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Remodelling The Time-Dependent Deformation Behaviour Under Different Constant Loads For Medium Strength Rocks

Orta Dayanımlı Kayaçlar Için Farklı Sabit Yükler Altında Zamana Bağlı Deformasyon Davranışının Yeniden Modellenmesi

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Abstract
Rock structures built in rock masses will remain under constant load during the process starting with the construction phase and continuing throughout their service life. Particularly, medium strength rocks will undergo time-dependent deformation under constant load after the commencement of mining or civil engineering works. Following the beginning of deformations start with the closing of the discontinuities, the rock material will undergo deformation depending on the load of which it is exposed to. In this case, the deformation properties of the rock mass can become important for the stability of an engineering structure. Generating empirical equations in the design of rock structures will pave the way for more practical designs as compared to more expensive and time-consuming in situ testing. These equations use laboratory-acquired uniaxial compressive strength and elastic modulus values of rocks as parameters. These formulas produced for design can be used safely in engineering. In this study, time-dependent deformation properties under constant load on four different and medium strength rocks from different locations were analyzed. The results showed that rocks of medium hardness deform differently under various constant loads. In addition, a significant time-load-strength-deformation function was obtained from the results of laboratory experiments performed on different rock types under various constant loads.
Key Words: Deformation mechanism, hypersurface approximation, medium strength rocks

Özet
Kaya kütleleri içine inşa edilen kaya yapıları, inşaat aşamasından başlayarak hizmet ömrü boyunca devam eden süreçte sürekli yük altında kalacaktır. Özellikle orta mukavemete sahip kayaçlar, madencilik veya inşaat mühendisliği çalışmalarının başlamasından sonra sabit yük altında zamana bağlı deformasyona uğrayacaktır. Süreksizliklerin kapanımıyla birlikte deformasyonlar başladıktan sonra kayaç malzemesi maruz kaldığı yüke bağlı olarak deformasyona uğrayacaktır. Bu durumda, kaya kütlesinin deformasyon özellikleri mühendislik yapısının stabilitesi açısından önemli hale gelmektedir. Kaya yapılarının tasarımında ampirik denklemlerin üretilmesi, pahalı ve zaman alıcı yerinde testler yerine daha pratik tasarımların önünü açacaktır. Bu denklemler, kayaçların laboratuvarda elde edilen tek eksenli basınç dayanımı ve elastisite modülü değerlerini parametre olarak kullanmaktadır. Tasarım için üretilen bu formüller mühendislikte güvenle kullanılabilmektedir. Bu çalışmada, farklı konumlardaki dört farklı ve orta dayanımlı kayanın sabit yük altında zamana bağlı deformasyon özellikleri analiz edilmiştir. Elde edilen sonuçlar, orta sertlikteki kayaçların çeşitli sabit yükler altında farklı şekilde deforme olduklarını göstermiştir. Ayrıca, farklı kayaç türleri üzerinde çeşitli sabit yükler altında yapılan laboratuvar deneylerinin sonuçlarından önemli bir zaman-yük-dayanım-deformasyon fonksiyonu elde edilmiştir.
Anahtar Kelimeler: *Deformasyon mekanizması, hiperyüzey yaklaşımı, orta dayanımlı kayalar.*

1. Introduction

In a rock engineering design, the properties of the rock should be appropriately represented. Many researchers developed empirical equations widely used instead of in situ tests, as in situ tests are expensive, time consuming and inconsistent (Palmström and Singh 2001). Therefore, it became more common to determine the deformation modulus of the rock mass with the empirical equations (Nicholson and Bieniawski 1990; Mitri et al. 1994; Hoek and Diederichs 2006; Aksoy et al. 2012; Aksoy et al. 2022). The other parameter is the rock mass strength, which can also be determined by empirical equations. The Uniaxial Compressive Strength (UCSi) of intact rock is a parameter in empirical equations (Cai et al. 2007; Dinc et al. 2011; Kalamaris and Bieniawski 1995; Brown 2008; Aksoy et al. 2018).

Barla (2002) stated that some rocks have high deformation ability which may take a long time. The time dependent behavior of the rock mass in fractured rocks is very important (Bieniawski 1973). In this study, the deformation behavior of four different rocks of medium strength under various loads was investigated. Finally, meaningful equations representing the time-load-strength dependent deformation properties of the rocks were introduced.

2. Material and Method

A hydraulic servo-controlled loading machine was installed to analyze the deformation behavior of rocks under constant load and over time. (Fig. 1)

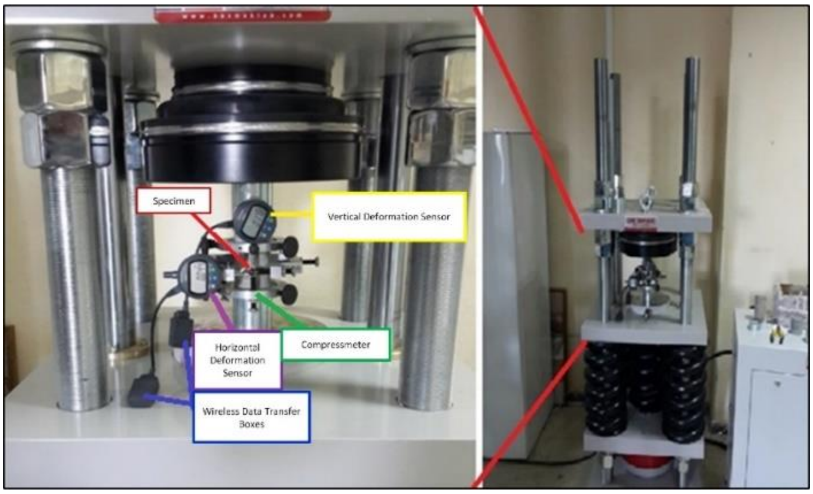


Fig. 1. Hydraulic servo controlled loading machine

After preparing the samples according to ISRM Recommended Method (2007), various constant loads were applied to samples taken from various rock types. The level of constant load to be applied was determined as 50%, 60%, 70% and 80% of the UCSi value of the rock. The set-up system (Fig. 2) was able to measure the deformations in the sample. The experiment was considered to be completed when no more deformation was recorded on the sample.

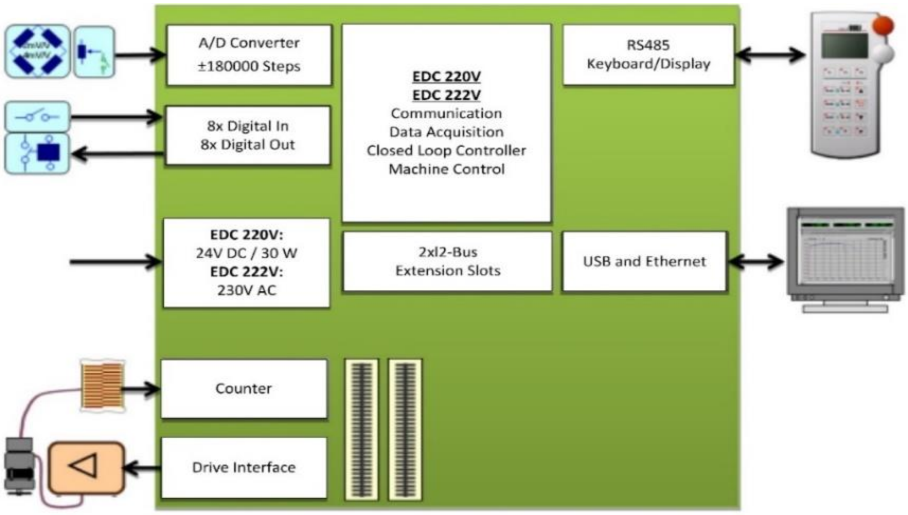


Fig. 2. Deformation recording system

This study aims to estimate the deformation that occurs over time under constant load in various rocks. The environmental parameters related to tests such as temperature and humidity were kept constant during the experiments. The detailed information regarding the rock samples used in this study is given in Table 1, while the results of the tests are illustrated in Table 2. Within the context of the study, deformability tests were performed on a sum of 64 rock samples with medium-strength and their average results are presented in Table 2.

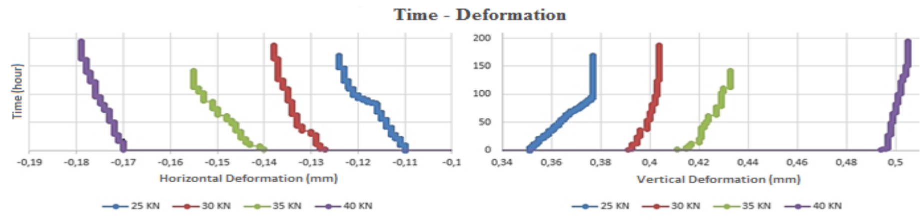
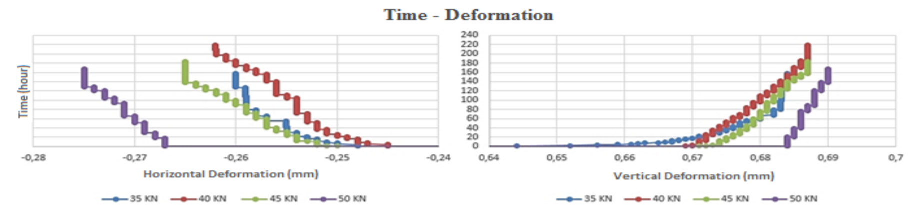
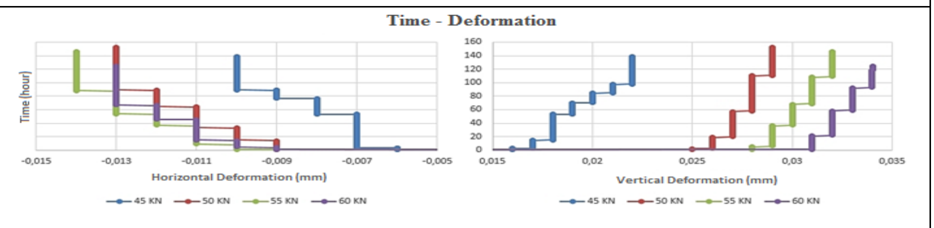
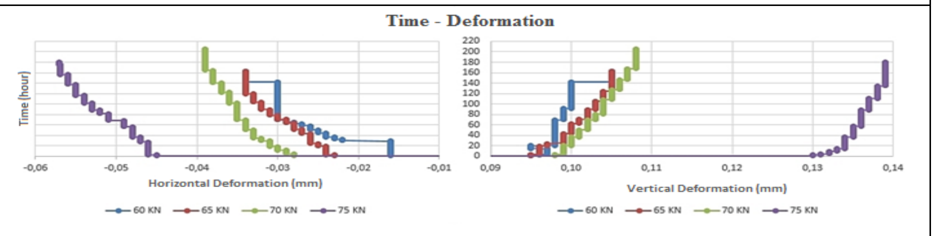
Table 1. Types, properties and lithology of the rocks tested

Sample No	Project	Rock Properties	Lithology and Rock Description
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: 27.02 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

IM	Soma-Işıklar Underground Coal Mine	UCS_i: 34,26 MPa E_i: 1560 MPa υ: 0.26 Φ_i: 47.70 c_i: 0.445 MPa	Homogeneous structure, hard and generally massive. Gray-light gray, and when they are broken, they turn into a light gray color called ash color. They are medium thick layers., Marl, GSI: 55
IL	Soma-Işıklar Underground Coal Mine	UCS_i: 47.11 MPa E_i: 4420 MPa υ: 0.27 Φ_i: 53 c_i: 0.862 MPa	Gray-light gray, generally massive, locally jointed, clay infilling, hard, sometimes medium, Limestone, GSI: 60

UCS_i: uniaxial compressive strength, E_i: elastic modulus of intact rock, υ: Poisson's ratio, Φ_i: internal friction angle of intact rock, c_i: cohesion.

Tab. 2. Time-Dependent Deformations for Rocks under Constant Load

Sample No	Rock Type	Time – Deformation graphs under constant loads
TC	Claystone	
IC	Claystone	
IM	Marl	
IL	Limestone	

3. Hypersurface model for time-dependent deformation behavior of rocks

The results of the time dependent deformation tests under constant load and uniaxial compressive strength of rocks were evaluated and the new mathematical model was developed to define load – time – uniaxial compressive strength hypersurface of rock deformation characteristics.

In this section, multivariable function $u = f(x, y, z)$ is defined on $\mathfrak{R}^4$ for the function with three independent variables x, y, z *and* u the dependent variable. The hypersurface $u = f(x, y, z)$ is considered to approximate over a region that is gridded by (x_i, y_j, z_k) on $\mathcal{R}^3$ and $u_{ijk} = f(x_i, y_j, z_k)$ data given for the function of three variables at the distinct points in the solid rectangular region where x is load (kN), y is time (h), z is the uniaxial compressive strength (MPa) and u is horizontal or vertical deformation (mm).

The partial derivative of the function having three variables is its derivative with respect to one of those variables where the others are held constant. Partial differentiation is used when we take one of the tangent lines of the graph of the given function and obtain its slope. For medium-strength rocks, the rate of change in the deformation with respect to the load or the time is linearly proportional to the deformation and their slopes are positive. The rate of change in the deformation with respect to the strength is inversely proportional to the deformation and its slope is negative. Accordingly, the following definition is:

Let

$$\frac{\partial u}{\partial x} = Lnb.u > 0 \, , \frac{\partial u}{\partial y} = Lnc.u > 0 \text{ and } \frac{\partial u}{\partial z} = Lnd.u < 0 \qquad (1)$$

where u *is* positive variable b, c and d are positive constants. The total differential du of the function $f(x, y, z)$ is

$$du = \frac{\partial f}{\partial x} dx + \frac{\partial f}{\partial y} dy + \frac{\partial f}{\partial z} \, dz \, . \qquad (2)$$

This differential is rewritten as

$$\frac{du}{u} = Lnb.dx + Lnc.dy + Lnd.dz \qquad (3)$$

and the general solution of this differential is obtained as

$$Lnu = Lnb.x + Lnc.y + Lnd.z + k \qquad (4)$$

$$u = e^{\log_e b\, .x + \log_e c.y + \log_e d.z + k} = \left(e^{\log_e b}\right)^x \left(e^{\log_e c}\right)^y \left(e^{\log_e d}\right)^z e^k \qquad (5)$$

and

$$u = f(x, y, z) = a\, b^x c^y d^z \tag{6}$$

where $a = e^k$ and k is the integral constant.

Given a hypersurface $u = f(x, y, z)$ to approximate over the solid rectangular region that $u_{ijk} = f\left(x_i, y_j, z_k\right) = a\, b^{x_i} c^{y_j} d^{z_k}$ passes through each point in the solid rectangular region. The problem of the hypersurface approximation satisfying the data with minimum error is called finding the most optimal function.

Let us suppose that there exists a nonlinear hypersurface with independent variables load, time and uniaxial compressive strength that are called x, y and z respectively, and dependent variables horizontal and vertical deformations named as $u_h = a_h\, {b_h}^x {c_h}^y {d_h}^z$ and $u_v = a_v\, {b_v}^x {c_v}^y$ can be formulated. Finally, the least squares method can be used for determining the coefficients a_h and a_v and parameters b_h, c_h, d_h, b_v, c_v , d_v which are obtained by various methods using the generalized inverses, especially the least squares method which is applied to the best approximate solution for the inconsistent system of the linear equations (Penrose 1955; Bazaraa et al. 1993).

These hypersurface can be transformed to the linear forms as follows:

$$U_h = A_h + B_h x + C_h y + D_h z = g(x, y, z) \tag{7}$$

and

$$U_v = A_v + B_v x + C_v y + D_v z = h(x, y, z) \tag{8}$$

where $U_h = Lnu_h$, $U_v = Lnu_v$, $A_h = Lna_h$, $A_v = Lna_v$, $B_h = Lnb_h$, $B_v = Lnb_v$, $C_h = Lnc_h$, $C_v = Lnc_v$, $D_h = Lnd_h$ and $D_v = Lnb_v$.

We now consider Eq. 7 and Eq.8 to approximate over the solid rectangular region. Assumed that $U_{h_{ijk}} = g(x_i, y_j, z_k)$ and $U_{v_{ijk}} = h(x_i, y_j, z_k)$ data are given for the function of three variables at the distinct points in the solid rectangular region, there are the best hyperplanes approximation on $\Re^4$.

In our experimental study, there have been about 9167 measurements involving horizontal and vertical deformation values of each rock. The problem is formulated for using data as

$$A_h + B_h x_i + C_h y_i + D_h z_i = U_{h_i}, \text{ for } i = 1,2, \dots, n \tag{9}$$

and

$$A_v + B_v x_i + C_v y_i + D_v z_i = U_{v_i}, \text{ for } i = 1,2, \dots, n \tag{10}$$

where n is experimental number of data. Eq. 9 and Eq.10 can be defined the matrix equation, which is used to find the coefficients as follows:

$$\begin{bmatrix} 1 & x_1 & y_1 & z_1 \\ 1 & x_2 & y_2 & z_2 \\ \vdots & \vdots & \vdots & \vdots \\ 1 & x_n & y_n & z_n \end{bmatrix} \begin{bmatrix} A_h \\ B_h \\ C_h \\ D_h \end{bmatrix} = \begin{bmatrix} U_{h1} \\ U_{h2} \\ \vdots \\ U_{hn} \end{bmatrix} \tag{11}$$

and

$$\begin{bmatrix} 1 & x_1 & y_1 & z_1 \\ 1 & x_2 & y_2 & z_2 \\ \vdots & \vdots & \vdots & \vdots \\ 1 & x_n & y_n & z_n \end{bmatrix} \begin{bmatrix} A_v \\ B_v \\ C_v \\ D_v \end{bmatrix} = \begin{bmatrix} U_{v1} \\ U_{v2} \\ \vdots \\ U_{vn} \end{bmatrix} \tag{12}$$

or

$$\mathbf{A}\boldsymbol{w}_h = \boldsymbol{t_h} \tag{13}$$

$$\mathbf{A}\boldsymbol{w}_v = \boldsymbol{t_v} \tag{14}$$

where $\mathbf{A} = \begin{bmatrix} 1 & x_1 & y_1 & z_1 \\ 1 & x_2 & y_2 & z_2 \\ \vdots & \vdots & \vdots & \vdots \\ 1 & x_n & y_n & z_n \end{bmatrix}$, $\boldsymbol{w}_h = \begin{bmatrix} A_h \\ B_h \\ C_h \\ D_h \end{bmatrix}$, $\boldsymbol{w}_v = \begin{bmatrix} A_v \\ B_v \\ C_v \\ D_v \end{bmatrix}$, $\boldsymbol{t_h} = \begin{bmatrix} U_{h1} \\ U_{h2} \\ \vdots \\ U_{hn} \end{bmatrix}$, $\boldsymbol{t_v} = \begin{bmatrix} U_{v1} \\ U_{v2} \\ \vdots \\ U_{vn} \end{bmatrix}$ and $\mathbf{A}$ is an $n \times 4$ coefficient matrix with rank 4, $\boldsymbol{w_h}$ and $\boldsymbol{w_v}$ are 4×1 vectors of the unknown parameters and coefficients, $\boldsymbol{t_h}$ and $\boldsymbol{t_v}$ are $n \times 4$ vectors consist of the horizontal and vertical deformations, respectively. The rank of $n \times 4$ rectangular matrix is 4 and the rank of the augmented matrix $[\mathbf{A} \vdots \ \boldsymbol{t_h}]$ or $[\mathbf{A} \vdots \ \boldsymbol{t_v}]$ is 5. Since systems have the same coefficient matrix, the matrix equation to find the best approximate solutions is defined as follows:

$$\begin{bmatrix} \mathbf{A} & 0 \\ 0 & \mathbf{A} \end{bmatrix} \begin{bmatrix} \boldsymbol{w}_h \\ \boldsymbol{w}_v \end{bmatrix} = \begin{bmatrix} \boldsymbol{t}_h \\ \boldsymbol{t}_v \end{bmatrix} \tag{15}$$

$$(\mathbf{A} \otimes \mathrm{I}_2)\boldsymbol{w} = \boldsymbol{t} \tag{16}$$

where I_2 is a 2×2 identity matrix, $\boldsymbol{w} = \begin{bmatrix} \boldsymbol{w}_h \\ \boldsymbol{w}_v \end{bmatrix}$ is the $8 \times 1 vector\ and\ \boldsymbol{t} = \begin{bmatrix} \boldsymbol{t}_h \\ \boldsymbol{t}_v \end{bmatrix}$ is the $2n \times 1$ and $\otimes$ is the Kronecker product. Furthermore, the optimal solution is the one that has the minimum length one of errors $\|(\mathbf{A} \otimes \mathrm{I}_2)\boldsymbol{w} - \boldsymbol{t}\|$. This solution with minimum norm is also the best approximate the least squares solution of any inconsistent linear system (Penrose, 1956).

The least squares method is applied to the system defined in Eq.16 as follows:

$$P(\boldsymbol{w}) = \|(\mathbf{A} \otimes \mathrm{I}_2)\boldsymbol{w} - \boldsymbol{t}\|^2 = (\boldsymbol{w}^T(\boldsymbol{A}^T \otimes \mathrm{I}_2) - \boldsymbol{t}^T)\ ((\mathbf{A} \otimes \mathrm{I}_2)\boldsymbol{w} - \boldsymbol{t}) = \boldsymbol{\varepsilon}^T\boldsymbol{\varepsilon} \quad (17)$$

is to be minimized respect to $\boldsymbol{w}$ coefficients elements of the matrix where $\boldsymbol{A}^T$ is the transpose matrix of $\mathbf{A}$ and $\boldsymbol{\varepsilon}$ is 2n× 1 error vector. The least squares estimator must satisfy

$$\nabla P(\boldsymbol{w}) = \frac{\partial \boldsymbol{P}}{\partial \mathbf{w}} = 2(\boldsymbol{A}^T\mathbf{A} \otimes \mathrm{I}_2)\boldsymbol{w} - \mathbf{2}\mathbf{A}^T\boldsymbol{t} = \mathbf{0} \quad (18)$$

which simplifies to the normal equation

$$(\mathbf{A}^T\mathbf{A} \otimes \mathrm{I}_2)\boldsymbol{w} = \mathbf{A}^T\boldsymbol{t}. \quad (19)$$

The Moore-Penrose generalized inverse $\mathbf{A}^+$ of A is obtained by using the normal equation and the unique solution of the normal equation is found in the form

$$\boldsymbol{w} = ((\mathbf{A}^T\mathbf{A})^{-1} \otimes \mathrm{I}_2)\mathbf{A}^T\boldsymbol{t} = \begin{bmatrix} \mathbf{A}^+ & \mathbf{0} \\ \mathbf{0} & \mathbf{A}^+ \end{bmatrix}\boldsymbol{t} \quad (20)$$

where $\mathbf{A}^+ = (\mathbf{A}\mathbf{A}^T)^{-1}\mathbf{A}^T$ is the Moore-Penrose inverse $\mathbf{A}^+$ of $\mathbf{A}$. Using Eq. 20, the vectors $\boldsymbol{w}_h$ and $\boldsymbol{w}_v$ of the unknown parameters and coefficients are computed easily as

$$\boldsymbol{w}_h = \mathbf{A}^+\boldsymbol{t}_h = (\mathbf{A}\mathbf{A}^T)^{-1}\mathbf{A}^T\boldsymbol{t}_h \text{ and } \boldsymbol{w}_v = \mathbf{A}^+\boldsymbol{t}_v = (\mathbf{A}\mathbf{A}^T)^{-1}\mathbf{A}^T\boldsymbol{t}_v. \quad (21)$$

The coefficients a_h and a_v and parameters b_h,c_h, d_h, b_v, c_v, d_v are calculated using Eq.21. Finally, the coefficient and parameters of the horizontal and vertical deformations formulas for 4 different medium-strength rocks types are computed, respectively.

4. Results and discussions

Consequently, it is seen that the amount of deformation tends to increase with increasing constant load. When the graphs are scrutinized, it is seen that deformation curves (horizontal and vertical) generally form a cluster. Deformation curves generally cluster at loads of 50%, 60%, 70% of the UCS_i of the rock. In experiments performed at 80% of the UCS_i of the rock, there is no change in deformation characteristic of the sample, but there is a visible rise for deformation which it is exposed to.

UCS_i is used as a parameter in the formulas when the strength of rock masses UCS_{rm} is calculated. Nonetheless, when the adequacy of rock mass strength is questioned in rock engineering designs, time and load on the rock mass are not considered. From this point of view, the strength of the rock material gains more importance. Although the deformation characteristics differ according to the discontinuity properties (Carter et.al., 2007; Carvalho et.al., 2007; Komurlu et al., 2017; Diederichs et.al., 2007), the amount of time-dependent deformation of the rock material under constant load and its characterization are significant in terms of stability. Especially, it should be considered while determining the deformation model of the rocks in numerical modeling analysis. While describing the deformation characteristics of the rock mass, it is useful to identify deformation behavior of rock masses under various loads.

The characterizations of the rock mass deformation dependent on time, load and uniaxial compressive strength were determined for four different medium-strength rock samples. The characterizations of the function with four variables were determined as a mathematical model. The defined hypersurfaces were stated with exponential function formulas and a mathematical model was developed to define load–time–uniaxial compressive strength hypersurface of rock deformation and the multivariable functions $u_h = a_h\, {b_h}^x {c_h}^y {d_h}^z$ and $u_v = a_v\, {b_v}^x {c_v}^y {d_v}^z$ are as follows:

$$\boldsymbol{w}_h = \mathbf{A}^{+}\boldsymbol{t}_h = \begin{bmatrix} 11{,}08501 \\ 0{,}01014 \\ 0{,}00091 \\ -0{,}47701 \end{bmatrix}, \boldsymbol{w}_v = \mathbf{A}^{+}\boldsymbol{t}_v = \begin{bmatrix} 12{,}56977 \\ 0{,}00166 \\ 0{,}000477 \\ -0{,}48055 \end{bmatrix}$$

From Eq. 7 and Eq. 8, the hypersurfaces are obtained as

$$u_h = 65186{,}77943(1{,}01019)^x(1{,}00091)^y(0{,}620634)^z \quad (22)$$

and

$$u_v = 287727{,}53882\ (1{,}00166)^x(1{,}00048)^y(0{,}61844)^z \quad (23)$$

As a result of the performed experiments, an equation was developed as explained in the previous section for the purpose of determining time-dependent deformation. It should be noted that the equation has unique constants for each rock type. Verification of the derived equations are given Eq. 22 and Eq.23.The correlation between the deformation values predicted by means of equations and the measured deformation values that were obtained from the results of the laboratory tests belonging 64 different rock samples, is given in Figure 3.

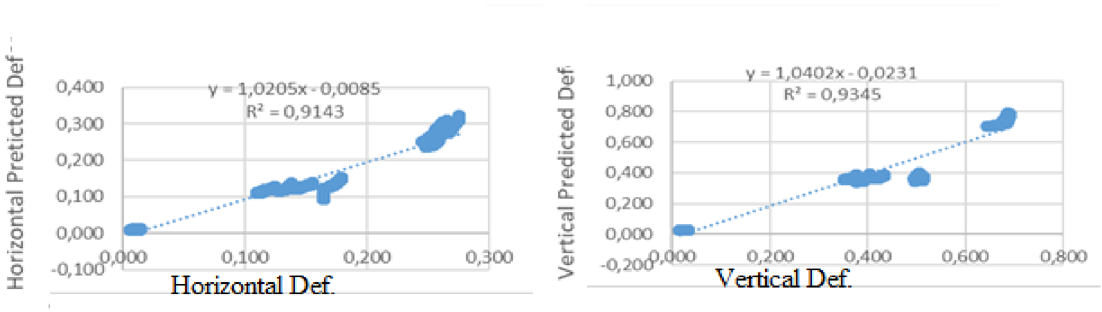


Fig. 3. Performance of the developed equation for horizontal and vertical deformation

When the graphs that illustrate the result of horizontal deformations obtained from the derived equation are scrutinized, it can be noted that accuracy ratios were calculated by the equation 0,9143 and 0,9345 for horizontal and vertical deformations, respectively (Figure 3). The amount of deformation measured for the same conditions under a constant load of 30kN (80% of the UCS_i) was nearly 0,391 mm while the final deformation amount after 168 hours under a constant load of 25 kN (70% of the UCS_i) was 0,377 mm in TC sample. The same rock underwent 96% more deformation under a constant load of (30kN). In TC, accuracy ratio happened to be 0.9345 when results obtained from the equation were analyzed.

As the amount of load applied to the rocks increases, the amount of deformation will also increase depending on the UCSi and type of intact rock. However, there will be no change in the behavior of deformation.

5. Conclusions

The studies in literature about time-dependent deformation behavior of rocks under constant load is limited. Since the rock structures remain under constant loads for a long time, the loads are crucial for long-term stability of rocks. The deformation behavior of the rock mass is also important for the safety of the design. In this research, an exponential empirical formula was developed to determine the deformation behavior of medium strength rocks under various constant loads. This formula predicts deformation with a high degree of accuracy when analyzed on the basis of rock type. The deformation estimated by this equation can be used to evaluate the amount of deformation allowed for the rock structure. In other words, all the characteristics of the rock mass, including the weakness, are taken into account when determining the rock class of the rock mass. The UCSi of the rock is an important parameter in many rock mass classification systems, being a constant derived from laboratory experiments as well as the elasticity modulus. The most important contribution of this research is to propose a new empirical formula for the estimation of rock deformation under different constant loads to which medium strength rock is exposed over time in rock structure design. This study will serve to guide practical mining and civil engineers working in underground conditions. The most significant contribution of the paper will be in tunnel construction projects, espacially in the phase of selecting excavation techniques. Also, it will assist underground engineers to plan the excavation and design of long-term support systems of underground structures thus enabling the managers for precise decision-making.

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