THREE-DIMENSIONAL SIMULATION OF FLUID FLOW THROUGH A DISCRETE FRACTURE AND MATRIX

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ABSTRACT

The study of fluid flow mechanics in fractured porous rocks is crucial in the area of oil and gas production industries, enhanced geothermal system (EGS), CO_2 sequestration, disposal of nuclear waste in deep geological repositories (DGR), etc. There are usually two types of flows in fractured rockmass setting. The dominant flow occurs through the fractures whereas there is also a slow movement of fluid through the matrix block. The fluid movement between fracture and matrix is often continuous across the fracture. The present study focuses on the development of a numerical model which can simulate the flow behavior through fracture and matrix simultaneously, which is also known as dual permeability model. To simulate this problem, a 3D model is built in COMSOL Multiphysics 4.3a where a cylindrical geometry is made, and a fracture is defined parallel to the axis of the geometry. The asperity of the fracture is defined by a variable 'a' which varies along the x-axis, in such a way that increases the value of 'a' alters the geometry of fracture and increases the roughness of fracture. Darcy flow physics is used to simulate the situation with known parameters like porosity, permeability, storage coefficient, etc. Pressure is applied as a boundary condition at two ends of the geometry which acts as driving force for fluid to flow through the block. The influence of fracture asperity on the flow behavior is examined by doing the parametric study and the study shows the decrement in the velocity magnitude with an increase in asperity. The formation of dual flow velocity regime, one along the defined fracture and the other along with the matrix, indicates the efficiency of the developed dual-porosity and permeability model.

Keywords: *Fracture flow, Dual porosity model, Darcy flow*

INTRODUCTION

Investigation of fluid flow behavior through matrix and discontinuities plays quite a major role in addressing the problems related to oil-gas exploration [1], carbon dioxide sequestration [2], enhanced geothermal system (EGS), disposal of nuclear waste in deep geological repositories [3], investigation of groundwater contamination [4], mine construction, dam designing and construction, slope stability analysis, etc. The flow structure in the karst lithology is generally comprised of multiple porosity and permeability, where the dissolution of the rock occurs due to acid action [5]. At the pore scale, the transport mechanism associated with the fluid flow causes solid structure alterations due to chemical reactions with minerals [6]. The multiple porosity model is the combination of matrix flow, fracture flow, and flows through other conduits. In different type of aquifers, these components of the flow may dominate over each other according to the properties of the aquifer. There are dual-porosity models as well as triple porosity models depending on the presence and dominance of flow components in the different type of flow paths (porous, fracture, cracks, etc.). Different types of analysis methods are used by the research community in the past to characterise the simultaneous flow through fracture and matrix[7–9]. In recent studies, these components are studied by coupling them using numerical modelling.

In fractured porous media, there are commonly two types of flows. Preferential flows occur through fractures, macropores, and other high permeability while there is also a relatively less dominant flow through the matrix. The simultaneous flow through the matrix and other discontinuities are usually studied using dual permeability model due to its computing ability. According to this model, the rockmass comprises of matrix and discontinuous domains which are overlapping as well as interacting. One domain doesn't have specific structure and direction, also known as matrix domain while dominant flow path occurs through the discontinuities such as fracture, fissure, cracks, etc. Matrix domain has relatively low permeability as compared to that of fast flow domain, but there is a continuous exchange of fluid between the two. The dual porosity and permeability model is very helpful in simulating problems related to landslide mitigation, subsurface flow mechanism, oil and gas exploration, etc. There are many hydrological problems that cannot be explained using single permeability Richards' and Darcian flow. But most of the software packages such as FLAC and PLAXIS use single permeability model to couple flow mechanics and rock mechanics for subsurface flow modelling. Single permeability formulation is also very useful for analyses related to many commercial geotechnical models but relatively less suitable for the quantification and proper understanding of the problem.

The discontinuities present in rockmass influence the mechanical behavior of the rock in many ways. They provide a plane of weakness along which failure may occur; also they provide conduits through which fluid flow can occur. The wall roughness of the fracture influences the hydro-mechanical and transport behavior of the rockmass[10]. The fracture roughness reduces the overall conductivity of the rockmass by locating the contact points of the wall and makes the flow path tortuous [11].

In order to advance in dual/triple porosity modelling, the understanding of pore scale study is very important. In the recent past, numerous pore scale models have been developed to characterise the flow behavior using numerical as well as empirical approach [12], [13], [14]. In this study, dual porosity and permeability model is developed by coupling pore scale flow and fracture flow. The interaction between these different components of the flow have also been investigated. The flow characteristics through a single fracture enclosed in the porous matrix is examined. The roughness of the fracture is varied using a defined variable and its effect on the flow parameters is discussed. The physical properties such as porosity, permeability, and matrix compressibility of different types of rocks are also used to study the role of rock properties on the flow behavior. To model the dual porosity and dual permeability model using numerical approach, two different dominant flows are taken in account. These are matrix flow and fracture flow, and the equations which govern this mechanism are shown and discussed in the next section.

GOVERNING EQUATIONS

Matrix flow

The fluid flow through the matrix is very common but the associated complexities make it difficult to completely understand the mechanism. The matrix flows are usually very slow and thus show laminar behavior. Equation (1) and (2) shows the time dependent formulation of Darcy's law and linearized storage model respectively.

$$\rho S \frac{\partial p}{\partial t} - \nabla.\left(\rho \frac{\kappa}{\mu} \nabla p\right) = 0 \tag{1}$$

$$S = \chi_f \varepsilon + \chi_p (1 - \varepsilon) \tag{2}$$

Where p is pore pressure, ρ and μ is the fluid density and viscosity, S is the storativity of the matrix, t is the time (s), ε and κ are the porosity and permeability of the matrix, is the dynamic viscosity of the fluid (Pa. s), χ_f and χ_p are the compressibility of the fluid and matrix (1/Pa).

$$\boldsymbol{u} = -\frac{\kappa}{\mu} \nabla p \tag{3}$$

The linear fluid flow velocity in the small pore interstices is more than Darcy's velocity, which shows that the flow velocity is distributed over pores as well as matrix.

No flow boundary condition is applied to all the faces of the cylindrical geometry as shown in equation 4.

$$\boldsymbol{n} \cdot \boldsymbol{u} = 0 \tag{4}$$

Where n is the unit vector pointing outward to the boundary, and zero dot product between **n** and **u** signifies that there is no flow across the boundary.

Fracture flow

Fractures are the most commonly occurring conduit for the fluid to flow through all kind of rockmass. The mechanism associated with the fracture flow are studied worldwide but still the proper understanding of the process is not clear to the scientific community. Experimental investigation of the flow associated with the fractures are very difficult because of the factors such as diversity, scale, and different origin of the fractures. But in the recent times after the introduction of the numerical modelling software, the fracture flow study has become relatively convenient and fruitful.

Flow in the COMSOL is generally defined perpendicular to the boundary, not along it. However, in this study, fracture is the taken as sequence of internal boundaries along which flow takes place and velocity equation in the fracture follows modified form of equation 1 as shown in equation 5.

$$\rho S_f d_f \frac{\partial p}{\partial t} - \nabla_T . \left(\rho \frac{\kappa_f}{\mu} d_f \nabla_T p \right) = 0 \tag{5}$$

Where, S_f, κ_f and d_f are the storage coefficient, permeability and thickness of the fracture respectively.

The variable **u** provides the volumetric flow rate per unit length because of the presence of thickness variable in the equation.

$$\boldsymbol{u} = -\frac{\kappa}{\mu} d_f \nabla_T p \tag{6}$$

Where ∇_T is the gradient operator limited to tangential plane of the fracture.

MODEL SET UP

The study has been performed on a three-dimensional cylindrical block, in which a discrete fracture plane is made parallel to the axis of the cylinder and the roughness of the discrete fracture is maintained with the help of a variable 'a' which varies along the x-axis. The model geometry used for the simulation with a rough discrete fracture is shown in Figure 1a. Darcy flow physics is selected in the model component to simulate the situation with known parameters like porosity, permeability, storage coefficient, etc. Pressure is applied as a boundary condition at two ends of the geometry which acts as the driving force for fluid to flow through the block. A fracture flow-node is employed on the interior boundaries to trigger the flow and interact with the matrix flow. The pressure change along the boundary are calculated automatically by the model in the form of tangential derivatives pTx, pTy, and pTz.

The asperity (a) of the fracture surfaces is also varied in such a way that an increase in the magnitude of variable 'a' increases the asperity of the fracture wall by using inherent geometric functions of the software. The variable 'a' has been provided a numerical value corresponding to the reach of the fracture in the direction normal to the fracture length. The magnitude of the 'a' is changed periodically around eight fixed points along the fracture length to make the surface of the fracture wall undulating and rough, and the fracture roughness is quantified using this variable. The value of a is varied from 0.05 mm to 2 mm to investigate the effect of roughness on the flow system in the porous media. The values of model parameters such as porosity, permeability, and storage coefficient are taken those of different rock types like sandstone, limestone, and granite. The effect of physical properties of the rock on the flow behavior is also studied with the help of this model.

Different types of fluids were also used as flowing media to flow through the matrix and fracture simultaneously to study the role of fluid properties in managing the fluid flow behavior in fractured porous media. In this furtherance, water, light oil, medium oil, heavy oil, and carbon dioxides are used as flowing media through a matrix of the block with a single discrete fracture. The change in flow behavior due to differences in the fluid properties such as density and fluid viscosity is also investigated.

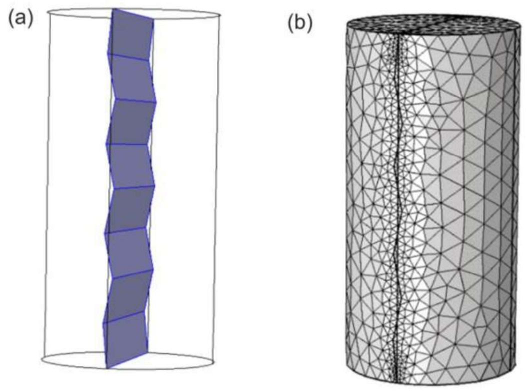

Fig. 1. *(a) Discrete fracture plane and (b) Meshing over the fractured core block*

The accuracy of the data and result obtained from the FEM model depends directly on the type of meshing used during simulation. This process of mesh refinement is a very crucial stage in validating a FEM model and gaining assurance in the model simulation results. Therefore, tetrahedral meshing is used in this model due to ease in the computation and fast processing of the model. The meshing is fine in the desired domain i.e., near the fracture plane and it is relatively coarse in the matrix domain which can be seen in Figure 1b.

RESULT AND DISCUSSION

Three-dimensional dual porosity and permeability model has been developed to simulate the flow through matrix and fracture simultaneously and investigate the mechanics associated with the flow. Generally, at a boundary, flow is defined perpendicular to the boundary, but in this study, fracture boundary is a sequence of interior boundaries that allows the flow along the boundaries. These internal boundaries are sequences using variable ‘a’ in such way that they form an undulating and rough fracture surface. The flowing media tends to favour the path along the zone of high permeability. The permeability of fracture is very high as compared to the matrix of the block. Therefore, flow is very prominent along the internal fracture boundaries but it slowly starts to move through the matrix with time. Since this is a time dependent study, the pressure drop in the cylinder is taken as a function of time. Figure 2**Error! Reference source not found.** shows the p ressure drop contours in the block at the final output time. The magnitude of the pressure distribution is shown in the legend. The arrows in the block represents the flow velocity magnitude and direction along the fracture boundary and represent the dominance of flow along the interior fracture boundaries.

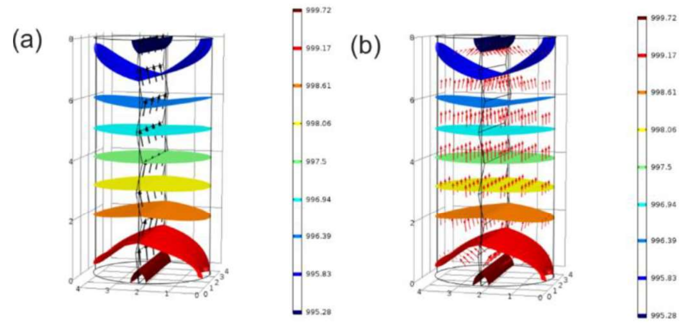

Fig. 2. *Fluid flow distribution in (a) discrete fracture, and (b) matrix block*

The flow through the fracture is dominant and the magnitude of the flow velocity along the fracture is represented by the black arrows as shown in the Figure 2a. The various colours of the isosurfaces are indicating different pressure in the geometry. The colour of the isosurfaces as shown in the legend ranges from (highest pressure) to dark blue (least pressure). The fluid is chasing the path of the fracture and the flow showing dominance along the rough path of the fracture. The shape of the pressure isosurfaces becomes curved near the extreme ends of the flow due to the enhanced flow activity at the fracture ends, later becomes relatively flatter because of regular exchange between matrix block and fracture. The curved nature of the pressure isosurfaces near the fracture inlet and outlet represents the distribution of the pressure at extreme boundaries due to excessive fluid movement in the fracture. As the fluid enters the fracture, it experiences high permeability, but due to relatively less permeable matrix block, the migration of the fluid from fracture to matrix becomes difficult. But as soon as fluid reaches the centre of the geometry, the pressure isosurfaces become flat because of even distribution of fluid pressure due to relatively easy exchange between fracture and matrix. The continuous distribution of the pressure in the block indicates the continuous exchange of flow between the blocks. However, the pressure isosurfaces bend represents the presence of different flow regime within the geometry. The arrows indicate velocities in the fracture zone and it is evident that the flow is dominant in the fractures. The distribution of the pressure isosurfaces suggests the drop in the pressure over time.

Similarly, Figure 2b represents the linear velocities of the fluid in the matrix along with the pressure isosurfaces. With no flow out of the matrix, the only fluid source is the fracture. The arrows indicate that fluid exits from the fracture at the outlet. The matrix flow is feed by the fracture at the inlet. The size of the arrow indicates the magnitude of the flow velocity, therefore is smaller than that of fracture.

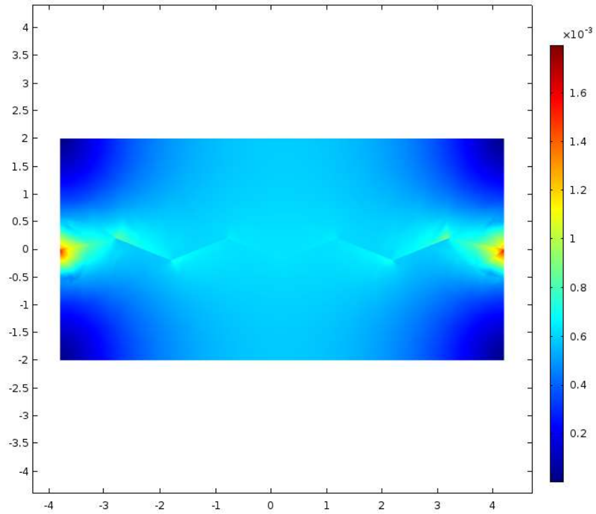

Fig. 3. *Surface plot of Darcy velocity parallel to the axis of the model geometry*

This model focuses on the qualitative investigation of flow through the matrix and fracture concurrently and shows anticipated flow behavior in the results. To study the role of fracture asperity on the flow behavior, asperity of the fracture is varied and the Darcy's velocity is plotted for each condition. The geometry of the fracture is varied using auxiliary sweep so that the asperity changes. Figure 4 shows the Darcy velocity profile for a range of asperities and surface plot of Darcy velocity parallel to the axis of the model geometry. It can be observed that with an increase in asperity, the velocity magnitude is decreasing. Also, Darcy velocity is maximum near the centre where the fracture is present, and it is lowering as fluid moves in the matrix. Asperity is varied using auxiliary sweep in the model geometry using a variable named 'a'.

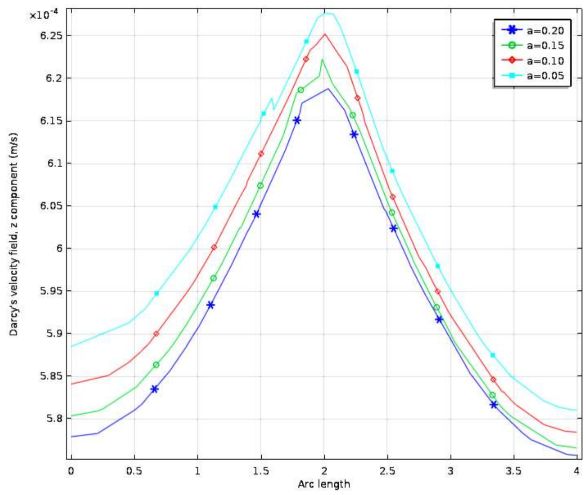

Fig. 4. *Flow velocity magnitude for different fracture asperities*

The Darcy's velocity magnitude is plotted and shown as the surface plot on the cross-sectional profile as shown in Figure 3. The colour spectrum shown in the legend represents the magnitude of the Darcy's velocity, dark blue colour indicates the least of the velocity as shown on the corner of the geometry. The flow through the matrix is relatively very slow as compared to the fracture, and thus represented by light blue colour. The flow through the fracture is dominant and also can be seen by the relatively light blue colour. The zig-zag pattern shown on the surface plot of Darcy's velocity indicates the fluid flow path along the fracture. The red colour of the spectrum represents the highest flow velocity and can be seen at the extreme ends of the fracture. As the fluid enters the fracture, the Darcy's velocity becomes maximum shown by red colour, and as it migrates and move towards the matrix the colour changes rom red to yellow, yellow to green and then green to blue, which represents the deceleration of the fluid in the matrix block.

The simultaneous flow through matrix and fracture can be simulated using the present dual-porosity and permeability model, which can provide information such as pressure drop, flow velocity magnitude and direction. The flow velocity distribution can be witnessed in fracture and matrix differently. The surface plot and cross-section profiles across and along the geometry helps in thorough understanding of the local velocity and pressure field.

CONCLUSION

The study focussed on the development of complex dual porosity and dual permeability model using a finite element approach to simulate the flow through matrix and a single rough fracture simultaneously. The results can be concluded in the following points:

1. The effectiveness of the model can be proved by analysing flow velocity and pressure plot in the study field. The velocity is maximum along the fracture and it is also distributed in the matrix due to the fluid exchange between fracture and the matrix depending on the porosity and permeability of the adjacent medium. The curved pressure isosurfaces plots indicates different flow stages can be observed in the early transition stage (Fracture to matrix) and the inter-porosity flow stage of matrix system to fracture system.

2. The role of fracture roughness on the flow mechanics is examined by defining a local variable that alter the relative roughness of the fracture geometry. It can be concluded that the affirmation by previous researches[10,15] that in a single fracture flow model, the flow velocity decrease with increase in fracture roughness holds true even in dual porosity and permeability model.

3. With necessary developments, this dual porosity and permeability modelling approach can be very useful in the geotechnical areas such as oil and gas reservoir modelling, Hydrogeological modelling, etc.

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