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Influence of time-dependency on elastic rock properties under constant load and its effect on tunnel stability

C.O. Aksoy*[1], G.G. Uyar Aksoy[2], A. Guney[3], V. Ozacar[4] and H.E. Yaman[1]

[1]Department of Mining Engineering, Dokuz Eylul University, İzmir, Turkey
[2]Department of Mining Engineering, Hacettepe University, Ankara, Turkey
[3]Department of Mining Engineering, Mugla Sıtkı Koçman University, Mugla, Turkey
[4]Torbalı Vocational School, Dokuz Eylul University, İzmir, Turkey

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Abstract. In structures excavated in rock mass, load progressively increases to a level and remains constant during the construction. Rocks display different elastic properties such as E_i and υ under different loading conditions and this requires to use the true values of elastic properties for the design of safe structures in rock. Also, rocks will undergo horizontal and vertical deformations depending on the amount of load applied. However, under constant loads, values of E_i and υ will vary in time and induce variations in the behavior of the rock mass. In some empirical equations in which deformation modulus of the rock mass is taken into consideration, elastic parameters of intact rock become functions in the equation. Hence, the use of time dependent elastic properties determined under constant loading will yield more reliable results than when only constant elastic properties are used. As well known, rock material will play an important role in the deformation mechanism since the discontinuities will be closed due to the load. In this study, E_i and υ values of intact rocks were investigated under different constant loads for certain rocks with high deformation capabilities. The results indicated significant time dependent variations in elastic properties under constant loading conditions. E_i value obtained from deformability test was found to be higher than the E_i value obtained from the constant loading test. This implies that when static values of elastic properties are used, the material is defined as more elastic than the rock material itself. In fact, E_i and υ values embedded in empirical equations are not static. Hence, this workattempts to emerge a new understanding in designing of safer structures in rock mass by numerical methods. The use of time-dependent values of E_i and υ under different constant loads will yield more accurate results in numerical modeling analysis.

Keywords: modulus of elasticity; Poisson's ratio; time-dependency; rock mass deformation; intact rock deformation

1. Introduction

Time-dependent behavior of rock has long been an issue for underground constructions since it may induce certain short term instabilities or, moreover, collapses which may occur even several years after the completion of the work. In underground tunnels or caverns, time-dependent deformation or failure of rock in the form of growing fractures, rock falls, etc. may result in considerable safety and cost problems if time dependent damage of surrounding rock is not investigated. To perceive the evolution of the damage around underground structures, experimental work was carried out to determine time dependent values of elastic rock properties (E_i and υ) under constant load to depict time dependent behavior of rock.

Elastic Modulus (E_i) and Poisson's Ratio (υ) are very significant elastic intact rock properties used in designing the structures excavated in rock masses since they are related to the deformation of rocks under load. Hence, several scientists have attempted to extensively research the time-dependent deformation behavior of rock masses under loads. Barla (1999) has stated that deformation in rocks with high deformation capability is a creep and can last for a long time, however, in the other rock types the situation is slightly different.

Time-dependent deformation behavior is very important in fractured rock (Bieniawski 1970) and the creep takes less time. Rock masses continue to deform over time under constant load. Depending on the variable parameters, the deformation ends in time and becomes stable. A unified micromechanics-based damage-friction model was developed for instantaneous and time-dependent inelastic behaviors of brittle rocks (Zhao *et al.* 2016). In the study of time-dependent deformation of shale gas reservoir rocks and its long-term effect on the in situ state of stress, in response to the differential stresses applied in the laboratory tests of rocks, viscous deformation has been revealed in a time-varying amount (Sone and Zoback 2014). It was observed a phase which the tension rate is stabilize in several samples (Fabre and Pellet 2006). It is known that the porous structure changes its permeability depending on its stress and, in this case, has an effect on the deformation characteristic (Bai *et al.* 1999). Results of the Bakhtiari dam plate load tests show that large failures have quantitative and qualitative dominant effects on rock masses deformation.

Discontinuities affect the deformation of the rock mass in two ways: (1) spatial configurations that act as a specific

∗Corresponding author, Professor
E-mail: okay.aksoy@deu.edu.tr

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deformation mechanism and (2) four deformation mechanisms have been determined as a result of analysis of the anisotropy, stress dependence, rock mass effect on total deformation and deformations measured by plate load tests and their properties are represented (Agharazi *et al.* 2012). Matsuki *et al.* (2001) approximately reproduced the experimental results of the Monte Carlo simulation about time-dependent closure and showed that time-dependent closure of Goodman's fracture does not depend on normal stress because of increasing in contact area during time-dependent closure of the fracture. The deformation characteristics of rock mass are very important in tunnel deformation. The experiments made in the field to estimate the deformation modulus are both taking time and expensive. Owing to this reason, the values obtained from empirical equations are widely used (Verman *et al.* 1997). The elastic modulus of the rock material is used as a parameter of the empirical equations used to determine the deformation modulus (Hoek and Diederichs, 2006). Many studies can be found in the literature about rock mass deformation (Aksoy *et al.* 2012, Gokceoglu *et al.* 2003, Kayabasi *et al.* 2003) and the pressure-dependent change of the elastic modulus (Brown *et al.* 1989, Duncan and Brown 1989, Dyke *et al.* 1991, Houlsby *et al.* 2005). On the other hand, there are many valuable research about new methods and new applications with laboratory and field works in the literature about rocks deformation behavior and characterization (Aksoy *et al.* 2016, Gu 2015, Jiang *et al.* 2018, Taravani and Ardakani 2018, Rooh *et al.* 2018, Zhang *et al.* 2018, Palchik, 2018).

It can be discussed that publications found in the literature are generally about rock mass and its discontinuities, discontinuity surfaces and their behaviors, time-dependent deformation behaviors and load-dependent changes in elastic modulus. In this study, differently, time-dependent variations in E_i and υ of intact rock was investigated under constant load. It is anticipated that the outcomes of this research will contribute a new dimension to the designing of rock structures especially by numerical modeling (Mitri *et al.* 1994). In numerical modeling of rock structures, use of time-dependent values of elastic properties of the rock will provide safer and more economical results than when constant E_{mass} and υ of rock mass are used.

2. Material and method

A hydraulic servo-controlled press (Fig. 1) was manufactured and used to investigate the deformation behavior of rocks under constant loads and time-dependent variations in E_i and υ. This servo-controlled press is intended to reveal the E_i value changes over time under constant loads instead of the E_i calculation test currently in use. The equipment includes highly accurate deformation meters (LVDT) in micron degree. The software in the control section of the equipment calculates and records the variable E_i values over time with the information from the deformation meters. The E_i value is calculated by using the simple formula in the software by using the data of the instantaneous stress, the shortening in the sample length and

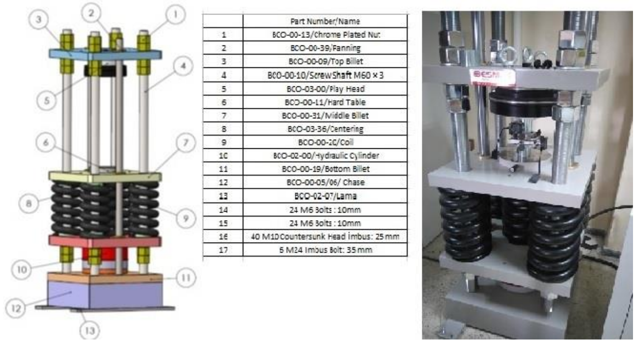

Fig. 1 Uniaxial compression testing equipment with constant loading capability

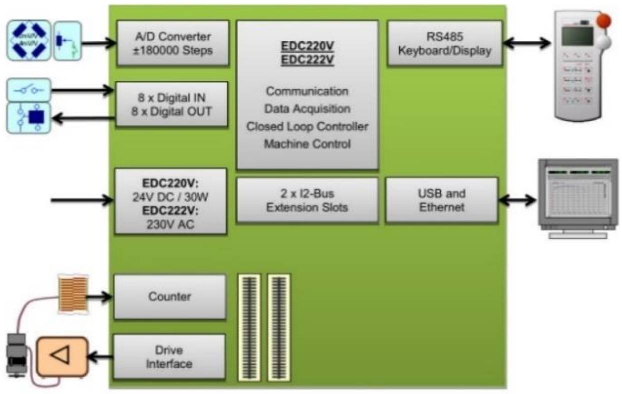

Fig. 2 Deformation recording and control system

the expansion in the sample diameter coming from the deformation meters during the test. Using all the data accumulated as a result of this long-lasting test (180-200 hours), E_i graphs are obtained for the constant load at which the test takes place. UCS_i of intact rock is taken into consideration in the selection of the applied loads. The constant loads applied on the rock were selected as 50%, 60%, 70% and 80% of the UCS_i of the same rock type. During the experiments, the amount of deformations of the sample was measured by the system, which can read the deformation at regular intervals (Fig. 2). In the experiments, the range in which no deformation was recorded during the period of one day was chosen as the moment of halting the experimental work which generally lasted between 180-200 hours. Experimental works yielded different E_i and υ values as the result of time-dependent deformations of the samples under constant load.

2.1 Indication of time-dependent changes in E_i and υ under different constant load

The main aim of the study is to observe the variations in E_i and υ values owing to the time-dependent deformation on different rock types under constant loads. Environmental parameters such as temperature and humidity were kept constant during the experiments. The types of the rocks used in this research are shown in Table 1. As can be seen in Table 1, the rocks with different geotechnical properties were selected from different strengths. The main reason for this is to keep the geotechnical perspective as wide as

Table 1 Rock types tested in the study

Sample Name	Project	Rock Properties	Lithology and Rock Description
ACong 1	Ankara-Afyon High Speed Railway Tuunel Construction	UCS_i=9.90 MPa; E_i= 1180 MPa υ= 0.26; Φ_i=42.11^0 c_i=0.173 MPa	Gray-ligth gray, wavy structure, weak-very weak, often clay band, Conglomera, GSI: 30
ACong 2	Ankara-Afyon High Speed Railway Tunnel Construction	UCS_i =28.43 MPa; E_i= 2050 MPa υ= 0.27; Φ_i=44.22^0 c_i= 0.191 MPa	Gray-ligth gray, wavy structure, hard-medium, often clay band, Conglomera, GSI: 40
EM	Soma-Eynez Underground Coal Mine	UCS_i= 24.29 MPa; E_i= 1910 MPa υ= 0.23; Φ_i=45.36 c_i=0.322 MPa	Homegeneous, hard, massive structure. Fresh surfaces are Ligth gray-green, They are medium thick layers. At some levels, leaf and plant traces are found in abundant quantities, Marl, GSI: 50
TC	Tavşanlı-Ömerler Underground Coal Mine	UCS_i= 28.40 MPa; E_i= 3210 MPa υ= 0.33; Φ_i=39.92 c_i=0.297 MPa	Gray-dark gray, generally jointed, hard-medium strength, Claystone, GSI: 45
IC	Soma-Işıklar Underground Coal Mine	UCS_i= 20.74 MPa; E_i= 4900 MPa υ= 0.31; Φ_i= 38.94 c_i= 0.793 MPa	Gray-dark gray, locally jointed, generally massive, hard-medium-weak strength, Claystone GSI: 50
IL	Soma-Işıklar Underground Coal Mine	UCS_i= 52.07 MPa; E_i= 4420 MPa υ= 0.27; Φ_i= 53 c_i= 0.862 MPa	Gray-ligth gray, generally massive, locally jointed, clay infilling, hard, sometimes medium, Limestone, GSI: 60
ICong	Soma-Işıklar Underground Coal Mine	UCS_i= 12.39 MPa; E_i= 8360 MPa υ= 0.37; Φ_i= 42.04 c_i= 0.167 MPa	Gray-dark gray, generally jointed, medium-weak strength, generally massive, locally jionted with clay infilling Conglomera, GSI: 40
IM	Soma-Işıklar Underground Coal Mine	UCS_i= 29.42 MPa; E_i= 1560 MPa υ= 0.26; Φ_i= 47.70 c_i= 0.445 MPa	Homogeneous structure, hard and generally massive. Gray-ligth gray, and when they are broken, they turn into a light gray color called ash color. They are medium thick layers., Marl, GSI: 55
MM	Ordu-Mesudiye Railway Tunnel Construction	UCS_i= 62.07 MPa; E_i= 1740 MPa υ= 0.30; Φ_i= 46.00 c_i= 1.048 MPa	Dark gray-gray, generally massive, locally jointed, hard-medium, Marl, GSI: 65
PS	Soma-Kınık Underground Coal Mine Drift Excavation	UCS_i= 20.16 MPa; E_i= 1210 MPa υ= 0.29; Φ_i= 45.86 c_i= 0.258 MPa	Gray – Ligth gray, often–very often jointed schistosity planes slippery shiny, disintegrated partially, weak-very weak, Schist, GSI:
TS-1	Tokat-Topçam Railway Tunnel Construction	UCS_i= 52.26 MPa; E_i= 4440 MPa υ= 0.31; Φ_i= 60.27 c_i= 0.923 MPa	Gray-dark gray, massive-jointed with clay band, generally hard-medium strength Siderite, GSI: 65
TS-2	Tokat-Topçam Railway Tunnel Construction	UCS_i= 80.63 MPa; E_i= 12020 MPa υ= 0.23; Φ_i= 62.41 c_i= 1.247 MPa	Gray-ligth gray, hard-very hard, generally massive, Siderite, GSI: 75

Table 2 Geotechnical properties of the rocks studied

SAMPLE	Ei (from Laboratory Tests) (MPa)	RMR	Q	GSI	σi (from Laboratory Tests) (MPa)
Afyon Conglomerate-1	1180	33	0.46	30	9.99
Afyon Conglomerate-2	2050	42	0.80	40	13.07
Eynez Marl	1910	54	3.04	50	24.29
Tuncbilek Claystone	3210	49	2.18	45	28.40
Isıklar Marl	1560	59	5.29	55	29.42
Isıklar Conglomerate	8360	48	1.56	40	12.39
Isıklar Claystone	4900	56	3.79	50	20.74
Isıklar Limestone	4420	63	8.26	60	52.07
Mesudiye Marl	1740	71	22.45	65	62.07
Polyak Schist	2090	53	2.72	45	20.16
Topcam Sandstone-1	4440	68	14.39	65	52.26
Topcam Sandstone-2	12020	80	68.19	75	80.63

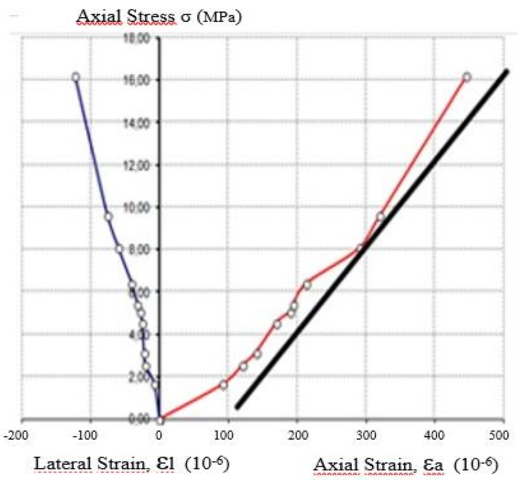

Fig. 3 The result of deformability test

possible. The geotechnical conditions of the study areas and the properties of the rocks used in the study are given in Table 2. E_i, which is used to estimate the E_{mass} of rock mass is included as a parameter in the formulas as displayed in Table 3. These equations have been developed for E_{mass} estimation by different researchers. E_i value is a static value and does not vary with time. Fig. 3 exhibits the E_i values obtained from the classical deformability test results. E_i value which is the slope of stress-strain curve at 50% of the ultimate load and the υ (horizontal/vertical deformation) are used as parameters. In the present method, the E_i value obtained with these experimental data is used in empirical formulas used in rock mass deformation modulus (E_{mass}) calculations. The E_{mass} value calculated in this way is a constant value independent of load and time.

In this study, instead of a constant E_i value (shown in Fig. 3) found by the method used today, investigations have been carried out to produce E_i values which take different values under different constant loads over time. In

Table 3 Some equations used in the determination of deformation modulus of rock mass (courtesy of Aksoy *et al.* 2012)

Researchers	Equation	Notes
Nicholson and Bieniawski (1990)	$E_{mass} = \frac{E_i}{100}\left[0.0028\,RMR^2 + 0.9\exp\left(\frac{RMR}{22.82}\right)\right]$	
Mitri *et al.* (1994)	$E_{mass} = E_i\left[0.5\left\{1-\cos\left(\pi\frac{RMR}{100}\right)\right\}\right]$	
Kayabasi *et al.*(2003)	$E_{mass} = 0.135\left[\frac{E_i(1+RQD/100)}{WD}\right]^{1.1811}$	
Gokceoglu *et al.*(2003)	$E_{mass} = 0.001\left[\frac{(E_i/\sigma_{ci})(1+RQD/100)}{WD}\right]^{1.5528}$	
Sonmez *et al.* (2004)	$E_{mass} = E_i(s^a)^{0.4}$ $s = \exp[(RMR-100)/9]$ $a = 0.5 + 1/6[\exp(-GSI/15) - \exp(-20/3))]$	
Sonmez *et al.* (2006)	$E_{mass} = E_i 10^{[((RMR-100)(100-RMR)/4000\exp(-RMR/100))]}$	
Hoek and Diederichs (2006)	$E_{mass} = E_i\left(0.02 + \frac{1-D/2}{1+e^{(60+15D-GSI)/11}}\right)$	If there is no deformation measurement on intact rock material: $E_i = MR \cdot \sigma_{ci}$

RQD: rock quality designation | E_i: deformation modulus of intact rock
RMR: rock mass rating | E_{mass}: deformation modulus of rock mass
RMi: rock mass index | MR: modulus ratio
Q0: rock mass quality rating | WD: weathering degree
GSI: geological strength index | D: disturbance factor
σ_{ci}: UCS of intact rock | s, a: Hoek-Brown rock mass constants

this way, when calculating the deformation module with empirical formulas, it will be possible to use E_i values which vary according to load and time. In this way, it is possible to produce different E_{mass} values in time depending on different constant loads in the design of rock structures and more accurate designs can be made by using these variable E_{mass} values in calculations. Figure 4 shows the variations in E_i and υ of the rocks from time-dependent deformations under constant loads applied on different rock types sampled from different regions.

Important result obtained in some experiments can be expressed as that E_i curves clustered under changing loads. However, just one part of the curve can be distinguished from the others. At this stage, E_i values can be much different from the previous behavior under any load. For example, experiments were carried out on the EM sample with 4 different loads. The curves appear to be clustered at 3 (20, 25 and 30 kN) of the experiments and the experimental curve under 35 kN load was separately located in other experimental curves. At the same time, there is also a difference in the trends of the curves. E_i was reduced from 1.60 GPa to 1.45 GPa after 143 hours of the outset of the experiment when a load of 20 kN was applied on EM sample. Reduction rate in 143 hours was about 9,38%. Then, after 177 hours of the outset of the experiment, E_i was reduced from 1.59 GPa to 1.49 GPa when a load of 25 kN was applied. The reduction rate in E_i after 177 hours of the outset of the experiment was obtained to be 6,29%. In an experiment with an applied load of 30 kN, E_i decreased from 1.65 GPa to 1.48 GPa in 147 hours of the outset of the experiment with a reduction rate of 10,31%. In another experiment with an applied load of 35 kN, E_i was reduced from 1.71 GPa to 1.63 GPa after 147 hours with a reduction rate of 4.68%.

Variances in E_i values over the time demonstrated a decreasing tendency under constant load. Hence, the deformation ability of the rock material appears to increase under unit stress condition, which also causes the rock to become more brittle. On the other hand, when the results of the experiments under a constant load of 60 kN on TS-2 samples were analyzed, Ei value seemed to reduce from 8.06 GPa to 7.67 GPa after 60 hours and to 7.48 GPa after 120 hours with reduction rates of 4.84% and 7.20%, respectively. Under a constant load of 70 kN, initial E_i value of 8.73 GPa decreased to 8.53 GPa following 60 hours and to 8.15 GPa after 120 hours. Reduction rate in E_i value was calculated as 6.64% at the end of 120 hours (5 days). In an experiment carried out at a constant load of 80 kN, initial Ei value of 9.15 GPa was reduced to 8.82 GPa after 60 hours (2.5 days) and to 8.67 GPa following 120 hours with a

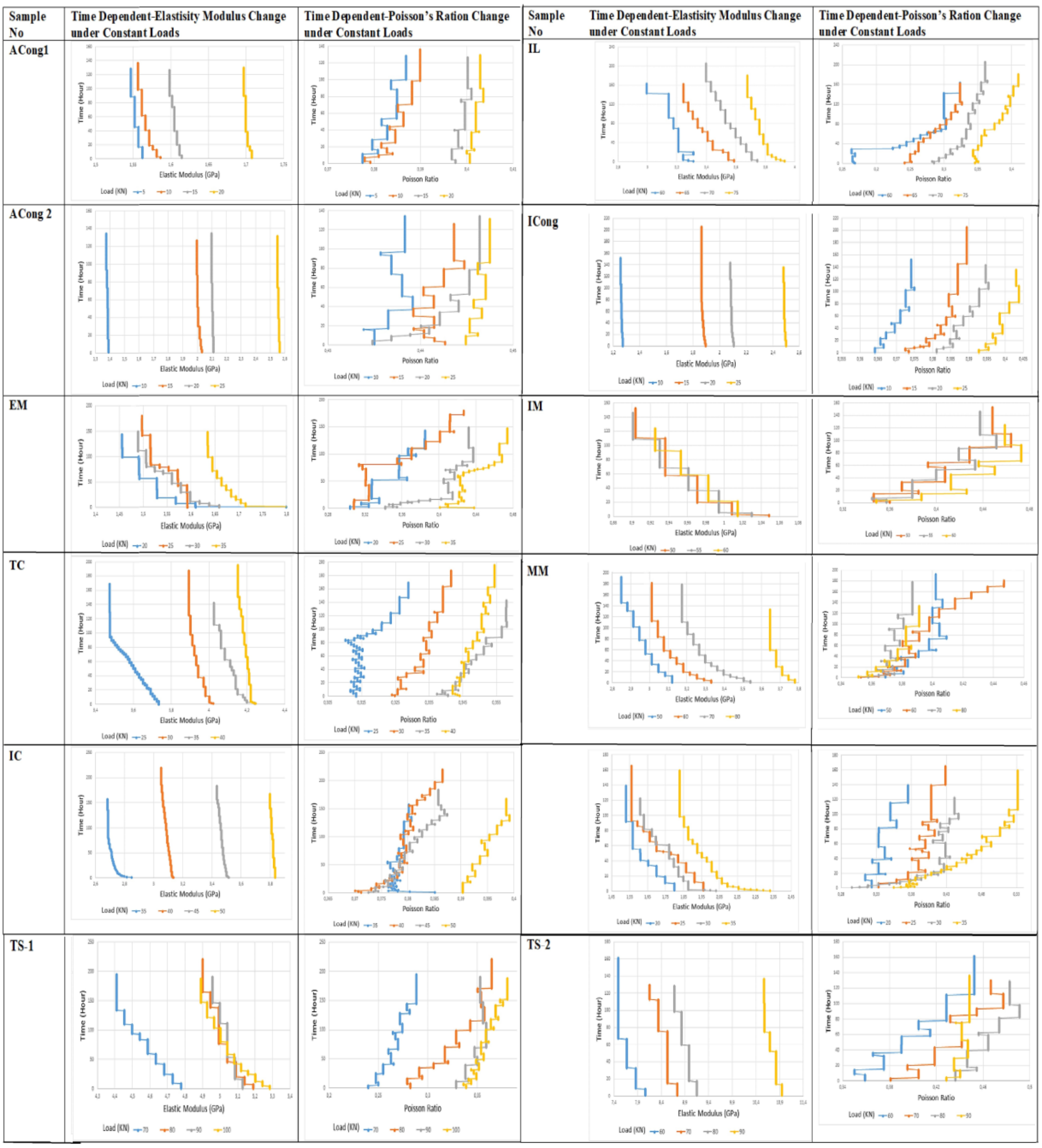

Fig. 4 Time-dependent variations in elastic modulus and Poisson's ratio under constant load

reduction rate of 5.24% after five days of constant loading. Furthermore, under a constant load of 90 kN, initial E_i value of 10.95 GPa decreased to 10.69 GPa after 60 hours and 10.57 GPa after 120 hours. On the other hand, the static E_i value of the EM sample was determined to be 1.91 GPa. However, under constant load, it varied between 1.45-1.71 GPa and the υ was 0.22. While, the static E_i value of the TS-2 sample was obtained to be 12.02 GPa., under constant load, it was measured between 7.48-10.95 GPa and the υ was found to be 0.28. The results obtained from the experiments are demonstrated in Table 3. υ which is defined as the ratio of the amount of lateral deformation to the amount of vertical deformation, is the inverse of E_i. Principally, as the constant load applied to the sample increases, υ will also increase. Namely, under constant load, lateral deformation of the samples will be more than vertical deformation. Hence, cohesion will play an effective role in time-dependent failures when the samples are under constant load. As can be seen in the trends in υ curves, it seems difficult to have a clear approach as in the curves of E_i.

3. Results and discussion

Poisson's ratio (υ) is defined as minus the transverse strain divided by the axial strain in the direction of applied load. As explained in the statement, during the creep experiments, Poisson's ratio was determined by proportioning horizontal deformations to vertical deformations that occur with time under constant load. Therefore, time dependent values of Poisson's ratio of rock sample were recorded. Also, modulus of elasticity (E_i) was calculated based on Hooke's Law which is expressed in terms of stress and strain (E = Stress / Strain). Stress (σ) is defined as load per unit area and strain (ε) is defined by the relationship $\varepsilon = \Delta L / L_0$, in which ΔL indicates the change in sample length with time and L_0 denotes the initial length of tested sample. Hence, time-dependent values of Poisson ratios (υ) and modulus of elasticity (E_i) were determined for each sample under various constant loads.Secant modulus was used for time modulus of elasticity. The experiments performed have been carried out many times (at least 5 times) and can be repeated by any researcher.

Table 2 shows the E_i values obtained from the deformation tests performed by classical method. Figure 4 displays the E_i values obtained from time-dependent deformation tests under various constant loads. Considering the E_i values in both tables significant differences can be noticed. For example, the E_i value obtained from the classical deformation tests in the Afyon Conglomerate sample is 1180 MPa, while the E_i minimum 1540 MPa and maximum 1710 MPa can be realized as a result of time-dependent deformation experiments under various constant loads. According to these results, the E_i value obtained from the experiments carried out under time and different constant loads is 30.5-44.91% higher than the E_i values obtained from the classical method experiment. In contrast to this, the E_i value obtained by the classical deformation test in the Topcam Sandstone-2 sample was 12020 MPa, while the E_i values could be minimum 7500 MPa and maximum 10900 MPa as a result of the deformation experiments performed under different constant loads depending on time. In this case, the E_i values obtained by the time-dependent method can be as small as 9.32-37.60% than the conventional method. In these two examples, the E_i value obtained by the classical method is more or less in the E_i values obtained from the deformation tests under time-dependent constant loads. The more complex one is the Polyak schist sample. The E_i value obtained as a result of the classical deformation test (as Fig. 3) performed on this sample is 2090 MPa. The minimum E_i value obtained from the deformation experiments carried out under time and constant loads on this sample is 1530 MPa maximum value 2330 MPa. In this case, the E_i values used in the new method can be 24.79% or 11.48% higher than the E_i value obtained by the conventional method. The important thing in the design phase is to calculate the load that the rock mass will be exposed to, which is not an easy thing. Moreover, it is important to remember that the loads have changed or repeated continuously during the excavation phases. For the E_{mass} values used in the design, it would be correct to make an evaluation based on the discussion of the values given in E_{mass} values are the values in which the E_i value in the formulas (from Table 3) is obtained by the classical deformation test. $E_{mass\text{-}v}$ (E_{mass}-Variable) values can obtained by using the E_i values obtained by time dependent deformation tests under different constant loads in the related formula. In this case, the static E_{mass} value calculated for Afyon Konglomera-1 rock mass is 800 MPa for the formula of Hoek and Diederich (2006), 813 MPa for the formula of Nicholson and Bieniawski (1990) and 919 MPa for the Ramamurty (2004) formula. According to Hoek and Diederich (2006) formula, 752-805 MPa, 766-810 MPa for the formula of Nicholson and Bieniawski (1990) and 775-952 for Ramamurty (2004) formula under E_i values obtained from deformation experiments under time and constant loads. In the case of the Hoek and Diederich (2006) formula, the E_{mass} value obtained in the conventional method may be approximately 6% lower than the value obtained by the time-load dependent tests or 1% higher. This difference may be more or less in other examples. This is particularly important for the design of rock masses, which score close to the boundary zones in rock mass classification systems during preliminary design.

In laboratory deformation tests, it has been confirmed that the rocks have different E_i and υ under different applied loads. E_{mass} values, which can be predicted by empirical equations, will differ as E_i value in empirical equations changes. In this case, different $E_{mass\text{-}v}$ values are obtained for different applied loads. Different $E_{mass\text{-}v}$ values allow the rock mass to exhibit different deformation behaviors under different loads in time.

E_{mass} is known as one of the most important rock mass property used in designing the structures. Several methods are used to determine the in situ value of E_{mass}. Although, various results were obtained from experimental work in this study, they are expensive and time-consuming (Palmström and Singh, 2001). For this, reason, determination of E_{mass} by the empirical equations should be more reasonable. In general, the empirical aquations are developed as a result of rock mass classifications. Particularly, both E_m and υ are important input parameters in numerical modelling which is employed extensively in the stability analysis of rock structures in rock mass. E_i value is widely used as a parameter in most of the empirical equations for the prediction of E_{mass} as displayed in Table 4, in which it can be clearly seen that the value of E_{mass} will vary as the E_i value varies. Obviously, variations in E_{mass} will influence the stability of rock structure.

Conditions of the design is an important subject which should always be kept in mind. For instance, stresses around an excavation will vary depending on the depth of overburden and lateral stresses around shallow tunnels are higher than vertical stresses. As soon as the tunnel excavation is commenced, not immediately but after a while, ultimate stress values will be reached. The rock surrounding the tunnel will remain under the influence of ultimate stresses for long periods. Therefore, under the constant load, use of the time-dependent E_i value in lieu of static E_i will ensure the stability of underground openings.

4. Conclusions

Static values of elastic rock properties are generally employed in the design of rock structures excavated in rock mases. However, rock masses may be exposed to constant loads for long periods of time and use of static values may be misleading in such designs. Particularly, the values of elastic rock properties such as E_i and υ will be time-dependent values in the equations of E_{mass} which are used as input in numerical modelling works, whereas the parameters will change under constant load. Both stress that has effects on the rock mass and time play roles on such parameters.

E_i value tends to decrease with time under constant load and deformability of rock will increase. However, it tends to increase as the stress increases. Both the decrease and increase in stress with time have not yet been mathematically expressed. This study confirms that the E_i value which is obtained from classical deformability tests is higher than the E_i value obtained from constant load tests. Namely, when static values are used in empirical equations, we define the rock material more elastic than it is and this, in fact, mislead the reliable designing of underground rock structures. The E_i and υ values in equations used in designing of rock structures are not static, moreover, they are time-dependent and influenced by the conditions of nature. Hence, use of time-dependent values of E_i and υ will be the best approach in designing safer and more economical engineering structures in rock masses. A numerical modeling study may be suggested to prove the findings of this study as a further work.

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