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In-situ Measurements of Time-dependent Rock Deformations at the Waste Isolation Pilot Plant in USA

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미국 Waste Isolation Pilot Plant에서의 시간변형 거동 계측

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ABSTRACT Systematic measurements in the field are the key component in the design process to ensure that optimal and safe designs result. The instruments installed at the Waste Isolation Pilot Plant, a underground nuclear waste repository in U.S., for measuring rock deformation was reviewed. Also discussions about installation and measurement for better understanding the complex time-dependent deformational behavior of underground excavation were made .

Key words : In-situ deformation, WIPP, Nuclear waste repository, rock salt, creep

초 록 현장에서의 체계적인 측정자료는 최적의 안전한 설계를 위한 중요한 정보라 할 수 있다. 본 연구에서는 미국의 방사성폐기물 저장 시설인 Waste Isolation Pilot Plant(WIPP)에서 수행된 현장 측정 기법들에 대해 고찰하였다. 또한 지하구조물의 시간 의존적인 복잡한 거동을 이해하기 위해서 필요한 측정기기의 설치와 측정에 대하여 논의하였다.

핵심어 : 현장변위, WIPP, 방사성 폐기물 처분장, 암염, creep

1. Introduction

Monitoring provides an economic means for reducing the risk of failure in underground construction and it constitutes an essential component of modern rock engineering. Systematic measurements in the field and computational methods have been introduced as powerful design aids in order to arrive at safe and economical structures. Because of the reasons, field measurements are now recognized worldwide as an indispensable aid for correct decision making in tunneling.

Among field measurements, deformation and stress are considered as the key parameters for defining the performance of an underground excavation in rock mass. The measurement of stress around an underground excavation in time-dependent rock mass has been difficult and techniques and results have often been controversial (Munson et al., 1990). In many cases, the measured stresses are not reliable for defining the stress distribution, for the following reasons: (a) the pressure measured by the instruments represents the local stress over a small area; (b) the measurement is usually made close to the opening surface where the stress distribution is significantly affected by the adjacent excavation (Eriksson and Michalski, 1986). In contrast, deformation measurements are usually considered as the principal information for understanding the behavior of underground excavations in rock mass. There are two main reasons why displacement measurements in underground excavations have proven to be the most useful. Firstly, displacement is a quantity which can be measured directly and monitored continuously. Secondly, displacement measurements provide information on overall movement of the rock mass within the measured distance and thus do not display a large variability (Bieniawski, 1984).

Generally, rock formation is assumed as an elastic body for theoretical analysis in rock mechanics. However, progressive failure or yield is frequently observed around underground excavations. The progressive failure would

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play an important role in the time-dependent pressure phenomena of the excavation. Martin (1989) reported significant time-dependent deformation at a shaft located at 353 m deep in granite. It is, therefore, expected that the underground excavations in deep deposit deform time-dependently, even though it is located in hard crystalline rock.

In this study, the instruments installed at the Waste Isolation Pilot Plant (WIPP), an underground facility for the permanent disposal of nuclear waste material, for recording the time-dependent deformation of the underground excavations were reviewed and suggestions were made for better understanding the complex deformational behavior of underground excavations.

2. Brief review of WIPP

The Waste Isolation Pilot Plant (WIPP) is a research and development facility authorized to demonstrate the safe disposal of Transuranic (TRU) radioactive waste arising from the defense activities of the Unite States. The WIPP is being developed by the Department of Energy (DOE) and is located in southern eastern New Mexico in a bedded salt formation at a depth if about 650 m below the surface.

The underground construction at WIPP was divided into 3 areas: (1) the Site and Preliminary Design Validation (SPDV) area; (2) the Experimental Area, requiring the construction and fielding of several large research and the expansion of the shaft system; and (3) the TRU Waste Storage Area, requiring construction for the operation of a waste disposal panel to demonstrate emplacement and retrievability of the waste, and if it is shown to be acceptable, to store radioactive contact-handled (CH) and remote-handled (RH) waste. The waste storage area will be made up of eight panels consisting of seven rooms each where each room is approximately 4 m high, 10 m wide, and 100 m long. The dimensions of the storage rooms were determined by calculations based on laboratory derived average creep parameters to satisfy the design criteria, with a vertical closure of 30 cm and a horizontal closure of 23 cm in 5 years. The four rooms in the SPDV area have similar configurations to the rooms in the waste storage area. The drift configuration ranges from 2.4 m to 4.3 m high and 3.7 m to 7.6 m wide.

There are four vertical shafts, salt handling shaft, air intake shaft, exhaust shaft and waste handling shaft. The salt handling shaft provides the principal means of access and also serves as the air intake opening. The air intake shaft and exhaust shaft are the primary channels for air intake and exhaust from the underground facility.

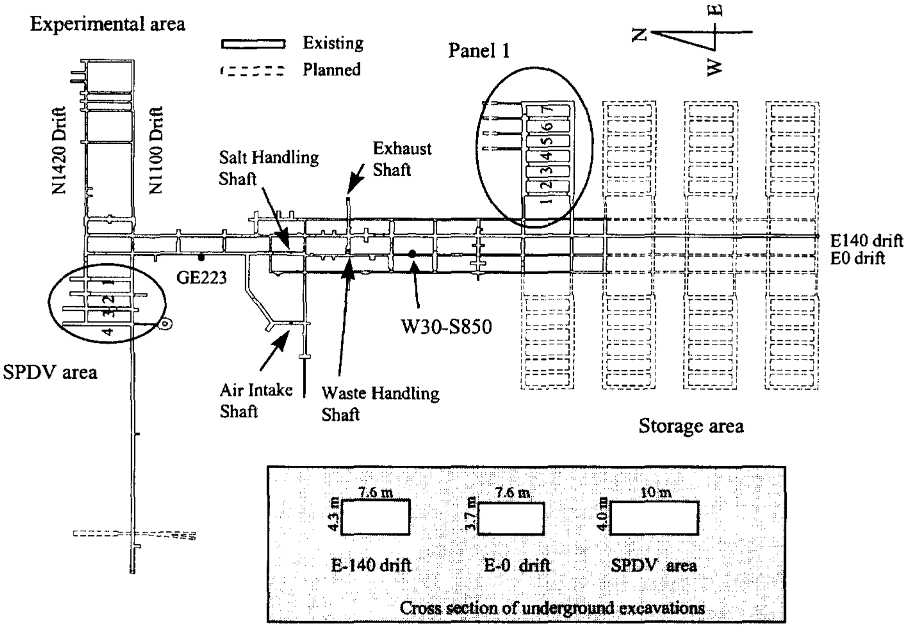

Fig. 1. Underground layout of the WIPP facility.

The waste shaft is designed to permit the transport of radioactive waste between the surface waste-handling facilities and the underground storage area. Fig. 1 shows the schematic layout of underground facilities and cross section of drifts and SPDV Rooms at the WIPP site.

After construction, instruments extensometers, closure meters, and inclinometers were installed systematically and measured deformation of the excavations. The first reading date was close to the excavation date and the rapid deformation immediately after the excavation was probably recorded.

The facility horizon lies within an evaporite sequence consisting of halite, argillaceous halite, and polyhalite. Anhydrite 'b', 6.4 cm thick, lies about 2 m above the roof and is underlain by Clay 'G'. Anhydrite 'a', about 20 cm thick, is about 4 m above the roof and underlain by Clay 'H'. A persistent 0.5 to 0.8 m thick bed of anhydrite and polyhalite, identified as MB 139, lies about 1.5 m below the opening floor. Compared to the surrounding halite, MB 139 is a stiff and brittle layer that does not deform plastically with time (U.S.DOE, 1993). The bottom of MB 139 is subhorizontal and underlain by Clay 'E'. A diffused clay, Clay 'F', is exposed in the ribs just below the roof. Fig. 2 shows the stratigraphy in the WIPP site.

3. Deformational Behavior of Rock Salt

3.1 Creep deformation

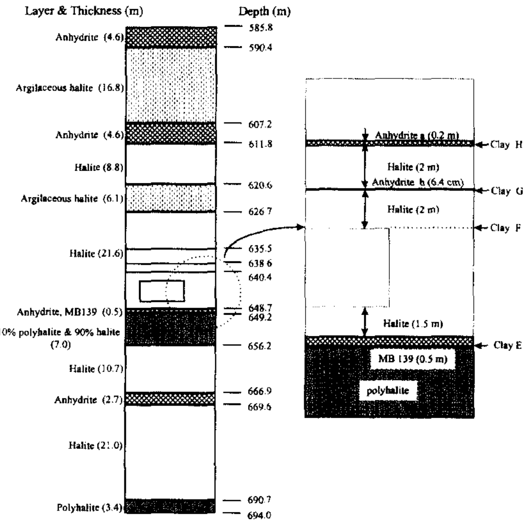

Fig. 2. Geological section at the WIPP site.

Rock salt, halite (NaCl), is isometric crystal having several slip-systems which allow easy slippage. Time-dependent deformation occurs along the slip planes when the stress state reaches a given limit (Pusch, 1993). Because of this, rock salt is usually considered as elasto-plastic material which deforms as an elastic material if the stress state is below this point. Limit of elasticity, or yield limit is used to define this limit, and time-dependent deformation beyond this limit is usually called creep. Creep strain cannot be recovered fully when loads are removed, since it is largely plastic deformation. Description of the deformational behavior of rock salt in the laboratory or in-situ is very difficult, because of the complex time-dependent properties of rock salt.

Generally, the time-dependent deformation curves measured from laboratory tests at constant stress consist of four stages, namely: (1) an elastic deformation stage, (2) a transient or primary creep stage, (3) a steady state or secondary creep stage, and (4) a tertiary creep stage. Fig. 3 shows a typical creep curve whose elastic deformation occurs immediately after the application or reduction of a load. In laboratory tests, the elastic deformation can be measured, however, the elastic deformation in situ cannot be directly measured, since it occurs before the installation of instruments and thus needs to be estimated using a computer simulation. Primary creep follows the elastic deformation. In the primary creep stage, a high deformation rate decreases exponentially with time mainly due to the development of a strain hardening effect. The secondary creep stage is characterized by a constant or near constant creep rate over a relatively long time period. During the tertiary

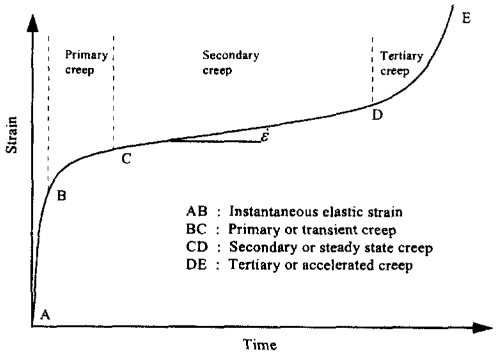

Fig. 3. Typical creep curve

creep stage, the strain rate rapidly accelerates toward rupture. Acceleration of creep is caused by fabric damage related to the growth and coalescence of microcracks (Dusseault and Fordham, 1993). The following equation describes the general creep behavior of rock salt under a constant stress condition.

$$\varepsilon=\varepsilon_e+\varepsilon(t)+At+\varepsilon_T(t) \tag{1}$$

where, ε is total strain, ε_e is elastic strain, $\varepsilon(t)$ is time-dependent function for expressing primary creep, At is a linear function representing secondary creep, and $\varepsilon_T(t)$ is the strain during the tertiary creep stage.

Even though the above equation is based on sample tests in laboratory, it can be used to describe the deformational behavior of an opening. Prediction of in-situ creep, however, is not as easy as that for laboratory tests, because the deformation and deformation rate of the rock mass around an excavation, as well as the duration of each stage, are significantly affected by many conditional factors. Important factors that must be considered are the rock properties; stress state; temperature; opening and pillar dimensions; moisture content and humidity; excavation sequence; proximity of adjacent excavations; impurities; and geology.

3.2 Physical and mechanical properties of rock salt

Over recent decades, the physical and mechanical properties of rock salt have been studied extensively because rock salt is being considered as the host rock for an underground nuclear waste repository. Natural salt deposits are usually considered as the best host rock for permanent disposal of nuclear waste, because of their unique properties and conditions. The following comments summarize important physical and mechanical properties of rock salt.

1. Ductile deformation: Rock salt is ductile even under a small deviatoric stress and at low temperature, because of its fairly low creep limits when compared to other rocks (Baar, 1977). Due to the ductile deformation, excavations in rock salt are usually considered to deform gradually without serious structural damage or fractures (Baar, 1977). Because of the ductile deformation of rock salt, any local stress difference is not allowed and thus hydrostatic stress conditions are generally assumed in rock salt.

2. High dependency on stress and temperature: Laboratory and field observations indicate that the deformational behavior of rock salt is highly dependent on stress and temperature (De Vries, 1988; and Senseny et al., 1992).

3. High heat conductivity and diffusivity: Rock salt has a high thermal conductivity and diffusivity compared to other crystalline and argillaceous rocks (Krieg, 1984).

4. Influence of discontinuities and impurities: In the case of rock salt interbedded with different evaporates, the impurities influence significantly on the deformational behavior of the underground openings in rock salt.

5. Influence of brine: Though rock salt is generally considered essentially dry, all rock salt contains a certain amount of water in the form of a concentrated brine. The deformation rate is significantly increased with increasing moisture content (Senseny et al., 1992).

6. Low strength : It is usually accepted that rock salt has a relatively low compressive strength (20~40 MPa) and an extremely low tensile (1~2 MPa) and shear strength compared to other rocks.

7. Site independent elastic modulus: Hansen et al. (1981) reported that the elastic moduli of rock salt are almost site independent, while the strengths vary for rock samples from different sites. According to their study, Youngs modulus is around 30 GPa and Poissons ratio is around 0.35.

8. Low permeability: The very low permeability of rock salt is its principal advantage as a medium for hydrocarbon storage and for use as a waste repository. According to the in situ permeability tests, the permeability of the WIPP salt is less than 5×10^{-8} darcy (Sutherland and Cave, 1980).

9. History dependent deformation: The deformational behavior, including rock damage and failure of rock salt, is dependent on the load and strain history.

4. In-situ Deformation Measurements

Various systems of measurement were used to monitor the performance of the underground excavations. Instrument installed for measuring the geomechanical response of the shafts and other underground openings include closure points, closure meters, borehole extensometers, rock bolt load cells, pressure cells, stress meters,

Table 1. Specification of the geomechanical instruments installed at WIPP (U.S.DOE, 1992)

Instrument type	Range	Precision	Measured parameter	Measuring method
Borehole extensometer	0-2 in	+/- 0.001 in	Deformation	Sonic probe
Closure points	2-50 ft	+/- 0.001 in	Deformation	Tape extensometer
Closure meters				
Sonic	0-2.5 ft	+/- 0.001 in	Deformation	Sonic probe
Wire	0-3 ft	+/- 0.004 in	Deformation	Rotary potentiometer
Inclinometers	0-30°	+/- 0.001 in/ft	Deflection	Accelerometer
Stressmeter	10000 psi	+/- 15 psi	Stress	Vibrating wire
Rockbolt load cell	0-300 kips	+/- 40 lbs	Load	Strain gage
Earth pressure cells	0-1000psi	+/- 0.5 psi	Lithostatic pressure	Vibrating wire
Piezometers	0-500 psi	+/- 0.5 psi	Fluid pressure	Vibrating wire
Strain gages	0-3000 uin/in	+/- 1 uin/in	Cumulative strain	Vibrating wire

strain gages, inclinometers, and piezometers. Closure points and extensometers are the main instruments for deformation measurements at WIPP. Rock bolt load cells are used to determine the ground loading and the effectiveness of rock bolts. Load, in kips, versus time can be plotted from the measurements. Earth pressure cells, stress meters, and strain gages are used in and around the shaft liners to determine their loads. Table 1 lists the specification of the geomechanical instruments installed at the WIPP underground facility. The total number of each instrument type installed at WIPP area is listed in Table 2. As shown in Table 2, bundle of instruments were installed in SPDV area. In the SPDV Room 2, 6 multi-point extensometers, 7 inclinometers, 4 closure points and 1 closure meter were installed at the center of the room. Fig. 4 shows the instrumentation for measuring deformational behavior in SPDV Room 2.

Table 2. Total number of measuring instruments installed at WIPP

	Shafts	Shaft stations	Access drifts	SPDV area	Panel 1 area
Extensometer	27	19	39	22	16
Closure points	14	65	368	144	283
Closure meter					
Sonic				2	5
Wire				16	
Inclinometers				22	
Stressmeter				4	
Rockbolt load cell		12			
Earth pressure cells	12				
Piezometers	45				
Strain gages	40				

4.1 Extensometer

Extensometers are one of the most commonly used instruments in deformation monitoring program. Extensometers measure the relative displacement between the collar of the emplacement hole and the multiple anchors placed at several depths in the hole over the range of deformation allowed by the instrument. Borehole extensometers are used to determine the absolute movement of the ground around the opening. With this instrument, stainless steel measuring rods are placed down a hole and anchored at various depths. The deepest anchor is assumed to be fixed in undisturbed ground.

Stainless steel measuring rod is affixed to each anchor

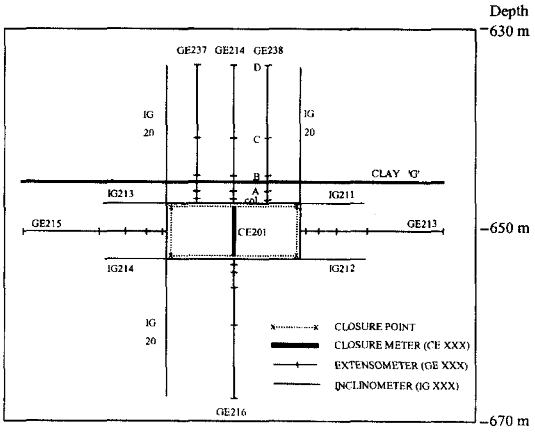

Fig. 4. Instrumentation in SPDV Room 2.

and runs from the anchor to the mouth of 7.6 cm (3 in) diameter borehole. At the WIPP site, the deepest anchor is normally located about 15 m from the opening, even though there is no natural limit on anchor depth. Normally five anchor stations were installed in a borehole and the relative displacement of each anchor from the deepest anchor was measured automatically. Sonic probe readout system was used to measure the distance between magnets in the connecting rods and a magnet in the measurement rod. The resolution of the extensometers used at WIPP is about +/- 0.0025 cm. For remote readout, the probe is left locked to the anchor and a cable is strung to the readout station. In such case, to protect the probe heads, the surface anchor may be recessed roughly 30 cm inside the borehole.

Including extension measurements, field measurements often contain erroneous data for the following reasons: (a) power failure, gage management (replacement), or disconnection of the gage; (b) low resistance shorts to ground because of the collection of moisture; (c) undetected reading error; and (d) computer acquisition error, or electrical scatter (Munson et al., 1990). Furthermore, measurements may not represent the actual deformational behavior of the opening because of other reasons, such as anchor slippage or large relative horizontal movements of the layers in the roof or floor. Fig. 5 shows an example of the original measurements contained erroneous measurements that arose from random error and anchor slippage. Fig. 6 shows the measurements after correction by extrapolation of the deformation rates before and after the anchor slippage.

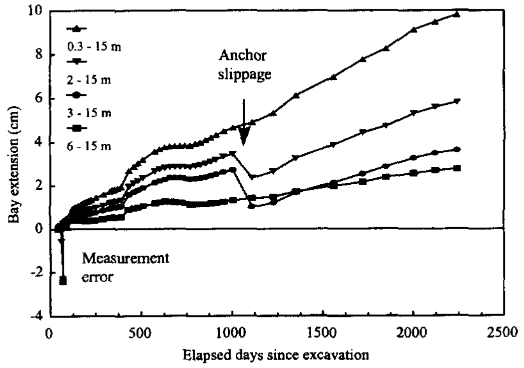

Fig. 5. Measured bay extension from an extensometer before error correction.

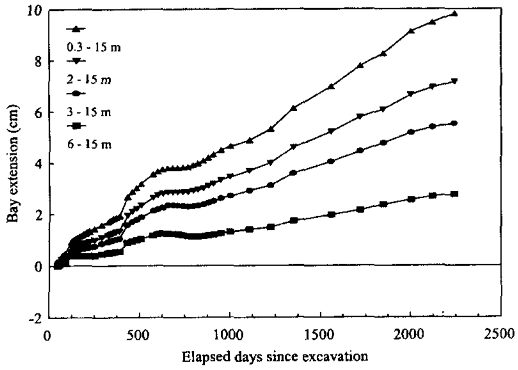

Fig. 6. Measured bay extension from an extensometer after error correction.

Even though the interpretation of extensometer data are complicated due to the following factors such as (a) delays in installing the instrument; (b) instability of electrical instruments over the extended periods of time; and (c) effect of nearby blasting on the anchor points, extension measurements provide important information about the performance of the underground excavation. For example, plots of strain distributions with respect to the distance from an opening is an useful way for understanding the overall deformation mechanism around an opening. Fig. 7 is a typical strain distribution pattern in the roof at WIPP. Due to the separation at the clay 'G' at about 2.5 m above the roof, there is a peak in the zone containing the clay seam. In contrast, extension measurements at rib usually show smooth decrease of strain with distance from opening. Since the strains are calculated from the cumulative extension since excavation, they increase with time. Based on this, Kwon (1996) could develop a technique for determining the separation across the clay seam continuously.

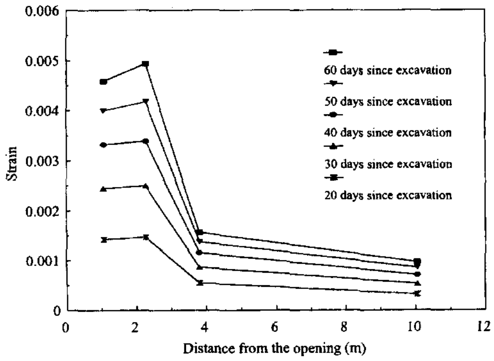

Fig. 7. Strain distribution with time in the roof.

4.2 Closure measurements

Closure measuring device is for measuring the change in distance between two measuring points in short boreholes drilled in opposite excavation walls or the roof and floor. Closure movements provide an excellent indicator of the overall ground response but, as independent observations, seldom contain sufficient information to identify the cause of failure or the failure process. Two types of closure measurement were used at WIPP: (a) closure point; and (b) closure meter.

Closure measurements using closure points are the most common method for recording the deformation of underground excavation. Usually, tape extensometer is used to measure the distance change between tow reference points, which are mounted into drilled holes. Typically the resolution of tape extensometer is +/-0.025 mm for tape length 15 m.

The sonic closure meter operates on the same principle as borehole extenso-meter, except that one end containing the sonic probe and magnet is anchored to the roof, while the other end contains another magnet anchored to the floor. Closure measurement using closure meter is more convenient to automatic recording of closure.

Fig. 8 shows the closure measurement, which is recorded at SPDV Room 1. Similar to the typical creep curve in Figure 3, the deformation curve can be divided into 3 stages, primary creep stage, secondary creep stage, and tertiary creep stage.

As shown in Fig. 8, the tertiary creep stage is quite short and technically it is very difficult to record the tertiary creep. Because of that, it is very difficult to get a creep curve showing the actual full life of an excavation. During the primary creep stage, the deformation is very rapid and the initial deformation rate would reflect the overall performance of excavation design, it is necessary to record the primary creep as accurately as possible. In order to do that, it is highly recommended that instruments should be installed as soon as possible.

Fig. 9 shows the closure rate plot, which is calculated from the closure measurement at SPDV Room 1 (Fig. 8). The SPDV Room 1 roof was collapsed on February 4, 1991 about 8 years after excavation. The vertical closure of SPDV Room 1 had been measured until immediately before the collapse. Compared to the closure measurement, Fig. 9 clearly show the status of excavation stability. Kwon (1996) could predict the roof fall in SPDV Room 2 with reasonable accuracy using the closure rate curves. Also, it is possible to recognize the influence of seasonal temperature variation from closure rate curves, even though the closure plot looks increasing smoothly. Deformation rates are, therefore, useful as a means of understanding the deformation mechanism of underground openings.

There are some other clear advantages of using deformation rate for investigating the deformation mechanism of underground excavations: (a) deformation rates (when comparing two sites) are independent of the installation date of the instruments; (b) deformation rates can clearly show the influence of excavating a subsequent adjacent excavation; (c) influence of temperature can be clearly recognized; and (d) deformation rates are closely related to the stress distribution around the excavation (Kwon, 1996).

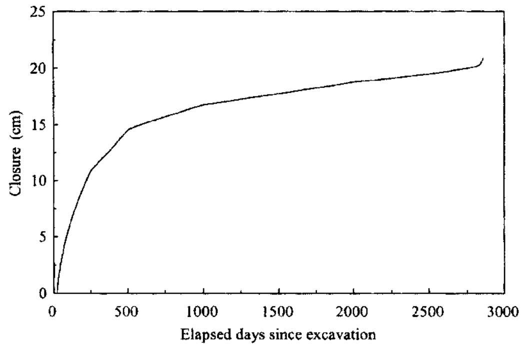

Fig. 8. Vertical closure measurements after the excavation until roof collapse at SPDV Room 1.

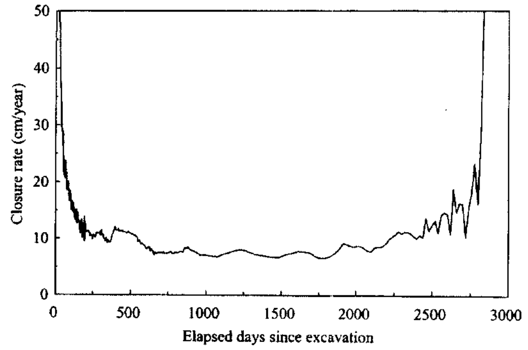

Fig. 9. Closure rate recorded immediately after excavation until roof collapse at the SPDV Room 1.

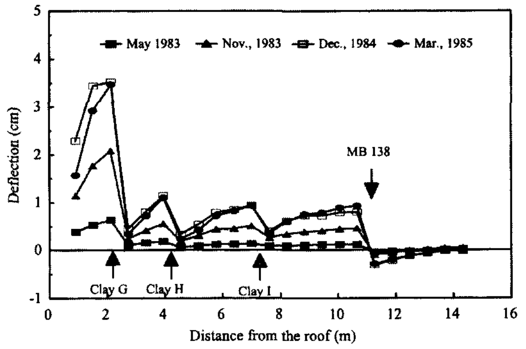

Fig. 10. Deflection measurements from the inclinometer in the SPDV Room 1 Roof West (IG203).

4.3 Inclinometer

Inclinometer data provide information on rock displacements in a direction perpendicular to the longitudinal axis of the borehole. The inclinometer system consists of a permanently installed casing with grooves at the quarter points and a portable probe readout. One pair of grooves is aligned parallel to an expected principle direction of rock displacement. A portable torpedo probe is moved along the borehole and records an inclination at a particular depth, which can then be reduced to displacement perpendicular to the borehole axis.

In the SPDV Rooms at WIPP, inclinometer measurements have been taken in vertical boreholes up to 15 m deep into the roof and floor (U.S.DOE, 1989). Fig. 10 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.

The displacements measured by inclinometers in the SPDV Rooms are plotted together in Fig. 11. The length and direction of the arrow lines represent the amount of the deflection and the movement direction. The deflections were magnified about 120 times compared to the opening width and height. Since the measurements were not carried out systematically, some data are missing on specific dates. In May 1983, about 2 months after Room 2 was excavated, the deflections of Room 1 and Room 2 floors were almost the same. At this time the vertical movement in the Room 2 East rib was higher than the horizontal movements in the roof and floor. From the figure for November 1984, it was concluded that the pillar deformation was almost symmetrical between the upward and downward movements. In 1986, the horizontal displacement of the immediate floor in Room 1 was higher than in Room 2. This suggests that something happened in the Room 1 floor before 1986, and could be a result of floor fracturing. In 1987, the horizontal movement in the roof was greater than the vertical movement of the pillars, especially in the immediate roof layer. This larger horizontal displacement of the immediate roof could have resulted from the separation across the Clay 'G'. The horizontal movements in Room 2 roof East side were much higher than those in the roof west side.

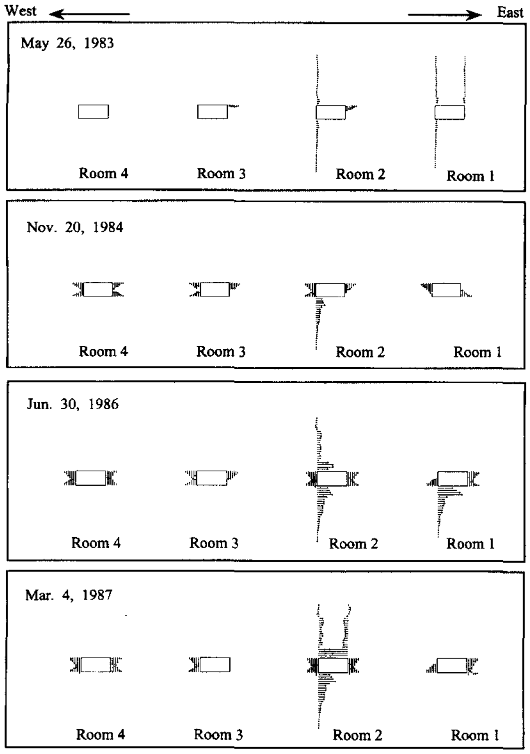

Fig. 11. Deflection measurements in the SPDV area at different measuring times.

5. Discussion and Conclusions

Underground excavation such as high level nuclear waste repository in deep deposit deforms time-dependently and thus in situ time-dependent deformation should be considered as the one of the most important information for assessing the performance of the underground excavations. In this study, the in situ measuring techniques at WIPP was briefly reviewed and the actual deformation measurements were presented. From this the following suggestions were made for better understanding of the deformational mechanism of underground excavation.

1) Use deformation rate. Deformation rates are independent of the entire history of displacment and as shown in Figure 9 the evaluation of opening stability using closure rate curve would be more clear than closure plot. It is therefore useful to use deformation rates, such as closure rate or rock extension rate, instead of cumulative deformation, for understanding the deformational mechanism more precisely.

2) Plot the strain vs. distance relationship. Plots of strain distributions with respect to the distance from an opening is an useful way for understanding the overall deformation mechanism around an opening. For example, the separation over a clay seam could be determined from the plot. More accurate evaluation of opening behavior, including the detection of fracture planes, may be possible with more measuring stations along a borehole and with a smaller distance between anchors.

3) It is recommended that instruments should be installed as soon as possible and thus measure the primary creep deformation in order to monitor the complete deformational behavior of an underground excavation. Measurement of the early stages of deformation is important to investigate the influence of controlling parameters on the deformational behavior of an excavation, since this influence is more significant during the early deformation phase.

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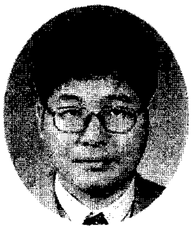

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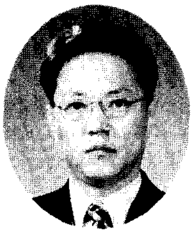

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