NAPSAC Verification Document
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Abstract

NAPSAC is a software package to model flow and transport through fractured rock. The models are based on a direct representation of the discrete fractures making up the flow-conducting network. NAPSAC uses a stochastic approach to generate networks of planes that have the same statistical properties as those that are measured for fractures in field experiments. The software is based on a very efficient finite-element method that allows the flow through many thousands of fractures to be calculated accurately.

This Technical Summary Document provides a list of the current capabilities of the program and a description of the numerical methods used.

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Preface

NAPSAC is a software package to model flow and transport through fractured rock. The models are based on a direct representation of the discrete fractures making up the flow-conducting network. NAPSAC uses a stochastic approach to generate networks of planes that have the same statistical properties as those that are measured for fractures in field experiments. The software is based on a very efficient finite-element method that allows the flow through many thousands of fractures to be calculated accurately.

The following documentation is available for NAPSAC:

- NAPSAC Technical Summary Document;
- NAPSAC On-line Help;
- NAPSAC Verification Document;
- NAPSAC Installation and Running Guide.

NAPSAC Capabilities

Simulation of fluid flow and transport in fractured rock is an essential tool for the study of water resources, oil and gas reservoir management, assessment of underground waste disposal facilities, evaluation of hot dry rock reservoirs, and for the characterisation and remediation of contaminated land. It can be used to interpret field and laboratory data, to validate conceptual models, to make quantitative predictions, and to develop practical solutions for a range of environmental, reservoir engineering, and civil engineering problems.

NAPSAC is a finite-element software package for modelling fluid flow and transport in fractured rock. A discrete fracture network (DFN) approach is used to model fluid flow and transport of tracers and contaminants through the fractured rock. NAPSAC incorporates fracture generation, flow simulation, upscaling, transport and 3D graphics capabilities using GeoVisage. The Graphical User Interface (GUI) to NAPSAC allows models to be generated and analysed quickly. A job submission ('batch') facility is included in the GUI that allows additional options not yet implemented in the GUI to be accessed - these features are indicated below[†].

NAPSAC has been developed over a 15-year period and includes a number of sophisticated capabilities, such as:
Geological modelling:

- NAPSAC has the flexibility to model a variety of scales varying from well/borehole scale to regional/reservoir scales. Detail can be included to model heterogeneity of a single heterogeneous fracture as well as models with many tens to millions of fractures at a regional or reservoir scale.
- the DFN approach allows users to compare aspects of their conceptual geologic models and field observations with simulated models. This comparison includes fracture orientation, size, transmissivity and flow distribution. An examination of the simulated network can be performed using hypothetical cores, stereonets, fracture maps and connectivity analysis.
- generation of regular and irregular meshes and structural grids (e.g. ZMap, VIP, FEMGEN and a CAD format);
- inclusion of deterministic fractures specified within the NAPSAC data or by importing a fracture file (e.g. GOCAD Vset, GOCAD Tsurf, Seisworks pointsets and other international formats). Deterministic Faults (or structures) can be used to control populations of stochastic fractures (i.e. proximity or 'Damage Zone' models). For example, NAPSAC allows the clustering of fractures around parent fractures, random points or surfaces. NAPSAC allows spatially varying fracture densities based on 3D maps of fracture drivers;
- variable distribution laws for stochastic fracture parameters. NAPSAC can generate stochastic fractures from a wide variety of probability distribution functions. Not just Fractal!
- coupling of distributions/parameters for the same feature i.e. length-aperture relationships.
- areal / volumetric distribution of stochastic fractures can be imported from external map or grid data e.g. bed thickness, curvature ('strain'), lithological (mechanical) variation.
- dynamic behaviour of 'production fractures' and present-day stress can be incorporated.
- all scale ranges, from core observation to seismic scale, can be simulated and integrated into the final model.
- high permeability 'matrix streaks' may be incorporated into models as extra flow conduits.
- flow in the matrix can be represented by additional flow channels

NAPSAC is able to:

- simulate steady-state or transient flow in a fracture-network;
- enable steady-state calculations to be performed on very large networks, because it uses an efficient finite-element scheme;
- calculate the full equivalent continuum permeability tensor including off-diagonals, principal values and principal directions. This is automated to sample flows in several different directions. This can be used for upscaling, analysis of scale dependencies and determination of the representative elementary volume (REV);
- calculate porosity and inter-fracture matrix block size;
- identify connected fracture clusters around wells;
- predict transient pressures and drawdowns at well bores for various types of pump tests;
- calculate steady-state and transient inflows to tunnels and shafts;
- calculate the effects of hydro-mechanical coupling. The hydraulic aperture is coupled to a stress distribution based on an analytical description of the stress field due to either rock overburden or a radial stress around a tunnel;
- simulate tracer transport through a network using a stochastic particle tracking method. Output[†] includes plots of breakthrough curves for many thousands of particles, particle tracks, swarms of particles at specified times or the points of arrival on the surfaces of the model. This can be used to calculate dispersion of a solute transported by the groundwater;
- simulate mass transport for a variable density fluid. This can be used to model coupled groundwater flow and salt transport[†];
- simulate unsaturated flow in fractured rocks;
- [†]analysis of percolation between surfaces.

NAPSAC can be used for the following applications:

- simulation of a range of hydrogeological tests (hydraulic borehole/well tests, including constant, head, pressure and flow tests);
- site and regional scale modelling to determine the effects of various forms of fracture flow on pressure distributions, flows and travel times to discharge points under natural conditions;
- to understand and simulate the behaviour of fracture-influenced sites/reservoirs by being able to parameterise and justify heterogeneous continuum models. For example, the estimation of equivalent parameters for input to conventional dual-porosity simulators;
- simulation of solute transport (tracer) experiments;
- simulation of the hydraulic impact of a tunnel or shaft construction;
- simulation of various simple hydromechanical models for the purpose of estimating the impact of rock overburden and in-situ stress.

NAPSAC has been used in the following industries:

- water resources for the purpose of hydraulic test and tracer simulation, fractured reservoir estimation and parameterisation, and remediation studies (such as the estimation of fracture flow in dual-porosity systems). In addition, it can be used to model saline intrusion and unsaturated flow;
- deep radioactive waste disposal, as both a tool useful for site-characterisation and safety assessments (simulation of hydrogeological tests and estimation of flow distributions and travel times to the biosphere);
- oil and gas industry to aid well planning, simulation of various well tests (PBU etc), and the parameterisation of oil simulation software by calculation of up-scaled equivalent continuum parameters (permeability, porosity and matrix block-size and distribution);

- hot-dry rock studies to estimate connectivity and parameters (permeabilities), to help analyse the effectiveness of the fractured reservoir;
- civil engineering projects concerned with construction or groundwater remediation in fractured rock. This includes the estimation of water ingress due to excavation of tunnels, studies of underground oil caverns, dam construction in fractured rocks, remediation or containment of contaminated fractured sites.

1   Introduction

The NAPSAC fracture network code was developed to simulate flow and tracer transport through fractured rock. It is assumed that flow through such rock is restricted to a connected network of fracture planes and that there is no flow through the rock matrix. The flow field is completely characterised by the pressure, and NAPSAC calculates this at points along the intersections between fracture planes.

Applications of NAPSAC include:

- analysing percolation (i.e. connectivity) between surfaces and between wells;
- interpreting site characterisation programme data;
- modelling of regional fracture network systems;
- obtaining effective properties as data input to a large-scale effective porous medium model.

In site characterisation programmes, NAPSAC has been used to validate the fracture network approach by comparing data from hydrogeological experiments in fractured rock (*e.g.* well tests) against model predictions. As part of the assessment of post-closure performance of potential deep repositories, NAPSAC fracture network models have been used to predict the groundwater pathways by which radionuclides released from a repository might return to the environment. In cases where an effective porous medium representation of fractured rock is appropriate (using for example the NAMMU program [1]), effective properties have been obtained using NAPSAC models of suitable volumes of the fracture network [2].

The following Sections briefly present the history of NAPSAC, and describe the verification and validation of the program. Section 6 lists all the test cases in the NAPSAC test library.

2   History of NAPSAC

The original version of NAPSAC was written by UKAEA in 1985. This first version addressed flow in small three-dimensional fracture networks comprising orthogonal rectangular fractures [3]. Since then the program has been extensively developed for the OECD/NEA Stripa Project and the Nirex Safety Assessment Research Programme.

The first formal Release of the program, NAPSAC Release 1a, incorporated flow modelling through networks with general fracture orientations in a cuboid solution region. In 1988, Release 1c extended the program capability to simulate flow within an arbitrary solution region. Release 2 of the program was created in 1990 and incorporated tracer transport. Comprehensive documentation was first written for NAPSAC Release 2e for the Stripa project [4, 5, 6, 7, 8, 9, 10]. The capability to model transient flow was developed for Release 3.0 of NAPSAC.

NAPSAC is subject to ongoing development. A complete description of the capabilities of NAPSAC [11, 12, 13, 14] is given in the *NAPSAC Technical Summary Document* [11].

3   Verification

A comprehensive set of approximately 40 test cases (see Section 6) is used to test each new release of NAPSAC. This library of test data sets has evolved, in part, from the historic cross-code verification studies described in this Section.

3.1   Introduction

Two cross-code verification exercises have been completed since 1990. The first verification exercise formed part of the Stripa project [6] (an OECD/NEA project relating to the final disposal of highly radioactive waste in crystalline rock that involved a detailed characterisation of the

granite formation in an abandoned iron ore mine at Stripa in central Sweden) and compared fracture generation, steady-state flow and particle tracking for the fracture flow codes NAPSAC, FracMan/MAFIC and FMG. The second verification exercise was carried out for Nirex as part of the Sellafield site characterisation programme and compared transient flow for the fracture flow codes NAPSAC and FracMan/MAFIC.

In the first exercise (Stripa) test cases were defined to test the calculation of network geometric properties, steady-state flow and tracer transport. Within these categories the test cases consisted of simple examples with analytic solutions, small examples with approximate analytic solutions, and more realistic test cases involving deterministically defined networks but with typical random fracture geometries. Where there was no analytical solution, the NAPSAC results were verified by cross-comparison with the results of FracMan/MAFIC. There was acceptable agreement between the results from NAPSAC and the FracMan/MAFIC program, and the NAPSAC results compared well with the available analytical solutions.

The second exercise (Nirex) was designed to test the calculation of transient flow. The first set of test cases involved 2 fractures, and the transient flow solution was compared with an approximate analytical solution for radial flow. The second set of test cases involved a small network of 332 fractures, and steady-state and transient flow solutions were determined for both specified pressure and no-flow boundary conditions. NAPSAC and FracMan/MAFIC gave qualitatively similar results; however, significant quantitative differences were observed even for quite simple test networks.

These are thought to be due to inadequate mesh discretisation of the source zone in FracMan/MAFIC; the NAPSAC results for the early time behaviour compared well with the available analytical solutions, whereas FracMan/MAFIC gave source zone responses that were inaccurate. The asymptotic NAPSAC results were shown to tend to the steady-state solutions.

3.2 Stripa Cross-Code Verification Study

Within the Stripa project a series of cross-code verification exercises was planned for inter-comparison of the fracture flow codes NAPSAC, FracMan/MAFIC and FMG [15]. Unanticipated problems occurred in executing these exercises, necessitating redefinition of some and abandonment of others [6]. A set of transport data sets was added later and these are described here after the amended geometry and flow data sets.

3.2.1 Geometry Data Set 2

Geometry Data Set 2 was designed to evaluate the ability of the codes to correctly calculate fracture geometries and intersections in a densely fractured rock mass. In this data set, 100 rectangular fractures were specified for a 200m cube. Because this geometry was also required for a later flow exercise, transmissivities were included as part of the original specification. A constant head boundary condition of 10m was set on all faces of the cube. A drift 5m square in cross section with centre-line co-ordinates from (50, 0, 50) to (-50, 0, 50) was given a constant head boundary condition of 0m.
Results

The discrete fracture networks generated by the three codes were almost identical. The results from FracMan/MAFIC and NAPSAC were very similar, with only 10 fracture planes differing in their number of calculated intersections. The trace lengths were also similar. A detailed comparison of trace lengths, for the 10 fractures that had different numbers of intersections, showed a maximum difference of 11.1% [6]. The results from FMG gave a slightly higher number of intersections than FracMan/MAFIC and NAPSAC.

In spite of some small differences, the codes were capable of generating virtually identical representations of complex networks that were deterministic in character. The accuracy of

representing a network was sufficient for practical problems, and therefore all three codes completed this cross-code verification test successfully.

3.2.2 Flow Data Set 1

This data set consists of a simple symmetric network of 6 fractures in a cube of rock with co-ordinates 0m < x, y < 40m and -40m < z < 0m. Each fracture is 10m in from a face and parallel to it, *i.e.* there are two fractures in each co-ordinate plane (Figure 1). The geometry of the fractures has been chosen to test the inclusion of several triple points (a point at which three planes intersect), because these points can be troublesome in network flow calculations. No-flow boundary conditions are applied to the x, y faces (z = -40m and z = 0m) and x, z faces (y = 0m and y = 40m) of the cube. Constant pressure boundary conditions of 0Pa and 10Pa are set on the y, z faces (x = 0m and x = 40m respectively) giving a gradient of 0.25 Pa m^{-1} in the x direction. The flow across any plane x = constant should be 4 10^3 m^{3}s^{-1}.

Results

NAPSAC calculated the correct total flow rate. The values of the hydraulic head along the fracture faces differed slightly from the analytical values, due to NAPSAC not assigning a constant head at the triple points formed by the boundary and two intersecting fracture planes. However, given the correct prediction of the flow rate, NAPSAC was considered to have completed this cross-code verification test successfully.

3.2.3 Flow Data Set 2

This data set consists of 8 fractures of different centres, apertures, sizes and angles in a cube of rock with co-ordinates 0m < x < 200m, 0m < y < 260m and 20m < z < 135m (Figure 2). Thus the fracture intersections are of varying lengths and orientations, and will not necessarily coincide with surface nodes.

Constant pressure boundary conditions of 1.335 10^{6}Pa and 1.215 10^{6}Pa are set on the x, z faces (y = 0m and y = 260m respectively). All the other faces are no-flow boundaries.

This test case has no analytical solution, and thus the basis of verification was cross comparison with the other codes. However, the flow is predominantly through three fracture planes, which form a highly transmissive pathway, while the flows through the other fractures are negligibly small. The analytical solution for the dominant pathway has a flow of 9.871 m^{3}s^{-1}, which provides a guide in interpreting the flows calculated by the codes.

Results

NAPSAC calculated a flow rate of 9.855 m^{3}s^{-1}, which compared well both with the analytical value above and with the other codes.

However, there were some relatively significant variations among the predicted head values. The largest discrepancies (up to 0.4m) were observed at interior nodes at the junction of small aperture fractures (*i.e.* away from the main flow path), and so had little effect on the total flow rate.

NAPSAC solves for the pressure field on each plane using a highly discretised finite element mesh, and grid convergence was confirmed by increasing this discretisation still further. In the third flow test case, the FracMan/MAFIC results converged to those calculated by NAPSAC when additional discretisation was used; here, the grid convergence of FracMan/MAFIC was tested only by ensuring that the bulk flow rate had converged. This is quite a crude measure of grid convergence. A better match would be expected between the predicted head values if the discretisation of the other codes was increased to that used by NAPSAC.

3.2.4   Flow Data Set 3

The details of the model region, fracture network, drift and boundary conditions for this data set were identical to Geometry Data Set 2 (Section 3.2.1). This test case has no analytical or approximate solution.

Results

Due to its formulation, the FMG package was unsuitable for this particular test case, and therefore the basis of verification was cross comparison of the FracMan/MAFIC and NAPSAC results.

The NAPSAC estimate of the flow rate through the outer boundary was about 24% less than that obtained from FracMan/MAFIC ($4.225 \ 10^{-4} \ m^3s^{-1}$ versus $5.56 \ 10^{-4} \ m^3s^{-1}$). Both codes preserved mass balance, with no difference between the calculated flows through the outer boundary and to the drift. The pattern of behaviour was consistent at each outer boundary surface, with the values estimated by NAPSAC always smaller than the corresponding values determined by FracMan/MAFIC.

A modified test case, **Flow Data Set 3b**, was set up in which the drift was moved and enlarged, thereby creating more fracture intersections. While this was expected to reduce the discrepancy, it actually enlarged it; the NAPSAC estimate of the inflow to the drift was 39% smaller than that obtained from FracMan/MAFIC ($3.70 \ 10^{-3} \ m^3s^{-1}$ versus $6.07 \ 10^{-3} \ m^3s^{-1}$).

Later analysis [6] showed that the discrepancy was due to insufficient refinement in the FracMan/MAFIC formulation. Increasing the refinement resulted in good agreement. NAPSAC completed this cross-code verification test successfully.

3.2.5   Transport Data Set 1

The first transport data set consists of 2 sets of parallel fractures with constant apertures of 10^{-4}m in a cube of rock with co-ordinates $0m < x$, $y < 40m$ and $-40m < z < 0m$ (Figure 3). The 2 vertical fractures cross the cube at $x = 10m$ and $x = 30m$, while the 2 horizontal fractures (at $z = -30m$ and $z = -10m$) stop 5m short of the surface of the cube, at $x = 5m$ and $x = 35m$ respectively.
No-flow boundary conditions are applied to the x, y faces ($z = -40m$ and $z = 0m$) and x, z faces ($y = 0m$ and $y = 40m$) of the cube. Constant pressure boundary conditions of $4 \ 10^6$Pa and 0Pa are set on the y, z faces ($x = 0m$ and $x = 40m$ respectively) giving a uniform pressure gradient across the model region, with a flow velocity in the horizontal fractures of 130 m s^{-1}. The particles were released along the inflow boundary, and therefore should break through after 1200s.

Results

Using the command `>> EXACT PARTICLE TRACKING` with its default accuracy parameters, NAPSAC underestimated the path lengths and travel times by about 5%. When the accuracy parameters were tightened[1], the NAPSAC calculation agreed with the analytical prediction, breakthrough occurring after 1200s.

3.2.6   Transport Data Set 2

This data set is a transport version of Flow Data Set 2 (Section 3.2.3). Within this small network of 8 irregularly sized and oriented fractures, there is extreme variation in aperture from 10^{-6}m to

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[1] in any numerical calculation, a sensitivity study is required to show that converged results are obtained

10^{-3}m. Assuming that flow is along 1 dominant pathway, an analytical estimate of the travel time is $1.77 \; 10^{6}$s.

Results

NAPSAC initially predicted travel times ranging from $1.5 \; 10^{6}$s to $1.8 \; 10^{6}$s. These values were slightly small when compared with the analytical estimate above, and therefore the problem was rerun with different accuracy parameters. The results from FracMan/MAFIC agreed with the analytical estimate.

Similarly to Transport Data Set 1, when using the command `>> EXACT PARTICLE TRACKING` with its default accuracy parameters NAPSAC underestimated the travel time by up to 15%. In this example, the effects of numerical dispersion were highlighted against a known sharp-fronted solution. When the `ACCURACY PARAMETER FOR DESTINATION` was reduced to 10^{-4}, a prediction of the time for breakthrough of the front accurate to about 1% was obtained.

3.2.7 Transport Data Set 3

The third transport data set consists of 4 sets of random fractures (153 fractures) in a cube of rock with co-ordinates 0m < x, y, z < 5m.

Constant pressure boundary conditions of $5 \; 10^{4}$Pa are set on the y, z faces (x = 0m and x = 5m). No-flow boundary conditions are applied to all the other faces.
An analytical solution is not available for this complex example.

Results

Calculations were performed using the command `>> EXACT PARTICLE TRACKING` with 3, 9, 15 and 18 transport nodes per intersection. It was found that the coarse discretisation, with 3 transport nodes per intersection, resulted in a large number of `lost' particles. Conversely, when there were a large number of transport nodes per intersection, few particles were lost and the results were considered to be accurate.

The results from FracMan/MAFIC compared reasonably well with those from NAPSAC. FracMan/MAFIC gave a steeper breakthrough curve than NAPSAC, but this was for a calculation with a large proportion of lost particles. (It was shown in the NAPSAC grid convergence study that transport calculations require a highly accurate flow solution.) If, instead of scaling the breakthrough curve to account for the lost particles, one compared the curve with the early 50% arrival predicted by NAPSAC, the results matched very well.

The level of accuracy was sufficient for practical problems, and therefore it was concluded that the codes had been successfully verified. It was not possible within this study to obtain fully grid converged FracMan/MAFIC results with which to verify the details of the NAPSAC results.

3.3 Transient Flow Cross-Code Verification Study

As part of the Sellafield site characterisation programme, Nirex commissioned a verification exercise to test the calculation of transient flow for the fracture flow codes NAPSAC and FracMan/MAFIC. The first set of test cases involved 2 fractures, and the transient flow solution was compared with an approximate analytical solution for radial flow. The second set of test cases involved a small network of 332 fractures, and steady-state and transient flow solutions were determined for both specified pressure and no-flow boundary conditions.

3.3.1 Test Cases 1 & 2

These data sets consist of 2 horizontal fractures in a cube of rock with co-ordinates -175m < x, y, z < 175m (Figure 4). The first fracture, centred on (0, 0, 0), has a transmissivity of $5\ 10^{-9}\ m^2 s^{-1}$, a length of 350m and intersects the vertical boundaries; the second, centred on (0, 0, 1), has a transmissivity of $1\ 10^{-7} m^2 s^{-1}$ and a length of 20m. The storativity of both fractures is calculated using $S = 0.4\ T^{0.74}$ [16].

Five vertical boreholes (extending from z = -10m to z = 10m) intersect the fractures. A source borehole is located at (x, y) = (0, 0), and has a constant flux boundary condition of 0.5 l min^{-1}. Monitoring boreholes are located at (x, y) = (10, 0), (-10, 0), (20, 0) and (50, 0).

Test Case 2 differs from Test Case 1 only in the external boundary condition; Test Case 1 has a constant head boundary condition of 0m and Test Case 2 has a no-flow boundary condition.

Results

NAPSAC and FracMan/MAFIC predicted similar shaped response curves for the boreholes (Figures 5 and 6), but the NAPSAC results were consistently higher. In the two monitoring boreholes closest to the source zone, the NAPSAC results were 12-16% higher than FracMan/MAFIC. The difference between the response curves decreased to less than 1% for the two distant monitoring boreholes at later time.

The results for Test Case 2 were similar (Figures 7 and 8); however, when the influence of the no-flow boundary condition took effect, the NAPSAC and FracMan/MAFIC predictions converged.

The results of the test cases were compared with an analytical solution to a similar problem (*i.e.* a circular geometry with the same transmissivity and boundary conditions) using Interpret 2^{TM}. The NAPSAC results were not more than 5% below the Interpret 2^{TM} solution at early times, before the effects of the different geometry are important, with the FracMan/MAFIC results being lower.

3.3.2 Test Cases 3, 4 & 5

These data sets consist of 3 sets of random fractures in a cube of rock with co-ordinates -100m < x, y, z < 100m (Figure 9).

Five vertical boreholes (extending from z = -10m to z = 10m) intersect the fractures. A source borehole is located at (x, y) = (0, 0). Monitoring boreholes 1 to 4 are located at (x, y) = (10, 0), (-10,10), (20,0) and (50,0).

Test Case 3 involves a steady-state calculation. Constant head boundary conditions of 100m and 0m are set on the x, z faces (y = -100m and y = 100m respectively). All the other faces are no-flow boundaries.

Test Cases 4 and 5 involve a transient calculation. A constant flux boundary condition of 0.5 l min^{-1} is set on the source borehole. Test Case 5 differs from Test Case 4 only in the external boundary condition; Test Case 4 has a constant head boundary condition of 0m and Test Case 5 has a no-flow boundary condition.

Results

In Test Case 3, NAPSAC predicted a flow through the volume of $3.12\ 10^{-7}\ m^3 s^{-1}$ which compared well with the FracMan/MAFIC result of $3.20\ 10^{-7}\ m^3 s^{-1}$. However, there were some variations among the predicted head values, as shown in Table 1 (*c.f.* Section 3.2.3).

Table 1   Calculated heads (m) at monitoring boreholes for Test Case 3.

	Source	Borehole 1	Borehole 2	Borehole 3	Borehole 4
NAPSAC	90.52	90.52	91.70	81.80	60.30
FracMan/MAFIC	90.16	90.16	91.15	81.65	55.88

In Test Case 4, NAPSAC and FracMan/MAFIC predicted similar shaped response curves for the boreholes (Figures 10 and 11). The NAPSAC results for the head in the source zone were consistently 15-20% higher than FracMan/MAFIC. In the monitoring boreholes, the FracMan/MAFIC predictions for the head started higher than NAPSAC, but became lower, and after 10^7s the difference was up to 13%. The NAPSAC results were shown to tend to the grid-converged steady-state solution at later time.

Test Case 5 (Figures 12 and 13) is similar to Test Case 4.

The results for Test Cases 4 and 5 were also compared with the analytical solution (*i.e.* the Jacob Approximation) for flow in the single fracture intersecting the source borehole. The solution should match the numerical results for early times, before the effect of other fractures further from the source zone become significant. The NAPSAC results were within 2% of the analytical solution at early times, with the FracMan/MAFIC results being 20-30% lower.

3.4   Conclusions

The NAPSAC flow code passed both the verification exercises. The first exercise (Stripa) tested fracture generation, steady-state flow and particle tracking for the fracture flow codes NAPSAC, FracMan/MAFIC and FMG. In these tests, the NAPSAC results compared well with available analytical solutions and the results of FracMan/MAFIC and FMG (when a formulation of the test case was possible).

The second exercise (Nirex) tested transient flow for the fracture flow codes NAPSAC and FracMan/MAFIC. NAPSAC and FracMan/MAFIC gave qualitatively similar results; however, significant quantitative differences were observed even for quite simple test networks. These are thought to be due to inadequate mesh discretisation of the source zone in FracMan/MAFIC; the NAPSAC results for the early time behaviour compared well with the available analytical solutions, whereas FracMan/MAFIC gave source zone responses that were inaccurate. The asymptotic NAPSAC results were shown to tend to the steady-state solutions.

4   Validation

NAPSAC has been used extensively to describe flow and tracer transport through fractured rock, giving confidence in the approach. This Section summarises the results from two historic validation studies.

One of the objectives of the Stripa project was the validation of the fracture network approach to simulating flow and transport through fractured rock. Towards this end, three phases of double-blind predictive modelling were carried out. The success of the predictive models builds confidence in the validity of models constructed using NAPSAC for the representation of a heavily fractured granite and, by extrapolation, to the representation of other sites with a similar groundwater flow system.

The first exercise involved the prediction of inflow to an array of boreholes through the middle of a previously undisturbed volume of granite, using models based on fracture mapping from around the boundaries of the site and the results of short-interval flow tests. The NAPSAC

modelling is described in [4], and the independent assessment of the results and comparison with the subsequent experimental results is given by [5].

The second phase involved predicting the inflow to a carefully blasted drift through the same site. A simple normal stress compliance model of the influence of the disturbed zone around the tunnel was tested. It was concluded that this did not provide a valid description of the disturbed zone, but that all other aspects of the model were appropriate. There was no explanation of the origin of the disturbed zone; the only models that were able to account for the disturbed zone involved empirical correction factors derived from other observations of tunnel inflow. The NAPSAC predictions are given in [7]. The independent assessment of the results and the comparison with subsequent experimental results is given by [8].

The third exercise involved predicting tracer transport from boreholes through a small fault zone, into the drift and to other boreholes intersecting the zone. The NAPSAC models used a calibrated flow field to account for the disturbed zone around the drift, and a calibrated factor relating effective transport aperture to effective flow aperture. This model was able to predict subsequent tracer transport breakthrough and account for dispersion in terms of the dispersive effect of the fracture network geometry. The NAPSAC modelling is given in [9]. The independent assessment of the results and the comparison with subsequent experimental results is given by [10].

To complement the work at Stripa, Nirex supported a research programme at the Reskajeage Quarry field site in West Cornwall.

The first phase, between April 1988 and April 1991, studied groundwater flow and solute transport in the highly-fractured, near-surface rock at the quarry. A series of shallow (*i.e.* less than 50m deep) boreholes were drilled, and data were acquired to characterise the geometry and transmissivity of individual fractures. These data were used by NAPSAC to predict flow across a representative volume of rock. Although the model was able to predict successfully the results for single borehole `validation' experiments over short length-scales, it significantly underestimated the effective permeability of the fractured rock over longer length-scales. This was considered to be due to the influence of extensive transmissive features in the fractured rock that were not present in the model [17, 18, 19].

The second phase, started in April 1991, studied groundwater flow and solute transport in the less-fractured, less-permeable rock at depth beneath the quarry. Three vertical boreholes (250m deep) were drilled in a linear array spanning a horizontal distance of 60m. The strategy for validating the fracture network modelling approach consisted of:

- acquisition of data (from boreholes in the quarry and from outcrop mapping) to describe the geometry of the fracture network;
- acquisition of hydraulic data (from short-interval single-borehole tests) to determine the transmissivity of individual fractures;
- generation of a range of conceptual models to describe groundwater flow in the rock. (The experimental data were used to define four fracture sets: two steeply-dipping barren joint-dominated sets, and two moderately-dipping quartz-chlorite- and sulphide-mineralised fault-dominated sets. Conceptual models were developed in which the fractures were further divided into two populations: a dense network of 'background' fractures, having lengths of 1-10m, and a sparse network of longer fractures, having lengths of 10-200m.);
- predictions, using NAPSAC, of the flow through a representative volume of the fracture network for the various conceptual models;
- comparison of the predictions with the results of sixteen large-scale cross-hole tests.

The results suggest that for the most plausible model (*i.e.* the model agreeing most closely with the effective permeabilities determined from the cross-hole tests) the highest fracture transmissivities are ascribed to the longest fractures. In this model, groundwater flows

predominantly through the sparse network of long, transmissive fractures; little flow takes place in the more densely fractured rock between the flowing zones.
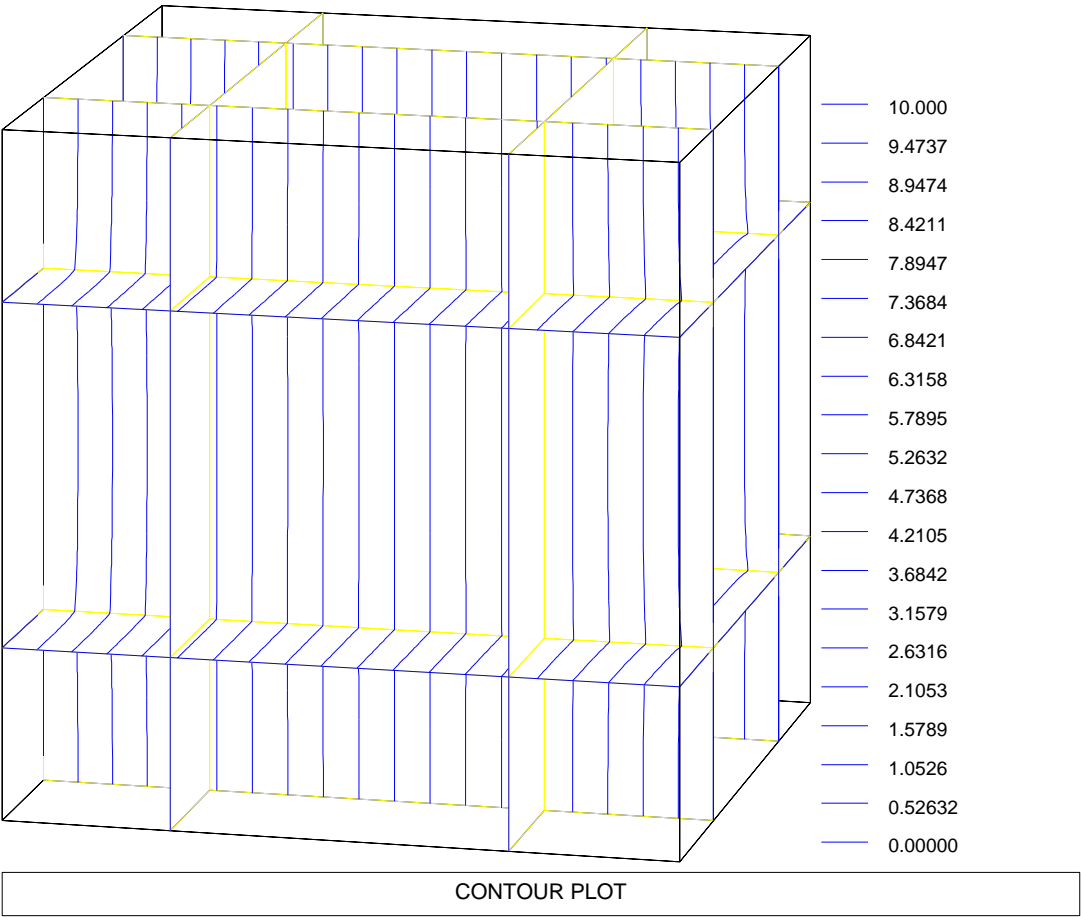
These exercises contribute to confidence in the validity of using fracture network models, based on the use of NAPSAC, to represent flow and transport through formations in which the permeability is dominated by a connected network of flow conducting fractures.

5   Quality Assurance

A Quality Assurance (QA) Programme defines a set of procedures for carrying out a particular type of work in such a way as to maintain the quality of the work. A well designed QA programme plays an important role in computer program maintenance by ensuring that high standards of coding are adhered to, that there are procedures for reporting and fixing program errors, and that there is a system for testing and issuing new releases of the program which ensures that the new program gives the correct results for a standard set of test cases.

NAPSAC is maintained and developed under an appropriate QA Programme [20] within the framework of the QA Software Procedures of the Environmental Management Department, Serco Assurance. The QA Programme conforms to the international standard BS EN ISO 9001 (1994) and to the TickIT Guidelines. The Concurrent Versions System (CVS) is used to store all source code and test data for NAPSAC. This automatically logs the author and date of each change to the system, and enables previous versions of the code to be accessed and recreated if necessary. All changes are thoroughly tested, and must be approved by the Software Manager before they are accepted. A comprehensive set of approximately 40 test cases (see Section 6) is used to test each new release. Through the NAPSAC QA Programme, Serco Limited seeks to continually improve the quality and reliability of NAPSAC.
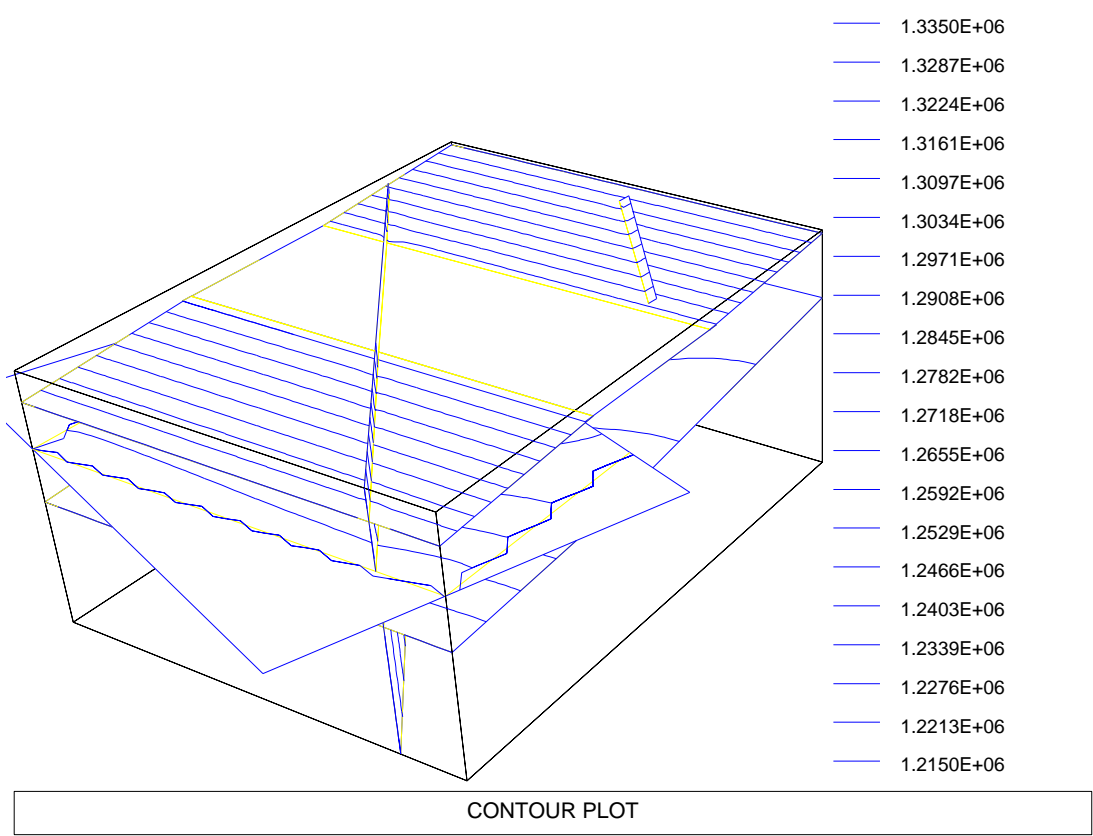
——	10.000
——	9.4737
——	8.9474
——	8.4211
——	7.8947
——	7.3684
——	6.8421
——	6.3158
——	5.7895
——	5.2632
——	4.7368
——	4.2105
——	3.6842
——	3.1579
——	2.6316
——	2.1053
——	1.5789
——	1.0526
——	0.52632
——	0.00000

CONTOUR PLOT

AEA

NAPSAC (version 4.1) Fri Apr 3 1998

Figure 1   The geometry and pressure solution for Flow Data Set 1.

	1.3350E+06
	1.3287E+06
	1.3224E+06
	1.3161E+06
	1.3097E+06
	1.3034E+06
	1.2971E+06
	1.2908E+06
	1.2845E+06
	1.2782E+06
	1.2718E+06
	1.2655E+06
	1.2592E+06
	1.2529E+06
	1.2466E+06
	1.2403E+06
	1.2339E+06
	1.2276E+06
	1.2213E+06
	1.2150E+06

CONTOUR PLOT

NAPSAC (version 4.1) Fri Apr 3 1998

Figure 2   The geometry and pressure solution for Flow Data Set 2.

FOUR PLANE TEST EXAMPLE

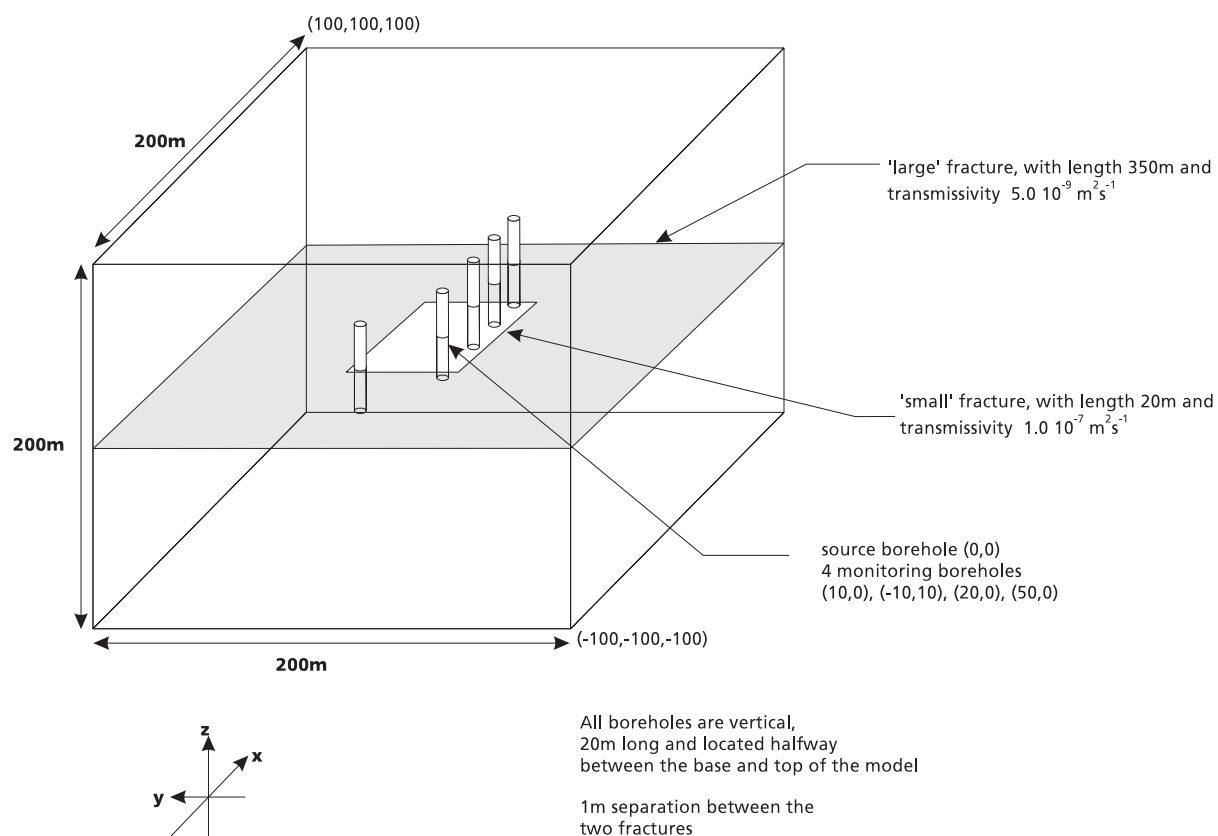|	
4.0000E+06
3.7895E+06
3.5789E+06
3.3684E+06
3.1579E+06
2.9474E+06
2.7368E+06
2.5263E+06
2.3158E+06
2.1053E+06
1.8947E+06
1.6842E+06
1.4737E+06
1.2632E+06
1.0526E+06
8.4211E+05
6.3158E+05
4.2105E+05
2.1053E+05
0.00000

CONTOUR PLOT

AEA

NAPSAC (version 4.1) Fri Apr 3 1998

Figure 3   The geometry and pressure solution for Transport Data Set 1.

(100,100,100)

200m

'large' fracture, with length 350m and transmissivity $5.0 \ 10^{-9} \ m^2 s^{-1}$

200m

'small' fracture, with length 20m and transmissivity $1.0 \ 10^{-7} \ m^2 s^{-1}$

source borehole (0,0)
4 monitoring boreholes
(10,0), (-10,10), (20,0), (50,0)

(-100,-100,-100)

200m

z
x
y

All boreholes are vertical,
20m long and located halfway
between the base and top of the model

1m separation between the
two fractures

Test Case 1: Constant head boundary condition
Test Case 2: No flow boundary condition

Both Test Cases are transient with a constant injection rate of 0.5 lmin^{-1}

Figure 4   The specification for Test Cases 1 & 2.
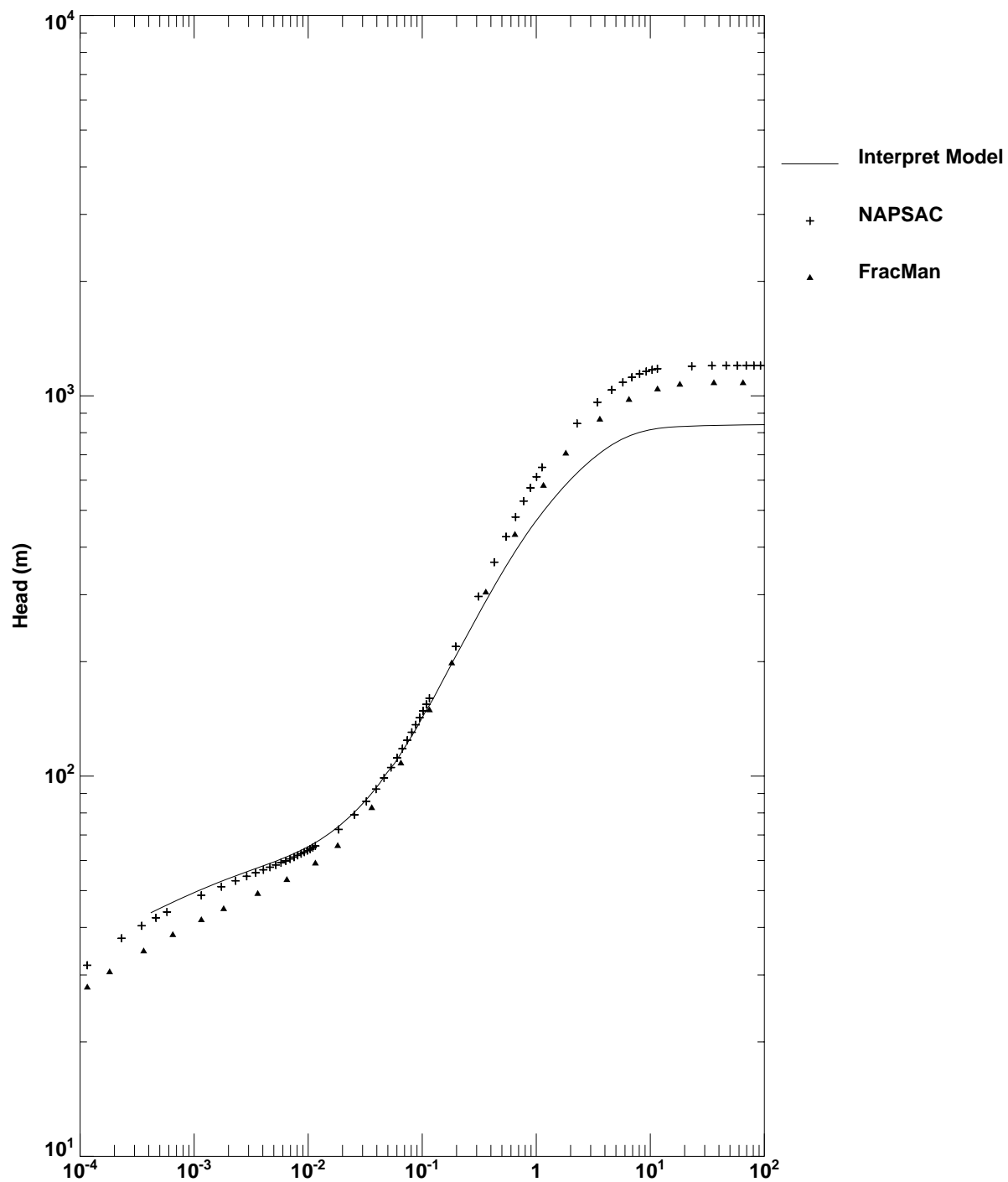
Figure 5   A comparison of the head in the source borehole for Test Case 1. The Interpret 2^{TM} Model assumes a circular geometry, and therefore is expected to differ from the fracture network predictions at large times.
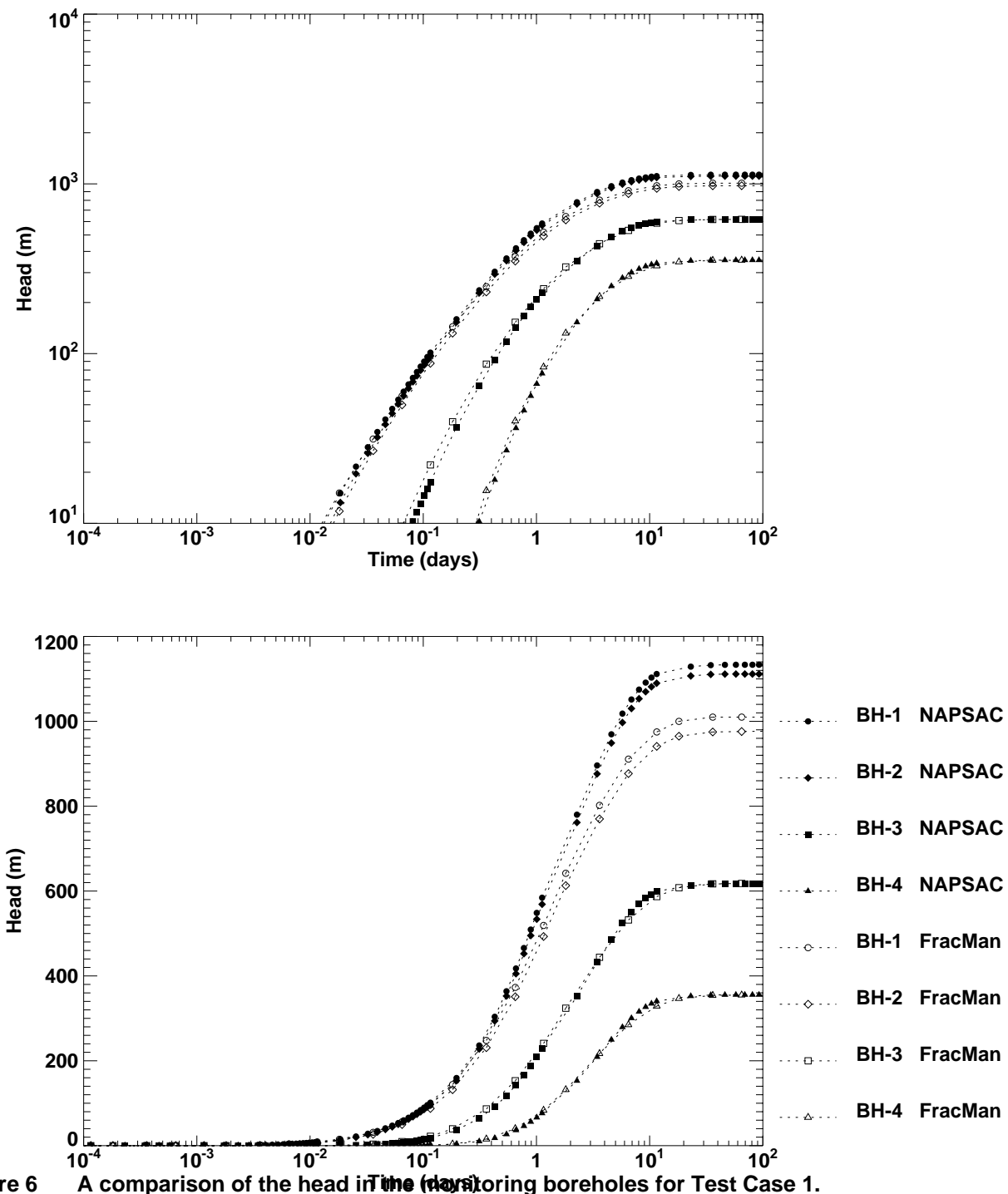
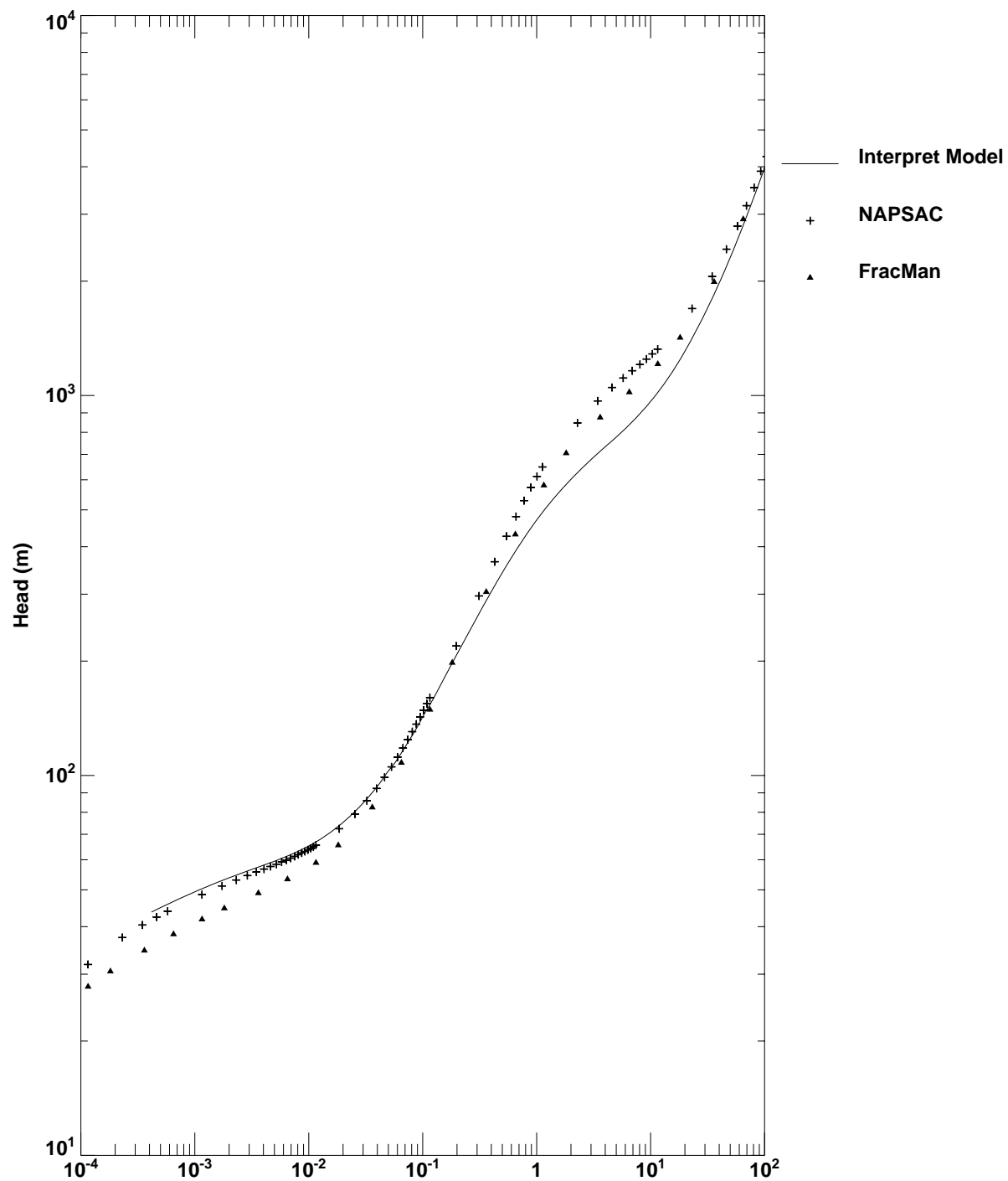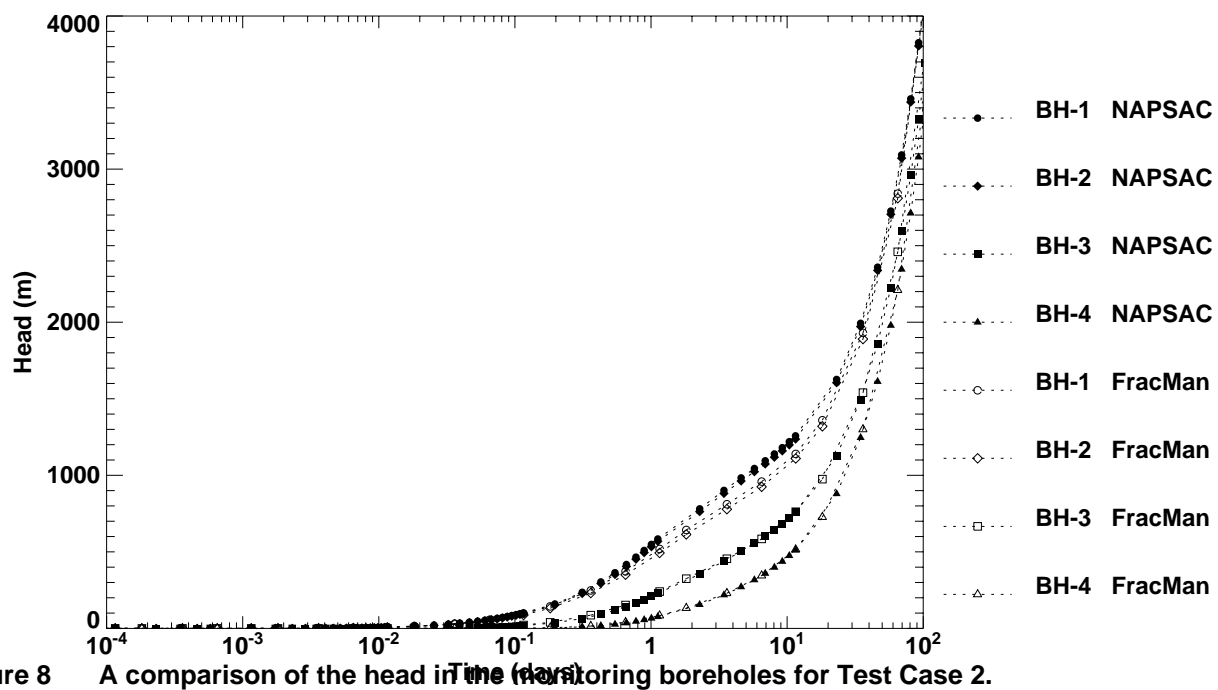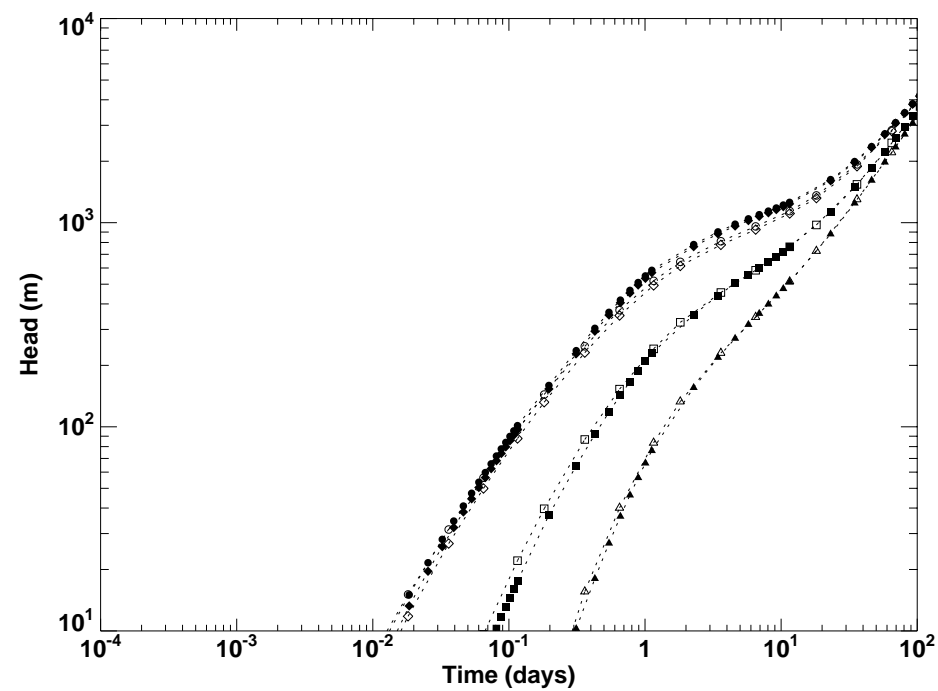**Figure 6   A comparison of the head in the monitoring boreholes for Test Case 1.**

Figure 7 A comparison of the head in the source borehole for Test Case 2. The Interpret 2^{TM} Model assumes a circular geometry, and therefore is expected to differ from the fracture network predictions at large times.
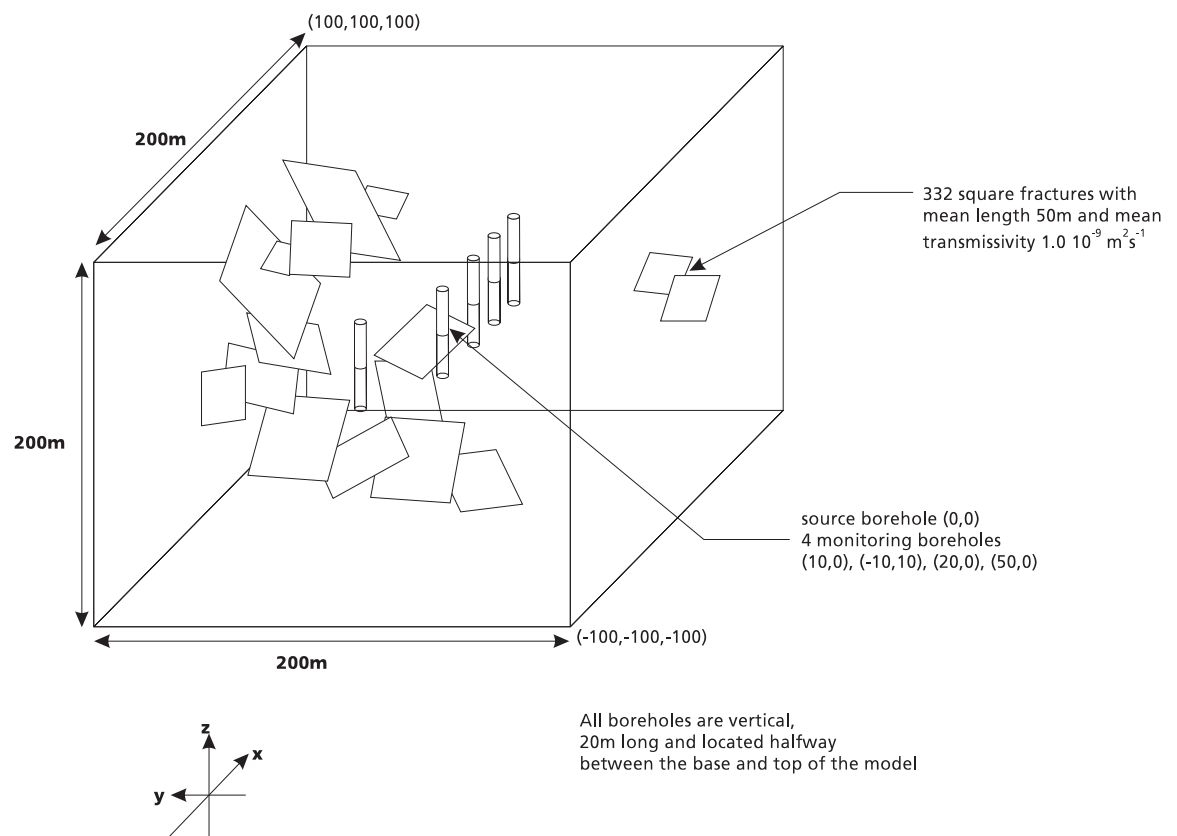
Figure 8   A comparison of the head in the monitoring boreholes for Test Case 2.

(100,100,100)

200m

332 square fractures with
mean length 50m and mean
transmissivity $1.0 \ 10^{-9} \ m^2 s^{-1}$

200m

source borehole (0,0)
4 monitoring boreholes
(10,0), (-10,10), (20,0), (50,0)

200m

(-100,-100,-100)

All boreholes are vertical,
20m long and located halfway
between the base and top of the model

Test Case 3: Steady state case with a uniform gradient from a head of 100m
at y=-100 to a head of 0m at y=100

Test Case 4: Transient Case with a constant injection rate of $0.5 \ lmin^{-1}$.
Constant head boundary condition

Test Case 5: Transient Case with a constant injection rate of $0.5 \ lmin^{-1}$.
No flow boundary condition

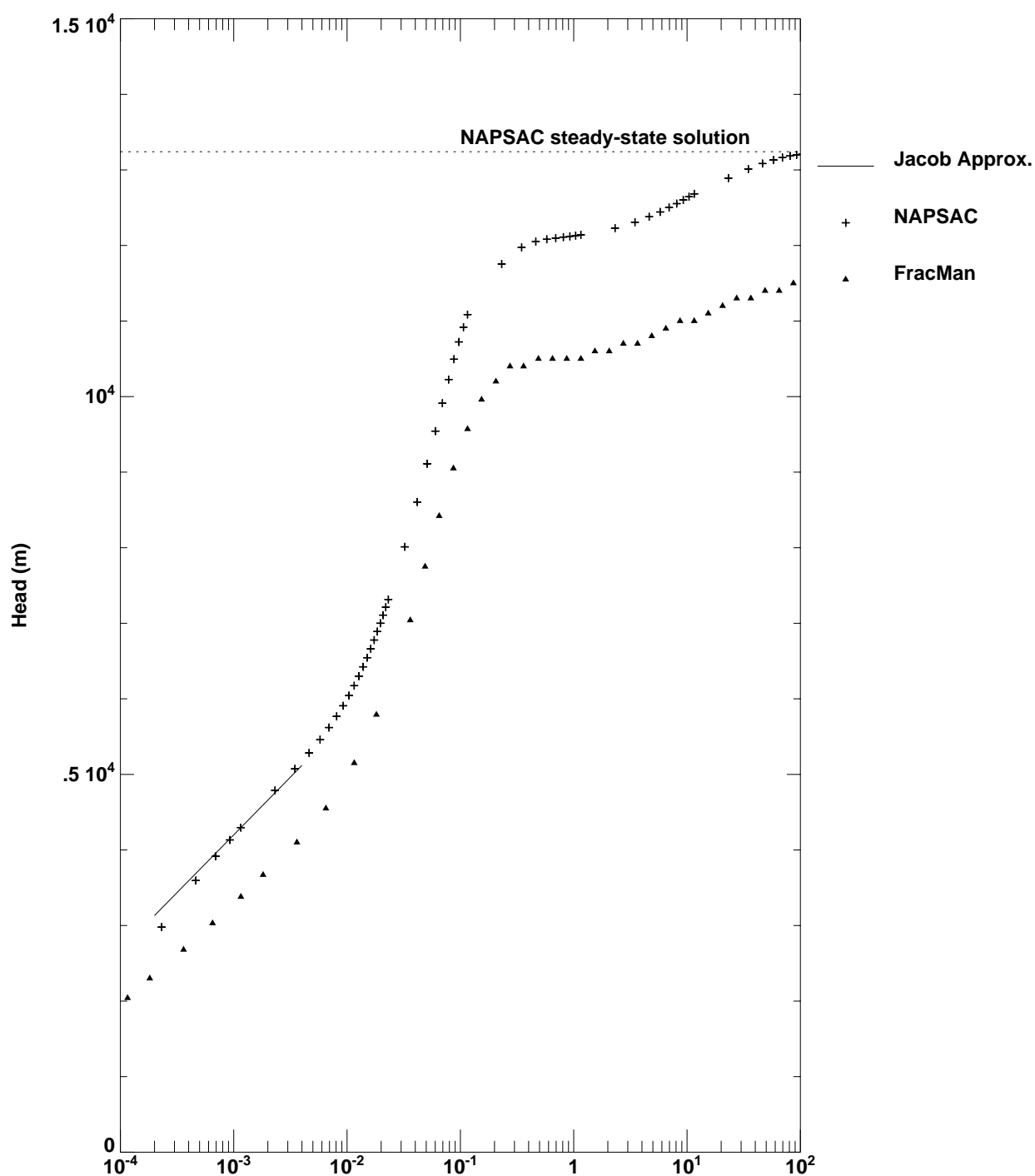**Figure 9   The specification for Test Cases 3, 4 & 5.**

Figure 10   A comparison of the head in the source borehole for Test Case 4. The Jacob
Approximation should match the numerical results for early times, before the
effect of other fractures further from the source zone become significant.
The NAPSAC results tend to the grid-converged steady-state solution at later
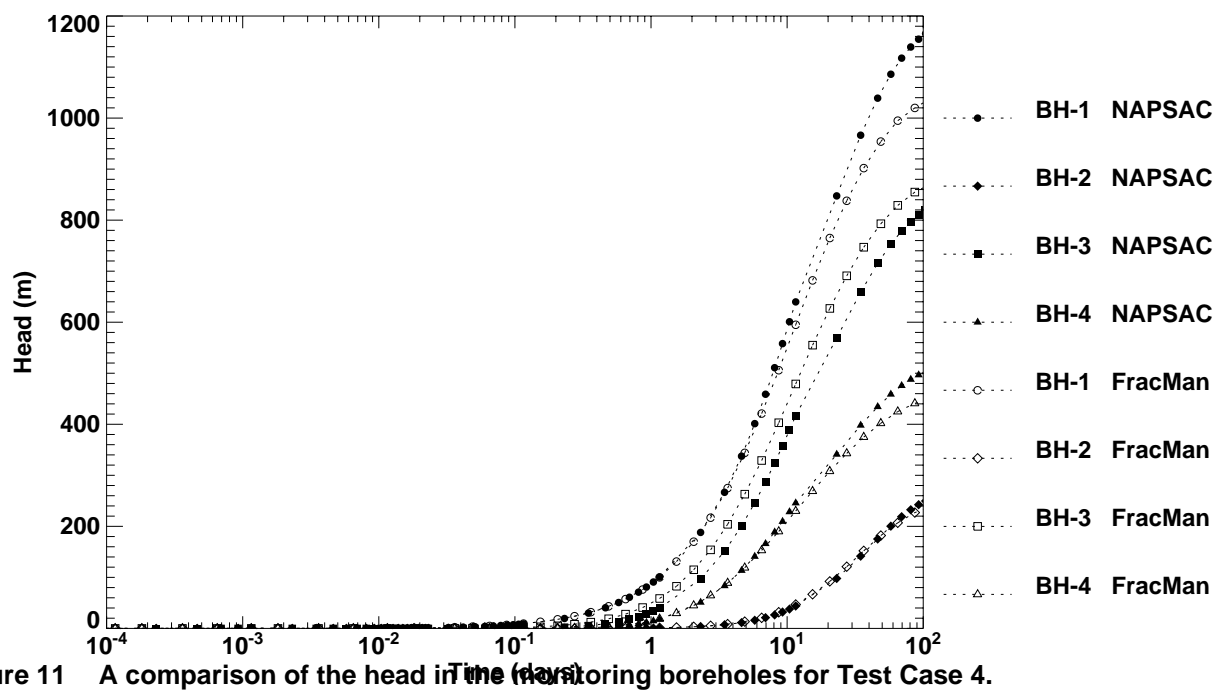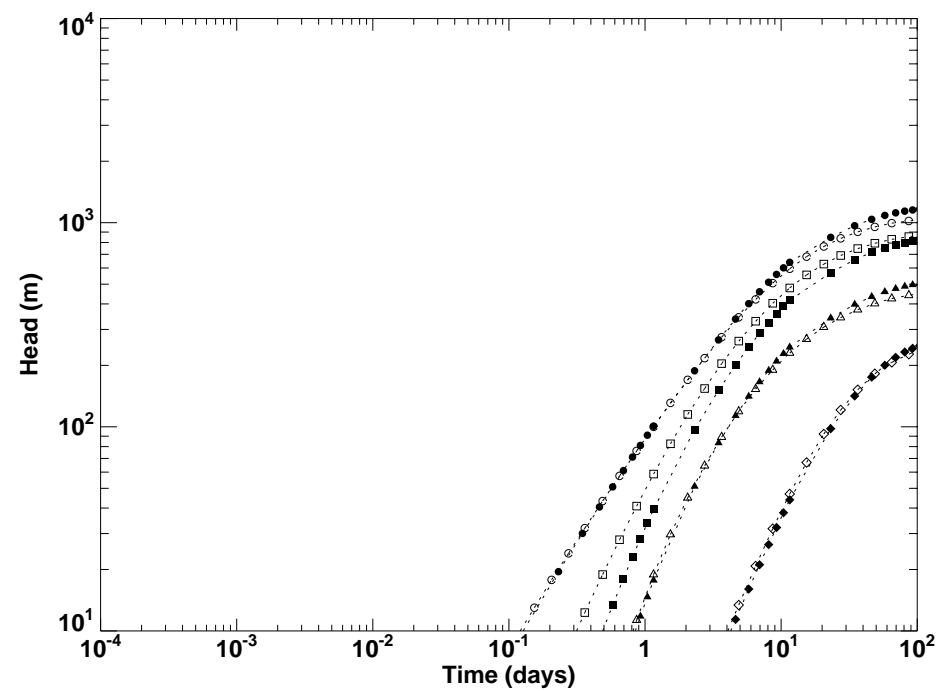time.

Figure 11   A comparison of the head in the monitoring boreholes for Test Case 4.
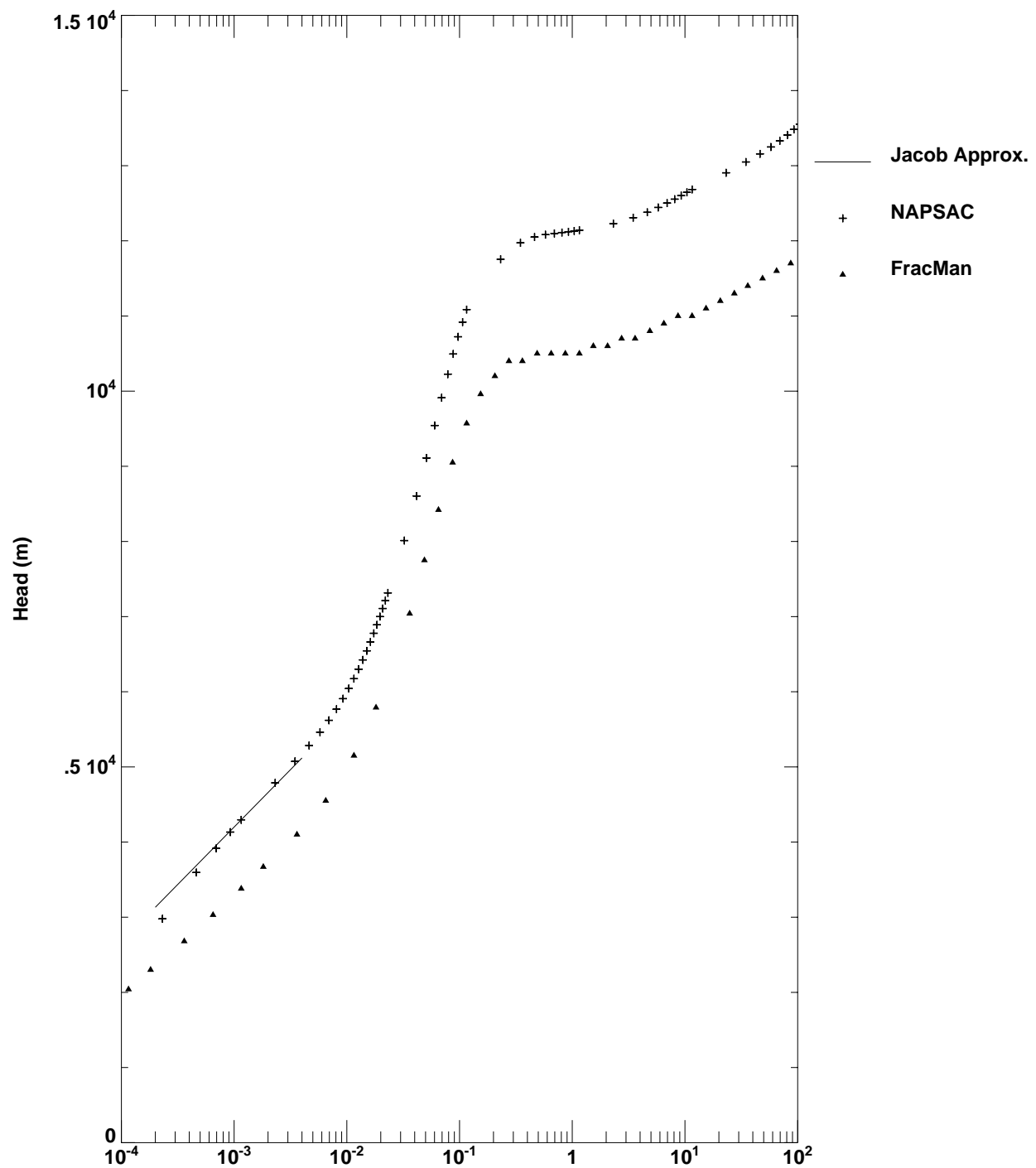
Figure 12 A comparison of the head in the source borehole for Test Case 5. The Jacob Approximation should match the numerical results for early times, before the effect of other fractures further from the source zone become significant.
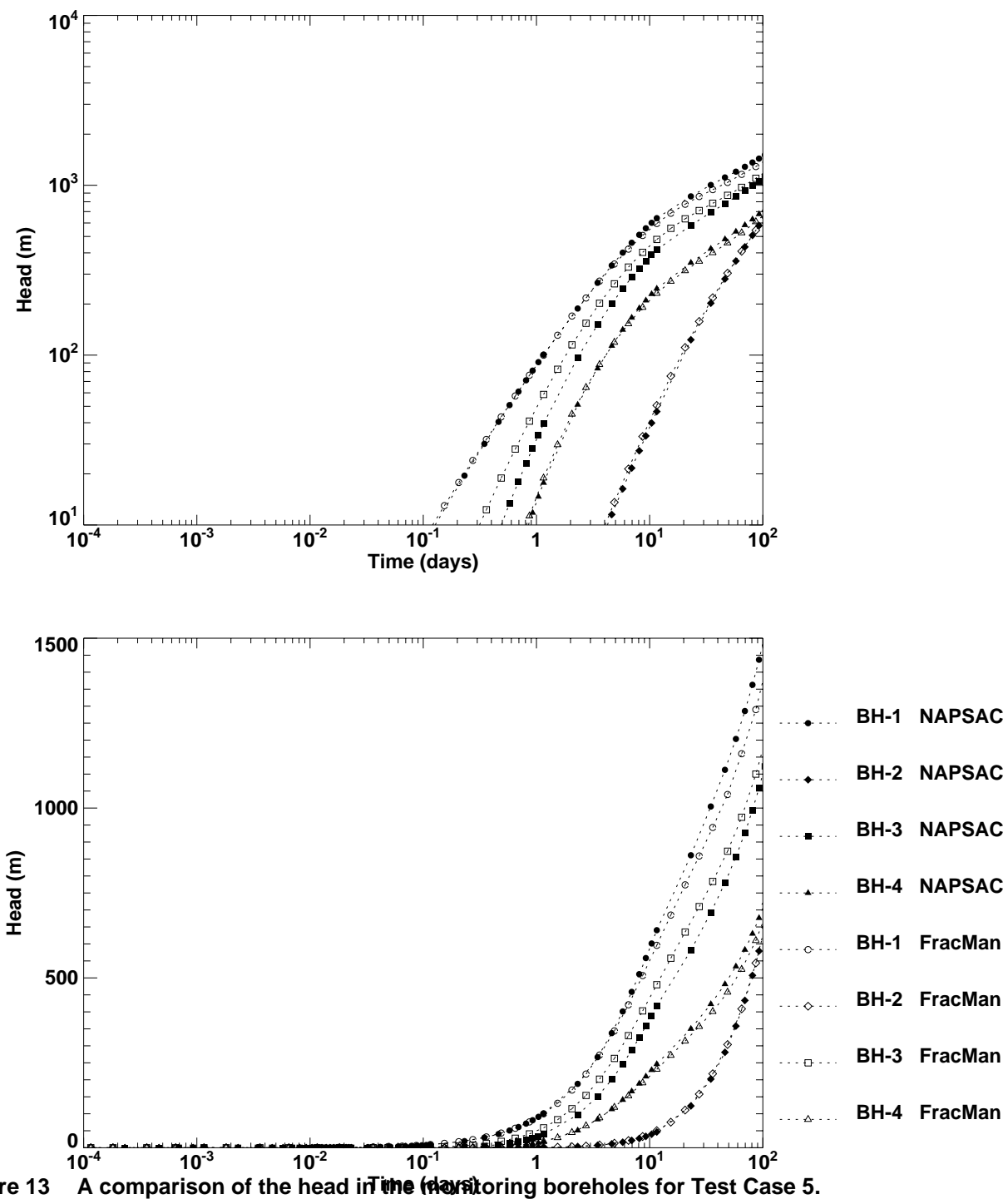
Figure 13   A comparison of the head in the monitoring boreholes for Test Case 5.

Legend:

- BH-1 NAPSAC
- BH-2 NAPSAC
- BH-3 NAPSAC
- BH-4 NAPSAC
- BH-1 FracMan
- BH-2 FracMan
- BH-3 FracMan
- BH-4 FracMan

6 The NAPSAC Test Library

The NAPSAC library of test data sets is designed to test the functionality of the program on all supported platforms. In particular,

- new developments are verified using test cases specific to the changes being made, and then the test library is used to check that the changes do not affect the program in any unexpected way.

- the test library is used to confirm that the program has been installed correctly, and therefore is an important part of Quality Assurance.

The test cases are divided into seven categories, showing a general progression from simple to highly complex models:

- simple deterministic fracture configurations in 2 and 3 dimensions, with steady-state flow calculations;

- simple deterministic fracture and borehole configurations, with steady-state flow calculations;

- deterministic fracture networks, with particle tracking solutions;

- random fracture networks, with steady-state flow calculations;

- random fracture networks, with particle tracking solutions;

- deterministic and random fracture networks, with transient flow calculations;

- miscellaneous.

Some of these test data sets have been used in either the Stripa cross-code verification study or the transient flow cross-code verification study commissioned by Nirex.

This section lists all the data sets in the NAPSAC test library.

Table 6.1   Test data sets for deterministic fracture configurations with steady-state flow calculations.

Data set	Model Region	Fractures	Engineered features	Boundary conditions	Solve	Output
fourpln	cube	4 known	–	constant P	percolation steady-state	contours on planes
genreg	irregular	3 known	–	constant P	percolation steady-state	contours on planes
sixpln	cube	6 known	–	constant P	steady-state	contours on planes solution for planes
crsprdn	cube	4 known[2]	–	constant P	steady-state	aperture plots vectors on planes
irreg	cuboid	8 known	–	constant P	steady-state	contours on planes solution for planes
upsc.simple	cube[3]	9 known	–	linear P variation	fit conductivity tensor	–
smscaltest01	2D square	20 known	–	constant P	steady-state	geometrical data hydraulic data

---

[2] the fracture planes have variable T

[3] the cube is rotated relative to the coordinate system

Table 6.2   Test data sets for deterministic fracture configurations and boreholes with steady-state flow calculations.

Data set	Model Region	Fractures	Engineered features	Boundary conditions	Solve	Output
borhol	cube	2 known	1 borehole	constant *P* linear *P* variation flow test	steady-state	planes contours on planes
borprdn	cube	2 known	8 boreholes	constant *P*	steady-state	planes vectors on planes
tess.steady	cuboid	1 known[4]	3 boreholes	nodal values	steady-state flow test	planes
bhskintest	cube	2 known	1 borehole[5]	constant *P* linear *P* variation flow test	steady-state	planes contours on planes
3shaft	cube	1 known	3 shafts	constant *P* linear *P* variation flow test	steady-state	planes contours on planes aperture plots
stress9pln	cube	10 known	1 shaft	constant *P* pressure test	steady-state[6]	plane aperture plots s
stress2d_3[7]	2D square	specified[8]	1 shaft	constant *P* pressure test	steady-state	planes plot pressure profile

---

[4] the fracture plane is tessellated

[5] the borehole has a 'skin'

[6] the *T* of the fracture planes is modified as a result of changes in stress near the shaft

[7] the data set corresponds to Decovalex Bench Mark Test 3 [21]

Table 6.3   Test data sets for deterministic fracture networks with particle tracking solutions.

Data set	Model Region	Fractures	Engineered features	Boundary conditions	Solve	Output
tran4pln	cube	4 known	–	constant P	steady-state exact particle tracking	planes contours on planes breakthrough curves
tranirrg	cuboid	8 known	–	constant P	steady-state exact particle tracking	planes breakthrough curves particle arrival
boretran	cube	2 known	2 boreholes	constant P pressure test	steady-state exact particle tracking	contours on planes solution for planes breakthrough curves
bhjoin	cube	2 known	5 boreholes[9]	constant P	steady-state approx. particle tracking	planes contours on planes particle tracks
rmd3	cuboid	37 known	–	constant P	steady-state approx. particle tracking	breakthrough curves[10]

---

[8] the properties of 6580 fracture planes are read from file

[9] the boreholes are joined

[10] the breakthrough curves take account of rock-matrix diffusion

Table 6.4   Test data sets for random fracture networks with steady-state flow calculations.

Data set	Model Region	Fractures	Engineered features	Boundary conditions	Solve	Output
randnet	cuboid	2 sets random	–	–	–	log core
cylinder	cube	2 sets random[11]	2 boreholes	constant P	–	planes
drradb02	irregular[12]	6 sets random	–	constant P	steady-state	planes
randflowdom	irregular[13]	1 known 2 sets random	7 boreholes	constant P	steady-state[14]	planes contours on planes
upsc.man[15]	cube	4 sets random	–	constant P	steady-state approx. particle tracking	planes
upsc.auto[16]	cube	4 sets random	–	linear P variation	fit conductivity tensor	planes
stress3d_2	cuboid	6 sets random	1 shaft	constant P	steady-state[17]	planes

---

[11] the fracture planes are generated in a cylindrical region

[12] the region is shaped like a doughnut

[13] the region consists of 3 cuboid layers

[14] the domain decomposition algorithm is used

[15] the data set is similar to upsc.auto

[16] the data set is similar to upsc.man

[17] the T of the fracture planes is modified as a result of changes in stress near the shaft

Table 6.5   Test data sets for random fracture networks with particle tracking solutions.

Data set	Model Region	Fractures	Engineered features	Boundary conditions	Solve	Output
tranrand	cube	4 sets random	1 borehole	constant P pressure test	steady-state exact particle tracking	breakthrough curves particle swarm particle arrival
suntp3D	cube	1 set random	–	constant P	steady-state approx. particle tracking	planes breakthrough curves
suntttr1	cube	1 set random	1 borehole	constant P pressure test	steady-state approx. particle tracking	particle tracks
randxhol	cube	2 sets random	2 boreholes	constant P flow test	steady-state approx. particle tracking	particle tracks
bigtransport	cube	3 sets random	1 borehole	constant P	steady-state approx. particle tracking	breakthrough curves particle tracks particle swarm particle arrival
bigsteady[18]	irregular	1 known[19] 3 sets random[20]	1 borehole	nodal values	steady-state approx. particle tracking	planes particle tracks
randflowpart	cube	1 known 2 sets random	1 borehole	constant P	steady-state exact particle tracking approx. particle tracking	planes log core contours on planes calculate flux particle profile

[18] output is produced by the data set bigsteady.post

[19] the fracture plane is tessellated

[20] the fracture planes are tessellated

Table 6.6 Test data sets for deterministic and random fracture networks with transient flow calculations.

Data set	Model Region	Fractures	Engineered features	Boundary conditions	Solve	Output
smalltfl	cube	2 known	1 borehole	constant *P* flow test	transient	planes
bor3plntfl	cube	3 known	1 borehole	constant *P* flow test	transient	planes transient pressures
tess.trans	cuboid	1 known[21]	3 boreholes	nodal values flow test	transient	planes
sunnttfl	cube	1 set random	–	constant *P*	transient	pressure profile transient pressures
randbortfl	cube	1 known 2 sets random	1 borehole	constant *P* flow test	transient	pressure profile transient pressures
bigtfl[22]	cube	1 known 3 sets random	5 boreholes	constant *P* flow test	transient	–
shaft	cuboid	48 known[23] 3 sets random[24]	36 boreholes[25]	linear *P* variation[26]	steady state transient[27]	planes

---

[21] the fracture plane is tessellated

[22] output is produced by the data set bigtfl.post

[23] the known fractures are used to define the shaft (their properties are changed as the shaft is sunk using the command `MODIFY MODEL`)

[24] the fracture planes are tessellated

[25] 12 of the boreholes are joined and used to define the shaft (their properties are changed as the shaft is sunk using the command `MODIFY MODEL`), and the remainder are `probe' boreholes

Table 6.7 Engineered feature interval conditioning test data sets.

Data set	Model Region	Fractures	Engineered features	Boundary conditions	Solve	Output
condition_known_tess_refined	cube	2 known[28]	1 borehole			
condition_random	cube	1 set	1 borehole			

Table 6.8 Miscellaneous test data sets.

Data set	Model Region	Fractures	Engineered features	Boundary conditions	Solve	Output
hexsalt	cuboid	hexagonal[29]	–	constant P constant C	transient flow and salt	planes saline pressure saline tracks
henry.hex	irregular[30]	hexagonal[28]	–	linear P variation specified flux constant C	transient flow and salt	planes saline pressure saline tracks

---

[26] the boundary conditions are changed as the shaft is sunk using the command `MODIFY MODEL`

[27] the domain decomposition algorithm is used

[28] fractures are tessellated

[29] 3 sets of fractures are joined together in a hexagonal lattice

[30] the region consists of 2 cuboid layers

References

1.	*NAMMU User Guide*, SA/ENV/CONNECTFLOW/10, Serco Assurance, Harwell.

2.	A. Hoch, C. Jackson, S. Todman, G. Lanyon, and C. Watson. *Self Consistency of a Heterogeneous Continuum Porous Medium Representation of a Fractured Medium*. Nirex Science Report, in preparation, 1998.

3.	P. Robinson. *Flow in Three-dimensional Fracture Networks*. AERE-R-11965, UKAEA, 1985.

4.	A. Herbert and B. Splawski. *Prediction of Inflow into the D-Holes at Stripa Mine*. Technical Report 90-14, Stripa Project, 1990.

5.	D. Hodgkinson. *A Comparison of Predictions and Measurements for the Stripa Simulated Drift Experiment*. Technical Report 91-10, Stripa Project, 1991.

6.	F. Schwartz and G. Lee. *Cross-verification Testing of Fracture Flow and Mass Transport Codes*. Technical Report 91-29, Stripa Project, 1991.

7.	A. Herbert, J. Gale, G. Lanyon, and R. MacLeod. *Modelling for the Stripa Site Characterization and Validation Drift Inflow: Prediction of Flow through Fractured Rock*. Technical Report 91-35, Stripa Project, 1991.

8.	D. Hodgkinson and N. Cooper. *A Comparison of Measurements and Calculations for the Stripa Validation Drift Inflow Experiment*. Technical Report 92-07, Stripa Project, 1992.

9.	A. Herbert and G. Lanyon. *Modelling Tracer Transport in Fractured Rock at Stripa*. Technical Report 92-01, Stripa Project, 1992.

10.	D. Hodgkinson and N. Cooper. *A Comparison of Measurements and Calculations for the Stripa Tracer Experiments*. Technical Report 92-20, Stripa Project, 1992.

11.	*NAPSAC Technical Summary Document*, SA/ENV/CONNECTFLOW/12, Serco Assurance, Harwell.

12.	*NAPSAC Command Reference Manual*.

13.	*NAPSAC Verification Document,* SA/ENV/CONNECTFLOW/13, Serco Assurance, Harwell.

14.	*NAPSAC, Installation and Running Guide*, SA/ENV/CONNECTFLOW/11, Serco Assurance, Harwell.

15.	W. Dershowitz, A. Herbert, and J. Long. *Fracture Flow Code Cross-Verification Plan*. Technical Report 89-02, Stripa Project, 1989.

16.	J. Geier, C. Axelsson, L. Hassler, and A. Benabderahmane. *Discrete Fracture Modelling of the Finnsjön Rock Mass*. Technical Report 92-07, SKB, 1992.

18. J. Bolt, D. Pascoe, and V. Watkins. *An Overview of the Experimental Techniques Developed during Hydrogeological Investigations at Reskajeage Quarry, Cornwall.* Science Report NSS/R279, Nirex, 1992.

19. J. Bolt, P. Bourke, R. Kingdon, N. Jefferies, D. Pascoe, and V. Watkins. *Validation of Stochastic Network Modelling of Flow through Fractured Rock: An Overview.* Science Report NSS/R281, Nirex, 1995.

20. S. Morris and G. Webster. *Quality Sub-Programme: Computer Packages Based on TGSL.* WEG/QAP/TGSL, AEA Technology, Harwell, 1996.

21. P. Wilcock. "Generic Study of Coupled T-H-M Processes in the Near-field (BMT3)}". In S. Stephanson and L. Jing, editors, *"Coupled Thermo-Hydro-Mechanical Processes of Fractured Media"*, Developments in Geotechnical Engineering **79**. Elsevier, 1996.