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The Laxemar and Forsmark repositories

An analysis of the water inflow distribution

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December 2006

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Abstract

A numerical simulation model is used to estimate the water inflow distribution to the Laxemar and Forsmark repositories. In particular statistics for the inflow to individual deposition holes, i.e. inflow distribution expressed as litre/min, deposition hole, is requested. Different grouting efficiencies are evaluated, including no grouting.

The simulations are based on the code DarcyTools version 3.0, which was also used in simulations of the impact of the Repositories in Forsmark and Laxemar /Svensson 2005b, 2006/. Both the code and the simulations include many novel features and all simulations should hence be regarded as tentative.

For the Laxemar repository it is found that less than 2% of all deposition holes will have an inflow larger than 1.0 l/min. This number will increase to about 20% if the inflow limit is put to 0.1 l/min.

For the Forsmark repository it is found that 99.9% of all deposition holes will have an inflow smaller than 0.01 l/min.

Sammanfattning

En numerisk modell används för att beräkna vatteninflödet, och dess rumsliga fördelning, till förvaren i Laxemar och Forsmark. Speciellt efterfrågas statistik för hur många deponeringshål som kan förväntas få ett visst givet inflöde. Som en del av analysen skall olika injekteringsfall analyseras.

Beräkningsprogrammet DarcyTools, version 3.0 används i simuleringarna, liksom i tidigare analyser av förvaren i Forsmark och Laxemar /Svensson 2005b, 2006/. Eftersom ett antal nya metoder utnyttjas i dessa simuleringar bör alla resultat betraktas som preliminära.

För Laxemarförvaret kan man förvänta sig att mindre än 2 % av deponeringshålen får ett inflöde som överstiger 1,0 l/min. Denna siffra ökar till ca 20 % om gränsvärdet ändras till 0,1 l/min.

För Forsmarkförvaret kan man förvänta sig att 99,9 % av alla deponeringshål får ett inflöde som är mindre än 0,01 l/min.

Contents

1 Introduction

1.1 Background

A repository for spent nuclear fuel will have atmospheric pressure in the tunnels during the excavation and operational phases. In order to reduce the resulting water inflow grouting will be carried out. Unless the inflow is totally eliminated (which is not feasible) a disturbance in the pressure and salinity fields will result.

From several points of view it is of interest to be able to predict these disturbances:

- The ground water table will be lowered due to the tunnel inflow. The water level in lakes and wells is thus affected as well as the flow rate in streams.
- The engineered barriers are known to be affected by the salinity of the surrounding water. It is expected that water from below the tunnel will be transported to the tunnel, carrying water with high salinity (upconing). Also the oxygen saturated water from the ground surface may affect the engineered barriers.
- From a construction point of view it is essential to know the expected inflow to the repository; this in order to perform suitable grouting, design pump systems, etc.

After the closure of the repository a resaturation phase starts. Also this phase and the coupling to the host rock is of interest to simulate. Finally, one needs to consider the possible transport of radionuclides from the repository to ground level.

In earlier repository studies /Svensson 2005ab, 2006/ the general impact (inflow, drawdown, upconing, etc) of a repository has been evaluated for the Simpevarp, Forsmark and Laxemar sites. An additional aspect, related to the water inflow, is also of interest; how sensitive is the backfill and buffer to a local high inflow? It has been discussed if a high inflow can erode the buffer material or perhaps create channels with increasing flow rates. The problem may need consideration during the construction phase, but the long term aspect is probably the more difficult to analyse, as the water chemistry will then come into play.

In this project a first analysis of the spatial distribution of the steady state inflow to a repository will be presented. It can be expected that the stability of the backfill is sensitive to how localized the inflow is (velocity of a spot-wise inflow). However, it was decided that the project should focus on the inflow to one deposition hole and provide statistics on this inflow, expressed as l/min*,* deposition hole. Two repositories will be analysed; Laxemar with 7,498 deposition holes and Forsmark with 6,824 deposition holes. A key question is how many of these that will have an inflow larger than, say, 1 l/min.

1.2 Objective

The main objective of the study is to provide statistics on the inflow to deposition holes, expressed as l/min, deposition hole, for the Laxemar and Forsmark repositories with layouts according to the SR-Can safety assessment analysis. All results are based on numerical simulations and it is not within scope to compare with any field data.

1.3 Outline

First the simulation model will be introduced, next section. This section will be brief and mainly state the specific features of this project. Results for the Laxemar and Forsmark sites then follow. Two sensitivity studies are presented thereafter and finally some discussions and conclusions are provided. An appendix provides a comparison with an analytical solution.

2 Simulation model

As in the above mentioned repository studies, the code DarcyTools /Svensson et al. 2006/ will be used for the simulations. It is outside the scope of this report to describe this code, but a few features of relevance to the addressed problem will be listed:

- A computational grid that can resolve the geometry of the repository, as embedded in a regional scale model. An unstructured Cartesian grid will be employed as a solution to this problem.
- A method to handle a free ground water surface.
- The repository geometry is given in form of high resolution CAD files. These files need to be imported to the code and the computational grid is to be constructed in a way that resolves the geometry.
- Grouting will reduce the hydraulic conductivity close to the repository walls. This effect needs to be simulated in a realistic manner.
- Deformation zones and fractures need to be accurately represented on the computational grid.

Further details about DarcyTools can be found in /Svensson et al. 2006/.

The model set-ups for the two sites considered are based on the corresponding set-ups for the open repository studies. However, some modifications have been introduced:

- Only steady state cases are considered.
- Salinity is not included in the simulations. Gravitational effects are believed to be of second order for the inflow distribution.
- The minimum fracture size will be put to 10 metres in the vicinity of the repository (30 metres was used for the open repository studies).
- Three grouting efficiencies will be evaluated; no grouting, $Cond_{\max}=10^{-7}$ m/s and $Cond_{\max}=10^{-9}$ m/s. The $Cond_{\max}$ criterion is applied to a 4 metres thick layer around the repository (if a conductivity larger than $Cond_{\max}$ is found, the conductivity is set to $Cond_{\max}$).
- The coordinates of the deposition holes are provided by SKB. In the earlier studies the deposition holes were part of the general CAD files and the coordinates for the individual deposition holes were not required.
- The grid resolution close to the repository is specified to 2 metres (4 metres was used for the open repository studies).

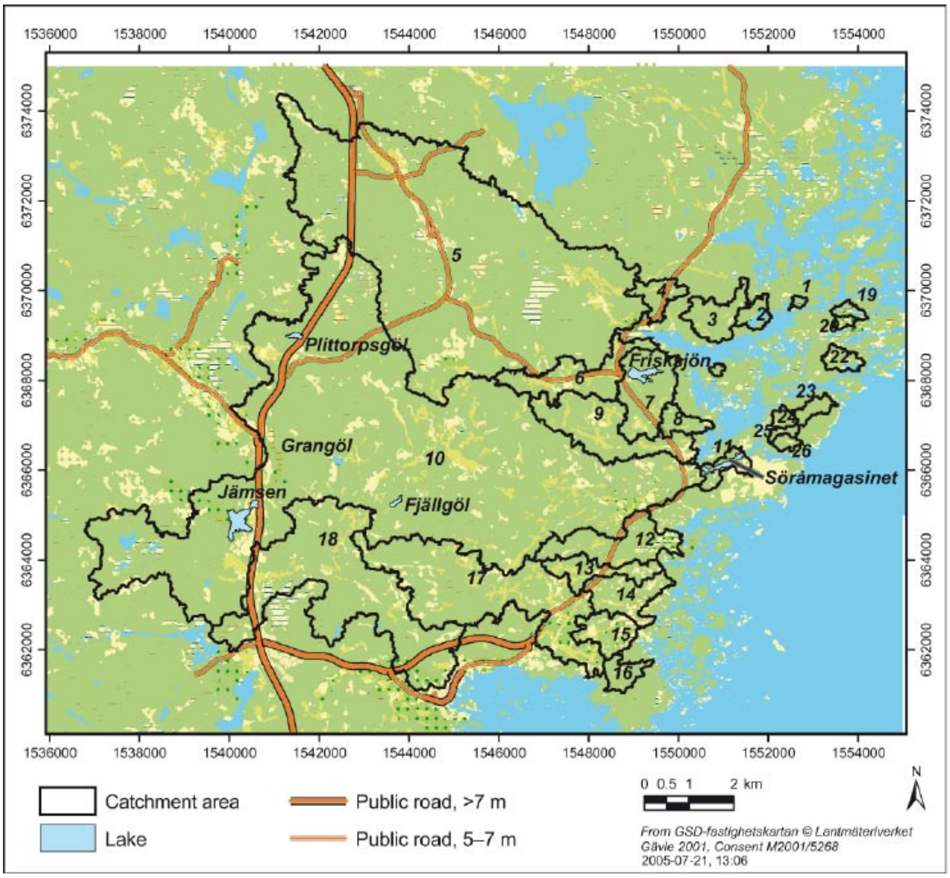
3 Results, Laxemar

3.1 Site

The Laxemar area is located near the Oskarshamn nuclear power plant, on the east cost of Sweden, see Figure 3-1. In this figure also the Regional Model domain is introduced; the Regional Model covers all catchment areas shown in Figure 3-1, parts of the Baltic Sea and has a depth of 2.1 km.

An outline of the repository is shown in Figure 3-2. The repository is located at a depth of about 500 metres. The layout of the repository is done with respect to major deformation zones in the area. The input data can be specified as the base case, defined in the Site-descriptive model /Hartley et al. 2006, SKB 2006/. An account of this data set can also be found in /Svensson 2006/. Some key features of the base case include:

- A set of deterministic deformation zones form the "backbone" of the fracture network.
- A stochastic network is specified for the fracture length interval 100 to 1,000 metres (see Table 3-17 in /Hartley et al. 2006/).
- A depth trend should be applied for the rock properties. Further, transmissivities are correlated to fracture length.



From GSD-fastighetskartan © Lantmäteriverket
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Figure 3-1. *Overview of the Laxemar area and the Laxemar regional model area. The repository is located in catchment areas 6, 7, 8 and 9.*

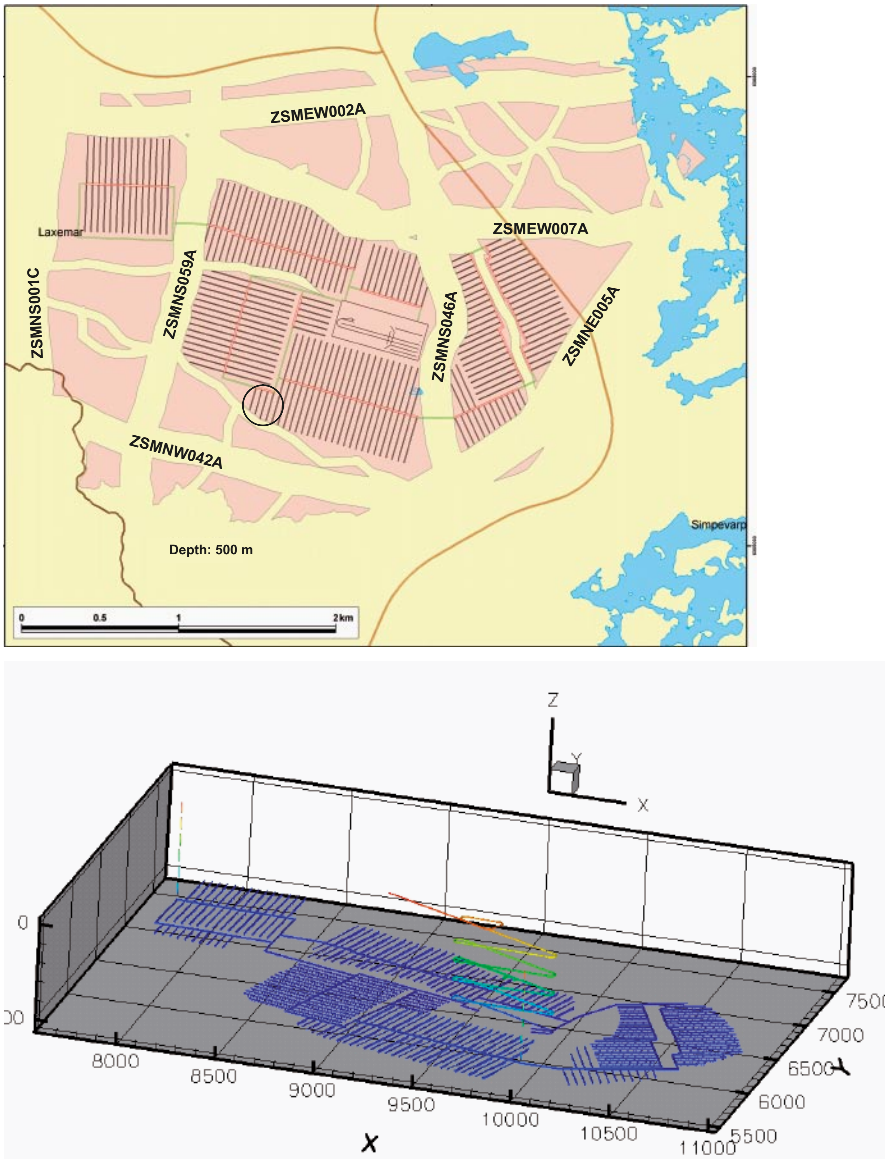


Figure 3-2 Layout of the repository. Position in the horizontal plane (top) and a perspective view. The x and y coordinates in this, and the following figures, refer to the local system in the regional model. The y-direction points to North. The circle in the upper figure marks the South-West part of tunnel part C, which will be illustrated in some detail below.

3.2 General

Although the main results of the study will be focused on inflow rates to deposition holes, we will start with some results where the inflow is shown for each computational cell in contact with the repository. As the cell size is 2 × 2 × 2 m^3, one may think of the inflow over a surface of 2 × 2 m^2. In Figure 3-3 all cells with inflow larger than 0.05 l/min have been marked; this for two grouting conditions. An analysis of the results is given by Table 3-1. It is found that very few cells (< 3%) contribute to most of the inflow (65%) for $Cond_{max}=10^{-7}$ m/s.

A close up view of the South-West part of tunnel part C (see Figure 3-2) is shown in Figure 3-4. This figure gives an impression of the numerical resolution, as each sphere represents a cell with an inflow larger than 0.05 l/min. Looking at the pattern of the spheres, one can expect that a large fracture crosses the four deposition tunnels shown. This is also the impression from Figure 3–5, where some simulations of particle tracks are shown. The particles were placed in all cells in contact with the repository (one particle in each cell) and then tracked in a reversed flow field, so called backtracking.

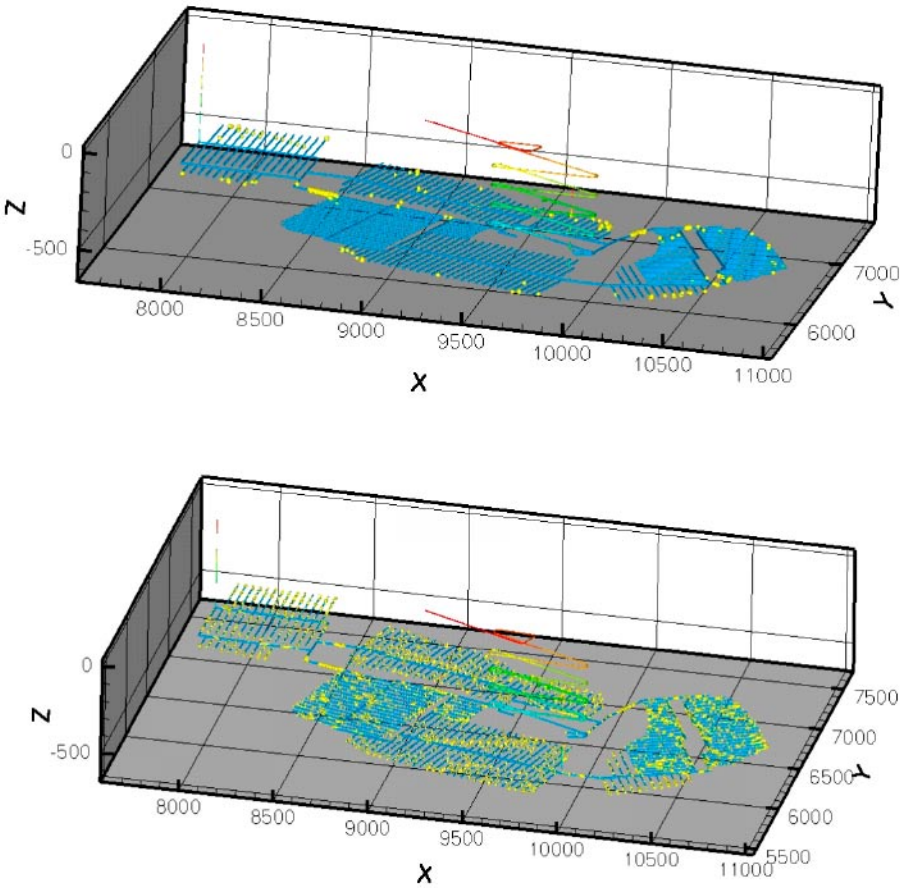


Figure 3-3. *Cells with an inflow larger than 0.05 l/min are marked for* $Cond_{max}=10^{-9}$ *(top) and* $Cond_{max}=10^{-7}$ *m/s.*

Table 3-1. Inflow to tunnels and deposition holes expressed as an inflow per computational cell (2 × 2 × 2 m³). Total number of cells in contact with the repository walls is 616,414.

	Grouting efficiency	
	$Cond_{max}=10^{-7}$ **m/s**	$Cond_{max}=10^{-9}$ **m/s**
Number of cells with inflow > 0.05 l/min	2.8%	0.05%
Total inflow (in l/min) due to cells with an inflow > 0.05	2,210 (65%)	18 (1%)
Total inflow l/min	3,394	1,822

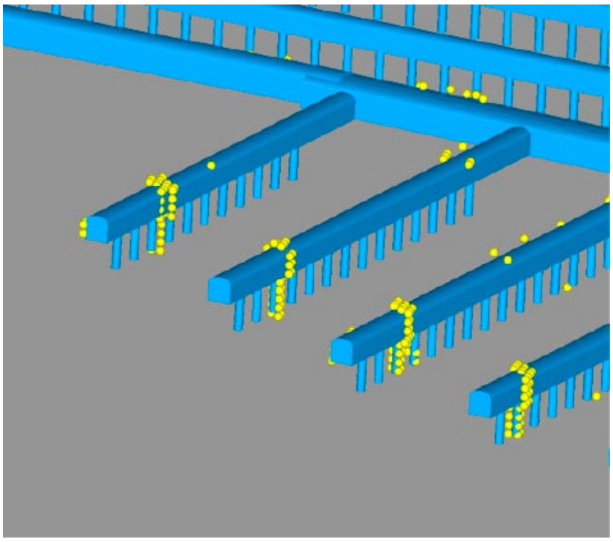


Figure 3-4. *Close up view of South-West part of tunnel section C. Cells with an inflow larger than 0.05 l/min are marked.* Cond$_{\max}$=10^{-7} *m/s.*

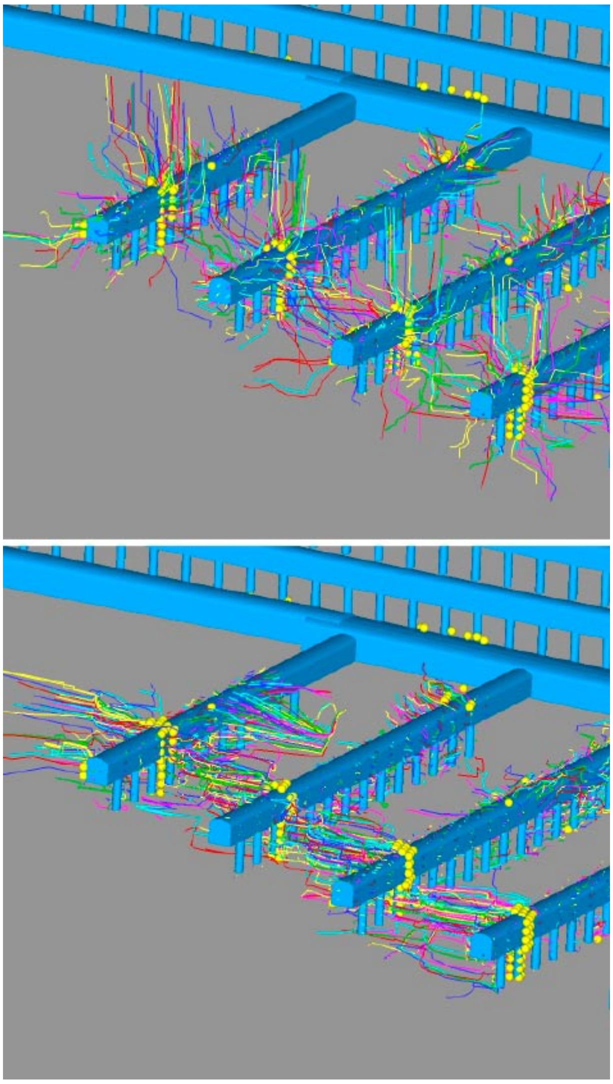


Figure 3-5. *Backtracking of particles for open repository (top) and without a repository. Integration time is one hour for the open repository (top) and 100 days for undisturbed conditions.*

The same simulation was also done for undisturbed conditions, i.e. without the repository. It is found, see Figure 3-5, that the flow pattern is more horizontal for the undisturbed conditions and the transport velocities are several orders of magnitude smaller. A cross-correlation diagram is shown in Figure 3-6 and it is clear that a high local velocity for undisturbed conditions is related to a high inflow velocity for an open repository.

3.3 Deposition Holes

Next we will show results for inflows to deposition holes. If the coordinates of the centre line of a deposition hole are given, it is of course easy to find all cells with an inflow to the hole and obtain the total inflow to the deposition hole. The reason for expressing the inflow per deposition hole is that it may give an indication of how many holes that need to be discarded, when canisters are to be placed in the holes.

The main result of this report is given by Table 3-2, where the inflow to deposition holes is given as a function of the grouting efficiency. As an example of the reading of the table, we find that 1.7% of all deposition holes will have an inflow larger than 1.0 l/min, provided $Cond_{\max}=10^{-7}$ m/s. This number will increase to 21.1% (1.7 + 19.4) if we include all holes with an inflow larger than 0.1 l/min.

An illustration of these results can be found in Figure 3-7, where deposition holes with an inflow larger than 1.0 and 0.1 l/min have been marked.

Table 3-2. Inflow to deposition holes as a function of grouting efficiency.

Inflow to deposition hole [l/min, hole]	Grouting efficiency No grouting %	Q	$Cond_{max}$ = 10^{-7} m/s %	Q	$Cond_{max}$ = 10^{-9} m/s %	Q
$Q_{dh} > 1.0$	1.9	293	1.7	223	0	0
$0.1 < Q_{dh} \leq 1.0$	18.2	380	19.4	410	23.9	325
$0.01 < Q_{dh} \leq 0.1$	34.9	103	35.0	103	46.7	160
$Q_{dh} \leq 0.01$	45.0	9	43.9	8	29.4	9
Total inflow [l/min]		785		744		494

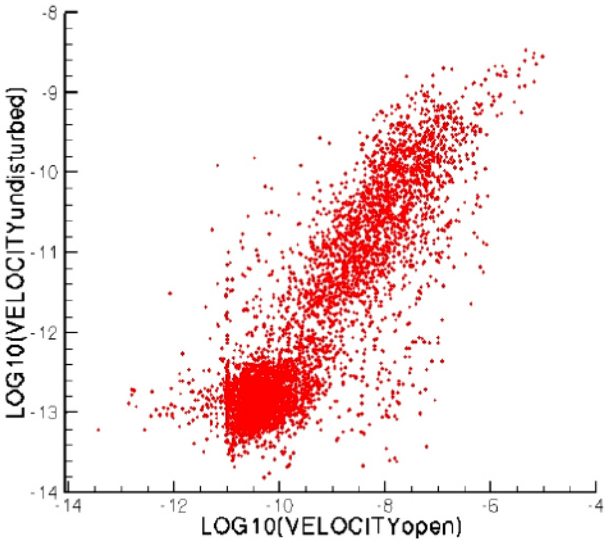


Figure 3-6. *Cross-correlation between Darcy velocities (in m/s) at the same location for open repository and undisturbed conditions.*

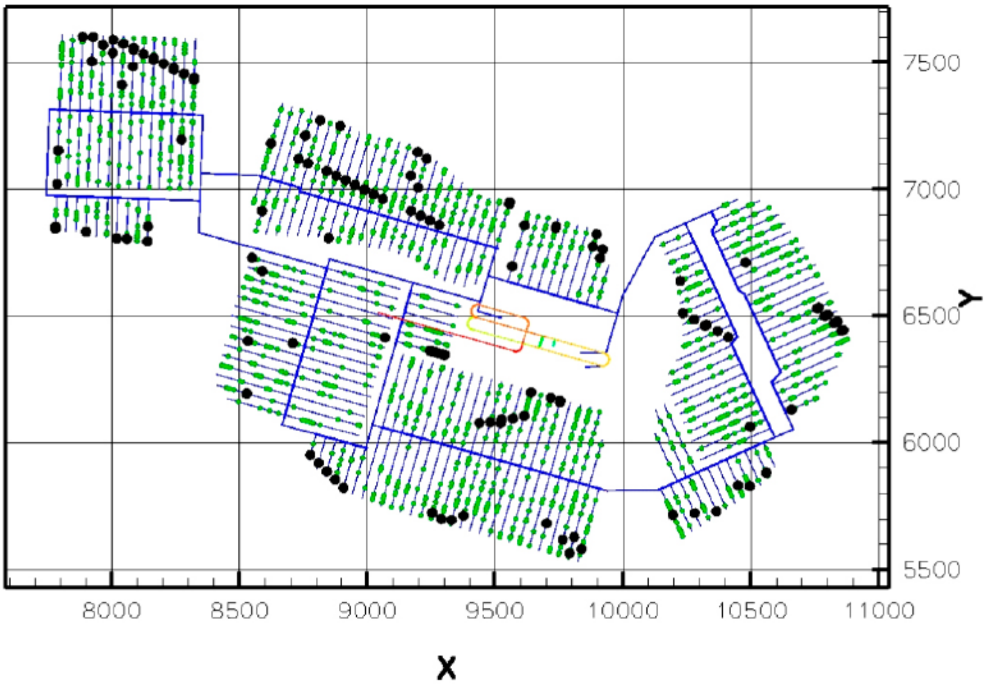


***Figure 3-7.** Deposition holes with an inflow larger than 1.0 (black) respectively 0.1 (green) l/min have been marked. Cond*$_{\max}$*=10*$^{-7}$ *m/s.*

4 Results, Forsmark

4.1 Site

The Forsmark area is located near the Forsmark nuclear power plant, in northern Uppland, on the east cost of Sweden, see Figure 4-1. In this figure also the Regional Model domain is introduced; this domain is also the largest one considered in this study. The dimensions of the Regional Model area are: 15 km (northeast), 11 km (northwest) and 2.1 km (depth).

An outline of the repository is shown in Figure 4-2. The repository is located at a depth of about 400 metres. The layout of the repository is done with respect to major deformation zones in the area. The input data can be specified as the base case, defined in the Site Descriptive model /Follin et al. 2005, SKB 2005/. An account of this data set can also be found in /Svensson 2005b/. Some key features of the base case include:

The key deformation zones are the Singö deformation zone (SDZ), the Eckartfjärden deformation zone (EDZ) and the dipping zones A1 and A2 (see Figure 4-3). In addition to these a set of smaller zones is also represented in the base case model. In between these zones the base case defines continuous porous medium (CPM) blocks, called CPM1, CPM2 and CPM3. The repository is located in CPM3. As CPM3 has a very low conductivity (10^{-11} m/s), it will prove that the properties of CPM3 is a major controlling factor for the repository.

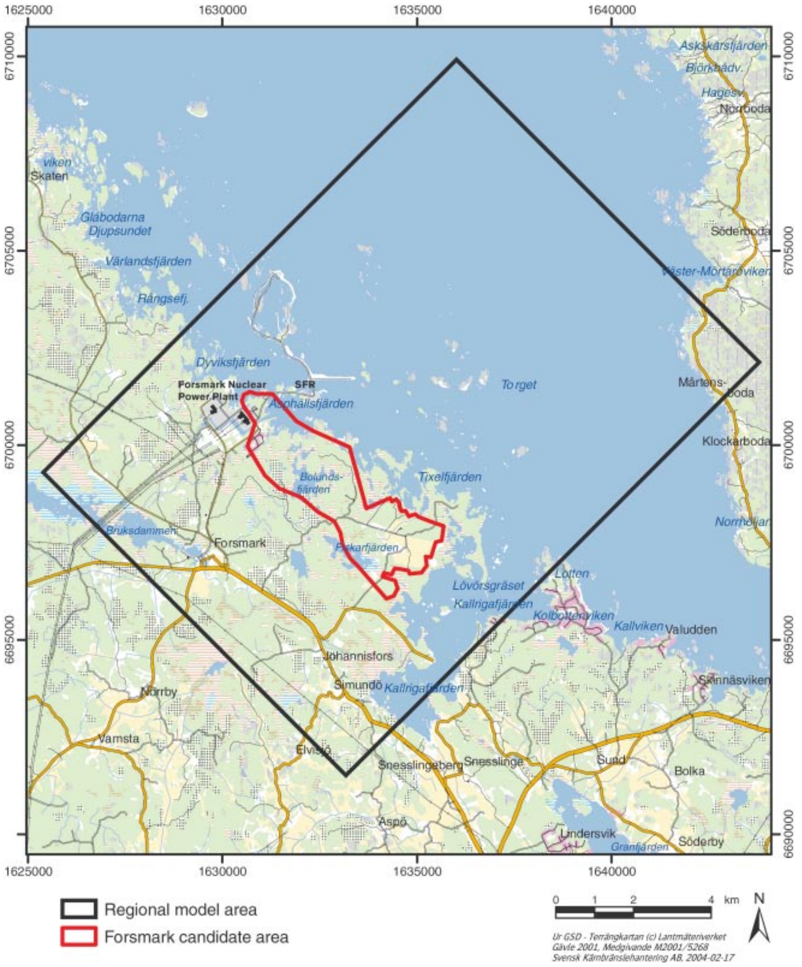


***Figure 4-1.** Overview of the Forsmark area and the Forsmark regional model area.*

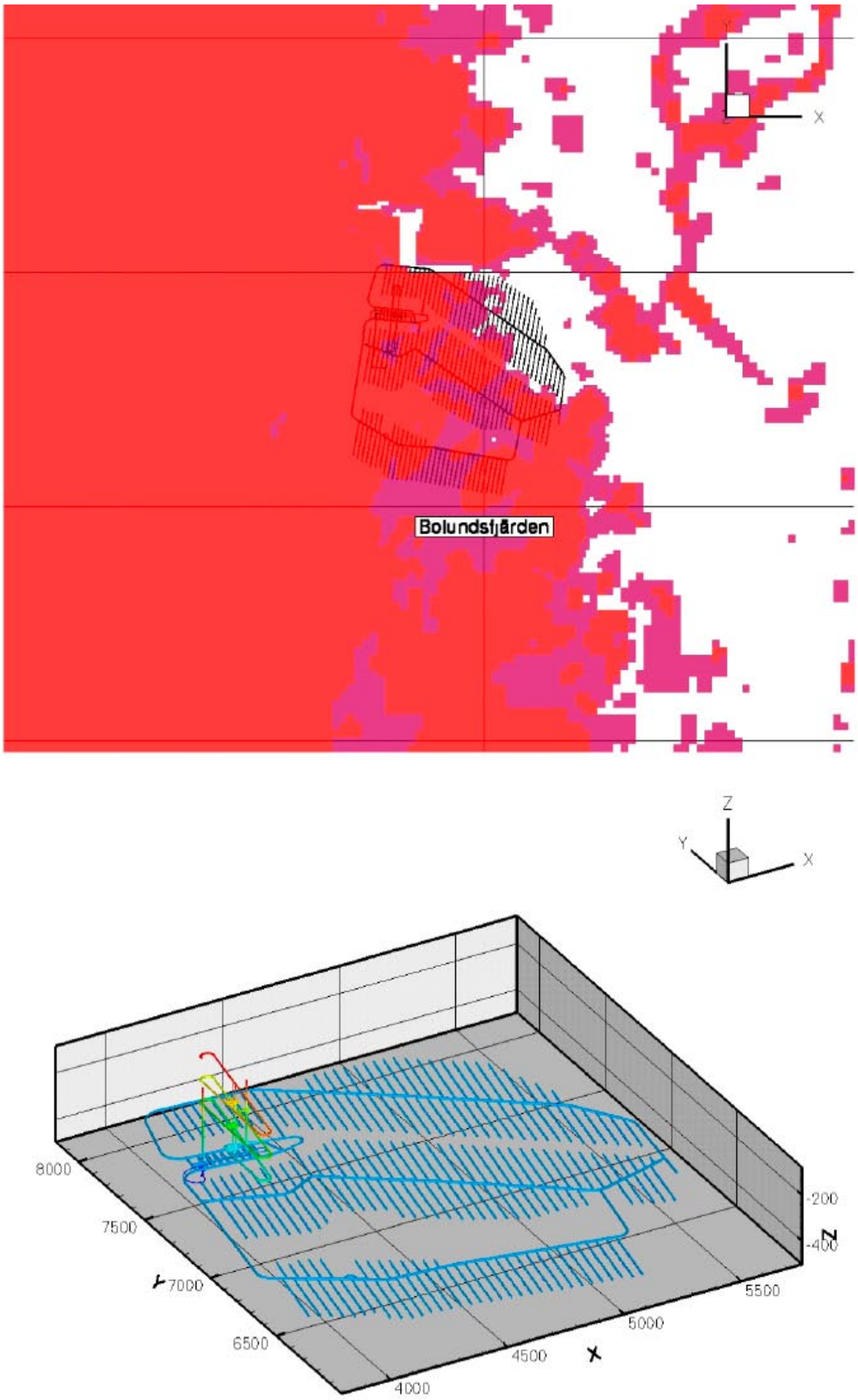
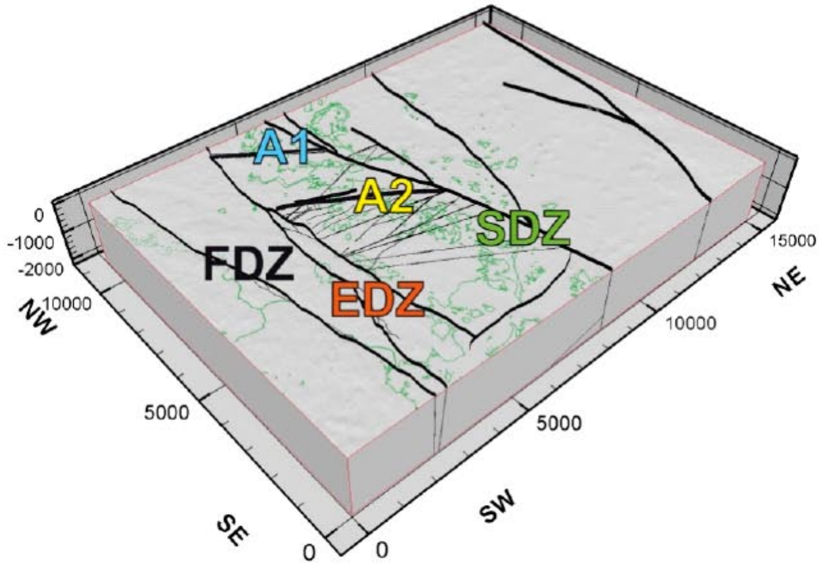


Figure 4-2. *Layout of the repository. Position in the horizontal plane (top) and a perspective view. In the top figure the white colour indicates the Baltic and the red land.*

Major deformation zones Forsmark 1.2

Base model



Multicomponent CPM below –400 masl

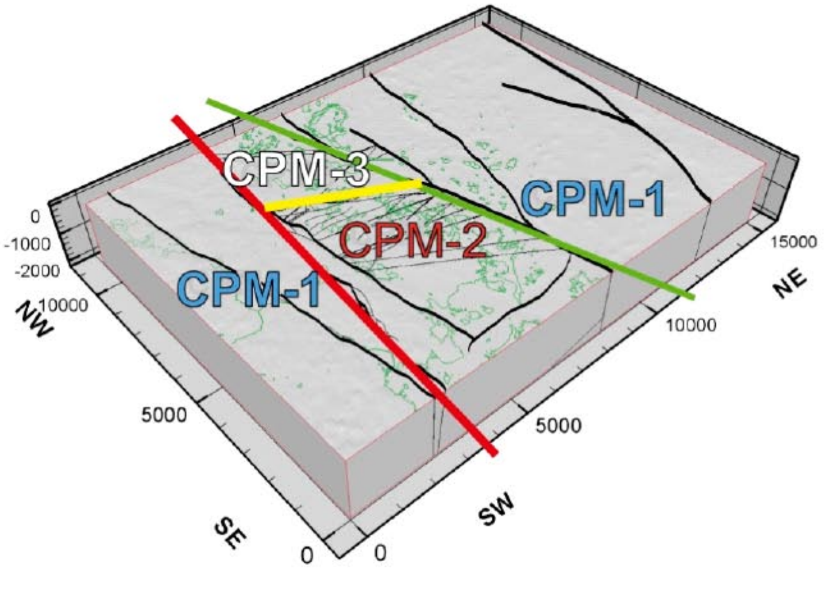


Figure 4-3. *The base case model. Deformation zones (top) and rock blocks in between the zones (from /SKB 2005/).*

4.2 Deposition holes

In the open repository study it was found that the inflow to the repository can be expected to be very small indeed, i.e. less than 5 l/s. The present simulations give the same general results and it is hence of limited value to analyze this site as carefully as the Laxemar site. In fact, the total inflow to all deposition holes is less than 3 l/min and 99.9% of all holes have an inflow smaller than 0.01 l/min. Figure 4-4 illustrates the result. In order to find some spots to mark, the criterion was chosen to 0.005 l/min. Seven deposition holes, out of 6,824, have an inflow that fulfil this criterion.

As a final comment to the Forsmark results one may note that the inflow is the same for $Cond_{\max}=10^{-7}$ m/s and no grouting, while inflows are reduced by roughly 50% for $Cond_{\max}=10^{-9}$ m/s.

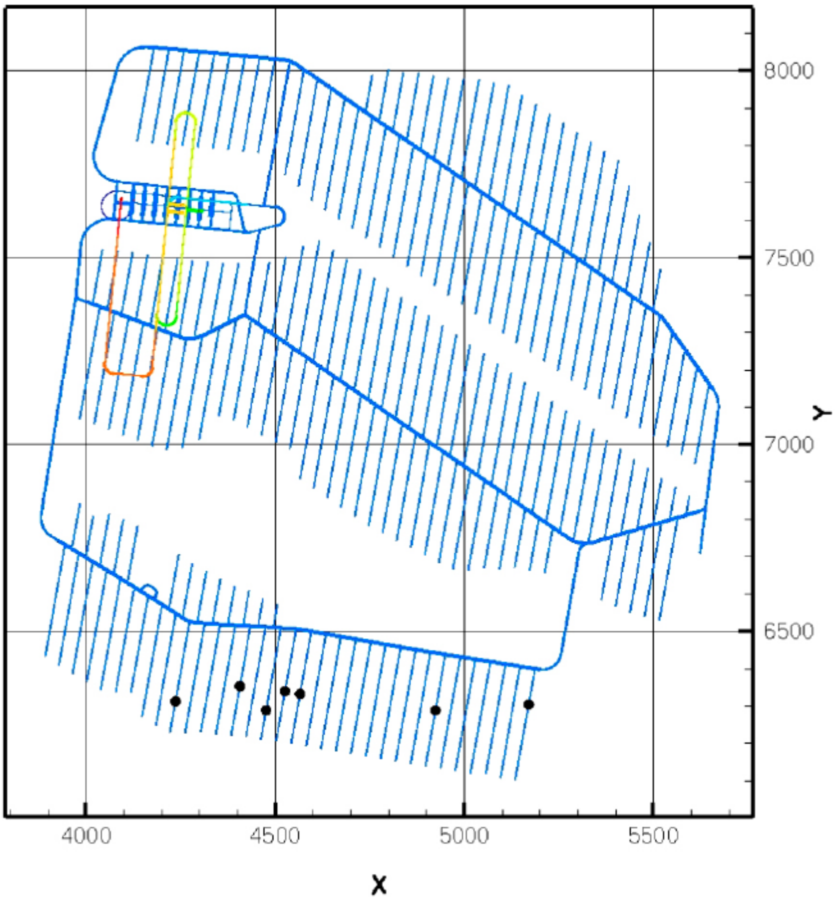


Figure 4-4. Deposition holes with an inflow larger than 0.005 l/min are marked with a black circle. Condmax=10^{-7} m/s.

5 Sensitivity studies

5.1 Introduction

The large difference in total inflow between the Laxemar and Forsmark repositories illustrates nicely the importance of the fracture network; Laxemar has a dense network while Forsmark is very sparsely fractured. The sensitivity to the fracture network properties is obvious. In this project a small sensitivity study concerned with the network will be carried out. For the Laxemar open repository study the smallest fracture generated was 30 metres and in this study the smallest fracture has been 10 metres. It will be investigated how sensitive the statistics on the inflow to the deposition holes is to the smallest fracture in the network.

A second sensitivity study concerns the size of the computational domain; is it necessary to include a domain with a surface hydrology model or can a smaller volume with hydrostatic boundary conditions be used?

5.2 Minimum fracture size

The influence of the minimum fracture size will be analysed for the Laxemar site with $Cond_{\text{max}}$=10^{-7} m/s. The steady inflow is calculated and the inflow distribution to deposition holes is then evaluated. In Table 5-1 the inflow distributions for three values on the minimum fracture size can be studied. As can be expected, the inflow will increase with the inclusion of more fractures. The total inflow to the repository will increase by roughly 20% (from 3,336 to 4,002 l/min), while the inflow to deposition holes will increase by 31% (from 567 to 744 l/min).

We conclude that the inflow is moderately sensitive to the minimum fracture size in the fracture network. It should be pointed out that this conclusion is valid for the transmissivity-size correlation defined in the base case for Laxemar; other transmissivity-size models may give different results.

Table 5-1. Inflow distribution for three different values on the minimum fracture size.

Inflow to deposition hole [l/min, hole]	**Minimum fracture size (m)**					
	10		**20**		**30**	
	%	**∑*Q***	**%**	**∑*Q***	**%**	**∑*Q***
Q > 1.0	1.7	223	1.7	225	1.6	220
0.1 < Q ≤ 1.0	19.4	410	15.2	340	12.8	292
0.01 < Q ≤ 0. 1	35.0	103	21.5	64	15.9	48
Q ≤ 0.01	43.9	8	61.6	7	69.7	7
Total inflow to deposition holes (l/min)		744		636		567
Total inflow to repository (l/min)		4,002		3,618		3,336

5.3 Domain size

It is known from field data that the pressure outside a tunnel approaches the ambient, nearly hydrostatic, pressure in a fairly short distance from the tunnel, i.e. tens of metres. This implies that the computational domain does not need to be much larger than the volume that includes the repository. On the other hand, prescribing a hydrostatic pressure boundary condition close to the tunnel means that we have an infinite source of mass at this boundary.

In order to shed some light on this question a smaller computational domain will be tested. A domain size of 3,500 m (east-west), 2,400 m (north-south) and 240 m (vertical), centred around the Laxemar repository, is specified for the purpose. This domain size will ensure that the boundary is always at least 100 metres away from the repository. A hydrostatic pressure is prescribed on all boundaries, while other conditions (grid, fracture network, etc) are the same as for the large domain.

The results can be studied in Table 5-2. Corresponding results for the large domain are given in brackets. The main conclusion is that the results are sensitive to the domain size; for $Cond_{\max}=10^{-7}$ m/s the total inflow to deposition holes increases from 744 to 2,110 l/min. A comment may be needed on the number of deposition holes with an inflow larger than 1.0 l/min. When $Cond_{\max}=10^{-7}$ m/s is changed to no grouting the value decreases from 6.8% to 6.4%. This may seem odd at a first glance. However, with no grouting some deposition holes get a very large inflow (> 10 l/min). These inflows reduce the general pressure level and most deposition holes thus get a lower inflow. The total inflow is however (as expected) higher for the no grouting condition.

Table 5-2. Inflow distributions for a smaller computational domain. Values for the large domain are shown in brackets.

Inflow to deposition hole [l/min, hole]	Grouting efficiency No grouting %	Q	$Cond_{\max}=10^{-7}$ %	Q	$Cond_{\max}=10^{-9}$ %	Q
Q > 1.0	6.4	1,368	6.8	1,201	0	0
	(1.9)	(293)	(1.7)	(223)	(0)	(0)
0.1 < Q ≤ 1.0	30.7	778	31.2	807	39.1	666
	(18.2)	(380)	(19.4)	(410)	(23.9)	(325)
0.01 < Q ≤ 0.1	29.7	94	29.3	94	36.8	132
	(34.9)	(103)	(35.0)	(103)	(46.7)	(160)
Q ≤ 0.01	33.2	7	32.7	8	24.1	10
	(45.0)	(9)	(43.9)	(8)	(29.4)	(9)
Total inflow to deposition holes (l/min)		2,247		2110		808
		(785)		(744)		(494)
Total inflow to deposition holes and tunnels (l/min)		8,760		8,340		2,880
		(3,528)		(3,396)		(1,824)

6 Discussion

As known to the author, it is the first time that the inflow to thousands of deposition holes, embedded in a regional scale model, has been simulated. Many novel model features have been employed, in particular the adaptive Cartesian grid, and one may then question how accurate the results are. Let us use the discussion section to give some views on this topic.

First of all, it is believed that DarcyTools provides the right answer for the given input. Extensive verification studies are reported elsewhere /Svensson et al. 2006/ and these confirm that DarcyTools is accurate and efficient as an equation solver. An example of a verification case, relevant for the present simulations, is included as Appendix A.

A brief review of the input data points to the fracture network as the key source of uncertainty. This is a quite obvious statement; no fractures, no inflow! However, we do have a fracture network and thus need to evaluate it:

- The largest deformation zones (l > 1,000 metres) form a connected network that constitutes the main "underground river system" and is hence a very important element. Presently it is not clear how many of the zones that are real hydraulic conductors and they are hence classified as "low", "medium" or "high" confidence structures. This uncertainty affects the present results significantly. Also the properties, in particular the transmissivity, are only determined for a minority of the zones.
- Fractures zones smaller than 1,000 metres are generated stochastically for the Laxemar case. Both the intensity of this network and the properties of the fractures will affect the present results. The sensitivity study in this project shows that the fractures with length-scales in range 10 to 30 metres will affect the total inflow to the repository. The present study did not analyse how sensitive the results are to the chosen transmissivity-size model for the stochastic network. Another model may give quite different results.
- Grouting can be considered as a modification of fracture properties and hence be discussed in this context. Once again it is obvious that the grouting efficiency controls the magnitude of the inflow. In the present study a maximum conductivity specification in a volume around the repository has been used as a simulation of grouting. Is this the best way to simulate grouting?

The recommendation is thus that the three points above are considered further; can improved field data be compiled? Can sensitivity studies provide bounds on the results?

7 Conclusions

The main objective of this study has been to estimate the water inflow distribution to the Laxemar and Forsmark repositories, expressed as l/min, deposition hole. The following is concluded:

- For the Laxemar repository 1.9, 1.7 and 0.0 % of the deposition holes will have an inflow larger than 1.0 l/min, for the three grouting efficiencies investigated (no grouting, $Cond_{max}=10^{-7}$ m/s and $Cond_{max}=10^{-9}$ m/s). These numbers will increase to 20.1, 21.1 and 23.9% if the inflow limit is changed to 0.1 l/min.
- For the Forsmark repository it is found that 99.9% of all deposition holes will have an inflow smaller than 0.01 l/min.

A sensitivity study has been carried out with the following results:

- The inflow rate is moderately sensitive to the smallest fracture size used in the stochastic fracture network. Changing this fracture size from 30 to 10 metres, increases the total inflow to the Laxemar repository by roughly 20%.
- A large sensitivity is found to the size of the computational domain. Using hydrostatic boundary conditions (not closer than 100 metres to the repository) will increase the inflow by a factor of 2 to 3.

An evaluation of the main uncertainties of the results points to the properties of the fracture network. This uncertainty applies to all scales; from the confidence classification of deformation zones to the intensity of the stochastically generated network and the methods to simulate grouting.

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Appendix A

Water inflow to a circular tunnel

A.1 Introduction

The steady state flow towards a circular tunnel in a semi-infinite isotropic and homogeneous aquifer will be investigated. If the radius of the tunnel is denoted r and the depth h it is well established that the inflow, q, is given by

$$q = 2\pi k \frac{h}{\ln \frac{2h}{r}} \qquad \text{(A-1)}$$

where k is the hydraulic conductivity. A review of analytical solutions is provided by /El Tani 2003/ and in this paper it is shown that (A-1) is valid if $r/h << 1$ (if $r/h \approx 0.1$, the error in q is of the order of 1%).

The objective of this test case is to verify that the numerical solution is in agreement with (A-1).

A.2 Numerical simulations

The simulation parameters are summarized in Table A-1. A vertical plane (the simulation is 2D) with dimensions 3,000 m (horizontal) and 1,000 m (vertical) specifies the computational domain. Part of the grid is shown in Figure A-1. As can be seen the tunnel is approximated with a polygon.

A.3 Results / Discussion

The inflow to the tunnel, as calculated by Equation (A-1) and by the numerical simulation, is shown in Figure A-2. A close agreement is found for the three tunnel radii tested.

In /El Tani 2003/ corrections for a finite r/h value are given. For the present cases it is found that the corrections are smaller than 0.5%; however they do act to bring the analytical results even closer to the numerical ones. It was found that the horizontal size of the domain needed to be quite large (3,000 metres). A smaller size (1,000 m) affected the inflow with several percent.

A.4 Conclusion

It has been demonstrated that water inflow to a circular tunnel with atmospheric pressure can be calculated with good accuracy.

Table A-1. Simulation parameters.

Domain	3,000 x 1,000 x 1 metres	
Boundary Conditions	Fixed pressure at ground. Zero flux on all other boundaries. Atmospheric pressure in tunnel.	
Properties	Conductivity = 10^{-5} m/s	
Tunnel	Centre at a depth of 100 metres. Radius varied: 2.5, 5.0, 10.0 metres	
Grid	Tunnel:	Δ_{max}=1.0
	Near field:	Δ_{max}=2.0
	Far field:	Δ_{max}=20

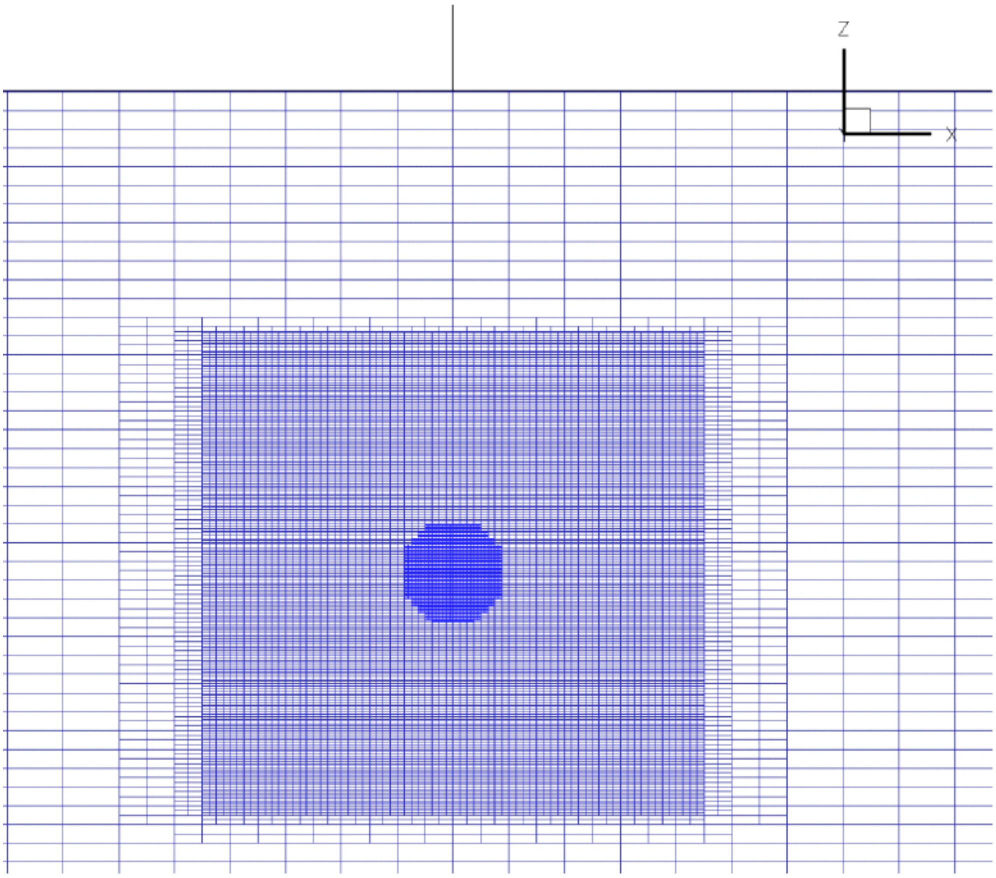

Figure A-1. The grid close to the tunnel.

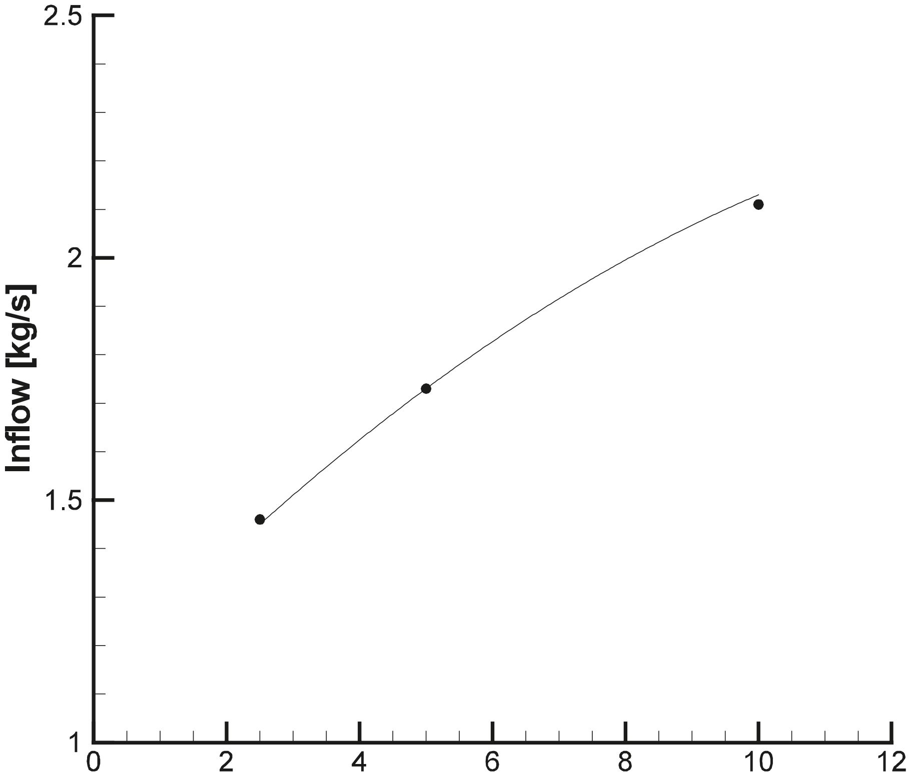

***Figure A-2.** Analytically (line) and numerically (symbols) determined relation between tunnel radius and inflow.*