A System for the Modelling of Flow and Transport in Porous and Fractured Media

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ABSTRACT: This work presents the development of a system for the three-dimensional modelling of flow and transport in porous and fractured media. The system is composed of five computational programs, which are respectively responsible for the generation of geologic surface, generation of fracture network, generation of the finite element mesh, numerical analysis of flow and transport and results visualization. The system is able to model the porous, fractured, fractured porous media (porous and fractured medias interposed) and a combination of these. In the fractured or fractured porous media, the fractures generated can be of deterministic type and/or random type. The characteristics of the random fractures are generated according to probabilistic distributions or with constant values. Finite element meshs are generated individually for each fracture, and the compatibility between them is accomplished by using a planar mesh intersection technique. After that, the solid mesh is generated. The numerical analysis program uses the Finite Element Method to solve the governing equations, considering steady-state and transient flow, in saturated and unsaturated conditions. In the solute transport, the advection, dispersion, diffusion, sorption and decay mechanisms can be considered. The obtained results (total and pressure head, concentration and velocity field) are visualized graphically, allowing an easy interpretation. Numerical example is presented to validate and demonstrate the system.

1 INTRODUCTION

Engineering and geology problems related to the fluid flow and solute transport, generally involve the porous and the rocky media (these are usually fractured). Such problems appear, for example, in petroleum reservoirs, rocky slope, underground water aquifer and mines. For the study of these problems, the modelling of flow and transport is usually performed.

The modelling is an important component for understanding the hydraulic behavior of the media. This approach allows the estimation of damages caused by an aquifer contamination, to determine the water/oil pumping well influence in the system where they are inserted, to choose the best location for pumping wells and to assist the study of remediation of contaminated areas (Telles *et al.*, 2006).

The modelling of flow and transport in porous and fractured media is performed in six stages, presented in Figure 1.



Figure 1. Stages to modelling of flow and transport in porous and fractured media.

The first two stages (Field data collected, and Field data handling and Parameters determination) are not treated in this work, as they are not the subject of our research. Therefore, the modeling stages, for this work, comprise the Generation of fracture network, the Generation of finite element mesh, the analysis of Flow and solute transport and the Visualization of results.

The modeling is performed using specific computational programs for each of the stages mentioned above. The combination of these programs forms an integrated computational system of modeling of flow and transport in porous and fractured media.

In literature it is possible to find several computational systems that congregate the three stages of the modeling of porous media. Examples of these systems are the GMS (GMS, 2005) and the Visual MODFLOW (Waterloo Hydrogeologic, 2005).

Few systems, however, are capable of working with both fractured and porous media. Examples of computational systems can be the Napsac (Hartley *et al.*, 2002), the FracMan (FracMan, 2005) and the Connectflow (Hartley and Holton, 2003). These three systems present the advantage to congregate the four stages of the modeling. However, the Connectflow is only able to develop models considering the porous and fractured media. The others two systems model only fractured media.

In this work an integrated computational system to the modelling flow and transport (solute and particles) in porous and fractured media is presented. This system is able to performed analyses in porous, fractured, fractured porous (fractured media and porous media interposed) media, and in a combination of these media, as presented in Figure 2. It is also capable of representing the fractures and of defining regions for generic surfaces, treating the geometry of the mesh correctly and not in an approximated way, as made in the majority of the available commercial systems.



Figure 2. Combinations of porous and fractured media.

2 SYSTEM DEVELOPED

The system developed is composed of five computational programs, as presented in Figure 3.

2.1 Gocad

Gocad (Gocad, 2005) is an integrated CAD and a geological oriented program that supplies all the necessary tools to construction of geology, geophysicist and engineering of reservoir models.

The program is a solid modelling system, being capable of representing geometric objects and modelling space properties. It can be used in the construction of simple surfaces or to produce complex solid models. Gocad can be applied in the following areas: structural geology, petroleum geology, geophysics, reservoir modeling, and mine.

In this work Gocad is used for the generation of surfaces that represent geologic structures, for example, the faults and the geologic bedding.

2.2 FracGen3D

FracGen3D (Three-dimensional Fracture Generator) is a threedimensional graphical interactive program responsible for the generation fracture networks (Telles *et al.*, 2005). The program is capable of generating deterministic fractures and random families of fractures, considering their respective characteristics (orientation, aperture, spacing, size, form and space position). Moreover, the program presents the following functionalities: generation of regions, generation of wells, importing well geometry, importing field data of wells, importing surfaces, application of initial and boundary conditions of flow and solute transport, definition of the fluid properties, and definition of the numerical analysis data.

The fractures generated for the program are represented by planar surfaces. Their form can be circular or polygonal. Fractures can be also represented by surfaces with arbitrary form. These surfaces are imported from Gocad.

Fractures are generated inside the regions, that represent the diverse geologic horizons, characterized for distinct properties. These regions can be a porous media, a fractured media or a

fractured porous media. Regions are defined as a parallelepiped or as an arbitrary surfaces.

Figure 4 presents the graphical interface of the program. A single region with two fracture families (vertical polygons) and a family of joints (parallel sub-horizontal surfaces) are presented.



Figure 3. Programs that compose the system developed.



Figure 4. Graphical interface of the FracGen3d program.

2.3 MG

The Geometric modeller MG (Coelho *et al.*, 2000) is responsible for the generation of the finite element meshes of the fractures and the porous media. The fractures are represented by triangular elements and the porous media by tetrahedral elements.

The generation of the mesh initiates after reading the data file created by the FracGen3D. MG first generates an initial mesh for each fracture and after that it intersects the individual meshes, generating a mesh of compatible finite elements (Figure 5). If necessary, volumetric meshes (tetrahedral elements) are generated inside of each domain representing the porous media.



Figure 5. Compatibility between the finite element meshes.

After that, the initial and the boundary conditions and physical properties are associates in the nodes and elements of the mesh. Finally, a data file is created for use in the numerical analysis program.

Figure 6 presents the summary of the necessary steps for the generation of the finite element mesh in an example composed of two regions. The superior region represents a porous media and the inferior region represents a fractured media. The Figure 6a was capture from FracGen3D and Figures 6b-d were captured from MG. In the Figure 6a, are presented the regions that define the model domain and the fractures that are inserted in the inferior region. In the Figure 6b are presented the initial and individual meshes associates to the fractures and the regions. Figure 6c shows the model after the intersection of the individual meshes. This figure also shows the clipping of the undesirable fractures parts. Figure 6d is presented the final mesh that will be sent for the analysis program.



(a) FracGen3D: fracture planes and regions that define the model domain.(b) MG: initial meshes associates to the fractures and the regions.(c) MG: result mesh after intersection and the clipping.(d) MG: final mesh.

Figure 6. Summary of steps in the finite element mesh generation.

2.4 FTPF-3D

The FTPF-3D (Simulating Flow and Solute Transport in Porous and Fractured Media - Three-dimensional) (Telles, 2006) is a three-dimensional program to flow and transport (solute and particle) analysis in porous media, fractured media, fractured porous media, and in a combination between the media (Figure 2). This program was developed based on SWMS3D (Simunek *et al.*, 1995) that simulates flow and solute transport in porous media.

The numerical method used to solve the governing equations is the Finite Element Method. The numerical analysis can be carried in steady-state or transient conditions, in saturated or unsaturated conditions. In the solute transport, the advection, dispersion, diffusion, sorption and decay mechanisms are considered.

The program uses the modified Picard method (Huyakorn and Pinder, 1983) to solve the non linear equation of unsaturated flow. For the solution of the system of linear equations of flow the preconditioned conjugate gradient method (Mendoza *et al.*, 1991) or Gauss elimination method is used. For the solution of the system of linear equations of solute transport package ORTHOMIN (preconditioned conjugate gradient method) is adopted (Mendoza *et al.*, 1991).

More detail on the implemented numerical formularization in the program can be found in Telles (2006).

2.5 Pos3D

The Pos3D (Pos3D, 2005) is an interactive graphical program for visualization three-dimensional finite elements models results (solid and surface models).

It is considered a generic program, because he allows the visualization of models with any type of finite element and considers any type of analysis. The description of the elements and type of analysis is made through a standard file that contains information on the finite element mesh and the results.

In this work the Pos3D is responsible for the visualization of total head, pressure head, velocity field and concentration results.

3 EXAMPLE

3.1 Flow and solute transport in fractured porous media

This example presents the results of a numerical analysis of flow and solute transport in unsaturated media. The model is composed of two regions. One represent the porous media (region 1) and the other represent rocky media (fractured porous media) (region 2), as it can be seen in Figure 7. The position of the contaminant source is also shown in the figure. The model presents dimensions of 100.0x50.0x50.0m, approximately.

In region 2 two deterministic fractures were generated, as presented in Figure 7. Fracture 1 presents an orientation of $0^{\circ}/80^{\circ}$ (dip direction/dip), an aperture of 10.0 mm, a hydraulic conductivity of 7.0 x 10^{6} m/day and a specific storage of 4.5 x 10^{-6} m⁻¹. Fracture 2 presents an orientation of $180^{\circ}/20^{\circ}$ (dip direction/dip), an aperture of 5.0 mm, a hydraulic conductivity of 1.7 x 10^{6} m/day and a specific storage of 4.5 x 10^{-6} m⁻¹.



Figura 7. Surfaces that delimit the region of the model (region 1 and region 2), fractures generated in region 2, and source position.

The porous media of the region 1 and 2 present hydraulic conductivities of 1.2 /day (representative of a silty sand) and 10^{-4} m/day (representative of a sandstone), respectively. The specific storage of the two regions is de 0.0003 m⁻¹.

The finite element mesh present 4850 nodes and 24794 elements, being 774 triangles and 24020 tetrahedrons. Figure 8 present the finite element mesh oh the model.

The model is initially unsaturated with pressure head of 0.0 m applied to the surface of the porous media.

Figure 9 presents the total head result in the time of 40.0 days. The flow occurs from top to bottom.

In the Figure, the influence of the fractures in the saturation of region 2 is verified clearly. In this region, high values of total head in the zones near to the fractures are observed. It can also be observed that for the time of 40 days, region 1 already is saturated.

Figure 10 presents resulted of the field velocity in a specific section of the model. These results were obtained in steady-state condition. The continuous lines indicate the localization of the contact surface between the two regions and the localization of the fractures.



Figura 8. Finite element mesh.



Figura 9. Total head result in the time 40.0 days.



Figura 10. Velocity field in steady-state condition.



Figura 11. Concentration result in 860 days.

Figure 11 presents the results of concentration in the time of 100 days. The contaminant is transported basically in region 1, and it does not reach the fractured porous media.

4 CONCLUSION

This work presented the development of a system for the threedimensional modelling of flow and transport in porous and fractured media. The system is composed of five computational programs, which are respectively responsible for the generation of geologic surface, generation of fracture network, generation of the finite element mesh, numerical analysis and results visualization.

To demonstrate the developed system an example of the flow and solute transport in fractured porous media was presented.

The results show the influence of the fractures in the saturation of the model. High values of head in the zones near to the fractures are observed. This fact shows that the fractures have been consider in studies of the flow and solute transport in porous and fractured media.

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