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HYDRAULIC-GEOMECHANICAL EFFECTIVE STRESS MODEL: DETERMINATION OF DISCRETE FRACTURE NETWORK PARAMETERS FROM A PUMP TEST AND APPLICATION TO GEOTHERMAL RESERVOIR MODELLING.

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ABSTRACT

Fracture networks dominate the permeability of crystalline geothermal reservoir rocks. Insitu stress conditions have a significant impact on the flow, transport and exchange characteristics of fracture networks. Here a geomechanical model is presented which describes fracture closure under effective stress and the change in parameters such as storage, permeability, porosity and aperture. The model uses geometrical considerations based on a fractal distribution of apertures on the fracture surfaces, and applies analytical elastic deformation solutions to calculate the strain response to increases in effective stress. The model is first applied to fit laboratory scale experimental data gained on the compressive closure of a fractured sample (Durham 1997) recovered from a depth of 3800m from the KTB pilot borehole (Emmermann and Lauterjung 1997). The elastic constants for these fits were established externally, the fitting parameters applied included the initial aperture of the fracture, the minimum contact area between the surfaces and the number of allowable contacts. After accurate fitting of the laboratory scale experimental data, the geomechanical model was applied at a field scale to aid in the modelling of a long term pump test in the KTB pilot hole, the open hole section being 3850 to 4000m. Effective hydraulic parameters determined by a finite element model of the fracture systems connected to the KTB pilot borehole were analysed on hand of the geomechanical model to allow the determination of the discrete fracture geometry operating within the fracture zone. This geomechanical model takes account of the changes in the flow parameters within the fracture systems due to changes in local effective stress as a result of the groundwater extraction. Applying the geomechanical model and an iterative procedure allowed the number of fractures in the fracture zones comprising the hydraulic signal, and their average aperture to be estimated. The number of fractures predicted to be hydraulically active in the fracture zone is of the same order as in-situ field measurements and the original fracture logs.

INTRODUCTION

Fracture systems dominate the mass and energy transport of deep crystalline rocks (Emmermann and Lauterjung 1997). The characteristics of the three dimensional fracture systems in terms of flow, transport and heat conduction are controlled by a number of critical factors. In particular the geometry of the system in terms of the orientation of the fractures in the pervasive stress system (eg. Kessels 2000), the fracture connectivity (Bour and Davey 1998, Manzocchi 2002), fracture permeability (Nicholl et al. 1999, Wang et al. 1988), porosity (Montemagno and Pyrak-Nolte 1995) and area of fracture system available for sorption and heat exchange (Renner and Sauter 1997, Wels et al. 1996, Watanabe and Takahashi 1995) form some of the most important factors which need to be addressed.

One important aspect highlighted by a number of authors in the development of long term behaviour of fracture systems is their response to stress changes which may be generated due to hydraulic alterations of the systems, long term stress field alterations, and thermo-elastic stress alterations due to a change in the amount of heat in the systems (hot dry rock heat extraction). Indeed O'Sullivan et al. (2001) particularly pointed out that long term geo-mechanical effects of thermal stress changes on geothermal reservoir characteristics need to be investigated.

The response of a fracture network to stimulation by either extraction or injection of fluid is a time dependent integral signal comprising the individual responses of the discrete fractures (McDermott et al. 2003). The individual responses of the discrete fractures within the fracture system are determined by interaction of the fluid injected or extracted and its physical characteristics such as density, viscosity, heat capacity and temperature. Within the solid medium factors such as the elastic response of the medium and pervasive insitu conditions including temperature and pressure have a critical impact. Alterations to the contact area of the fractures, storage, effective porosity, flow channelling and permeability within the fracture system can be expected with alterations to the pervasive conditions.

Modelling Approach

Here an elastic model is presented for the closure/opening of a fracture under increased effective stress. Both the far field stress conditions and the asperity distribution are considered. The aperture distribution is represented as a fractal function. (Babadagli and Develi 2000, Watanabe and Takahashi 1995, Belfield 1994, Wang et al. 1988). The use of a fractal distribution provides a number of advantages, in particular the system can be considered either as a two dimensional closure and contact of a number of asperities (i.e. aperture and length are considered), or three dimensional closure of two fracture planes (aperture length and depth). The mathematics and distribution of the asperities are identical in each case due to the inherent self similarity of the fractal distributions. This important property coupled with averaging techniques and the application of a number of established soil and rock mechanic formulas for settlement in elastic half space under loading originating from the famous Boussinesq approach for point loads (Boussinesq 1878), and the application of spatial integration of this theory to define several shape dependent analytical solutions (eg. Poulos and Davis 1974, Davis and Selvaduri 1996) allows the simplified consideration of what is a complex system under closure.

The fracture response is considered to be totally elastic and the possible time dependency of closure is assumed to be negligible given the relatively short period of time over which the amount of closure alters in comparison to the length of time of the processes being investigated. Time dependent closure has been recently investigated by Matsuki et al. (2001), who considered time dependent closure of fractures under the normal stress as determined by Brown and Scholz (1985) for fractures comprising a given probability function distribution of aperture sizes. Their results indicated that within 40 hours the system had reached stable conditions, and that most of the response of the fractures to external stress changes happened within a matter of hours of application. The model developed here is used to define and model long term changes in the fracture systems.

A big advantage of this fracture closure model is that it considers changes in effective stress in the fracture plane and allows an increase in contact area of the fracture surface. This allows consideration of both external loading and changes in the porewater pressure (e.g. fluid injection or extraction) within the fracture under constant loading. The change in contact stress resulting from the change in effective stress is considered to be uniformly distributed throughout the asperities, and therefore the cumulative contact stress at each point is not important.

The whole rock body is considered to be involved in the deformation and not just the asperities themselves, although naturally they are predominant factors in deformation. This reduces the problem of unrealistically high contact strains as commented on by Beeler and Hickman (2001) and predicted by some Hertzian based models.

The elastic response is defined by the elastic constants (v) poissons ratio and (E) the elastic modulus, there is no need for a time dependent relaxation modulus. Plastic yield and deformation are not considered at this point.

Model Application: Laboratory & Field scale

The model has been applied to match the laboratory experimental closure of a fracture taken from a sample of rock from a depth of 3800m in the KTB pilot hole (Durham 1997). The key parameters for the model were field measured elastic parameters and an estimation of the starting contact area as a percentage of the fracture profile. Once the fracture closure could be modelled with satisfaction the results were then applied to predict the field scale geomechanical response of a three dimensional equivalent fracture network model to a depth of 8km from the KTB site under long term pumping test from the pilot hole which started June 2002. Fluid withdrawal from the fractured host rock occurs in the open hole section of the pilot borehole at a depth of 3850m to 4000m. Application of this model allowed the prediction of the discrete parameters of the fracture network from the integral signal response of the pump test data.

HYDROGEOMECHANICAL PRINCIPLES

The fracture plane is considered to comprise two non perfectly matching surfaces (Figure 1). The heights of the asperities on the surfaces are described by a fractal distribution (Glover et al. 1999, Watanabe and Takahashi 1995). The fracture surface is considered only as a cross section i.e., aperture and length, and not depth. This assumption is valid in terms of understanding the compressive response of the fracture, as the fractal distribution in two or three dimensions will be constant. This assumption, is, however, not carried through to the calculation of permeability as this would then be a function of the harmonic mean (Barake-Lokmane et al. 2003); for permeability the third dimension is considered.

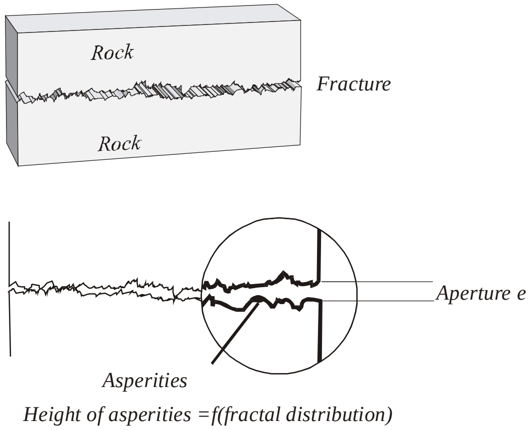


Figure 1: Conceptual approach to the closure of the fracture planes

The fracture is then presented as a series of asperities (Figure 2) which form a number of flow channels on closure (Figure 3).

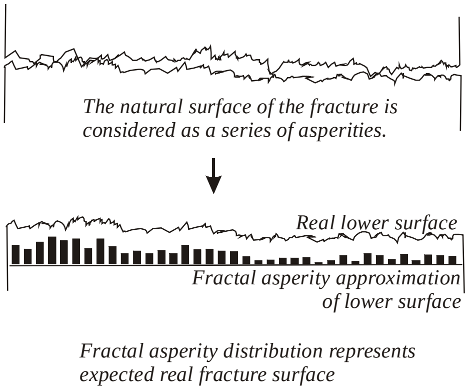


Figure 2: Fracture as a series of asperities

Further compression of the fracture increases the number of contacts between the two surfaces, and therefore the number of flow channels (Figure 4). Correspondingly with increasing compression, the overall stiffness of the fracture increases as the area of contact between the fracture-faces increases. More details of the geometrical considerations of the closure model are presented in McDermott & Kolditz (2004).

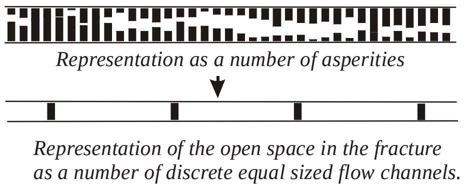


Figure 3: The asperity distribution is converted to a fracture comprising equal volume channels and a certain number of contacts.

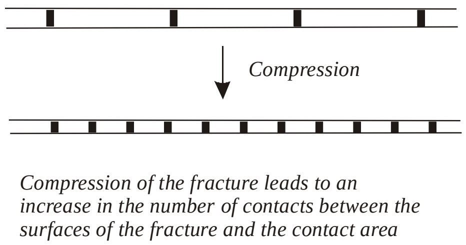


Figure 4: Increase in the number of contacts in the fracture as compression reduces the size of the aperture.

Stress Considerations

The effective stress (σ') is given by:

$$\sigma' = \sigma_n - u \qquad (1)$$

where (u) is fluid pressure and (σ_n) is the total normal stress. The total normal stress on a fracture plane orientated with directional cosins l,m,n to the x,y,z axis respectively and forming the normal vector $\hat{n}$ to the plane is given after Davis and Selvaduri (1996) as

$$\sigma_n = \left(\boldsymbol{\sigma}^T \hat{n}\right) \cdot \hat{n} \qquad (2)$$

Where

$$\boldsymbol{\sigma} = \begin{bmatrix} \sigma_x & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_y & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_z \end{bmatrix} \qquad (3)$$

The normal stress comprises what the authors term wall stress (σ_w) and contact stress (σ_c) (Figure 5). The wall stress represents the difference between the surrounding normal stress and the fluid pressure in the fracture, the contact stress (σ_c) is the average stress carried across the contacts in the fracture maintaining the fracture aperture. Here wall stress is used rather than the term effective, similarly defined, to show that the areas where asperities contact are not considered.

When the fluid pressure (u) is reduced for instance through fluid extraction, the total normal stress (σ_n) does not change, the wall stress increase by the same amount as the reduction in the fluid pressure, the contact stress increases by the effective stress increase divided by the area of the contacts.

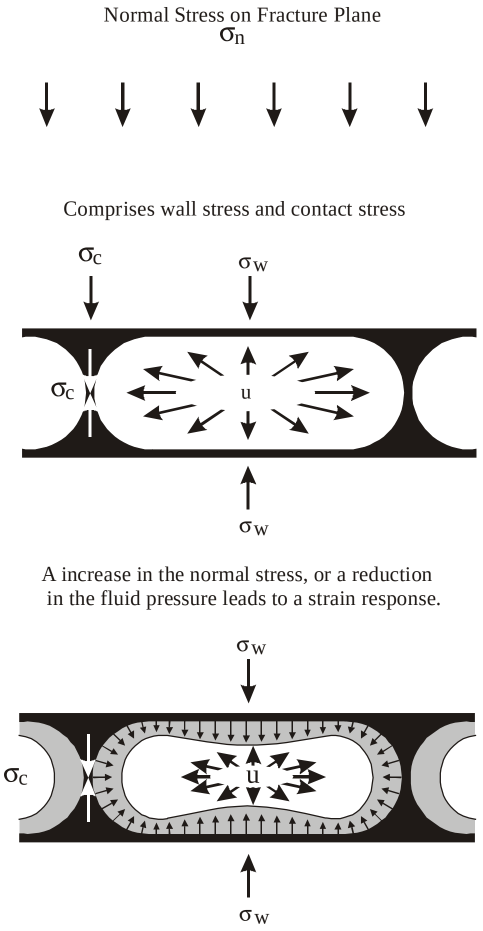


Figure 5: Wall stress, contact stress and strain deformation

Likewise if external pressure is applied, i.e. loading, the wall stress increases by the difference to the fluid pressure and the contact stress increases by the effective stress increase divided by the area of the contacts.

$$\Delta\sigma_c = \frac{\Delta\sigma'}{tCa} \tag{4}$$

For fluid pressure alteration

$$\Delta\sigma_w = -\Delta u \tag{5}$$

or for a change in normal stress

$$\Delta\sigma_w = \Delta\sigma_n \tag{6}$$

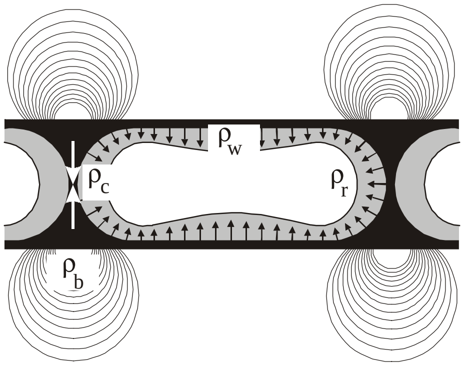
At this point it is possible to see that the change in effective stress can either be given by a change in the fluid pressure (u) , i.e. fluid injection or extraction, or an increase in the normal stress (σ_n), i.e. external loading. This means that by considering effective stress both the effects of fluid extraction or injection can be considered as in the case of a geothermal reservoir, and the effects of changing the confining pressure on the sample as in laboratory compression tests (Durham 1997).

Strain response//Deformation of Rock and Fluid

The strain response to the increase in effective stress is modelled as a combination of four factors in the rock wall (Figure 6): -

(a) Fracture wall deformation (ρ_w)
(b) Fracture column deformation (ρ_c)
(c) Fracture base deformation (ρ_b)
(d) Fracture end deformation (ρ_r)

Fluid deformation (ρ_f) in terms of pressure changes due to fluid extraction or injection is also be considered.



Boussinesq bulbs of pressure causes deformation in the rock mass

Figure 6: Breakdown of strain response to changes in effective stress.

(a) Fracture wall deformation (ρ_w)

To determine the fracture wall deformation (ρ_w) firstly the displacement of the fracture wall is calculated after Poulos and Davis (1973):

$$\rho_w = 2\left(1-\upsilon^2\right)\frac{\Delta\sigma_w}{E}\left(c^2 - x^2\right)^{\frac{1}{2}} \tag{7}$$

Here σ_w is the wall stress, E the elastic moduli, υ is poisson's ratio, c and x are geometric terms described in Figure 7. The value of ρ_w is given at a distance c from the centre of the channel. This formulation is similar to that used by Bia et al. (2000) for the prediction of elliptical fracture aperture under tectonic stress.

The total displacement of the wall in terms of a volume (assuming unit depth) is given by the integral of (7) along the length of the width of the channel.

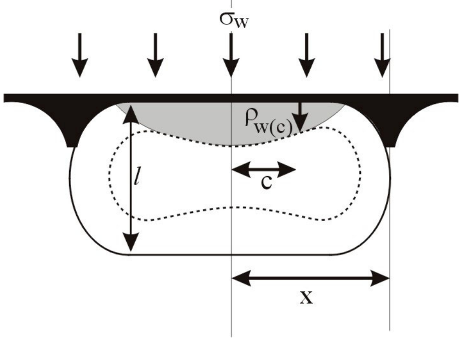


Figure 7: Inward movement of the fracture wall as a consequence of a reduction in fluid pressure or increase in normal stress.

(b) Fracture column deformation (ρ_c)

Column deformation, comprises a compression parallel to the contact stress (ρ_v) and a lateral expansion normal to the contact stress (ρ_h). Here *l* is the height of the column and *Ca* is the contact area of the individual contacts across the fracture plane.

$$\rho_v = \frac{l\Delta\sigma_c}{E} \tag{8}$$

$$\rho_h = \frac{Ca\upsilon\Delta\sigma_c}{E} \tag{9}$$

(c) Fracture base deformation (ρ_b)

The deformation of the base of the fracture is estimated by applying analytical solutions for the deformation of strip footings on elastic material as given by Giroud (1968) and summarised by Poulos and Davis (1974). Here the following formulation is derived for the specific case to derive the mean settlement

$$\rho_b = \frac{Ca\Delta\sigma_c\left(1-\upsilon^2\right)}{E}I \tag{10}$$

I is an influence factor depending on the geometry of the strip footing (Poulos and Davis 1974). For all the calculations the fracture was assumed to have a length of 1m, the asperities were sub millimetre scale.

(d) Fracture end deformation (ρ_r)

As the number of contacts increase so the formulation of the fracture end deformation becomes more important than the formulation of the fracture wall deformation. Again analytical solutions are used from the field of elastic analysis (11) derived from Poulos and Davis (1974). The end of the fracture area is considered to be equivalent to a circular opening in a uniform stress field. The change in stress is given by the change in the fluid (u) or wall pressure.

$$\rho_r = \frac{2\left(1-\upsilon^2\right)}{E}\Delta u\ r \tag{11}$$

It is interesting to note at this stage is that in (11), the displacement is a function of the original radius of the hole. In the case of a large number of contacts, as would be expected under high effective stress loads, the formulation of the closure problem reduces eventually to (11). With increasing closure pressure the hole gets smaller, but never actually closes. It should be noted that this formula is valid for incremental displacements, and gives an incorrect answer if one extremely large stress increment is applied instantaneously.

Examining this formula and allowing only elastic deformation of rock materials in none perfectly fitting fracture surfaces, it can be seen that it is impossible by normal stress alone to cause the fractures to be closed. There will always be a residual opening. Closure must therefore be due to a secondary influence such as deposition of minerals, plastic deformation, or shear and breaking movements.

(e) Fluid deformation (ρ_f)

Fluid deformation is given by

$$\rho_f = f_v C_f \Delta u \tag{12}$$

Where C_f is the fluid compressibility under the respective temperature and pressure conditions and f_v is the volume of the fracture.

<u>Hydraulic Parameters</u>

Permeability

Roughness in the fracture system is inherently included in the fractal distribution which is represented by an aperture distribution. From this distribution McDermott and Kolditz (2004) show that the fracture permeability is then given by

$$k_f = \frac{e^2}{12} \tag{13}$$

where e is the average fracture aperture. It follows then that the flow through the fracture for a pressure gradient *i (Pa/m)* is given as

$$Q = \frac{e^2}{12\mu}Ai \tag{14}$$

where *A* is the cross sectional area of the fracture through which flow is occurring.

In hydrogeology the equivalent permeability of the system is often considered. Here the formulation for determining the equivalent water permeability, i.e. that for a 1m² cross sectional area containing the fracture to provide for the flow in the system, can be derived from (14) as

$$k_e = \frac{e^3}{12} \quad (15)$$

also known as the cubic law (Witherspoon et al. 1980).

Storage

The storage of the fracture system is given by the sum of the change in fluid volume and fracture volume for a given pressure interval. This value is given by considering points ***(a)*** to ***(e)*** described above.

MODEL VERIFICATION, LABORATORY AND FIELD SCALE

Closure of a fracture: Experimental Data

The stress profile along the depth of the KTB boreholes has been investigated in detail by Brudy et al. (1997). As confirmed by Takatoshi and Zoback (2000) the stress field in the crust is dominated by the presence of fracture zones and the corresponding normal stress across those fractures combined with their resistance to movement. The total normal stress across the fracture coupled with the fracture fluid pressure, the material elastic and plastic properties, and corresponding deformation has an effect on the fracture opening and thereby the permeability, porosity and storage of the fracture system. Durham (1997) experimentally investigated the effect of confining pressure on a fracture taken from circa 3800m in the KTB pilot hole, measuring the closure of the fracture and the corresponding permeability. These results are taken and fitted with the geomechanical model described above using the known elastic parameters from the KTB site.

Figure 8 presents a fit of the experimental results obtained from Durham's work and those predicted by the model described above. The "fracture permeability", here k_d, given by Durham in his Figure 2 refers to "the fracture permeabilities for producing the same water flux in the same pressure gradient." distributed through the bulk of the sample.

A comparison of the parameters used to fit the experimental data and parameters available from the literature are given in Table 1.

The values of the poisson's ratio and the elastic modulus come from geophysical investigation described by Brudy et al. (1997). The geometrical parameters are similar but not identical to the geometrical parameters indicated by Durham (1997), in particular Durham gives the contact area for the fracture with an aperture of 0.05mm at around 40%. Here the contact area is estimated as being somewhat higher.

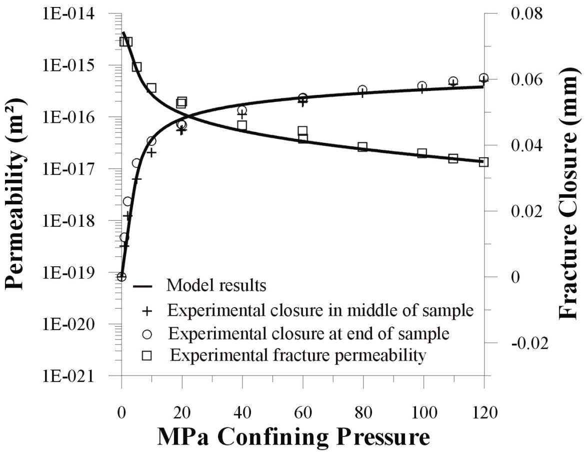


Figure 8: Comparison of experimental (Durham 1997) and modelled results.

The fit of the experimental results can be seen to be extremely good. This model is now applied to describe the geomechanical changes in the hydraulic characteristics of a fracture network under changes in effective stress in the KTB pilot hole long term pump test.

Table 1: Model parameters and literature parameters

Parameter	**Model**	**Literature**	**Source**
Elastic Modulus	120	100	Brudy et al. (1997)
Poisson's Ratio	0.28	0.28	Brudy et al. (1997)
Init. Contact Area	50%	to 40%	Durham (1997)
Max. Closure Contact Area	98%	Not avail.	
Min. Number of Contacts	100	Not avail.	
Max. Number of Contacts	100000	Not avail.	
Init. Aperture Opening	0.067mm	0.067mm	Durham (1997)

Field scale investigation.

A large amount of literature is available on the geological setting of the KTB boreholes and the fracture geometry, type and nature. Emmermann and Lauterjung (1997) provide a lead paper to a special edition in the Journal of Geophysical Research, concerned with research at the KTB site. The work of Hirschmann and Harms in several KTB reports and particularly Hirschmann et al. (1997) coupled with geophysical investigations of the borehole site, Harjes et al.. (1997), provide the basis for the development of a regional hydraulic model comprising principally a fracture network to define flow and transport. For the purpose of a more detailed modelling approach, the entire fracture zone was reduced to an volume of 4 km x 4 km x 2 to 8 km deep, and the meshing density was increased around the vicinity of the drill hole to enable a more accurate numerical representation of the system.

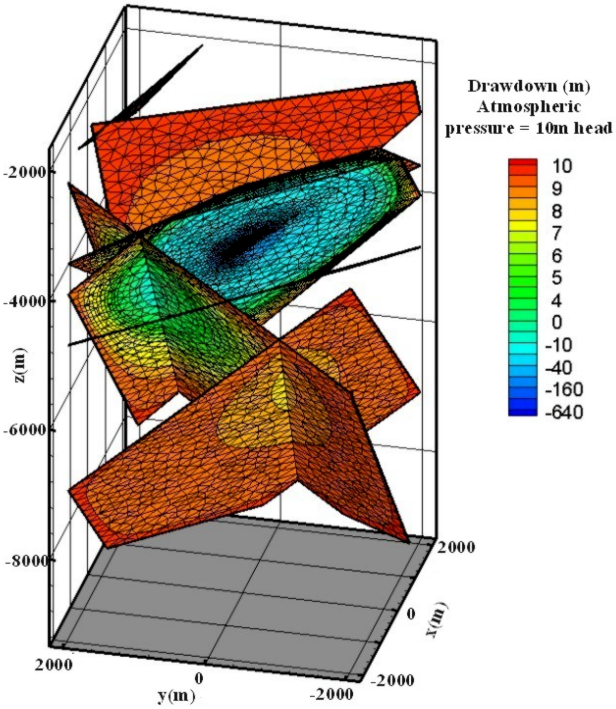


Figure 9: Fracture network for the KTB long term pump test.

In this model the fracture planes presented are considered to comprise several interacting smaller fractures. They are not localized breaks in the rock, rather shear zones which can be of the order of 100m+ in thickness. Hydraulic connection of the fracture network with the pilot hole occurs only over the last 150m open hole section of the 4000m deep pilot borehole. This fracture system was stimulated via a pump test starting June 2002. The results of over 350 days of this pump test are modelled here applying the geomechanical model described above coupled with a finite element program, RockFlow/GeoSys (Kolditz et al. 2003).

The effective stress in the fracture network is calculated as a function of depth, and the density of the fluid, as given by Huenges et al. (1997) at circa 1.06g/cm³. Changes in effective stress can be related over the geomechanical model to changes in the hydraulic parameters of the fluid conducting fractures as a consequence of extraction or injection. As a first approximation the stress field is considered to be isotropic and homogeneous so that the orientation of the fracture does not affect the normal stress across it. Kolditz (2001) summarises non-linear flow in fractured rock. Comparison with the fracture geometries and induced pressure difference indicates that non linear flow will occur only up to a distance of approximately 0.5m from the centre of the borehole. This calculation was based on an undisturbed fracture network, however in reality there is an excavation disturbed zone around the borehole resulting in the release of stress normal to the borehole and an increase in local permeability. This plus the fact that the area modelled was much larger in comparison to the 0.1m scale required for non linear flow modelling and that no clear non linear flow characteristics were observed in the hydraulic response, led to the decision to approximate the whole system as a linear flow regime.

Derivation of discrete parameters from the integral pump signal

Derivation of discrete parameters from the integral pump signal is possible because the storage and the permeability are individually related to the fracture aperture. Therefore the task is to fit the pumping response with a certain number of fractures at a certain depth with a specific aperture which all combine to give the required response in terms of storage and permeability according to the pressure conditions. Here the Durham fracture (Durham 1997) is considered to be the type fracture at the start of an iterative procedure against which the response is modelled. The geomechanical model described above gives the relationship between the permeability, storage, fracture aperture, mechanical constants and pressure conditions. The finite element model is uses the results of the geomechanical model as an input to model the field results. The iterative procedure is described in

Figure 10, two key relationships are given in (16) and (17) below, the symbols explained in Figure 10.

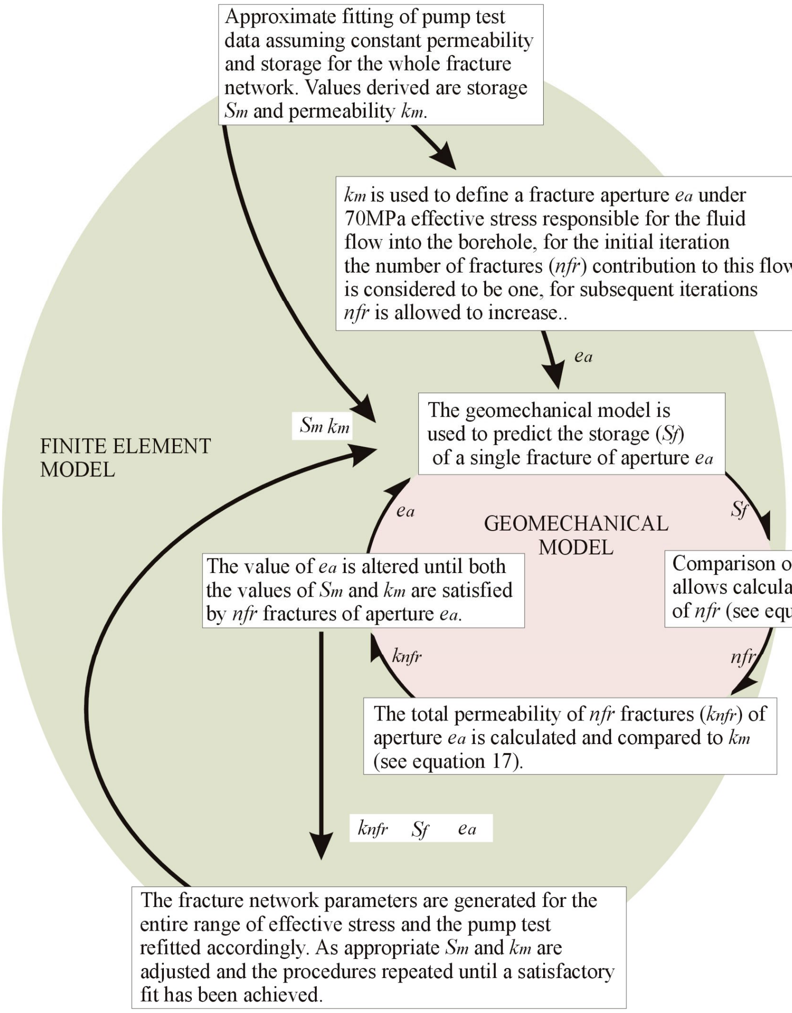
$$nfr = \frac{S_m}{S_f} \tag{16}$$

$$e_a = \sqrt[3]{\frac{12k_m}{nfr}} \tag{17}$$

The modelled fit of the pump data is given in Figure 11, the parameters used for this modelling fit are given below in table 2. The fracture parameters dependent on effective stress are illustrated in Figure 12.

Table 2: Parameters used for modelling the long term KTB pump test in the pilot hole.

Parameters for model fitting	
Number of fractures (nfr)	1105
Av. fracture aperture at 70MPa effective stress (mm)	0.0537
Temperature of Extracted Fluid (°c)	119
Density of Fluid (Kg/m³)	1.06
Viscosity of Fluid (cp)	2.45
Average Rock Density for Model Area (Kg/m³)	2800


Approximate fitting of pump test data assuming constant permeability and storage for the whole fracture network. Values derived are storage Sm and permeability km.

km is used to define a fracture aperture ea under 70MPa effective stress responsible for the fluid flow into the borehole, for the initial iteration the number of fractures (nfr) contribution to this flow is considered to be one, for subsequent iterations nfr is allowed to increase..

The geomechanical model is used to predict the storage (Sf) of a single fracture of aperture ea

Comparison of Sf and Sm allows calculation of nfr (see equation 16).

The total permeability of nfr fractures ($knfr$) of aperture ea is calculated and compared to km (see equation 17).

The value of ea is altered until both the values of Sm and km are satisfied by nfr fractures of aperture ea.

The fracture network parameters are generated for the entire range of effective stress and the pump test refitted accordingly. As appropriate Sm and km are adjusted and the procedures repeated until a satisfactory fit has been achieved.

Figure 10: Iterative procedure for derivation of discrete fracture parameters and fitting of pump test results.

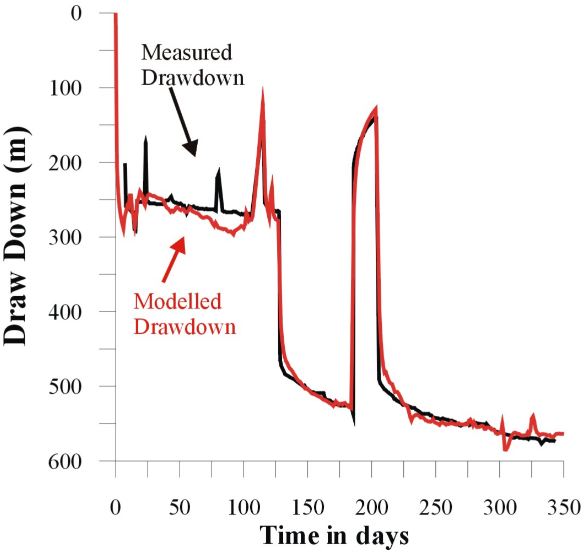


Figure 11: Modelling of field pump test values.

Results and Discussion

Applying this approach for the fracture zones in KTB, particularly the fracture zone SE2a, suggests that there are approximately 1000 fractures involved in flow. Referring to internal data of the KTB geological working groups, there are some 130 fractures or breaks in the zone directly hydraulically connected to the open hole section of the KTB pilot hole where this pumping test was carried out. From fracture logs of the main KTB borehole, located some 200m from the pilot hole, the shear zone SE2a can be seen to extend several hundred meters, indicating assuming around 1000 fractures to be simultaneously involved in flow is not unreasonable. The above fitting has been obtained by allowing all the fractures to have a constant width. However, in reality we can expect a certain, in this case unknown, distribution of fracture apertures in which the larger fractures would contribute significantly to the permeability, and a large number of smaller fractures/joints more significantly to the storage. Gräsle et al. (2003) present insitu experimental flow measurements and a model which indicates that there are two significant influx areas in the pilot hole. However without more detailed information on the fracture distribution it is not possible to go any further at this stage in the definition of the discrete fracture parameters.

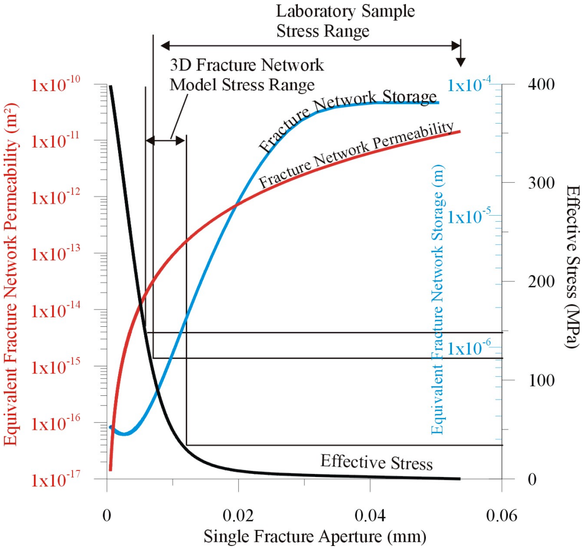


Figure 12: Storage and permeability of the fracture network, and effective stress as a function of the fracture aperture.

CONCLUSIONS

A coupled hydro-geomechanical model is presented which describes fracture closure under effective stress and the change in parameters such as storage, permeability, porosity and aperture. The model uses geometrical considerations based on a fractal distribution of apertures on the fracture surface, and applies well established analytical elastic deformation solutions to calculate the strain response in a fracture to increases in effective stress.

The model is applied with success to both laboratory scale single fracture experimental results and coupled with a finite element model to investigate a field scale long-term pump test.

At the laboratory scale experimental data on the closure of a fractured sample from the KTB borehole is modelled accurately. Fitting parameters comprising the elastic constants match independently measured parameters closely.

After accurate fitting of the laboratory experimental data, the model was applied to the long-term pump test at the KTB site. Equivalent hydraulic parameters determined by a finite element model of the fracture systems connected to the KTB pilot borehole were then analysed on hand of the geomechancial model to determine the number of fractures operating within the fracture zone. This geomechanical model was then used to improve the fitting of the pump test data to take account of the changes in the flow parameters within the fracture systems as a consequence of changes in effective normal stress across the fractures due to fluid extraction. In the end a fully integrated hydraulic and geomechanical model is constructed.

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