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DU COMBUSTIBLE NUCLÉAIRE AUX DÉCHETS : RECHERCHES ACTUELLES

FROM NUCLEAR FUELS TO WASTE: CURRENT RESEARCH

Geomechanics issues related to long-term isolation of nuclear waste

Charles Fairhurst

Itasca Consulting Group, Inc., c/o 417 Fifth Avenue North, South St. Paul, MN 55075-2035, USA

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Abstract A short review of current geomechanics issues is presented with respect to nuclear waste isolation in salt, clay, granite and volcanic tuff. Mention of the significance of regional seismicity is followed by examination of the importance of the disturbed rock zone (DRZ) in each rock type. ***To cite this article: C. Fairhurst, C. R. Physique 3 (2002) 961–974.***

geomechanics / nuclear waste / seismicity

Les enjeux géomécaniques liés à l'isolement géologique des déchets nucléaires

Résumé Une brève étude des enjeux actuels en géomécaniques, liés à l'isolement des déchets nucléaires dans le sel, l'argile, le granit et le tuf volcanique est présentée. Mention est faite de l'importance de la sismicité régionale, elle est suivie par l'examen de l'importance de la zone endommagée pour chaque type de roche. ***Pour citer cet article : C. Fairhurst, C. R. Physique 3 (2002) 961–974.***

géomécaniques / déchets nucléaires / sismicité

1. Introduction

Although under consideration earlier [1], the recommendation that geological isolation, i.e., permanent emplacement in deep underground mined cavities, could provide a solution to long-term isolation of toxic radioactive waste appears to have been first proposed formally at a meeting convened by the US National Academy of Sciences in Princeton, NJ, 10–12 September 1955 [2]. Since that time, a wide variety of alternatives have been considered but all have been rejected in favour of geological isolation. Significant research effort is being given in several countries to the possibility of reducing the magnitude of the waste isolation problem by separation (S) and transmutation (T) of radionuclides from the original waste.

E-mail address: fairh001@tc.umn.edu (C. Fairhurst).

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A conclusion of the meeting in 1955 was that salt was an attractive medium for waste isolation. In 1996, after extensive review of possible S and T technologies, a US National Academy of Sciences Committee on Separations Technology and Transmutation Systems noted, [3] as the first of its conclusions: "*None of the S&T system concepts reviewed eliminates the need for a geological repository*."

More than thirty countries are considering geological isolation in a variety of rock types. Salt, Clay, Granite and Volcanic Tuffs are currently the most popular. Since transport in water flowing from the waste repository to the living environment, or *biosphere*, is the principal way in which toxic radionuclides may be released, it is natural that low permeability of the host rock formation and/or absence of water will be primary considerations. Selection of a repository site will also be constrained by non-geological considerations such as risks involved in transportation of the waste from a generator site to the repository, rock formations available within national boundaries, and local political opposition to a particular site.

Studies over the past five decades have led to the recognition that prediction of the isolation performance of a potential repository site over tens or hundreds of thousands of years, as is required, may involve considerable uncertainty. For this reason, simplicity of the geological characteristics of a site is a prime consideration. Ideally, the repository formation should be a thick, uniform, low permeability layer, highly retarding to radionuclides, in a flat-lying region where the hydraulic gradient is low. The overlying rock is free of water-conductive faults or fractures. Under such circumstances, it should be possible to demonstrate that ground water travel times from the repository to the biosphere are likely to be very long, as is desired.

In reality, even when conditions appear to be ideal, it can be a challenge to demonstrate this.

Usually, the properties of the rock mass on the scale of interest in prediction of repository performance cannot be measured directly and must be inferred. Usually, for example, the response of the rock mass to heating is not known, and some scale-up of the corresponding behaviour observed on laboratory specimens of the rock is required. Groundwater flow in three-dimensional fracture networks is still not well understood. Extrapolation of the physical properties of fabricated materials (e.g. waste containers), known over short times only, to repository times often has little or no experimental backing. These and a variety of additional uncertainties can be introduced.

2. Geomechanics issues in site selection

The mechanical characteristics of the repository rock affects both the selection and the safety performance of the repository in several ways, on different scales of both size and time, and are frequently coupled with hydrological, thermal and chemical characteristics of the rock mass.

A particular feature of geoengineering design problems is the pre-loaded nature of the structures.

Rock in situ is loaded by tectonic and gravitational forces that will vary with depth. Engineering activities such as excavation disturb the pre-existing equilibrium and cause a redistribution of these forces in the rock mass. Stress concentrations in the immediate vicinity of the activity can result in permanent damage to the rock and, in some cases, may lead to instability and possible collapse of the rock, e.g., around underground openings. It is important, therefore to attempt to determine the state of stress in situ during the site exploration phase of repository investigations.

3. In situ stress state

Several techniques have been developed to attempt to determine the in situ state of stress in rock, but most require close access (within several metres) to the measurement location. The hydraulic fracturing technique allows stress determinations to be made in deep boreholes drilled from the surface. Although stresses can be determined at several horizons in each borehole, the number of boreholes tested is usually limited, so that few measurements are usually available to characterize a region. It is important to recognize, however, that stresses may vary in magnitude and orientation depending on the proximity of local heterogeneities, and care should be taken not to extrapolate point values too far beyond the measurement location. Fig. 1 (courtesy of Atomic Energy of Canada Limited (AECL)) shows the results of a series of stress

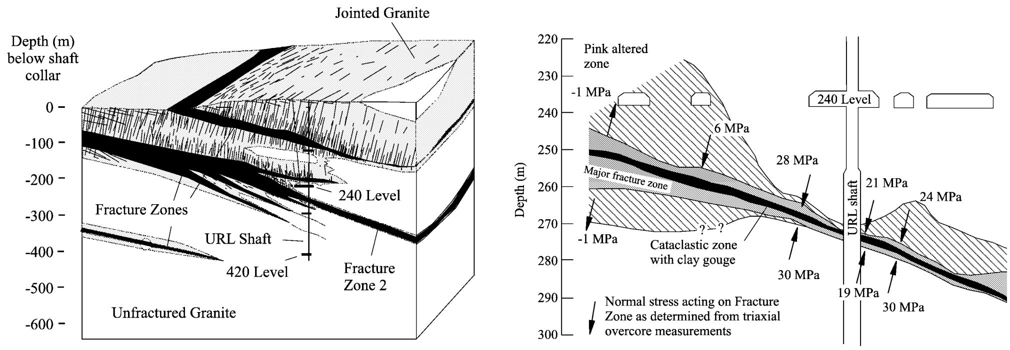

Figure 1. Variation of normal stress in the vicinity of a thrust fault in Lac du Bonnet granite, Pinawa, Canada (courtesy of AECL).

measurements taken at a depth of about 240 m at several locations in the vicinity of a thrust fault at the URL (Underground Research Laboratory), constructed by (AECL), at Pinawa, Manitoba. It is seen that the stress varies considerably over short distances (the horizontal extent of the cross-section is of the order of 100 m only). This is due mainly to the variability in normal stiffness along the fault plane. Water flow along the fault also occurs along the low stress regions. The massive (essentially unfractured except for microcracks) granite below the thrust fault zone is also much more highly stressed tectonically (ca 55 MPa) than the more fractured granite above the thrust faults (ca 25 MPa). This stress relief above the fault is due to slip along the fault system at the time the faults were generated. Thermal stresses generated by heat produced by radioactive decay of the buried waste can also result in slip along faults in the vicinity of the repository. Fig. 2(a) shows the result of an analysis of such a situation examined for a hypothetical repository layout at the Pinawa URL. Results indicate that, if all of the slip occurred instantaneously, sufficient energy would be dissipated by fault plane slip to result in a magnitude 3 (Richter scale) earthquake. In reality, the energy is likely to be dissipated progressively in small increments due to the inhomogeneous nature of the fault plane, as shown in Fig. 1.

Preliminary screening of potential repository locations has been made in several countries using a number of 'generic' factors to exclude sites from detailed consideration. Seismic activity of a region has been considered a negative attribute. It is important to note, however, that this judgement may be too broad and could eliminate sites that could be acceptable. Fig. 2(b) illustrates the situation at the Gard site in southeastern France. The region is moderately active seismically. The proposed repository location was in clay shale sediments to the Northwest of the Nimes fault [BD in Fig. 2(b)]. The basement rock to the southeast of the fault was upthrown with respect to the rock on the northwest. A salt seam several metres thick was found at the contact between the sediments and basement below the proposed repository location. At this depth of several kilometres, the rock temperature would be high and the salt would act essentially as a fluid. The salt interface would be essentially frictionless. Transmission of the high lateral stress in the basement rock across the fault could occur via the basement to basement contact CD only. High normal and shear stress concentrations would develop in the vicinity of this region near C, and seismic slip would be likely. Thus, seismographs at the surface would detect seismic activity in the region.

Even so, the block in which the repository was to be located would be shielded from the seismic activity. Flow along the salt layer would prevent any stress accumulation in the sediments.

It should also be noted that underground excavations are much less vulnerable to seismic loading than are surface structures. This is especially the case when the repository is closed and the access tunnels and shafts are backfilled. It is also known that seismic events usually produce displacements along existing faults and fractures. Since such discontinuities are usually revealed during construction of a repository, adjustments can be made in placement of the waste to avoid the area in the vicinity of such features.

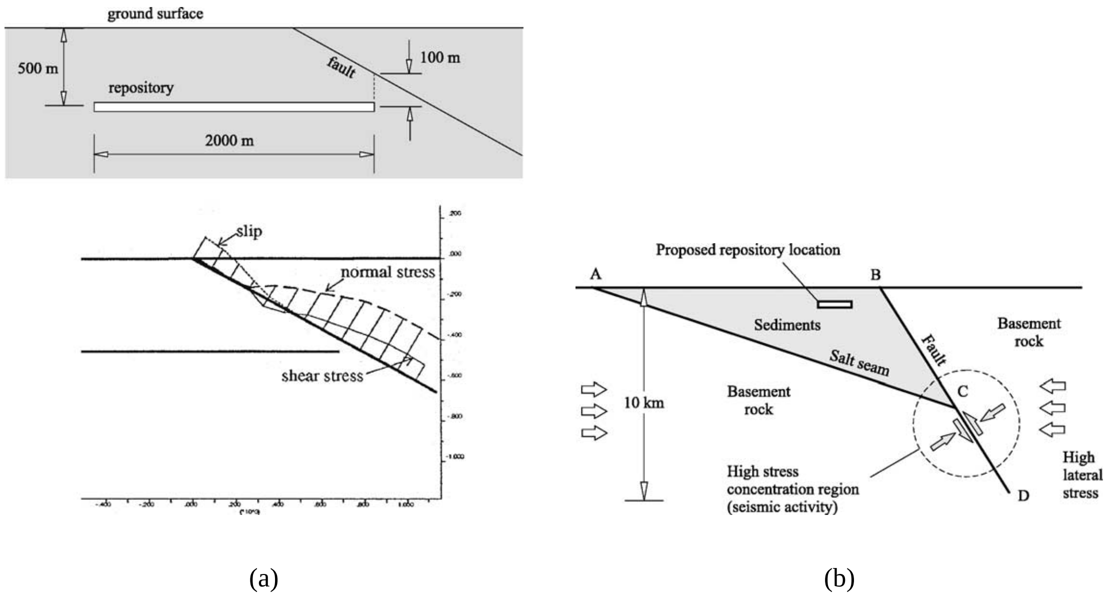

Figure 2. (a) Repository and fault arrangement used in analysis of thermally induced slip on a cohesionless, frictional fault, with FLAC analysis of sheer stresses on the fault; (b) example to illustrate that seismicity may not disqualify a potential repository site.

4. The Excavation Disturbed Zone (EDZ) and effective sealing of the repository

Assessment of the long-term safety of a potential repository is frequently based, in the first instance at least, on the performance of the undisturbed site, i.e., one in which the shafts and tunnels required to emplace the waste are assumed not to exist. This implies, in effect, that these access ways, and any rock adjacent to the excavations that has been damaged in the excavation process, have been sealed or repaired such that they do not and never will constitute a preferred pathway for release of radionuclides to the biosphere.

As noted earlier, excavation changes the pre-existing distribution of stresses in the rock, especially in the immediate vicinity of the excavation. Depending on the initial state of stress, stress concentrations developed around the excavation may be sufficient to produce inelastic damage, usually in the form of microcracking in the rock, and possibly spalling of the walls. This zone of damage, referred to as the Excavation Damage Zone, or EDZ (EDZ is also used to refer to the Excavation *Disturbed* Zone, where ‘disturbance’ may include elastic changes that develop slightly beyond the damage region in addition to the inelastically damage), extends along the full length of the excavation. (The excavation process itself, e.g., by drilling and blasting or by Tunnel Boring Machine, must also be carried out with care to minimize adverse effects on the integrity of the wall of the excavation.) This annulus of more or less fractured rock, typically $(0.1 \sim 0.3)R$ in extent, where R is the tunnel radius, may constitute a pathway of increased hydraulic conductivity directly to the surface. (The presence of the EDZ is also an important consideration in the planning of experiments in an Underground Research Laboratory intended to determine the properties of the intact rock mass, i.e., unaffected by the excavation process.) Heat generated by the waste develops thermal stresses in the rock, and may extend this radius slightly. Elimination of this conductive zone is as important as sealing of the excavations if the repository is to be effectively isolated from the biosphere.

Sealing of the excavations is usually carried out by back filling with crushed rock that is compacted to a density considered sufficient to reduce the hydraulic conductivity of the back-fill to an acceptably low value. Particular care must be taken to ensure that horizontal tunnels are filled completely to the roof if the desired low conductivity is to be achieved. The importance of ensuring intimate contact between the fill and the tunnel wall is illustrated by the following example. Assume that a 1 mm gap develops over the upper quadrant of the boundary of a circular tunnel backfill that has been compacted to achieve a hydraulic conductivity of 10^{-9} m·s^{-1}. The 1 mm gap will increase the overall conductivity of the backfilled tunnel to 10^{-3} m·s^{-1}! Such a gap could arise from a failure to completely fill the tunnel or from compaction of the backfill subsequent to emplacement. One method intended to avoid such a situation is to add a small percentage of bentonitic clay to the fill. This clay, dispersed through the fill, will expand upon contact with water sufficiently to eliminate the gap and, ideally, apply a radial pressure ($\sim$100 kPa) to the wall. Should the water be saline, the clay will expand less or not at all. Clearly, the interface between the tunnel and the fill is a potential pathway for water flow that needs to be eliminated. There is a similar need to eliminate the DRZ as a preferred pathway.

Research is currently underway in several countries to establish design guidelines for tunnel and shaft seals that will ensure that the DRZ and the tunnel/backfill interface do not serve as preferred pathways. Fig. 3 shows an isometric view of the Tunnel Sealing experiment (TSX), an international (Canada, France, Japan, USA) collaborative experiment conducted in the URL, in essentially unfractured granite of the Lac du Bonnet batholith (see Fig. 1) at Pinawa, Manitoba, Canada. Two bulkheads, one consisting of pre-fabricated compacted (expansive) clay blocks assembled to fill an enlarged section of the 3.5 m diameter tunnel, the other a concrete bulkhead 'keyed' into the rock to a depth sufficient to penetrate through the EDZ into the undamaged rock, were constructed underground.

The principal of the key is as follows: the extent of stress concentration—and hence damage-induced around a cavity in a stressed elasto/plastic medium—is proportional to the (local) radius of curvature of the cavity. Thus the region of high stress at the tip of the sharp notch will be of very limited extent. If the depth of the key extends sufficiently beyond the limit of the EDZ then a region of undamaged rock will exist on each side of the key and the continuity of the EDZ will be interrupted.

The clay blocks and the concrete were fabricated on surface and transported underground for emplacement. The region between the bulkheads was filled with (loose) sand. Water was then fed into the inner region and the pressure slowly increased over a period of approximately one and a half years to the full static head of 4.2 MPa (corresponding to the 420 m horizon of the tunnel). Small amounts of leakage past the two seals was observed and recorded. This decreased as the (expansive) clay blocks became saturated. Seepage past the concrete seal was somewhat higher. Although some small seepage occurred directly through the seals, the principal flow pathways were along the interfaces between the tunnel wall and the seals.

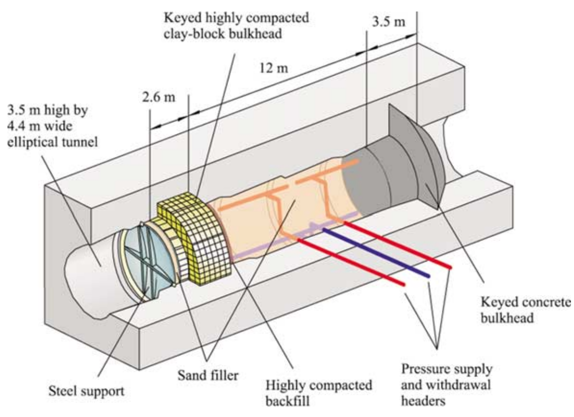

Figure 3. Isometric view of Tunnel Ceiling Experiment, Pinawa, Canada (courtesy of AECL).

Plugging and sealing experiments are also underway (e.g., at the Aspo underground laboratory, in fractured granite,in Sweden and at the Mont Terri laboratory in the Opalinus Clay in Switzerland).

Informal observations indicate that the interface between the tunnel and backfill may also be a leakage path at Aspo, at least in this early stage of the experiment.

These observations suggest that attention may need to be given to the development of effective techniques to eliminate water flow along these interfaces, at least in rock types that do not flow or expand to close them. The current strategy of adding bentonite to backfill to ensure that the interface will close in the presence of water is costly and alternatives are being considered.

The difficulty of effectively sealing tunnels and shafts and the associated EDZ varies considerably depending on the rock type involved. It is instructive to examine each of the most popular host rock types from this perspective.

5. Salt

Salt (primarily sodium chloride) is one of a group of minerals formed by the evaporation of saline water bodies in inland seas, isolated coastal waters, lagoons, etc. to which the generic name ‘evaporite’ is given. Salt deposits occur world wide either in extensive layers as ‘bedded salt’, or in thick masses as ‘salt domes’. Domes, or *diapirs*, occur as the result of a mechanical instability when denser rock overlying the salt causes the latter to deform, thickening progressively and pushing through overlying formations over geological time to develop regions of salt that may be hundreds of metres thick.

The committee of the US National Academy of Sciences [2] that met in 1955 to consider how to dispose of nuclear waste noted as follows: “*The most promising method of disposal of high level waste at the present time seems to be in salt deposits. The great advantage here is that no water can pass through salt. Fractures are self-sealing.*”

This succinct statement describes two important advantages of salt as a host medium for waste isolation, viz. (i) it is impermeable and (ii) fractures generated in it will heal.

Fig. 4 presents the stages of viscous creep and the governing rheological relationships as determined for the bedded salt at the Waste Isolation Pilot Plant (WIPP) in Carlsbad, New Mexico, USA. It is found that specimens subjected to deviatoric stresses will deform continuously until the deviatoric stress vanishes, i.e., the stress field becomes isotropic. This is confirmed by the fact that the in situ state of stress in the salt at the WIPP site is also isotropic.

Tests on salt specimens in which fractures have been induced indicate that the fractures will heal over a period of a few days or less depending on the value of the mean applied stress [4].

Total steady-state creep rate:

$$\dot{\varepsilon}_s = \sum_{i=1}^{3} \dot{\varepsilon}_{si}.$$

Individual steady-state rates:

$$\dot{\varepsilon}_{s1} = A_1\,\mathrm{e}^{Q_1/(RT)}\left(\frac{\sigma}{\mu}\right)^{n_1}, \qquad \dot{\varepsilon}_{s2} = A_2\,\mathrm{e}^{Q_2/(RT)}\left(\frac{\sigma}{\mu}\right)^{n_2},$$

$$\dot{\varepsilon}_{s3} = H(\sigma-\sigma_0)\left[B_1\,\mathrm{e}^{Q_1/(RT)} + B_2\,\mathrm{e}^{Q_2/(RT)}\right]\sinh\left[\frac{q(\sigma-\sigma_0)}{\mu}\right].$$

Salt creeps at vanishingly small deviatoric stresses. Salt is inpermeable.

$$\dot{\varepsilon}_s = k(\sigma_1-\sigma_3)^n \quad \text{with } n \simeq 5.5.$$

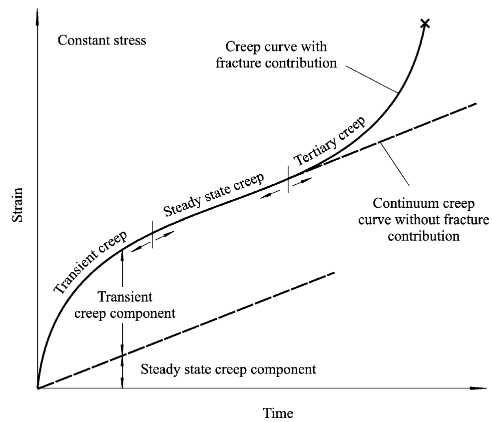

Figure 4. Viscous behaviour exhibited by WIPP salt.

Some authors consider salt to have a finite, albeit very small, permeability. It is found, for example, that brine will flow into a hole drilled into salt at depth. If it is *assumed* that salt is a classical medium to which Darcy's Law of fluid flow in permeable rock applies and, further, that the regional ground water pressure acts on the salt in the far-field, then it is a simple matter to compute a permeability for the salt [5].

Studies at the WIPP site support an alternative explanation. The WIPP salt contains about $1 \sim 2\%$ of water (brine) that is occluded within the crystal structure of the salt. Introduction of a cavity in the salt produces a DRZ and cracking in the vicinity of the wall of the cavity. The cracks release some of the occluded brine, which then flows into the hole. As noted above, application of the classical Darcy flow model will then result in calculation of a permeability for the salt. There are, however, several problems with this model. As noted by McTigue [4, p. 116], after close study of the WIPP salt, states: "*The classical model invokes an unbounded domain of interconnected porosity. This concept is contradicted by both mechanical arguments and geochemical observations.*"

The mechanical arguments presented by McTigue are similar to those mentioned earlier viz. salt creeps at vanishingly small deviatoric stress (i.e., stress difference). Thus, over long time frames, interconnected porosity cannot be sustained.

The geochemical observations were that: "… [WIPP] *brine chemistry is highly variable, even among samples separated by distances of the order of tens of centimetres. If these brines were derived from an interconnected pore network, one would expect that molecular diffusion would have eliminated any significant contrasts in brine composition over the very long existence of the formation …. Over a period of* 230 *Ma the diffusion length* L_a *is … of the order of hundreds of meters. The observation that compositional differences persist in the brines over short length scales and very long time, then, suggests strongly that the brine in undisturbed salt is local, isolated domains*."

Although salt compositions vary from deposit to deposit, the rheological behaviour is qualitatively similar. The domal salt at Gorleben, Germany, for example has significantly lower water content (ca $0.1 \sim 0.2\%$) and creeps more slowly but flow laws essentially similar to those in Fig. 4 have been derived for this salt. The in situ stress state at Gorleben is also isotropic.

5.1. EDZ in salt

The viscous nature of salt makes it an ideal medium from the point of view of isolation. While an EDZ forms around the excavations, backfilling with crushed salt and creep of the rock mass develops a radial pressure on the rock/backfill interface that increases progressively with time. Fractures in the rock are healed and the crushed salt compacts until all internal voids are eliminated. In this medium it is possible to assert that the man-made excavations can be made to disappear over time. Depending on the type of salt and water content, the rehealing/sealing process will be essentially complete in the order of a few hundreds of years, or less in some cases.

Convincing evidence of the ability of salt to flow, closing excavations and sealing around mining implements and artefacts, can be seen in the salt mine at the village of Hallstatt in upper Austria, where salt has been mined since early Celtic times (ca 1200 B.C. or earlier) (see Natural History Museum in Vienna).

One of the concerns frequently expressed with respect to waste isolation is the increasing uncertainty of predicting performance over increasing time into the future. Salt creep provides an example of where uncertainty will decrease with time, as the rock flows to re-establish the equilibrium that existed in the rock mass before excavation.

Heat generated by high level waste will increase the temperature of the rock within the first one or more thousands of years after waste emplacement. This will cause the creep rate of salt to increase (see Fig. 4), leading to more rapid encapsulation of the waste. Heating of the occluded brine in the salt could generate 'pockets' of high fluid pressure that could conceivably result in local microfracturing of the salt. Creep processes will, over time, tend to reheal these fractures, particularly as the rate of heat generation declines. The WIPP repository is used for transuranic waste only. Heat generation is negligible.

5.2. Disadvantage of salt as a repository medium

The impermeability of salt serves to trap low density fluids such as oil and gas, so that salt deposits are an attractive location for oil and gas exploration. Salt and other evaporites (e.g., potash) are also valuable mineral resources. The probability of human intrusion (by drilling and subsequent oil/gas production stimulation techniques such as hydraulic fracturing, reservoir flooding, etc.) is considered to be higher for a repository in salt than for other potential host rocks.

These issues were given considerable attention at the WIPP site, where a number of 'severe' human intrusion scenarios were examined. It was found that the repository met the radioactive release limits set by the US Environmental Protection Agency even under these scenarios [4]. The writer is of the opinion that 'resources' in the future may be very different from those of today and that salt may be no more vulnerable, over the lifetime of a repository, than any other medium. Oil and gas fields, for example, have a life that is typically less than 100 years. Underground space is seen increasingly as a valuable resource for a variety of uses both industrial and urban, as populations increase. Thus a stable granite mass could also be seen as a valuable resource to future generations.

6. Clay

Clays and clay shales are attractive principally because of their very low permeability and high ion exchange capability. The permeability ensures low groundwater flow rates; the ion exchange effectively retards the movement of radionuclides in the water so that, together, the rate of release of (sorbable) radionuclides towards the biosphere is very low.

Clays consist of assemblages of very small, layered platelets. Individual layers, consisting of alternations of different clay elements, are of the order of 10 Angstrom thickness, and contain water, tightly bound to the layers. The exterior surfaces of the platelets are surrounded by a diffuse double layer of ionic water. The assemblages, arranged randomly about an anisotropic direction related to the bedding planes, contain free water. The mobility of the free water determines the permeability of the clay.

Some forms of clay, particularly montmorillonite, swell in the presence of free water. The EDZ in clay develops in a more complex way than other candidate repository rocks. The exposed clay desaturates (slowly) and strong capillary suction pressures are generated in the unsaturated region that develops around the tunnel. Exposure to humid air results in uptake of water into the rock, a consequent loss of mechanical strength, and some inelastic deformation. This behaviour affects boreholes as well as large excavations, creating difficulties in field testing. Many rock mechanics tests assume elastic behaviour of the rock and/or require installation of transducers in 'elastically' deformed boreholes. Considerable effort is being devoted currently (especially at Mont Terri, Switzerland) to resolution of such testing obstacles.

The time-dependent mechanical behaviour of clays and the response to temperature increase are active subjects of investigation. Girard and Rousset [6] have carried out tests on cores of a brittle clay from the Eastern part of the Parisian basin. They propose a 'viscoplastic-with failure-model', which suggests that there is a threshold level of deviatoric stress below which the clay responds elastically. This is consistent with recent field tests which indicate that the in situ state of stress at depth in this region is probably not isotropic, although the deviatoric stresses are not high. This suggests that after $\approx$250 million years, the rock mass still supports deviatoric principal stresses.

Recent additional laboratory tests on the Callovo–Oxfordien clay shale from the same region however, indicate that this clay shale continues to deform under very low deviatoric stresses. Tests under undrained and drained conditions appear to indicate that the time-dependence is associated with both a time-dependent mechanical deformation of the skeletal structure of the clay and a time-dependent expulsion of water from the clay. Some tests have been conducted to determine the 'relaxation' response of the clay, i.e., the progressive loss of applied force required over time to maintain a constant level of deformation of a specimen. These suggest that some time-dependent recovery of deformation occurs during relaxation. This could indicate partial closing of micro-fissures generated during loading. Tests to assess the ability of micro-fissures, induced by applied deviatoric stresses, to heal when the principal stress loading directions are reversed can provide valuable insight into the long-term response of the EDZ in clay, after excavations have been back-filled and sealed.

The complexity of the mechanical response of clay is illustrated by recent tests by Hueckel and Baldi [7]. Most laboratory tests of the mechanical response to increased temperature suggest that clays respond as do other rocks, i.e., increased temperature will tend to increase the pore pressure as the pore water expands. Thus, the effective stress is reduced; microcracking and eventually fracture may result. Hueckel and Baldi heated Pontilda silty clay and Boom clay between 18 °C and 115 °C in drained tests at constant effective stress, and observed the reverse effect, i.e., the specimen contracted and pore pressures decreased. Apparently the clay microstructure changes to a denser grouping of the montmorillonite 'flakes'. If stresses are applied, the microstructure can collapse. This effect is observed only when the rate of temperature increase is very low ($1\,^{\circ}\mathrm{C}\cdot\mathrm{hour}^{-1}$, or lower) [Hueckel, Personal communication]. But the rate of temperature increase in a repository will be even lower. This illustrates the need for attention to the influence of loading rates when extrapolating laboratory (both surface and underground) results to prediction of repository performance.

Intuitively, it would seem that the EDZ in clays should 'regain' a low permeability in the times relevant for repository isolation, but considerable research is needed to develop a scientifically 'robust' demonstration that this will be the case.

7. Granite

Granite and related crystalline rocks are under active consideration for waste isolation in several countries, particularly Sweden, Finland and Canada. At the Underground Research Laboratory (URL) near Pinawa, Manitoba, the Lac du Bonnet batholith is found to be massive with relatively few fractures in the region below the thrust faults (see Fig. 1). The intrinsic permeability is very low, but the in situ stresses are very high. At a depth of 450 m, the principal stresses have been determined to be $\sigma_{\mathrm{H1}} = 55$ MPa, $\sigma_{\mathrm{H2}} = 48$ MPa, $\sigma_{\mathrm{V}} = 14$ MPa (with σ_{V} oriented 14° from vertical).

Fig. 5 shows the intensity of rock damage in the EDZ around an originally circular excavation. The damage developed over a period of several weeks after excavation. Initial research studies using continuum analyses were unable to predict 'break-out' shapes consistent with those observed. Recently, studies based on the numerical particle flow code PFC, a micro-mechanical (particle–particle interaction) model of the rock, have yielded very encouraging results.

Fig. 6 shows a detailed photograph of rock fracture in the notch region of Fig. 5. The figure on the upper right shows the damage predicted by PFC. The agreement is very good.

The PFC code uses an explicit finite difference, time marching routine to follow deformation and damage. It is fully dynamic, so that location and magnitudes of energy release when particle bond rupture occurs can be followed in time. A microseismic network was installed around the (potential) fracture zone to monitor its development. The lower two diagrams show the predicted and observed locations and magnitudes of energy release as the notch develops. Again, the agreement is impressive.

Introduction of a 'stress-corrosion' mechanism, whereby bonds between the granite particles are assumed to be weakened or eroded by chemical attack over time, has also shown very good agreement between predicted and observed rates of development of the notch. The stress corrosion parameters used in this prediction were derived from analysis of creep tests on the Lac du Bonnet specimens. Further details of the PFC model are given in [8].

Studies in fractured granites in Sweden suggest that DRZ formation is of limited extent (presumably due to the lower in situ stress levels) and influenced by the fracture systems that intersect the excavations.

EDZ effects in granite are considered to be permanent, i.e., there is no possibility of micro-fracture healing. Elimination of the DRZ as a preferred pathway of water flow in granite must rely on the development of effective plugs and seals designed to interrupt the DRZ at sections along the drifts. Tunnel sealing experiments are currently underway in Canada and Sweden.

Figure 5. 'Damaged' profile of an originally circular excavation in Lac du Bonnet granite, Pinawa, Canada (courtesy of AECL).

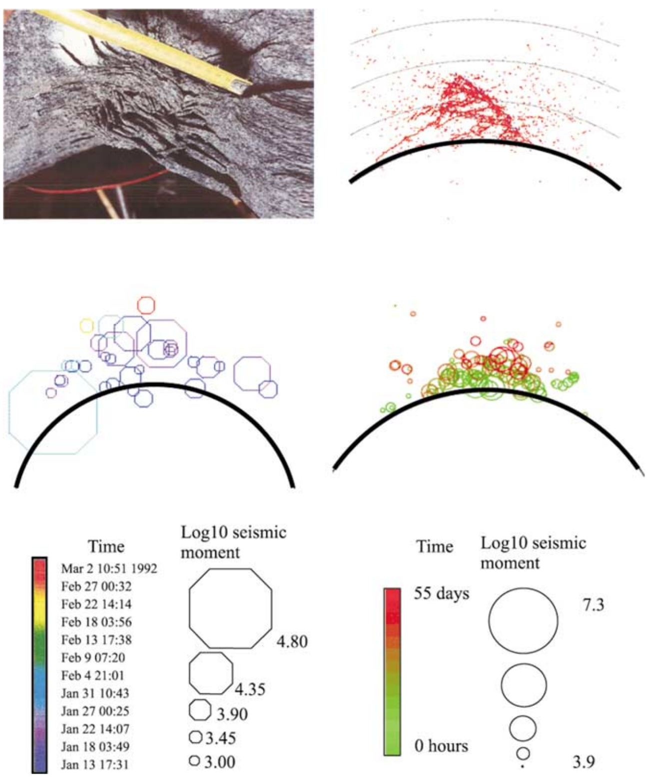

Figure 6. Analysis of damaged rock in notch region of the excavation in Fig. 5. Top left damage region; top right PFC predicted damage; bottom left observed microseismic activity in damaged region; bottom right PRC prediction of microseismic activity.

8. Volcanic tuff

Yucca Mountain is the only potential repository site currently under investigation in the world that is planned to be located above the water-table, in the unsaturated zone of the (10–12 million years old) volcanic tuffs in the Nevada desert, approximately 150 km northwest of Las Vegas, Nevada, USA. The characteristics of this site are very different from others. The rock is extensively fractured and very permeable. The region is undergoing extension, with horizontal stresses lower ($\approx$3 MPa) than the vertical stresses ($\approx$5 MPa at the repository horizon, 200 m below surface). The site is part of a seismically active region. In the arid desert region, almost 90% of the 60 mm or so annual precipitation is evaporated at the surface, leaving approximately 6 $\mathrm{mm \cdot y^{-1}}$ infiltration. Most of this is believed to flow through the network of sub-vertical fractures. Currently, approximately 80% of the proposed waste emplacement area is in the so-called lithophysal tuff. This rock mass contains large, more-or-less spherical, voids of various sizes, ranging up to 50 cm in diameter. How these lithophysal will affect flow is currently not well understood. Yucca Mountain is not a geologically simple site with respect to waste isolation.

US regulations require that the site be demonstrated to comply with the radioactive release standard for 10 000 years, although it is anticipated that the releases will continue to rise for the order of 300 000 years. Currently, considerable reliance is placed on the waste containers in demonstrating compliance with the regulations. At the same time, research is continuing towards the goal of demonstrating that the natural characteristics of the site can provide adequate isolation of the waste to ensure public safety in the long term.

The following example illustrates the challenges facing efforts to characterize the Yucca Mountain site.

Phillip [9] has shown that, when an excavation is placed within an unsaturated zone of homogeneous (soil) rock, in which the groundwater flows vertically, the flow tends to be diverted around the excavation, as shown in Fig. 7. This suggests that, in the case of Yucca Mountain, water would not contact the waste package. This would appear to be an important benefit of placing waste in the unsaturated zone.

If one now considers the situation at Yucca Mountain with the capillary suction potential appropriate for a fractured medium, it is found that Phillips' model is changed. The capillary effect of the excavation is of much shorter range around the excavation.

Modelling the fractured rock as an equivalent homogeneous continuum it is found that the water is diverted around the opening but that the zone of diversion is restricted to a boundary layer from the tunnel

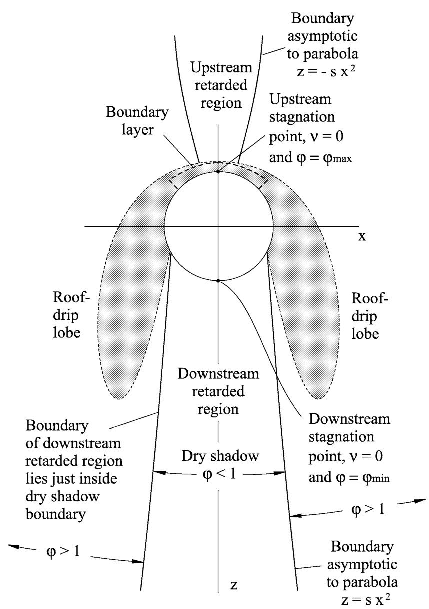

Figure 7. Diversion of ground water flow around a circular cavity in unsaturated permeable ground (after Phillip [9]).

wall, i.e., the water flows vertically under gravity until it reaches the narrow (2–3 cm thick) boundary layer. The analysis assumes a smooth circular tunnel. In reality, the wall is likely to have a roughness such that locally, the wall is 'indented' to a depth that cuts into most, if not all, of the boundary layer. In this case the water will flow (drip) into the tunnel. The narrow width of the boundary layer compared to the Phillips' model suggests that the equivalent continuum approximation may not be valid for a medium in which discrete fractures dominate the behaviour. A discontinuum analysis in which the fractures are modelled explicitly is required.

It is currently envisaged to leave the emplacement drifts at Yucca Mountain open, i.e., without backfill, permanently. Access roadways will be filled. Under these conditions, the EDZ has a different significance than in the previous examples. Water flow axially along the EDZ is not an issue. The effects of thermal and seismic stresses, and stress corrosion weakening, on fall-out of rocks blocks and tunnel stability are of greater concern. Analysis of groundwater flow in both the unsaturated zone and the saturated zone below the repository is complicated by the dominance of flow in fractures.

9. Conclusions

Geomechanics issues arise on both the regional and local (tunnel vicinity) scales in repository safety analysis. In most situations, characterization of the EDZ is of particular concern. The necessity to provide assurance of satisfactory repository performance over times that are very long compared to those experienced in traditional engineering requires the development of a better understanding of fundamental deformation processes in rock. This requires considerable research effort. Salt is an attractive medium for waste isolation because of its special ability to flow and seal excavations, its impermeability and the fact that, in contrast to other rock types, long-term behaviour is well understood.

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Discussion

Question from Y. Bréchet

Is the known mechanical anisotropy of mechanical properties of textured rocks of any relevance or concern for the 'civil engineering design' you have considered?

Reply from C. Fairhurst

Anisotropy of layered rocks such as is typical of shales does not change the stress distribution around underground excavations significantly in the elastic domain. However, the shear strength is typically lower along bedding planes than it is perpendicular to them. Thus, effects such as bedding plane slip can result in differences in the extent of what is known as the excavation damage zone (EDZ) around excavations. Also, where fluid pressures are generated in a sealed excavation (e.g., gas pressures generated due to corrosion of waste containers), they may be sufficient to overcome the normal (compressive) stress acting across the bedding planes, such that they will tend to open and, in some cases, become highly conductive. These planes may then constitute preferred pathways for transport of radionuclides towards the biosphere. All of these possibilities [1] need to be examined for the specific repository situation under consideration, and design measures taken to avoid any such adverse effects.

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Question from C. Madic

Two years ago, a paper was published in Nature (January 1999) related to the migration of Plutonium in the underground nearby a cave created by a nuclear test at the US Nevada test site. Plutonium was found 1.3 km far from the explosion place (cave) which happened 30 years before. Do you have any explanation for such a fast movement of water in the underground?

Reply from C. Fairhurst

The paper to which you refer is, I believe, Kerstin et al. [1]. My colleague, Dr. D.K. Smith, one of the authors of the paper, has provided me with the following brief summary:

"*This paper demonstrates that plutonium derived from a high yield underground nuclear weapons test can be mobilized by sorption on inorganic colloids where it is moved through fractured rock aquifers at near ambient groundwater velocities. Nearly all of the radionuclides* (60*Co*, 137*Cs*, 152*Eu*, 154*Eu*, 155*Eu, and* 239 + 240*Pu*) *with the exception of tritium are associated with clay and zeolite colloids that are less than* 500 *nanometers in size. Resulting plutonium concentrations are quite low with maximum concentrations measured in groundwater of* 1 E − 14 M. *The plutonium traveled* 1.3 *kilometers from the high yield test down to a down-gradient well cluster over the course of* 28 *years; the source of the plutonium was identified by matching* 239/240*Pu isotope fingerprints in the groundwater with that of the nuclear test*."

When a nuclear explosive device is detonated underground, the rock in the immediate vicinity of the device is vaporized and, at slightly larger distances, melted. An intense shock wave, generated virtually instantaneously, radiates spherically from the explosion source creating a spherical cavity. The radius of the cavity depends on the energy release of the explosive. Typically, the cavity radius, R_c, is of the order of $R_c = (8\ \text{m} \sim 12\ \text{m})\cdot Y^{1/3}$, where Y is the explosive (energy) yield in kilotons. (The announced yield of the test referred to in the article in Nature was 1.15 megatons, so the cavity radius would be of the order of 84 m ∼ 125 m.) Radionuclides produced by the explosion form part of the vaporized/molten mass. All stress components of the wave, tangential and radial, are compressive. Consequently, no fractures are generated in the rock adjacent to the cavity during passage of the shock. The molten rock, containing the radioactive products, solidifies on the wall of the cavity. Thus, no radionuclides can be released from the cavity during the shock propagation. As the cavity cools, the pressure within it falls and the roof will collapse (usually within some days of the explosion), forming a rubble-filled cylindrical chamber extending typically $(5 \sim 8)\ R_c$ above the centre of the cavity. If the chamber is below the water table the chamber eventually fills with water, which is heated by the hot rubble. A convection cell develops as hot water rises in the chamber and into the overlying rock, to be replenished by cold water flowing from the surrounding rock into the bottom of the chamber. Thus, water can come into contact with radionuclides within the chamber.

It may also be that, soon after passage of the initial shock wave, the pressure in the hot cavity may be sufficient to generate tangential tension in the rock at the cavity wall. This could result in generation and/or opening of radial fractures from the cavity wall. Hot high-pressure gases may enter and extend these fractures, eventually condensing and coating the fracture walls. Thin coatings (or 'stringers') of radioactive lava in fractures have been reported in the vicinity of tests at the Nevada Test Site (Smith et al. [2]).

The rock mass at the Nevada Test Site is a fractured volcanic tuff. Many of the underground explosions, especially those of higher yield, were carried out at depths below the water table (the proposed Yucca Mountain nuclear waste repository, also in fractured tuff is above the water table). The fractures are interconnected, so that the permeability of the fracture network and groundwater velocities in the fracture network are very high. Colloidal suspensions in groundwater travel essentially at the speed of the water. It is not surprising, therefore, that plutonium adsorbed on colloids in the water can travel at velocities as high as those observed, i.e., 1.3 kilometers in 28 years, or approximately 50 $m \cdot yr^{-1}$.

References

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Question from W. Brewitz

What about retrievability in rock salt?

Reply from C. Fairhurst

As I noted in my article, I agree with the conclusions of geoscientists when first considering the concept of geological isolation of high-level radioactive waste (US National Acad. Sci., 1957) viz. salt is a very attractive medium, for reasons that I have outlined. The fact that salt is a viscous material that will flow to seal the waste within the salt mass is a major attraction of this rock medium. The concept of 'retrievability', i.e., having the ability to remove the waste some tens or more years after it has been emplaced underground in a repository requires special attention in the case of salt. Different strategies will be needed depending on the length of time envisaged for the period of retrievability. Main access tunnels can be maintained open for tens of years, as is required routinely in operating salt mines. Waste canisters that have been emplaced in holes and backfilled can be removed by techniques not very different from those envisaged for other rock types. Salt is not difficult to excavate. If retrievability is considered at some period after the repository has been filled and access tunnels sealed, then, as proposed in Germany, it would be possible, albeit expensive, to extract the radioactive waste using classical mining techniques. The waste would be treated as an ore-body and the waste recovered. Knowing the location of the waste, new shafts and tunnels would be driven and the waste retrieved.

Thus, I do not believe that the question of retrievability should be allowed to detract from the excellent attributes of salt as a medium for geological isolation of high-level radioactive waste.