ARTICLE IN PRESS

Thin-Walled Structures xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Thin-Walled Structures

journal homepage: www.elsevier.com/locate/tws

Full length article

Damage to shallow tunnels in different geomaterials under static and dynamic loading

Swapnil Mishra[a], K.S. Rao[a], N.K. Gupta[b], Ankesh Kumar[a,*]

[a] Department of Civil Engineering, Indian Institute of Technology, Delhi, Hauz Khas, New Delhi 110016, India
[b] Department of Applied Mechanics, Indian Institute of Technology, Delhi, Hauz Khas, New Delhi 110016, India

ARTICLE INFO

Keywords:
Underground structures
Dynamic loading
Static loading
Geo- materials
Deformation
Influence zone
Synthetic material

ABSTRACT

In the present study, an attempt is made to understand the behavior and pattern of tunnel damage subjected to the static and dynamic loading conditions, through the simulation of natural as well as artificial stress states such as loads due to overburden, building, earthquake and blast. The analysis is carried out by using FEM based numerical tool i.e. ABAQUS for different geo-materials. The Mohr-Coulomb plasticity model is used for modeling the rock mass and Johnson–Cook plasticity model have been used for the simulation of stress–strain response of drop hammer. The results of the analysis are studied for stresses, deformation and safety zones in surrounding rock. The displacement of the crown along the axis of tunnel is quantified. It is observed that the strength properties play a crucial role in quantifying the yielded zone in rock mass under both static and impact loading. The effect of weathering is investigated and the deformations for different weathering stages is measured. The crack dimensions reduce as the brittleness of the material increases. Different zones of influence are investigated for all the materials. It is noticed that the zone is significantly crushed in the case of dynamic loading, due to the high velocity of impact and the length of crack is large in the case of static loading as compared to the dynamic loading.

1. Introduction

Large deformation in underground structures at shallow depth has always been a threat to engineering safety in the process of tunnel construction, especially when the tunnel is crossing the highly stress induced area e.g joints/fracture zone and weak/soft rocks. The deformation in rock mass is dependent on the basic engineering properties such as water softening, uniaxial compressive strength (UCS), the rheological characteristics. Therefore, the primary objective of design engineer is to counter these deformations by minimizing the stress concentration in rock mass. The problem of stress concentration is countered by creating a stress field as uniformly distributed as possible in the excavation of underground structures. Hence, the optimum support systems can be provided without compromising the safety of the structure. When an opening is excavated, the stress field is locally disrupted and a new set of stresses are induced in the surrounding rock mass. Therefore, the lining is designed to support the new stress field and the weight of the overburden. The primary lining is usually designed to resist all transient loads occurring during construction activities as well as the short-term ground loads.

Different parameters that influence the safety of a tunnel are rock-type (geological and engineering properties), lining properties, depth of overburden, in-situ stresses, loading conditions etc. The tunnel in soft rock mass at shallow depths is highly sensitive to disturbance. Under the influence of disturbance and continuous deformation the mechanical properties (Elastic modulus, UCS, Tensile strength, Cohesion and Friction angle) of the surrounding rock mass are deteriorated. The tunnels in soft ground are typically circular in shape because this shape has inherently greater strength and ability to readjust to subsequent load changes.

Stress is an important parameter to characterize the soil/rock mass in terms of its stability, which proves to be very useful to the designers and the project authority. The in-situ stress state largely influences the construction and performance aspacts of an engineering structures inside a rock mass, be it a tunnel, a shaft or a cavern [1,2]. Any attempt to design engineering structures in rock mass requires the knowledge of the prevailing in-situ stress field [3,4]. Visualization of principal stress contours serves as a useful guidelines to the designers in understanding how the stress condition can be induced for certain excavation shape and orientation [5,6]. In-situ stresses released during excavation of tunnels may cause rock bursting, spilling, buckling or other ground control problems. Factors affecting the magnitude and orientations of in

* Corresponding author.
E-mail addresses: swapnilmishraa@gmail.com (S. Mishra), raoks@civil.iitd.ac.in (K.S. Rao), nkgupta@am.iitd.ac.in (N.K. Gupta), kumarankesh09@gmail.com (A. Kumar).

https://doi.org/10.1016/j.tws.2017.11.051
Received 1 March 2017; Received in revised form 30 November 2017; Accepted 30 November 2017
0263-8231/

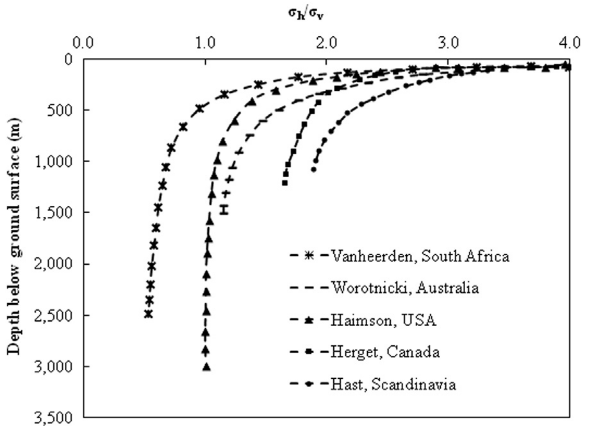

Fig. 1. Variation of ratio of average horizontal stress to vertical stress with depth below surface [13] and [14].

situ stress include the weight of overlying materials, geologic structures (on local and regional scales), tectonic forces within the earth's crust, residual stress and thermal stress [7,8]. The horizontal stresses acting on an element of rock at a depth 'z' below the surface is much more difficult to estimate than the vertical stresses.

$$\sigma_h = k.\ \sigma_v \tag{1}$$

Many researchers observed that the induced stresses at civil and mining sites around the world are such that the ratio k = $^{\sigma_h}/_{\sigma_v}$ is relatively high at shallow depth (up to 500 m) [3,9] and reduces at greater depth i.e. more than 500 m, where $\sigma_v = \sigma_h$ (hydrostatic condition) as shown in Fig. 1. Currently, the tunnels are designed for gravitational loads and impact/blast loads. Several researchers have investigated such type of loading conditions numerically as well as analytically. Ahmed and Iskander [10] investigated the effect of ground movements induced by tunneling, on structures (above ground and underground) through physical modeling. Most of such the experimentations are performed on the soils [11], however the underground structures are constructed in weak rock mass or soft rocks. In such fragile conditions the underground structures are subjected to different type of loading (earthquake loading, blast loading, impact loading, loading due to increase in the litho-static pressure) for which the study of strength-deformation behavior of rockmass and its effect on both lined and unlined underground structures (Table 1) is also essential. Therefore, it is essential to quantify the damage occurring in such loading and ground conditions.

Soft rocks under static loading conditions undergo elastic and plastic deformation before failure [12]. In elastic failure, deformation will be uniform and recoverable after the load is removed. As soon as elastic limit is crossed, plastic failure starts where deformation is not recoverable. Furthermore, Plastic deformation behavior of underground structures in rocks and soils at different strain rates has continued to attract research interest in order to understand their deformation and failure mechanisms at rapid rates of loading [16]. Strain rates generated under rapid loading condition such as seismic loads and high volume traffic load can be in excess of 10° s^{-1}. The deformation pattern and fracture behavior of geomaterial and different rock mass under same stressed conditions are very different from each other. Therefore, in the present work an attempt is made to perform 3-D nonlinear analysis of scaled and prototype tunnel models under static and impact loading conditions through the numerical modeling using FEM tool Abaqus. The numerical analysis is performed to understand the tunnel deformation and failure behavior in different geomaterials under varied loading conditions. The dimensions and material properties for validation are considered from the physical modeling conducted by Rao et al. [17]. The surrounding rock material is modeled using Mohr-Coulomb plasticity model [18] and [19]. The stress-strain behavior of steel is simulated using the Johnson-Cook plasticity model [20]. In addition, the failure patterns of unlined tunnel in different types of rock masses with varying degree of weathering and zone of influence is predicted and compared. Further, the analysis on prototype is performed under impact loading for different rock mass. The results obtained from scaled models and prototypes are compared. In the present work the effect of weathering on tunnel deformations is also investigated by considering different weathering stages of rock. The present rock condition constantly changes with change in the surrounding environment. Correct estimation of rock conditions is essential otherwise it may lead to the failure of rocks under different loading conditions. Many failures of tunnel portal and rock slopes along Mumbai – Pune expressway and Katra – Banihal route are the examples of the weathering effects on the infrastructure.

Table 1
Different loading conditions [15].

Loadings	Strain Rate	Type
Static	0 to 0.1	Construction or Demolition of heavy/ multi storey structures (Overburden pressure) • Continuous vehicular movements/ High traffic volume
Quasi –Static/ Dynamic	0.1 to 10,000	Cyclic loading /Missile attacks / Bomb penetration (Under terrorist activities) Excavation and Construction by Blasting Seismic load / Heavy machine foundation

2. Model material characterization and geometry

In the present study, an attempt is made to study the strength behavior of unlined tunnels in different rock mass under static loading. A synthetic rock is prepared in the laboratory by mixing Plaster of Paris (PoP), Badarpur sand, and Kaolinite clay in order to simulate the soft rock. The material used as soft rock is selected according to its stress-strain behavior and its ductile nature. The composition of material for synthetic rock is 50% PoP, 35% Sand and 15% Clay by weight and the water- powder ratio considered is 0.6. Petrography study through Scanning Electron Microscopy (SEM) and X-Ray Diffraction (XRD) is also carried out in order to understand the bonding and dislocations of the different constituent particles of the model material. Comparisons are made between model material and other constituent materials (sand, PoP, clay) through the microscopic analysis (Figs. 2 and 3). It is observed that the average grain size of the Badarpur sand is about 0.6 mm. The sand is uniformly distributed in the mix and no two grain particles are in direct contact. Therefore the effect of sand is to increase the density of the material. The cohesion is increased by mixing the clay. Furthermore the total strength of synthetic rock is low as compared to 100% PoP.

The engineering properties of the cylindrical samples made from synthetic materials (38 mm diameter) are summarized in Table 2. Index and engineering properties for the model material are evaluated as per the standards procedure for rock mechanics laboratory and are given in Figs. 4 and 5 respectively.

After determining all the properties of model material, dimension of model is decided in order to simulate the tunnel with surrounding rockmass in field condition. The dimensions for the numerical model are considered in accordance with Rao et al. [17]. The dimensions of the model adopted are 350 mm × 300 mm × 300 mm, as shown in Fig. 6. The analysis for selected model material is carried out for the validation of the numerical model followed by set of different rock masses with varying grades of weathering. The parametric analyses are performed for different rocks, e.g., PoP, Kota Sandstone, Basalt (fresh), Basalt (slightly weathered), Basalt (moderately weathered), and Basalt (highly weathered). In the analysis overburden depth of 5 cm from top is considered. Table 3 indicates different material properties assigned