

## **Rational and Economic Disposal of Hazardous Waste: Use of Abandoned Mines**

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### **Abstract**

Deep geological disposal of dangerous waste like mercury, solidified organic pesticides and radioactive rest products, requires suitable engineered barriers. Use of deep abandoned mines is a rational and economic alternative to construction of a repository in virgin rock but requires knowledge of the structural constitution of the rock for assessment of groundwater flow and rock mechanical conditions. Such information is much more detailed through the activities of mining companies than from exploration of virgin rock. Organizations responsible for disposal of radioactive waste in crystalline rock count on the host rock as a barrier to migration of released radionuclides to the biosphere but present investigations reduce its role to provide mechanical support of the waste packages while effective hindrance of migration of contaminants can be offered by engineered barriers, i.e. waste containers and clay embedding them. For certain waste in granular form, like Hg batteries, mixing with expandable clay and layerwise placement and compaction is deemed possible as described in the paper. The primary role of the clay is to make the clay-mixed waste very tight and ductile. By constructing liners of highly compacted clay blocks along the periphery of the disposal rooms the rock is given sufficient support and effective isolation of the waste. If the liners have a thickness of 0.5-1 m and placed in dry form the time for complete water saturation of the clay/waste mixture can be several thousands of years. Not until then migration of hazardous waste elements to the rock can start.

A major role in the hydrological performance of the host rock is that of the excavation-disturbed zone (EDZ). It short-circuits the natural system of flow paths and causes quick transport of released contaminants to downstream wells

**Keywords:** Excavation disturbance, expandable clay, groundwater flow, hazardous waste, mines, rock structure.

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## 1 Rock Structure

The physical behaviour of a rock mass depends almost entirely on its discontinuities. They are represented by weaknesses of all sizes, ranging from crystal vacancies of atomic dimensions to fracture zones with lengths exceeding thousands of kilometres. Fractures are more or less plane, permeable discontinuities and are called faults, fracture zones, slip zones, gouge zones, fissures etc in daily talk. Such terms can be used for general description of the discontinuities in a rock mass but for describing its mechanical and hydraulic performances in bulk one needs to consider the location and physical properties of the individual structural components. Certain kinds of waste like spent reactor fuel (HLW) are of course particularly hazardous but become less dangerous with time while chemical waste (CW) remains poisonous and requires long-term isolation from the groundwater. The principles for performing groundwater flow analyses coupled to rock structure are the same for both types of waste and were described in conjunction with an earlier study of groundwater pollution as part of the EU project Low Risk Deposition Technology (LRDT), [1]. In the present document we will get deeper into this matter, focusing on rock of granitic type but confining ourselves to CW.

We will use a categorization scheme (Table 1) proposed a number of years ago for use in the stone industry and for characterization of rock in the planning and construction of repositories for (HLW), [2,3]. The discontinuities of 1st and 2nd orders - major fracture-rich zones - cause difficulties in the construction stage and determine regional groundwater flow. They can be identified by deep drillings and application of geophysical methods in the site selection phase, while discontinuities of 3rd and higher orders can usually not be revealed until construction has started. The scheme is particularly helpful in characterization of weaknesses like discrete fractures intersection holes, tunnels and shafts for selecting suitable positions for waste disposal. Examples are seen in Figure 1.

Table 1: Rock discontinuity scheme. 1<sup>st</sup> to 3<sup>rd</sup> are fracture zones, 4<sup>th</sup> to 7<sup>th</sup> are discrete fractures. VH=very high, H=high, M=medium, L=low, VL=very low, VVL=insignificant.

Order	Length	Hydraulic conductivity	Gouge content	Strength	D-system (SKB)
1st	>Kilometers	VH	VH	VVL	D1
2nd	Kilometers	H	H	VL	D2
3rd	Hundreds of meters	M to H	M	L	D3
4th	Tens of meters	M to H	L	L to MH	D4
5th	Meters	L	VL	MH to H	-
6th	Decimeters	VL	VL	H	-
7th	<Decimeters	VVL	VVL	VH	-

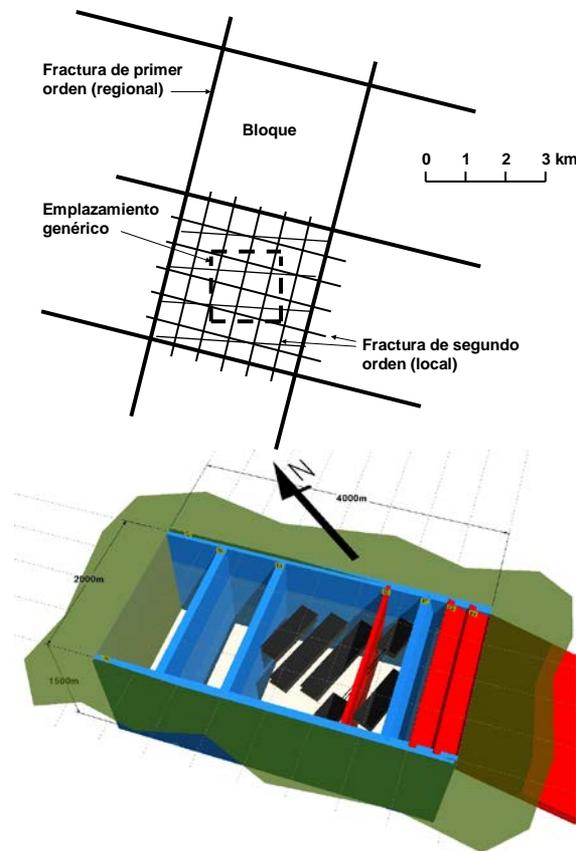


Figure 1: Rock structure models for hydraulic and mechanical calculations. Upper: ENRESA's general rock structure model with 1<sup>st</sup> and 2<sup>nd</sup> order discontinuities (major fracture zones). Lower: Simplified model of rock with 2<sup>nd</sup> and 3<sup>rd</sup> order discontinuities for possible location of a HLW repository (flat panels), [3,4].

In practice, the regularity of the various discontinuities and the rock stress conditions vary considerably, especially at depths down to a couple of hundred meters as illustrated by Figure 2, which represents granitic rock in the Forsmark area north of Stockholm. Deeper down the stress conditions are more homogeneous but still considerable as indicated by Figure 3 that shows trends in orientation and spacing of hydraulically and mechanically active (unsealed) 4<sup>th</sup> order discontinuities and of the rock pressure in the horizontal plane at 360 m depth in the granitic dome in the Stripa area a few hundred kilometres westwards from Forsmark, [2].

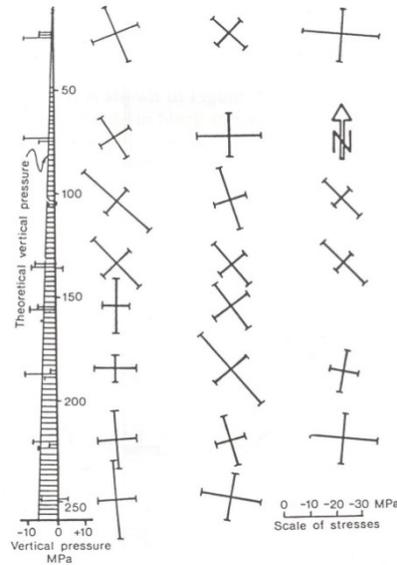


Figure 2: Variation in the stress field in shallow granitic rock in the Forsmark area north of Stockholm (After Carlsson & Olsson), [2].

The variations in orientation and interconnectivity of these structural features, which determine the macroscopic bulk conductivity, explain why the average gross hydraulic conductivity can vary by orders of magnitude. These examples also demonstrate that several tunnels and rooms for disposal of hazardous waste can be oriented favourably with respect to the principal stresses in the horizontal plane while others, differently oriented, can have high hoop stresses and be unstable.

A further difficulty in characterization of rock structure for calculating groundwater flow and quantification of stability conditions is the excavation-damaged zone around shafts tunnels and rooms. It is called EDZ here and results from the mechanical disturbance and the stress changes related to the movement of the remaining rock towards the created opening [2,3,4]. The role of the EDZ for groundwater flow in rock with blasted tunnels and rooms using modern techniques is moderate to significant but very significant in mines where the comprehensive use of blasting did not have the purpose of preserving the rock.

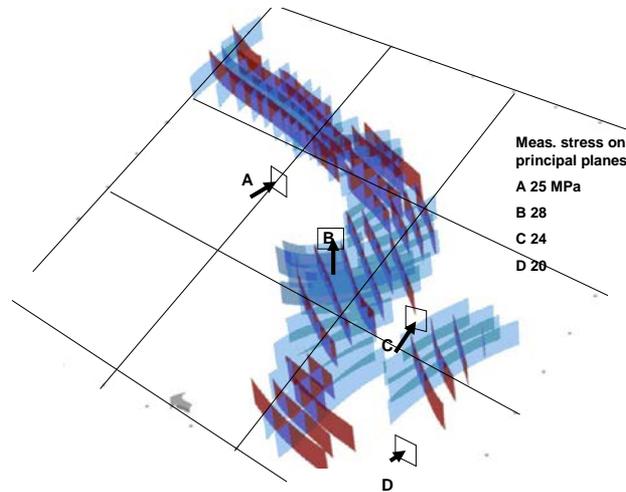


Figure 3: Sets of steeply oriented fractures in an approximately orthogonal pattern in granite. Blue sets are oriented in the direction of the highest rock stress and carry more water than the red ones that are compressed by this stress component [3]. Distance between the lines is 30 m.

## 2 Groundwater Flow and Transport in Fractured Porous Media

### 2.1 Pressure Issue

The issue considered here is the risk of contamination of wells for drinking water caused by inflow of groundwater that has passed through rock with a repository hosting hazardous waste. Three specific questions dealt with are: 1) the impact of different rock structural components on the inflow rate into a well bored at a certain distance from such a repository, 2) the impact of the excavation technique, blasting, on the groundwater flow, and 3) how effective engineered barriers can be in preventing the risks of contamination of the well water [5].

Following recent hypotheses regarding distribution of groundwater flow under hydraulic gradients we assume here channel flow implying that hydraulic gradients drive water along intersections of discrete fractures and fracture zones schematically shown in Figure 4.

Porous media exhibit a variety of heterogeneities. The crystalline bedrock consists of solid rock, cut by a network of fractures and fracture intersections through which water flows unevenly. Water flows along a portion of inter-connected fractures, while the rest contain essentially stagnant water.

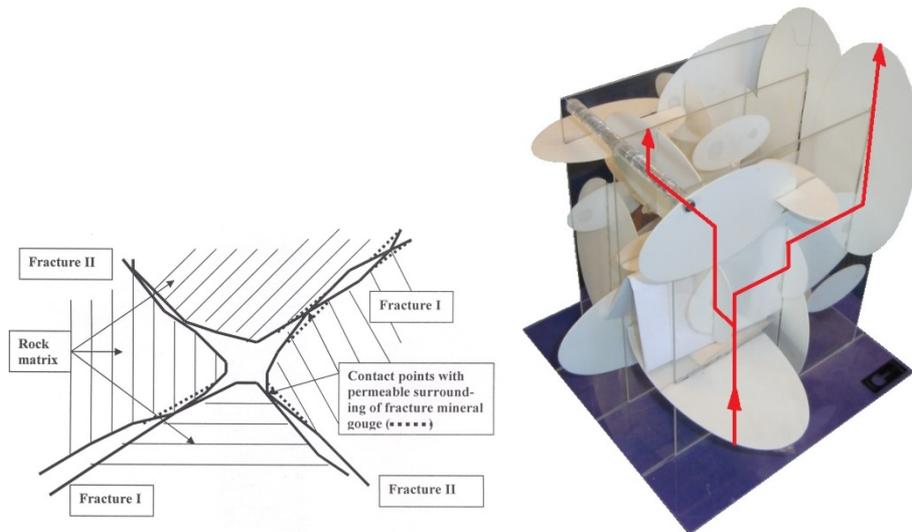


Figure 4: Channels at intersection of discrete water-bearing fractures and fracture zones.

The selection of the modelling approach is usually carried out considering the geometry and scale of the fractured rock, the field data available and some practical limitations like capabilities of computational resources. General references on porous media flow and solute transport make use of the Darcy law for the flow, and the advection-dispersion equation for the transport [6,7].

Non-homogeneous models can be used for relatively accurate analysis of flow and transport processes in fractured porous media, where porosity and permeability are allowed to vary discontinuously and rapidly but the computational and data requirements are often too high for many practical applications. The discontinuous nature of the permeability and porosity can be avoided by replacing them by averaged values as in the equivalent continuum model [8], which does not contain fractures. A progress in the continuum model approach used in the present study has been achieved with the dual porosity models [9]. The model assumes that the fractured porous media is a continuum consisting of two overlapping regions and therefore there is one equation for each region. A coupling term is used in the equations describing the exchange between the two pore systems [10].

## 2.2 3D Model for Flow and Transport in Fractured Porous Media

The model proposed here employs the discrete fracture model and the equivalent continuum model. The firstmentioned enables us to include the major water-bearing fracture zones into the model, which have high impact on the flow and species transport. The equivalent model helps to take into account fractured rock where the fractures are not significant enough to be accounted for separately. In constructing models for the present purpose one needs to consider the distance from a point of interest. A fracture zone close to a point of interest – the well – that would be taken into account as a separate element might be included in the equivalent continuum model if sufficiently far from the point of interest. A good way of testing whether it should be included in the model is to perform a sensitivity analysis at a point of interest. Crossings of water-bearing fracture zones are considered here to be major channels (Figure 5).

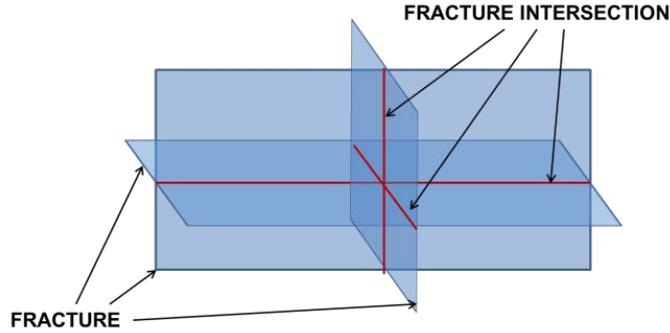


Figure 5: Intersecting fractures/fracture zones and their intersections in the model. Rock (3D entity using the equivalent continuum approach), fractures (2D entities in the discrete fracture model), fracture intersections (1D entities in the discrete fracture model), intersection of fracture intersections (0D entities in the discrete fracture model).

### 2.2.1 The discrete fracture model

The discrete fracture (DF) model considers the fractured porous media as an incompressible non-homogeneous medium. The transient case of saturated flow in isotropic porous media can be written porous matrix, fractures and fracture intersections as:

$$C \cdot \frac{\partial h}{\partial t} + S_{source} = K \cdot \nabla^2 h \quad (1)$$

where  $C$  is the specific storativity [ $m^{-1}$ ],  $h$  the hydraulic head [m],  $K$  the hydraulic conductivity [ $ms^{-1}$ ],  $t$  is time [s] and  $Source$  the source term [ $s^{-1}$ ].

The flow velocity field is described by Darcy's law:

$$\vec{V} = -K\nabla h \quad (2)$$

The following equation for transient solute transport is used:

$$\frac{\partial c_i}{\partial t} = \frac{1}{R} \left[ \nabla D \nabla c_i - \vec{V} \cdot \vec{\nabla} c_i + \sum_j S_j \right] (i=1,n) \quad (3)$$

where  $c_i$  is the concentration of pollutant  $i$ ,  $D$  is dispersion coefficient

$$D = V\alpha + D_m \quad (4)$$

and  $\alpha$  is the dispersivity ( $m$ ),  $D_m$  is the molecular diffusion coefficient ( $m^2s^{-1}$ ),  $V$  is the average water velocity ( $ms^{-1}$ ).  $S_j$  represent sources and sinks of the pollutant and  $R$  is retardation factor

$$R = 1 + \frac{\rho}{\eta} K_D \quad (5)$$

where  $\rho$  is the bulk solids' density (mass/volume) and  $\eta$  the porosity. Assuming local equilibrium,  $K_D$  is obtained as

$$K_D = \frac{c_i^{soil}}{c_i^{aq}} \quad (6)$$

in the linear portion of the isotherm (low concentrations), where  $c^{soil}$  stands for the concentration of species  $i$  in the immobile solid rock/soil phase and  $c^{aq}$  stands for concentration of species  $i$  in the mobile aqueous phase.

The first term on the righthand side of (3) describes the influence of the dispersion on the concentration distribution; the second term, in the brackets, is the change of the concentration due to advective transport.

### 2.2.2 Equivalent-continuum model

In the equivalent-continuum (EC) approach, the same equations as for the DF model, (1) and (2) for flow and (3) for solute transport, are used, except that the fractures are not modelled explicitly. In this case they are treated as a continuum with properties derived from an averaging procedure. The hydraulic properties of the domain are averaged over the sub-volume, or representative elementary volume (REV), containing sufficiently large number of fractures.

The equivalent dispersion coefficient is calculated according to the following expression:

$$D_{equi} = D_m \cdot \frac{V_m}{V_t} + D_f \cdot \frac{V_f}{V_t} \quad (7)$$

where  $D_f$ ,  $D_m$  are dispersion coefficients in the fractures and matrix blocks [ $m^2/s$ ], respectively.

Although the EC model is commonly employed in describing fractured bedrock, the results obtained with the EC model represent averaged values over sufficiently large volumes of the domain, and it is therefore impossible to make a reliable estimate of the hydraulic head or concentration in a certain point of the domain. However, for the far field it is sufficient to obtain the averaged values of the field variables [11,12].

### 2.2.3 Integration of the entities in the 3D model

Figure 6 shows the way that matrix blocks, fractures and fracture intersections interact. The model has been solved by using the boundary element method (BEM). The BEM is particularly suitable in this case for solution of the 3D porous blocks as discretization into elements is required on the boundary surfaces of the blocks, which effectively converts 3D into 2D problems. More on the implementation of the model can be found in Peratta and Popov [13].

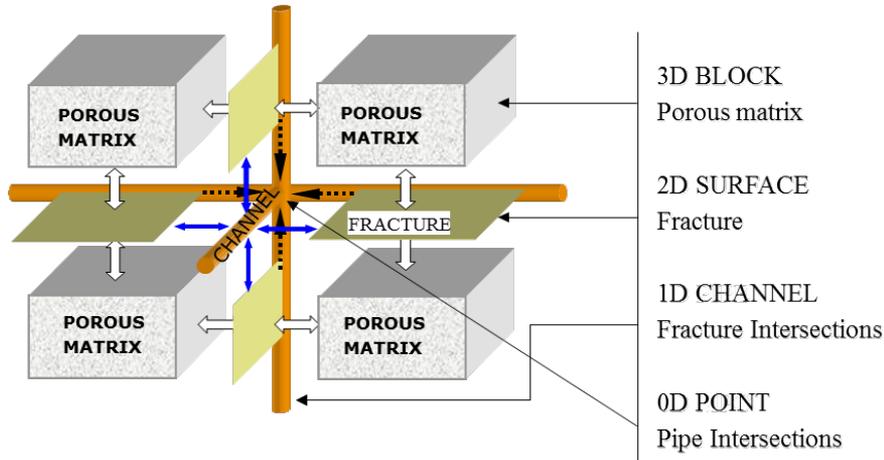


Figure 6: Coupling of matrix blocks, fractures and fractures intersections (pipes), [13].

#### 2.2.4 Influence of the EDZ on the flow in the near-field

The role of the excavation-disturbed zone (EDZ) has been under debate for several decades but it is generally accepted that it is real and particularly important for the groundwater flow in the floor of blasted tunnels [5,13]. In the present study EDZ was included in the model by considering it as a 2D entity wrapping-up the repository.

The influence of the EDZ on the flow around a repository is demonstrated by the example in Figure 8, consisting of a room of size  $100\text{m} \times 100\text{m} \times 150\text{m}$ . The repository is filled with chemical waste isolated in clay. Three fracture zones intersect the EDZ. The size of the domain is  $300\text{m} \times 300\text{m} \times 450\text{m}$ . The hydraulic conductivities used were: for the EDZ  $E-7$  m/s, for the clay  $E-10$  m/s, for the rock  $E-9$  m/s, for the fracture zones  $E-7$  m/s and for fracture intersections  $1E-6$  m/s. These values emanate from comprehensive field measurements in representative rock volumes and fit with Table 1. As can be seen the fracture intersections (channels) have the highest permeability.

In Figure 7a the flow is shown around the repository for the case with no EDZ included in the model. It can be seen that the velocity field around the room has got a component that is directed away from the room. The reason is the lower permeability inside the room, due to the clay, which makes most of the flow be diverted around the room. The effect of the EDZ is obvious in Figure 7(b) where the flow velocity has got a component, which is directed towards the repository. The reason for this effect is that the EDZ has a higher permeability than the surrounding rock so part of the fluid that would otherwise flow through the surrounding rock is diverted towards this zone. A continuous EDZ in an underground waste repository hence serves as a major flow path in the repository rock unless it is cut-off by constructing seals in strategic positions [3]. The chemical stability of ordinary Portland cement cement is being questioned and mutual degradation of contacting smectite clay and concrete containing such cement can be expected. For certifying long-term isolation of hazardous waste the function of such seals has to be disregarded.

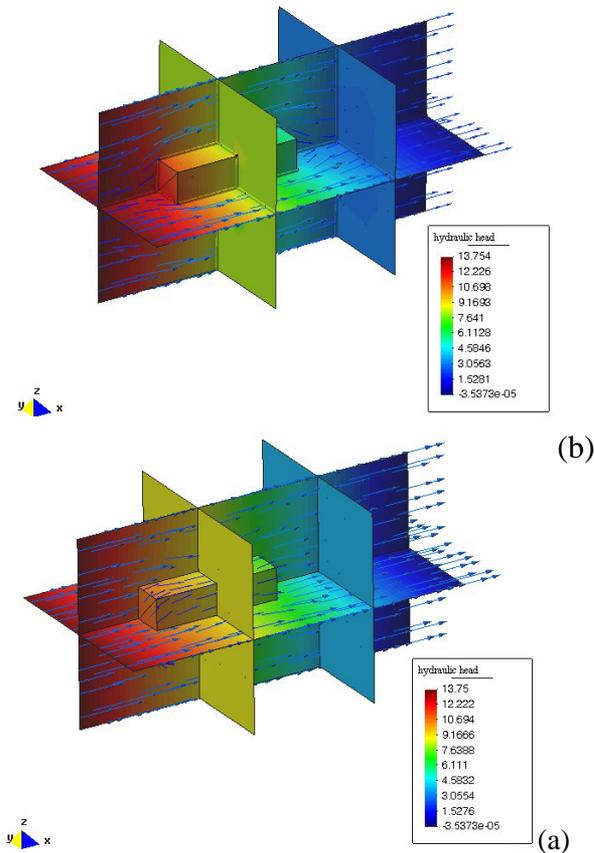


Figure 7: (a) Flow around a room embedded in rock, when the EDZ is not included in the model; (b) Flow around a room embedded in rock, when the EDZ is included in the model. The prevailing regional hydraulic gradient drives groundwater from left to right.

### 3 Rock Stability Conditions

#### 3.1 Practicality

While new underground repositories can be shaped and constructed with respect to the prevailing rock stress situation, which can vary very much, use of abandoned mines means that some drifts and rooms has to be judged with special respect to the need for stabilization. The same issue related to the categorization of rocks for the case of calculation of groundwater flow and solute transport, applies here as well. In this respect the impact of different rock structural components on the stability in a long term perspective can be substantial and the EDZ is particularly important in this context.

In practice, every single shaft, drift or room in an abandoned mine in crystalline rock that is being considered for disposal of hazardous waste has to be examined with respect to the stability by using common ways of estimating the forces acting on rock blocks of different size and shape and by using methods like the RQD system and utilizing the experience of the mining company in question [2]. One of the parameters for evaluation of the rock quality is the mechanical strength of the rock matrix that is conventionally determined by uniaxial compressive testing, but an even more important measure of the

stability conditions is the character of the discontinuities (Ja, Jr). The first mentioned is the number of fracture (joint) sets in the examined rock volume, usually 3-6 and occasionally higher than 10-12 indicating rich fracturing and poor stability. The parameter Jr refers the roughness of the fractures and is measured on site. For rough and undulating fractures the parameter has a value of about 3 while it is down to 0.5 for slickensides.

### **3.2 Theory**

#### **3.2.1 Mohr-Coulomb failure concept**

For certain well defined cases, commonly referring to large homogeneous rock volumes one can define the critical state using the Mohr-Coulomb criterion using  $\sigma_{cm}$  as the uniaxial compressive strength:

$$\sigma'_1 = \sigma_{cm} + k\sigma'_3 \tag{8}$$

Where  $\sigma'_1$  is the maximum principal stress (Eigen-value of the stress tensor), and  $\sigma'_3$  the minimum. If  $\sigma'_1$  exceeds the linear function of  $\sigma'_3$  the criterion is not satisfied. In the equation k represents a multiplication factor for the minimum stress and is equal to:

$$k = \left( \frac{1 + \sin \phi}{1 - \sin \phi} \right) \tag{9}$$

#### **3.2.2 A reference case**

Figure 8 shows the constellation of a big room and a tunnel (drift) located at 360 m depth in granitic rock both being intersected by fracture zones of 3rd order. The case represents an abandoned mine that we will take as an example in determining the rock stability and the contaminating effect on flowing groundwater on the water in a well located downstream.

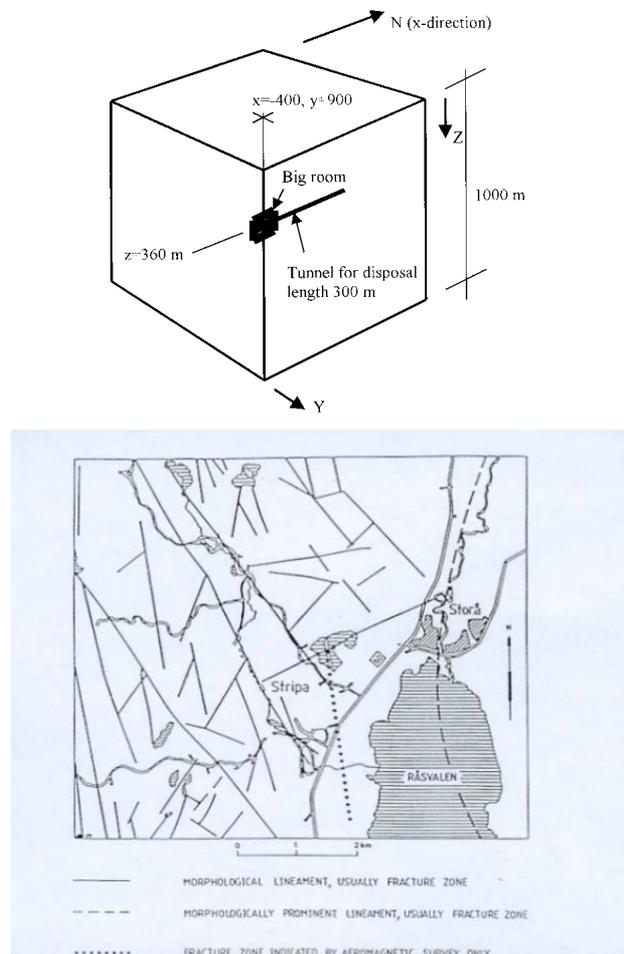


Figure 8: Example of host rock of repository used for stress/strain and hydraulic calculations. Left: Cavern with tunnel leading into it. Right: Stripa rock structure model [2]. Spacing of discontinuities of 2<sup>nd</sup> order 500-1000 m, of 3<sup>rd</sup> order discontinuities 50 to 100 m, and of 4th order 5 to 10 m.

#### EDZ divided in sub-zones

Since the EDZs are generally thin layers surrounding the excavated spaces in order to avoid numerical problems the EDZ around tunnel and room are divided into suitably shaped zones (see Figure 9).

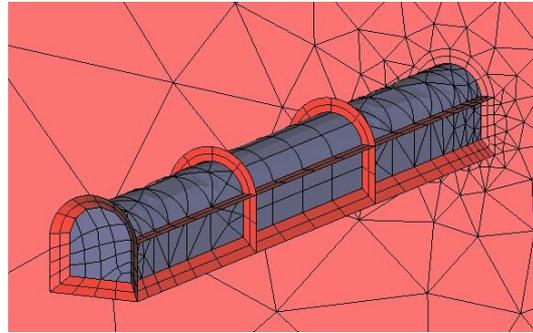


Figure 9: EDZ sub-modelling of a tunnel that is intersected at half its length by a vertical 3rd order fracture zone.

For handling the geometry a sub-modelling technique was used, where the EDZ zone is divided into sub-zones including big units of rock. The new method uses a technique, which can be used not only for this case, but also for a general case of hybrid implementation of the finite element method (FEM) and the boundary element method (BEM) models. Models with and without EDZ were assessed, at the normal tectonic pressure of 20 MPa and at an increased pressure. Rock that only contains fractures of 4th and higher order is treated as a porous medium while zones of 3<sup>rd</sup> and lower order discontinuities are the ones that determine the gross flow of the rock and their crossings are fundamental importance in applied hydraulic analyses. Figure 10 illustrates shows a structural model derived from deep borings and geophysical measurements. The apparent stringency is in fact only approximate because the axial extension of the structural units can not be proven, and because the flow properties vary strongly axially and across any section.

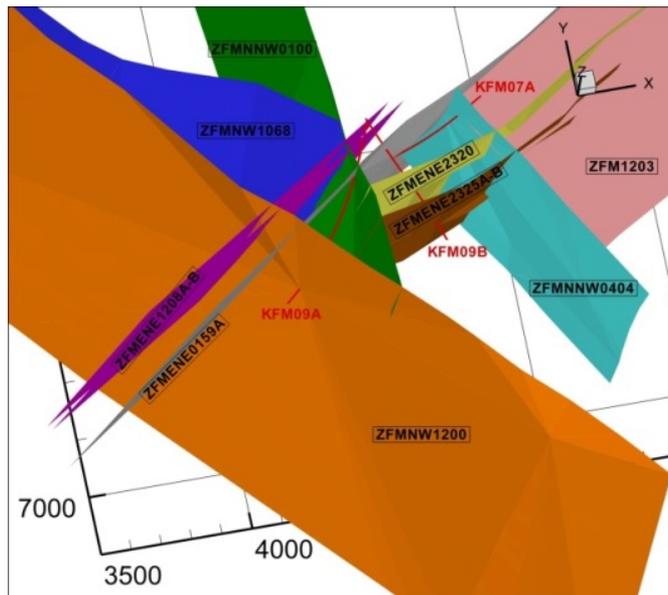


Figure 10: Fracture zones and their crossing according to SKB. The letter combinations represent deep boreholes for samples and measurements. The scale in the XY plane is given. The depth Z extends down to 900 m [14].

### Stability

Caverns of possible use for waste storage are large and can have a height of more than 50 m, which makes the EDZ much larger and weaker than for drifts and tunnels. This is illustrated by the example in Figure 11 from which one concludes that the movement of the eastern wall by 40 mm gave the presumably 2-3 m deep EDZ a vertical and horizontal hydraulic conductivity of more than 1000 times that of the virgin rock.

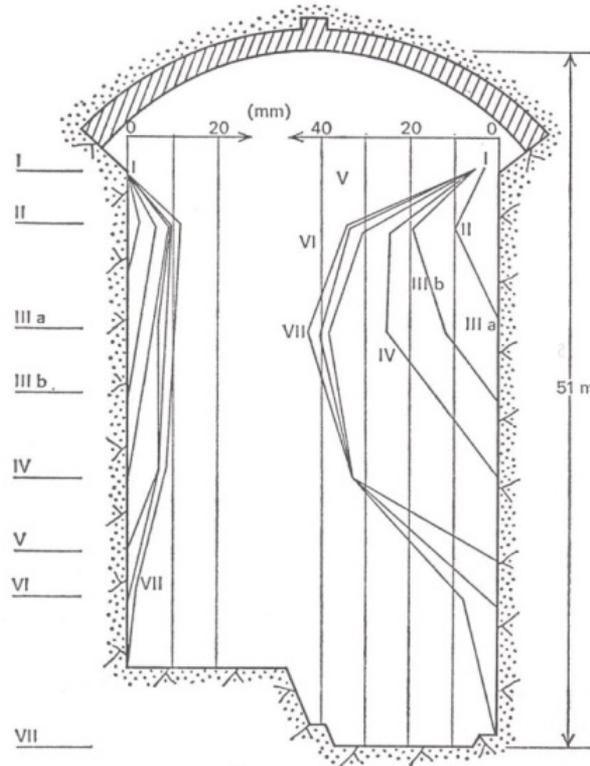


Figure 11: Example of lateral movements recorded at different stages of excavation of a large cavity in crystalline rock [2].

## 4 Performance of Reference Case

### 4.1 Rock Structure

Based on comprehensive structural analyses a simple rock structure model has been defined and shown in Figure 12, with boundaries represented by discontinuities of 2nd and 3rd orders. For the various hydrological and mechanical modelling attempts in the project these boundaries are given the physical properties shown in Tables 2 and 3.

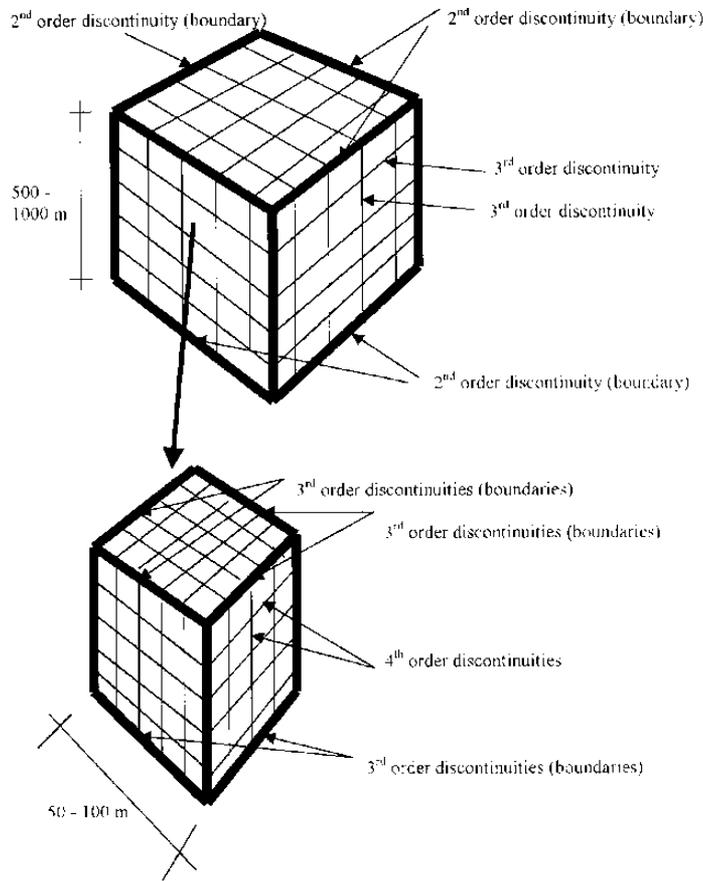


Figure 12: Generalized rock structure model. The bulk mass consists of rock matrix with 4<sup>th</sup> and higher order discontinuities [15].

Table 2: Assumed physical properties of discontinuities and crystalline rock matrix for crystalline rock [1]. R4, R5 and R6 mean rock with discontinuities finer than 4<sup>th</sup>, 5<sup>th</sup> and 6<sup>th</sup> order, respectively.

Rock	Hydraulic conductivity, m/s	Transmissivity, m <sup>2</sup> /s	Mohr/Coulomb friction angle, $\phi$	Mohr/Coulomb cohesion, $c$ MPa
1 <sup>st</sup> order disc.	E-7 to E-5	E-5 to E-2	15-20	0
2 <sup>nd</sup> order disc.	E-8 to E-6	E-7 to E-4	20-25	0
3 <sup>rd</sup> order disc.	E-9 to E-7	E-9 to E-6	20-30	0
R4	E-11 to E-9	-	20-35	0.1-1
R5	E-12 to E-10	-	35-50	1-10
R6	E-13 to E-11	-	45-60	10-50

The rock structure model in Figure 12 with all discontinuities grouped orthogonally adapts in principle to the Stripa region. The following generalised geometrical data of 3<sup>rd</sup> and 4<sup>th</sup> order discontinuities were applied for rock mechanical and hydrological modelling.

### 3rd order discontinuities

Steeply oriented 3rd order discontinuities with 75 m spacing are conformous to the 2nd order zones. The actual spacing is about 50-100 m and typical of many granite rocks.

### 4<sup>th</sup> order discontinuities

Most of the 4th order discontinuities are conformous to the 3rd order discontinuity sets. Their spacing is in the range of 2-4 m and they persist for several tens of meters.

The Stripa mine has a number of drifts and caverns of various sizes. Several of them are suitable for waste disposal and two, a drift and a big cavern, have been selected for the modelling work that is described here. With some generalisation they can be defined as drifts with 25 m<sup>2</sup> horseshoe-shaped cross section, and a cavern with 50 m width, 50 m height, and 100 m length in principal agreement with Figure 9. The center of both are located at approximately  $z=360$  m. Thus, in the cubical rock element with 600 m edge length that contains the mine rooms:  $x=600$  to 1200 m, W-E direction,  $y=100$  to 700 m, S-N direction, and  $z=0$  to 600 m, from ground surface downwards, there are three 2nd order discontinuities.

The roof of the drift is curved with 5 m radius, while the walls are vertical and 5 m apart. The distance between the flat floor and the crown is 5 m. Large-scale ventilation tests and comprehensive packer tests for determining the hydraulic properties of the rock around representative drifts have shown that excavation disturbance extended to 1 m distance from the periphery of the drift [1]. The higher charge used for blasting the big room more than 50 years ago was estimated to have caused a 3 m deep EDZ.

We will focus on the cavern here because of the high capacity to host waste and since the stability is more critical than that of the drift.

## **4.2 Groundwater Flow**

### **4.2.1 The “clay/waste” fill**

The presently proposed principle of waste placement and isolation is illustrated in Figure 13 [1]. The solid waste is assumed here to consist of Hg batteries mixed with equal amounts of air-dry granulated clay and compacted by 10 runs of 5-7 t vibratory rollers to an average dry density of the clay component of 1500 kg/m<sup>3</sup>. This moderate compaction does not expel any fluid from the batteries so assuming the water content of the clay component to be about 5-10 % the initial degree of fluid saturation will be 15-30 %. The clay will ultimately sorb water to 100 % saturation giving it a density of 1950 kg/m<sup>3</sup>. A suitable way of constructing the clay/waste fill is to place and compact layers with 20-30 cm thickness.

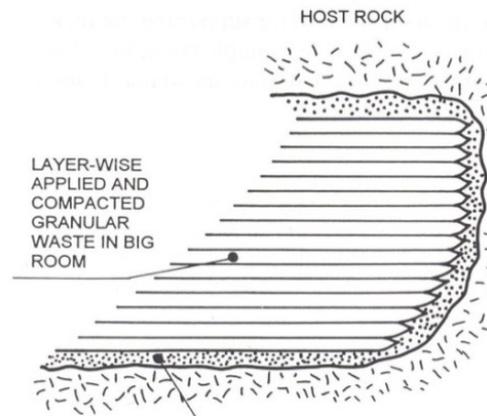


Figure 13: Use of clay for isolating hazardous waste. The layers of waste are separated by thin layers of expansive clay (“bentonite”) compacted on site. The lower pointer indicates 0.5-1 m on-site compacted expansive clay or blocks of highly compacted smectite clay.

Selection of clay material should be made so that its hydraulic conductivity is lower than that of the surrounding rock, i.e. the EDZ, and that its expandability is sufficient to avoid compression of the mass under its own weight and so that the roof of the cavern will be supported for avoiding rock fall. Since the effective pressure on the lowest layer by the overlying material will be about 1 MPa for a 50 m high clay/waste fill the clay shall be expandable and exert a swelling pressure of this magnitude on the boundaries of the cavern. For a dry density of the clay component of  $1500 \text{ kg/m}^3$  the smectite content should be at least 30 %, which is provided by mixed-layer clays like the German Friedland Ton or the Danish Holmehus clay. Considering that the hydraulic conductivity of the EDZ can be as low as  $E-9 \text{ m/s}$  the two clay materials, compacted to a dry density of at least  $1500 \text{ kg/m}^3$ , fulfil this criterion. According to ongoing investigations their hydraulic conductivity for percolation with salt water (3.5 %  $\text{CaCl}_2$  solution) are  $E-10$  and  $2E-11 \text{ m/s}$ , respectively. The swelling pressure (0.4 MPa) of the Friedland Ton with this density fulfils the requirements if the fill has this density and is not higher than 20 m, while the swelling pressure of the Holmehus clay is 1.5 MPa and hence sufficient to carry a 50 m high fill without yielding.

#### 4.2.2 Role of rock structure

In general the far-field hydrology is determined by the 2<sup>nd</sup> and 3<sup>rd</sup> order discontinuities and the continuous EDZ. The near-field hydrology is determined by the 4<sup>th</sup> order discontinuities and the EDZ that forms a continuum and short-circuits the system of discontinuities. In the Stripa mine the undisturbed granite mass that is confined by 3<sup>rd</sup> and lower order discontinuities has an average hydraulic conductivity of  $E-11 \text{ m/s}$  as evaluated from careful inflow tests in tunnels [15,16]. For 2<sup>nd</sup> and 3<sup>rd</sup> order discontinuities Table 2 applies. All flow in the rock is assumed here to take place along the intersections of the various discontinuities forming pipe networks in the flow models.

Based on comprehensive field investigations it is assumed that the EDZ around the periphery of the big room extends to 3 m depth and has a hydraulic conductivity that ranges between  $E-9$  and  $E-6 \text{ m/s}$ , averaging at  $E-7 \text{ m/s}$ . The EDZ around the drifts and tunnels extends to about 0.5 m from the walls and roof and to 1.5 m from the floor. Its

hydraulic conductivity is E-9 to E-8 m/s with an average value of 5E-9 m/s.

The geometry of the investigated part of the mine is shown in Figure 14. The big room and the drift, taken to be 150 m long in the calculations, were assumed to be filled with hazardous waste consisting of zinc-rich batteries, embedded in expandable clay Of Friedland Ton type. The hydraulic boundary conditions representing steady flow and stress states implies a maximum hydraulic gradient of 5 %. The hydraulic and transport properties of the constituents are shown in Table 3. The role of the clay component is to delay groundwater ingress into the waste and to provide support to the rock by its expandability. The transport of dissolved chemical species in rock fractures takes place both by moving with the flow of groundwater and by diffusion.

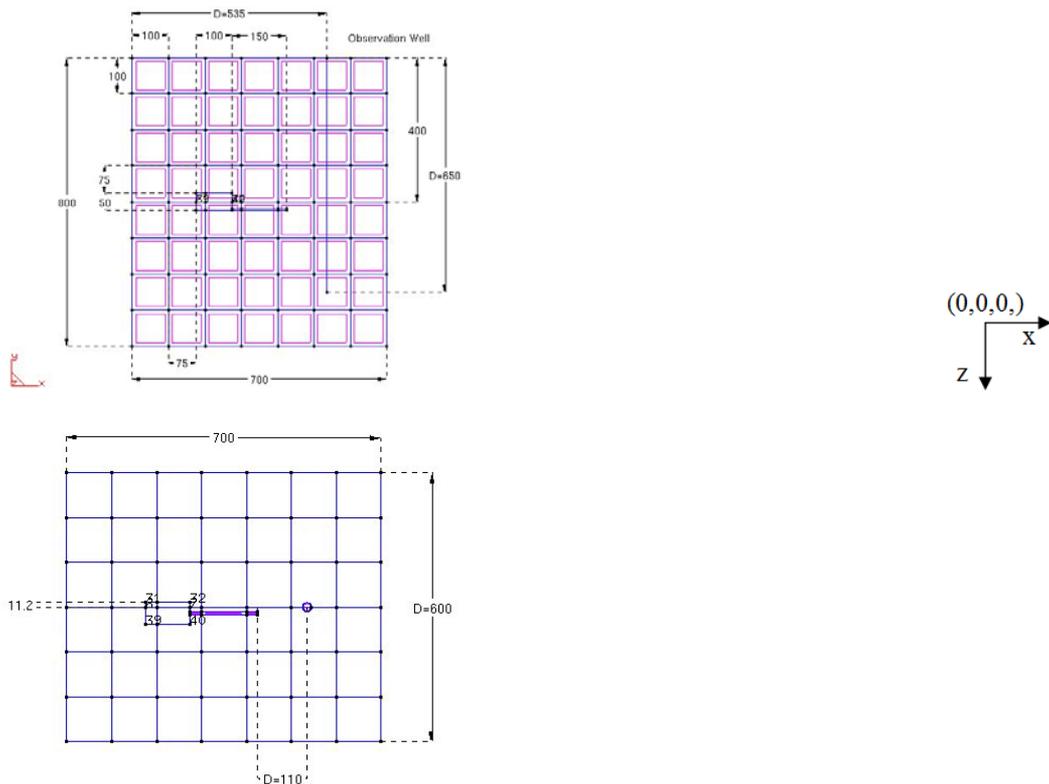


Figure 14: Side view (left) and top view (right) of the considered domain showing the geometry of the mine and tunnel and the respective position of the well (circle).

Table 3: Hydraulic and transport properties of the different entities used in the model.

Parameter		Clay fill (room and tunnel)	Rock (porous matrix)	Fracture zones, 1 m width	EDZ close to the big room, 3 m width	EDZ close to the tunnel, 1 m width
$K$	$m/s$	1E-10	1E-9	1E-7	1E-7	1E-7
$D$	$m^2/s$	1E-10	1E-9	1E-7	1E-7	1E-7
$R$	-	1	1	1	1	1
$k_r$	$l/s$	0	0	0	0	0

Typical values of the velocity in the rock matrix are two orders of magnitude lower than in the network of fracture zones due to the difference in hydraulic conductivities in the rock matrix rock and in the zones. The flow is directed towards the EDZ in the inflow part of the EDZ of the big room in the figure bottom-left side of the room, and away from the EDZ/room in the outflow part. This is a consequence of the higher hydraulic conductivity of the EDZ than of the surrounding rock, making the EDZ responsible for the larger part of the flow in the vicinity of the room.

**4.2.3 Contamination of well water**

The contamination of the water in a well located 110 m from the end of the tunnel (see Figure 8), is taken as a measure of the role of the system of discontinuities in distributing the groundwater flow. Water flowing through the cavern and drift would be retarded by the low conductivity and ion-absorbing capacity of the clay isolation, which is on the order of 30 mg per 100 g for Friedland Ton. For determining the degree of contamination the source term must be defined and it is taken here as the average concentration of zinc at the interface at the clay/EDZ contact, assuming that the water here has reached complete saturation with dissolved zinc at the start of the groundwater percolation of the big room (10000 ppm). The total porewater mass in the room, 50000 m<sup>3</sup>, contains 5000 metric tons of dissolved zinc corresponding to a total battery mass of about 20 000 metric tons.

It is conservatively assumed that at t = 0 years the clay mixed with batteries in ratio 50:50 by volume is fully water saturated, and that the batteries, of which 25 % consists of zinc, have decayed such that these cations can travel through the mixture into the surrounding EDZ. The sorption coefficient *K<sub>d</sub>* is taken to be 0.02 m<sup>3</sup>/kg. Using the following equation in which *ρ* is density and *m* mass of the clay:

$$R = 1 + \frac{\rho}{m} K_d$$

it is estimated that the retardation factor by sorption is approximately R = 121.

Figure 15 shows the evolution of the concentration of zinc in the well, assuming it to be 1 km deep. One finds that the peak value is reached at 400 m depth after 121000 years and that the concentration of zinc in the well will not exceed 2 ppm, which is much lower than generally accepted by national authorities. Most of the retardation is due to the slow transport through the rock.

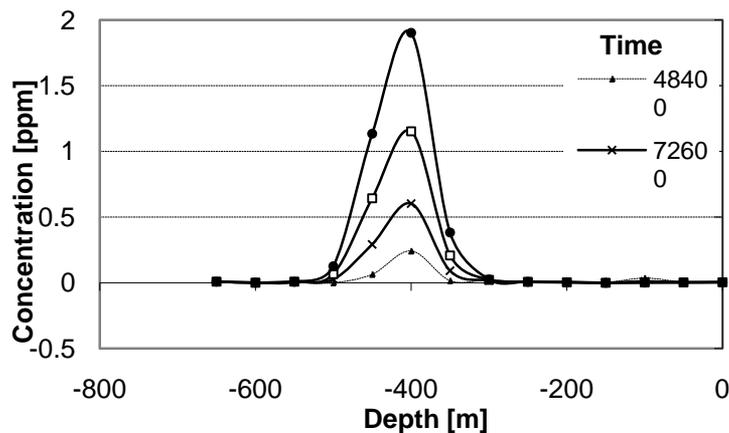


Figure 15: Zinc concentration in the well as a function of time.

### 4.3 Stability Conditions

#### 4.3.1 General

The stability of drifts and rooms in abandoned mines intended for disposal of hazardous waste depends of the time passing from abandoning to backfilling the mine. In ordinary mining backfilling implies filling drifts and rooms with rock debris that is compressible and with no other impact on the stability than active Rankine earth pressure. For the presently considered case the clay/waste fill exerts a swelling pressure on the rock of hundreds to a few thousands of kPa when the hydration is ultimately complete. This pressure shall be sufficient to resist loosening of blocks according to common principles [2] and will stabilize the walls. Rigorous calculation of rock stresses and strain are recommended for determining the long-term stability of the surrounding rock, e.g. the EDZ, especially for the case of radioactive waste because of the very long time required for effective isolation. Both creep strain and thereby generated loss of strength of the EDZ and the loss of expandability of the clay component in the fill by chemical reactions have to be considered [1].

#### 4.3.2 The Stripa case

For hazardous waste like batteries, the required period of time for effective isolation may not exceed a few thousand years depending on national legislation. This time is sufficient for reaching a high degree of water saturation of the clayey fill in the big room adjacent to the EDZ [1] meaning that the support provided by the clay component guarantees stability as illustrated by the example in Figure 16. If the EDZ element is 50 m high and stable before applying the clay/waste fill the unconfined compressive strength at its base is at least 1.4 MPa and more than 0.9 MPa under water. After placing the fill the swelling pressure  $p$  will reduce the shear stress and the required compressive strength will drop to  $\frac{1}{3}(1-k.p)$  according to Eqs. 8 and 9, where  $\frac{1}{3}$  is the vertical pressure at the base of the element. Taking the internal friction angle  $\frac{1}{3}$  conservatively as 30° the compressive strength will be as low as  $\frac{1}{3}(1-3p)$  or 70 % of the vertical pressure. The swelling pressure  $p$  hence has a tremendous stabilizing effect and does not have to be higher than about 0.3 MPa for the big room and even less when the entire mine has ultimately become water saturated.

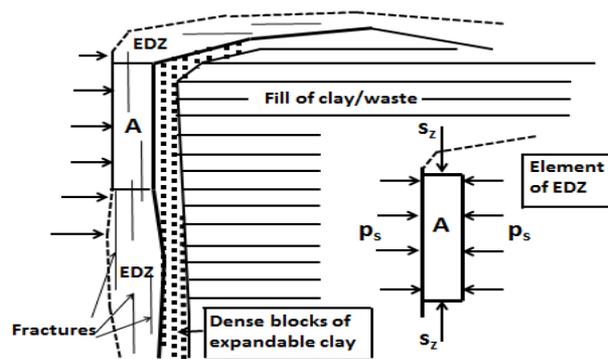


Figure 16: Element of EDZ exposed to an axial pressure  $s_z$  and a horizontal pressure  $p$  provided by the clay blocks and clay/waste fill. The element is separated from the rock mass by an open fracture.

## 5 Conclusions and Discussion

The following major conclusions can be drawn from the study that focused on the risk of contamination of drinking water in wells located near a repository for disposal of batteries the give off zinc as major hazardous element:

- the methodology used is suitable for determining the risk of contamination of wells bored in regions that contain repositories for hazardous waste. The boundary element method is particularly well suited for solving transport problems that include motion of dissolved chemical substances requiring only limited computer capacity,
- the way of defining flow paths by considering them to consist of intersecting fracture zones gives flow data that are of expected order of magnitude (Table 2, [3]),
- the EDZ plays a major role for groundwater flow through a blasted repository by short-circuiting the system of major discontinuities in the rock. Cutting it off by constructing long-lasting plugs of concrete and dense expanding clay seals is required,
- the creep strain of the EDZ and major discontinuities will go on for ever and lead to changes in flow paths and rates. Seismically and tectonically generated strain can increase or decrease both, making safe prediction of the future contamination uncertain,
- the retarding impact on the migration of dissolved waste elements by the cation-sorbing potential and low conductivity and ion diffusivity of expandable clay is of fundamental importance. Installing the clay at low water content means that it will take several hundreds or thousands of years for it to become water saturated. Since the mobility of the porewater in the clay is vanishingly low the controlling rate of migration of hazardous elements like zinc to repository surroundings will be the diffusion coefficient in water,
- under the low regional hydraulic gradients that prevail in regions suitable for locating a mine repository for hazardous waste, contamination of drinking water in downstream wells can be negligibly low for any period of time.

## References

- [1] Popov, V., Pusch, R., *Disposal of hazardous waste in underground mines*, WIT Press, Southampton/Boston, 2006.
- [2] Pusch, R., *Rock Mechanics on a Geological Base*, Developments in Geotechnical Engineering 77. Elsevier Publ. 1995.
- [3] Pusch, R., *Geological storage of radioactive waste*. Springer Verlag, 2008.
- [4] Svemar, Ch., *Cluster Repository project (CROP)*. Final Report of European Commission Contract **FIR-CT-2000-2003**, Brussels, Belgium, 2005.
- [5] Pusch, R., Ramqvist, G., Hedin, M., *Final report of experiments with rock blocks interacting hydraulically with smectitic pellet fills*. SKB Research Report **R-11-26**. Swedish Nuclear Fuel and Waste Management (SKB), Stockholm, 2011.
- [6] Duguid JO, Lee PCY. Flow in fractured porous media, *Water Resources Research*, **13**(1977), 558-566.
- [7] Pruess, K., Narashiman, T.N., A practical method for modelling fluid and heat flow in fractured porous media. *Society of Petroleum Engineers Journal*, **25** (1985) 14-26.

- [8] Berkowitz, B., Bear J., Braester, C. Continuum models for contaminant transport in fractured porous formations. *Water Resources Research*, **24** (1988), 1225-1236.
- [9] Gerke HH, van Genuchten MT. A dual-porosity model for simulating the preferential movement of water and solutes in structured porous media. *Water Resources Research*, **29**(1993), 305-319.
- [10] Gerke HH, van Genuchten MT. Evaluation of a first-order water transfer term for variably saturated dual-porosity flow models. *Water Resources Research*, **29**(1993), 1225-1238.
- [11] Samardzioska, T., Popov, V., Numerical comparison of the equivalent continuum, non-homogeneous and dual porosity models for flow and transport in fractured porous media, *Advances in Water Resources*, **28**(2005), 235-255.
- [12] Bear J, Tsang C, Marsily G. *Flow and contaminant transport in fractured rock*. San Diego California: Academic Press Inc; 1993.
- [13] Peratta, A., Popov, V., A new scheme for numerical modelling of flow and transport processes in 3D fractured porous media, *Advances in Water Resources*, **29** (2006), 42-61.
- [14] Pusch, R., Ramqvist, G., Bockgård, N., Ekdahl, L. *Final report of phase 4 by Pusch, Ramqvist, Bockgård & Ekdahl*. SKB Research Report **R-11-20**, Swedish Nuclear Fuel and Waste Management (SKB), Stockholm.
- [15] Pusch, R., *Waste disposal in rock*, Dev. in Geotechnical Engineering 76, Elsevier Publ. Co. 1994.
- [16] Pusch, R., L. Börgesson and G. Ramqvist (2003), Hydraulic characterization of EDZ in a blasted tunnel in crystalline rock – measurements and evaluation. *Proceedings of a European Commission CLUSTER conference*, Luxemburg on 3-5 November (2003), 69 - 76.