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Evaluating the Moisture Content Variation on Critical Strain of Geomaterials: A Case Study

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ABSTRACT

The tunnel's stability during construction is a very important matter. Some methods have been proposed for stability evaluation, but the hazard warning levels (HWLs) are more applicable among these methods. Despite monitoring and applying HWLs, several collapses in Shibli twin tunnels in Iran have cast doubts on the accuracy of this criterion in the presence of water. In this study, the critical strains under different water contents were measured through uniaxial compressive strength tests on 11 different shale and marl samples. A comparison of laboratory tests and numerical results shows that the influence of the moisture content on the critical strain is negligible. In addition, the results show that there is no direct relationship between the critical strain and uniaxial compression strength.

Keywords: Moisture content, Critical strain, UCS, Shibli twin tunnels.

تقييم تغييرات محتوى الرطوبة على الانفعال الحرج للمواد الارضية دراسة حالة

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الخلاصة

استقرارية الانفاق اثناء الانشاء هي المسألة المهمة هناك طرق عديدة لتقيم الاستقرارية، من بين هذه الطرق تبقى طريقة تحذير مستوى الخطر (Hazard Warning levels, HWLs) اكثر عمليا من الطرق الاخرى. وبرغم من مراقبة مع استخدام HWLs لقد حدث عدد من الانهيارات في نفق شبلى(Shibli) المزدوج في إيران، مما أثرت الشكوك على دقة هذه الطريقة فى التقيم و خصوصا بوجود المياه. في هذه الدراسة الحالية تم اجراد فحوصات مقاومة الانضغاط احادى المحور (uniaxial compression strength) والانفعال الحرج ل ١١ نموذج لنسب محتوى الرطوبي المختلف من shale و marl و تم مقارنة النتائج المختبرية

مع نتائج والعددية تبين ان تأثير المحتوى الرطوبي على الانفعال الحرج ليس لها تأثير ملموس. بالاضافة فان النتائج اظهرت بان لا يوجد علاقة مباشرة بين الانفعال الحرج و مقاومة الانضغاط احادى المحورز

الكلمات الرئيسية: المحتوى الرطوبي، الانفعال الحرج، UCS ، نفقي شبلى.

1. INTRODUCTION

(Sakurai, 1981) used displacement to predict deformation around the tunnel and therefore proposed a stability assessment technique based on the concept of critical strain to assess stability. The concept of critical strain is defined as the relationship between the ultimate compressive strength and the initial tangent modulus. This concept is used as one of the criteria to determine the stability of the tunnel during the excavation stage. Research on the critical strain was initiated by **(Sakurai, 1981)** and continued by **(Stacey, 1981)**, **(Fujii et al., 1998)**, **(Hoek, 1998)**, **(Li, Villaescusa2005)**, **(Singh et al., 2007)**, **(Park et al., 2008)**, **(Kohmura, 2012)** and **(Park and Park, 2014)**. There have been many studies on critical stress, but only **(Hoek, 1998)**, **(Sakurai, 1997),** and **(Li, Villaescusa2005)** carried out some research that led to the HWL proposal. **(Sakurai, 1997)** proposed three hazard warning levels (HWL) to evaluate the stability of the tunnel during the construction stage based on critical strain. He divided the hazard warning levels into three stages according to the degree of stability. **(Sakurai, 1997)** observed that there is no problem with the tunnel when the strain is lower than warning level I. Considering that a tunnel problem was discovered where the strain was close to alarm level III. He found that the critical strain is almost independent of joints, moisture content, and temperature. **(Hoek, 1998)** proposed to determine the baseline of tunnel stability using the rock mass uniaxial compressive strength and deformation. He believed that the tunnels do not require special consideration if the strain level is smaller than 1%. Despite occurring strain less than the hazard warning level, the incidence of several collapses in Shibli twin tunnels in the presence of water has cast doubts on the accuracy of this criterion. This study investigates and evaluates moisture content variation on the critical strain of geomaterials via lab tests and numerical simulation.

2. PROJECT DESCRIPTION

The Shibli tunnels have been constructed in Eastern-Azarbaijan along Tabriz – Zanjan freeway in Northwest Iran **(Fig. 1)**. The tunnels sections area is 110 m^2 with 12.1 m width, 9.75 m height, and have a length of 2288 and 2244 m. The distance between the axes of two adjacent tunnels is about 60 m. The most outstanding aims of this project are to remove Shibli defile and decrease driving casualties. The peak overburden thickness above the tunnels is 180 and 185 m.
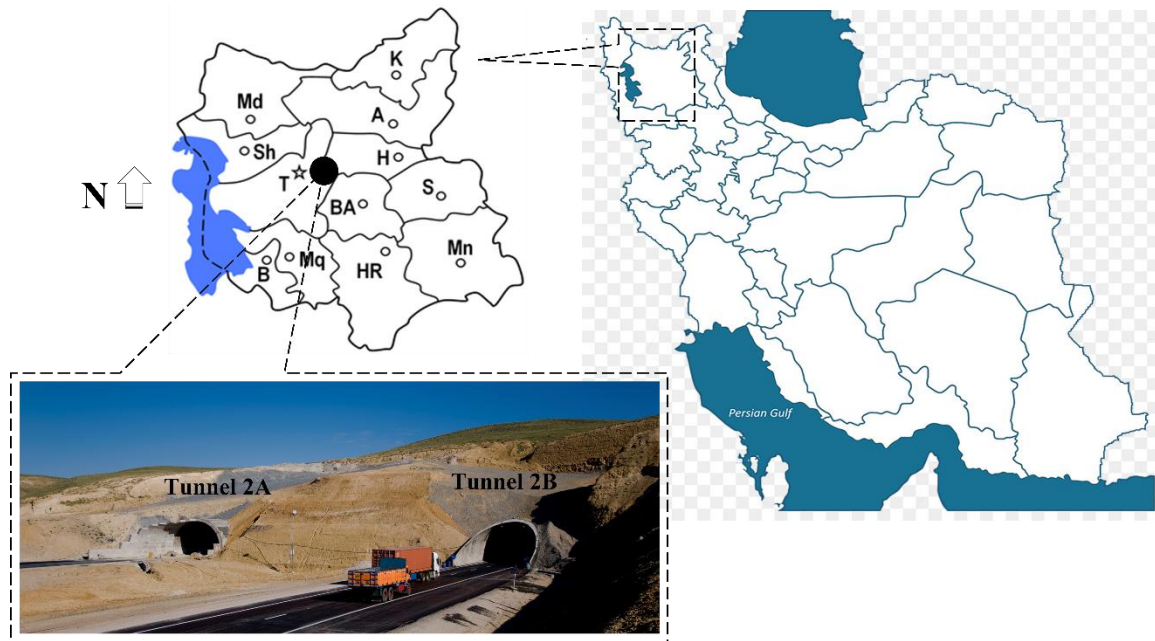
Figure 1. Study area.

2.1 Geomechanical parameters and Support systems

The study area is located in Iran's center of the Alborz tectonic zones. Mostly, two types of geological engineering units are mapped in the tunnel route, namely Shale and Marl, which have a fair to poor strength. The support systems of the tunnels are often a composite of steel ribs (IPE180@0.5m) embedded in shotcrete with a thickness of 25cm, rock bolts with a length of 6m to 9m, and a diameter of 25mm installed in a pattern of 1×1 m. In order to determine the geotechnical properties of the host rocks, some laboratory tests were carried out on the intact samples. The rock mass parameters were determined by using the generalized criterion of Hoek-Brown. According to the geotechnical properties of the host rocks, three blocks were considered along the tunnel path **(Fig. 2)**.
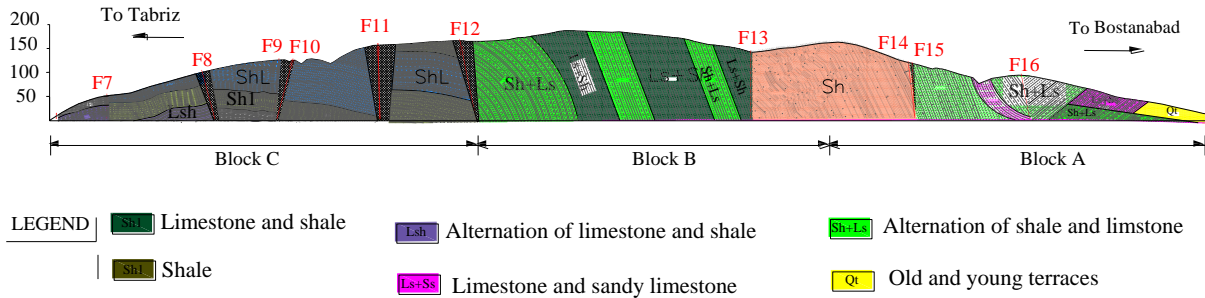
Figure 2. Longitudinal section of Shibli tunnels.

Table 1. Geomechanical properties

Block	RMR	GSI	Friction angle °	Dry unit weight (gr/cm^3)	Cohesion (kPa)	E_{intact} (GPa)	E_{mass} (GPa)
A	49-52	44-47	36	2.35	328	19.64	1.4
B	43-46	38-41	34	2.32	357	19.71	1.18
C	38-42	33-37	33	2.2	340	19.41	1.58

2.2 The collapsed zone

In September 2007, despite the tunnels' instrumentation and monitoring, a big collapse with dimensions of 36×16 m (depth ×diameter) occurred in chainage 27 + 340 of tunnel 2A **(Fig. 3)**. This collapse has questioned the precision of the hazard warning levels presented by Sakurai in spite of the smaller values of the strains measured by monitoring compared to hazard warning level I.
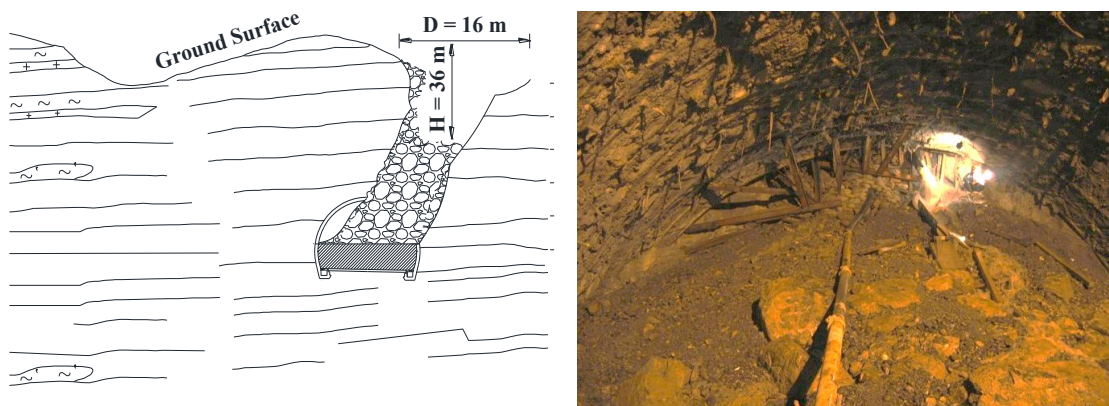

Figure 3. Cross-section of big collapse at chainage 27 + 340.

Convergence pins and an extensometer record the monitoring in the tunnels. Based on the geotechnical properties, the monitoring stations were installed at 128 points at 30 to 60 m intervals. The recorded data in station 27+340 indicated relative displacements of 72 mm for the (L–R), 34 mm for the (C–L), and 36 mm for the (C–R). The relative displacement of the collapsed zone has been shown in **Fig. 4**.
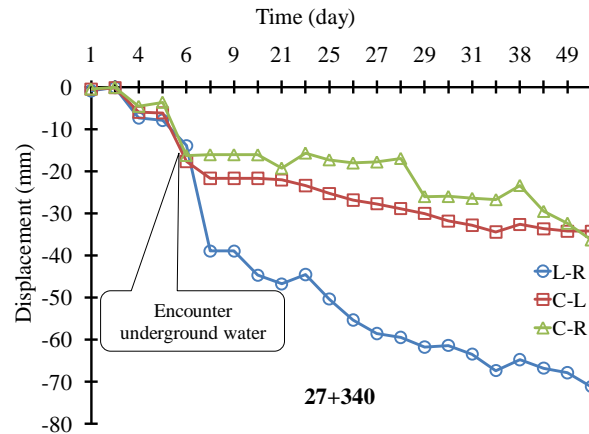
Figure 4. Relative displacement at chainage 27 + 340.

3. METHODOLOGY

3.1 Preparation of Specimens

Eleven cylindrical samples with a minimum diameter of 54 mm were obtained from the project site. The samples consisted of five samples of shale and six marl samples. The length to diameter ratio was 2, and the longitudinal axis of the samples, oriented perpendicular to bedding, was prepared for the tests. The tests have been done based on ISRM guidelines. The samples are shown in **Fig. 5**.

Figure 5. The samples collected from the project site.

3.2 Determination of Moisture Content and the Critical strain

To determine the moisture content, the specimens were first weighted (wt), then dried based on ISRM guidelines. Then, they were removed and cooled gradually to determine the dry weight (w_s).

The difference between the resulting two amounts was the water weight (w_w). The water content (m) is also calculated by using Eq. (1).

$$m_{nat.}(\%) \;=\; \frac{w_{nat.} - w_{dry}}{w_{dry}} \tag{1}$$

The samples were tested by using a hydraulic testing apparatus. The loading rate was considered 0.5 to 1 MPa/s. Having installed the strain gauges, the samples were placed inside the apparatus as per **Fig. 6** to measure their compressive strength. Based on the measurements taken during the UCS tests, stress-strain curves were drawn for all the samples tested. The results are shown in **Fig. 7**.

Figure. 6. UCS testing machine and strain gauges set up on the samples.
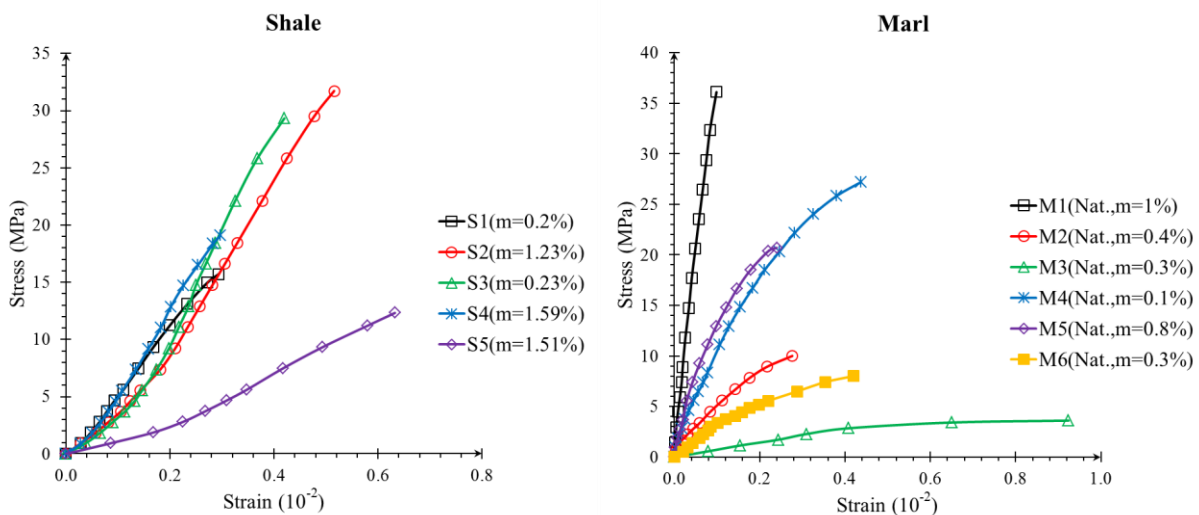
**Figure. 7.** Stress-strain curves of the samples.

Based on **(Sakurai, 1981, 2017)**, the critical strain is defined as the ratio of uniaxial compression strength to initial tangent modulus. The moisture content and the critical strain of specimens have been shown in **Table 2**.

Table 2. The critical strain and moisture content of the samples.

Lithology	Sample No.	Moisture content (%)	Critical strain (%)	UCS (MPa)
Marl	M1	1	0.05	37
	M2	0.4	0.1	9.5
	M3	0.3	0.12	3
	M4	0.1	0.1	23
	M5	0.8	0.06	21
	M6	0.3	0.1	8
Shale	S1	0.2	0.15	15
	S2	1.23	0.42	31
	S3	0.23	0.28	30
	S4	1.59	0.18	18
	S5	1.51	0.38	13

4. NUMERICAL SIMULATION

FLAC software developed based on the FDM has been used in this study. The model dimensions and the constitutive behavioral model were considered as 120×110 m and Mohr-Coulomb, respectively **(Fig. 8)**. In order to estimate k_o in the model, the Rummel equations have been used. It should be noted that the influence of k_o is significantly important in displacement **(Fattah, et al., 2011)**. The stress relaxation in the models was gradually applied to the model based on GRC and SCC (**Carranza-Torres and Fairhurst, 2000**). It should be noted that numerical modeling was done in some stages, including the model equilibrium, excavation of stages, and set up supporting of roof and walls.
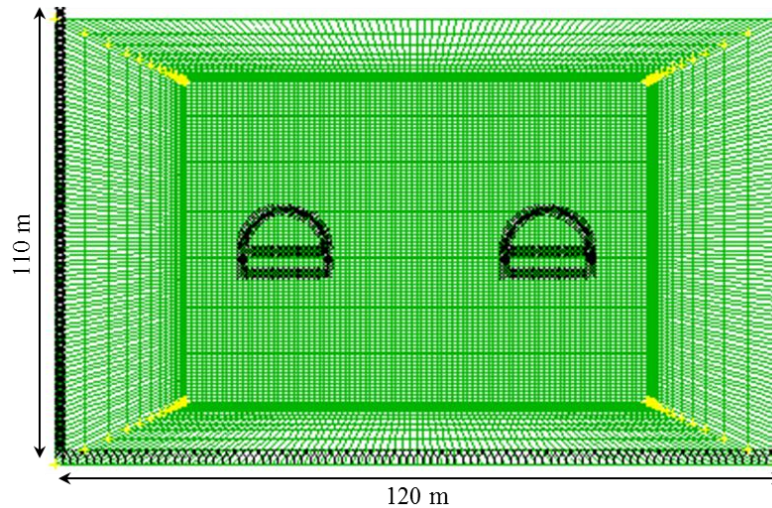
Figure 8. Numerical model .

4.1 Changing moisture content in the model

To study the influence of the variations of moisture content on the critical strain in the numerical model, the saturation capacity of the host rock was first determined equal to 1.19 via testing. Then, the host rock density was increased up to the saturation degree to simulate the variations of the moisture content in the model. To this end, the densities related to three moisture content levels were determined using Eq. (2). According to Eq. (2), the host rock density in the various moisture content is illustrated in **Table 3**.

$$\gamma_d = \frac{\gamma_m}{1+m} \Rightarrow \gamma_m = \gamma_d \times (1+m) \tag{2}$$

m = moisture content (%)

γ_m = moisture density.

Table 3. The host rock density in the various moisture content.

Shale (m_{max} = 1.19 %)		
Stage	m (%)	γ_m (kg/cm^3)
1	0.5	2.21
2	1	2.22
3	1.19	2.23

Based on (**Vasarhelyi, 2003, 2005**), elastic modulus up to a maximum of 30% of saturation degree was gradually reduced during the simulation. Also, the influence of the moisture content on the compression strength in the Shibli tunnel (2A) was calculated by using Eqs. (3), (4), and (5).

$$\sigma_{csat} = 0.759\sigma_0 \tag{2}$$

$$\sigma_c(w) = a + ce^{-bw} \tag{3}$$

$$b = -\ln\left(\frac{0.1}{\sigma_{c0} - \sigma_{c.sat}}\right) \tag{4}$$

$$c = \frac{(\sigma_{c0} - \sigma_{c.sat})}{1 - e^{-b}}, a + c = \sigma_{c0} \tag{5}$$

a, b and c are constants.

5. RESULTS and DISCUSSIONS

According to **Fig.9**, no clear trend is observed despite the variation in the critical strain proportionate to the moisture content. Nevertheless, the difference between the minimum and maximum values of the critical strain due to the variation in the moisture content is 0.05 to 0.4 % (0.0005 - 0.004 mm/mm), respectively, which is very small and negligible. On the other hand, the failure strain in the Shibli tunnel was computed equal to 0.009 mm/mm (0.9 %), taking a 36 mm displacement at the collapsed zone as shown in **Fig. 4**. According to **(Singh et al., 2007)**, **(Sakurai, 1997)**, and **(Kim and Kim, 2009)**, the failure strain is 1.5 to 2.5 times larger than the critical strain. Hence, the critical strain at the collapsed zone had a minimum of 0.006 mm/ mm (0.6%). By converting failure strain to critical strain and plotting it the **Fig. 9**, it is observed that the variations of the moisture content have had inconsiderable effects on critical strain values. The obtained critical strain from the numerical model is shown in **Table 4.**
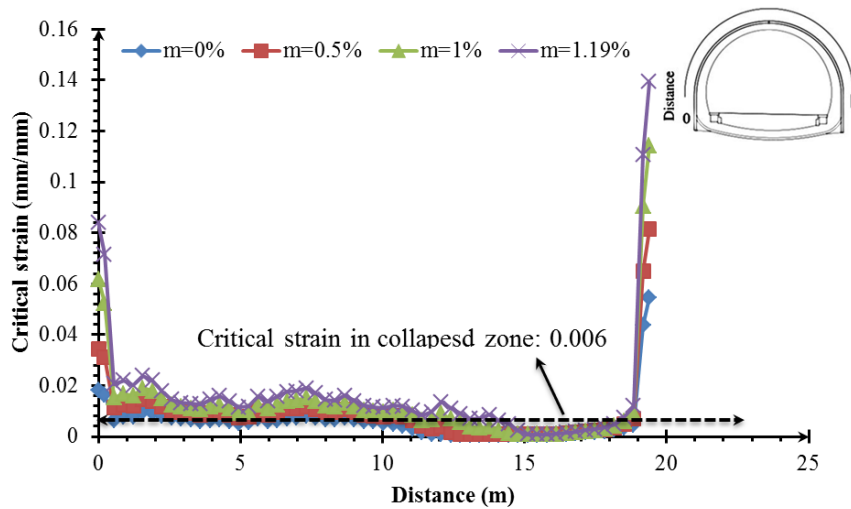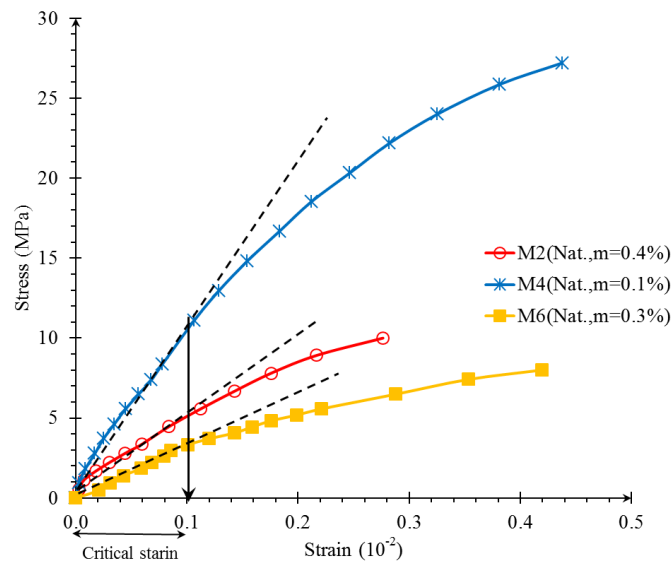

Figure 9. Critical strain vs. moisture content in change 27+340.

Table 4. Variation of Critical strain with moisture content in the numerical model.

No. of model	Moisture content (%)	UCS (MPa)	Critical strain (%)
1	0	31	0.6
2	0.5	18	0.6
3	1	15	1
4	1.19	19	1.1

Considering no influence of the moisture content on the critical strain, the reason why the tunnel collapsed under the groundwater table can be elaborated as follows. By drawing the critical strain on the stress-strain graphs as shown in **Fig. 10**, a similar critical strain is achieved in some samples, despite the variation in their compression strength. This indicates that despite changes in compressive strength due to changes in moisture content, similar critical deformations may still occur. The quantity of critical strain in the samples is shown by the arrow in **Fig.10**. Hence, it can be concluded that the decrease in the rock strength in a constant critical strain is the main reason for the collapse of the Shibli twin tunnels.

Figure 10. Critical strain in some tested samples.

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6. CONCLUSIONS

The influence of the variations in the moisture content on the critical strain was studied by numerical modeling and conducting laboratory tests on 11 shale and marl samples. There is no direct relationship between the critical strain and uniaxial compression strength of samples. In accordance with the test results which are shown in Table 2, the moisture content has a negligible influence on the critical strain. Besides, there is a rule less variation trend in the critical strain in different moisture contents. Since the hazard warning levels are formulated based on critical deformation, the influence of moisture content on them can also be ignored.

7. REFERENCES

- Carranza-Torres C., and Fairhurst, C., 2000. Application of the convergence-confinement method of tunnel design to rock masses that satisfy the Hoek-Brown failure criterion. Tunneling and Underground Space Technology 15(2): 187-21.
- Sakurai, S., 1981. Direct strain evaluation technique in construction of underground opening. 22nd U.S. symposium on rock mechanics, 29 June-2 July.
- Stacey, T. R., 1981. A simple extension strain criterion for fracture of brittle rock. Int. J. Rock Mech. Min. Sc .and Geomech. 18(6): 469-474.
- Fujii Y., Kiyama T., Ishijimay, Y., and Kodama, J., 1998. Examination of a Rock Failure Criterin Based on Circumferential Tensile Strain. Pure Appl. Geophys 152(3): 551–577.
- Hoek, E., 1998. Tunnel support in weak rock, The symposium of sedimentary rock engineering. Taipei, Taiwan, November 20-22
- Li, J., Villaescusa, E., 2005. Determination of rock mass compressive strength using critical strain theory, 40th U.S. Rock mechanics symposium, paper 663
- Singh, M., Singh, B., Choudhari, J., 2007. Critical strain and squeezing of rock mass in a tunnel, Tunneling and underground space technology 22(3): 343-350.
- Park, S. H., Ha, M. H, Park, G. R., and Shin, Y. S., 2008. A study on the safety assessment technique of a tunnel using critical strain concept. Word tunnel congress, India
- Kohmura, 2012. A study on critical strain of rocks. Journal of Japan society of civil engineers 68(3): 526
- Park Sh., and Park, Su., 2014. Case studies for tunnel stability based on the critical strain in the ground. KSCE Journal of Civil Engineering 18(3): 765–771.
- Sakurai, S., 1997. Lessons learned from field measurements in tunneling, Tunneling and Underground Space Technology 12(4): 453-460.
- Sakurai, S., 2017. Back analysis in rock engineering. CRC Press. Taylor and Francis.
- Vasarhelyi, B., 2003. Some observations regarding the strength and deformability of sand stones in case of dry and saturated conditions, Bull. Eng. Geol. Environ. 62(3):245-249.
- Vasarhelyi, B., 2005. Statistical analysis of the influence of water content on the strength of the Miocene limestone, Rock Mechanic and Rock Engineering 38(1):69-76.

- Kim and Kim, 2009. evaluation for applications of displacement criterion by the critical strain of uniaxial compression in rock mass tunnel. Journal of Korean Civil Engineering 29 (6C): 321-329.
- Fattah, M. Y., Shlash, K. T., Salim, N. M., 2011. Effect of Reduced Ko Zone on Time-Dependent Analysis of Tunnels, Advances in Civil Engineering, Vol. 2011, Article ID 963502, 12 pages, 2011. doi:10.1155/2011/963502, Hindawi Publishing Corporation.