CHAPTER 3

Criteria for selecting repository mines

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Abstract

This chapter discusses the most important criterion for selecting repository mines. The ideal mine to be converted to a safe waste repository is a rather small, modern, remotely and relatively deeply located, mine with intact power supply, pump systems and ventilation. The geological host medium is very important. Crystalline rock has excellent stability of the drifts and rooms even at large depths but it has a relatively high hydraulic conductivity. Salt contains no free water and offers very good isolation of the waste, but brine in local sediment lenses may cause difficulties in the preparation of the mine for waste application. Argillaceous rock has a very low hydraulic conductivity but poor stability and the vicinity of the drifts may be very conductive. The chapter gives examples of deep abandoned mines in granite, i.e. the Stripa mine in Sweden, formerly used for exploitation of iron ore, and of mined rooms in a salt dome as well as in limestone. They are taken as a basis of calculations of the mechanical stability, evolution of engineered barriers, and migration of released toxic elements to an imaginary well located close to the waste-filled rooms.

3.1 Introduction

The most important criterion for selecting repository mines is that the host rock should be low-permeable and mechanically stable, and that the mines should have suitable drifts and rooms for placement of waste packages. The ideal mine to be converted to a safe waste repository is a rather small, modern, remotely and relatively deeply located mine with intact power supply, pump systems and ventilation.

The geological host medium is very important. Crystalline rock has excellent stability of the drifts and rooms even at large depths but it has a relatively high
hydraulic conductivity. The creep potential is very low and self-sealing and hence unimportant. Salt contains no free water and offers very good isolation of the waste, but brine in local sediment lenses may cause difficulties in the preparation of the mine for waste application. The creep potential is very high which means that the drifts and rooms converge and self-seal. Argillaceous rock has a very low hydraulic conductivity but poor stability and the vicinity of the drifts, i.e. the excavation-disturbed zone (EDZ), may be very conductive. It can undergo substantial creep and can self-seal depending on the diagenesis. Limestone rock has a low stability and is pervious. It has some creep and self-sealing potentials. Its most valuable property is the high pH of the porewater.

Mines in several other types of geological media, like metamorphous rock, shales and marble, can be considered for waste disposal but they are regarded here as representatives of the four types mentioned above. Thus, gneiss, shales and marble in principle behave like granite or argillaceous rock.

3.2 Rock structure

The structural constitution of the rock mass in which the mine is located determines the rate and distribution of the groundwater flow through the mine to the surroundings and hence the transport to the biosphere of toxic elements that can be released from the waste. For comparison and forming a basis for flow calculations it is necessary to work out relevant generalized rock structure models.

The transmissivity of the host rock determines its isolating capacity and is therefore the most important factor for the long-term function of the mine. It is controlled by the rock structure, which is hence a primary factor for the performance. It is also a determinant of the mechanical stability of the mine. The scheme in Table 3.1 is applicable to most rock types except salt.

3.2.1 Crystalline rock

Many granites can be represented by a generalized orthogonal-type rock structure model like the one shown in Fig. 3.1, which includes practically important discontinuities of different orders. Metamorphic rock like gneiss commonly has a more wavy macroscopic nature and more anisotropic structural organization but it can still be represented by the same model except that the spacing of sixth- to fourth-order discontinuities is usually much smaller in one direction than in the two other. We will consider a deeply located underground research laboratory in Sweden, extending from a former iron ore mine in Sweden, as the reference case (Stripa mine) [2].

3.2.2 Argillaceous rock

Mines in argillaceous rock are common in many countries, the exploitable ore often being impregnations of lead, copper and a number of other metals (Fig. 3.2).
Table 3.1: Categorization scheme for rock structure with typical geometrical, hydraulic and strength data [1, 2]. (The crystal matrix has typically $K < 10^{-13}$ m/s.)

<table>
<thead>
<tr>
<th>Discontinuity</th>
<th>General properties</th>
<th>Length</th>
<th>Width (m)</th>
<th>Hydraulic conductivity ($K$) (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Low-order discontinuities (conductivity of respective discontinuity)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>First order</td>
<td>Very large faults, water-bearing, gouge, very low strength</td>
<td>&gt;Kilometres</td>
<td>Hundreds</td>
<td>$10^{-7}$–$10^{-5}$</td>
</tr>
<tr>
<td>Second order</td>
<td>Major fracture zones, water-bearing, gouge, low strength</td>
<td>Kilometres</td>
<td>Tens to hundreds</td>
<td>$10^{-8}$–$10^{-6}$</td>
</tr>
<tr>
<td>Third order</td>
<td>Minor fracture zones, water-bearing, some gouge, relatively strong</td>
<td>Hundreds of metres</td>
<td>Metres to tens of metres</td>
<td>$10^{-10}$–$10^{-7}$</td>
</tr>
<tr>
<td><strong>High-order discontinuities (conductivity refers to rock with no discontinuities of lower order)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fourth order</td>
<td>Discrete major fractures, water-bearing, little or no gouge, strong</td>
<td>Tens of metres</td>
<td>–</td>
<td>$10^{-11}$–$10^{-9}$</td>
</tr>
<tr>
<td>Fifth order</td>
<td>Little water, no gouge, high strength</td>
<td>Metres</td>
<td>–</td>
<td>$10^{-12}$–$10^{-10}$</td>
</tr>
<tr>
<td>Sixth order</td>
<td>Decimetres, no water, no gouge, very high strength</td>
<td>Decimetres</td>
<td>–</td>
<td>$10^{-13}$–$10^{-11}$</td>
</tr>
<tr>
<td>Seventh order</td>
<td>Centimetres and smaller (fissures, voids)</td>
<td>Centimetres and smaller</td>
<td>–</td>
<td>$&lt;10^{-13}$</td>
</tr>
</tbody>
</table>
The figure is typical in the sense that the mode of formation, i.e. deposition and consolidation of sediments, has often resulted in very strong variation in composition and geotechnical properties.

Argillaceous rock can be considered as a less brittle version of metamorphic rock and can also be represented by Fig. 3.1 although with even smaller spacing of the discontinuities in one plane (direction), and hence significant anisotropy.
Comprehensive experience from exploration of such rock in France and Switzerland has shown that low-order discontinuities are less conductive than in crystalline rock because tectonically induced shearing has led to disintegration and significant sealing. The rock matrix, i.e. the rock between the low-order discontinuities, has a hydraulic conductivity and a transmissivity as low as those of crystalline rock or somewhat lower.

Drifts and tunnel systems in northern Switzerland serve as typical representatives of rooms for disposal of hazardous waste in sedimentary rock. Such rooms are presently used as underground research laboratories for development of techniques for disposal of highly radioactive waste (Mont Terri), [3].

3.2.3 Salt rock

Rock in the form of domal salt – usually of sodium or potassium type – or bedded salt is very suitable for waste disposal except if it contains brine pockets. It is already being utilized in many countries like Germany and France because completely homogeneous salt is perfectly tight with respect to water and gas. A necessary prerequisite is to construct long-lasting seals in the form of plugs in the shafts leading down to the repository level since water inflow from shallow soil and rock can cause very difficult problems. Salt mining has been made at all levels but only mines located several hundred metres below the ground surface should be considered.

Figure 3.3 is a schematic drawing of a salt dome, surrounded by other rock that caused salt in an underlying salt bed to be squeezed up to form the dome. The process forced up material from the surroundings yielding internal flow structures and irregularly spaced and oriented lenses of clay/silt/sand, which represent inclusions of brine. All these discontinuities affect the stability of rooms in the salt rock and can contain brine. The figure also shows a cross section of the Asse salt mine that has been used as an underground research laboratory by the Gesellschaft fuer Anlagen- und Reaktorsicherheit GmbH (GRS) in the last decades [3]. It may well be used for disposal of hazardous chemical waste. The spacing of major discontinuities varies with the size of the salt domes and for the Asse case it is assumed to be 50–100 m within 200 m distance from the boundary of the dome and 100–200 m in the interior. They do not intersect, and hence the only connection with the biosphere is where the rooms are intersected by lenses that extend all the way up the ground surface. The lognormal persistence of the lenses is assumed to vary between 100 and 1000 m, the shorter ones being termed here third-order discontinuities and the longer ones second-order discontinuities.

Despite the excellent isolating potential of salt caused by the absence of free water, there are two not solved problems yet: (1) gas production in the waste saturated with brine can cause extremely high pressures that may lead to upward penetration of gas and expulsion of heavily contaminated brines; (2) the very significant creep properties of salt rock will make retrieval of waste packages impossible after some 50–100 years since heavy objects sink in an unforeseeable
Figure 3.3: Structural nature of a salt domes. Top: Generalized rock structural model. Bottom: The Asse salt mine [3].
way in the salt mass. For these reasons disposal in salt cannot be proposed as a first choice method.

3.2.4 Other rock types

In certain countries mining has been extensive in very porous rock like limestone and abandoned mines in such geological media may be the only alternative. Mines located in regularly bedded limestone as well as heterogeneous limestone like ancient coral reefs, may have to be considered as options for disposal of hazardous waste. The hydraulic conductivity and transmissivity may be very high and the mechanical stability very low, which is of course not suitable. However, the high pH of the groundwater provides good chemical conditions for minimizing dissolution of various types of waste. The permeable nature of many limestone regions requires construction of very effective engineered barriers. We will use a bauxite mine in limestone environment in Greece as a reference in later chapters dealing with stability and waste isolation efficiency.

3.3 Requirements for the use of mines as repositories

3.3.1 Function of the host rock

A major criterion for use of abandoned mines as waste repositories is that elements released from the waste must not contaminate groundwater in the mine area more than what is accepted by regulatory authorities. The geological medium must provide mechanical protection of the ‘chemical apparatus’, i.e. the backfilled rooms with waste embedded in and surrounded by engineered barrier systems (EBS), and yield slow release of toxic elements to the biosphere. The processes that can threaten and degrade the geological medium hosting the repository mine are tectonic events, glaciation involving deep abrasion and erosion, and loss of sealing ability of the engineered barriers.

The capacity of mine repositories to isolate waste is determined by:

1. The physical stability of the rock and the physical and chemical performance as well as the stability of the EBS.
2. The rock structure and related hydraulic conductivity and the conductivity of the EBS are key factors for the performance of mine repositories.
3. The impact of groundwater chemistry on the longevity of the EBS, and the chemical nature of dissolved hazardous waste elements released from the EBS are key factors.

3.3.2 Conversion of mines to repositories

The major issues are the location of the mine with respect to the risk of contaminating drinking water in the closest wells, the status of the mine with respect to the mechanical stability and the cost for converting it into a repository. The most
important parameters in addition to the issue of groundwater contamination are:

- size,
- remaining exploitable ore,
- rock structure, hydrology, and stability,
- transport to and in the mine,
- technical facilities,
- stabilization,
- cost.

3.3.3 Size

Mines that can be considered for disposal of toxic chemical waste are those with relatively large underground space suitable for storing the waste, 5000 m³ being a practical minimum. Drifts for disposal should have a geometry that is suitable for rational application of waste packages. Horse-shoe or rectangular cross section shape of drifts and rooms with 5–30 m height and width and a length of 50–200 m are preferable. Big rooms may require significant stabilization and sealing of the rock.

3.3.4 Remaining exploitable ore

The reasons for abandoning a mine is commonly that practically all the ore has been mined out or that continued extraction of ore gives too little profit. However, in the second case, future methods for extracting and refining valuable minerals may make such mines interesting again. Thus, careful analysis has to be made of what the possibilities are to continue mining operations. Metal ore may be of quite different economic value today and in a few tens of years from now, of which uranium, titanium, gold and platinum are historical examples. It is much less significant for iron ore mines, which therefore represent attractive alternatives. Other mines of considerable interest are those in which clay minerals have been mined. An attractive principle in selecting mines for disposal of chemical waste is to use mines in which the exploited ore contained the same types of hazardous elements as the waste. Thus, mines in sulphide ore districts where mercury, arsenic, and lead have impregnated the rock and contaminated the groundwater are suitable for disposal of waste containing these elements.

One can also include abandoned, deeply located railway and road tunnels in the group of fully exploited mines. Examples are certain road tunnels in the Alps region located kilometres below the ground surface.

3.3.5 Rock structure, hydrology, and stability

3.3.5.1 General

The suitability of an ore mine to be used for waste disposal depends primarily on the risk of contamination of the groundwater, especially water for drinking
purposes and irrigation. Most rocks are permeable because of the presence of natural fractures and systems of fracture zones, which determine the transport of contaminants and make certain host rocks less suitable. An important fact is that the drifts and mined-out rooms are surrounded by an excavation-disturbed zone (EDZ) with reduced mechanical stability and increased hydraulic conductivity. Where the EDZ interacts with natural strongly water-bearing fracture zones there are conditions for poor stability and quick and extensive transport of contaminants to the biosphere. This is the reason why all waste disposed in any underground repository must be effectively isolated by engineered barrier systems. The transmissivity of a rock mass is much higher when the frequency of water-bearing discontinuities is high than if the spacing of such features is low and their interconnectivity poor. Even the first mentioned type of rock can be used successfully for safe waste disposal but more effort and money have to be spent on the engineered barriers than in the latter case. Hence, stable and low-permeable rock is preferable.

It is desirable to select mines with neutral or slightly alkaline ground-water because it minimizes the solubility of heavy metals and enhances the longevity of cement- and clay-based engineered barriers provided that pH is not too high.

### 3.3.5.2 Rock structure modelling

Rock structure is a key issue since reliable calculation of the transport of chemical elements released from the waste requires that a representative rock structure model can be defined and used. The matter has been considered in several practical hydropower projects and comprehensive research programmes related to the disposal of radioactive waste. In this book we will show how rock structure models can be used for both rock mechanical and hydrological calculations. The basis is the rock categorization scheme in Table 3.2, which is a simplified version of Table 3.1. Figure 3.4 shows a generalized structural model.

<table>
<thead>
<tr>
<th>Order</th>
<th>Length</th>
<th>Hydraulic conductivity</th>
<th>Gouge content</th>
<th>Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>First</td>
<td>&gt;Kilometres</td>
<td>VH</td>
<td>VH</td>
<td>VVL</td>
</tr>
<tr>
<td>Second</td>
<td>Kilometres</td>
<td>H</td>
<td>H</td>
<td>VL</td>
</tr>
<tr>
<td>Third</td>
<td>Hundreds of metres</td>
<td>M to H</td>
<td>M</td>
<td>M</td>
</tr>
<tr>
<td>Fourth</td>
<td>Tens of metres</td>
<td>M to H</td>
<td>L</td>
<td>H</td>
</tr>
<tr>
<td>Fifth</td>
<td>Metres</td>
<td>L</td>
<td>VL</td>
<td>H</td>
</tr>
<tr>
<td>Sixth</td>
<td>Decimetres</td>
<td>VL</td>
<td>VL</td>
<td>VH</td>
</tr>
<tr>
<td>Seventh</td>
<td>&lt;Decimetres</td>
<td>VVL</td>
<td>VVL</td>
<td>VVH</td>
</tr>
</tbody>
</table>

VH, very high; H, high; VL, very low; L, low; M, medium; VVL, insignificant; VVH, very very high.
The stability of the host rock is of importance since tectonic events will cause shearing of discontinuities of fourth and lower orders, affecting their hydraulic conductivity and the stability of drifts and rooms. For the rock matrix with only fifth- and higher-order discontinuities, Griffith’s or other failure criteria apply and fracture mechanics must be used for calculation of fracture strain and propagation. Furthermore, creep will take place that can cause critical strain and failure of the near-field rock field of drifts and rooms.

3.3.6 Transport to and in the mine

Transport of waste material to the mine should be simple and safe. Railway transport is preferable and most mines have such facilities. The issue is not critical but if a choice between otherwise equally suitable mines has to be made, access to good and safe ways of waste transport is an advantage. Transport of toxic
chemical waste for storage in deep mines should be on land while ship transport on rivers or near the coast should be avoided or – in sensitive areas - not allowed. Almost all mines have railway connections, which is naturally valuable for transport of waste for disposal and for transport of material in the reconstruction phase. Mines with internal transport facilities like decauville railways and elevators are preferable especially if they are intact or need only little repair and maintenance.

Preparation of the waste, like solidification of liquid waste, casting of solid waste in cement, and compaction of clay packages containing dispersed solid waste, can be made in buildings on the ground surface in the mine area but can also be performed down in the mine. The latter way is advantageous since the transport distance will be smaller and the risk of damaging containers and packages hence lower, but the space required may disqualify small mines.

### 3.3.7 Facilities and installations

Modern mines have safe electric power supply and good ventilation and pump systems for drainage. If these facilities remain at the time of converting the mine into a repository it implies substantial cost saving.

### 3.3.8 Stabilization

Old mines represent dangerous conditions with unstable rock and failed anchorings and comprehensive stabilization may be required. This again speaks in favour of utilizing modern mines or even better mines that are still in operation.

A major problem is represented by the risk of accumulation of explosive gas. This is the case for coal mines, which may be considered for waste disposal if the coal seams are part of cyclothemes with smectite clay as one component. Very significant safety measures have to be taken and such mines are not suitable especially since permeable sandstones are often associated with the clay.

An important issue is the long-term performance of mine repositories with respect to significant internal strain due to rock stresses that prevail or imposed by tectonics and glaciation. The effect can be difficult to predict and may imply that certain rocks like argillites should not be used. The usually good mechanical stability of crystalline rock makes it a good candidate despite the presence of water-bearing fracture zones. Salt rock is also suitable since internal strain, which will be very significant, ultimately leads to convergence and self-sealing because of the extreme creep properties.

### 3.3.9 Cost

It is of utmost importance that the cost for safe disposal of toxic chemical waste in abandoned mines be kept as low as possible. Thus, while disposal of radioactive waste is part of the nuclear fuel cycle and budgeted from start, the cost for
handling and disposal of chemical waste has to be carried by the society or the waste-producing companies, i.e. in practice by the tax payers. The most expensive activities and facilities in preparing abandoned mines for waste storage and in applying waste are (1) backfilling of ramps and shafts and isolation of the waste, (2) stabilization and sealing of the mine, (3) pump systems, drainage and ventilation, and (4) elevators.

3.4 Reference mines

3.4.1 General

We will define reference cases, representing crystalline, argillaceous, salt and limestone rock for illustrating what sort of data and calculations that are required in performing some of the design work required for converting abandoned mines into repositories for hazardous chemical waste. Calculations will be made mainly for crystalline rock since it represents a common case and special difficulties. A further reason is that argillaceous rock and limestone of sedimentary origin often show similar structural features.

3.4.2 Crystalline rock

3.4.2.1 The Stripa Mine

The reference case is the abandoned Stripa iron ore mine that reaches down to 410 m depth in a granite dome. Iron ore has been exploited in this mine from the year 1400 to about 1980. It was then used by the Swedish Nuclear Fuel and Waste Management Co (SKB) and Lawrence Berkeley Laboratories, California, as an underground laboratory for testing techniques for isolating nuclear waste, later in the form of the international Stripa Project [2]. The mine is presently owned by a waste handling company (Ragn-Sell AB) and considered as a possible repository for Hg disposal.

As outlined earlier in the book the rock structure and rock stress conditions are of major importance and they will be described here for this mine. Rock mechanical calculations for assessing the stability of typical drifts and rooms for waste disposal and for getting a basis for designing stabilizing constructions, and hydrological calculations for determining the risk of contamination of a hypothetical well for drinking water, will be described in subsequent chapters.

3.4.2.2 Regional rock structure

The granitic region where the Stripa mine is located is characterized by first- and second-order discontinuities oriented and spaced as in Fig. 3.5. On this large scale the major low-order discontinuities make up two steep NW-SE and NE-SW oriented sets. Close examination of finer weaknesses has shown that those of third and fourth orders also have these orientations and that there is one more set of breaks on all scales that is more or less subhorizontal.
3.4.2.3 Local rock structure

Based on comprehensive structural analyses the basic rock structure models in Fig. 3.6 have been defined, representing 'unit cell'-type versions of the generalized rock structure model in Fig. 3.4 with boundaries represented by discontinuities of second and third orders, respectively. For the various hydrological and mechanical modelling attempts the physical properties at the boundaries are given in Tables 3.3 and 3.4.

The rock structure model in Figs 3.4 and 3.6, with all discontinuities grouped orthogonally, applies in principle to the Stripa area. The following generalized geometrical data of third- and fourth-order discontinuities can be applied for rock mechanical and hydrological modelling:

**Third-order discontinuities** Steeply oriented third-order discontinuities with 75 m spacing conform to the second-order zones. The actual spacing is about 50–100 m and typical of many granite bodies.

**Fourth-order discontinuities** Most of the fourth-order discontinuities conform to the third-order discontinuity sets. Their spacing is in the range of 2–4 m and they persist for several tens of metres.

Figure 3.5: First- and second-order discontinuities in 48 km² around the Stripa mine [2].
3.4.2.4 Rooms

The Stripa mine has a number of drifts and tunnels and rooms of various size. Several of them are suitable for waste disposal and one room and one drift, have been selected for the modelling work that is described in subsequent chapters. With some generalization they can be defined as a drift with 25 m$^2$ horseshoe-shaped cross section, and a room with 50 m width, 50 m height, and 100 m length (Fig. 3.7). The centre of both are assumed to be located at $z = 360$ 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 second-order discontinuities.
The actual shape of the tunnel means that the roof is curved with 5 m radius, while the walls are vertical and 5 m apart. The distance between the floor and the crown is 5 m.

Excavation disturbance extends to 1 m distance from the periphery of the drift and to 3 m distance from the big room.

### 3.4.2.5 Rock stress conditions

In general the vertical rock pressure represents the minor principal stress and equals the overburden pressure. Typical primary stress conditions according to measurements (mainly door-stopper and hydraulic fracturing) are illustrated in Table 3.5.

Measurements in Stripa at 360 m depth have given \(\sigma_H = 15-30\) MPa, \(\sigma_h = 5-15\) MPa and \(\sigma_v = 10\) MPa. The average values \(\sigma_H = 23\) MPa, \(\sigma_h = 12\) MPa and \(\sigma_v = 10\) MPa are used in the rock mechanical modelling.

### Table 3.3: Assumed physical properties of discontinuities and rock matrix for crystalline rock [1, 2].

<table>
<thead>
<tr>
<th>Rock discontinuities</th>
<th>Hydraulic conductivity ((m/s))</th>
<th>Transmissivity ((m^2/s))</th>
<th>Mohr/Coulomb friction angle, (\phi^o)</th>
<th>Mohr/Coulomb cohesion, (c) ((MPa))</th>
</tr>
</thead>
<tbody>
<tr>
<td>First-order</td>
<td>(10^{-7}-10^{-5})</td>
<td>(10^{-5}-10^{-2})</td>
<td>15–20</td>
<td>0</td>
</tr>
<tr>
<td>Second-order</td>
<td>(10^{-8}-10^{-6})</td>
<td>(10^{-7}-10^{-4})</td>
<td>20–25</td>
<td>0</td>
</tr>
<tr>
<td>Third-order</td>
<td>(10^{-9}-10^{-7})</td>
<td>(10^{-9}-10^{-6})</td>
<td>20–30</td>
<td>0</td>
</tr>
<tr>
<td>R4</td>
<td>(10^{-11}-10^{-9})</td>
<td>–</td>
<td>20–35</td>
<td>0.1–1</td>
</tr>
<tr>
<td>R5</td>
<td>(10^{-12}-10^{-10})</td>
<td>–</td>
<td>35–50</td>
<td>1–10</td>
</tr>
<tr>
<td>R6</td>
<td>(10^{-13}-10^{-11})</td>
<td>–</td>
<td>45–60</td>
<td>10–50</td>
</tr>
</tbody>
</table>

R4, R5 and R6 represent rocks with discontinuities finer than fourth, fifth and sixth orders, respectively.

### Table 3.4: Mohr/Coulomb parameter data as functions of the size of the crystalline rock volume [1].

<table>
<thead>
<tr>
<th>Rock volume ((m^3))</th>
<th>Cohesion ((MPa))</th>
<th>Peak friction angle ((^o))</th>
<th>Discontinuities in the rock volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;0.001</td>
<td>10–50</td>
<td>45–60</td>
<td>Sixth order</td>
</tr>
<tr>
<td>0.001–0.1</td>
<td>1–10</td>
<td>40–50</td>
<td>Sixth order</td>
</tr>
<tr>
<td>0.1–10</td>
<td>1–5</td>
<td>35–45</td>
<td>Fifth, sixth order</td>
</tr>
<tr>
<td>10–100</td>
<td>0.1–1</td>
<td>25–35</td>
<td>Fourth, fifth, sixth order</td>
</tr>
<tr>
<td>100–10000</td>
<td>0.01–0.1</td>
<td>20–30</td>
<td>Third, fourth, fifth, sixth order</td>
</tr>
<tr>
<td>&gt;100000</td>
<td>&lt;0.1</td>
<td>&lt;20</td>
<td>All</td>
</tr>
</tbody>
</table>

The actual shape of the tunnel means that the roof 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.

Excavation disturbance extends to 1 m distance from the periphery of the drift and to 3 m distance from the big room.
The following processes are of importance:

- block fall from roofs and walls,
- overstressing of the periphery of the rooms,
- blasting (excavation disturbance).

Critical constellations of fourth-order can cause unstable rock wedges that may drop down, and rock rich in fifth- and higher-order discontinuities may cause comprehensive rock fall. This requires analysis of rock structure models and securing of potentially unstable blocks. Too high hoop stresses may cause breakage and rock spalling. Such breakage and blasting-induced disturbance causes the ‘excavation-disturbed zone’. This zone has a high hydraulic conductivity and serves as an effective flow path.

The big caverns of the Stripa mine are known to have a poor stability because the EDZ extends to about 5 m from the walls and at least 2 m from the roof and comprehensive rock fall has taken place due to critical fracture constellations and

Table 3.5: Magnitude of rock stresses at Stripa [1].

<table>
<thead>
<tr>
<th>Depth, z (m)</th>
<th>Vertical stress (MPa)</th>
<th>Maximum horizontal stress (MPa)</th>
<th>Ratio of maximum and minimum horizontal stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–900</td>
<td>10 + 0.027z</td>
<td>10 + 0.037z</td>
<td>2–4</td>
</tr>
<tr>
<td>900–2200</td>
<td>33 + 0.01z</td>
<td>35 + 0.01z</td>
<td>1–2</td>
</tr>
</tbody>
</table>

3.4.2.6 Rock stability issues
The following processes are of importance:

- block fall from roofs and walls,
- overstressing of the periphery of the rooms,
- blasting (excavation disturbance).
hoop stresses. The statistical risk of fall of big blocks can be determined by using the rock structure models.

A basis for investigating whether critically high hoop stresses will cause breakage and what the associated extension of the EDZ will be is determined by the compressive strength of the rock. It can be taken according to Table 3.4. Other major rock material data are taken to be: Young’s modulus, $E = 50$ GPa, Poisson’s ratio $= 0.20$, Creep law: $ε = σ^n/E + (σ^n/η)t^α$, with $n = 3$, $η = 10^{18}$ Pa s, and $α = 0.3$.

### 3.4.2.7 Hydrology in the far-field and near-field

In general, the far-field hydrology is determined by second- and third-order discontinuities and the continuous EDZ that short-circuits the discontinuities. The near-field hydrology is determined by the fourth-order discontinuities and the EDZ that forms a continuum and short-circuits the discontinuities.

In the Stripa mine the undisturbed granite mass that is confined by third- and lower-order discontinuities has an average hydraulic conductivity of $10^{-11}$ m/s as evaluated from careful inflow tests in tunnels [1]. For second- and third-order discontinuities Table 3.3 applies.

It is estimated that the EDZ around the periphery of the big caverns extends to about one-fifth of the width of drifts and rooms. The hydraulic conductivity of the EDZ is in the range of $10^{-9}$–$10^{-8}$ m/s; the average value can be taken as $10^{-7}$ m/s for the big room. The blasting-induced 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 $10^{-9}$–$10^{-8}$ m/s.

### 3.4.3 Salt and argillaceous rock

The present project includes consideration of salt and clayey sedimentary rock for disposal of hazardous waste but focus is on crystalline rock in which the reference disposal site, the Stripa mine, is located. No selection of corresponding typical mines in salt and argillaceous rock has been made but for illustrating the different conditions for adapting such mines to repositories some general material data are summarized in Table 3.6.

Table 3.6: Typical physical–chemical properties of the host media and the engineered barrier system. The top value in each cell refers to the near field and the second to the far field.

<table>
<thead>
<tr>
<th>Property</th>
<th>Granite</th>
<th>Salt (halite)</th>
<th>Clay shale</th>
<th>Limestone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk density ($\text{kg/m}^3$)</td>
<td>$2650$–$2700$</td>
<td>$2200$</td>
<td>$2500$–$2600$</td>
<td>$2200$–$2700$</td>
</tr>
<tr>
<td>Total porosity (%)</td>
<td>$0$–$2%$</td>
<td>$&lt;&lt;0.01$</td>
<td>$1$–$5%$</td>
<td>$5$–$20%$</td>
</tr>
<tr>
<td>Surface area ($\text{m}^2$/ton)</td>
<td>$1 \times 10^2$</td>
<td>$0$</td>
<td>$1 \times 10^4$</td>
<td>$10^3$</td>
</tr>
<tr>
<td>Tortuosity $\times 10^{-4}$</td>
<td>$10$–$10^{-4}$</td>
<td>$-$</td>
<td>$10^{-1}$</td>
<td>$10^{-1}$</td>
</tr>
<tr>
<td>Organic carbon fraction ($f_o$)</td>
<td>$0$</td>
<td>$0$</td>
<td>$0.1$–$5%$</td>
<td>$1$–$10%$</td>
</tr>
</tbody>
</table>
References