Numerical Back Analyses of Time-dependent Deformations of Tunnel in the Himalayas

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Abstract. Excavation of tunnels in squeezing ground conditions results in large deformation. Total deformation is a combination of instantaneous and time-dependent phenomena. To ensure the stability of the tunnel excavation, it is imperative to consider the deformation which manifests over time and design an adequate support system to ensure a stable configuration. In this study, finite element simulations are conducted to examine the time-dependent deformations around the tunnel in various geological settings. Three tunnel sections in the Himalayan region with overburden depths between 284 m to 426 m are considered. The selected sections pass through Quartzitic Phyllite, Phyllitic Quartzite, and Biotite Mica Schist. The time-dependent phenomena are modelled using the Visco-Elastic Perfectly Plastic (VEPP) constitutive model. The parameters of the model are calibrated and the efficiency of the VEPP to simulate the time-dependent deformation is established. Finally, the influence of overburden depth on time-dependent deformations for one of the chainages is investigated.

Keywords: Squeezing, Creep, Time-dependent Deformation, Finite Element Analysis, Visco-Elastic Perfectly Plastic.

1 Introduction

The deformation and progressive damage around the tunnel subjected to high in-situ stress is a complex phenomenon. Redistribution of stresses occurs around the excavation, resulting in stress concentration at the excavation boundary of the tunnel opening. Failure of rock mass takes place when the stresses exceed the strength of rock mass. Even after the completion of the excavation, the rock mass may undergo viscous behavior with time due to its rheological properties (Wu and Shao, 2019). It is essential to study the time-dependent deformations around the tunnel for its safe design and operation as it contributes 70% of total deformation (Sulem *et al.*, 1987; Paraskevopoulou and Diedrichs, 2018). Numerous phenomena, such as creep, consolidation, stress relaxation, swelling, and strength degradation are time-dependent. One such typical phenomenon is "squeezing" ground conditions which fall under the category of creep deformation. Throughout the construction and operation, effects such as face extrusion, increasing convergence and support pressures manifest as a result of the creep phenomena associated with squeezing ground conditions (Barla *et al.*, 2012). There are many cases of tunnels in India where squeezing ground conditions have been observed, for example, Syama Tunnel (Goel *et al.*, 2012; Goel *et al.*, 2013), Pir Panjal Railway Tunnel (Rao, 2009), Rohtang Tunnel (Singh *et al.*, 2018; Mehra *et al.*, 2019; Jain and Rao, 2022), Nathpa Jhakri (Goel *et al.*, 2012) and Khimti Tunnel and Tata hydroelectric project (Shrestha, 2006).

Time-dependent deformation can be simulated by either rheological models (Sulem *et al.*, 1987; Fahimifar *et al.*, 2010; Manh *et al.*, 2015; Song *et al.*, 2020) or empirical model (Shalabi, 2004; Chen and Small, 2017). Rheological models comprise of various combinations of mechanical elements such as spring, dashpot, and plastic switch, to replicate the viscoelastic, visco-plastic, or visco-elasto-plastic model. The most commonly adopted models are the kelvin-voigt, maxwell, and burger model which are a combination of springs and dashpots arranged either in series or parallel or a combination of them. Many studies have investigated the time-dependent deformation around the tunnel openings considering the medium as visco-elastic (Sulem *et al.*, 1995; Fahimifar *et al.*, 2010; Paraskevopoulou and Diederichs, 2018), visco-plastic (Manh *et al.*, 2015, Sainoki *et al.*, 2017), visco-elastic visco-plastic (Song *et al.*, 2020; Kabwe *et al.*, 2020). Some notable attempts at numerically capturing the time-dependent deformation have been reported (Fahimifar *et al.*, 2010; Barla *et al.*, 2012; Manh *et al.*, 2015; Lee et al., 2016; Sainoki *et al.*, 2017; Al-Maamori *et al.*, 2018; Song *et al.*, 2020; Paraskevopoulou and Diederichs, 2018; Khan *et al.*, 2019; Kabwe *et al.*, 2020, Iasiello *et al.*, 2021; Siddiquee and Hamdi, 2019). It should be noted that the accuracy of the numerical prediction is dependent on the appropriate selection of parameters which can either be obtained through extensive laboratory and field-based rock mass characterization or through back analysis of field instrumented data.

In this study, FE analysis is performed using the Visco-Elastic Perfectly Plastic (VEPP) constitutive model in Plaxis 2D. For the purpose of deriving the appropriate parameters of the model, three instrumented sections of a tunneling project passing through the Himalayas are considered. A simplified numerical model is set up and back analyses are conducted to obtain the set of input parameters to accurately capture the field instrumented time-dependent deformation. The results from the calibrated model are utilized to understand some mechanisms associated with time-dependent deformation. The calibrated model presented here is expected to serve future research studies to develop more robust numerical models and derive insights into the time-dependent behavior of tunnels in the rock mass.

2 Study area and Difficulties encountered during tunneling

India's physiographic attributes are interrelated to the country's diverse geology. The peninsular area in the south, the Himalayan terrain in the north, and the Indo-Gangetic plains in the center, all of which are drained by the rivers Indus and Ganges and their tributaries, are the three different physiographic types. The horse-shoe shape tunnel considered in the present study lies approximately 100 km south of the Indus structure zone and in the Pir Panjal range of the Himalayas. The study area belongs to varying geology consisting Chail (phyllite), Jutoh (gneisses, mica schist, biotite chlorite schist), and Vaikrita (migmatite) lithotectonic belts in the HHC, and these units have undergone metamorphism. Jutoh thrust marks the continuation to Main Central Thurst (MCT). It also crosses drainage Chandra in north and river Beas in the south. The prinicipal tectonic feature splits the Spiti-Zanskar basin's Lahaul-Spiti section from the Tandi basin, Chamba-Bhadarwah basin, and deposition of doubly plunging domes. This zone comprises of mantled gneiss with migmatites. The terrain is constantly covered with snow on the top, with heavy flora covering the entire valley and its slopes.

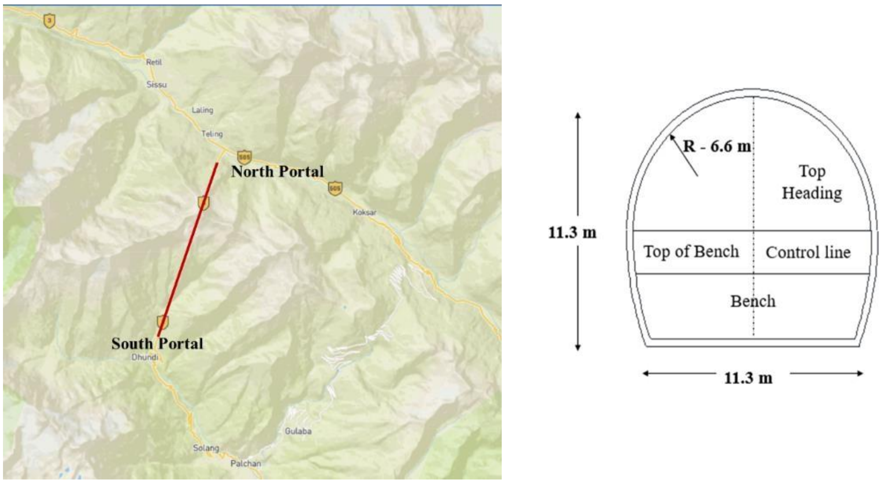


Fig.1 Study area, tunnel cross-section, and schematic longitudinal profile of tunnel representing overburden and geology (Jain and Rao, 2022)

The tunnel passes through an overburden depth ranging from 100 – 1900 m. The folded and faulted mountains in the study area have a broad foliation strike of NW-SE. The average angle of foliation is 350^{o} and the dip direction is 220^{o} along with the three governing joint planes and one random joint plane (Singh *et al.*, 2017). The cross-section of the horseshoe tunnel and geological section of the study area are shown in Fig. 1.

The Seri Nala fault is the largest fault encountered in any highway tunnel in the world. Its drainage is structurally controlled and subparallel. It crosses the tunnel alignment between chainage 2000 m to 2400 m. Seri Nala fault was encountered 300 m prior to the prediction. Due to this, construction activities were delayed by four years.

After a year of tunnel excavation, problems like muck flow and heavy water ingress of 60-70 lit per second were experienced at the face of the Seri Nala section. The rock falls were also encountered during heading throughout the tunnel face. Apart from this, debris flows and the formation of cavities were also critical issues in the project (Mehra, 2019). There were many geological problems such as rock bursts, squeezing, the occurrence of hot water springs, gas inflow, etc faced during excavation. It is often observed that construction in weak rocks gets delayed due to problems associated with tunneling in weak rocks as it fails due to higher overburden pressure. Such rock undergoes squeezing and results in larger deformation.

3 Numerical Simulation

3.1 Visco-Elastic Perfectly Plastic Model

In the present study, the Visco-Elastic Perfectly Plastic (VEPP) constitutive model is employed to capture the time-dependent deformation in the numerical model. The VEPP model comprises four kelvin-voigt elements connected in series with the plastic slider replicating the mohr-coulomb element as shown in Fig. 2. The kelvin-voigt (KV) elements are responsible for the time-dependent irreversible strains. It is possible to activate some or all of the kelvin-voigt elements depending on the nature of the time-dependent data available. The stress-strain constitutive relationship for a kelvin-voigt element is given by:

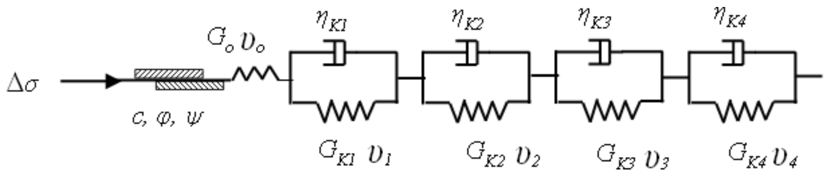


Fig.2. Schematic representation of VEPP model (Plaxis, 2015)

$$\sigma = \varepsilon_t E + \eta \frac{ds_t}{dt} \quad (1)$$

where, E and η are the elastic modulus and viscosity of the kelvin element. By substituting the shear modulus and integrating the differential equations, the following time-dependent relationship can be obtained.

$$\varepsilon(t) = \frac{\sigma o}{G_K}[1 - exp\,(\frac{G_K}{3y_K})] \quad (2)$$

where, σ_0 is the effective stress, G_{Ki} and η_{Ki} are shear modulus and viscosity respectively. υ_i is the Poisson's ratio and T_{ki} is the retardation time.

In order to determine the parameters of the VEPP model, back analysis has been performed on field-instrumented deformation data. In general, back analysis is a method for determining unknown parameters by substituting the recorded output in the form of displacement, stress, strain, and pressure (Fakhimi *et al*., 2014). In time-dependent problems, back analysis is applied for the evaluation of the mechanical parameters of the rock mass surrounding the excavation boundary which comprises the shear modulus and viscosities of the rheological elements.

It is possible to perform back analysis using the direct approach or inverse approach (Cividini *et al.*, 1981). Direct approaches are used for non-linear problems. It adopts an iterative method to find out the correct values of unknown parameters. Iterations are performed until the difference in numerical modelling results and measured/recorded data is minimized. On the contrary, in the inverse approaches, stress analysis equations are modified using optimization techniques in such a way that a system contains a number of equations more than the number of unknown parameters. In this study, a direct approach has been adopted to find the mechanical parameters.

3.2 Numerical Model

The numerical simulation is conducted in a finite element software Plaxis 2D. A plane strain model with a horseshoe-shaped tunnel profile is considered. The dimensions of the tunnel have been derived based on available reports and published literature (Jain and Rao, 2022). The size of the numerical model is kept as 200 m x 200 m to ensure external boundaries do not have an adverse effect on the results. The mesh employed comprises 15 noded triangular elements with finer element distribution in the vicinity of the tunnel. In terms of the boundary conditions, all the sides are kept fixed while the field stress option invokes the stress in the horizontal and vertical directions. It should be noted that isotropic stress conditions are employed as a first approximation. A monitoring point at the crown is installed to record the displacement with time. The rock mass is modelled using the VEPP model described above. Three chainages whose instrumentation data are available have been established and are considered for the analyses. The rock types at these locations comprise Quartzitic Phyllite (QP), Phyllitic Quartzite, and Biotite Mica Schist (BMS). The depth of the tunnel varies between 264 m to 426 m. The rock mass parameters for these sections are taken from Jain (2019) and are listed in Table 1. Calibration of the remaining parameters of the VEPP model is achieved by conducting a number of simulations to confirm the validity of VEPP is effectively replicating the field-instrumented displacement behavior.

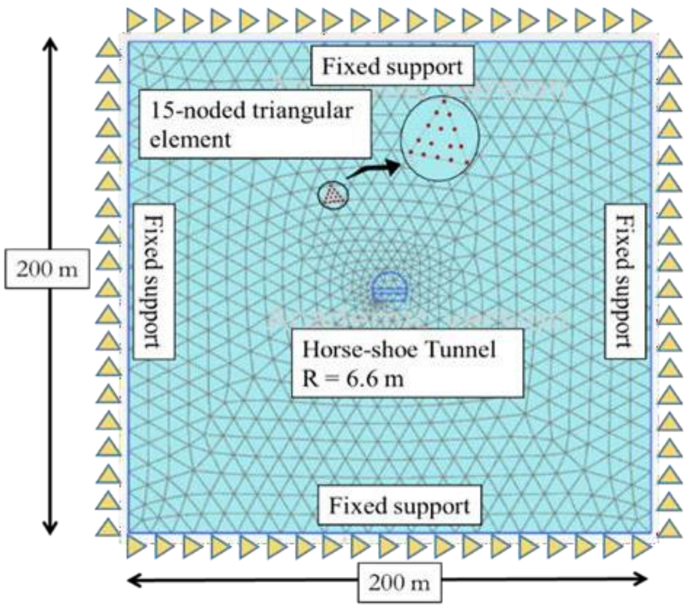


Fig. 3. Geometry and boundary conditions of the Plaxis 2D model.

Table 1. Rock mass parameters (Jain, 2019)

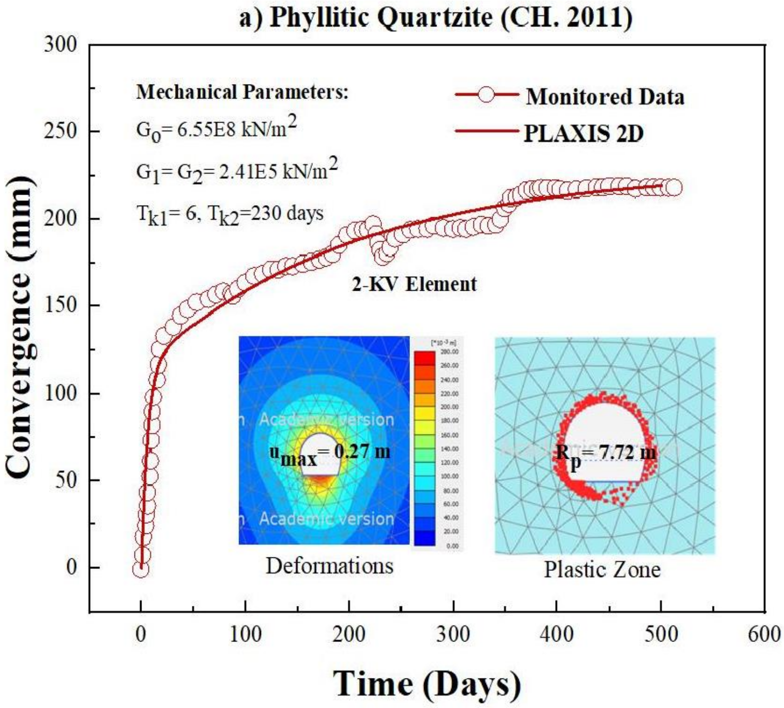
	2011	2084	8544
Rock Type	PQ	QP	BMS
Overburden Depth – H (m)	284	264	426
Tunnel Radius – r (m)	6.6	6.6	6.6
Unit Weight – γ (kN/m^3)	27.4	27.4	26.3
Poisson's Ratio - ν	0.3	0.3	0.21
Modulus of Elasticity of rock mass - E_{rm} (MPa)	2990.7	4365.2	9239
Intact UCS – σ_c (MPa)	83.6	83.26	60.43
Saturated Density - γ_{sat} (gm/cc)	2.74	2.74	2.63
Cohesion - c (MPa)	1.646	1.18	1.659
Angle of friction - Φ (°)	44.517	46.16	40.048

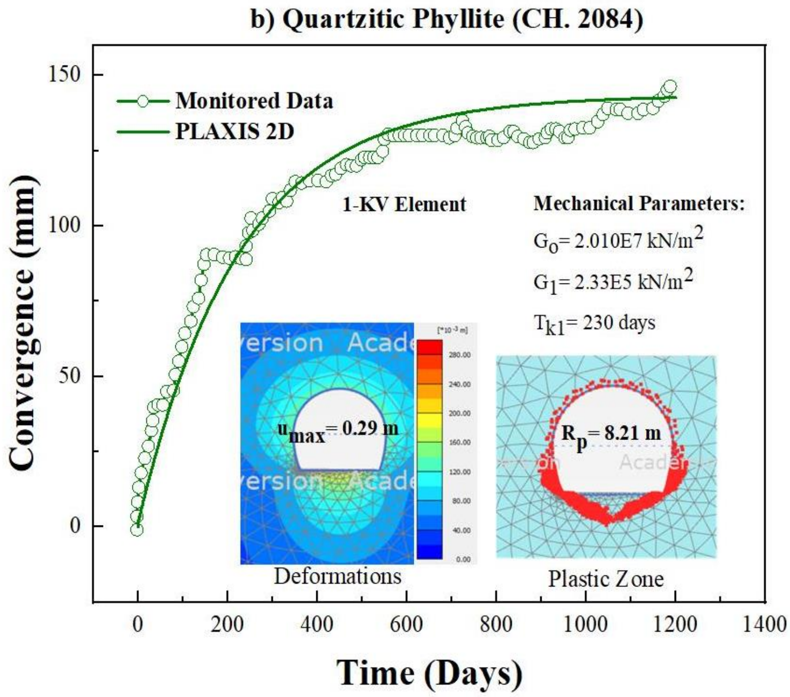
4 Results and Discussions

A number of numerical simulations were performed to ascertain the best possible combination of parameters to replicate the time-dependent deformation. From initial simulations, it was found that the nature of the deformation predicted from the numerical model is dependent on the number of kelvin-voigt elements. Based on the initial trial runs and the field instrumented data available, it was found that two kelvin-voigt elements are required to accurately capture the field data for the section passing through PQ while a single element is sufficient for the other two sections. Following the decision about the number of kelvin-voigt elements, calibration of the parameters was carried out for all three sections. The results of the calibration are shown in Table 2. The results of the numerical simulations for the three selected sections are shown in Fig. 4(a)-(c).

Table 2. Back Analysis Results

Section	Parameters
Phyllitic Quartzite	G_o = 6.55E8 kN/m^2, G_{k1} = G_{k2} = 2.41E5 kN/m^2, T_{k1} = 6 days, T_{k2} = 230 days
Quarzitic Phyllite	G_o = 2.01E7 kN/m^2, G_{k1} = 2.33E5 kN/m^2, T_{k1} = 230 days
Biotite Mica Schist	G_o = 4.06E7 kN/m^2, G_{k1} = G_{k2} = 1.61E6 kN/m^2, T_{k1} = 120 days


a) Phyllitic Quartzite (CH. 2011)
Mechanical Parameters:
G0= 6.55E8 kN/m2
G1= G2= 2.41E5 kN/m2
Tk1= 6, Tk2=230 days
Monitored Data
PLAXIS 2D
2-KV Element
umax= 0.27 m
Rp= 7.72 m
Deformations
Plastic Zone
Convergence (mm)
Time (Days)


b) Quartzitic Phyllite (CH. 2084)
Monitored Data
PLAXIS 2D
1-KV Element
Mechanical Parameters:
G0= 2.010E7 kN/m2
G1= 2.33E5 kN/m2
Tk1= 230 days
umax= 0.29 m
Rp= 8.21 m
Deformations
Plastic Zone
Convergence (mm)
Time (Days)

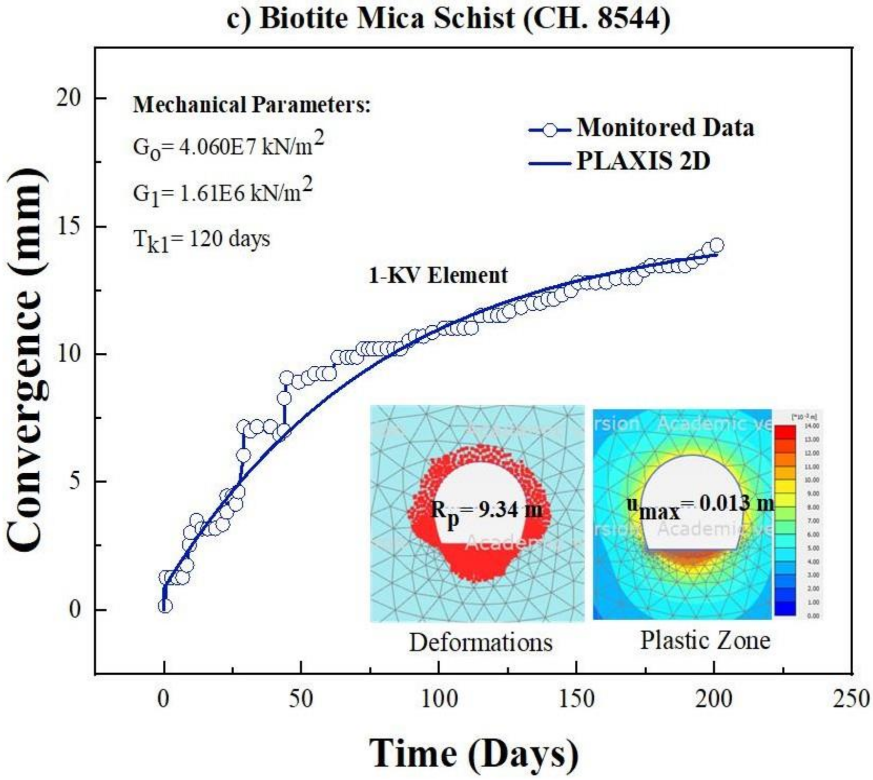


Fig. 4. Comparison of convergence-time plots: a) PQ b) QP c) BMS

The stress contour and the plastic zone associated with the three sections are shown in the inset of Fig. 4. It is observed that the results of the numerical simulations agree well with the field instrumented data. Thus, the VEPP constitutive model shows promising capability in capturing time-dependent phenomena.

4.1 Influence of Overburden Depth on Time-dependent Deformation

The calibrated numerical models can be utilized to investigate the influence of various parameters on final deformation. Considering the length of this paper, the influence of the overburden depth for one section is only discussed here. Five additional overburden depths ranging from 300 m to 500 m are considered. The trend of the deformation from the numerical simulations for various depths is shown in Fig. 5. As expected, the deformations increase with an increase in the overburden depth. Table 3 summarizes the deformation over time at distinct intervals of time for all the depths considered for the PQ section.

Table 3. Predicted time-dependent deformations at various overburden depths

Depth (m)	Number of Days								
	100	150	200	250	300	350	400	450	500
	Convergence (mm)								
284	155.9	171.1	182.8	191.03	197.4	202.1	208.6	209.8	211.0
300	171.6	188.5	198.5	210.20	218.4	223.1	227.8	225.5	233.7
350	206.5	228.7	243.8	253.79	263.7	271.9	278.3	276.1	279.0
400	244.8	274.1	290.9	302.63	319.5	326.0	330.7	331.9	334.9
450	286.7	319.4	341.5	354.96	368.3	378.3	386.5	391.2	395.9
500	337.3	369.9	393.8	416.01	427.6	439.3	449.3	454.0	460.4

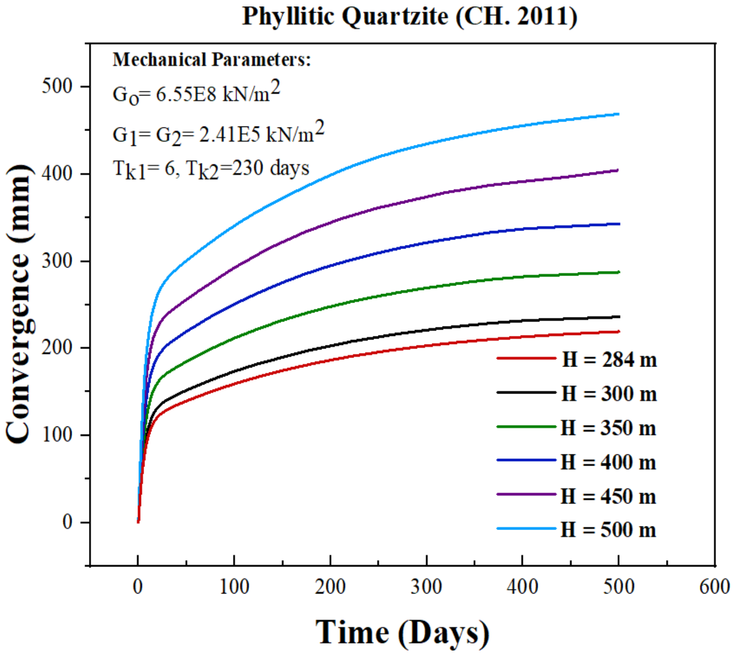


Fig. 5. Effect of overburden on tunnel convergence

5 Conclusions

Time-dependent deformation is an important phenomenon for the construction of underground structures at a greater depth. When such a condition is not predicted prior to the construction of a tunnel or any underground structures it may result in construction delays and increased costs. Numerical simulation of time-dependent deformations in tunnels is a strenuous task as it involves time-dependent parameters which may not be available.

This study aimed to capture the time-dependent deformation response of a horseshoe-shaped tunnel passing through the Himalayas using a finite element-based numerical model. First, field-instrumented deformation data over a period of time was extracted for three sections passing through Quartizitic Phyllite, Phyllitic Quartzite, and Biotite Mica Schist. This was followed by establishing a plane strain model capturing the geometrical details of the tunnel. The visco-elastic perfectly plastic constitutive model was employed to simulate the rock mass. A series of simulations were performed to gain an understanding of the number of kelvin-voigt elements required to accurately capture the nature of the field-recorded data. Calibration of the parameters was established and a close agreement between the numerical predictions and field data was confirmed. The calibrated model was further utilized to evaluate the effect of the overburden depth on the time-dependent deformation of the tunnel. Future work, considering the influence of additional parameters and the suitability of support systems to restrict the deformation is planned.

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