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GEOMASS: GEOLOGICAL MODELLING ANALYSIS AND SIMULATION SOFTWARE FOR THE CHARACTERISATION OF FRACTURED HARD ROCK ENVIRONMENTS

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ABSTRACT

This paper presents the development and functionality of a suite of applications which are being developed to support the geological investigations in the Tono URL. GEOMASS will include 3D geological modelling, 3D fluid flow and solute transport and 3D visualisation capabilities.

The 3D geological modelling in GEOMASS will be undertaken using a commercially available 3D geological modelling system, EarthVision. EarthVision provides 3D mapping, interpolation, analysis and well planning software. It is being used in the GEOMASS system to provide the geological framework (structure of the tectonic faults and stratigraphic and lithological contacts) to the 3D flow code. It is also being used to gather the geological data into a standard format for use throughout the investigation programme.

The 3D flow solver to be used in GEOMASS is called Frac-Affinity. Frac-Affinity models the 3D geometry of the flow system as a hybrid medium, in which the rock contains both permeable, intact rock and fractures. Frac-Affinity also performs interpolation of heterogeneous rock mass property data using a fractal based approach and the generation of stochastic fracture networks. The code solves for transient flow over a user defined sub-region of the geological framework supplied by EarthVision.

The results from Frac-Affinity are passed back to EarthVision so that the flow simulation can be visualised alongside the geological structure. This workflow allows rapid assessment of the role of geological features in controlling flow. This paper will present the concepts and approach of GEOMASS and illustrate the practical application of GEOMASS using data from Tono.

1 Introduction

One of the principle mechanisms for the transport of radionuclides from a repository to the surface is the movement of groundwater. Understanding groundwater flow through the sub-surface geological environment is thus a key requirement of site characterisation activities. Developing this understanding requires characterisation of the geological structure and setting; and the acquisition and modelling of hydrogeological information. However, these aspects of site characterisation are commonly treated separately during site investigations and a need to make site characterisation data more accessible for modellers has recently been recognised by Geier (1997).

In hard fractured rocks the principal groundwater pathway for the migration of radionuclides are the fractures within the rocks. This has led to the development of a dual approach to modelling groundwater flow in which the regional flow is calculated using porous medium approaches and local flow is modelled by fracture network modelling techniques (e.g. Nirex, 1997). Both the integration of these approaches and the conceptual approaches used in the modelling have well-known shortcomings. Firstly, in a pure porous medium approach there are difficulties in representing the fast flow channels or preferential pathways due to fractures and faults. Secondly, pure fracture network models fail to account for any flow in permeable parts of the intact rock in which the fractures are located, which means that the simulated flow is critically dependent on the connectivity of the fracture network.

In order to overcome both the problems of the lack of integration of geological and hydrogeological investigations and the limitations of standard porous medium or fracture network modelling a new software system, GEOMASS (GEOlogical Modelling, Analysis and Simulation Software), has been developed for application at the Tono research centre in Japan. This paper describes the GEOMASS system and presents results from testing of the code.

2 Overview of the GEOMASS System

The workflow for the GEOMASS system is illustrated in Figure 2-1. The system provides software solutions for three aspects of the characterisation of hard fractured rocks. Firstly, the EarthVision geological modelling system provides the capability to construct 3D geological models and provides a suitable environment for the organisation of geological data into a standard format for interpretation, visualisation and analysis. Secondly, fluid flow is simulated using Frac-Affinity. Frac-Affinity is a code which allows the user to simulate three-dimensional flow in a heterogeneous, fractured rock.

The main new feature in Frac-Affinity is that it adopts a “hybrid medium” approach to the representation of fractured rock, which includes both permeable, intact rock and fractures. Thirdly, visualisation of the output from Frac-Affinity against the geological models is provided by EarthVision visualisation routines.

2.1 Geological Modelling using EarthVision

Geological modelling systems are families of software programmes which allow the construction of integrated 3D models of site investigation data, including subsurface geology, surface geography and engineering features. These systems concentrate on the development of static models which aim to produce a descriptive representation of the surface and subsurface and thereby provide the user with the ability to increase his understanding of the area of interest and to predict away from data locations.

3D geological models are commonly built by combining a structural framework with information on rock and fluid properties (e.g. porosity, hydraulic conductivity, fluid density or hydrochemistry) which have been interpolated away from data locations. The structural framework consists of 2D surfaces which represent stratigraphic boundaries or discontinuities (e.g. faults, fractures and dykes). In EarthVision, 2D surfaces are represented by a regular xy grid in which the elevation z is defined as a variable at each xy point. Property interpolation in EarthVision is undertaken onto a 3D array of points in which the 3D array is treated in a manner analogous to a 2D grid.

In order to test the integration of the GEOMASS system 3D geological models were constructed of the Tono area at a number of scales. These included a regional model encapsulating the drainage divide which is 12.21 x 11.23 km (Figure 2-2) and a local model centred around the area of site characterisation data which is 4.725 x 2.45 km (see Figure 2-7). The Tono area is underlain by a large Cretaceous granite pluton (the Toki Granite, Figure 2-2). Overlaying the unconformity surface at the top of the granite are a series of Miocene basins which host uranium mineralisation. The Mizunami Basin (see Figure 2-7) is the site for the Tono URL. This basin is offset by a reverse fault named the Tsukiyoshi Fault (see Figure 2-7).

The first step in the construction of the geological models was to organise the geological data into a standard format for integration and modelling of surfaces. A series of protocols and working practices were designed in order that the model construction process could be fully traceable and that subjective decisions could be recorded within the database. These protocols were based around three principles. Firstly, all data was collected into a sub-directory of the database to record the data in the form it was collected. Secondly, file naming protocols were adopted which allowed any user of the system to identify a file easily. Thirdly, description logs were added to the file headers to describe the generation and use of each file within the database.

The geological models were then constructed by generating grids for each surface represented in the geological model, defining the topological relationships between the grids (by constructing a file called a *sequence file*) and then using the programs within EarthVision to integrate the grids and build a visualisation file. The geometry of the grids for each surface were controlled by the input data. Where the input data were sparse extra data were interpolated or shape transfer procedures were used to guide the gridding process. The sequence file used to define the geological models is a critical part of the GEOMASS workflow, in that it controls the construction of the geological models and the construction of the flow simulation grid.

2.2 Flow Simulation using Frac-Affinity

The basic idea behind the hybrid medium approach is represent a volume of fractured rock as two main components: "discrete features" and "intact rock" (Figure 2-3). Discrete features are objects such as faults or fractures that introduce linear/surface variations in the properties of the rock. A distinction is made between "deterministic discrete feature" which are relatively large scale features whose geometry might be determined accurately by a regional geological investigation, and "stochastic discrete features" which are the smaller scale fractures about which partial information may be interpreted from core logging or mapping (Figure 2-4). The intact rock is the remaining rock which is either completely intact or only contains "micro-fractures".

An additional feature of the hybrid medium approach is that it incorporates spatial variability in the properties of the intact rock and discrete features, both as a result of stratigraphy and more local heterogeneity. The stratigraphy is accounted for by using the output from the geological modelling as the framework in which rock properties are distributed. The local heterogeneity is simulated using geostatistical and fractal methods to generate interpretations of borehole data.

Properties of the intact rock are most naturally thought of as being associated with a volume (a "cell"). The approach adopted in Frac-Affinity is therefore to populate the cells in a grid with flow properties (conductivity, porosity and specific storage coefficient) which may be different in different stratigraphic zones. The rock properties may be uniform or spatially variable in different stratigraphic zones and may also be conditioned on borehole data.

Properties of the discrete features are more naturally associated with channels inside the features. The approach adopted in Frac-Affinity is therefore to generate a network of flow channels. In the large-scale deterministic features this is undertaken indirectly, by first gridding the feature's surfaces, and then identifying the equivalent network. In the stochastic features, the flow pathways network is identified directly.

Initially, the intact rock, deterministic discrete features and stochastic discrete features are handled separately. They must however be "merged" to form a hybrid medium. The approach adopted in Frac-Affinity is to convert the intact rock grid to an equivalent flow network, so that the representations of the three components of the hybrid medium are comparable. The three networks can then be joined, although particular care must be taken in handling the connectivity within and between the three networks, since the connectivity of pathways plays a key role in flow. A visualisation of a full hybrid medium network is illustrated in Figure 2-5.

Frac-Affinity is accessed using the Frac-Affinity Interface in either input or output mode (Figure 2-1). Both the input and output modes of Frac-Affinity are controlled by command-line prompts. The input mode of the Frac-Affinity Interface is used to define the geological structure and hydrogeological properties, and the boundary conditions and flow solver controls used in the simulation.

Frac-Affinity has been designed for application during the characterisation and operation of the proposed Tono URL. Therefore, the flow solver has the necessary conditions to simulate this scenario. These include time dependency, in terms of time dependent boundary conditions and hydrogeological parameters, and internal boundary conditions to simulate shafts and galleries.

2.3 Analysis and Visualisation of Flow Simulation Results

The output from Frac-Affinity is controlled by the Frac-Affinity Interface in output mode. The main outputs available from Frac-Affinity are; the intact rock and discrete feature properties; the head field across the model; monitor points, lines or planes at which the head values are output; flux planes; and pathlines. All of these outputs are output in a format suitable for importing either to a standard spreadsheet package or for visualisation and analysis in EarthVision. Two examples of the visualisation of Frac-Affinty calculation results are illustrated in Figures 2-6 and 2-7.

Figure 2-6 illustrates the calculation of the head field for the Regional Model. In this simplified example the boundary conditions were set to topographic, the east and west boundaries were defined as no-flux planes and the hydrogeological parameters were set to uniform (the hydraulic conductivity being an order of magnitude higher in the sedimentary cover than the granitre basement). Figure 2-6 illustrates the effect of thickening of the sedimentary basins towards the centre of the model has on the head field.

Figure 2-7 illustrates the interpolation of heterogeneous rock mass properties on the Tsukiyoshi Fault in the Local Geological Model. In this instance the Tsukiyoshi Fault was modelled as a deterministic discrete feature. It can be seen from Figure 2-7 that the Tsukiyoshi Fault has been defined with boundaries inside the model region and this provides no difficulty within GEOMASS. Also visualised alongside the geological structure in Figure 2-7 is a schematic representation of a pathline. This pathline represents the tracking of a particle through the flow simulation with a data point output from the simulation each time the particle moves from one network node to another.

3 Discussion

The GEOMASS system provides a number of advantages over traditional approaches to the characterisation of hard fractured rocks for radioactive waste disposal. One of the most significant advantages of the GEOMASS system is the integration between the geological and hydrogeological interpretations of the site. The transfer of the geological framework model to the fluid flow network has been automated. Therefore, this process does not require the simplification of the geological framework (which can introduce artefacts into the simulation grid) and can be achieved within hours.

The rapid transfer of 3D geological interpretations for flow simulation allows the influence of the geological interpretation on the result of the flow calculation to be more readily assessed. This provides the ability for a number of different conceptual models of the geological and hydrogeological data to be investigated and the impact of geological uncertainty on the flow solution to be investigated.

The geological models provide significant added value to site characterisation. Firstly, they can be used as quantitative representations of the understanding of the site presenting the latest interpretation of all of the site features (3D geological framework; interpolations of rock mass (hydraulic conductivity, porosity etc.) and fluid (salinity distribution) properties; locations and trajectories of boreholes; borehole testing intervals etc.). These standard representations can be used as a basis for the analysis of a number of different aspects of the site. For instance, a consistent interpretation of the geological structure can be used for 2D and 3D hydrogeological simulation if they are both derived from the same geological model. Secondly, the 3D geological models can be used to plan further investigations at the site (e.g. the drilling of boreholes based on an integration of the results of hydrogeological simulation with an interpretation of the 3D geological structure) and these further investigations can be predicted in advance.

The implementation of a hybrid model for hydrogeological simulation is also an important development within the GEOMASS system. This is a more realistic representation of the geological structure through which flow occurs and allows the calculation of porous and fracture flow mechanisms simultaneously. Therefore, the rock mass and fracture flow properties will control the flow solution not the connectivity of the fracture network. In addition, the development of Frac-Affinity overcomes the necessity of using a porous medium model for regional calculations and a fracture network model for investigations at the local scale. This has significant advantages in the development of integrated site characterisation studies.

It is intended that the GEOMASS system will be used throughout the investigations associated with the Tono URL. These include regional investigations into the geological environment; the construction of the shaft, including modelling, simulation and prediction prior to the shaft excavation; and the operation of the URL itself.

4 Conclusions

A 3D geological modelling, flow simulation and results visualisation system called GEOMASS has been developed to support the geological investigations at the Tono URL. The system allows integration of geological interpretation and fluid flow simulation. A new concept in fluid flow simulation, a hybrid medium representation which integrates intact rock and discrete features has been implemented in the 3D flow simulator Frac-Affinity. The GEOMASS system is available for the evaluation of the regional setting, excavation and operation of the Tono URL.

References

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Nirex, 1997. The Hydrogeology of the Sellafield Area: 1997 Update. UK Nirex Ltd, Science Report S/97/008, Harwell, UK.

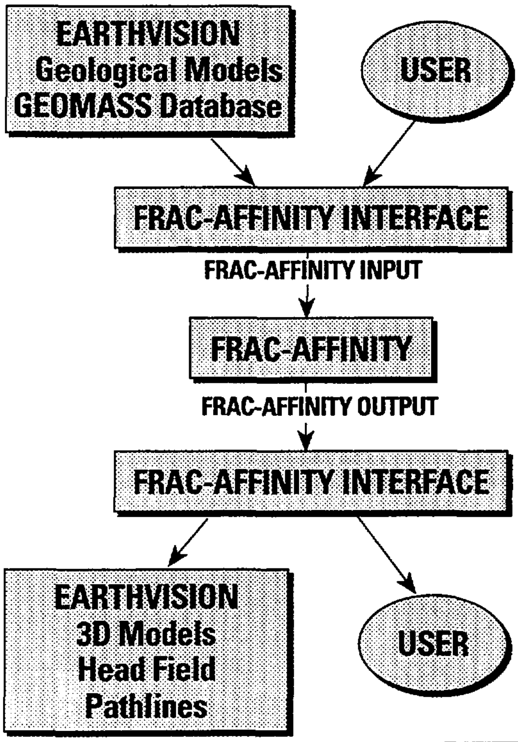

Figure 2-1 Workflow used in the GEOMASS system.

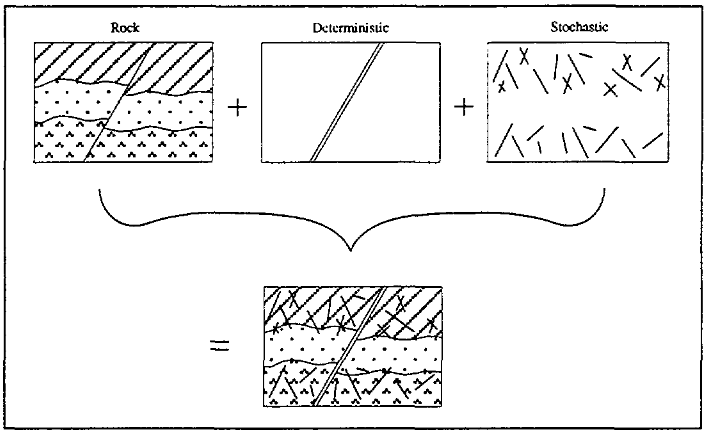

Figure 2-3 Schematic of the components of the hybrid medium: intact rock; deterministic discrete features; and stochastic discrete features.

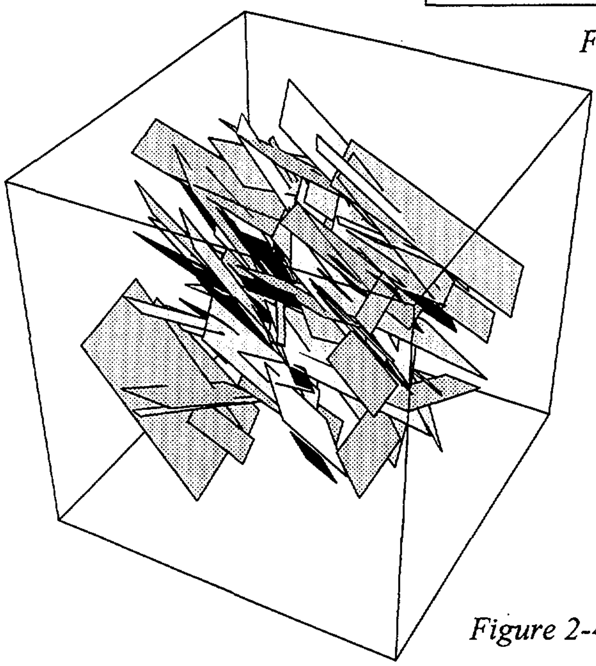

Figure 2-4 Example of a single-family stochastic fracture network.

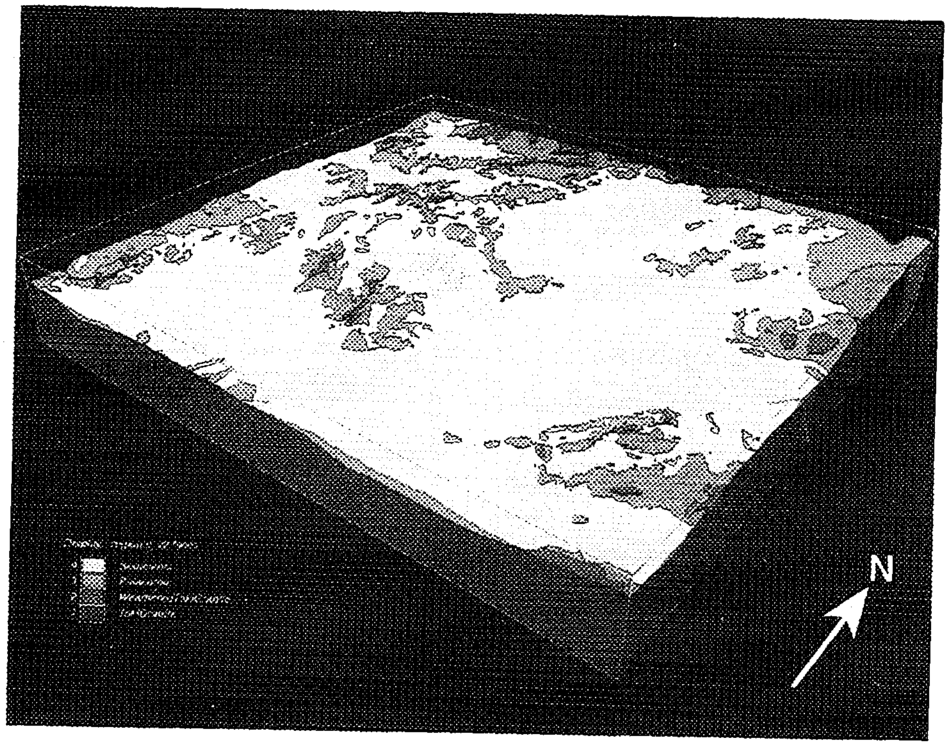

Figure 2-2 Visualisation of the geological model of the Tono Region area. The model area is 12.21 x 11.23 km and it contains four stratigraphic units and four faults.

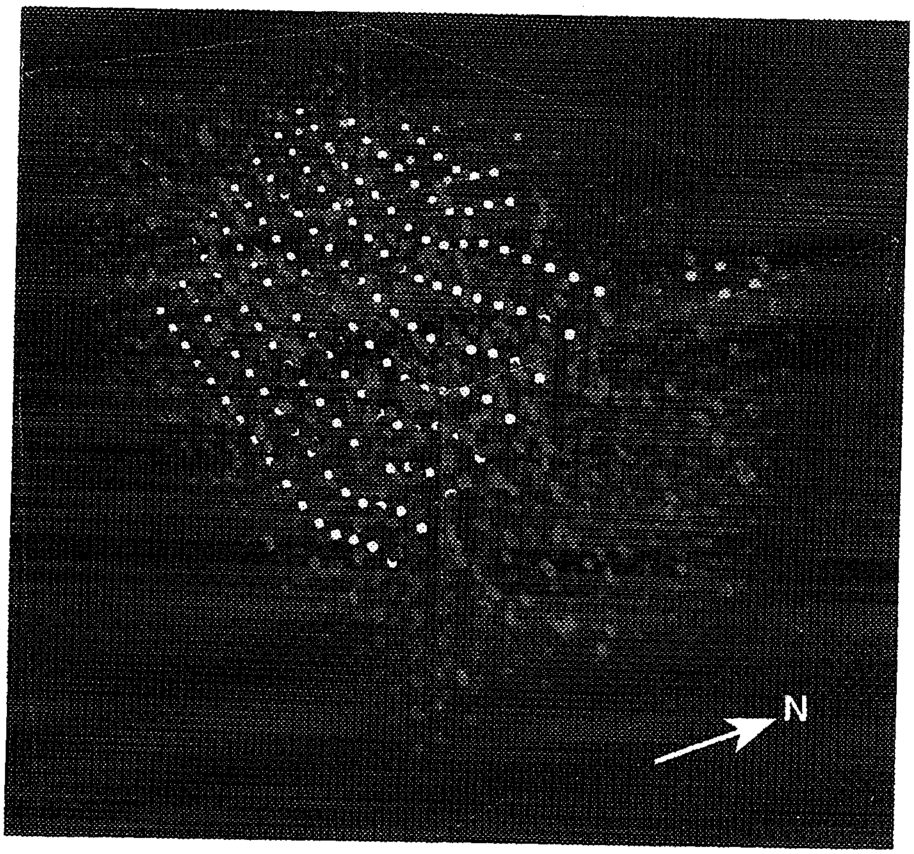

Figure 2-5 Visualisation of the network nodes for a small number of nodes in the Local Model. The red nodes indicate stochastic discrete features, yellow nodes a deterministic discrete feature and the purple and blue nodes the intact rock.

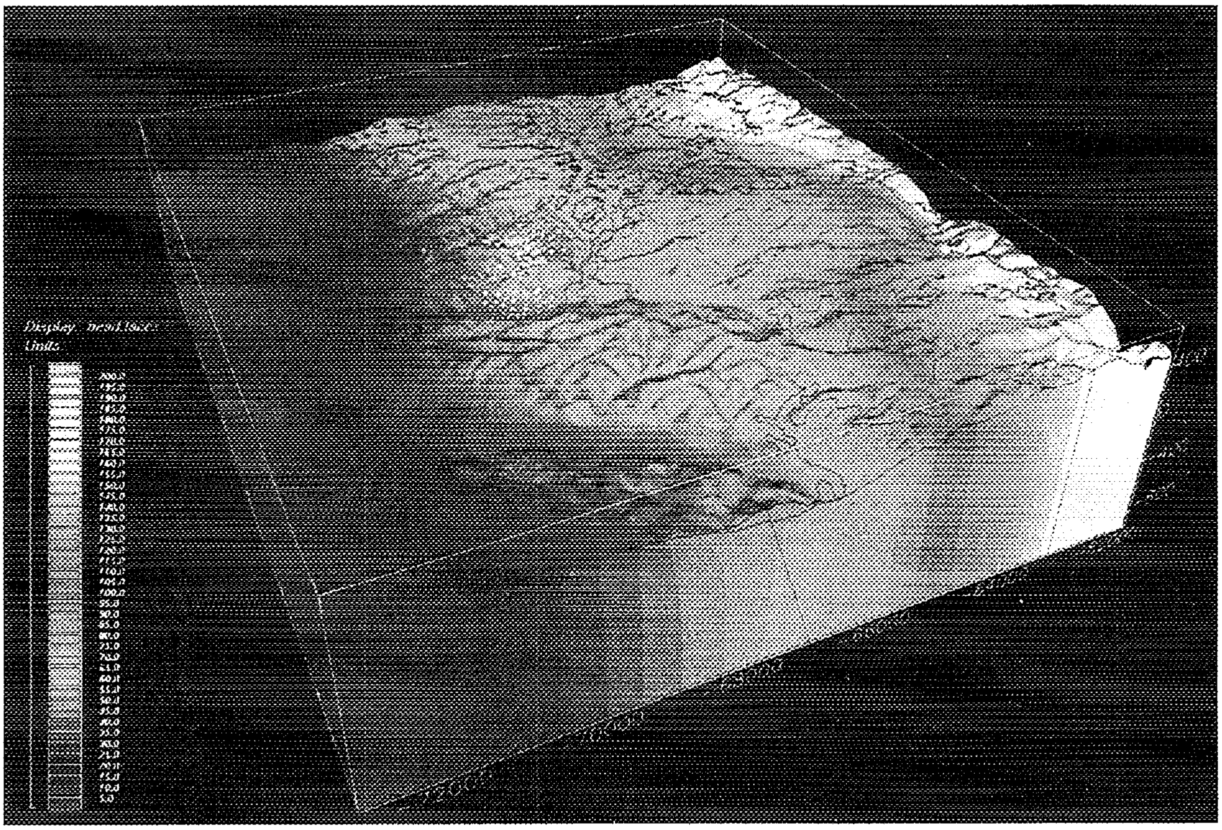

Figure 2.6 Visualisation of the calculation of the head field. In this steady state model uniform hydrogeological parameters have been assigned to the stratigraphic units. The boundary conditions are topographic head, with no flux boundaries to the east and west.

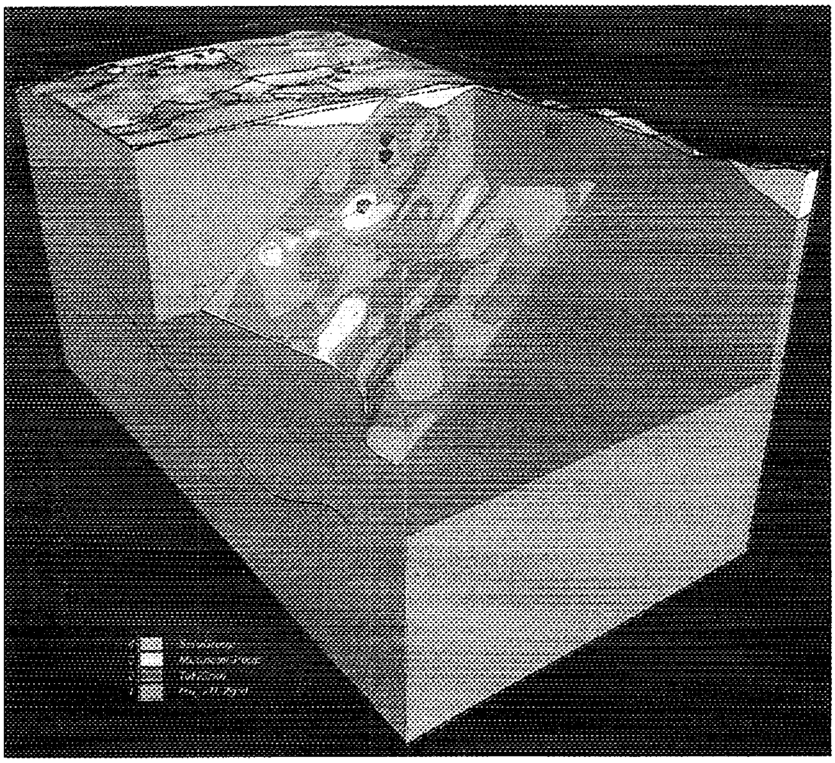

Figure 2.7 Visualisation of the Local Model (with simplified stratigraphy), with heterogeneous properties mapped on Tsukiyoshi Fault and a schematic representation of the visualisation of pathlines alongside the geological structure.