Three-dimensional simulation of tunnel excavation using 2D finite element software

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***Abstract*—This paper highlights a simple procedure to simulate stresses in a Tunnel when the excavation is being progressed. The paper is based on use of PHASE^2 software which is a simple 2D software and needs no special training. This remains to be an important aspect for predicting displacement while using NATM in order to calibrate the supports.**

Keywords—numerical 3D simulation; 2D analysis; NATM; excavation simulation.

I. Introduction

New Austrian Tunnelling Method (NATM) is increasingly becoming the most preferred method of tunnelling in India especially in the Himalayan conditions owing the complex heterogeneous rock mass conditions. The method uses the twin concept of sequential excavation and calibrated support system. The support system is calibrated using deformation monitoring using 3D targets or other modern means. Convergence – confinement analysis is the main methodology used for calibration of support systems.

Convergence-Confinement method was introduced [1] with primary application to tunnel lining design. Panet and Guenot demonstrated that the 3D ground response to tunnelling could be analysed with a plane strain approach, provided a fictitious pressure was introduced inside the tunnel area in the 2D model. This pressure could be derived from the initial stress in the ground. The method can be properly evaluated by means of comparison of 2D with fully 3D simulations. Ground reaction curves remain the mainstay of this method.

While execution of tunnel works using NATM approach it is quintessential that ground reaction curves are plotted. These help the tunnel engineers to decide the type of support systems and time of installation of these supports as per the actual rock mass deformation behaviour.

To achieve such calibration while tunnelling, before the actual supports are installed, it is essential to predict the behaviour of the ground under the planned support systems. The fastest and most reliable method to predict such behaviour is by using Numerical simulations as analytical solutions are available only for simplified cases with regular geometries and non-complex geology while an actual site is likely to encounter non-linear, anisotropic, non-homogenous material behaviour and a complex underground opening geometry.

It is a well-known fact that the deformation or convergence at a given section of an underground opening like a tunnel increases as the excavation face progresses further from the section. This behaviour is clearly seen in a longitudinal deformation profile shown at (Fig. 1), from Rock-Support Interaction analysis for tunnels in weak rock masses, rocscience [2].

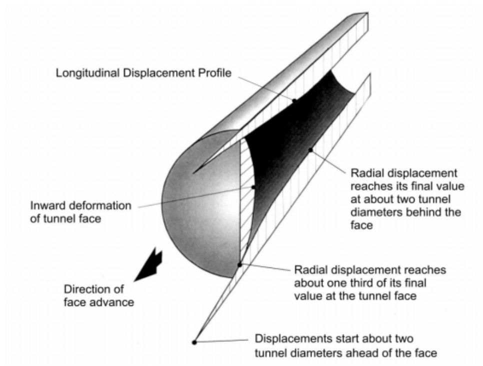

Fig. 1. Typical longitudinal displacement profile

In order to simulate such behaviour, a 3D simulation of the excavation process would be essential which would require an expensive and complex 3D software. Such software programs generally need special training and extra ordinary computational power which may not always be available on site. Hence use of 2D software programs remains to be the most pragmatic option.

In three dimensions, as the tunnel excavation moves away from the area of interest, increasing settlement will occur. One can model this effect in 2D by filling the tunnel with material of decreasing stiffness. Generally, one would install the support after the tunnel excavation has moved forward some distance (depending on the tunnel size, rock mass properties etc). If the amount of settlement that occurs when the tunnel has advanced the desired distance is known (by 3D modelling, axis-symmetric modelling or simply through experience or intuition), then one can model this settlement in 2D by using a material of the correct softness inside the tunnel.

In this paper one such simulation is illustrated using rocscience PHASE^2 software. PHASE^2 is a powerful 2D elasto-plastic finite element stress analysis program for underground or surface excavations.

II. SIMULATED NUMERICAL MODEL

The rock mass properties used during the analysis are shown in Table 1.

TABLE I. Rock Mass Properties of Sheared Phyllite & Metabasite imuated Numerical Model

Parameter	Value
Rock Type	Sheared Phyllite & Metabasite
Unit Weight	0.027 MN/m^3
Elastic Type	Isotropic
Young's Modulus	1500 MPa
Poisson's Ratio	0.3
Failure Criteria	Mohr Coulumb
Material Type	Elastic
Tensile Strength	0.5 MPa
Peak Cohesion	2.5 MPa
Peak Friction Angle	28 degree

The simulation was based on a horse shoe shaped tunnel with 10 m span and rise. The analysis was done using gravitational loading under 1000 m overburden. The model is illustrated at (Fig. 2 & 3).

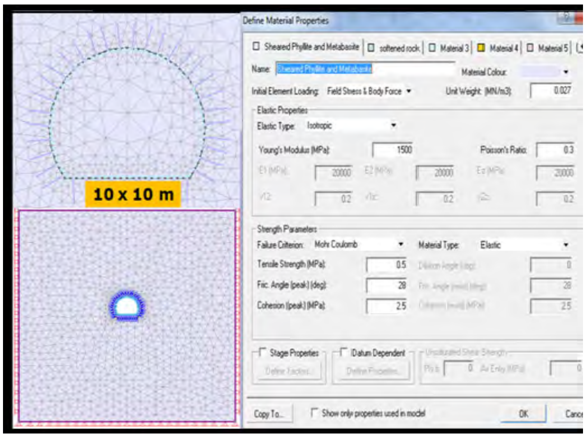

Fig .2. PHASE^2 modeling of 10 X 10 m horse shoe shaped tunnel

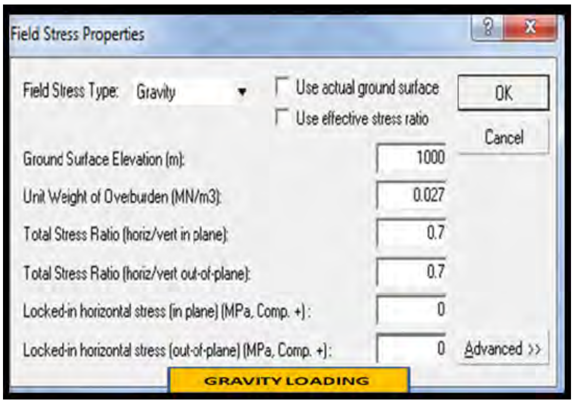

Fig. 3. Phase^2 modeling under gravity load

III. SIMULATION OF FACE SUPPORT (3D SIMULATION)

Let us consider a site condition where round length being excavated in one go through drill and blast is 4 m i.e. excavation is being advanced by 4m before installation of

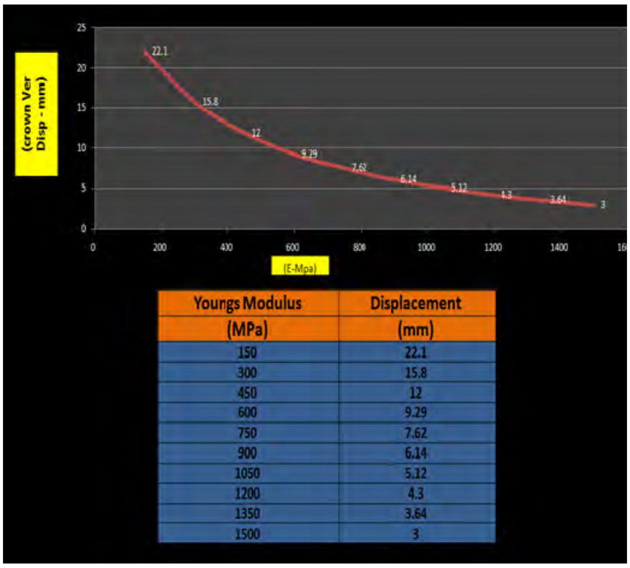

Fig. 4. Crown displacement Vs young's modulus for 3D simulation

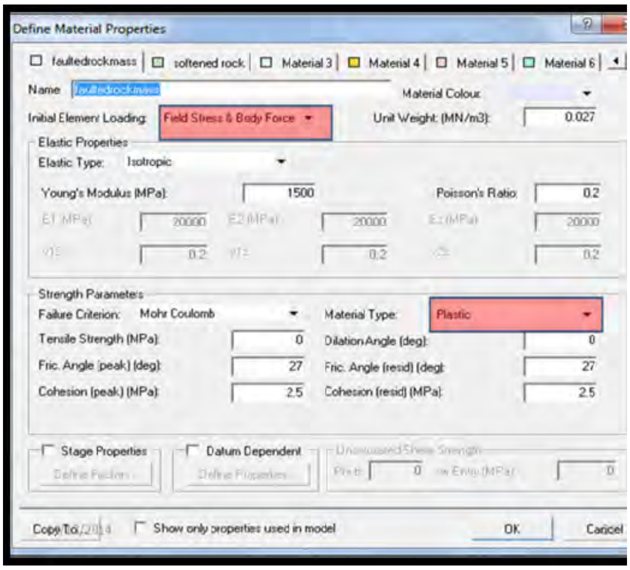

Fig. 5. Modelling of the rock mass

the support. It was observed through monitoring data that that the settlement or convergence at the crown at this juncture was 22.1 mm. It is important to note that this convergence is experienced with the face support at the distance of 4m and would increase when the excavation progresses.

Now, In order to carry out a representative 3D simulation in the 2D numerical model it is required that a material of such stiffness be filled inside i.e. excavated softened portion has such stiffness that crown settlement is 22.1 mm. This can be achieved by analyzing the model multiple times for crown displacement with gradually decreasing the young's modulus. The graph shown at (Fig. 4), is obtained when such analysis is done for the model being considered.As seen from (Fig. 4), 22.1 mm displacement is achieved when Young's Modulus is 150MPa. Hence a material with same properties as rock mass but a reduced Young's Modulus of 150 MPa is used to represent the softened rock mass post blasting/excavation.

The 3D modelling is finally achieved as shown in the (Fig. 5 and 6). Note that the rock mass is modeled as plastic and initial element loading is taken as field stress and body force.

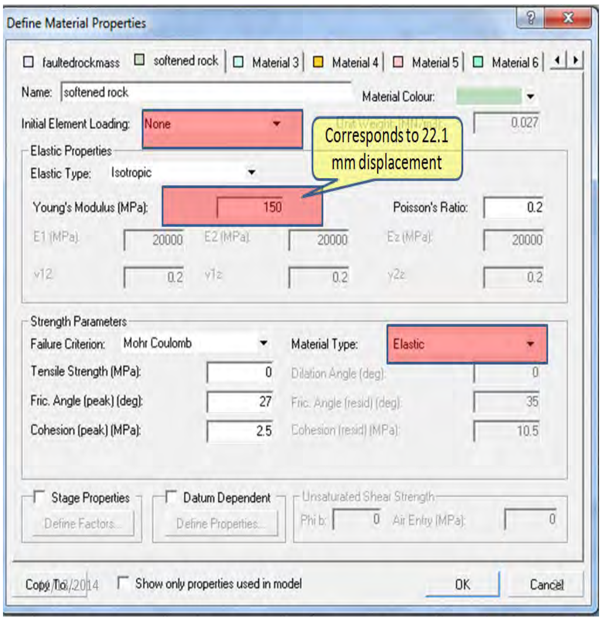

Fig. 6. Modelling of the softened rock

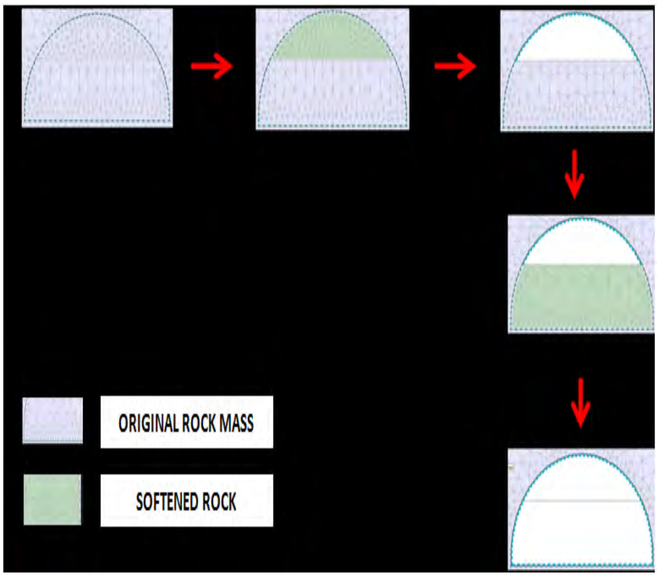

Fig. 7. Five stage 3D simulation for two step face excavation

Note that Young's modulus is taken corresponding to 22.1 mm crown displacement, initial element loading is avoided and material type is elastic. Once the properties have been assigned as shown above a two step face excavation can be modelled as shown in (Fig 7).

In this simulation the excavated portion is first replaced by the softened material and then completely excavated. Supports may be applied in the stage when softer material is put inside as it represents the face support available and in actual supports can be installed. Hence the simulation process helps take advantage of the face support and actual 3D deformations can be modeled.

IV. CONCLUSIONS

This process necessarily uses stiffness reduction as a means for 3D simulation of the excavation process using 2D software. Similar simulation can be achieved by introducing internal pressure inside the opening in other software programs. Whichever method is used it is important that the support available due to tunnel face is taken into account to prevent having an over conservative tunnel support system. This can also be used for design of support systems by using the basics of convergence confinement analysis as illustrated. The backbone of such an analysis is use of a well administered and designed 3D monitoring system which can aid a designer to calibrate a tender design to meet actual ground requirements without investing into complex 3D models which may actually be lesser accurate as they do not incorporate actual tunnel displacements.

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