Time-Dependent Modulus of Deformation in Tunnels

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ABSTRACT

Modulus of deformation is recognised as one of the important parameters governing the rock mass behaviour. It is experienced that tunnel sections generally take long time to stabilise. These time-dependent deformations effect the tunnel lining along with the modulus of deformation of the rock mass.

The in-situ deformation/closure data from 37 arched tunnel sections through non-squeezing ground conditions have been collected and equations obtained from two models viz. Burger's four elements and Polynting's three elements were used to develop correlation for estimating time-dependent deformation modulus.

The study suggests that time for ninety per cent tunnel closure/deformation is less both for good quality rock and larger span of tunnel. The concept of retarded creep appears to be valid for weak and dry rock masses around a supported tunnel in non-squeezing conditions.

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1.0 INTRODUCTION

Dams and tunnels have to be founded on or in the natural geomaterials. An assessment of these structures for safety and stability necessitate a geotechnical characterisation of these geomaterials. In the context of this note, it implies determination of rock mass deformability which has been established by Muller (1974) as an important design parameter. In general, the presence of cracks, fissures, joints, shear zones and bedding planes in the rock mass makes the modulus function so complex that it is not possible to write a simple expression which encompasses all the important variables. Some empirical relations are, however, available which provide a first order estimate of the rock mass behaviour without having to perform time consuming and expensive field tests (Singh and Goel, 1999).

In India, a large number of hydroelectric power projects have been completed recently and several projects are under construction. These projects have generated a bulk of instrumentation data which have been analysed by Mitra (1991), Mehrotra (1992), Verman (1993), Goel (1994), Goel and Dubey (1995) and Singh (1997). These new data and their analysis has led to a revision of the existing empirical relations and formulation of new correlations which are subsequently described in this paper.

2.0 FUNDAMENTAL CONCEPTS AND SOME EXISTING EMPIRICAL RELATIONS

The load-deformation of rock mass generally appears as shown in Fig. 1. A change in the modulus of deformation, i.e., slope of the curve, under a number of loading-unloading cycles is attributed to irrecoverable deformation of the joints. The instantaneous modulus of elasticity which is approximately the same as the modulus of elasticity E_e has been obtained from fast unloading cycle using Boussinesque's theory as shown in Fig. 1. The modulus of deformation E_d is ratio of stress to ultimate value of time - dependent strain. It has been inferred from tunnel closure-time relations. Practically E_e is not much time-dependent and is assumed to be instantaneous modulus of elasticity.

In the first approach, the modulus of deformation of the rock mass is expressed as a function of the corresponding value for the intact rock E_r according to the following expression,

$$E_d = E_r \cdot MRF \tag{1}$$

where MRF = modulus reduction factor which is given as,

(i) Nicholson and Bieniawski (1990):

$$MRF = \frac{E_d}{E_r} = 0.0028\,RMR^2 + 0.9 \cdot e^{(RMR/22.82)} \tag{2}$$

(ii) Mitri et al. (1994):

$$MRF = \frac{E_d}{E_r} = 0.5 \cdot \left[1 - \cos(\pi \cdot RMR/100)\right] \tag{3}$$

where RMR = Rock Mass Rating according to Bieniawski (1978).

In the second approach, the E_d value is specified directly in terms of known parameters. Some typical correlations are given in Table 1. The following symbols are used in Table 1.

Q = Rock Mass Quality according to Barton et al. (1974),

J_w = Joint water reduction factor in Q system,

q_c = Uniaxial unconfined compressive strength of rock material at natural moisture content,

GSI = Geological Strength Index according to Hoek (1997), and

H = Tunnel depth from ground surface in metre.

Mehrotra (1992) also studied the effect of degree of saturation on the modulus of deformation. The state of initial stress in the rock mass depends on its depth from the ground surface, therefore, its deformation behaviour should depend upon the depth from ground surface as demonstrated by Verman (1993) and Singh (1997).

Table 1 - Empirical correlations for modulus of deformation of rock mass

Authors	Expression for E_d (GPa)	Conditions
Bieniawski (1978)	2. RMR - 100	q_c >100MPa and RMR > 50
Barton et al. (1980)	25 log Q	$Q > 1$, $q_c > 100$MPa
Serafim & Pereira (1983)	$10^{(RMR-10)/40}$	$q_c \geq 100$MPa
Verman (1993)	$0.3\ H^{\alpha}.\ 10^{(RMR-20)/38}$	$\alpha = 0.16$ to 0.30 (higher for poor rocks) $q_c \leq 100$MPa; $H \geq 50$ m; $J_w = 1$ Coeff. of correlation = 0.91
Hoek & Brown (1997)	$\frac{\sqrt{q_c}}{10}\ 10^{\frac{(GSI-10)}{40}}$	$q_c \leq 100$Mpa
Singh (1997)	$E_d = Q^{0.36}\ H^{0.2}$ $E_e = 1.5\ Q^{0.6}\ E_r^{0.14}$	$Q < 10$; $J_w = 1$ Coeff. of correlation for $E_e = 0.96$; $J_w \leq 1$

Note: The above correlations are expected to provide a mean value.

3.0 TIME-DEPENDENT CHARACTERIZATION

The rock mass characterization of the previous section is essentially time independent. In a time-dependent characterisation additional factors like the rate of load application and load duration also play an important role. In the utilisation of instrument data from a tunnelling project for a time-dependent characterisation of rock mass, care has to be exercised. The time dependence at the measuring location may arise due to the time-dependent tunnelling operation and the creep properties of the rock mass. For a true creep characterisation of rock mass, the two effects must be carefully separated. This section is devoted to a creep characterisation of rockmass which excludes the squeezing and swelling phenomena. It is known that the support pressure on lining continues to increase due to time dependent deformation of rock mass on account of its creep behaviour.

The previous work on this aspect is due to Wawersik (1974) and Bieniawski (1978). It may be noted that the creep behaviour is different from rheological behaviour where all time-dependent phenomena is considered.

The creep behaviour of rock mass consists of three stages.

(i) The transient stage in which strains gradually increase,
(ii) Steady state in which the strains increase at a constant rate, and
(iii) Rupture stage in which strain rate is very fast.

Lomnitz (1956) showed that in the case of silicate rocks such as grano-diorite and diorite, the steady state creep stage does not appear.

The creep characterisation of rock mass starts with the assumption of a model consisting of springs and dash pots of unknown characteristics. These are determined from the field data as shown by Langer (1969). Two commonly used creep models are shown in Figs. 2 and 3. The creep behaviour of these models are expressed as,

$$\varepsilon\ (t) = \left[\frac{1}{E_e} + \frac{1}{E_2}\left\{1 - \exp\left(\frac{-E_2 t}{\eta}\right)\right\}\right]\sigma \qquad (4)$$

$$\varepsilon\ (t) = \sigma\left[\frac{E_1 + E_2}{2\ E_1\ E_2} + \frac{1}{2\eta_2}t - \frac{1}{2E_2}e^{\frac{-E_2 t}{\eta_1}}\right] \qquad (5)$$

where,

E_2, η	=	Creep parameters,
E_e, E_1	=	Instantaneous modulus of elasticity,
t	=	Time in days,
σ	=	Applied uniaxial stress, and
$\varepsilon(t)$	=	Creep strain.

The parameters of springs and dashpots are also identified in Figs. 2 and 3.

The test results of Roger and Chin (1987) support the model shown in Fig. 3. In the present study, the tunnel closure data of 37 arched roof tunnels through nearly dry and non-squeezing ground reported by Goel (1994) and Goel and Dube (1995) is utilised in the rheological characterisation. Since the time-dependent deformations continue for a long time, the final recorded time is assumed as T. The relation between T_{90} and T is as obtained below.

3.1 *Time for Steady State*

$$T_{90} = 0.83\,T$$

$$T = \frac{350}{\left(0.20\,Q^{0.90}\ B^{1.45} - 1.0\right)^{0.30}} \text{ days}[\ 0.30< Q< 30;\ J_w = 1] \qquad (6)$$

$$\therefore \quad T_{90} = \frac{290}{\left(0.20\,Q^{0.90}\ B^{1.45} - 1.0\right)^{0.30}} \text{ days} \qquad (7)$$

where

T_{90}	=	Time for ninety per cent tunnel closure in days,
T	=	Approximate time in days when tunnel closure is stabilised, and
B	=	Tunnel diameter or span in meters.

The above Eq. 6 has a correlation coefficient of 0.91. Equations 6 and 7 show that the behaviour of dry rock mass is size dependent such that T is less in both larger tunnels and in better quality rock mass. It is also known that T is very large for saturated rocks as in hydroelectric projects (Mitra, 1991). More research is needed in this direction.

3.2 *Modulus of Deformation*

The Eqs. 4 and 5 may be rewritten as follows,

$$\varepsilon\,(t) = \frac{\sigma}{E(t)} \qquad (8)$$

$$\frac{1}{E(t)} = \frac{1}{E_e} + \frac{1}{E_d}.Y\left(\frac{t}{T_{90}}\right) \qquad (9)$$

where E(t) is time dependent modulus of deformation of rock mass and t is time at any instant in days.

The function Y is assumed to take the following two forms.

$$Y\left(\frac{t}{T_{90}}\right) = A\left(\frac{t}{T_{90}}\right) - B\left(\frac{t}{T_{90}}\right)^2 \tag{10}$$

$$Y\left(\frac{t}{T_{90}}\right) = 1 - \mathrm{Exp}\left\{-C\left(\frac{t}{T_{90}}\right)^D\right\} \tag{11}$$

Equation 10 represents both straight line as well as curvilinear curve through first and second degree of polynomial of t/T_{90}. Also it is similar to Burger's model representing retarded creep. The technique of non-linear curve fitting is used in the determination of value of parameters A, B, C and D of Eqs. 10 & 11 from the field data. These values are

A	=	1.65
B	=	0.73
C	=	2.30
D	=	1.20

Figure 4 drawn between t/T_{90} and the percentage deformation $[100.u_a(t)/ u_a(T)]$ shows that the curve obtained from Eq. 10 provides a superior correlation than Eq. 11 and it is corroborating with the field data. Here $u_a(t)$ is the radial tunnel closure at any given time t and $u_a(T)$ is the ultimate radial tunnel closure in time T.

4.0 CONCLUSIONS

Following conclusions are offered on the basis of study of closure-time data at 37 arched roof tunnel sections.

(i) Time for ninety per cent closure (T_{90}) is less both for good quality rock and larger span of tunnel according to Eq. 7. Extensive research in this direction may be fruitful.

(ii) Concept of retarded creep appears to be valid for weak and dry rock masses around a supported tunnel in non-squeezing conditions. Closure-time curve and time-dependent modulus of deformation may be deduced approximately using Eq. 10 and Eqs.9 &10 respectively. The correlations for pressure dependent E_d (Verman, 1993) and E_e (Singh, 1997) are found to be quite reliable for nearly dry, weak and highly jointed rock masses.

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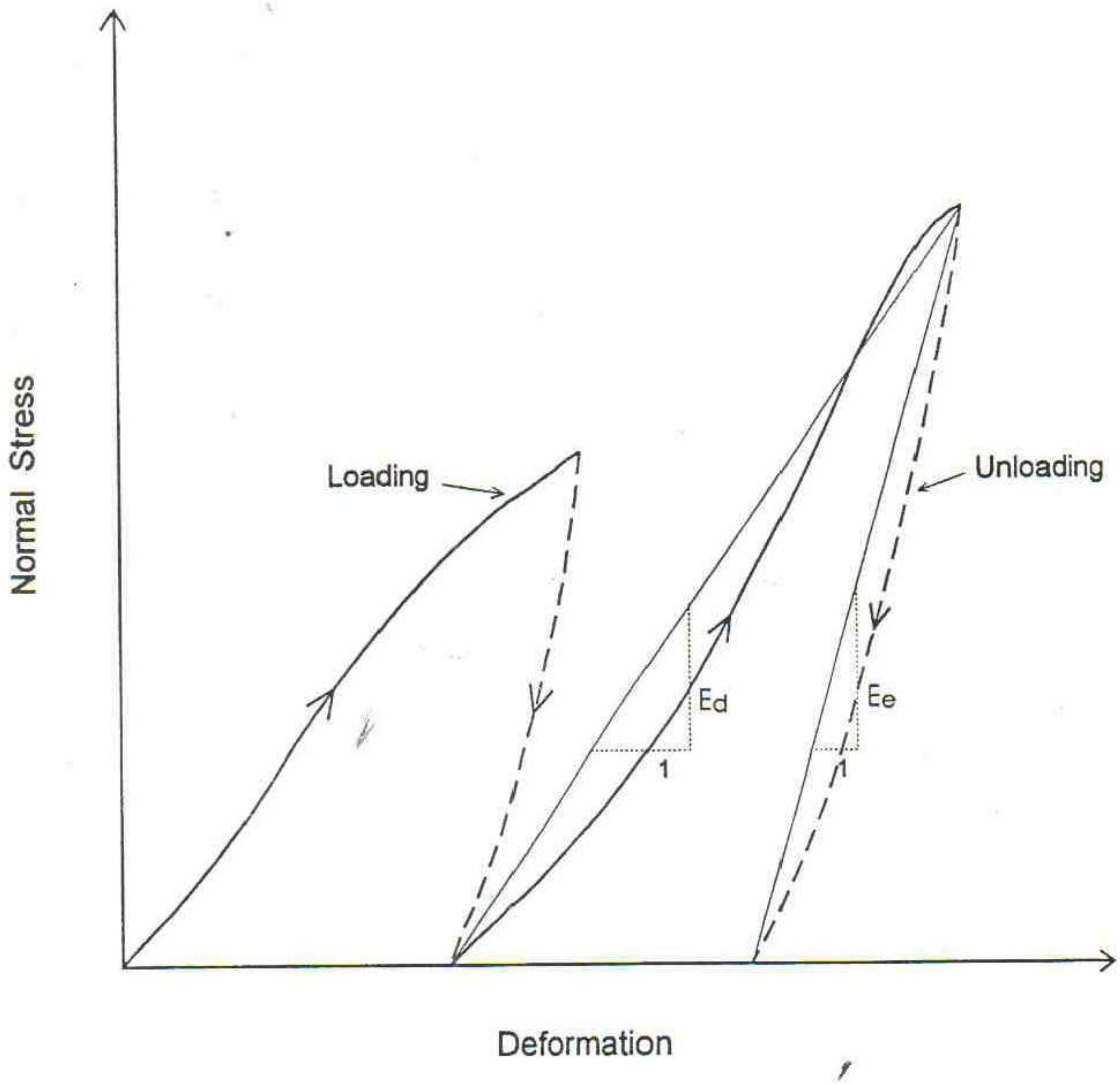

Figure 1 - Estimation of modulus of deformation (E_d) and modulus of elasticity (E_e) from loading and unloading cycles in a uniaxial jacking test

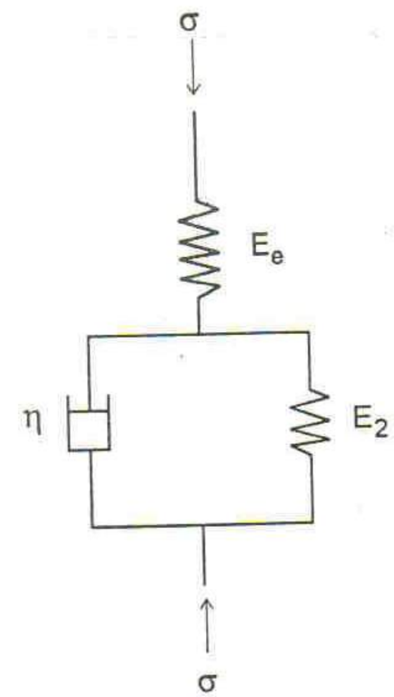

Figure 2 - Polynting's rheological model

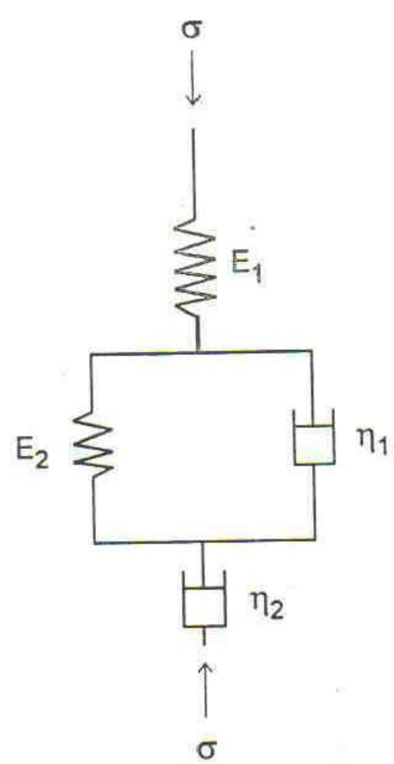

Figure 3 - Burger's rheological model

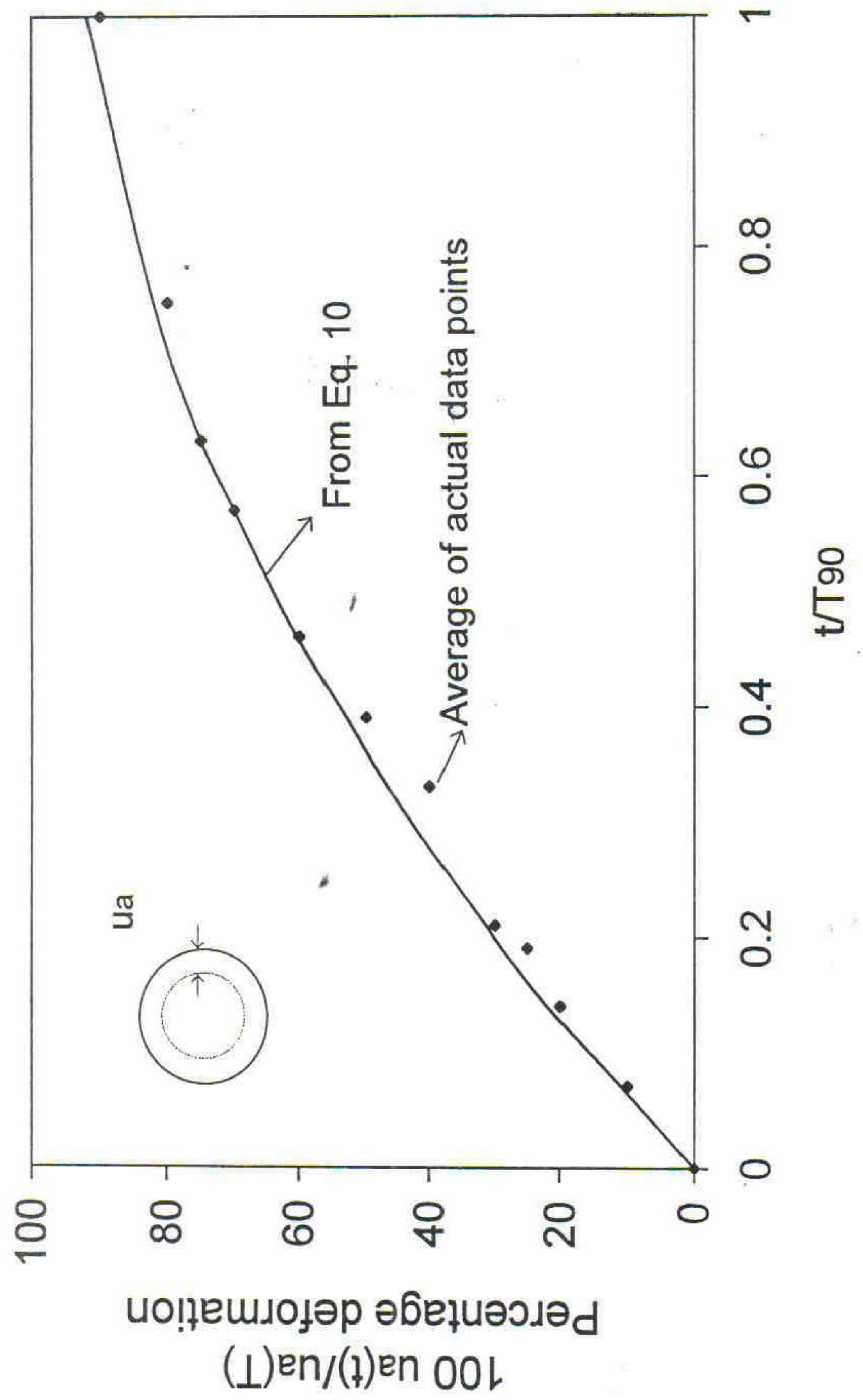

Figure 4 - Tunnel closure - time curve predicted by Eq. 10 vs average of actual data points