



Missouri University of Science and Technology  
Scholars' Mine

---

International Conference on Case Histories in  
Geotechnical Engineering

(1998) - Fourth International Conference on  
Case Histories in Geotechnical Engineering

---

11 Mar 1998, 4:30 pm - 6:30 pm

## Investigation of the Influence of the Clay Seams Around an Underground Excavation in Rock Salt

S. Kwon

*University of Missouri--Rolla*

John W. Wilson

*Missouri University of Science and Technology, [jwilson@mst.edu](mailto:jwilson@mst.edu)*

Follow this and additional works at: <https://scholarsmine.mst.edu/icchge>

 Part of the [Geotechnical Engineering Commons](#)

---

### Recommended Citation

Kwon, S. and Wilson, John W., "Investigation of the Influence of the Clay Seams Around an Underground Excavation in Rock Salt" (1998). *International Conference on Case Histories in Geotechnical Engineering*. 8.

<https://scholarsmine.mst.edu/icchge/4icchge/4icchge-session06/8>

This Article - Conference proceedings is brought to you for free and open access by Scholars' Mine. It has been accepted for inclusion in International Conference on Case Histories in Geotechnical Engineering by an authorized administrator of Scholars' Mine. This work is protected by U. S. Copyright Law. Unauthorized use including reproduction for redistribution requires the permission of the copyright holder. For more information, please contact [scholarsmine@mst.edu](mailto:scholarsmine@mst.edu).



## INVESTIGATION OF THE INFLUENCE OF THE CLAY SEAMS AROUND AN UNDERGROUND EXCAVATION IN ROCK SALT

**S. Kwon**

Department of Mining Engineering  
University of Missouri-Rolla  
Rolla, Missouri-USA-65401

**J.W. Wilson**

Department of Mining Engineering  
University of Missouri-Rolla  
Rolla, Missouri-USA-65401

6.17

### ABSTRACT

The presence of clay seams in the roof is especially important for assessing the stability of the excavations in salt and potash mines, since they allow separation as well as horizontal slip. The deformational behavior at clay seams in the roof of excavations was investigated by using actual field measurements made at the Waste Isolation Pilot Plant (WIPP) site. From the in situ deformation measurements, the separation and separation rate across the clay seams in the roof and floor could be estimated by using the technique developed in this study. The horizontal displacement along the clay seams was determined from the deflection measurements and compared with the predictions from a computer simulation using FLAC and elastic beam theory.

### KEY WORDS

Clay seam, salt and potash mines, separation, horizontal slip, WIPP

### INTRODUCTION

In the case of rock salt interbedded with different evaporates such as carbonate and anhydrite, rock salt tends to deform plastically while the interlocated rocks tend to exhibit elastic behavior. The clay seams in the roof and floor may have a significant effect on opening stability as they allow separation and slippage of salt beds which subsequently may fall (Baar, 1974). The impact of clay seams on the performance of rock at the WIPP excavations was investigated using in situ observations and numerical modeling by Saeb et al. (1995). When horizontally bedded rock lies above a mine roof, the thinner strata near the opening will tend to detach from the main rock mass and form separate beams (Goodman, 1980). In salt and potash mines, therefore, the existence of clay seams in the roof and floor should be considered as a particularly important factor in determining the overall stability of an excavation. These seams may allow bed separation as well as horizontal movement due to their negligible tensile strength compared to the surrounding rock salt (Saeb et al., 1995). An example of the influence of the separation across a roof clay seam on opening stability is given by the roof fall in SPDV Room 1 at WIPP. A 700 ton rock measuring 10 m wide by 2 m high by 55 m long fell on February 4, 1991. The separation of Clay 'G' located at the top of this block determined the maximum height of the fallen rock mass. At the WIPP site, five clay seams have been located around the existing

excavations, Clay 'G', Clay 'H', and Clay 'I' are in the roof, Clay 'E' is in the floor, and Clay 'F' lies in the rib just below the roof. Figure 1 shows the stratigraphy in the WIPP site. Even though the overall deformational behavior and stability of the openings are significantly affected by the separation across a clay seam in the roof or floor, no measuring tool has been installed to continuously record the separation. In this study, an indirect method for estimating the amount of separation across the clay seams in the roof and floor was developed and applied to the extension measurements obtained at the WIPP site. Furthermore, the horizontal displacement along the clay seam was calculated using the elastic beam theory and compared with the deflection measurement from the WIPP site, as well as the results from a computer simulation using FLAC.

### CALCULATION OF DISPLACEMENT ALONG THE CLAY SEAM USING ELASTIC THEORY

The shear displacement between two beams with uniform load can be determined using the elastic beam theory. When two beams have the same thickness and the same elastic properties and each is loaded by gravity, each beam will deflect the same amount without separation. The deflection along the interface between the two beams is given by the equation :

$$\eta = \frac{qx^2}{24EI} (L-x)^2 \quad (1)$$

where,  $x$  is the distance from the abutment,  $L$  is the span of the beam,  $q$  is the uniformly distributed load,  $I$  is moment of inertia, and  $E$  is the Young's Modulus of the bed. The slope of the deflection curve at any point can be determined from the equation :

$$\frac{d\eta}{dx} = \frac{q}{12EI} (2x^3 - 3x^2L + xL^2) \quad (2)$$

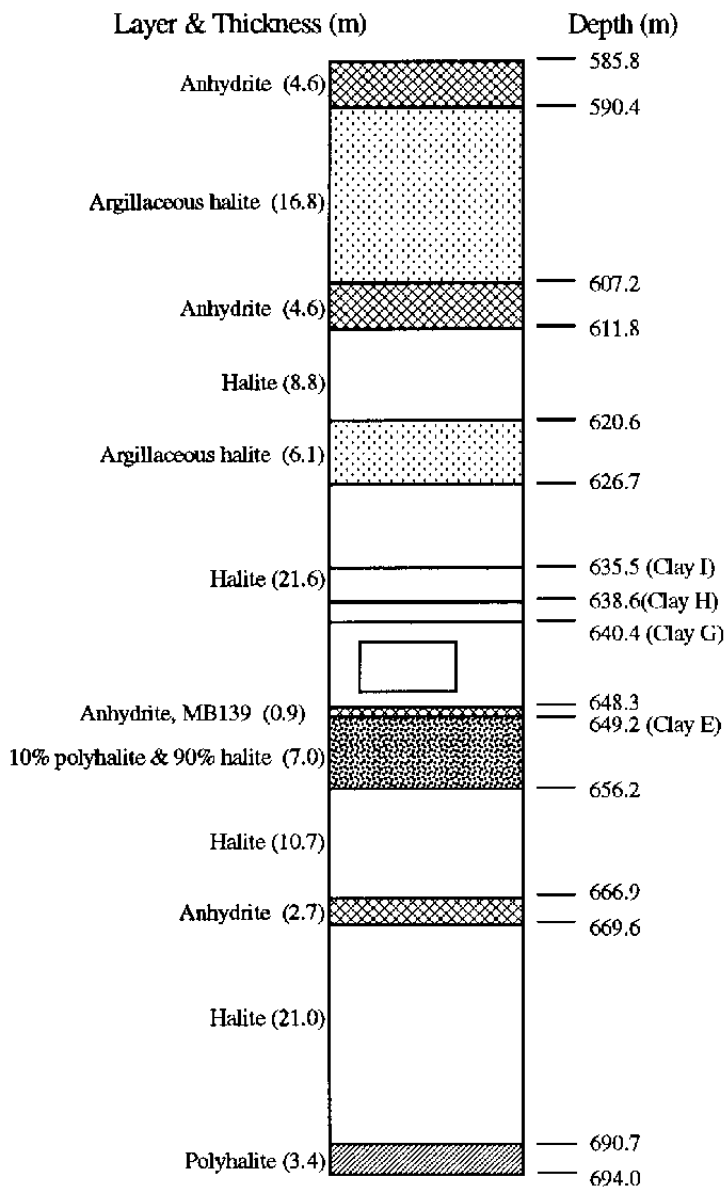


Fig. 1 Geological section at the WIPP site.

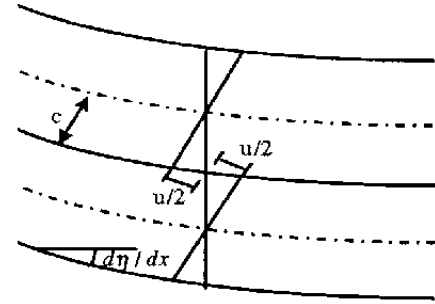
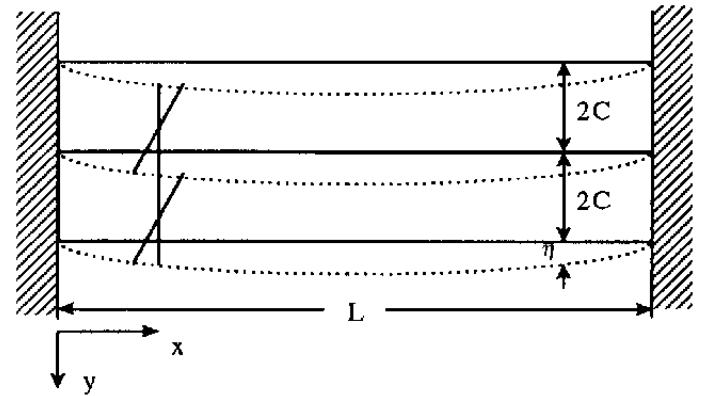


Fig. 2 Bedding plane slip displacement.

From the geometry shown in Figure 2, it can be seen that for small deflections the horizontal displacement at the interface is given by :

$$\frac{u}{2} = c \frac{d\eta}{dx} \quad (3)$$

Thus, the relative slip  $u$  between the beams is :

$$u = \frac{cq}{6EI} (2x^3 - 3x^2L + xL^2) \quad (4)$$

The location of the maximum slip can be determined as  $x=0.21L$  and  $x=0.79L$  by setting  $du/dx=0$ .

The shear strain along the interface between two clamped beams under non-uniform loading was calculated by Stimpson (1983). The load distribution was assumed to be described by the following relationship :

$$q = q_0 + bx(1-x) \quad (5)$$

where  $q_0$  is the load at  $x=0$  and  $b$  is constant. With this loading condition, the deflection along the beam is given by :

$$\eta = \frac{L}{EI} \left( \frac{q_0 x^3}{6} - \frac{bx^5}{60} + \frac{bx^4 L}{24} + \frac{Ax^2}{2} + Bx \right) \quad (6)$$

From this equation, the slip displacement can be determined by differentiation and shows that the maximum slip takes place at a distance of approximately  $0.21L$ .

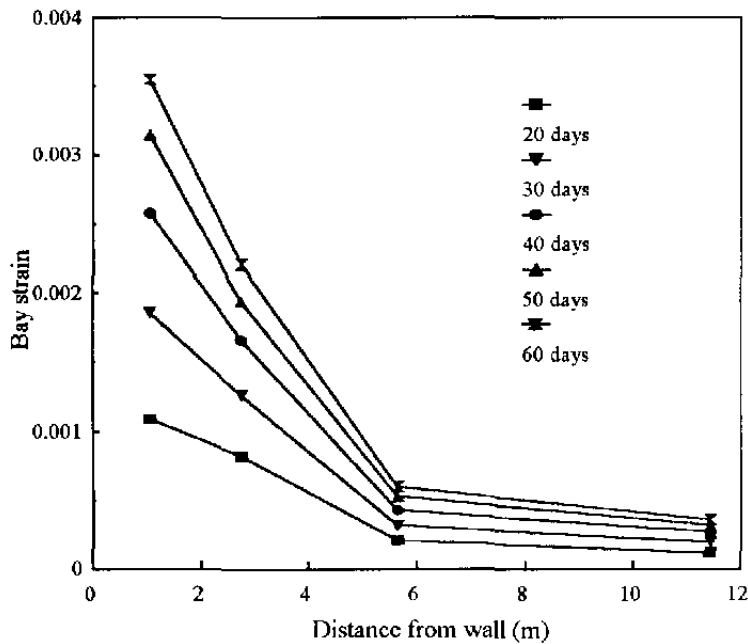


Fig. 3 Bay strain distribution in SPDV Room 1 East rib.

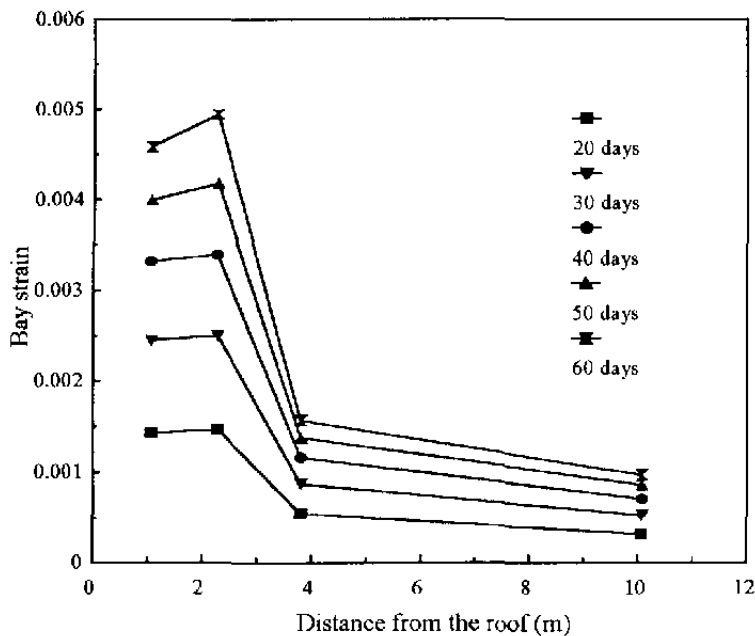


Fig. 4 Bay strain distribution in SPDV Room 1 roof.

## SEPARATION ACROSS THE CLAY SEAM

The deformation around an opening excavated in a rock mass is mainly due to the deviatoric stress developed after excavation. It is usually accepted that the maximum shear stress develops at some distance from the excavation (Obert and Duvall, 1967). Tensile stresses develop inside the shear stress boundary and because the shear stress boundary develops at some distance from the opening, strains in the rock mass around the excavation will increase to a peak value and then decrease to zero with increased distance from the excavation. The boundary of the maximum shear stress value determines the location of the peak strain, and similar results can be achieved from computer simulation with assumptions of homogeneous, isotropic, rock properties. In a salt or potash mine, the rock closest to the opening surface experiences greater fracturing due to the tensile stress, because of the extremely low tensile strength of salt. Due to this fracturing, the rock near the opening surface usually shows high strain. For instance, all the rib extensometers installed in a salt layer showed a similar strain distribution pattern as shown in Figure 3 (Kwon, 1996).

Because of the complex influence of a separation layer on the stress distribution around an opening, an evaluation of the exact influence of the separation layer on the deformational behavior of the rock strata, is very difficult. In order to estimate separation across a clay seam in the roof and floor, it was necessary to assume that the general trend of the strain distribution in the roof without separation layers is the same as that in the rib. When there is a layer that allows separation in the roof or floor, the strain distribution is different due to the layer. Since the difference in strain distribution might be due to the extra displacement over the bay in which a clay seam is located, then the plot of bay strain with distance from the excavation will show a peak in the bay containing a clay seam. Figure 4 shows a typical strain distribution pattern in the roof when there is a separating layer. With the assumption of similar patterns of strain distribution in the roof and rib, it is possible to estimate the separation at a clay seam by comparing the measured strain distribution with the assumed strain distribution without separation. Figure 5 shows how to calculate the separation from the strain-distance relationship in the roof. To simplify the calculation, the bay strains are perceived as decreasing linearly from Collar-A to B-C, if there is no separation layer. Then the separation across the clay seam located between the anchor A and B can be represented by the shaded area in Figure 5. From the relationship between the bay strains of Collar-A and B-C, the equation of the dotted line can be obtained. Using this equation, it is possible to find the bay strain at the location of the clay seam.

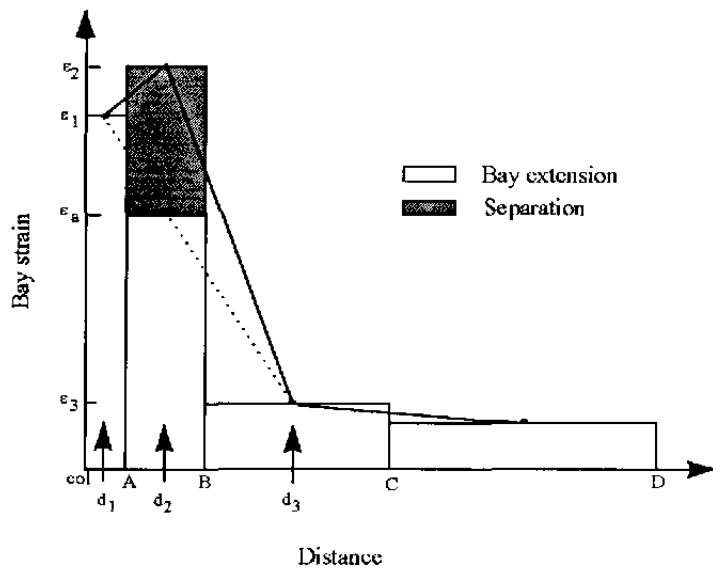


Fig. 5 Calculation of the separation of the clay seam between the anchors A and B.

$$\varepsilon_a = \varepsilon_1 - \frac{d_2 - d_1}{d_3 - d_1} (\varepsilon_1 - \varepsilon_3) \quad (7)$$

where,  $d_1$ ,  $d_2$ , and  $d_3$  are distances from the roof, and  $\varepsilon_1$ ,  $\varepsilon_2$ , and  $\varepsilon_3$  are the bay strains measured between each anchor. From the difference between  $\varepsilon_a$  and the measured bay strain,  $\varepsilon_1$ , the separation effect can be calculated.

$$S = (B - A)(\varepsilon_2 - \varepsilon_a) \quad (8)$$

where,  $B - A$  is the distance between the anchors A and B. From Equation (7) and Equation (8), the separation across a clay seam can be estimated.

$$S = (B - A)\varepsilon_2 - (B - A) \left[ \varepsilon_1 - \left( \frac{\varepsilon_1 - \varepsilon_3}{d_3 - d_1} \right) (d_2 - d_1) \right] \quad (9)$$

### Case study

The equation described in the previous section was applied to several locations at WIPP to calculate the separation across the clay seams in the roof and floor. Figure 4 is a plot showing the strain-distance relationship in SPDV Room 1 roof. The influence of Clay 'G' is detectable even in the early stages. The bay strain between the anchors A and B is higher than the other strains due to movement at the clay seam, even at 20 days after excavation. Separation of the roof center in Room 1 and Room 2 was calculated and is

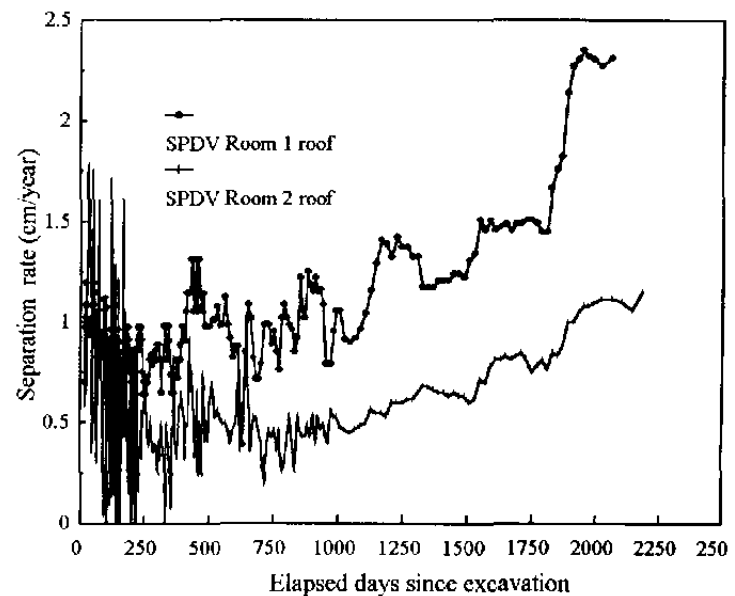


Fig. 6 Calculated separation rates in SPDV Room 1 and Room 2.

Table 1. Calculated separation in SPDV Room 1 and 2

Elapsed days	Room 1 (cm)	Room 2 (cm)
20	0.04	0.03
100	0.26	0.23
500	1.26	0.77
1000	2.57	1.43
2000	6.63	3.42

shown in Table 1. The separation in Room 1 is always higher than that in Room 2 and the difference between them becomes greater with time. In Room 1, the calculated separation at Clay 'G' is about 6.6 cm at 2000 days after excavation, while it is 3.4 cm in Room 2. Possible causes for the greater separation in Room 1 compared to Room 2 are differences in geology and the influence of adjacent excavations due to the excavation sequence of the Rooms. The separation of Clay 'G' in the roof was measured in Room 1 and was found to be about 5 cm in 1988. The calculated separation went from 5 cm to 6.4 cm during that time period. From the calculated separation, the separation rates were calculated and plotted as shown in Figure 6. In both rooms the relatively high separation rates in the early stages showed a decrease with time. About two years after excavation the separation rate started to accelerate. Room 1 always showed a higher separation rate than Room 2 and the difference increased with time. At 2000 days after excavation, the separation rate of Room 1 was approximately 2.3 cm/year, while it was 1.1 cm/year in Room 2. This bed separation in Room 1 may be a major reason for

the roof collapse that occurred in Room 1 three years earlier than a similar failure in Room 2. The influence of temperature on the separation rate also seems to be significant. The separation rates in both rooms varied over a period of exactly 1 year. Normally, the separation rates were high around September and low around February. This result suggests that the seasonal temperature variation has more influence in the bay which includes the clay seam than in the bay in the immediate roof layer. More study is required to confirm or otherwise the influence of the temperature on the separation rate.

#### DEFLECTION MEASUREMENTS FROM THE WIPP SITE

Field measurements are important in understanding the deformational behavior of underground excavations, since they reflect all of the governing factors such as opening geometry, in situ stress, temperature, rock properties, geology, and extraction ratio. Careful investigation of field measurements will identify the influence of each parameter on the deformational behavior of the opening. The inclinometer, one in situ deformation measurement instrument, can provide information on rock displacements in a direction perpendicular to the longitudinal axis of the borehole. In the SPDV Rooms, inclinometer measurements have been taken in vertical boreholes up to 15 m deep into the roof and floor (U.S.DOE, 1989). Figure 7 shows the deflection measurement from the inclinometer which is installed in the roof close to the abutment. Because of the influence of the clay seams in the roof, there are sudden changes on the deflection plots. From Figure 7, the slip deformation along each clay seam could be calculated and plotted in Figure 8. The slip displacement along Clay 'G' which is located about 2 m above the roof was significantly high compared to the slip along other clay seams. About 600 days after excavation, the slip along Clay 'G' was estimated to be more than 3 cm.

#### FLAC SIMULATION

##### FLAC simulation

In this study, a two-dimensional finite difference simulation program, FLAC (Fast Lagrangian Analysis of Continua) was used to model the SPDV area at WIPP. The WIPP reference behavior model was used for pure halite and argillaceous halite, and the Mohr-Coulomb model was used for anhydrite and polyhalite. The properties used for clay seams are listed in Table 2. The clay seams were modeled with interfaces which allow separation and slip along them. 179 x 129 elements were used to simulate an area 1040 m wide and 200 m high.

Table 2. Properties of the clay seams

Properties	Value
Normal stiffness (Pa)	1e12
Shear stiffness (Pa)	5e10
Friction angle (degree)	5
Cohesion (Pa)	0

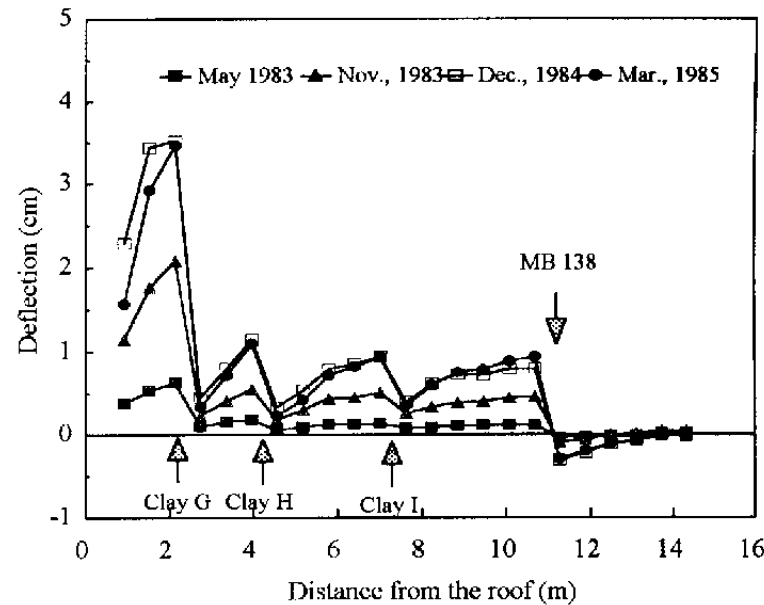


Fig. 7 Deflection measurements from the inclinometer in the SPDV Room 1 Roof West.

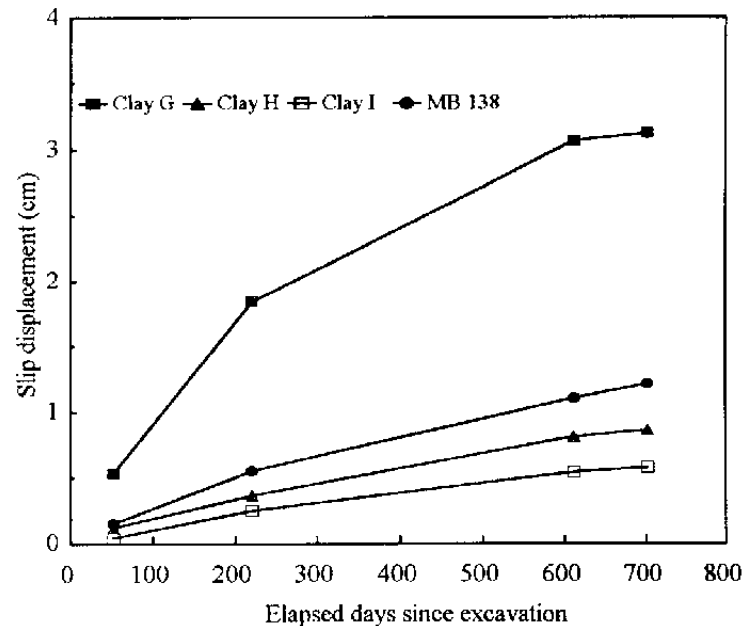


Fig. 8 Horizontal slip along the clay seams in the SPDV Room 1 roof.

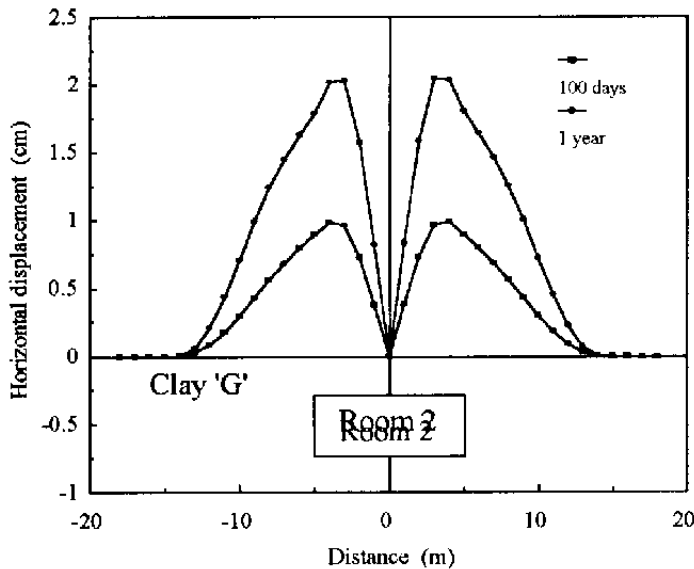


Fig. 9 Horizontal displacement along Clay 'G' from the FLAC simulation.

The constitutive equation for the WIPP site, the WIPP reference creep law, can be written as

$$\dot{\varepsilon} = D(\sigma_{eff})^n \exp\left(-\frac{Q}{RT}\right) \quad (10)$$

where,  $\dot{\varepsilon}$  is the secondary creep rate, R is the universal gas constant, Q is the activation energy, T is temperature, D and n are material constants, and  $\sigma_{eff}$  is the effective stress.

#### Horizontal slip from the simulation

The horizontal slip along Clay 'G' above SPDV Room 2, which is 10 m wide, was calculated and is plotted in Figure 9. The maximum slip 100 days after excavation was about 1 cm. Slip deformation increased continuously to the location of maximum slip (about 2 m from the pillar) and then decreased almost linearly to zero at the center of the opening. The behavior of horizontal displacement along Clay 'G' can explain the roof bolt failures in the roof in Panel 1 Rooms. The rock bolts installed near the side walls were broken more frequently than those close to the opening center. This corresponds to the pattern of horizontal displacement along the clay seam in Figure 9. Figure 10 shows an increase in the horizontal displacement with respect to time, at different distances from the opening center. The horizontal displacement was always highest at 2 m from the abutment. This matches the expected location of the maximum slip displacement from elastic beam theory. As commented earlier, the point of maximum slip was located about 2.1 x the span from the abutment. Figure 11 shows a comparison

between the prediction of the slip displacement along Clay 'G' above the rib line ( $x=0$ ), using the FLAC simulation and the actual measurement using an inclinometer. Even though the calculated slip from the deflection plot is normally higher than the prediction from the FLAC simulation, the simulation could predict precisely the slip velocity, especially in the steady state creep stage. The measured slip velocity from 220 days to 700 days was about 0.97 cm/year, while the FLAC analysis predicted the slip velocity as 1 cm/year during that time period.

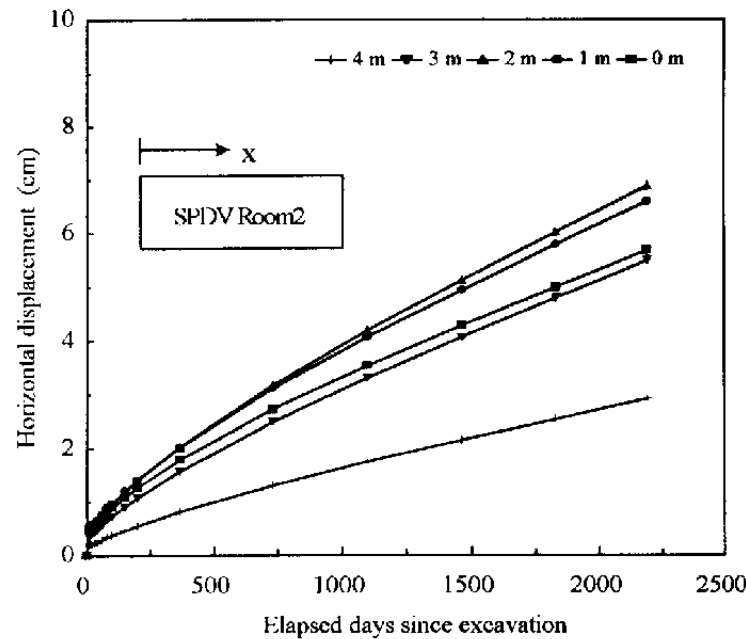


Fig. 10 Variation of the horizontal displacement along Clay 'G'.

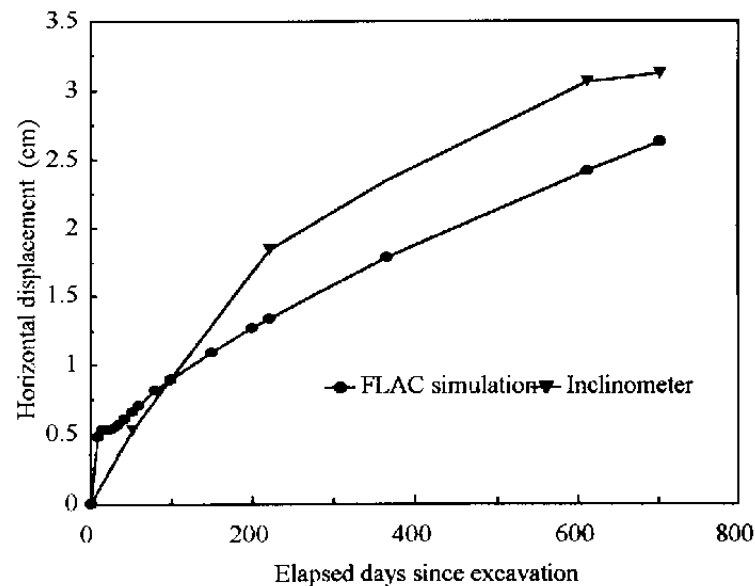


Fig. 11 Slip displacements along Clay 'G' above the rib line from the FLAC simulation and inclinometer.

## CONCLUSIONS

The deformational behavior around an excavation in rock salt and potash mines is significantly influenced by the existence of the clay seams in the roof and floor, since they allow bed separation as well as slip displacement. In order to study the influence of clay seams, deformation measurements from the WIPP site were analyzed and FLAC simulation was carried out. Also, the results from the FLAC simulation was compared with an elastic beam theory analysis, and from this study the following conclusions were drawn:

1. Equation (9) was developed to calculate the separation and separation rate in the roof and floor and applied to the sites at WIPP. Even though several assumptions were made to simplify the calculation, the separation effect of a clay seam was determined continuously from the extension measurements. Since the calculation was based on actual measurements and the separation effect is directly related to the opening stability, the calculated separation in the roof can be used effectively to evaluate opening stability.

2. As shown in Figure 4, the influence of the clay seams in the roof on the strain distribution is evident, even in the early stages after excavation.

3. The separation across Clay 'G' in the roof was much higher in SPDV Room 1 than in SPDV Room 2. In Room 1, the separation was calculated as 6.6 cm at 2000 days after excavation, while it was 3.4 cm in Room 2. This may be the main reason why the roof fall in Room 1 occurred three years before that in Room 2.

4. Clay 'H' showed a much lower separation than Clay 'G'. Thus the deformation at Clay 'H' does not appear to be important from the opening stability point of view. The lower separation at Clay 'H' could be explained by the difference in the beam thickness, horizontal displacement of the ribs, and fracturing in the immediate roof beam which reduces the stiffness of the beam.

5. The effect of temperature on the deformational behavior of Clay 'G' was found to be significant. The separation rates follow the trend of seasonal temperature variations and the separation rates were found to be normally high around September and low around February.

f. Using FLAC simulation, the horizontal displacement along Clay 'G' was calculated. The maximum slip deformation along the clay seam was located about 2 m from the abutment. This was almost the same location as the point of maximum slip displacement determined from the elastic beam theory. The higher horizontal displacement close to the rib can explain the more frequent failure of the rock bolts installed close to the side walls. The FLAC simulation could accurately predict the slip velocity in the secondary creep stage, as shown in Figure 11.

g. The calculated separation rate and the measured slip displacement along the clay seam can be used in the design of a roof support system, which must consider the slip and

separation of the clay seams in the roof as important parameters. In this study, the maximum separation was calculated to be about 6.6 cm at about 2000 days after excavation in SPDV Room 1 roof, and the slip displacement was measured as much as 3 cm at about 600 days after excavation.

## REFERENCES

- Baar, C.A. [1974]. "Discussion." *Int. J. Rock Mech. Min. Sci. & Geomech. Abstr.* 11, 291-293.
- Goodman, R.E. [1980]. "*Introduction to rock mechanics.*" John Wiley & Sons, New York.
- Kwon, S. [1996]. "*An Investigation of the deformation of underground excavations in salt and potash mines.*", Ph.D. thesis, Univ. of Missouri-Rolla.
- Obert, L. and Duvall, W.I. [1967]. "*Rock mechanics and the design of structures in rock.*" John Wiley & Sons, Inc., New York.
- Saeb, S., Francke, C.T., and Patchet, S.J. [1995]. "Effect of clay seams on the performance of WIPP excavations." *Mechanics of Jointed and Faulted Rock*, Vienna, 835-840.
- Stimpson, B. [1983]. "The influence of rock bolt location on the reinforcement of horizontally bedded roof by full column grouted bolts." *Proc. of the International symp. on Rock Bolting*, Abisko, 195-204.
- U.S.DOE [1989]. "*Geotechnical field data and analysis report, June 1987 - June 1988.*" DOE/WIPP 89-009.