THE EXCAVATION DAMAGE ZONE -

AN INTERNATIONAL PERSPECTIVE

NOTE: A MORE DETAILED WRITTEN DISCUSSION, INCLUDING DIAGRAMS AND COMPUTATIONS, WILL BE PREPARED AND DISTRIBUTED AT THE WORKSHOP.

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INTRODUCTION

The terms Excavation Damage Zone (EDZ) and Disturbed Rock Zone (DRZ) are used synonymously to describe the region of rock adjacent to (i.e., usually within one or two tunnel radii of) an underground excavation that has been significantly damaged or disturbed due to the redistribution of in-situ rock stresses that occur upon creation of the excavation. Depending on the rock type, the magnitude of in-situ stresses and the method of excavation, the stress redistribution may produce more or less damage to the rock structure, and an associated change in the resistance to fluid flow.

Although the EDZ may develop around any underground opening it is of particular significance in nuclear waste repository design. Before discussing the EDZ in detail, however, it is useful to outline briefly the central importance of groundwater flow and radionuclide transport with respect to geological isolation of nuclear waste.

Regional Ground Water Flow and Radionuclide Transport

The most probable pathway for the release of radionuclides from an underground repository is by transport of the radionuclides in groundwater flowing through repository to the biosphere or 'accessible environment.' Radionuclides must be isolated for times of the order of tens of thousands of years, so rates of groundwater movement at a repository site must be very low. With planned repository depths typically 500m - 1000m, flow paths will also be of the order of kilometers. Careful assessment of the flow regime on this regional scale is their primary consideration in repository site selection. A further challenge is presented by the requirement in every country where the problem is geological isolation of nuclear waste is faced, to provide reasonable assurance that the repository performance will be sufficient to isolate the waste for the long time frames (10^4 or more years) envisaged. This implies a level of credible quantitative calculation of geological parameters such as mass permeability over unprecedentedly long times.

Such assessments of isolation performance usually assume Darcy flow of the groundwater, i.e. the flow occurs through a porous-permeable solid medium and obeys the law:

$$Q = -KA\,dh/dl$$

where

Q is the volume of fluid passing per unit time (t) through a planar cross-section, area A, of the solid;

K is the resistance to flow, or hydraulic conductivity of the solid; (units of velocity)

dh/dl is the hydraulic pressure gradient over a distance dl.

The ratio Q/A, which has the dimensions of velocity, is a fictitious value referred to as the Darcy velocity or specific discharge, V_D and is widely used in groundwater flow calculations. The actual velocity, V_p, through the interconnected pore spaces will be much higher. Thus, if the porosity is 10%, (i.e. the actual cross-sectional area of the pores 'a' is 0.1A) then the actual (average) pore velocity will be ten times greater than the Darcy velocity. The flux Q will be the same in both cases, i.e., where V_D and A, or V_p and a are used. Darcy's law represents average conditions of flow through a medium that is considered to be homogeneous. It is, in effect, a statistical result of the actual flow through individual pathways in the porous-permeable medium.

Assessment of the regional groundwater flow regime in a rock mass is usually based on the assumption that flow is governed by Darcy's law.

Obviously, a homogeneous rock mass where the permeability and hydraulic gradient are low is desirable, but actual repository conditions are rarely so ideal. Frequently, a rock of intrinsically low permeability e.g. granite, may be transgressed by systems of conductive fractures, so that the overall rock mass permeability may be determined primarily by the conductivity of the fractures. Assessment of an overall permeability can be compounded by the fact that fracture systems often exhibit a log-normal relationship between spacing and shear displacement or 'offset' of the fracture, i.e. fractures will vary from closely separated fractures with small offset to more widely spaced fractures of large offset. Since the larger fractures may be more conductive, definition of a scale-independent Darcy permeability for a fractured rock mass can be difficult. There is considerable debate as to what constitutes a Representative Elementary Volume (REV) over which an equivalent homogeneous Darcy permeability can be defined in such situations. The influence of planar, fluid-conductive discontinuities on the rock mass permeability is an important issue in groundwater flow through fractured rock that, although studied extensively by numerical modelling (Stripa Final Overview Report, 1992), has not been fully evaluated in practical situations.

Radionuclide Transport

Fracture flow takes on added significance when radionuclide transport in the groundwater is considered. Water that has come into contact with the waste may contain radionuclides either in solution or 'attached' to colloidal particles suspended in the moving water. As the radionuclides come into contact with rock surfaces, physical and chemical reactions may occur which trap or 'sorb' some of the radionuclides species. As a result, the average rate at which specific radionuclides are transported through the rock will vary and can be considerably lower than that of the groundwater. The transport rate for a specific radionuclide can depend critically on a number of factors such as the rock type and surface conditions (porosity, coating material, ...), pH and eH of the water, and the total surface area of contact of the groundwater with the rock as it flows through the rock mass.

In the case of flow through joints, the area of contact is likely to be considerably less than the total area of the joint surfaces. The 'aperture' of a joint results from the non-planarity or 'roughness' of the joint surfaces, and the forces acting across these surfaces. Flow through the joint occurs in 'channels', so that the radionuclides will not come into contact with the full joint cross-section, and will also flow more rapidly through the joint as a consequence. This will influence the degree of physical and chemical interaction and, hence, retardation of the radionuclides. Assessment of the retardation of a specific radioisotope under in-situ conditions - as compared to the retardation observed in laboratory experiments - is an important, unresolved question of geological isolation of radioactive waste. This is particularly the case where significant groundwater flow occurs through discrete discontinuities in the rock mass.

IMPORTANCE OF THE EDZ IN REPOSITORY DESIGN

1. Underground Research Laboratory Experiments

Considerations such as those outlined above led logically to the view that determination of the rock mass properties directly at depth under in-situ conditions was necessary in evaluating site suitability for nuclear waste repositories. The International Stripa Project, started in 1980, after a 3 year preliminary study, was the first major comprehensive effort to characterize a rock mass hydrologically for nuclear waste isolation, and to develop the appropriate tools and techniques for this purpose. Many countries contributed to the Stripa Project which concluded in 1992, and a great deal was learned (Stripa Final Overview Report 1992).

Several countries have since established underground research laboratories in order to evaluate rock mass conditions relevant to the development of repositories in these countries, and significant advances in understanding flow and transport in rock masses continue to be made. One of the most important results, however, has been the recognition that the act of excavating an underground opening will usually produce changes in the rock such that, locally, it is no longer in the condition of the rock mass more remote from the excavation.

The difference arises because of the deformations induced by the stress changes due to the excavation, i.e. the formation of an EDZ.

Thus, an understanding of how the flow properties of the rock mass are influenced by the EDZ is important to assessment of regional groundwater flow and radionuclide transport, and to the planning and interpretation of experiments in underground research laboratories.

2. Influence of EDZ in Repository Sealing

The assumption in the above discussion that the most probable release of radionuclides will be associated with the groundwater regime in the region of the repository implies, of course, that direct release via the shafts and tunnels created to allow introduction of waste to the repository will not occur, i.e. that the shafts and tunnels will be effectively sealed. It is not sufficient, however, to seal the openings alone; the EDZ around the openings will form a continuous, high-permeability path from the repository to the biosphere, and so must also be sealed. Excavation of the EDZ and introduction of pre-fabricated, low permeability seals in several sections of the repository may suffice to interrupt the flow. Supplemental grouting of the EDZ is also under consideration. Several seal designs are approaching the stage of field testing to assess their effectiveness.

3. Influence of Repository Layout and Canister Thermal Loading on the EDZ

All repository designs involve the placement of the waste filled drums (for intermediate-level waste) or longer-lived canisters (for high-level waste) either in the main underground excavations or in supplementary holes, drilled either vertically into the floor or horizontally into the sides of the main excavations. Drilling of these hole will create additional stress concentrations and augment the EDZ. In the case of high-level waste, radioactive decay of the waste produces substantial quantities of heat for several hundreds to thousands of years. Depending on the waste type and layout (waste loading density) the maximum temperature generated in the rock close to the canister can reach in excess of 200°. Most repository designs limit maximum rock temperatures to below 100°C.

In the confined situation of the underground repository such temperatures produce substantial additional thermal stresses in the entire EDZ, increase its extent and the intensity of damage. Increased pore pressure can also be substantial and further increase damage.

The temperature increases extend across the entire repository and thermal convection cells can develop which influence the groundwater circulation and radionuclide transport patterns, especially in the proximity of the repository.

Several underground experiments have been conducted internationally to assess the influence of thermal effects of waste heating on the EDZ. The effects can be particularly substantial in jointed rocks, due to the strong coupling or interaction between thermal, mechanical, hydrologic and chemical effects. Coupled effects are discussed further below.

COUPLED EFFECTS IN THE EDZ

As noted above, creation of underground excavations produces significant redistribution of stresses and groundwater potential in the vicinity of the excavation. Since the forces applied to the rock are supported in part by the rock (solid stresses) and in part by the water (fluid pore pressure) the distribution between the two components will probably also change. This, in turn, may result in additional damage in the EDZ, or it could improve the stability of the excavation. Changes in fluid pressure can be particularly significant in discretely jointed material, where the inter-relationship between fluid pressure in a joint, flow rate in the joint, and joint aperture is very strong. For fluid flow of an incompressible fluid between two almost parallel, impermeable boundaries, the flow rate (q) is proportional to the cube of the aperture (a) i.e., $q \alpha a^3$. Increase of the aperture would tend to increase the compression of the solid blocks on each side of the joint; this would propagate through the jointed system. Also, increase of fluid pressure in a joint may change the shear resistance and slip of the blocks could occur. Thus, coupling between the solid and fluid components of a jointed rock mass subjected to fluid pressure must be considered in order to assess the equilibrium of the system.

Addition of thermal loading by the waste canisters will result in both temperature gradients in the rock mass and in the fluid and thermal stresses in the rock. These changes will affect the mechanical/hydrological interactions. In some cases, temperature changes can lead to dissolution in the water of material from one part of the system, to be precipitated elsewhere, where the temperature is different. This may result in changes in aperture in the joints and possibly local blocking of the flow.

Add the fact that joint orientations are unlikely to coincide with the axis of the excavation, and it is seen that fluid flow and stress distribution in the EDZ formed in jointed rock will involve complex thermal-hydro-mechanical-chemical coupling relationships of a three-dimensional joint network.

Evaluation of the appropriate equivalent Darcy flow parameters for the regional ground-water regime from underground tests in jointed rock is a particular challenge. Considering the joints as the primary water flow pathways, underground testing is in some respects a large scale analogue to inferring Darcy flow constants from tests at discrete points within the pore structure of a laboratory specimen.

Some examples are presented below of unanticipated results of underground laboratory studies to date.

SPECIFIC EXAMPLES OF EDZ EFFECTS FROM UNDERGROUND LABORATORY EXPERIMENTS

The following examples illustrate (a) the type of insights obtained from in-situ experiments, results that would not have been anticipated from classical (surface) laboratory studies, (b) the essential role of underground laboratories in the effective design of repositories.

1. Simulated Drift Validation (SDV), Site Calibration and Validation (SCV) Programme, Stripa, Sweden

Using the results of field data on the hydraulic conductivity of joints in-situ, four international groups (U.K., USA (2), Canada) attempted, independently, to estimate ground-water flow conditions in the region of the SDV drift. Three groups used discrete fracture network models directly, while the fourth relied on an equivalent continuum porous medium representation of the fracture network.

In the SDV drift experiment six holes, each 100m long, were drilled parallel to each other, five along the future periphery and one along the centre axis of a projected tunnel of 2.4m radius. (As actually excavated, the tunnel was 3m wide by 2.4m high.) The water inflow to each borehole was observed. It was noted that 85% of the inflow was produced from a single section, of higher permeability essentially crushed rock, perpendicular to the axis of the proposed tunnel, defined as H zone. Each team was given structural and hydrological information on the rock mass penetrated by the boreholes and asked to predict the inflow to the tunnel after it was excavated along the projected path. Simple Darcy flow continuum calculations indicate a slight increase in flow (the six holes produce zero fluid pressure at each hole with a reduced pressure along the line between the holes, whereas the tunnel would produce zero pressure along the entire line between the holes). The four predictions essentially agreed with that of the Darcy continuum.

The actual measured inflow to the tunnel was found to be approximately 12% only of the flow into the drill holes. A similar result in which flow into holes drilled ahead of the shaft was some four times greater than subsequently observed in the shaft has been observed in Canada (Dormuth, personal communication). A popular explanation for this observation was that the tangential stress concentration around the excavation 'tightened' the fractures in a narrow annulus around the tunnel (or shaft), thereby restricting flow as observed.

A recent analysis by Damjanac (1996) indicates that, for the in-situ stress conditions in the SCV drift, the tangential stress will increase, and hence tend to close fractures, over two quadrants of the circle around the tunnel, - but the stress will decrease in the other two quadrants, thereby opening fractures. This suggests that formation of a uniformly low permeability 'skin' around the tunnel is not a plausible explanation for the reduced inflow.

An alternative possibility, in which the stress redistribution ahead of the advancing face could result in a compaction (along the tunnel axis) of the material in the 'soft' H zone, thereby reducing its permeability, was also examined by Damjanac (1996). While this is plausible, it was found that for typical loading and unloading behavior of such material, once the tunnel has advanced through H zone, the material in this zone would be decompressed and the permeability again increased. Compaction of H zone was thus rejected as an explanation of the reduced inflow.

An alternative hypothesis has been proposed by Long (Stripa Overview Report 1984), in which gas dissolved in the groundwater under the temperature and pressure conditions of the undisturbed rock, comes out of solution under the low fluid pressure conditions created in the vicinity of the tunnel. "Bubbling" flow of the exsolved gas produces a lower total water content in the flow into the tunnel. Field studies are continuing to examine this hypothesis in more detail.

2. Waste Isolation Pilot Plant (WIPP)

The Waste Isolation Pilot Plant (WIPP) is a fully developed potential repository for defense-related transuranic [i.e., intermediate level] nuclear waste in Carlsbad, New Mexico. The repository has been constructed in the Permian age Salado salt formation, at a depth of 650m, and underground experiments have been conducted on a variety of problems for over 15 years. Numerous estimates of the permeability of the salt have been made by tests on core samples taken both from the surface and underground, and by in-situ testing in boreholes. Values ranged typically over several orders of magnitude, from $10^{-17}m^2$ to $10^{-22}m^2$ (10^{-5} to 10^{-10} millidarcies). It was decided that a more reliable estimate may be possible by careful observation of brine inflow into a horizontal circular tunnel bored in the salt. The Room Q experiment was undertaken, in which brine inflow into a 2.5m diameter, 100m long tunnel was observed over several years, was undertaken. Although some doubt remains, there is considerable evidence to support the thesis that the salt is indeed impermeable, but that damage, including fracturing of salt in the EDZ of Room Q, links together isolated intra-granular pockets of brine in the salt; this brine then flows into the Room. Since salt is a viscous material, the EDZ extends with time, so that progressively more brine is released into the Room. If it is *assumed* that the brine inflow is the result of Darcy flow, then a finite permeability can be obviously computed. If, however, the origin of the brine is confined to the EDZ, then the salt mass is, in fact, impermeable, and the brine inflow into the room does not imply any communication between the repository and the far-field geology. McTigue (1995) points to additional evidence in support of the 'impermeable salt' hypothesis for the WIPP observations both for borehole data and Room Q. He has examined this alternative model in detail and notes:

Data for flow to boreholes in WIPP Room D are represented well qualitatively by the classical [i.e. Darcy] *model. However, the capacitance indicated by fitting model calculations to the field data is orders of magnitude larger than that expected on the basis of the compressibilities of salt and brine. That is, the decay of the brine flux into the boreholes takes place over a time scale that is much too long to be explained in terms of the processes assumed in the development of the classical model. 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 point out that salt creeps at vanishingly small deviatoric stress (i.e. stress difference). Thus, over long time frames, interconnected porosity can not be sustained. Brine will be confined to local domains of isolated porosity containing fluid at a pressure equal to the lithostatic stress in the salt.

The geochemical observations indicate that:

-- *brine chemistry is highly variable, even among samples separated by distances of the order of tens of centimeters. 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 million years the diffusion length, L_d, 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 in local, isolated domains.*

McTigue (1991) also analyzed brine seepage rates into Room Q and again concluded that this experiment confirms the view that undisturbed salt is impermeable.

It should be noted also that, as with Room Q, an EDZ will develop around a small borehole at depth in salt so that permeability calculations based on brine inflow to boreholes in salt could similarly be suspect - as suggested above by McTigue with reference to the boreholes in Room D. Indeed, the influence of the EDZ on flow measurements in boreholes generally could be worthy of additional study.

An attractive feature of salt as a host medium for nuclear waste is the fact that, due to the viscous behavior of salt, damage, including cracks, in the EDZ can heal if the zone is subjected to confining pressure. Thus, if excavations such as shafts and drifts are filled with compacted salt, creep of the salt towards the filled excavation will occur until the pressure in the salt fill reaches equilibrium with the lithostatic (i.e. overburden) pressure in the salt formation. At this time the permeability (if any) of the salt will have achieved the original value of the intact salt. Dale and Hurtado (1996) have shown by tests on laboratory specimens that stress-induced fractures in salt can be effectively healed (as judged by the return of the specimen to the sonic velocity of the original undamaged specimen) within a period of several days when subjected to a confining pressure of the order of 5MPa. Callahan et al (1996) have conducted numerical modelling studies for several constitutive models for salt incorporating damage and conclude that, under the conditions (depth, pre-compaction of salt in the shaft) anticipated for shaft-sealing, the EDZ around the WIPP shafts should be effectively eliminated in less than 50 years from placement of crushed salt in the shaft.

3. Use of Micro-Seismic Networks in Underground Experiments - URL, Canada

The Mine-By Experiment at the Underground Research Laboratory (URL) of Atomic Energy of Canada Limited (AECL) in Pinawa, Canada provides a very good example of the application of the use of micro-seismic techniques in underground experiments. A network of geophones and other sensors was installed in the rock mass prior to excavation of a tunnel. This was carried out by line drilling and rock splitting in order to avoid the complication of blasting vibration effects on the micro-seismic signals. The granite of the URL site is homogeneous and remarkably unjointed.

The geophysical results clearly identified the onset of rock damage ahead of the face and the progressive development of "break-outs" and the EDZ, consistent with the high in-situ stresses (55MPa, 48MPa lateral stresses, and approximately 14MPa at 10^{o} to the vertical) at the 420m level of URL.

The Mine-By Experiment provided a number of additional valuable insights on fundamental rock mechanics and the EDZ, which will be discussed.

4. Underground Heater Experiments in Jointed Rock

Although the example discussed below incorporates some features of the Yucca Mountain site now being evaluated as a high level nuclear waste repository is not a direct simulation of a specific test. It is useful as an illustration of the difficulties inherent in designing and conducting tests in jointed rock.

A three-dimensional network of orthagonal joints, two vertical and one horizontal, was assumed to be subjected to principal stresses of 5MPa vertical and 2.5MPa (constant in the horizontal plane). A hydrostatic fluid pressure equal to 100m head of water was assumed to exist at the level of the experiment. This system, at equilibrium, was to be 'perturbed' by excavation of tunnels, one (the access tunnel) to gain access to the site, another (the test tunnel), at right angles to the first to define the edge of the test block, and a third, an alcove, at right angles to the test tunnel, to define a second planar surface of the test tunnel to which a heater, of specific power 300W/m^2, was to be applied. Results of an analysis using a recently developed three-dimensional, coupled thermal-mechanical-hydrologic numerical model (Damjanac, 1996) clearly indicate that stress and fluid pressure changes produced in the process of excavating the test site can result in significant changes to the joint apertures and fluid pressure distribution at the site. As a result, the influence of the heating of the test block on the rock stress and fluid pressure behavior during the test will be different than if the block could be tested in the pre-excavation condition. This poses significant difficulties in both the design and interpretation of such in-situ experiments.

CONCLUSIONS

- The EDZ is, in general, a feature of all excavations at depth in rock, a consequence of pre-existing solid and fluid forces in the rock that are changed by creation of the excavations necessary to access the underground site. Underground tests are necessary in order to evaluate rock mass properties and fluid flow/radionuclide transport behavior relevant to the design of nuclear waste repositories.
- Joints and discontinuities are a common feature of rock masses that can have an important effect on the results of in-situ experiments on rock masses. It is important that the effects of excavation on these discontinuities, and other inhomogeneities in the rock, be understood as part of the testing programme.
- Three-dimensional thermo-mechanical-hydrologic numerical modelling procedures are now available to assist in the appropriate design of underground laboratory tests.
- The use of non-invasive micro-seismic location of rock activity (e.g. slip on specific joints) stimulated by the excavations used to create the test environment, together with detailed local mapping of the joint systems and numerical modelling, can greatly assist in the success of in-situ experiments.
- Sealing of the EDZ is an essential -but technically feasible - part of the final sealing of repository access shafts and drifts.

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