



Ground Response Curve for the Crown, Wall and Floor of Shallow Tunnels under Non-Isotropic Stress Field: Application Range of Analytical Solutions

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ABSTRACT: Ground response curve is a component of convergence-confinement method in rock support interaction analysis which is used for determining the displacement around tunnels excavated by New Austrian Tunneling Method. Analytical solution of the ground response curve is based on the assumption of isotropic in-situ stress field and is applicable for deep tunnels. Today, urban tunnels mainly excavated in shallow levels and often under anisotropic in-situ stress field. In this paper, for 2D models with geometry and specific environmental characteristics, the response curves for different depths and different in-situ stress ratios, are determined in two ways: 1) By analytical solution and using anisotropic stress field equivalent to an isotropic stress field. 2) Numerical solution. The results of these analyzes were compared with together and range of application of analytical solution of the ground response curve is determined. Based on the results, tunnel wall displacement is mainly influenced by the ratio of the initial in-situ stresses in comparison of tunnel depth. The results showed that crown and floor numerical displacements deviate more from analytical solution than the wall displacement. The only displacement that can be accurately obtained from the analytical solution for the shallow tunnel is the displacement of the tunnel wall under isotropic stress. In the case of isotropic stress field, the results given by the analytical solution agree with the numerical ones at depths higher than 14 times radius of the tunnel. The difference between numerical and analytical solutions becomes higher while increasing the initial in-situ stress ratio, even for deep tunnels.

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1- Introduction

Ground Response Curves (GRC) is one of the components of Convergence Confinement Method (CCM) in the analysis of tunnels. Convergence confinement method has been presented by some researchers [1-4] and it is a method normally used in designing support system in tunneling in conventional ways and through it the three-dimensional rock-support interaction problem is simplified into a two-dimensional model.

The underlying assumption of convergence confinement method is that the support load required for sustainability of excavation is decreased with radial displacement of tunnel inwards. When rock mass moves inward, tangential stresses increase which both cause rock yielding and increase of all-around environmental stress. This method consists of three main components: ground response curves (GRC), ground's longitudinal deformation profile (LDP) and support characteristic curve (SCC). In ground response curve, decrease of internal pressure of support is associated with increase of radial displacement of tunnel wall and junction of GRC and SCC determines pressure and deformation of tunnel

at the point of balance between support and ground. The important advantage of convergence confinement method is that the problem of three-dimensional development of tunnel is simplified into a two-dimensional model through connection between the distance from front surface the tunnel in LDP and the internal pressure in the GRC [2].

For obtaining ground response curves, analytical methods are usually used [5]. Analytical methods are very useful and valuable in the design of the tunnel support, because not only they can consider the type of support, but also consider its installation time. But these methods are applicable only under certain conditions and the main weakness point of them is that they cannot consider complex conditions of in-situ stresses and geometry. Assumptions on which analytical methods are based include: 1) Tunnel section is circular. 2) The tunnel surrounding rock mass is assumed to be homogeneous. 3) The in-situ stress field is isotropic. 4) Plane strain condition (long tunnel) is considered. 5) The weight force is neglected. These assumptions are often violated in real conditions of tunneling. For this reason Pan and Chen (1990) have proposed the concept of ground response curves family [6]. These two authors have provided deeper understanding of internal pressure and deformation of tunnel at different points of tunnel wall which is dependent on the circumstances of

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initial stresses and tunnel shape. Basis of their method is using numerical finite element method with elasto-plastic conditions and failure criteria of Mohr-Coulomb.

The purpose of this paper is to investigate limitations of the ground response curves, obtained from analytical method for shallow tunnels under non-isotope field stresses. To achieve this objective, numerical modeling using finite differences and FLAC2D software for tunnels with different depth in non-isotope in-situ stress conditions and their results are compared with the results of analytical solution. But the limitations of the work are as follows: 1) The quality of rock mass is assumed to be relatively good. 2) Rock mass is modeled as continuous and without considering joint and crack. 3) Tunnel section is assumed circular with a constant radius in all analyses.

At first, analytical solution of rock-support interaction is brought and then numerical modeling is performed and the results are discussed. Verification of the methodology and comparison of GRC curves and radius of plastic zone obtained from the analytical solution with numerical solution is given in the appendix of paper.

2- Conditions of numerical and analytical modeling

Numerical models: The conditions of models for drawing ground response curves for shallow and deep tunnels are as follows: the ratio of the in-situ stresses has varied between 1 and 6 and also the depth of the tunnel placement has changed from 5 to 25 meters. Diameter of tunnel is fixed in all models as 5 meters. Also, modeling is two-dimensional and plane strain is assumed. Characteristics of environmental materials have been taken according to Table 1 and they follow Mohr-Coulomb failure criteria.

Also, in created models, applying vertical pressure is done as gravitational, such that with increasing depth, the vertical pressure on land increases and horizontal pressure at any depth is obtained by multiplying coefficient of lateral pressure k , by the vertical pressure of the same surface.

Numerical modeling environment with dimensions 50×50 m² is meshed in a 200×200 grid. After applying boundary conditions and loading, the models are run by FLAC2D software [9]. Stress release percent is performed in ten steps and radial displacements of wall, crown and floor of the tunnel is recorded at each stage, and ground response curves are plotted based on them.

Table1. Characteristics of environmental material in modeling

Parameter	Sign	unit	value
Mass density	ρ	Kg/m ³	2700
Radius of tunnel	a	m	2.5
Friction angel	ϕ	Degree	40
Adhesion resistance	C	MPa	1
Elasticity modulus	E	GPa	15
Poisson's ratio	ν	-	0.25
Dilation angel	ψ	Degree	0
Tensile strength	σ_t	MPa	3

Analytical solution: Analytical solution has been performed by equivalent loading of numerical method and assuming the elastic environment and in-situ isotropic stress, so that the confining pressure is considered equal to average horizontal and vertical load.

3- Conclusion

Ground response curve is one of the components of convergence confinement method in rock-support interaction analysis and design of the tunnel support. Analytical methods of ground response curve are based on the assumption of in-situ isotropic stresses and ignoring weight force. The main objective of conducting this research was to investigate the limitations of the analytical method of ground response curve for shallow tunnels under in-situ non-isotropic stresses and to study changes in displacements caused by in-situ stresses. For this purpose, using two-dimensional numerical model, analyzes were performed for different depths and under different in-situ stresses. According to the results:

- For shallow tunnels, shape of deformed section of tunnel is ovaling and big displacements always occur in walls and fewer displacements happen in the crown and floor of the tunnel.
- Displacements of tunnel wall are affected more by ratio of initial in-situ stresses than the depth of tunnel placement.
- For in-situ stress ratio greater than about 1.5, crown of the tunnel moves upwards that is ground response curve provides negative values for displacement.
- The only displacement that can be achieved with appropriate accuracy from analytical solution for shallow tunnels is displacement of the tunnel wall under isotropic stresses.
- Displacements of crown and floor of tunnel under isotropic conditions and depths more than 14 times the radius of tunnel can be obtained from the analytical solution with good accuracy, but with the increase of in-situ stresses, analytical and numerical solutions get far from each other more.

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