2015

Analytical Procedure to Estimate the Horizontal Anisotropy of Hydraulic Conductivity in Coal Seams

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ANALYTICAL PROCEDURE TO ESTIMATE THE HORIZONTAL ANISOTROPY OF HYDRAULIC CONDUCTIVITY IN COAL SEAMS

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ABSTRACT: The horizontal hydraulic conductivity anisotropy of coal seams is a controlling parameter for designing gas drainage boreholes. The ratio between the maximum and minimum horizontal hydraulic conductivity (RkH-kh) and the orientation of maximum horizontal conductivity defines this anisotropy in horizontal plane. This paper presents a new analytical procedure based on the field stress data and geometrical properties of coal cleats to calculate these two parameters. The application of this procedure for a real case in Eastern of Australia resulted in an average ratio of 20.9 for RkH-kh and orientation of NE for maximum horizontal conductivity. The comparison between these results with the measured values validated the accuracy of proposed procedure to estimate the anisotropy of horizontal hydraulic conductivity of coal seams.

INTRODUCTION

Hydraulic conductivity of coal seams is a key parameter for successful designing of gas drainage operations. For gas drainage, the pore pressure (reservoir pressure) is lowered which causes desorption of gas molecules from coal matrix. Then the free gas flows toward drainage borehole through coal fractures (cleats) and its diffusion within coal matrix. Contribution of diffusion to the fluid flow in coal seam is negligible compared to flow throughout cleat network (Robertson and Christiansen, 2008). Therefore, coal seam is simulated as fractured reservoir with respect to fluid flow. Similar to all fractured rocks, hydraulic conductivity of coal seam is an anisotropic character and flow rate of gas and water mixture (two phase flow) would be higher in the direction with higher hydraulic conductivity.

For practical applications, anisotropy in hydraulic conductivity can be explained by two ratios; 1) ratio between maximum and minimum horizontal conductivity and 2) ratio between maximum horizontal conductivity and vertical conductivity ($R_{kH\text{-}kV}$). $R_{kH\text{-}kh}$ controls the orientation of drainage boreholes. Massarotto *et al.,* (2003) found that the reported RkH-kh of coal varies from 1.8 to 17. They performed triaxial permeability tests on Permian coals from Bowen Basin, Queensland, and Sunan Basin, China. Based on these experiments, they reported a range of 1.35 to 19 for RkH-kh. Furthermore, they found that the RkH-kV varies from 0.11 to 4 for Permian coal.

In this paper, an analytical procedure was introduced to estimate RkH-kh based on cleat geometry and in-situ stress. The new procedure was applied to a real case which is located in Eastern Australia. A comparison was made between estimated value and results obtained from field interference tests.

METHODOLOGY

In practical applications, water flow within rock joints (rough surfaces) is simulated as laminar flow through two parallel plates, (cubic law) (Snow, 1969). Based on this assumption, hydraulic conductivity of individual joints is obtained as:

$$k_j = \frac{ga_j^2}{12\vartheta} \quad (1)$$

where, g is the gravitational acceleration, ϑ is the kinematic viscosity and a_j is the joint hydraulic aperture. This formulation can be extended to a joint set with spacing of S as:

$$k_j = \frac{ga_j^2}{12S\vartheta} \quad (2)$$

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Snow (1969) introduced the first comprehensive analytical method for hydraulic conductivity of jointed rocks:

$$k_{ij} = \frac{g}{12\vartheta}\sum_{k=1}^{n}\frac{a_k^3}{s_k}\,(\delta_{ij} - n_{ik}n_{jk}) \qquad (3)$$

where, $k_{ij}$is hydraulic conductivity tensor, *n* is number of joint sets, a_k and s_k are hydraulic aperture and spacing of k_{th} joint set, δ_{ij} is the Kronecker Delta and nik and n_{jk} are direction cosines of the unit vector normal of each joint set in the x, y and z direction. Rock joints are considered as infinite plane; therefore, they extend all over the considered volume of rock mass (objective volume) and intersect its boundary. Orthogonal geometry (Figure 1) is common to simulate the network for cleats within coal (Robertson and Christiansen 2008). Then Snow's formulation can be further applied to the cleat network to estimate its hydraulic conductivity tensor.

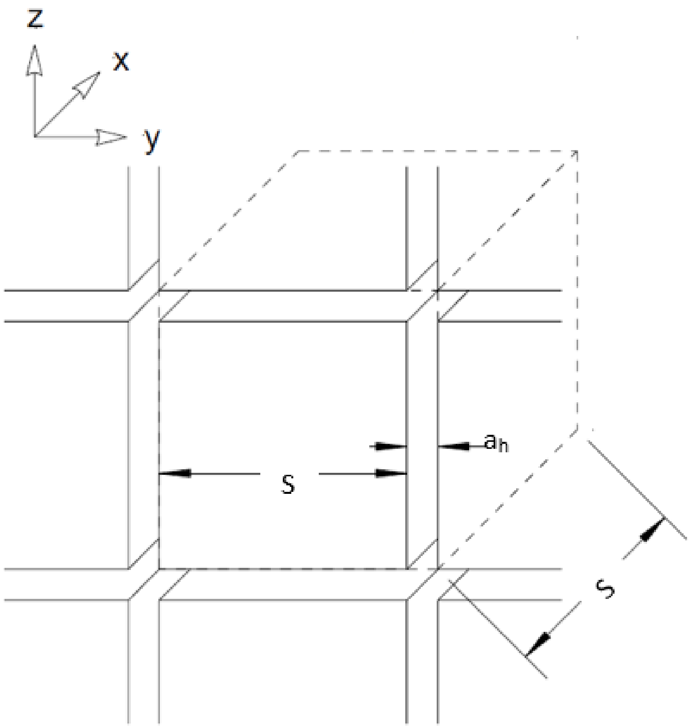

Figure 1: Schematic orthogonal geometry for coal cleats (Modified after Robertson and Christiansen, 2008), ah is hydraulic aperture and S is spacing

The orientation and spacing of cleats can be measured by using defect logs, acoustic scanner and field mapping. As can be seen from Equation (3), hydraulic aperture of cleats is the main controlling parameter (hydraulic aperture gets power of 3). Nevertheless, there is no direct method to estimate the hydraulic aperture of rock discontinuities. Zoorabadi *et al.,* (2014) proposed empirical formulations to estimate the hydraulic aperture of rock discontinuities at different depth (Figure 2).

In this method, approximate acting stress on each discontinuity set is determined firstly by considering the orientation of that discontinuity set and field stress orientation (Figure 3). Then equivalent depth (Zeq) for each discontinuity set can be estimated as follows:

$$z_{eq} = \sigma_i/\gamma \qquad (4)$$

where σ_i is the applied stress on the discontinuity set of i and γ is the unit weight of rock mass. Following the calculation of the equivalent depth for each discontinuity sets, the hydraulic aperture is calculated using following equation (Zoorabadi *et al.,* 2014).

$$a_h = 250\left(1 - \frac{Z_{eq}}{40+0.98\,Z_{eq}}\right) \qquad (5)$$

where a_h is hydraulic aperture of rock discontinuity considering applied stress.

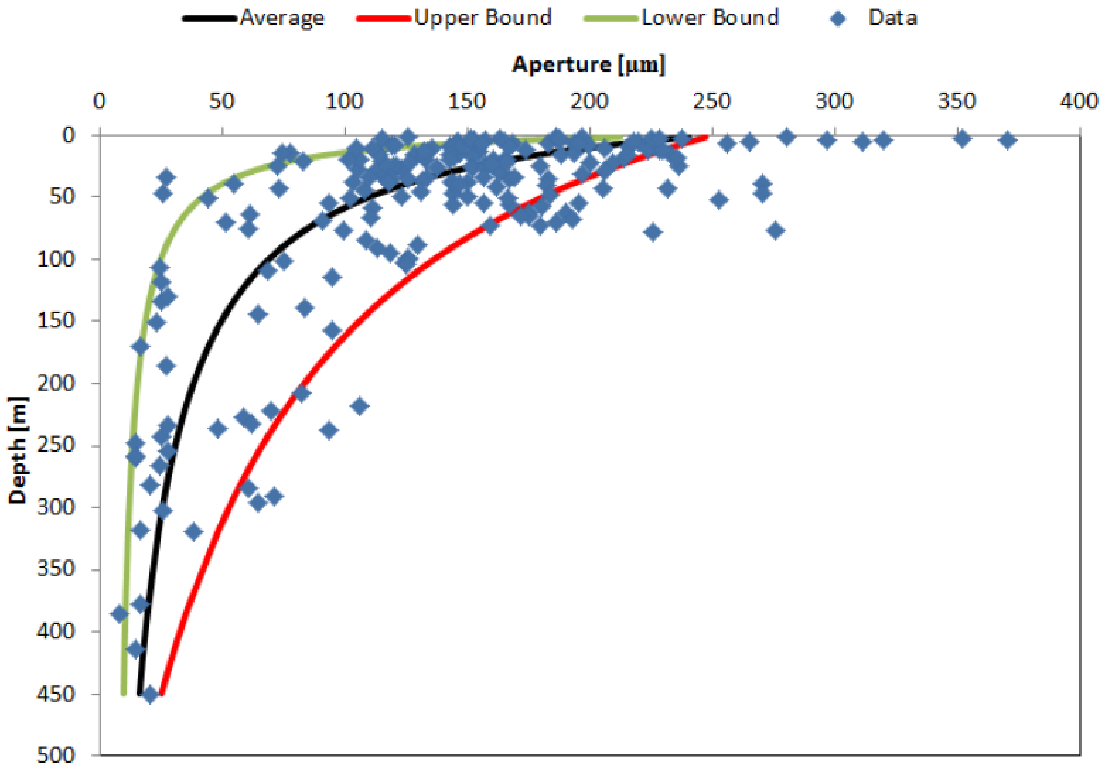

Figure 2: Variation hydraulic aperture of rock fractures by depth (Zoorabadi *et al.*, 2014)

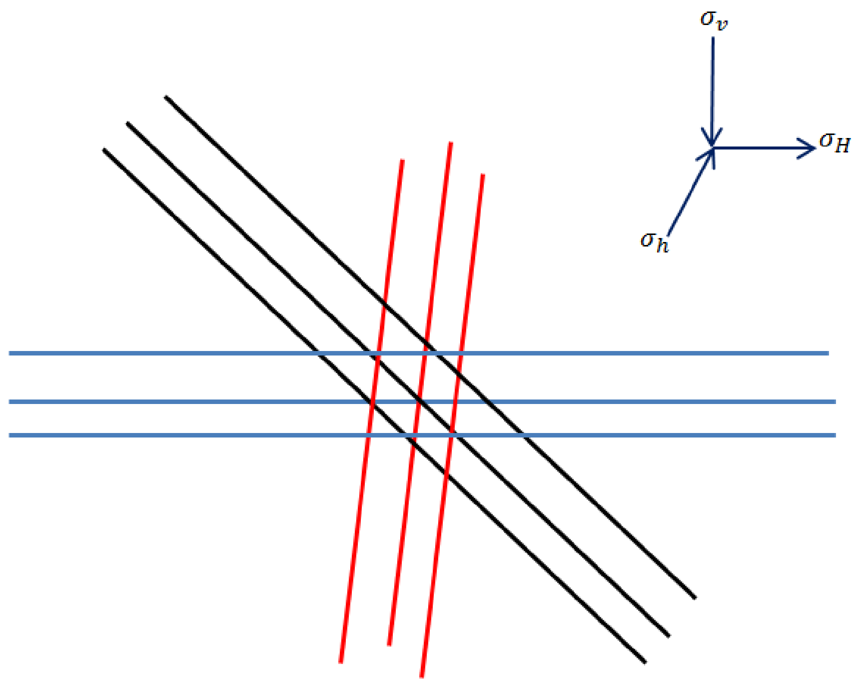

Figure 3: Approximate acting stress on each discontinuity set as a function of field stress orientation and orientation that discontinuity set

CASE STUDY

The above mentioned procedure was applied to a real case. This case was a mining project which was located in Eastern Australia. Detected cleats in different boreholes were statistically analysed to determine the orientation and spacing of cleats. Figure (4) shows contours diagrams of detected cleats in different scanned boreholes. Furthermore an average spacing of 0.53 m was estimated for cleats.

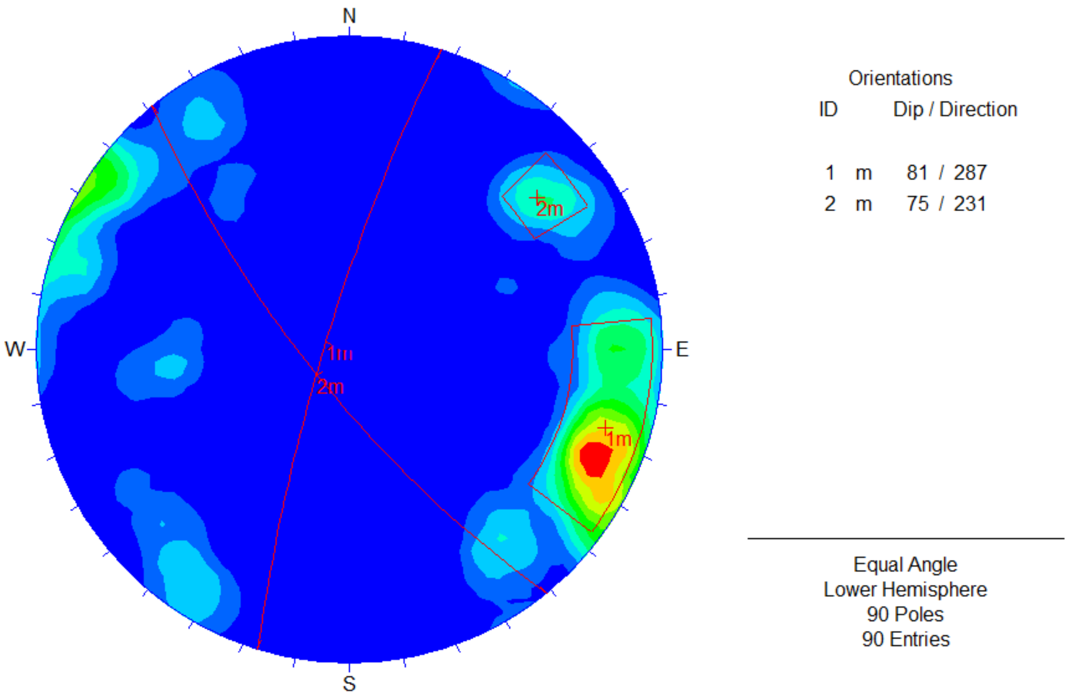

Figure 4: Contour diagram of all cleats detected by acoustic scanner

In this study, the average depth of coal seam was 225 m. Field stress measurement and borehole breakouts analysis demonstrated that the direction of maximum horizontal stress was NE. Based on the field measurements the tectonic factor for this site varied between 0.7 and 1. The data which was published by Nemcik *et al.,* (2005) gave approximately the same range for the tectonic factor at depth around 200 m. By considering the elastic modulus of 3 GPa for coal and by using the concept of tectonic stress concept (Nemcik *et al.,* 2005), the ratio between maximum horizontal stress and vertical stress for this site would be between 0.8-1.

Before starting of interference tests, the step-rate-test was performed to determine the maximum allowable flow rate. Moreover the inflection point on water pressure – flow rate curve of step-rate-test provided an estimate for the minimum stress within coal seam (Figure 5). Using this method, the ratio between minimum horizontal stress and vertical stress for this project was determined from 0.26 to 0.36. Combination of filed stress orientation and magnitude with orientation of cleats, resulted in equivalent depth of and hydraulic aperture for cleat sets as in Table 1 (using Equations 4 and 5).

Table 1: Geometrical properties of discontinuity sets for depth 150 m (100-200 m)

Cleat Set	*Dip/Dir*	*Dip*	*Spacing [m]*	*Equivalent Depth [m]*	*Hydraulic Aperture* $[\mu m]$
C1	287	81	0.53	58 - 81	80-100
C2	231	75	0.53	180-225	34-42

The hydraulic conductivity tensor of coal seam was calculated by applying Equation (3) to the geometrical properties for cleat sets. In Table 2, the calculated results including the range of RkH-kh and the orientation of the maximum horizontal conductivity are listed.

In this study, hydraulic interference test was carried out in a coal seam to evaluate the horizontal hydraulic conductivity of the seam. The interference test included an injection well, which was fully screened in seam thickness and three observation boreholes in around the injection well. Water injects with a constant flow rate and the corresponding head changes were measured in the observation wells (Figure 6). The recorded head change versus time provided data to calculate the principal hydraulic conductivities in horizontal plane (Papadepulos 1965).

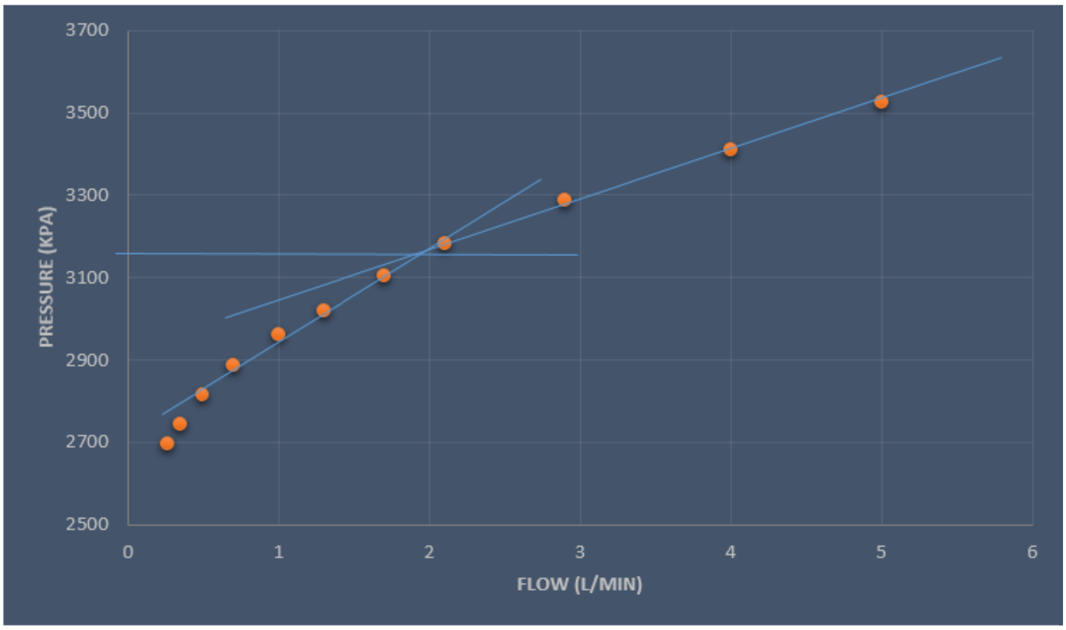

Figure 5: An example for estimating of minimum stress by step-rat-test

Table 2: Calculated RkH-kh and it orientation

	For Minimum Hydraulic Aperture	For Maximum Hydraulic Aperture
$R_{kH\text{-}kh}$	20.5	21.2
Orientation	NE	NE

Different combinations of recoded head change curves in this project were considered to calculate the anisotropic horizontal hydraulic conductivity. The average measured RkH-kh was 20.2 at NE orientation. Comparison between the measured and calculated anisotropy ratios demonstrates that proposed analytical procedure has the capability to be used for practical estimations. This procedure has potential to be used to calculate the hydraulic conductivity changes which happen by water withdrawal as well. As it commonly known, the water withdrawal increases the effective stress which results in reducing of cleat aperture. On the other hand, coal shrinkage due to gas release increases that hydraulic aperture of cleats (Robertson and Christiansen 2008). The combination of proposed procedure with the Sorptive-Elastic models such as Palmer and Mansoori (1998), Shi and Durucan (2003), Robertson and Christiansen (2006) provides the capability to calculate the variation anisotropic horizontal hydraulic conductivity by water withdrawal.

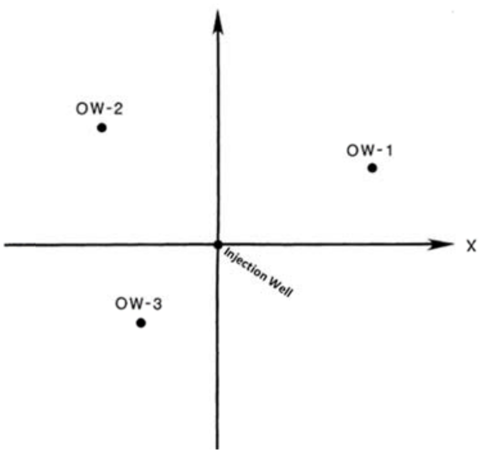

Figure 6: Schematic view of interference test (ow, observation well)

CONCLUSIONS

A new analytical procedure is proposed in this paper to calculate the ratio between the maximum and minimum horizontal conductivity of coal seam by combination field stress data with the geometrical properties of coal cleats. The proposed procedure was applied to a real case in Eastern Australia. The calculated ratio between the maximum and minimum horizontal conductivity and the orientation of maximum horizontal conductivity were compared with the measured values from interference test. The comparison showed that the proposed analytical procedure has a reasonable accuracy to predict the anisotropic conductivity of coal seams.

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