Prediction of the Extent of the Disturbed Rock Zone around a WIPP Disposal Room, USA - 8057

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ABSTRACT

This paper is one of a series of papers outlining the recent performance assessment for the Waste Isolation Pilot Plant repository conducted by Sandia National Laboratories. The disturbed rock zone (DRZ) is an important feature that is included in the performance assessment process models to predict future repository conditions and brine flow to the accessible environment. Furthermore, the properties of the DRZ control a significant portion of the brine that can flow into the waste rooms. Extensive laboratory salt creep data demonstrate that damage can be assessed in terms of volumetric strain and principal stresses. Stress states that cause dilation are defined in terms of stress invariants, which allow reasonable models of DRZ evolution and devolution. In this paper, the change of DRZ extent with time is calculated based on a dilatant damage potential criterion. The constant *C* in the dilatancy criterion is determined by comparing the numerical analysis results of the Room Q access drift with the field data obtained at the same location for the analysis. The most extensive DRZ exists during early times, within the first ten years after an opening is mined. As the back stresses from the waste stack resist deformation, the damage to the salt decreases. The maximum extents of the DRZ calculated below and above the room reach approximately 2.24 m and 4.74 m, respectively. The maximum lateral DRZ extent in the side of the room is calculated to be roughly 2 m.

INTRODUCTION

The Waste Isolation Pilot Plant (WIPP) is a deep geologic repository operated by the U.S. Department of Energy (DOE) in southeastern New Mexico as a disposal facility for transuranic (TRU) radioactive waste. The WIPP facility is regulated by the U.S. Environmental Protection Agency (EPA) according to the regulations set forth in Title 40 of the Code of Federal Regulations, Part 191 (40 CFR 191). The DOE demonstrates compliance with the containment requirements according to 40 CFR 194 by means of performance assessment (PA) calculations carried out by Sandia National Laboratories (SNL). WIPP PA calculations estimate the probability and consequences of radionuclide releases from the WIPP repository to the accessible environment for a regulatory period of 10,000 years after closure of the facility.

The WIPP repository is excavated in a halite layer of the Salado Formation directly above one of the thicker anhydrite layers known as Marker Bed (MB) 139. The stress state is sufficient to promote considerable creep deformation of halite. Compared to other rocks, salt creeps readily in response to differential stresses. Stress-field alteration and creep closure will create a disturbed rock zone (DRZ) around the excavation exhibiting fracturing near the surface. Relative to the intact salt, the DRZ exhibits increased porosity as a result of rock fracturing and increased permeability as a result of connecting fractures. The DRZ properties change with time as salt creep occurs.

The DRZ is an important feature that is included in the performance assessment (PA) process models to predict future repository conditions and brine flow to the accessible environment. Furthermore, the properties of the DRZ control a significant portion of the brine that can flow into the waste rooms.

The DRZ dimensions and permeability ranges used in the current PA baseline models have not changed since the initial certification of the WIPP in 1998 [1]. However, field measurements, laboratory observations, numerical modeling, and operational experience show that the extent of the DRZ can now be more accurately represented. This property decreases as the salt undergoes deformation, contacts the waste, and a backpressure is applied. In conjunction with this decrease in the extent of the DRZ, its permeability also decreases, thereby limiting the amount of brine that could flow from the Salado Formation into the disposal rooms.

It is clear that the DRZ will be limited in extent over the regulatory period. Hansen [2] presents the several avenues of scientific approach that lead to this conclusion. Extensive laboratory salt creep data demonstrate that damage can be assessed in terms of volumetric strain and principal stresses. Stress states that cause dilation are defined in terms of stress invariants, which allow reasonable models of DRZ evolution and devolution [3, 4]. In this paper, a procedure to calculate the extent of the DRZ around a disposal room and the results will be provided. The results of this analysis will be used in WIPP PA process models.

APPROACH

The change of DRZ extent with time will be calculated based on a dilatant damage potential criterion. The constant *C* in the dilatancy criterion will be determined by comparing the numerical analysis results of the Room Q access drift (Location 1 in S-90 drift as shown Figure 1) with the field data obtained by Holcomb and Hardy [5]. Figure 2 illustrates the flow diagram for how these calculations are used to determine the DRZ extent.

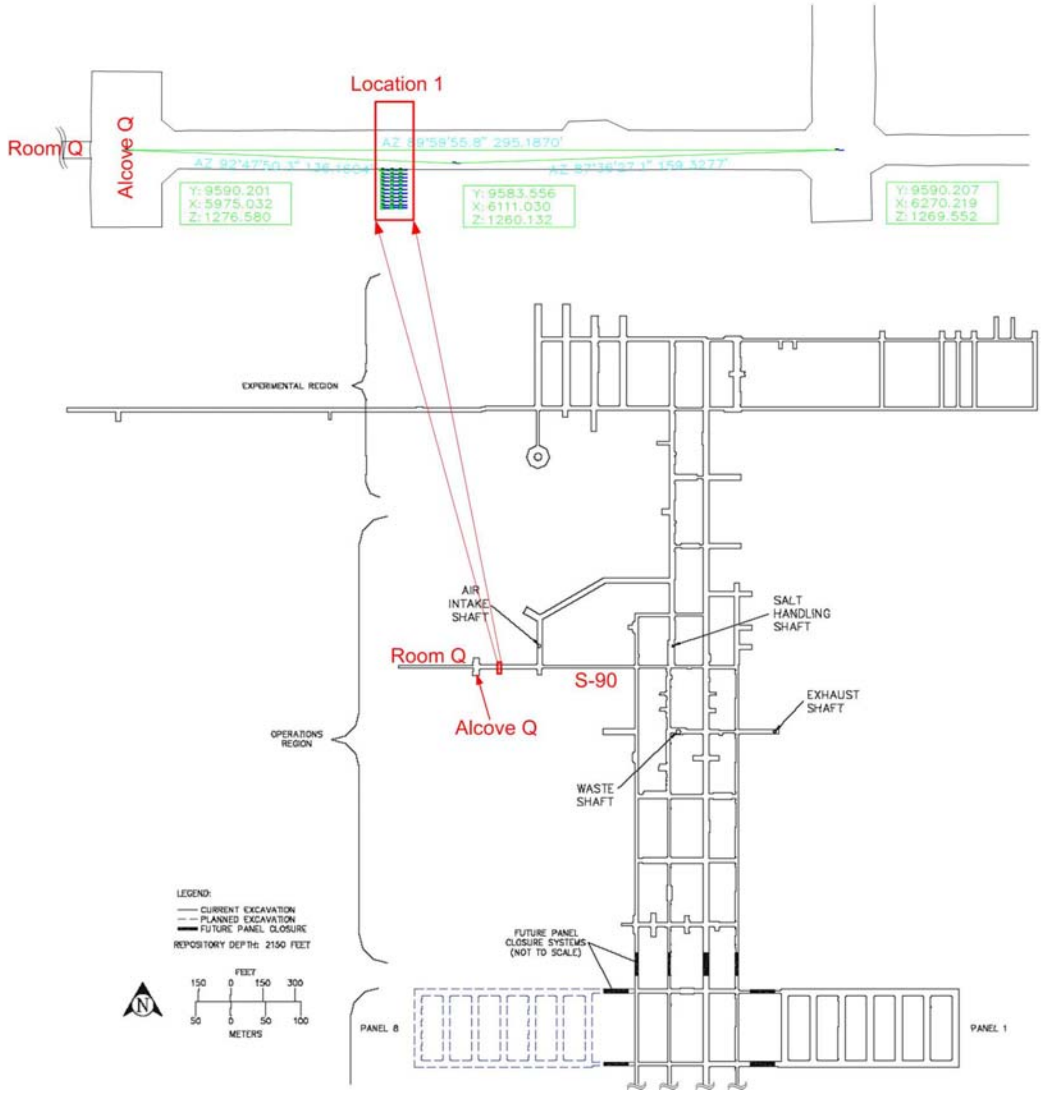


Fig. 1. Location 1 in S-90 Drift in WIPP repository.

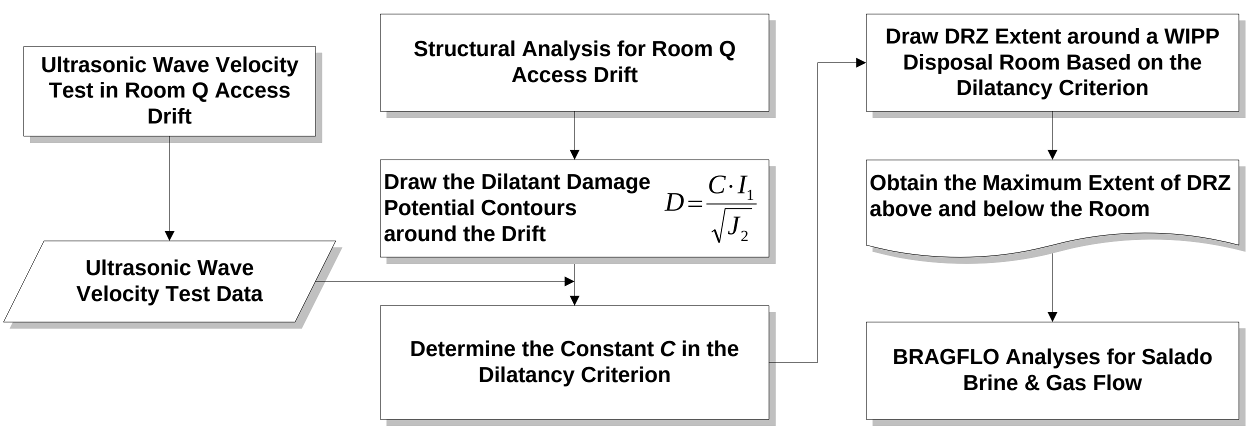


Fig. 2. Activity flow diagram for determining the extent of the DRZ around a WIPP disposal room.

DAMAGE POTENTIAL CRITERION

Dilatancy, defined as an increase in volumetric strain under compressive stress [6], is attributed to micro-fracturing or changes in the pore structure of the salt, resulting in an increase in permeability. The following dilatant damage criterion is used to delineate potential zones of DRZ in the salt formation:

$$D = \frac{C \cdot I_1}{\sqrt{J_2}} \quad \text{(Eq. 1)}$$

where D is the dilatancy damage factor;
C is the dilatancy damage potential constant;
$I_1 = \sigma_1 + \sigma_2 + \sigma_3 = 3\sigma_m$ is the first invariant of the stress tensor;
$J_2 = \frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{6}$ is the second invariant of the deviatoric stress tensor;
σ_1, σ_2, and σ_3 are the maximum, intermediate, and minimum principal stresses, respectively; and
σ_m is the mean stress.

When $D < 1$, the shear stresses in the salt (J_2) are large relative to the mean stresses (I_1), and dilatancy damage is predicted; similarly, when $D \geq 1$, the shear stresses are small relative to the mean stress, and dilatancy is not predicted.

ULTRASONIC WAVE VELOCITY TEST

Holcomb and Hardy [5] performed ultrasonic wave velocity measurements to characterize the DRZ in Location 1 of the S-90 access drift to Room Q (Figure 1). Measurements were taken at 30 cm (1 ft) intervals over paths vertical, horizontal, and perpendicular to the drift axis. Measurements were taken using paths through the salt near the back, floor, and center of the rib to detect how the varying stress state affects the development of the DRZ in these locations. Figure 3 shows the arrangement and naming scheme for the measurement holes in Location 1.

Ultrasonic wave velocities are decreased by open cracks and loosened grain boundaries. The effect is strongest for cracks oriented perpendicular to the particle motion induced by the wave. Thus the physical extent of the disturbed zone can be determined by propagating ultrasonic waves through successive portions of the formation. Cracking responsible for the disturbed zone is expected to vary as a function of distance from the face of rib and to depend on the position of the measurement path relative to the back and floor. The undisturbed zone is defined as that region where the elastic wave speed remains constant with increasing depth from the rib. Measurements were made between pairs of holes ("cross-hole") cored perpendicular to the axis of the drift along horizontal and vertical paths lying in vertical planes parallel to the rib. Between each pair of holes, travel time measurements were made at 30 cm (1 ft) intervals to a depth of about 7 meters (~20 ft), as measured from the rib face. In addition, measurements were made within one hole ("same-hole") along paths perpendicular to the drift wall. The paths for the cross-hole measurements were nominally one meter long, while the same-hole measurements all had the a fixed path length of nominally 33 cm. Travel time measurements were made using the technique commonly used for laboratory determinations of ultrasonic sound velocity in rock, a sound pulse is applied to the rock at a known time and place and, after traveling through the rock, is received by a transducer at a known distance. P- (compression) wave velocity, V_P, and S- (shear) wave velocity, V_S, data were used for the measurements. The travel time and distance combine to give the average velocity over the path.

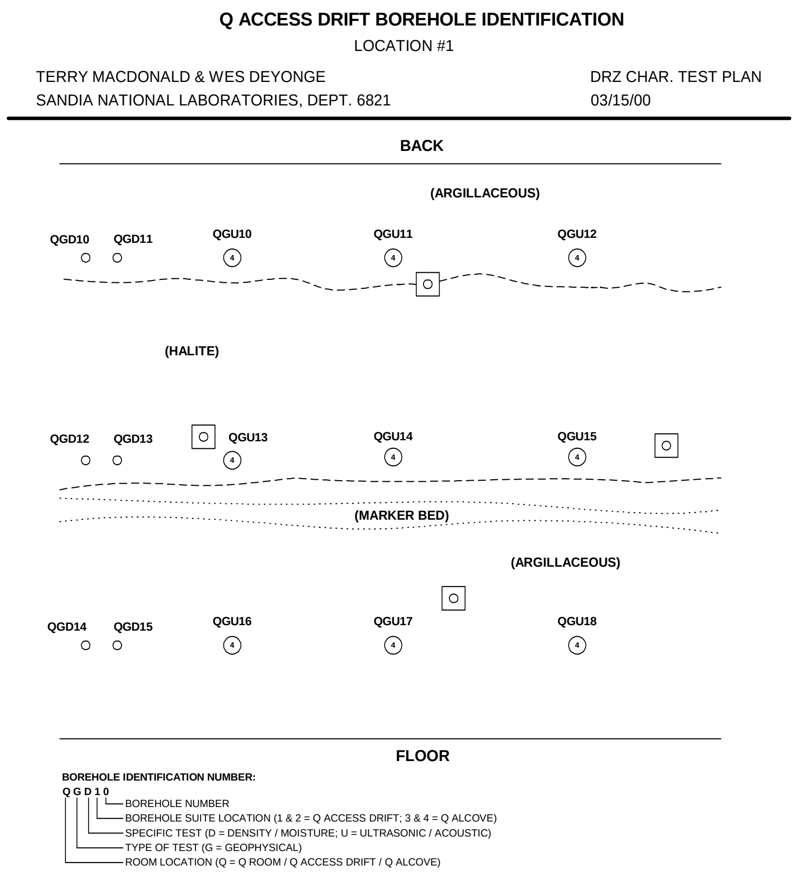
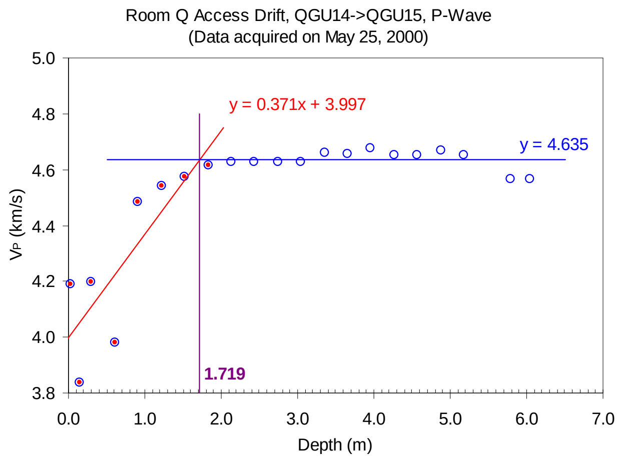


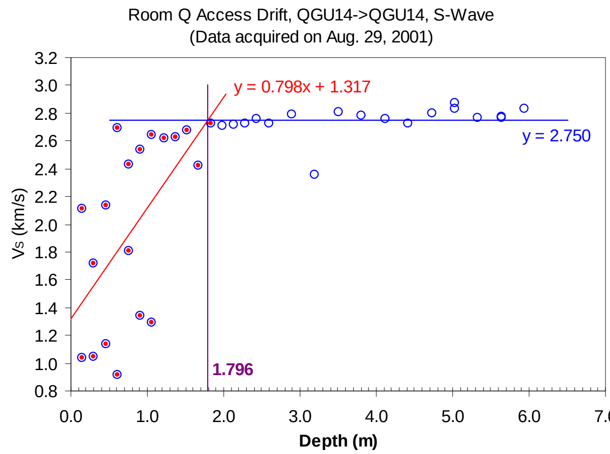
Fig. 3. Arrangement and naming scheme for the measurement holes [5].

The depths of DRZ are inferred from the ultrasonic wave velocity data measured at Location 1. Figure 4 (a) shows the velocity data versus depth as determined on May 25, 2000 from cross-hole P-wave measurements between boreholes QGU14 (Transmitter) and QGU15 (Receiver) as an example. The velocity increases from 3.84 km/s at 0.15 m depth to 4.61 km/s at 1.83 m depth. The velocity does not increase beyond 1.9 m depth but exhibits variations around constant value of 4.63 km/s. Figure 4 (b) shows the velocity versus depth for a same-hole test in QGU14 using S-waves on August 29, 2001. The velocity increases from 1.04 km/s at 0.15 m depth to 2.73 km/s at 1.8 m depth. No systematic velocity variations were observed beyond 1.8 m, although there were variations about the best-fit value of 2.75 km/s.

A bilinear model was used to describe the velocity-vs.-depth data. To develop the model parameters, a depth was chosen by inspection that marked the deepest extent of the DRZ. Then a line of the form y=V_0 was fit to the data points at depths greater than the deepest point of the DRZ and a line of the form y=ax+b was fit to the data points at shallower depths. The fits were performed using the trend line capability of MS Excel. The average velocity beyond the DRZ, V_0, is considered to be the wave velocity in the undisturbed salt. The intersection of the trend line y=ax+b and the average value line can be regarded as an inferred DRZ depth. The inferred DRZ depths for (a) and (b) in Figure 4 are calculated as 1.719 m and 1.796 m, respectively.



(a)



(b)

Fig. 4. Velocity data versus depth with trend and average lines from a cross-hole test between boreholes QGU14 (Transmitter) and QGU15 (Receiver) using P-wave on 2000 (a), and a same-hole test in borehole QGU14 using S-wave on 2001 (b).

STRUCTURAL ANALYSIS AT LOCATION 1 IN S-90 DRIFT

A two-dimensional plane-strain model is used to represent the S-90 drift and surrounding rock. The model grid (Figure 5) represents the cross-section of the drift in two dimensions. Invoking symmetry, only half of the drift is modeled. The drift is modeled as being subjected to regional far-field boundary condition acting from an infinite distance away. The distance to the confining boundary is 50 m. This distance is about ten times the width of drift. This ratio exceeds the generally accepted ratio of five for the maximum dimensions to minimum excavation sizes in numerical analysis [7]. A lithostatic stress ($\sigma_x = \sigma_y = \sigma_z$) that varies with depth is used as the initial stress boundary conditions; gravity forces are included.

A zero-displacement boundary condition in the horizontal direction (U_X = 0.0) was applied on both the left and right boundaries of the model to represent the symmetric nature of a drift and far-field stresses respectively. A prescribed normal traction of 13.57 MPa was applied on the upper boundary and a vertical zero-displacement boundary condition (U_Y = 0.0) was applied on the lower boundary to react to the overburden load. The initial half-symmetry drift dimensions are 3.72 m high by 2.82 m wide. To determine the constant, C, in the dilatancy criterion, a structural analysis for the Room Q access drift is conducted using the quasistatic, large-deformation finite element code SANTOS developed by SNL [8].

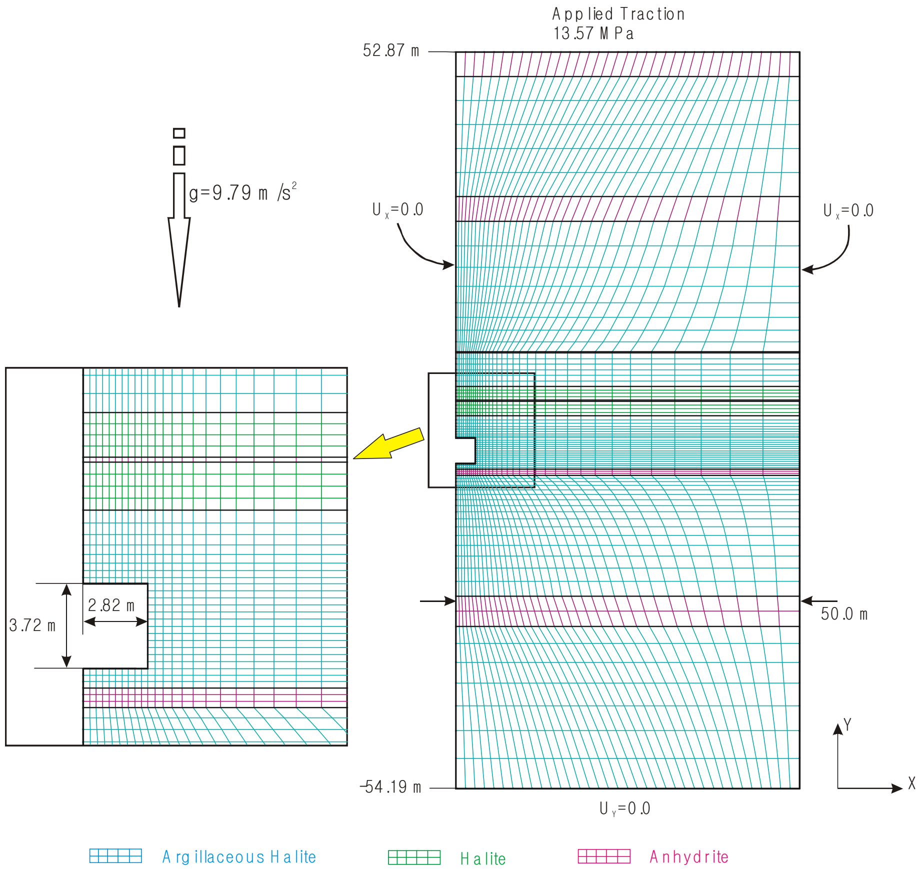
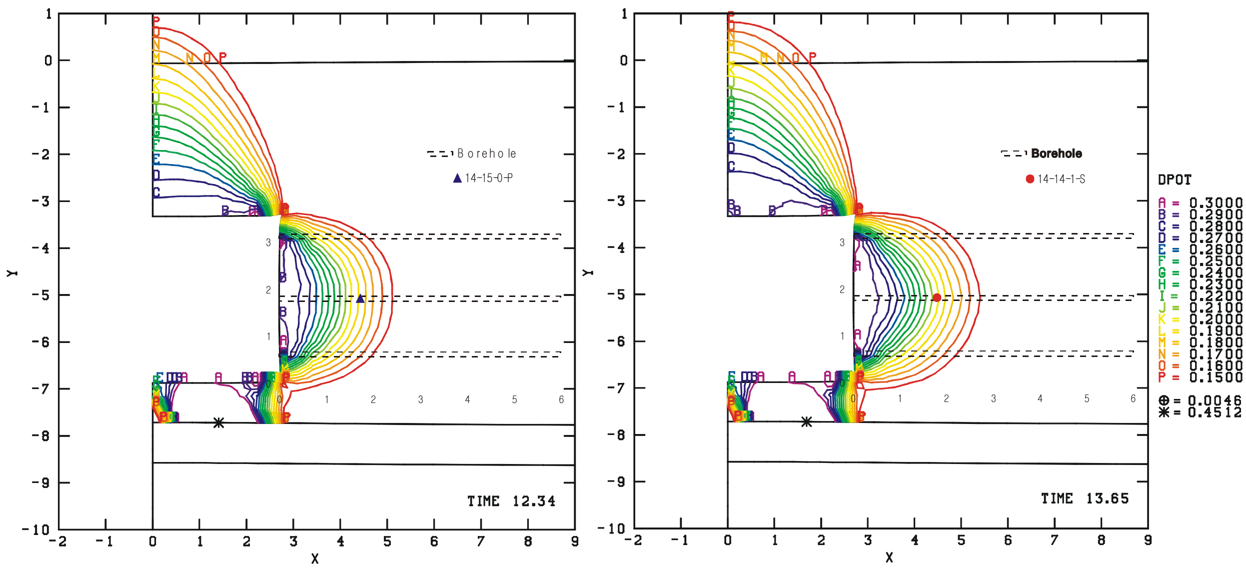


Fig. 5. Mesh discretization and boundary conditions around the drift.

DETERMINATION OF *C* IN THE DILATANT DAMAGE CRITERION

The completion date of mining the S- 90 drift from the W-620 drift to Room Q alcove was January 15, 1988. Holcomb and Hardy performed ultrasonic wave speed measurement from May 23 to 25, 2000 and again in August 28 to 29, 2001. Thus the data were acquired at approximately 12.3 years and 13.7 years after excavation of the drift. The stresses in the DRZ are expected to change as a function of time. Because of salt creep, the dimensions of the Room Q access drift began to decrease as soon as excavation was completed. Thus, knowledge of the amount of time that lapsed between completion of the excavation and the acquisition of the ultrasonic velocity data is necessary to correctly estimate the value of the constant *C* in the damage criterion. We also note that the DRZ is created soon after the room is excavated when stress differences are relatively high and confining stresses are relatively low. As time goes by, the stress distribution changes because salt deforms plastically. This suggests that in the rib where the sonic data were taken, the damaging stress conditions may have existed deeper into the pillar at the earliest of times than at later, i.e. at the time the sonic velocity measurements were made. Therefore the stress conditions determined at 12.3 and 13.7 years may not be the same as the ratio of the stresses that created the DRZ in the first place. Our modeling suggests that this stress alteration has only a small effect.

From the structural analysis for the drift, contours of the maximum extents of dilatancy damage around the drift can be drawn for different values of *C* using Equation 1. Each contour, therefore, represents a different potential for dilatancy damage to occur to the salt and is referred to as dilatancy damage (DPOT) contour. Figure 6 shows the DPOT contours at 12.3 years and 13.7 years after excavation from the analysis. Inferred DRZ depths as calculated in Figure 4 are also plotted on the figure as an example. The DPOT contours correspondent to different *C* values in Equation 1. A smaller value of constant *C* in the equation yields a greater extent of damage. The constant *C* for WIPP repository is determined from reading the contour values of DPOT corresponding to the inferred DRZ depth data points. The *C* values corresponding to the inferred depths, 1.719 m (Figure 4 (a)) and 1.796 m (Figure 4 (b)) are 0.189 and 0.202, respectively.



(a) (b)

Fig. 6. Damage potential contours around S-90 drift at Location 1 acquired during May 2000 (a) and Aug. 2001 (b) including ultrasonic velocity data points which infer DRZ depths in Figure 4 (X- and Y-axes in m).

Table I lists C values corresponding to every inferred DRZ depth acquired from the ultrasonic wave velocity test during 2000 and 2001 [5]. The first and second numbers in the Sheet ID column of Table I indicate the borehole identification number in which a transmitter and a receiver were installed as shown Figure 3, respectively. Where the first and second numbers are the same, the transmitter and receiver were installed in the same hole. The third number indicates the year data were acquired (0 and 1 indicate 2000 and 2001, respectively). The fourth element in the Sheet ID column is a letter indicating the ultrasonic wave type used for measuring the velocity (P and S denote P-wave and S-wave, respectively).

The average DPOT is calculated to be approximately 0.19. Therefore the in situ constant, *C*, in the dilatant damage criterion is determined to be 0.19 for the salt surrounding WIPP. The constant *C* is an inherent value of the salt. The *C* value only depends on the salt properties. It relates the magnitude of the deviatoric stresses to the mean stress at failure. We assumed the *C* value is the same for the whole area of WIPP site since the same salt strata are considered. However, the value of *C* may be different for another level or site.

Table I: Inferred DRZ Depth and the Corresponding *C* Values.

Excavation Date		1/15/1988			
Date Data was acquired		5/23/2000		8/29/2001	
Years since Excavation		12.34		13.65	
	Sheet ID	Inferred DRZ Depth (m)	Corresponding *C*	Inferred DRZ Depth (m)	Corresponding *C*
Upper Boreholes	11-10-0-P	1.105	0.180		
	12-11-0-P	1.113	0.180		
	12-12-0-S	1.562	0.160		
Middle Boreholes	13-15-1-P			2.028	0.186
	14-13-0-P	1.876	0.178		
	14-14-0-P	1.815	0.181		
	14-14-1-P			1.809	0.201
	14-14-0-S	1.929	0.174		
	14-14-1-S			1.796	0.202
	14-15-0-P	1.719	0.189		
	14-15-1-P			1.390	0.233
	14-15-1-S			1.407	0.230
Lower Boreholes	17-16-0-P	1.002	0.200		
	17-17-0-P	1.177	0.189		
	17-18-0-P	1.440	0.175		
	Average *C*	0.19			

DRZ EXTENT AROUND THE DISPOSAL ROOM

Given the in situ value of *C*, the extent of the DRZ can be assessed by determining the dilatancy damage contour using Equation 1 and stress data obtained from around a modeled repository room [4]. The structural analyses [4] were carried out to a simulation time of 10,000 years for calculating the porosity histories around a WIPP disposal room. Thirteen different rates of gas generation were investigated. Two cases, no gas generation (*f*=0.0) and maximum gas generation (*f*=1.2 [9]), are selected to as bounding cases to illustrate the DRZ extent around the room. The gas generation potential assumes that no gas bleeds off through the surrounding lithologies, because SANTOS does not have a fracture mechanism to bleed off high gas pressure. On the other hand, BRAGFLO, which simulates the brine and gas flow in and around the repository, allows fracturing to proceed when internal gas pressure approaches lithostatic.

Figures 7 and 8 show the change with time of the DRZ around a disposal room for the gas generation factors *f*=0.0 and 1.2, respectively. The violet zone in the figures is defined by $D \geq 1$ in Equation 1, that is, when the dilatancy damage criterion does not predict damage in the salt. The most extensive DRZ occurs during early times, within the first ten years after the opening is mined. As the back stress from the waste stack resists deformation, the damage in the salt as predicted by the stress invariant criterion becomes less and less. Experimental and observational evidence suggests that the process for damage healing is invoked here. Pressure solution and reprecipitation is a very effective fracture healing process when the stress state changes from dilating space into healing space.

The dilatancy damage criterion (Equation 1) no longer predicts a disturbed zone after 199 years for *f*=0.0 as shown in Figure 7 and after 73 years for *f*=1.2 as shown in Figure 8. The DRZ extents are larger than those found in previous analyses [4] because the value of *C* used in this analysis is smaller than 0.27 which was determined by Van Sambeek et al. [10] based on laboratory test data. Since the value of 0.19 is obtained from the field-measured ultrasonic wave velocity test data, the results in this study are expected to be closer to the actual state.

The maximum extent of the DRZ calculated for both gas generation cases reaches approximately 1.4 m, the distance to the anhydrite layer (MB 139), below the room. The anhydrite layer should be included in the DRZ since it is brittle and expected to fracture [4]. The DRZ does not extend beyond the anhydrite layer, which acts as a buffer. Therefore the thickness of DRZ below the room is 2.24 m.

Again for both bounding gas generation rates, the maximum extent of the calculated DRZ above the room reaches to the anhydrite “a”. Thus, the maximum thickness of DRZ above the room is 4.74 m. Shortly after the back of room contacts the waste, the dilatancy damage factor (D) in the damage criterion becomes larger than 1 and damage ceases or is reversed. The maximum DRZ in the side of the room is calculated to be roughly 2 m. In the salt beside the disposal rooms the dilatancy damage criterion predicts disturbance until 199 years for f=0.0 and 73 years for f=1.2.

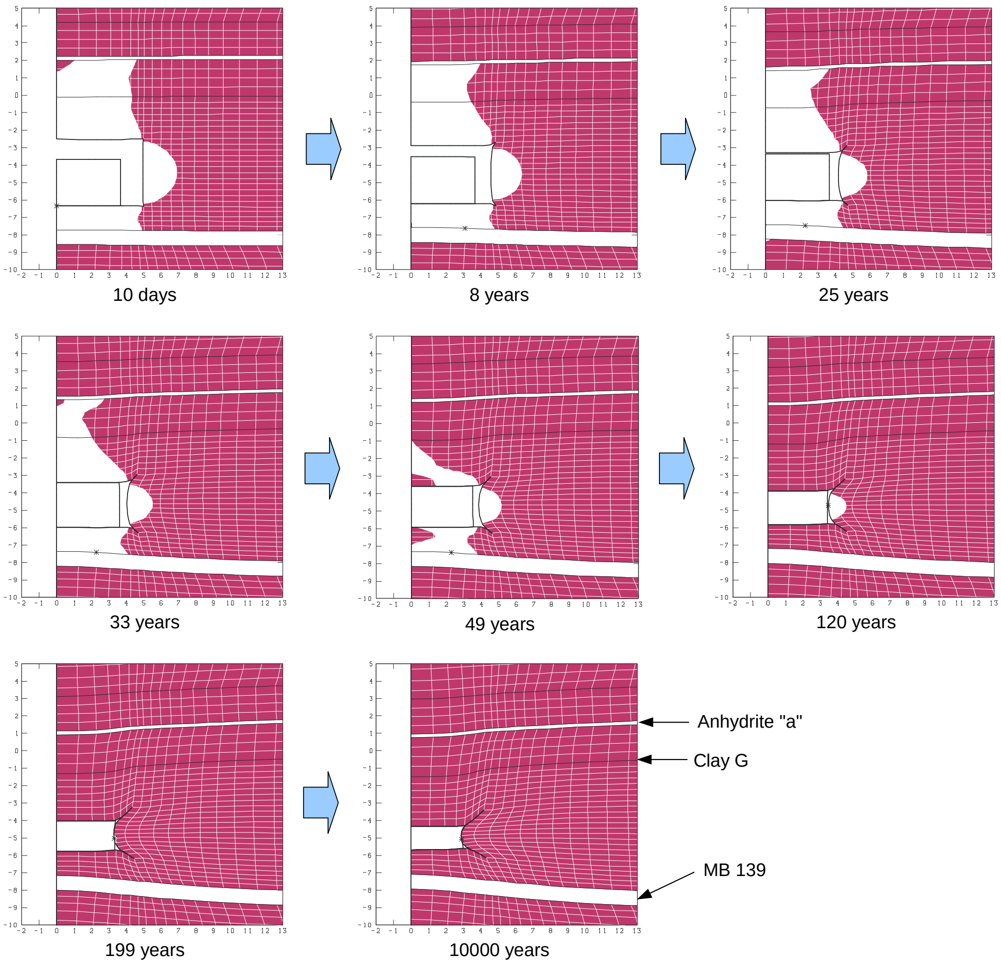


Fig. 7. Prediction of areas around a disposal room for gas generation *f*=0.0 (no gas pressure generated by waste) in which the dilatancy criterion is not satisfied (*D* < 1) with *C* = 0.19 (X- and Y- axes in m).

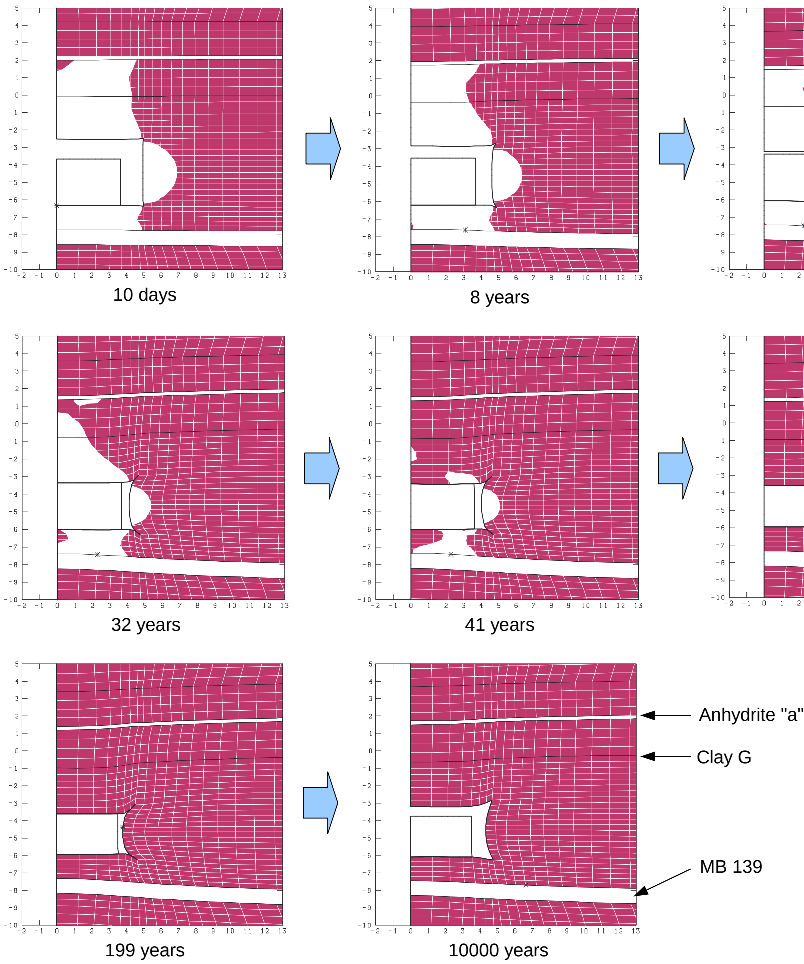


Fig. 8. Prediction of areas around a disposal room for gas generation *f*=1.2 (maximum gas pressure generated by waste) in which the dilatancy criterion is not satisfied (*D* < 1) with *C* = 0.19 (X- and Y- axes in m)

CONCLUDING REMARKS

The DRZ is an important feature that is included in the WIPP PA process models to predict future repository conditions and brine flow to the accessible environment. The primary purpose of this study is to determine the parameter values related to the DRZ around a disposal room for use in BRAGFLO analyses. Field measurements, laboratory observations, numerical modeling, and operational experience so far show that the extent of the DRZ can be more accurately represented. The present analysis suggests that the DRZ dimensions used in the current WIPP PA baseline are overestimates.

In this study, the maximum extents of the DRZ above and below the room are predicted to be 4.74 m and 2.24 m, respectively. This upper limit is approximately one half the current extent (11.95 m) implemented in the WIPP PA technical baseline, whereas the lower limit remains unchanged. These values are proposed to be used in other WIPP PA process models. The constant, *C*, in the dilatancy criterion was determined to be 0.19, which is based on the ultrasonic velocity data measured at Location 1 within the WIPP S-90 drift. This value is less than 0.27

which was determined by Van Sambeek et al. [10] during laboratory testing. A smaller value of *C* predicts a larger DRZ extent. The *C* value developed in this paper is believed to be more representative of the actual field value because it is based on an extensive set of measurements made in a drift at the WIPP site.

Acknowledgements

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