Back Analysis of Displacements Measured During Excavation of Underground Storage Caverns

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요 지

이 논문에서는 역순법 원리를 이용한 역해석 결과를 제시하였다. 국내에서 건설된 두 곳의 지하비축기지 공사 중에 계측한 자료를 이용하여 비축기지 진입터널 주위 암반의 변형계수와 초기지압을 계산하였다. 역해석에서 얻어진 결과를 입력자료로 하여 유한요소해석을 수행하였으며 그 결과를 계측치와 비교, 검토하였다.

Abstract

In this paper, the results of back analysis based on the inverse method are presented. Using the field measurements obtained from the two different underground storage caverns in Korea during their construction, the deformation modulus and the initial in-situ stresses of the rock masses around the access tunnels are calculated. The finite element analysis is carried out by using these results as input parameters. The calculated displacements are compared with the measured ones.

Keywords : Back Analysis, Finite Element Method, Displacement Measurement, In-Situ Stresses, Elasticity Modulus.

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1. Introduction

In planning a construction, stability analysis of the underground opening is a fundamental design requirement to ensure structural stability. The common numerical method

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utilized to assess the stability of underground openings is the finite element method. Therefore, the estimation of in-situ stresses prior to excavation and the material properties, which constitute the input parameters for the stability analysis, is very important. The initial stress state of the ground may be determined by various types of in-situ tests including overcoring and hydrofracturing. The deformability of rock mass may be estimated by both field and laboratory tests. But the field tests are usually time-consuming and expensive. And the results reflect only limited part of the ground and cannot be free from size and shape effects.

It is difficult to predict precisely the behaviour of the rock mass in the design stage and there may be a great difference between the field measurements during construction and the results from stability analysis conducted in the design stage. When the support system does not meet the support requirement, the system should be modified optimally according to the measured data obtained during the construction and/or the geological conditions. In this case, a rapid and precise method for evaluating field measurements and feeding them back to the construction process is necessary. One of the most attractive methods which meet this requirement is the back analysis.

More efforts are being made to devise numerical methods that can perform back analysis systematically (Cividini et al., 1981 ; Sakurai & Takeuchi, 1983 : Feng & Lewis, 1987). The inverse method(Sakurai & Takeuchi, 1983), the direct method(Cividini et al., 1981), Bayes' approach(Cividini et al., 1983) and Kalman filter method (Murakami & Hasegawa, 1988) are currently applied to the geotechnical problems. In most back analysis methods, the optimum parameters are obtained by minimizing the sum of the squared differences between computed and observed measurements.

In this paper, the results of back analysis based on the inverse method are presented. Using the data from field measurements at the two different underground storage caverns in Korea, the deformation modulus and the initial in-situ stresses of the rock masses around the access tunnels are calculated. The finite element analysis is conducted by using these results as input parameters. The calculated displacements are compared with the measured ones.

2. Computer Code

In order to determine the initial in-situ stresses and the elastic moduli, a computer code based on the inverse method was built and excuted under the plane strain condition. The data obtained through both convergence meters and extensometers were used as input parameters. The flow chart of the program is shown in Fig.1. In this program, it is assumed that the rock mass is isotropic and linear-elastic and that the initial state of stresses is constant over the region considered. Supporting materials such as shotcrete, lining, and rock bolts are not considered.

The normalized initial stresses $\{\sigma^{\circ}/E\}$, which are the initial stresses divided by the elastic modulus of rock mass E, are obtained as a result of the back analysis. By assuming that the vertical component of the initial stresses σ^{o}_{v} is proportional to the overburden depth h and the unit weight of rock mass γ, the elastic modulus of rock mass is determined by

$$\sigma^{o}_{v} = \gamma \cdot h$$

$$E = \frac{(\gamma \cdot h)}{(\sigma^{o}_{v} / E)}$$

The other two components of the initial stress, namely, shear and horizontal components, are calculated by

$$\sigma^{o}_{x} = E \cdot \left(\frac{\sigma^{o}_{x}}{E}\right)$$

$$\tau^{o}_{xy} = E \cdot \left(\frac{\tau^{o}_{xy}}{E}\right)$$

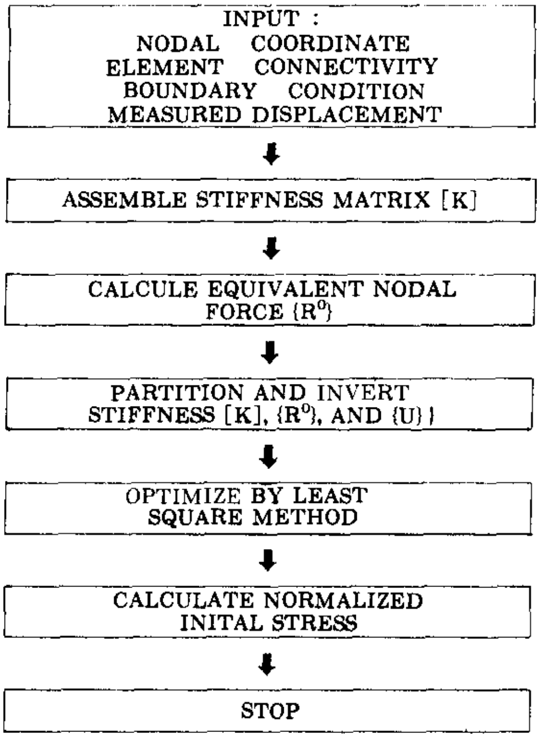

Fig. 1 **Flow chart of back analysis program**

3. Geology

The dominant rock type of the site of Yukong LPG underground storage cavern(Ulsan) is the Cretaceous sandstone. This area shows parallel structure of sandstone strata having different grain sizes. Porphyritic andesite is also shown partially. The joint spacing of this area is 0.2~2.0m. The faces of most joints are smooth and undulating. The tunnel is located at 175m below the ground surface.

In the site of the L-1 LPG underground storage cavern(Asan-man), the Precambrian gneiss is dominant and shows foliation. Four joint sets are observed. Each of the joint sets has the joint spacing of 0.2~2.0m range. Most joints are slightly altered and filled with calcite. The tunnel is located at 200m below the surface.

The laboratory test results for the intact core samples from the above sites of application are shown in Table 1.

Table 1. Laboratory test results

	Yukong cavern	L-1 cavern
Unit weight(KN/m^3)	24.5~27.6	25.6~28.1
Uniaxia strength(MPa)	20~390	140~250
Elastic modulus(GPa)	50~130	30~90
Poisson's ratio	0.17~0.25	0.12~0.30

4. Field Measurements

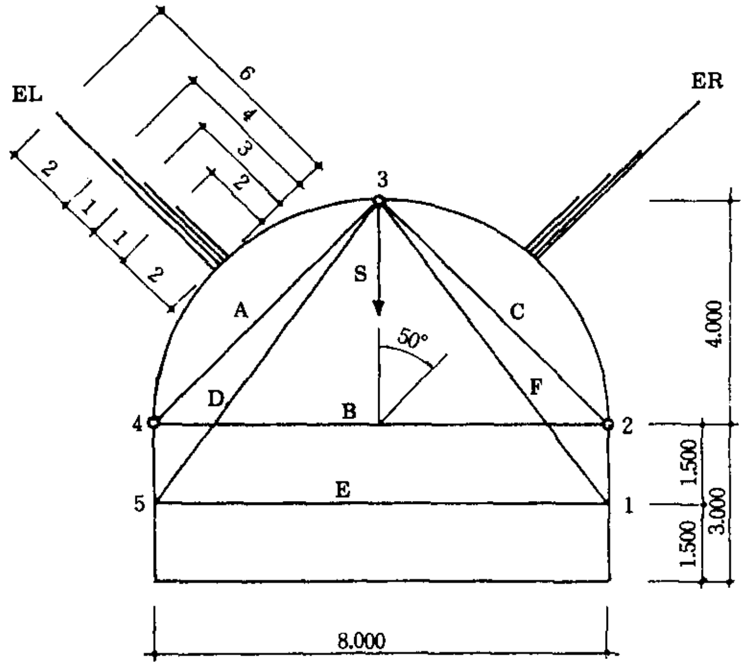

Fig. 2 **Monitoring section in Yukong storage caverns**

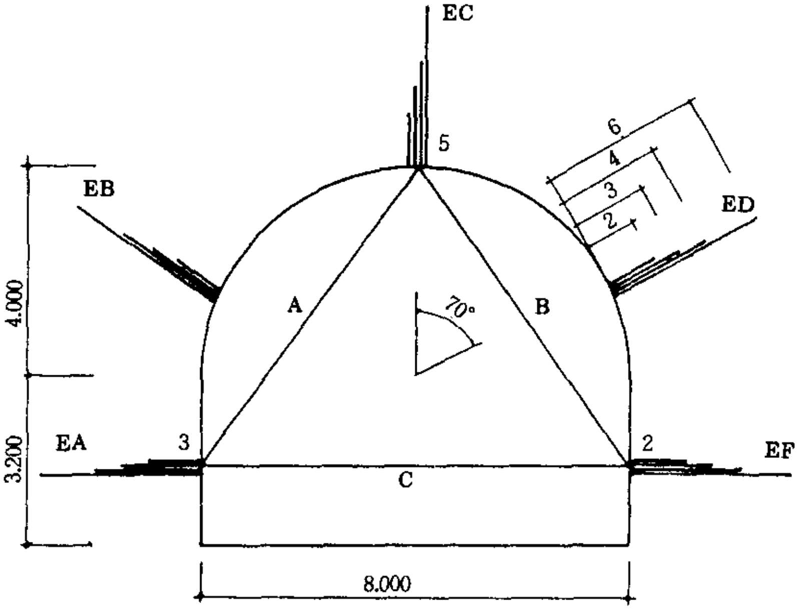

Fig. 3 Monitoring section in L-I storage caverns

In an underground excavation, deformation occurs at the tunnel surface and peripheral ground owing to the release of the initial stress at the excavation surface. In underground constructions, such deformation is measured by the convergence and borehole extensometer measuring system.

During the construction of the Yukong storage caverns, the measuring system shown in Fig. 2 was adopted to monitor the behaviour of the rock mass around the access tunnels. Convergence was measured along the measuring lines A to F and the ground displacements were measured by multi-rod extensometers (EL and ER). The measured data at ST 635, one of the monitoring stations of the access tunnel, was used for back analysis. But the roof settlement S in Fig. 2 was not measured at this station.

In the access tunnels of the L-1 storage caverns, the measuring system shown in Fig. 3 was adopted. The measured data at ST 315 was used for back analysis. Convergence was measured along the lines A, B, and C. Four one-point rod extensometers were installed at five positions of this measuring station.

5. Results of Back Analysis and Discussion

5.1 Yukong Storage Cavern

The equivalent elastic modulus and the initial stress of the ground, based on the measured displacements at ST 635, are determined. The assumed Poisson's ratio and the unit weight are 0.25 and 26.0 KN/m^3 respectively. To compare the calculated displacements with the measured ones, the finite element analysis is carried out.

As the roof settlement is not measured at this measuring station, the three cases of roof settlements, i.e., 2.0, 1.0 and 0.5mm are assumed. The horizontal displacements at points 1 and 5 in Fig. 2 are both −0.3mm and 0.3mm and these values are regarded as absolute displacements. And then by using the horizontal displacements at point 2 and 4, which are −0.25mm and 0.25mm, instead of points 1 and 5, another three cases of back analyses are carried out. Among the three roof settlements, the settlement which minimizes the average root mean squared error between the measured convergences and the corresponding calculated convergences is regarded as the estimated roof settlement. The influence of the variation of roof settlements and the position of absolute displacements at the tunnel surface on the elastic modulus and initial stress, is also examined.

The results of back analysis are summarized in Table 2. In the cases of 1 to 3, the assumed roof settlements are 2.0, 1.0 and 0.5mm respectively and the horizontal displacements at points 1 and 5 in Fig.2 are used as absolute values. In the cases of 4 to 6, the assumed roof settlements are the same as those in cases 1 to 3, but the horizontal displacements at points 2 and 4 are used as absolute values.

Table 2. Results of back analysis for Yukong storage cavern

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Vertical Stress(Mpa)	4.54	4.54	4.54	4.54	4.54	4.54	4.54	4.54
Horizontal Stress(MPa)	2.18	2.99	4.48	1.43	1.50	1.63	9.45	4.28
Initial Stress Ratio(K)	0.48	0.66	0.99	0.31	0.33	0.36	2.08	0.94
Elastic Modulus(GPa)	14.90	29.00	54.88	13.92	27.73	55.07	42.04	46.84
Poisson's Ratio	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Assumed Roof Settlement(mm)	2.0	1.0	0.5	2.0	2.0	0.5	0.5	0.5

Case 1~Case 6 : Convergence measurements
Case 7 : Extensometer measurements
Case 8 : Convergence + Extensometer measurements

As shown in Table 2, the elastic moduli fo case 1 to case 3 are 14.9, 29.00 and 54.88 MPa and that of case 4 to case 6 are 13.92, 27.73 and 55.07 MPa respectively. It can be seen that the elastic modulus is very sensitive to the magnitude of the roof settlement. And it appears that the modulus is not significantly affected by the position of the absolute horizontal displacements at the tunnel wall. But the result shows that the estimated initial horizontal stresses by back analysis are affected by the positions of the absolute horizontal displacements. The initial stress ratio K in cases 1 to 3 ranges from 0.48 to 0.99. But in the cases of 4 to 6, the range is 0.31 to 0.36. Among the cases 1 to 3 and the cases 4 to 6, cases 3 and 6 show the least root mean squared error between the field measured convergences and the corresponding calculated values. So the estimated roof settlement is 5mm in this study.

The comparison between the calculated and the measured displacements proves the accuracy of back analysis. In Fig. 4 and Fig. 5, the data from convergence and extensometer measurements and the calculated ones are compared. The calculated results are from analyses by ordinary finite element program using the results from back analysis for case 3 and case 6 respectively. In these cases, the extensometer measurement data are not used for back analysis. The extensometer measurement data in EL shown in Fig. 2 are 0.15mm at tunnel boundary and 0.7mm at the position of 3m above the tunnel boundary. In extensometer ER, the measurement at a depth of 3m above the tunnel boundary is 0.3mm and

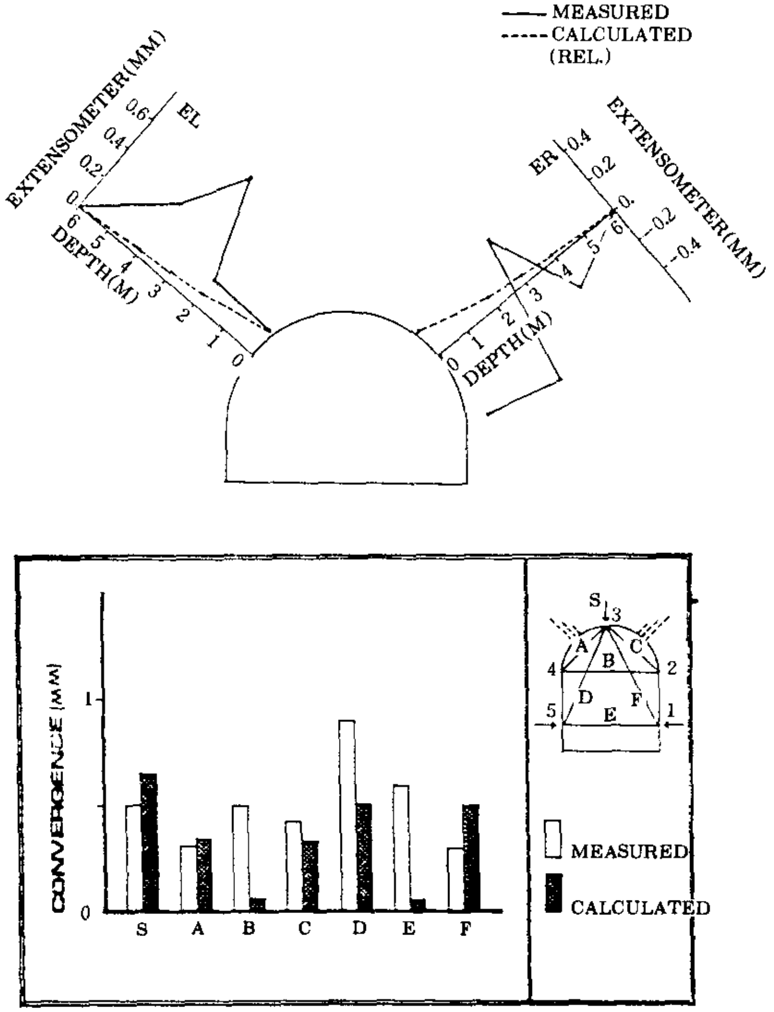

Fig. 4 Comparison between the measured and calculated displacements in Yukong caverns(Case 3)

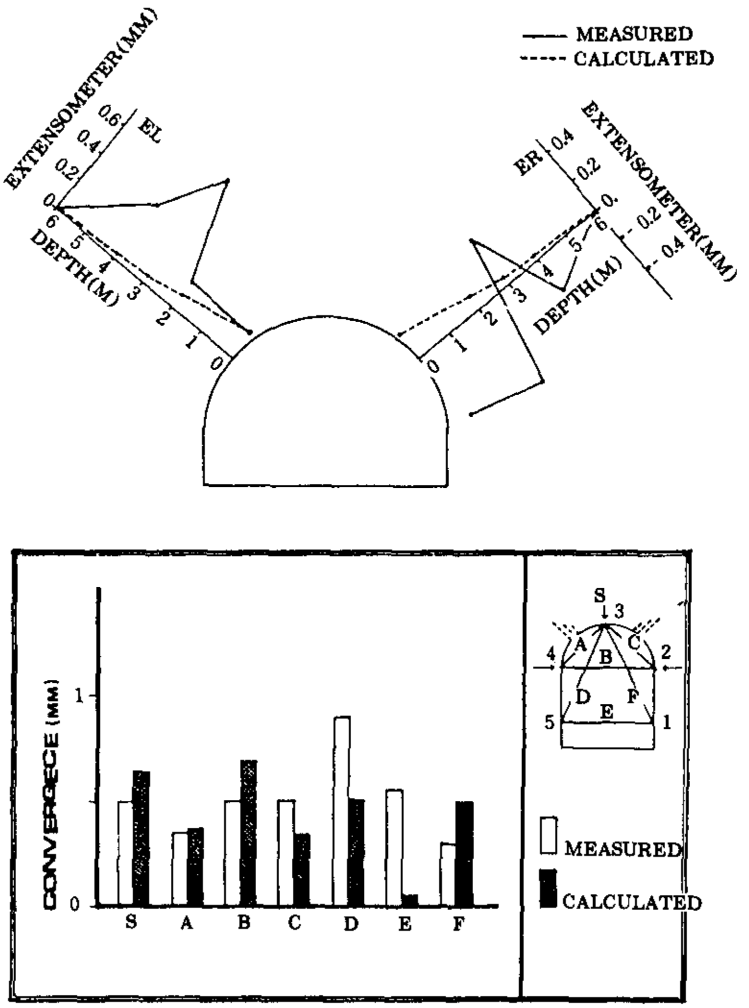

Fig. 5 Comparison between the measured and calculated displacements in Yukong caverns(Case 6)

the negative values are read at other positions. These results may be due to the measuring error or the presence of discontinuity plane at the depth of 3m. The back calculated displacement at the surface of EL is very close to the corresponding measured value. A good agreement is obtained between the measured and computed convergence values.

In Fig. 6, the displacements, which are back analysed through the use of data from extensometer measurements, are compared with the measured displacements. The data points used for back analysis are presented as open circles in Fig. 6. The elastic modulus and initial stress calculated are shown as case 7 in Table 2. It can be seen that the elastic modulus is slightly lower compared to that of case 3. On the other hand, the horizontal stress is

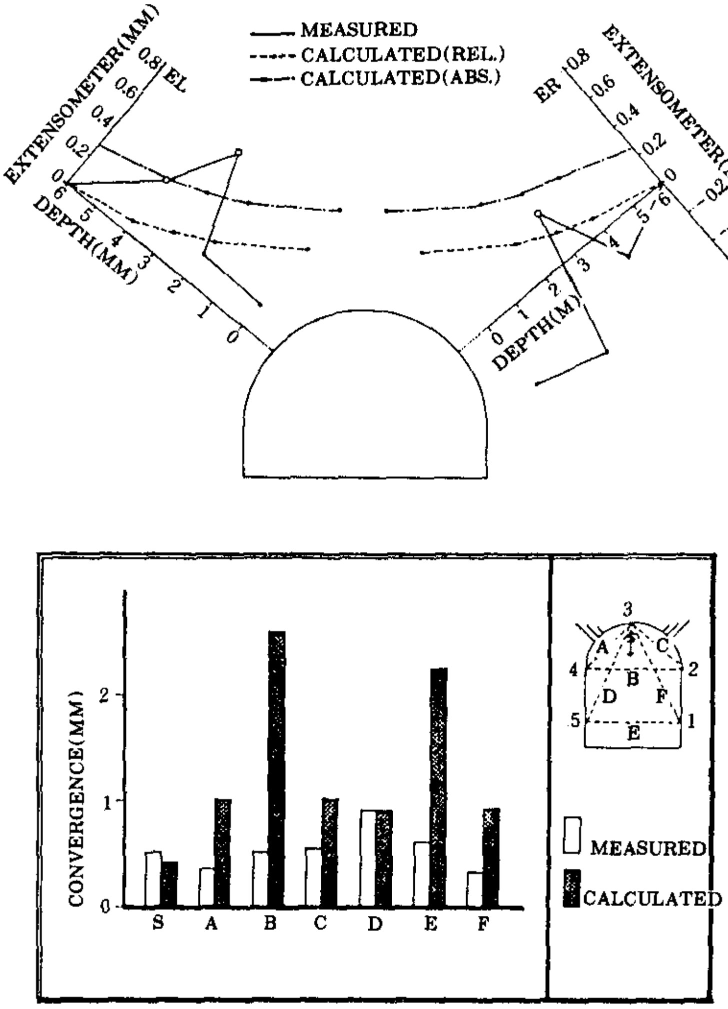

Fig. 6 Comparison between the measured and calculated displacements in Yukong caverns(Case 7)

twice as large as that of case 3. The back calculated convergences in the measuring lines A to F are about twice as large as the measured values. At the depth of 3 and 4m of the extensometer(EL) and 3m of the extensometer(ER), the calculated displacements are about 40% of the measured values which are used as input data for back analysis. But in Fig. 4, the calculated displacements at these points, using convergence data only, are 10% of the measured values. The calculated displacements above are relative displacements assuming that the 6m points are fixed. The reason for this is that although the ground displacement around the tunnel is large, the convergence measurement can be small due to compaction of the loosened zone near the excavation surface by stiff supporting materials. So the elastic

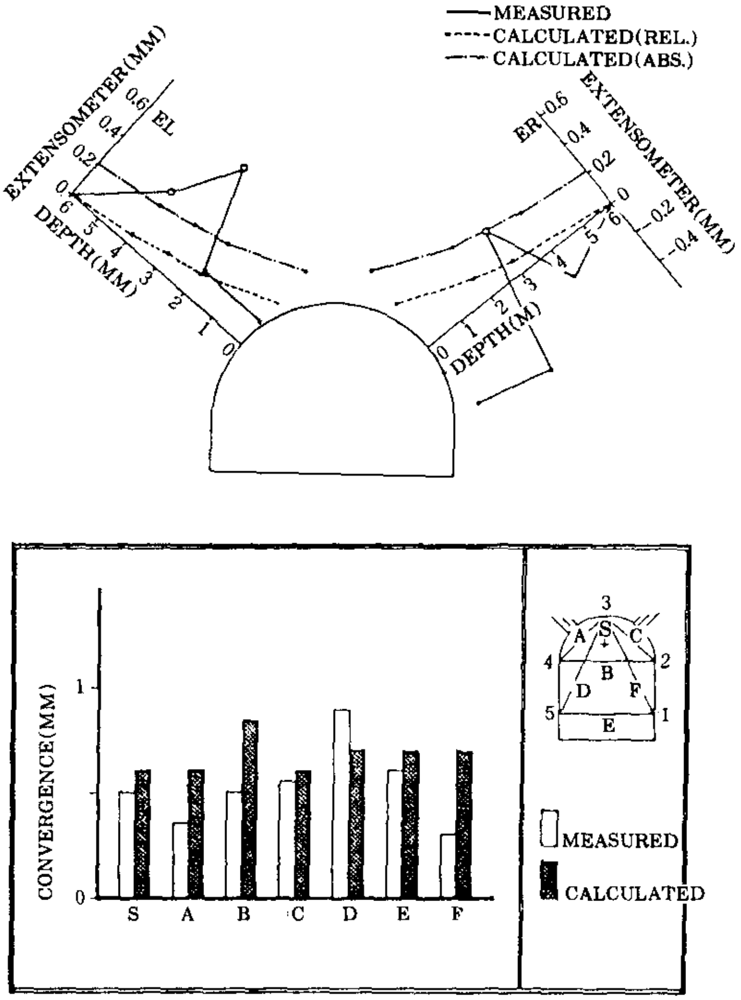

Fig. 7 Comparison between the measured and calculated displacements in Yukong caverns(Case 8)

modulus calculated with convergence data only shows a lower value than the result calculated by using extensometer measurement data. Comparing cases 3 and 6 to case 7, this can be proved.

In Fig. 7, the back analysed displacements using both extensometer and convergence measurements are also compared with the data from field measurements. The elastic modulus and initial stress calculated for this case are shown as case 8 in Table 2. As expected, the calculated convergence and ground displacement results are in between the results shown in Fig. 4 and Fig.6.

5.2 L-1 Storage Cavern

At the measuring station ST 315 of the L-1 storage cavern, data for convergence and extensometer measurements were obtained. These measurements were used as input data for back analysis. Poisson's ratio and unit weight were assumed as 0.25 and 26.0 KN/m^3 respectively.

The results are summarized in Table 3. Since the roof settlement was not measured for L-1 storage cavern, three cases of roof settlements of 0.2, 1.0, and 1.5mm were assumed. the horizontal displacements at points 2 and 3 in Fig. 3 were −0.37 and 0.37mm respectively. These values were assumed as absolute displacements. The convergence measured along the line A in Fig. 3, which shows negative value, was not used in all cases. The results show that the elastic modulus becomes smaller as the magnitude of the roof settlement increases from 0.2 to 1.5mm. The initial stress and elastic modulus, which were the results of back analysis, were used as input data for ordinary finite element analysis. Of the three cases, case 3, where the roof settlement is 1.5mm, showed the least root mean squared error when the measured convergence values are compared with the corresponding back calculated results. The comparison between the calculated and measured displacements for case 3 is shown in Fig. 8. It can be seen from this figure that there is a good agreement between the measured and calculated values except for line A. But this figure also shows that there is a marked discrepancy between the data in the extensometer measurements. The reason for this may be that only the convergence data were used.

The back analysis results using only the extensometer measurements are marked as case 4 in Table 3. The measured data show that the displacements measured by extensometer EC is in the state of compression, and so are the displacements by extensometers EA and EB to the depth of 3m. In extensometers ED and EE, the decrease of displacements from a depth of 2m to the excavation boundary was observed. This fact implies that the loosening zone exists to the depth of 2m. The displacements measured at the depth of 3m of EA, at the depth of 4m by EB, at the depths of 2, 3, and 4m by ED

Table 3. Results of back analysis for L-1 storage cavern

	Case 1	Case 2	Case 3	Case 4	Case 5
Vertical Stress(Mpa)	5.19	5.19	5.19	5.19	5.19
Horizontal Stress(MPa)	9.35	2.98	2.90	18.72	6.02
Initial Stress Ratio(K)	1.80	0.57	0.56	3.60	1.16
Elastic Modulus(GPa)	193.06	37.83	25.09	78.11	27.15
Poisson's Ratio	0.25	0.25	0.25	0.25	0.25
Assumed Roof Settlement(mm)	0.20	1.00	1.50	–	1.50

Case 1～Case 3 : Convergence measurements
Case 4 : Extensometer measurements
Case 5 : Convergence + Extensometer measurements

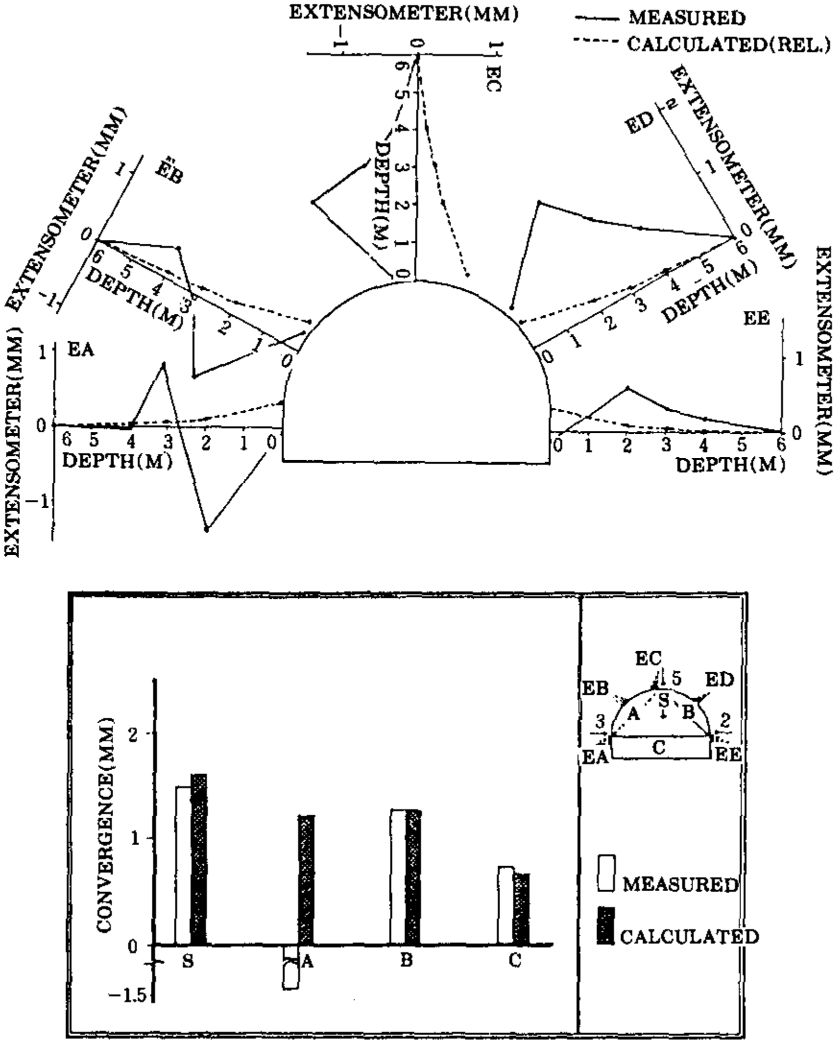

Fig. 8 Comparison between the measured and calculated displacements in L-1 caverns(Case 3)

and EE were used as input data for back analysis. The comparison between the measured and calculated displacements is shown in Fig. 9. The calculated displacements listed above are relative values to the points at 6m where the 6m points were assumed to be fixed. However, the calculated convergence in measuring line B is smaller than expected. This is belived to be due to the exclusion of the vertical displacements on extensometer EC. This resulted in large horizontal stress which is used for back calculation of the calculation of the convergence. So it was found that the selection of measuring points is very important for back analysis.

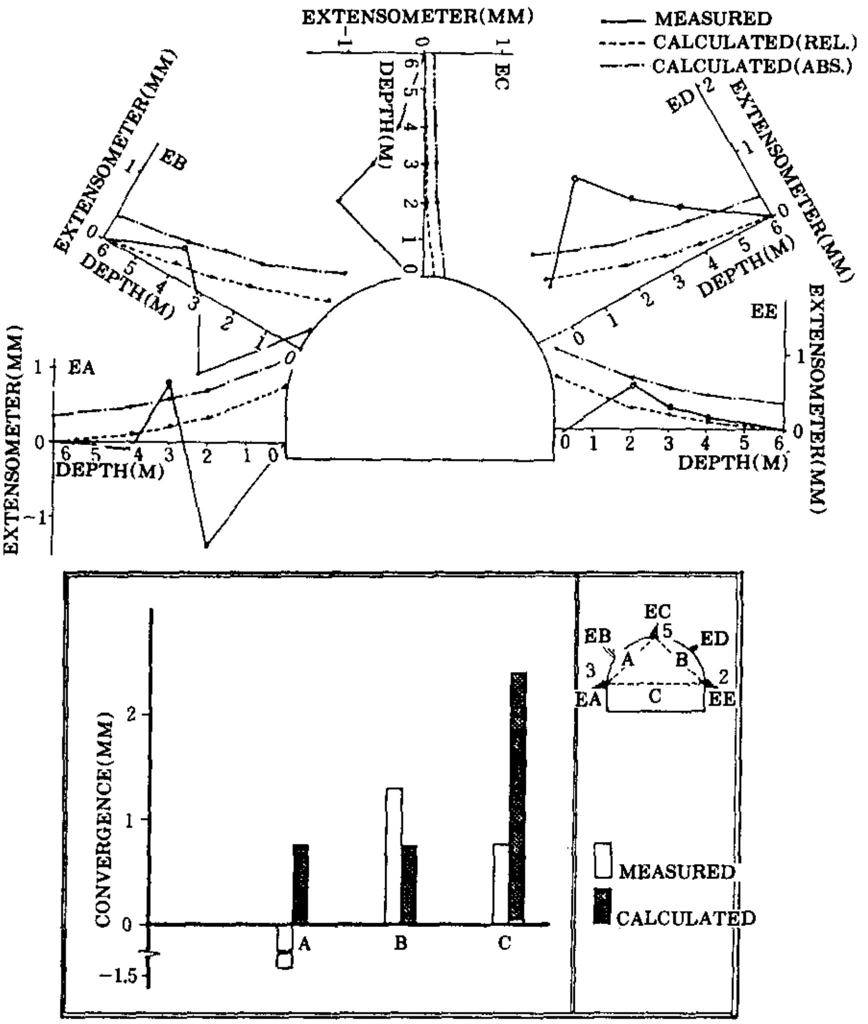

Fig. 9 Comparison between the measured and calculated displacements in L-1 caverns(Case 4)

In case 5, the displacements back analysed by using both the data from the extensometer measurements of case 4 and the data from convergence measurements are also compared with the measured data in Fig. 10. In this case, the roof settlement of 1.5mm was assumed. The resulting elastic modulus and the initial stress are shown in Table 3. Except for the reading from extensometer EC, the ground displacements are smaller than the corresponding values in case 4.

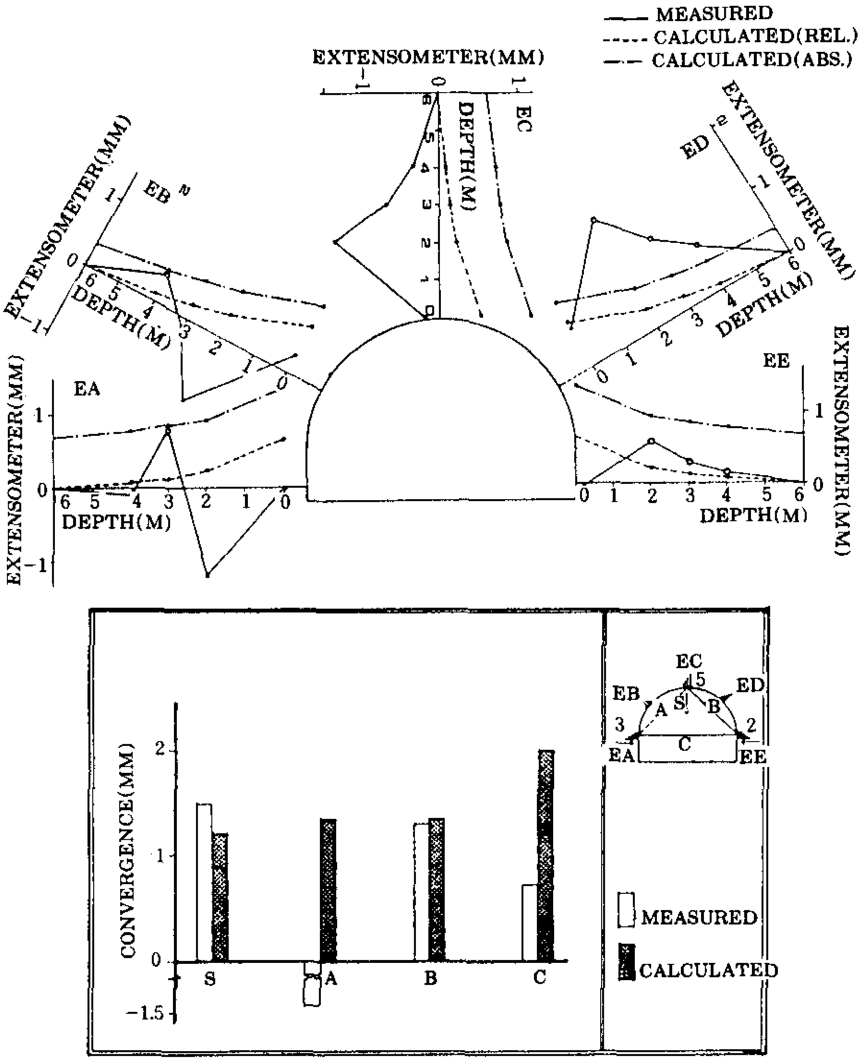

Fig. 10 Comparison between the measured and calculated displacements in L-1 caverns(Case 4)

6. Summary and Conclusion

The back analysis of measured displacements is one of the most attractive methods to obtain the equivalent mechanical propoerties of the rock mass and the initial stress, not disturbed by excavation. When the support system does not meet the suport requirements during construction, rapid support modification can be carried out by using the results.

In this paper, we have presented a result of back analysis based on the inverse method. It is shown that the back analysed results using the displacements measured at the tunnel boundary only are affected considerbly by the magnitude of the roof settlement. Thus it is thought that great care should be taken in measuring the roof settlement. It is understood that the selection of measuring points is very important for back analysis because the results of back analysis are affected by the measuring position of input data. The back analysed displacements using the extensometer measurements are larger than the corresponding results from the convergence measurements only. The reason for this is that convergence measurements can be small owing to the compaction of the loosened zone near the excavation boundary by stiff supporting materials. So, the extensometer measurements beyond the loosened zone is neccessary for accurate back analysis.

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