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Changes in Rock Salt Permeability Due to Nearby Excavation

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ABSTRACT: Changes in brine and gas permeability of rock salt as a result of nearby excavation (mine-by) have been measured from the underground workings of the WIPP facility. Prior to the mine-by, the formation responds as a porous medium with a very low brine permeability, a significant pore (brine) pressure and no measurable gas permeability. The mine-by excavation creates a dilated, partially saturated zone in the immediate vicinity of the excavation with an increased permeability to brine and a measurable permeability to gas. The changes in hydrologic properties are discussed in the context of pore structure changes.

1 INTRODUCTION

A Disturbed Rock Zone (DRZ) develops around the excavations of the Waste Isolation Pilot Plant (WIPP), a US Department of Energy research and development facility in bedded salt (halite) near Carlsbad, New Mexico. The DRZ has been defined as the zone of rock in which mechanical and hydrologic properties have changed in response to excavation (Borns and Stormont, 1989). The presence of a DRZ has numerous implications for the performance of the WIPP. The DRZ is relatively permeable compared to the undisturbed formation, and must be considered in seal systems designed to help isolate waste. The increased porosity of the DRZ may also serve as a sink within which fluids (brine or gas) accumulate. Most research has focused on the properties and response of the rock mass outside the DRZ. Current mechanical and hydrologic models for rock salt do not account for the observed behavior in the DRZ.

An in situ experiment was conducted between 1988 and 1990 which monitored the hydrologic response of a halite layer to nearby excavation and provided a hydrologic measure of the DRZ. An array of twelve small-volume pressurized brine- and gas-filled test intervals located about 8 m from an underground room was first established. Their pressure response was monitored with time prior to, during and after the excavation of a nearby large-diameter hole. Sometime later, gas and brine injection tests were conducted in the boreholes. The emphasis of measurements and analyses was to quantify the changes in gas and brine permeability as a result of excavation. The data also provide qualitative information regarding changes in dilation and saturation in response to excavation. These results suggest a more fundamental definition of the DRZ in terms of pore structure changes.

2 EXPERIMENTAL CONFIGURATION AND METHODS

The twelve small-diameter "monitoring" boreholes were drilled vertically down from the floor of the L1 room in the experimental portion of the WIPP facility. These 4.8-cm diameter boreholes were drilled to a depth of 8 m with air as the drilling fluid. A test interval was created in the bottom of each borehole by placing an inflatable rubber packer nominally 65 cm from the bottom of the borehole. A schematic diagram of the monitoring boreholes is given in Figure 1. In order to minimize the volume of test interval, a 4.3-cm diameter steel rod was placed near the bottom of the borehole. The packers have a tubing feedthrough to allow access to the test interval for fluid injection or withdrawal. The test interval pressure is measured by means of a strain-gaged diaphragm pressure transducer. A nearby data acquisition shed houses the excitation, signal conditioning and data recording instrumentation.

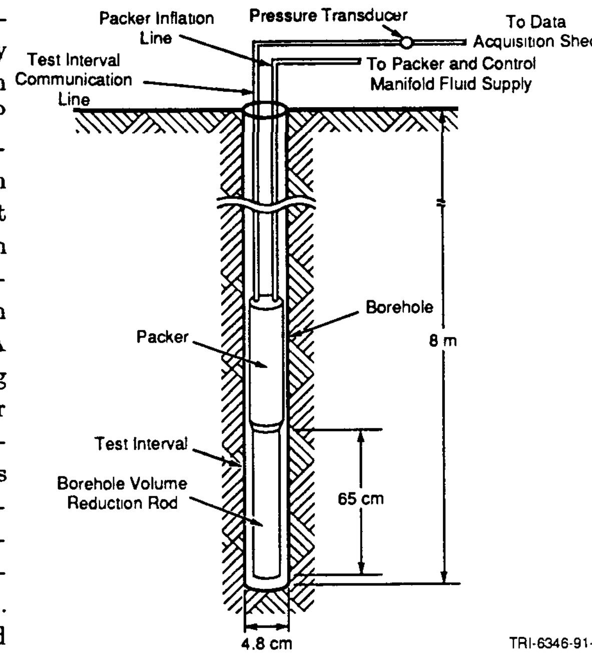

Figure 1: Schematic of monitoring borehole configuration.

A plan view of the monitoring boreholes is given in Figure 2. As shown in Figure 2, both brine-filled and gas-filled monitoring boreholes were placed at 1.25, 1.5, 2, 3, and 4 r from the center of the planned large-diameter hole, where r is the radius of the large-diameter hole (r = 48.3 cm). Two monitoring boreholes of each type (gas and brine) were located at 1.25 r to provide redundancy at this location where the greatest changes in response to excavation were anticipated. At 8 m from the floor of Room L1, the rock adjacent to the test interval is clear to moderately reddish orange halite with some polyhalite stringers and very little disseminated clay. The nearest anhydrite or distinct clay seam is more than 2 m from the test intervals.

Both the brine-filled and gas-filled test intervals were established within 4 days of completion of the borehole drilling by placing the steel rod and packer at the desired location and inflating the packer. The packers were inflated and maintained at a pressure of about 5 MPa using fresh water. For the brine-monitoring boreholes, saturated brine was first placed in the bottom of the borehole prior to placement of the packer and steel bar to reduce the likelihood of trapping gas in the test interval. The brine and gas test intervals were pressurized to about 2 MPa, shut-in, and monitored for about 150 days until the large-diameter hole was drilled. Time zero is taken as the time the first test interval was established. In one brine-filled test interval at 1.25 r, the borehole fluid and rock temperatures were measured with thermocouples. Approximately 40 days after the first test interval was established, test interval compressibility measurements were made in the brine test intervals.

The "mine-by" excavation was achieved by drilling a 96.5-cm diameter hole. This hole was deepened incrementally: A 5-cm diameter pilot hole was first drilled, followed by

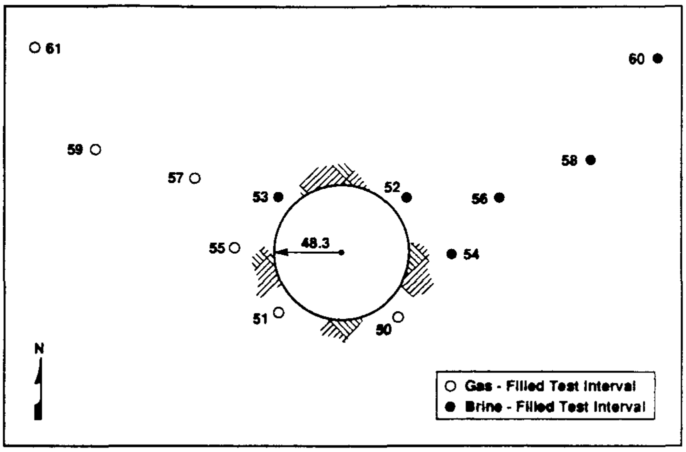

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Figure 2: Plan view of mine-by borehole (96.5-cm diameter) and monitoring boreholes (4.8-cm diameter) on the floor of Room L1.

the coring of the 96.5-cm diameter hole to a similar depth. The pilot hole provided directional stability and aided in large core removal. The drilling time was less than 8 hours for both the pilot hole and the large diameter core from about 1 meter above to 1 meter below the mean test interval depth (8 m). Packers within 2 r of the large-diameter borehole were shut-in prior to the mine-by to reduce the potential for packer-induced damage.

About 240 days after the mine-by drilling, injection tests were conducted in all of the test intervals. Constant-pressure tests were conducted in all of the brine-filled test intervals and two of the gas-filled test intervals. The test interval pressures were increased by up to 0.7 MPa, and the flow rate necessary to maintain this pressure was measured with a flow manifold connected to the test interval communication line. Shut-in or pressure-decay tests were performed in three gas-filled test intervals by raising the pressure in the test interval by 1.4 MPa and measuring the pressure decrease as fluid moves out into the formation.

3 RESULTS AND ANALYSES

The principal focus of the data analysis from the in situ experiment is to determine permeability changes of the rock salt as a result of nearby excavation. The analysis approach is to first establish a pre-excavation permeability and then determine the permeability after the excavation. The data are interpreted in terms of transient flow through a compressible, porous medium. The flow is assumed to be radial, applicable for flow to or from a borehole. A finite difference numerical scheme is used to produce simulations of flow to estimate the formation properties.

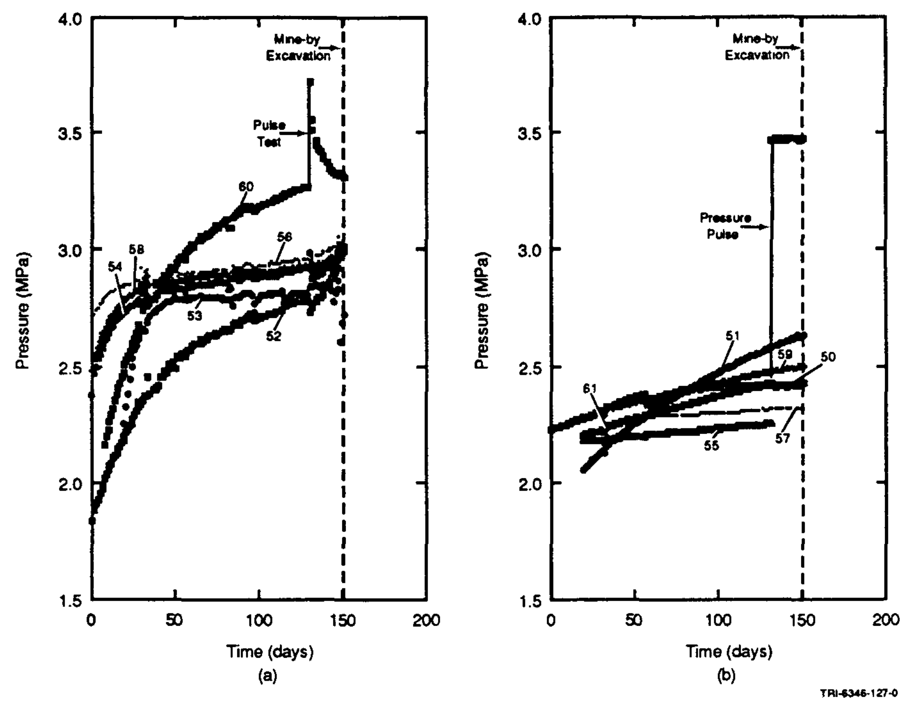


Figure 3: Pressure-time data prior to excavation for (a) brine-filled and (b) gas-filled test intervals. Data from borehole 55 are truncated due to data acquisition problem.

3.1 Pre-excavation responses

The responses of the brine- and gas-filled test intervals after they were shut-in but before excavation of the mine-by borehole are given in Figure 3. Once shut-in, the brine-filled test interval pressures increase and approach a value of about 3 MPa. Borehole 60 appears to be approaching a somewhat greater value. The gas-filled test interval pressure increases at a slower but more linear rate. Pulse tests were conducted in boreholes 60 and 61 prior to the mine-by.

The responses of both the brine- and gas-filled test intervals are consistent with the formation modeled as a very low permeability, low porosity medium with a significant pore (brine) pressure. Flow of brine from the formation into the lower pressure test intervals results in pressure increases in both the brine- and gas-filled test intervals. The flow rates into the test intervals, and consequently the pressure changes, decrease as the test interval fluid pressures approach the formation pressure, and finally level off near the formation pressure. In the gas-filled test intervals, pressures increase at slower rates due to the relatively great test interval fluid compressibilities. The gas in the test intervals does not flow into the formation because (1) the formation brine is at a higher pressure, and (2) there is a threshold or displacement pressure which the gas would have to overcome in order to flow into the formation.

The formation properties are estimated by means of numerical simulations of the test. Permeability, porosity, formation pressure, test interval dimensions (including closure or opening of the test interval), test interval compressibility, formation compressibility, and fluid properties are input to the simulation, and the resulting calculated pressure history

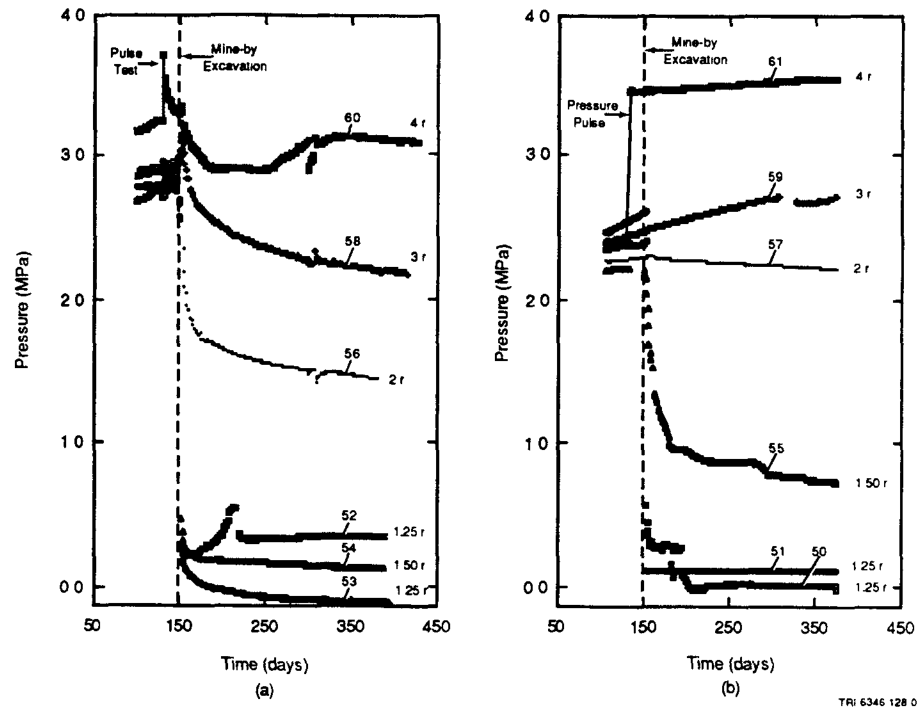


Figure 4: Pressure-time data during and after excavation for (a) brine-filled and (b) gas-filled test intervals.

is compared to the data. The unknown parameters are adjusted until a reasonable agreement between the numerical simulation and measured response is obtained.

The data from the brine-filled test intervals can be bounded with a formation pressure of 2.7 to 3.6 MPa and a permeability of $1\text{x}10^{-22}$ to $8\text{x}10^{-21}$ m^2. The interpreted formation pressures and permeabilities which bound the response of the gas-filled test intervals prior to the mine-by are 3.0 to 3.6 MPa and $2\text{x}10^{-20}$ to $3\text{x}10^{-22}$ m^2, respectively. The range of the interpreted permeabilities is consistent with other measurements for undisturbed rock salt (e.g., Peterson et al., 1987). The pre-excavation response shows that gas does not flow from the test intervals out into the formation, indicating that the effective gas permeability of the formation prior to excavation is zero.

The magnitude of the formation pore pressure interpreted from the pressure build-up (about 3 MPa) is less than the probable pore pressure of the undisturbed formation (about 10 MPa, Peterson et al., 1987). This indicates that the test intervals were located close enough to Room L1 (8 m) to be in a region of depressed pore pressure, or this halite layer had an anomalously low pore pressure.

3.2 Responses during and after excavation

The responses of the brine- and gas-filled test intervals during and after excavation are given in Figure 4. All of the test intervals experienced decreasing pressures tending toward equilibrium values. Their responses are a function of the distance the particular test interval is from the excavation; the closer to the excavation, the more the pressure drops and the lower the equilibrium pressure.

The pressure decreases in the brine- and gas-filled test intervals are due to (1) dilation of the formation, and (2) formation pore pressure changes in response to flow toward the zero pressure boundary of the excavation. The pressure response to dilation will occur relatively quickly, whereas the pressure response due to flow will happen more slowly because of the low permeability of the formation. The test interval responses are consistent with a dilatant zone surrounding the large-diameter borehole out to about 1.5 r. In this region, there appears to be sufficient increase in pore volume so that brine-filled test intervals almost immediately lose nearly all of their pressure. Relatively large increases in pore volume may not be able to be instantaneously saturated by the surrounding low permeability formation. The gas-filled test intervals at 1.25 r also lose their pressure. In order for this to happen, the formation must become undersaturated with respect to brine. At 1.5 r, the gas pressure decreases from over 2 MPa and stabilizes at 0.7 MPa, indicating that some gas flowed out of the borehole into the formation and then stopped. If the pore pressures are symmetric about the excavated borehole, the brine-filled test interval response indicates that the formation pressure at 1.5 r is zero. The equilibrium pressure of 0.7 MPa in the gas-filled test interval at 1.5 r, therefore, may be a measure of a displacement or threshold pressure in the disturbed region.

Beyond 1.5 r, the changes in response to excavation are less dramatic. The pressure responses of the brine-filled test intervals decrease with distance from the large-diameter borehole. In the gas-filled test interval at 2 r, the slow decrease in the test interval pressure suggests that the formation pressure at this location has reduced to below the test interval pressure. Either the gas pressure is sufficient to overcome the threshold pressure, or the brine which has accumulated in the test interval during the pre-excavation inflow period is forced into the formation. Beyond 2 r, the gas-filled test intervals are not affected by the excavation.

3.3 Post-excavation injection tests

Approximately 240 days after excavation, injection tests were conducted in the test intervals. The formation properties were estimated from the injection tests by means of matching the measured response with numerical simulations. All of the injection tests in the brine-filled test intervals were constant-pressure injection tests. The pressures in both test intervals at 1.25 r were increased 0.45 MPa above the previous pressures; the pressures in the remaining test intervals were increased 0.7 MPa over the previous pressures. The results are summarized in Table 1. The permeability and porosity values interpreted from the brine injection tests decrease as the distance from the mine-by borehole increases. At 3 r and 4 r, the interpreted permeabilities and porosities are comparable to those before excavation, indicating that the excavation had no measurable effect on the brine permeability at 3 r and beyond.

Table 1: Summary of Post-Excavation Brine Injection Test Results

Borehole number	Position (r)	Permeability (m^2)	Porosity
52	1.25	5.7×10^{-18}	0.01
53	1.25	5.7×10^{-18}	0.01
54	1.5	1.5×10^{-19}	0.005
56	2.	1.8×10^{-20}	0.001
58	3.	4.5×10^{-21}	0.001
60	4.	5.5×10^{-21}	0.001

The gas injection test results are summarized in Table 2 In the two gas-filled test intervals at 1.25 r, constant-pressure (0.24 MPa) injection tests were conducted These measurements were interpreted as gas flow into the partially saturated and de-pressurized region near the mine-by borehole

Table 2: Summary of Post-Excavation Gas Injection Test Results

Borehole number	Position (r)	Permeability (m^2)	Porosity
50	1.25	9.0×10^{-16}	0.01
51	1.25	5.0×10^{-18}	0.01
55 *	1.5	2.0×10^{-19}	0.005
57 *	2	3.0×10^{-21}	0.001
59 *	3	5.0×10^{-21}	0.001

* Tests were interpreted assuming the test interval gas driving brine flow in the formation Post-excavation injection test not conducted in borehole 61

In the gas-filled test intervals at 1.5, 2, and 3 r, pressure-decay tests were conducted by increasing the test interval pressure by 1.4 MPa above the previous pressure and shutting in the test interval. The responses from these tests were controlled by flow of brine (not gas) in the formation, the increased gas pressure in the test intervals was driving brine flow in the formation At 1.5 r, there was sufficient flow of gas from the test interval during the injection test (about 300 cm^3) so that it appears that gas is moving into the formation The uneven pressure history measured during this test is consistent with that expected during viscous fingering or channeling (Dullien, 1979) This phenomenon occurs when the viscosity of the displacing fluid is less than that of the saturating fluid, as is the case for gas displacing brine Thus, we conclude that the injected gas flow is displacing existing pore brine during this test

At 2 and 3 r, the shut-in tests result in very small pressure decays The volume of gas which moves from the test interval into the formation is so small (a few cm^3) that it is not possible to determine if the gas actually moves into the formation Perhaps gas is displacing brine in the formation, but only in a small zone of enhanced permeability surrounding the test intervals An alternative explanation is that brine that was produced into the test interval during the pre-excavation inflow phase is now being forced back out into the formation In either case, it appears that the flow of brine in the formation controls the test interval gas pressure response

5 DISCUSSION AND CONCLUSIONS

The mine-by experiment provides direct evidence of changes in hydrological parameters of rock salt as a result of nearby excavation The test results are summarized in Figure 5

The previous definition of the DRZ has been a qualitative, non-specific term which indicates that some formation properties have been altered in response to excavation A more fundamental definition of the DRZ is the volume of rock which experiences a change in its pore structure, or the microstructure of its porosity, in response to

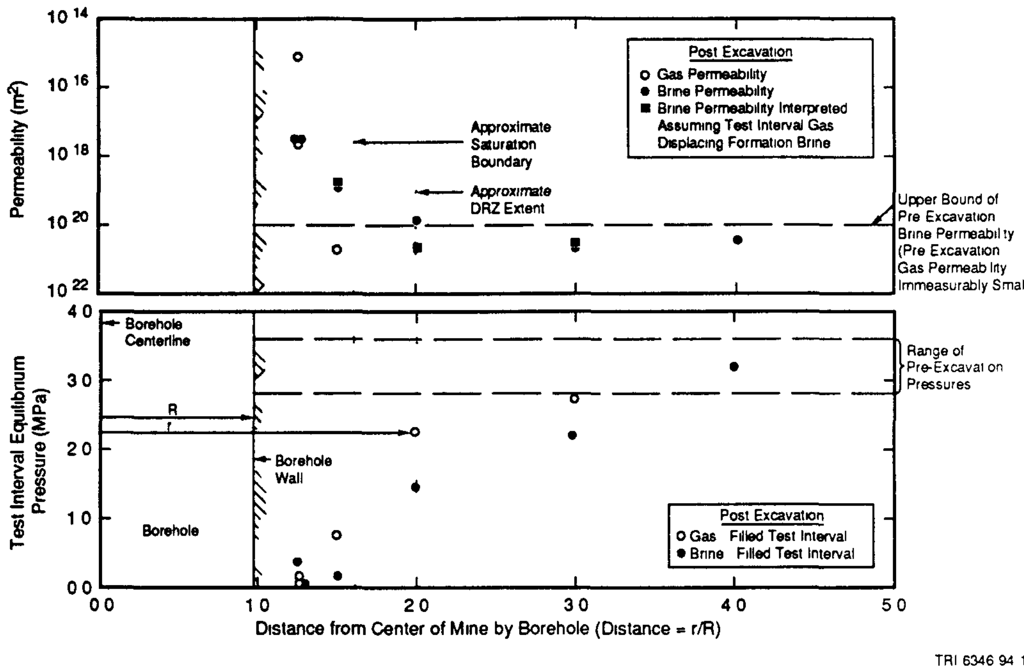
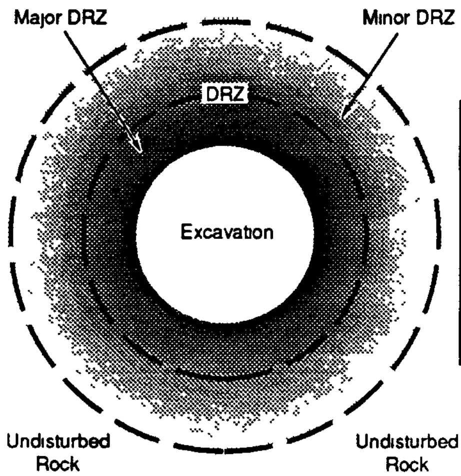


Figure 5: Summary of experimental results.

excavation Defining the DRZ in terms of pore structure changes allows physical insight into the response of the rock mass Pore structure is the link between the mechanical and hydrologic response of a porous medium For example, an increase in mean stress tends to close existing pores and cracks, this closure, in turn, reduces the connnected porosity and permeability To predict permeability or permeability changes from a fundamental basis, a model or representation of pore structure must be used

Pore structure can be altered in two fundamental ways changes in the existing pore structure and creation (or deletion) of pore space Most pore structure models concern changes in the existing pore structure For example, models which relate permeability and mean stress have been developed by assuming elastic, recoverable deformation of the existing pore structure (e g , Walsh, 1981) Creation of new porosity, i e , damage, will also induce permeability changes These permeability changes are due in part to changes in deviatoric stresses, and may or may not be recoverable

A conceptual model of the DRZ in terms of pore structure changes in the rock surrounding the mine-by borehole is given in Figure 6 The rock mass is defined in terms of three regions In the first region adjacent to the excavation, the rock is the most damaged (major DRZ) The damage is manifested principally as grain boundary microcracking accompaned by dilation (Stormont, 1990), and is a result of relatively high deviatoric and low hydrostatic stresses induced by the excavation This damage does not imply failure or loss of strength of the rock salt With increasing distance from the excavation, the stresses are less conducive for damage The second region contains a combination of damage with little dilation and changes in the existing pore structure (minor DRZ) The first and second region comprise the DRZ Beyond some distance from an excavation, there is no significant effect of the excavation on the pore structure (neglecting the very small elastic and unknown time-dependent response of the pore structure) This



Major DRZ	Minor DRZ
• Due to Damage and Dilation	• Due to Changes in Existing Pore Structure and Limited Damage and Dilation
• Measurable Gas Permeability	• No Measurable Gas Permeability Due to Great Threshold Pressures
• Relatively Great Brine Permeability	• Some Increase in Brine Permeability
• Low Pore Pressure	• Some Pore Pressure Decrease Due to Dilation, but Remains Saturated
• Partial Saturation	

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Figure 6: Conceptual model of pore structure changes in rock salt surrounding an excavation.

so-called undisturbed region is still affected by the excavation, and processes which do not require pore structure changes such as isovolumetric creep and pore pressure changes occur in this region.

Pore structure damage is responsible for the majority of the effects attributed to the DRZ in rock salt When accompanied by dilation, damage reduces the pore pressure and may induce a partially saturated zone. The development of measurable gas permeability is possible under these conditions. Brine permeability will be increased due to the increased size and connnectivity of the damage-induced pore structure. Damage increases the effective or bulk compressibility of a material, not only decreasing the effective elastic moduli but also increasing the hydraulic storage capability of the material

The experimental results summarized in Figure 5 are consistent with the concept that pore structure change alters the hydrologic properties of rock salt Gas permeability probably only exists in the region which has experienced substantial damage, and will be nearly coincident with the limit of partial saturation Brine permeability will be affected by changes in the existing pore structure, and will therefore extend beyond the depth of measurable gas permeability to the limit of the DRZ Pore pressure changes do not require pore structure change, and can therefore extend outside of the DRZ

The test results reveal that the extent and magnitude of the DRZ depends on which parameter is considered The greatest changes in hydrologic parameters are confined to 1 5 r, and are asssociated with pore structure damage. Defining the DRZ in terms of pore structure change and damage provides a framework for gaining physical insight into the processes active in the development of the DRZ and developing the fundamental relationship between mechanical and hydrologic behavior of rock salt

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