generic Mohr-Coloumb analysis on 621 fractures with a wide range of dip and dip directions to study the sliding potential of a fracture plane subjected to different stress reigmes. As a result of this study they identified five potential zones of instabilities as shown in Figure 6. In this Figure the upward direction is the direction of minimum horizontal stress (σ_h) and the fracture surface properties are cohesion of c=0 and friction angle of ϕ=30°. These are the typical values for the fracture properties and the results of Figure 7 can be used as a guideline for fracture sliding potential assessment in a CBM. For example, as the coal seams are usually at low depths the stress regime is likely to be strike-slip and hence from Figure 6 it is seen fractures with dip direction of approximately ±30° from the direction of minimum horizontal stress are more prone to sliding. If the coal seam is at deeper depths, then the normal stress regime would be dominant, in which case fractures whose orientations are perpendicular to the direction of minimum horizontal stress have the largest potential for reactivation.

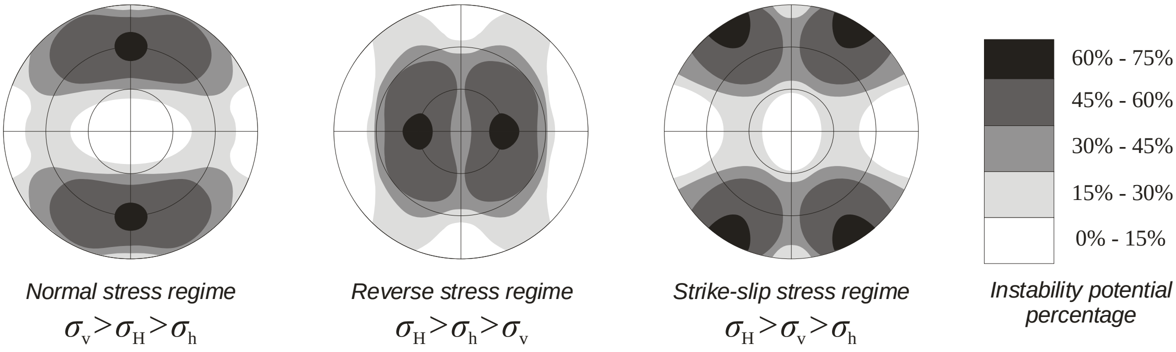

Figure 6: Fracture sliding potential corresponding to different stress regimes [Younessi and Rasouli, 2010].

As it was mentioned in section 2, the fracture network structure generated as a result of cleats (face and butt) provides a path for the gas to be desorbed from the coal and be produced. A more effective connection between these natural fractures means a higher permeability and thus easier production. From Geomechanical point of view the fracture planes which are critically stressed, provide a better flow path and the more the intersection between such stressed fractures the more permeable the coal seam will be. As the production from the coal seam progresses the effective stresses will vary and this will change the sliding status of the fracture planes, in this case the cleats. Depending on the geometry of each cleat with respect to the direction of in-situ stresses some of the cleats which are stable at a certain depletion phase may change their status to being unstable and vice versa. This will change as the depletion continues on a dynamic basis. This is while at each stage the permeability of the coal seam changes depending on how the stressed fracture planes are distributed with respect to each other.

To illustrate the above concepts let’s assume a coal seam deposited at an average depth of 1000m. The stress magnitudes are expected to be less in coal seams than other oil and gas reservoirs, as the coal layers are located in shallower depths. Assuming an average stress gradient of 1 psi/ft (0.023 MPa/m), [Rasouli *et al.*, 2011], the vertical stress at this depth would be approximately σ_V=23 MPa. With an average Poisson’s ratio of 0.30 for the formations and employing the elastic theory the horizontal stresses could be considered around 10 MPa, in a normal fault stress regime. Considering that horizontal stresses are anisotropic, as it is very likely to be the case, especailly when the field is tectonically active, the magnitude of the two horizontal stresses are assumed to be σ_H=15 MPa and σ_h =10 MPa, respectively.

Here, we have generated 50 cleats with random dip and dip directions. These planes are distributed randomly within a limited coal seam window. Figure 7 (left) shows the cleats represented on a stereonet with Figure 7 (right) being the corresponding Mohr plot analysis for this case. In this figure the normalised normal and shear stresses are plotted along the *x* and *y* axes, respectively. Here, zero cohesion and a friction angle of 30° is assumed for all cleat surfaces. A pore pressure of 8 MPa was assumed for this analysis. From this figure it is seen that those cleats which are located above the rock failure envelop, and marked in red, are critically stressed. In this example, a total of 15 cleats are critically stressed.

In Figure 8, a 2D section of the coal seam with cleats distribution as appear in this plane is shown. In this example, a limited size with a length of 100 unit and a width of 40 unit was considered for illustration purposes. The length of cleats change between 3 to 8 units, as is shown in this figure.The planes marked in red correspond to critically stressed cleats, which is shown in Figure 8.

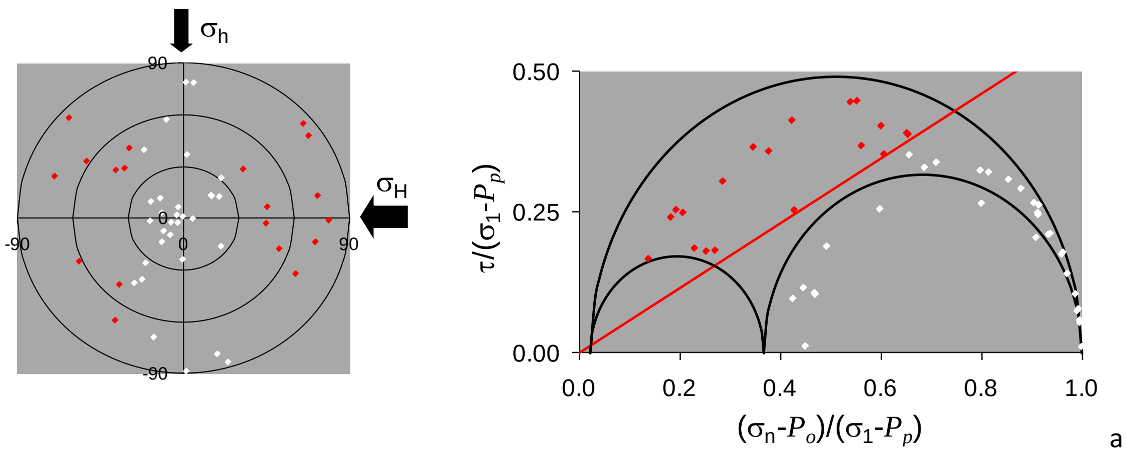

Figure 7: Plot of 50 randomly generated cleats (left) and their Mohr plot analysis (right).

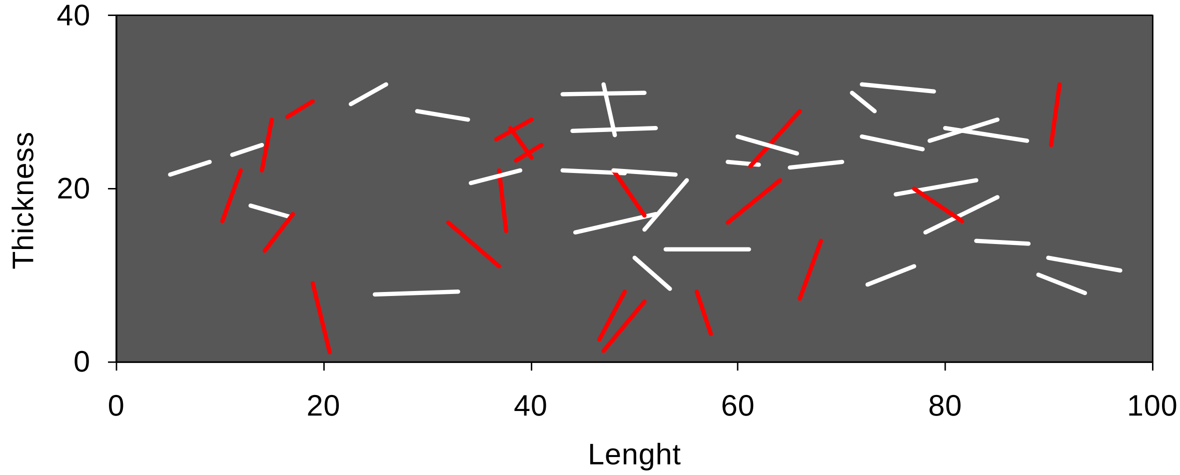

Figure 8: A 2D view of the coal seam with cleats distribution. Red planes are highly stressed cleats.

The ratio of the number of critically stressed cleats to the total number of cleats (assuming similar length for all cleats) could be considered as a simple measure of cleats' contribution into coal seam second porosity. If lcs_i is the length of i^{th} critically stressed cleat and L_c represents the total length of all cleats the cleat's intensity index may be defined as:

$$I_c = \frac{\sum_{i=1}^{n} lcs_i}{Lc} \qquad (2)$$

From practical point of view, the critically stressed cleats could potentially increase the permeability of the coal seam by providing a more effective path for the gas to flow. However, the interconnection of such highly stressed fractures is another important aspect to be considered for the final assessmentn of effective porosity of the coal seam. Higher porosity in general results in a larger effective porosity but as one can imagine, this depends significantly on the spatial distribution of the cleats with respect to each other. It is likely that in the presence of large number of critically stressed cleates a very low permeability is generated due to the lack of intersection of the cleats.

In the example shown in Figure 8 the cleat's intensity index, consdieing the length of the cleats into account, is obtained as I_c= 34%. From this figure it is observed that only two pairs of cleats are effectively intersecting each other and create a longer path for the gas to flow. This indicates the significant effect of cleat network system in the total permeability of the coal seam.

Reduction in pore pressure due to production results in a larger effective stress and this would change the potential for fracture sliding by changing the magnitude of the normal stress acting perpendicular to the fracture plane. Performing similar analysis with different values for pore pressure it was seen that a reduction in pore pressure down to 5 MPa results in only 5 cleats to be critically stressed (see Figure 9). No unstable cleat is expected below pore pressure of 2 MPa for the studied case. From Figure 9 a low permeability is expected as none of the critically stressed cleats are intersecting each other to provide an effective flow path. This is while a cleat's intensity index of I_c= 12.5% is obtained in this case.

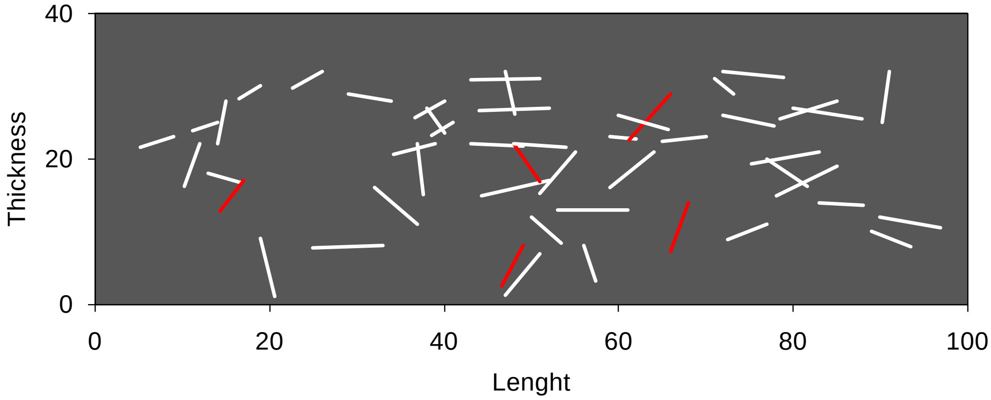

Figure 9: Critically stressed cleats corresponding to a reduced pore pressure of 5 MPa.

In a different attempt and in order to investigate the impact of stress regime on coal seam propository and permebility similar analysis was conducted but this time the order of vertical and maximum horizontal stresses was swapped (σ_H=23 MPa, σ_V=15 MPa, σ_h=10 MPa), i.e. the stress regime was changed from normal to strike-slip. In the presence of a pore pressure of 8 MPa it was observed that, comparing to the previous case, two more cleats became critically stressed. These are shown in blue in Figure 10. Further analysis considering different pore pressure values indicated that the coal seam have a larger second porosity at this stress regime than that of normal stress regime as more cleats appear to be prone to sliding. This demonstrates the importance of in-situ stresses and also the depth of the layer in terms of the permeability of the coal seam.

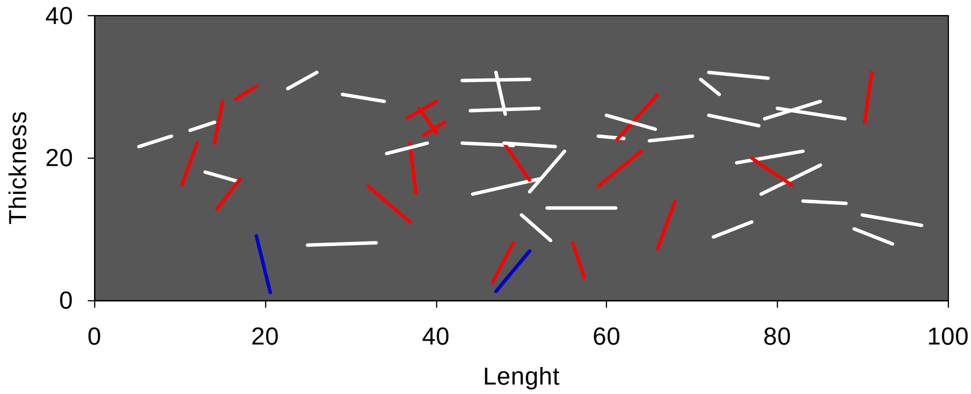

Figure 10: More cleats become critically stressed at pore pressurew of 8 MPa when stress regime changes to strike-slip.

In Figure 11 a different randomly generated cleat network is presented with the two sets of face and butt cleats being nearly orthogonal, to mimic a more general pattern for cleat structures. The length of face cleats oriented NW-SE is larger than those of butt cleats. Here, a strike-slip stress regime similar to the previous case ((σ_H=23 MPa, σ_V=15 MPa, σ_h=10 MPa) was assumed. In Figure 11 the results correspond to a very large pore pressure of 11 MPa, showing that a number of face and butt cleats are critically stressed. The cleats' orientation may be different in which case the results would be expected to vary accordingly. This can be simulated by changing the direction of applied stresses, here the azimuth of minimum horizontal stress. As an example, Figure 12 shows the results corresponding to a 7 degree change in the azimuth of minimum horizontal stress, while all other parameters are constant. This figure shows how the stability of the cleats can be influenced by changing the azimuth of applied stresses, or similarly the orientation of cleats structure.

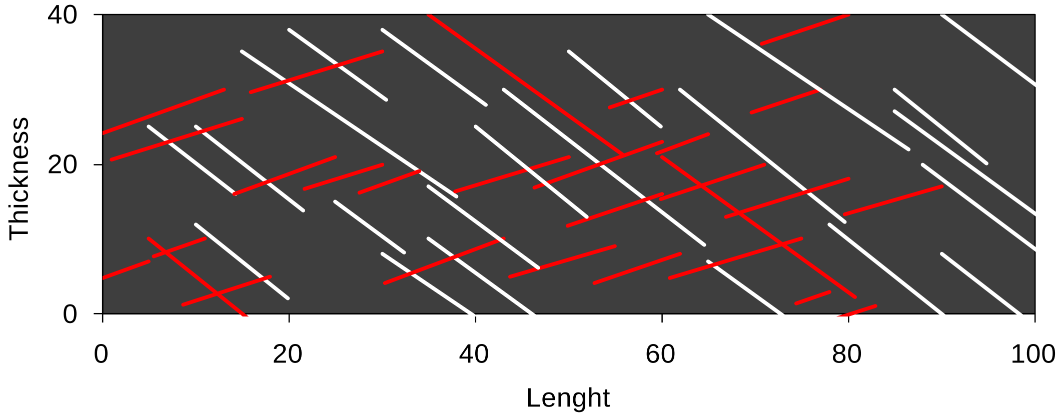

Figure 11: A nearly orthogonal netwrok with critically stressed cleats shown in red. The stress regime is strike-slip.

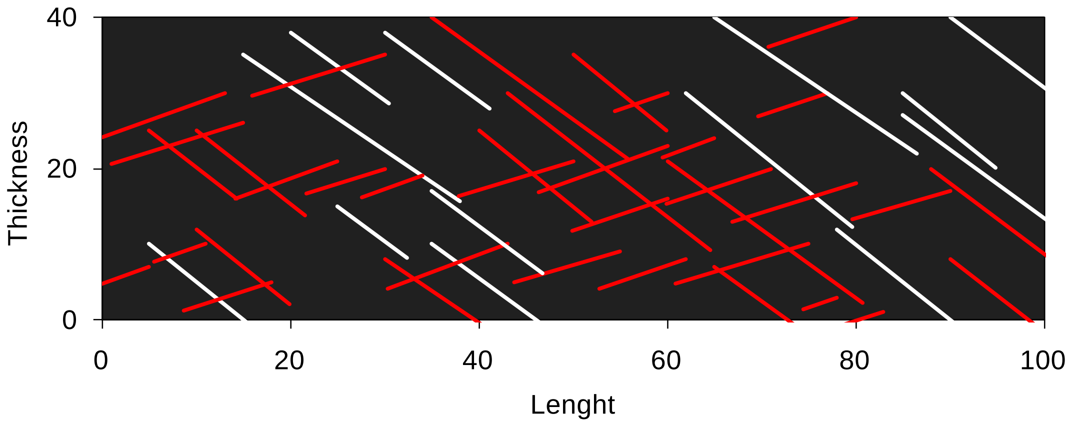

Figure 12: Changing the orientation of applied stressed (or cleats orientation) will change the status of cleats sliding potential.

5. Conclusions

In this paper the importance of large scale fractures as well as cleats structure on the permeability of the coal seam were discussed. Explaining the fracture sliding failure mechanism, it was shown how, depending on the magnitude and orientation of in-situ stresses, some of the cleats may be critically stressed. These are the planes which contribute to a higher effective porosity of the coal seam. The results of analysis carried out for some data close to what is expected in a coal seam indicated that this status may change as a result of gas production.Therefore, a good knowledge of the coal geological structure and its mechanical properties as well as the state of the in-situ stresses is essential prior to production form a coal seam.

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