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S7-6

A NEW FEEDBACK TECHNIQUE FOR TUNNEL SAFETY BY USING MEASURED DISPLACEMENTS DURING TUNNEL EXCAVATION

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ABSTRACT: This research project was carried out to develop the technique to assess quantitatively and rapidly the stability of a tunnel by using the measured displacement at the tunnel construction site under excavation. To achieve this purpose, a critical strain concept was introduced and applied to an assessment of a tunnel under construction. The new technique calculates numerically the strains of the surrounding ground by using the measured displacements during excavation. A numerical practical system was developed based on the proposed analysis technique in this study. The feasibility of the developed analysis module was verified by incorporating the analysis results obtained by commercial programs into the developed analysis module. To verify the feasibility of the developed analysis module, analysis results of models both elastic and elasto-plastic grounds were investigated for the circular tunnel design. Then the measured displacements obtained in the field are utilized practically to assess the safety of tunnels using critical strain concept.

It was verified that stress conditions of in-situ ground and ground material properties were accurately assessed by inputting the calculated displacement obtained by commercial program into this module for the elastic ground. However for the elasto-plastic ground, analysis module can reproduce the initial conditions more closely for the soft rock ground than for the weathered soil ground. The stability of tunnels evaluated with two types of strains, that is, the strains obtained by dividing the crown displacement into a tunnel size and the strains obtained by using the analysis module. From this study, it is confirmed that the critical strain concept can be fully adopted within the engineering judgment in practical tunnel problems and the developed module can be used as a reasonable tool for the assessment of the tunnel stability in the field.

Keywords: Risk Management; Feedback Analysis; Critical Strain in the ground; Tunnel Safety

1. INTRODUCTION

Generally, methods to assess the stability of a structure are divided into stress concept and strain (or displacement) concept. Measurements are carried out to assess the stability of a tunnel by these two methods at the tunnel construction site(KTA, 1999). Measurement results can be used as the most important criteria for stability of a tunnel at the tunnel construction site. At the tunnel construction site, control criterion for displacement is presented, and if measured values are within the control criterion, it is determined that the stability of tunnel is secured. If the measured values that were obtained from stress cells set up on the support are within the strength of the material, the stability of the support is determined to be secured. But displacement is measured to assess the stability of the tunnel in most cases at the real tunnel construction site and generally stress measurements are carried out at the only section that should be controlled specially.

In this study, a new assessment technique to rapidly and quantitatively determine the stability of a tunnel under construction by strain concept, not by stress concept, using critical strain concept, that was introduced in *Tunnel Lining Design Guide*(BTS, 2004), which was amended recently by the British Tunneling Society, is introduced. In addition, an analysis module was developed based on the proposed analysis technique in this study, and the developed module's applicability was verified.

2. CRITICAL STRAIN CONCEPT AND ITS APPLICATION

We think that it is most useful to use the results of displacement that were measured such as convergence and crown settlement, to quantitatively and economically assess the stability along all sections of the tunnel at the construction site where the tunnel is being excavated. In this study, we want to define the deformation characteristics of the ground by critical strain to assess the stability of the tunnel being excavated quantitatively, by using the displacement caused by the tunnel's excavation.
For the first time, Sakurai (1997) from Japan proposed the critical strain concept, and in the early days, this concept was established mainly based on the lab test results on the soil and rock specimens collected at the construction site. Critical strain is acquired by the stress-strain relation that is the uniaxial compression test results of the specimens that were collected at the site like in Fig. 1. That is to say, critical strain can be defined as Eq. 1 by using the characteristics of behavior at the initial elastic region and uniaxial compression ultimate strength, which were acquired through the uniaxial compression test. From an engineering point of view, more conservative assessment is possible if the critical strain concept is used because the critical strain value is lower than the failure strain value.

$$\varepsilon_0 = \frac{\sigma_c}{E_i} \tag{1}$$

Here, σ_c and E_i indicate uniaxial compression strength and initial tangent modulus of elasticity for each.

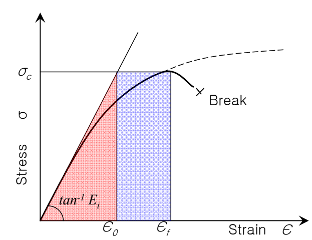

Fig. 1. Stress-strain relation according to uniaxial compression test

The relations between critical strain and uniaxial compression strength in respect to soil and rock are expressed in Fig. 2. As seen in Fig. 2, values of critical strain decrease when values of uniaxial compression strength increase. The criteria for determining whether it is rock or soil is made using uniaxial compression strength 1 MPa in ISRM(1981), and the range of critical strain is 0.1% ~ 1.0% for rock, and the range of critical strain is 1~8% for soil (mainly clayey soil). Also, in Fig. 2, it shows the same trend as was described above from the soil that has 0.05 MPa of uniaxial compression strength to hard rock, which has 200 MPa of uniaxial compression strength, and width of dispersion is nearly unaffected by strength, and values of critical strain exist within certain limits of the two parallel straight lines.

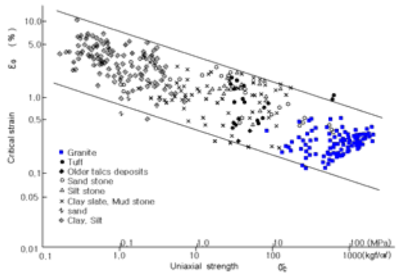

Fig. 2. Relation between critical strain and uniaxial compression strength

Hoek(Hoek and Marinos, 2000) tried to apply the critical strain concept to a tunnel construction site. Fig. 3 was assessed using the critical strain concept, with data from a tunnel construction site in Taiwan. The vertical axis in Fig. 3 shows the strain value which is calculated using the measured displacement simply divided by tunnel size during excavation. We can verify that deformation never happened below the critical strain line, which was acquired by critical strain concept. This example clearly shows the characteristics of critical strain, and indicates that assessment of the stability of a tunnel is possible, by using the displacement information measured on the construction site.

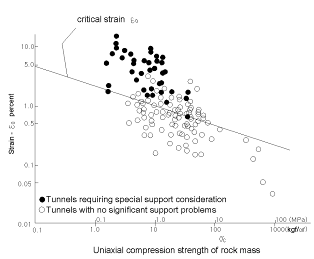

Fig. 3. Example of assessment by the concept of strain caused by crown settlement

The characteristics of critical strain concept is that the maximum allowable displacement, from a construction manager's point of view in respect to displacement that occurs during excavation, can be determined if the mechanical characteristics of the corresponding ground and tunnel scale(size) are fixed, like the example expressed in Fig. 3.

Moreover, if the strain distribution of the surrounding ground can be directly acquired by using the displacement caused by the tunnel excavation, after setting the critical strain of the ground where the tunnel is excavated. A numerical analysis method, which was proposed for this purpose, is newly developed below.

3. ANALYSIS TECHNIQUE

The numerical analysis technique to grasp the entire strain distribution of the ground surrounding the tunnel by using the strain-based design, not to assess the stability of the tunnel by the strain which is calculated using the measured displacement simply divided by tunnel size during excavation, is arranged as follows using the finite element method. We developed a unique system to determine the strain value of the ground. The detailed description about the system is omitted in this paper.

4. THEORETICAL BASIS FOR THE CRITICAL STRAIN CONCEPT

The strains in the ground are calculated using the measured displacement(crown settlements) divided by the radius of the tunnel from the previous researches (Sakurai, 1997; Swarup et al, 2000; Hoek and Marinos, 2000). Then the obtained strains are plotted in the critical strains diagram for the evaluation of the stability of a tunnel. In the previous researches, the uniaxial compressive tests are performed to define the critical strain in the ground and to establish the critical strains diagram from the specimen collected at the sites. However the strains that are to be applied to the practical use for the stability of a tunnel are decided by the crown settlements and the size of the excavated section. It seems that the two methods of making the definition of the critical strains and applying it to the practical field are different. Thus it needs to make clear the difference mentioned above and theoretical basis of the critical strain concept.

There are various theoretical equations (Szechy, 1974) related to the stresses in the ground surrounding tunnel and the displacements at the excavated surface. Some equations are based on the theory of elasticity and others are the elasto-plastic theory. There are different types of the assumed loading forces. Kirsh's theory is one the equations and Fig. 4 is similar to it.

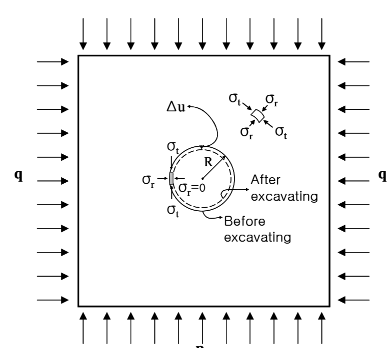

Fig. 4. Ground behavior for the circular tunnel

There are two sections of the circular tunnel before and after the excavation. The stresses on the side wall element are illustrated and the radial stress (σ_r) is equal to 0 due to the stress release. Tangential stress (σ_t) increases at the same point. It is well known that the tangential stress increases to maximum two times in the axisymmetric circular tunnel (p=q in Fig. 4) for the elastic medium. The tangential strain (ε_t) can be expressed as

$$\varepsilon_t = \frac{\Delta L}{L} = \frac{2\pi R-(2\pi(R-\Delta u))}{2\pi R} = \frac{2\pi\Delta u}{2\pi R} = \frac{\Delta u}{R} \qquad (2)$$

According to the ground behavior mechanism described above, the strains in the ground due to tunneling can be expressed using the crown settlement divided by the radius of the tunnel. Based on this investigation, it is reasonable to calculate the strain in the ground approximately due to tunneling and to evaluate the stability of the tunnel using the critical strain concept. The characteristics of critical strain concept is that the maximum allowable displacement, from a construction manager's point of view in respect to displacement that occurs during excavation, can be determined if the mechanical characteristics of the corresponding ground and tunnel size are fixed.

5. REVIEWS OF CRITICAL STRAIN CONCEPT USING A NUMERICAL ANALYSIS METHOD

In this part, in order to grasp the engineering meanings of the critical strain concept in the ground, we conducted precise reviews using a numerical analysis method. These reviews eventually assessed the feasibility of the analysis module developed in this study.

The flow which aims to assess the feasibility of the analysis module is as follows.

① Conduct tunnel excavation analysis through commercial finite element method program assuming initial ground conditions

② Obtain tunnel displacement values resulting from tunnel excavation

③ Use obtained displacement values as input data to perform numerical analysis using the analysis module developed in this study.

④ Compute the value of $\bar{c}$ (Eq. 8) by using the analysis module.

⑤ Obtain vertical stress with the assumption of $\gamma H = \sigma_{y0}$ by taking into account the distance between the tunnel and the ground surface. When vertical stress is assumed, obtain the remaining values (E_g , σ_{x0} , τ_{xy0}).

The flow which aimed to grasp the engineering meanings of the critical strain concept is as follows.

① Run commercial program, obtain strains which had divided the tunnel crown displacement by the size of the tunnel. Compare the obtained strains with the critical strain graph(Fig. 2), and evaluate the tunnel stability.

② Obtain the strain distribution of the ground surrounding the tunnel excavation by elastic analysis using the ground property and stress values through the analysis module. Obtain the maximum compressive strain of the ground, compare it with the critical strain graph(Fig. 2), and evaluate the stability of the tunnel.

5.1 Examination of the feasibility of the analysis module

Pentagon-3D(Emerald soft Co., 2004) was used for the commercial finite element method program and the initial ground conditions are as shown in Fig. 5

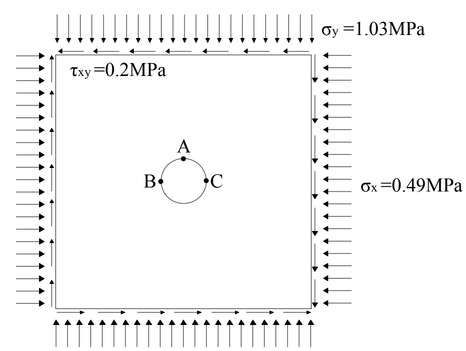

Fig. 5. Ground conditions of the commercial program

The diameter of the tunnel is assumed to be 10*m*. The numerical analyses were conducted for elastic ground and elasto-plastic ground without tunnel supports after excavation. The initial stress conditions of the ground were σ_x =0.45MPa, σ_y =1.03MPa, τ_{xy} =0.2MPa, where the stress conditions were uniform throughout the entire ground region.

While the stress states are different for the top and bottom of an actual tunnel, the values converge as the tunnel runs deeper. Since a uniform stress state was taken into consideration when developing the analysis module, it maintained a certain stress level in order to examine the feasibility of the analysis module. Assuming that the vertical stress is caused by overburden pressure, one can deduce that there is about 40~50m of depth from the ground surface. Also, the reason for taking into consideration the shear stress is to reproduce a ground condition as real as possible by reflecting a slope of the surface and the anisotropic state of the ground. The ground properties are used as shown in Table 1.

Both the weathered soil and the soft rock ground were assessed. After having performed analysis, the excavation displacements of the crown section (Point A) and the sidewall section (Points B and C) have been summarized in Table 2.

Table 1. The material properties of the ground used in numerical analysis

Classif-ication	Unit weight γ (KN/m^3)	Ground modulus of elasiticy E_g (KPa)	Poisson's ratio ν	Cohesion c (KPa)	Frictional angle ϕ (°)
W/S	19.60	98065.9	0.35	50	30
S/R	26.27	980659.2	0.25	250	40

* W/S : Weathered Soil, S/R : Soft Rock

Table 2. The displacements of tunnel by a commercial Finite Element Method program

CASE	Ground type	Displacement(*mm*)					
		Point A		Point B		Point C	
		X	Y	X	Y	X	Y
1	W/S in E/B	-17.5	-68.8	+21.2	+17.5	-21.2	-17.5
2	W/S in EP/B	-2.66	-117	+115	+4.21	-115	-4.21
3	S/R in E/B	-2.09	-7.18	+1.52	+2.09	-1.52	-2.09
4	S/R in EP/B	-2.23	-7.51	3.75	1.92	-3.75	-1.92

* W/S : Weathered Soil, S/R : Soft Rock
E/B : Elastic body, EP/B : Elasto-plastic body

As we can see in Table 2, the displacements of elasto-plastic ground is greater than those of elastic ground. We can also see that the difference in displacement is more significant for the weathered soil than the soft rock ground.

As mentioned previously, the analysis module developed in this study requires only at least three displacement data. For this study, four displacements were used from the displacement data shown in Table 2(shaded) as input values to the analysis module. As for the input displacements, we incorporated 100% and 70% of the analysis results. The reason for incorporating only 70% is that the displacement obtained from an actual tunnel construction site is less than the total displacement.

Also, conducting analysis using the analysis module requires that the vertical stress should be assumed, we used the two cases of 100% and 70% of the initial vertical stress as shown in Table 3. Overburden pressure of 70% indicates that the vertical pressure and the overburden pressure at an actual tunnel construction site may differ.

Table 3. The stress state of the ground obtained through the developed analysis module (MPa)

CASE	Analytical assumptions			Analytical results		
	Ground type	Displac-ements	Vertical stress	E_g	σ_x	τ_{xy}
5	W/S in E/B	100%	-1.03 (100%)	98.00	-0.49	-0.20
6	W/S in EP/B	100%	-1.03 (100%)	51.26	-1.02	-0.02
7	W/S in EP/B	70%	-1.03 (100%)	73.23	-1.02	-0.02
8	W/S in EP/B	70%	-0.72 (70%)	51.26	-0.71	-0.01
9	S/R in EP/B	100%	-1.03 (100%)	868.57	-0.71	-0.19
10	S/R in EP/B	70%	-0.72 (70%)	868.57	-0.50	-0.13
Initial condition	W/S		-1.03	98.00	-0.49	-0.20
	S/R			980.00		

* W/S : Weathered Soil, S/R : Soft Rock
E/B : Elastic body, EP/B : Elasto-plastic body

It can be seen from Table 3 that the initial stress state was perfectly reproduced for the elastic condition (CASE 5). The material property(E_g) and the stress values(σ_x , τ_{xy}) are different when having applied the displacements generated by the elasto-plastic ground (CASE 6, CASE 9).

This can be attributed to the fact that the analysis module is based on the theory of elasticity. The actual ground is more similar to elasto-plastic ground than it is to elastic ground. Therefore the conditions of the ground are not reproduced 100%, as shown in Table 3, when using an analysis module based on elasticity.

Table 2 shows that the difference between tunnel displacement for elastic and elasto-plastic ground was less significant for the soft rock than the weathered soil. Such observation is also indicated in Table 3. In other words, the analysis cases for soft rock(CASE 9~10) show resulting values close to initial ground conditions. However, for the weathered soil of which the difference between the elastic and elasto-plastic displacements was greater, the results are rather discrepant from the elasto-plastic analysis results(CASE 6~8) and the originally assumed initial ground conditions.

What we need to be cautious of is that the ultimate goal of using the analysis module is not to reproduce the original ground conditions of Table 3 but is to use them to compute the maximum compressive strain and evaluate the tunnel stability. These ideas are described in further detail in the next part.

5.2 Examination of the engineering meanings of the critical strain concept

In order to examine the engineering meanings of the critical strain concept, we evaluated the stability of tunnels following two methods using the critical strain graph.

The first method examines the strains obtained by dividing the crown displacement that occurs as a result of tunnel excavation into tunnel size. As introduced earlier, this method had been applied to real projects by Sakurai and Hoek. In this study, we aim to newly evaluate the stability of tunnels for the elastic and the elasto-plastic grounds by using the results from the commercial Finite Element Method program. Table 4 shows the strains obtained by using the crown displacements (displacement Y of point A in Table 2). Evaluating the stability of the tunnel in this manner is indeed meaningful in the field actively deploying the crown displacements.

The obtained strains in Table 2 were illustrated in Fig. 6, is the critical strain graph. The critical strain graph classifies grounds into five different types according to the strength of the ground. This classification is based on the ISRM standards and allows for convenient practical use.

Table 4. Strains computed through crown displacement

CASE	Crown displacement(*mm*)	Strain (%)
		Crown displacement/tunnel radius
1	68.8	1.38
2	117	2.34
3	7.18	0.14
4	7.51	0.15

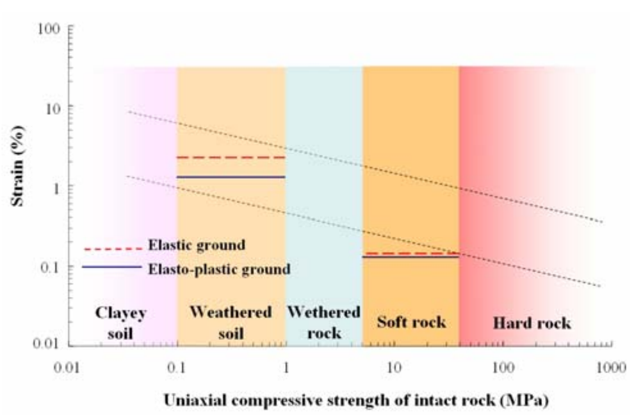

Fig. 6. Tunnel stability evaluation using crown displacement

The weathered soil results show that both the elastic and plasto-elastic analysis results surpass the lower limit line while are bound within the upper limit. All analysis results of the soft rock are lower than the lower limit line.

We can derive the following meanings when evaluating the stability of tunnels using Fig. 6. In other words, it is difficult to secure the stability for both elastic and plasto-elastic grounds in the weathered soil where elasto-plastic ground is even less stable. Tunnel supports need to be installed in order to secure tunnel stability with reducing tunnel displacement. For the soft rock, both elastic and elasto-plastic grounds do not require supports in securing stability.

Before adopting the concept of critical strains, it was typical to evaluate if the ground is in an elastic state or in a plastic state when evaluating the stability of the ground using numerical results. While one may confirm that some region is in a plastic state, it wasn't merely sufficient enough to determine the stability of the ground in reality. However, as suggested in this study, the critical strain concept allows us to quantitatively evaluate the stability of tunnels by using the crown displacement generally measured when excavating tunnels, with high practicality in the field.

The next method is using the analysis module proposed in this study. The ground property and stress values are obtained by the analysis module and these values are used to derive both strain distribution and maximum strain for the ground surrounding the tunnel. This strain refers to compressive strain. The maximum compressive strain is compared with the critical strain graph to evaluate the stability of tunnels. Sakurai conducted compression tests on core specimens collected in the field in order to creat the critical strain graph. Therefore, in reality's perspective, the critical strain graph represents the compressive strain of ground materials. While its practicality has been proved in case studies(Sakurai, Hoek, Fig. 6), the strain obtained by dividing the crown displacement by the size of the tunnel can hardly be the compressive one. In that sense, it would be more reasonable to use the analysis module to directly compute the (maximum) compressive strain of the ground surrounding the tunnel and use it to evaluate the stability of the tunnel.

Fig. 8 shows the distribution of the compressive strain of the ground surrounding the tunnel obtained by using the analysis results from Table 3. The maximum compressive strain obtained by using the results in Fig. 7 are summarized in Table 5. Table 5 also includes data in Table 4. Fig. 8 illustrates the critical strain graph and represents strains obtained by the two different methods in Table 5.

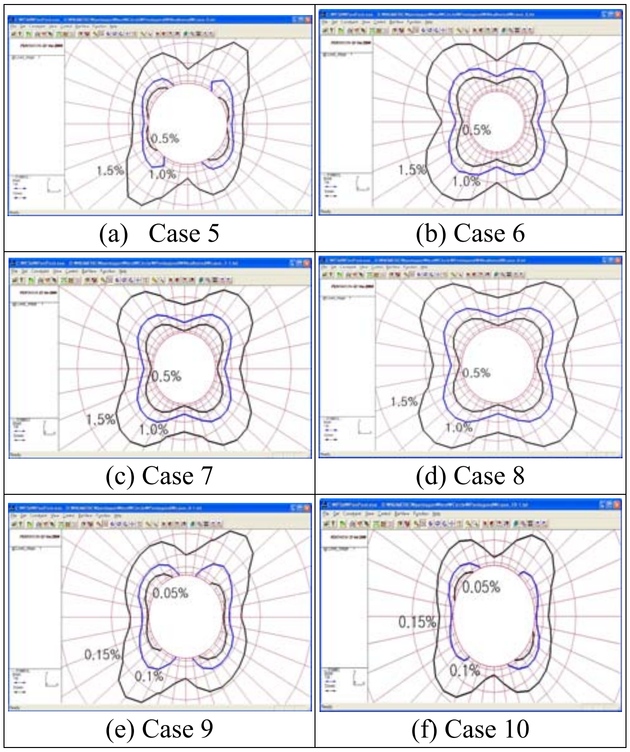

Fig. 7. Compressive strain distribution of ground by tunnel excavation

Table 5. Maximum compressive strain obtained by the analysis module

CASE	Crown displacement (mm)	Strain (%)	
		By Table 4	By analysis module
1	68.8	1.38	-
2	117	2.34	-
3	7.18	0.14	-
4	7.57	0.15	-
5	-	-	2.06
6	-	-	4.16
7	-	-	2.91
8	-	-	2.91
9	-	-	0.25
10	-	-	0.18

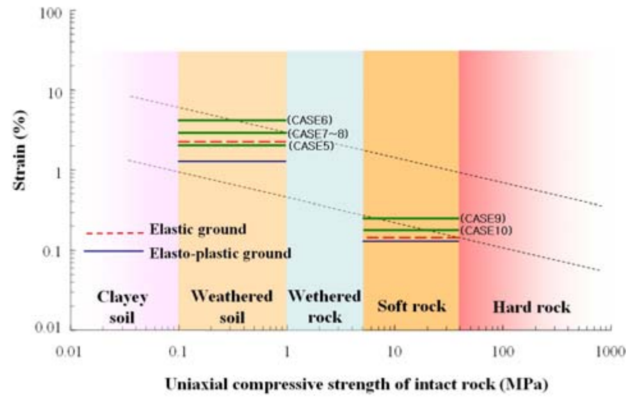

Fig. 8. Tunnel stability evaluation through maximum compressive strain

Fig. 8 also includes strains by crown displacements in Fig. 6. We can see that the results from the analysis module show greater values for both weathered soil and soft rock than those from the crown displacements. Despite having reduced the tunnel displacements and vertical stress conditions below the initial ground conditions (CASE 7~8, CASE 10), we can see that the strains obtained by the analysis module greater than those by crown displacements. Such results are expected to be of use in practical aspects because we can use a simple stability evaluation method through crown displacement and use the analysis module when a more detailed stability evaluation is required. In addition, since the analysis module in this study takes into account tunnel supports, we can perform tunnel stability evaluations after having installed supports. Finally, after having inputted excavation displacements and vertical stress conditions lower than the initial ground condition values, we confirmed that the critical strain concept can be fully adopted within the engineering judgment in real tunnel problems.

6. CONCLUSIONS

In this study, the stability assessment method by strain-based concept was investigated. It was easy to assess the stability of a tunnel that was excavated by using the measured tunnel displacement that is measured everyday at a tunnel construction site. The critical strain concept was used to assess the stability by strain concept analysis method, by which the measured displacement was transformed into the strain described. The analysis module was developed based on these results, and finally, the feasibility of the developed module was verified. The summarized conclusion of this study is as follows:

1) To assess the stability of a tunnel under construction, a new analysis technique to assess strains by introducing the critical strain concept was proposed.

2) A new analysis module was developed based on the method by which a strain is assessed by using excavation displacement. For the developed analysis module, a reverse formulation by Finite Element Method analysis was used, and a new method to which shotcrete lining and anisotropic characteristics of the ground are applied by considering the ground's initial stress condition, measured displacement, and material properties of the surrounding ground.
3) The feasibility of the developed analysis module through this study was verified by incorporating the analysis results obtained by commercial programs into the developed analysis module.
4) To verify the feasibility of the developed analysis module, analysis results of models both elastic and elasto-plastic ground were investigated for the circular tunnel design. Finally, it was verified that stress conditions of in-situ ground and ground material properties were accurately assessed by inputting the calculated displacement obtained by commercial program into this module for the elastic ground.
5) Analysis module can reproduce the initial conditions more closely for the soft rock ground than for the weathered soil ground. This is because the difference between tunnel displacements for elastic and elasto-plastic ground was less significant for the soft rock than the weathered soil.
6) The stability of tunnels evaluated with two types of strains using critical strain graph, that is, the strains obtained by dividing the crown displacement into tunnel size and the strains obtained by using the analysis module. Consequently, tunnel stability can be assessed by using two types of strains and the analysis module provides a more detailed examination.
7) It is confirmed that the critical strain concept can be fully adopted within the engineering judgment in real tunnel problems.

ACKNOWLEDGEMENTS

This study was partly funded by the Korea Institute of Construction and Transportation Technology Evaluation and Planning under the Korean Ministry of Construction and Transportation in Korea (Grant No. 05-D03-01).

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