DEVELOPMENT OF A RISK ASSESSEMENT MODEL FOR UNDERGROUND OPENINGS

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ABSTRACT

Design and construction of underground openings are associated with many uncertainties with regard to input data. In the construction process of underground openings various levels of risks exist and these affect the safety and profitability of the project. The development of underground openings can be broadly categorized into three major phases of data collection, design, and construction. A significant level of uncertainty is associated with some of the key parameters involved in the aforementioned development phases. Moreover, it is very difficult to evaluate and quantify the effects of uncertainties on the underground project construction process. Additionally, the interactions between important risk elements are typically not well understood. The intention of this study is to develop a general risk model for underground opening projects located in soils and weak rock masses. The goal of the research is to identify and quantify important geotechnical risk elements. Moreover, a weighting procedure will be proposed for the identified risk elements.

Finally, all important risk elements will be assembled into a general model with emphasis on geotechnical parameters. The final objective of this study is to apply the proposed model to a real underground project scenario and verify it for actual field conditions. The proposed model, once calibrated properly, will provide a useful support tool for the decision making process.

KEYWORDS

Risk management, Underground openings, Risk elements, Geotechnical risk assessment

INTRODUCTION

Underground engineering is distinguished by high level of risks and uncertainties and risk management is essential to successfully fulfilling project objectives. There have been several cost overruns, time delays and quality problems reported from underground projects around the world in recent years. Many of the reported problems are associated with risks and uncertainties related to geotechnical conditions which are not managed sufficiently in the planning, design and execution phase of the projects.

Due to fundamental non-homogeneity of nature, factors governing geotechnical conditions and their engineering solutions are inherently more uncertain than certain. Therefore the role of the geotechnical engineering is the management of that uncertainty and found the actual failure probability of geotechnical systems based on that uncertanities. A probability analysis is more appropriate since it provides a means of explicitly reflecting the effect of uncertainties and of distinguishing important from unimportant uncertainties, since the existence of model uncertainty can lead to project risk.

In the literature there are limited studies that consider the stochastic evaluation of strength parameters (c, φ) and independent variables of soil stiffness (E, υ). Li and Low (2010) used a first-order reliability method (FORM) to calculate the reliability index of a circular tunnel. Al-Ajmi and Al-Harthy (2010) developed a probabilistic wellbore stability by uncertainty in inputs through running a Monte Carlo simulation. Fenton and

Griffiths (2003) studied the influence of spatial variability and cross-correlation of friction and cohesion of soils on bearing capacity.

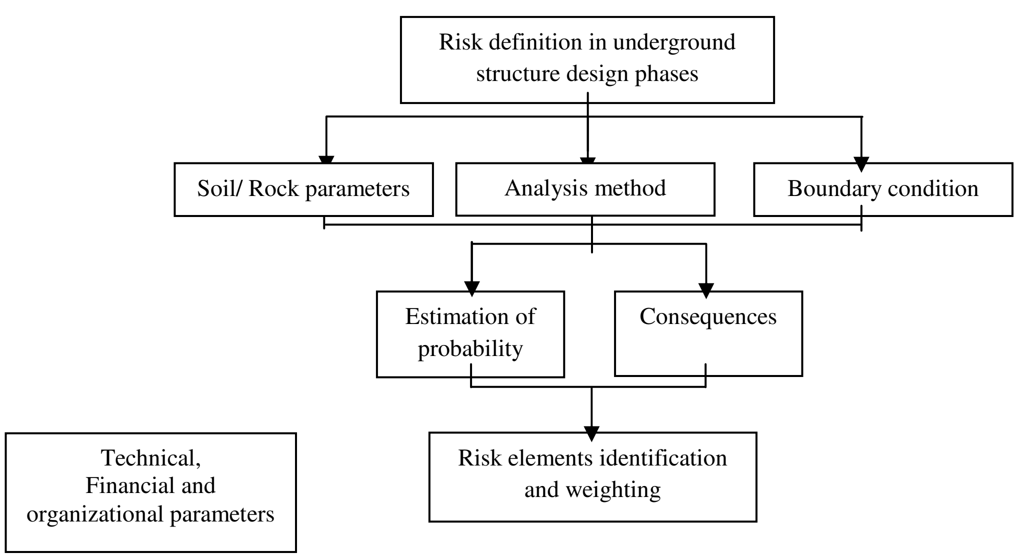
In this paper after identifying the risk elements, probabilistic parameters and Monte Carlo simulation were used for sensitivity analysis. Monte Carlo simulation has been widely used in many applications related to risk analysis. The simulation process is built on iterations that make use of internally generated random numbers to generate results. Monte Carlo simulation can be used to calculate the required amount of risk premium (Mohamed Abdelgawad, 2011). A sensitivity analysis was conducted using the @Risk computer program; the importance of each parameter was evaluated and weighted. In the Monte Carlo method, the uncertainties of the soil strength and stiffness parameters were incorporated into a spread sheet model using statistical distributions. It is the intention to develop a relationship between important parameters once enough information is collected from case studies.

DEVELOPMENT OF A GEOTECHNICAL RISK ANALYSIS MODEL

Risk Model Algorithm

Cities are not sustainable without infrastructure and, in many cases the best choice for much of this infrastructure will be a tunnel. Accordingly, there is already, and will be in the future, a great demand for tunnels to be constructed in difficult and crowded urban settings. Not only are the constraints that these urban settings pose to tunnel construction, quite challenging, but there are also extremely demanding performance requirements for minimal disturbance to the public and to the surrounding utilities, structures and the environment (Guglielmetti, Grasso, Mahtab & Xu, 2007).

Construction of underground facilities such as tunnels deal with many unknowns and limited data. This is especially true for those projects in urban areas that involve construction in or on soil and rock masses. However a considerable overrun in cost and time is due to the not known and uncertain parameters and nature condition in many infrastructure projects. In order to achieve a cost-effective and a more predictable outcome of the projects to a cost that can be estimated before the projects start, it is essential to manage the geotechnical risks and uncertainties involved in an adequate manner. For this reason a new approach to tunnel risk management in geotechnical engineering is proposed. The proposed method is basically developed for probabilistic evaluation of variations observed in Tehran alluvium soil parameters. The general flowchart of the proposed methodology is shown in Figure 1.



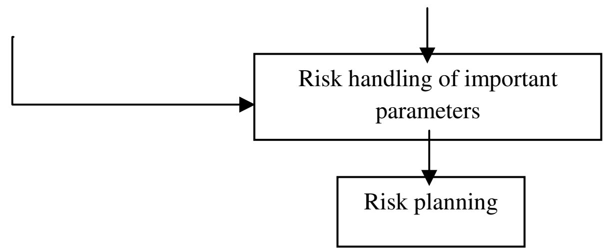


Figure 1 – Risk model algorithm

Identification of Important Risk Elements

Since natural materials like soil are inherently heterogeneous and variable, their nature of uncertain characteristics needs to be appropriately described in the preliminary design investigations. There are three kinds of uncertainties that could affect the credibility of an underground design process:

1. Uncertainty in geotechnical parameters.
2. Uncertainty in the method of analysis.
3. Uncertainty in the considered boundary condition.

In the first phase of this study the effect of the first group of uncertainties (geotechnical parameters) are investigated and presented in this paper. Analysis of two other groups is work in progress and will be the subject of future publications.

<u>Geotechnical Parameters</u>

Soil properties may be uncertain due to the spatial variability of soil property, test uncertainty and insufficiency in the number of tests. The risk associated with geotechnical parameters are very important and affect the whole design and construction process. Characteristics of some geotechnical design parameters are outlined below.

Deformation Modulus:

The deformation modulus is a mechanical property of soil/ rock masses, and one of the key parameters which are needed for the design. The strength and deformation modulus of weak rock masses or soils cannot be directly determined, because the dimensions of representative specimen are too large for laboratory testing. To overcome this limitation, it is possible to use in situ tests, such as plate jacking, plate loading, radial jacking and flat jack, etc. However, the application of in situ tests to determine the deformation modulus of soils or weak rock masses requires extensive and difficult test procedures. The modulus of deformation is one of the most important parameters that represent the mechanical behavior of soil mass, in particular when it comes to underground excavations. Moreover, in most numerical modeling analysis associated with geotechnical design, the deformation modulus is a key parameter in the determination of displacement/stress field.

Cohesion:

Cohesion is one of the most important strength parameters. It plays a significant role in the deformation of soil and weak rock masses. The mechanisms that material cohesion is mobilized during the failure process, is very complicated. Hence it is very difficult to determine the soil mass in-situ cohesion. On the other hand the failure process of weak grounds is considerably governed by the material cohesion and, therefore, cohesion is an important design parameter.

Friction Angle:

The soils and weak rock masses friction angle is also another key parameter in the design. Friction angle plays an important role in the failure process of geomaterials. Determination of in-situ friction angle of material is also very difficult. The variability among laboratory measurements of effective friction angle, φ, is considerably less than that among in situ tests. Typically, a greater care is usually taken with laboratory tests as compared to in situ tests, and the specimen quality for laboratory tests is always better than in situ tests (Baecher & Cristian, 2003). In table 1 the variability of friction angel of various soils are presented from which one can find that the coefficient of variance (COV) in clay is more than the other soil types.

Table 1 –Variability of laboratory measured φ for various soils

Soil type	COV	Source
Various soils	9	Lumb 1966
Clay	40	Kotzias et al. 1993
Alluvial	16	Wolff 1996
Sands	2-5	Lacasse and Nadim 1996
Tailings	5-20	Baecher et al. 1983

Poisson’s Ratio:

Poisson's ratio is the ratio of the diametric strain to axial strain under the applied load. Poisson’s ratio is another mechanical property that plays an undeniably important role in the elastic deformation of soils masses subjected to static or dynamic stresses. Furthermore, its effects emerge in a wide variety of soil engineering applications, ranging from basic laboratory tests on intact soils to field measurements for in situ stresses or deformability of soil masses and design process (Gercek, 2007). The variability observed in the Poisson’s ratio is generally less than the other mechanical parameters.

Analysis Method

In geotechnical applications, all information at hand, together with personal experience and judgment are brought to bear in estimating the subjective probability of an event or condition. Because subjective probability inherently depends on one’s state of knowledge at the time it is formulated, any such value can be expected to vary, both from one person to another and with time, as information and knowledge are gained (Baecher & et al., 2003). In weak rock and soil masses, the consequences of considering a two-dimensional model, however, have been found to be not very significant and, at the same time, considering a two dimensional model allows us to perform more extensive simulations that explore the effects of slight differences at the tails of the statistical distributions. The models we fit to naturally varying phenomena need to be tailored to natural process by observing how those processes work, by measuring important features, and by statistically estimating parameters of the models. When it comes to the design of complex structures and complicated boundary conditions, the selection of analysis method becomes very important. The major issues that are associated with complicated problems are as below:

- 2D versus 3D nature of the problem
- Elastic versus inelastic behavior
- Static or dynamic loading

A realistic treatment of the above issues necessitates the use of sophisticated methods. Hence, in problems of complicated nature inappropriate design methodologies may lead to erroneous design and instability risks. Therefore, characterization of risks associated with analysis method is very important.

Governing Boundary Condition

One of the most important aspects of every design process is the problem boundary condition. Because of the soil variability and complex behavior in tunnel portals, intersections, etc. it is challenging to characterize complex problem boundary condition. Some of the major issues associated with boundary conditions are as below:

- The ratio of maximum horizontal stress to maximum vertical stress (K value)
- Structure depth
- Nature of loading
- Structure size
- Pore pressure distribution
- Ground water level

Accordingly, the stress ratio has an important effect on the failure mode of geomaterials. Pore pressure can reduce the effective stress in discontinuities that lead to a reduction in resisting forces and finally the occurrence of failure. Pore pressure in swelling and squeezing soil types leads to unforeseen failures and damages. Other parameters also affect the soil/rock mass failure mechanism. Hence, selection of an appropriate boundary condition in the design can be a source of risk in complicated problems.

DUNCANE FAMA FAILURE CRITERIA

During excavating an underground opening the in situ stresses around the opening is redistributed and induced stresses causes the creation of a plastic zone around opening. Several analytical solutions have been developed in the literature for elasto-plastic stress and strain relationship. Almost all of these solutions use the Mohr–Coulomb (M–C) yield criterion or the Hoek–Brown (H–B) yield criterion, among which Duncan Fama (1993) and Carranza-Torres (2004) solutions are the typical two which are widely used in practice. In this paper the Duncan Fama solution, which is based on the M–C criterion was used for the evaluation of tunnel wall strain and evaluating parameters affecting it. In Duncan Fama criteria it is assumed that a circular tunnel is excavated in a continues, homogenous, isotropic, initially elastic soil mass subjected to a hydrostatic far field stress, p_0, and uniform support pressure, p_i, as shown in Fig. 2. The soil mass surrounding the tunnel will have an annular plastic zone when the internal pressure provided by the tunnel lining is less than a critical support pressure, p_{cr}. According to the M-C criterion, the normal stress p_{cr} at the plastic-elastic zone interface is given by (Lu, Sun & Low, 2011):

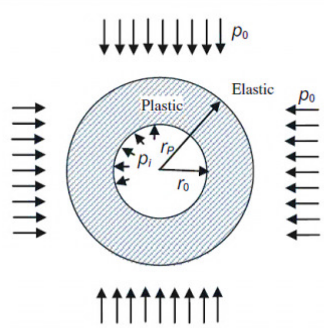


Figure 2– A circular opening subjected to hydrostatic far field stress and uniform support pressure

$$P_{cr} = \frac{2P_0 - \sigma_c}{k + 1} \tag{3}$$

$$k = \frac{1 + sin\varphi}{1 - sin\varphi}, \qquad \sigma_c = \frac{c(k-1)}{tan\varphi} \tag{4}$$

Where φ is the friction angle and c is the cohesion. If the uniform support pressure, p_i, is less than the critical pressure, p_{cr}, a plastic zone radius r_p is given by:

$$\frac{r_p}{r_0} = \left[\frac{2(p_0 + s)}{(k+1)(p_i + s)}\right]^{\frac{1}{k-1}}, \qquad s = \frac{\sigma_c}{k - 1} \tag{5}$$

The inward displacement of the tunnel wall, u_{ip}, is given by:

$$\frac{u_{ip}}{r_0} = \left[\frac{1+\vartheta}{E}\right]\left[2(1-\vartheta)(p_0 - p_{cr})\left(\frac{r_p}{r_0}\right)^2 - (1-2\vartheta)(p_0 - p_i)\right] \tag{6}$$

Where E is the deformation modulus and ϑ is the Poisson's ratio.

CASE STUDY

Construction of underground structures in urban area has particular constraints and a risk analysis of possible induced movements is necessary. The city of Tehran is founded on a material called Tehran Alluvium. This alluvium is divided into 4 formations based on geological characterization: A, B, C and D formations. Stratigraphy of Tehran Alluviums and its attributes features are presented in Figure 3. Tehran No.3 subway line consists of 23 underground stations and 7 on-surface stations with a total length of 35 km. Based on the geology map of the Tehran this project is located within zones D & C of Tehran alluvium. The soil parameters that are used in the analysis are presented in Table 2.

Following the definition of uncertain properties of soil parameters, in this research we used a stochastic model to determine the influence of the parameters on the underground opening strain region. As Beacher and Cristian (2003) outlined many measures of soil strength appear to be well-modeled by normal distributions, a normal distribution was thus used for the soil parameters.

The developed model provides a simple and an intuitive implementation of a Monte Carlo simulation together with the generalized Duncan Fama Failure Criterion which affords the straight forward assessment of the sensitivity of each parameter on the strain region around the opening. A spreadsheet model was thus used for the carrying out @Risk simulations, with a listing of all cell formulate for input and output parameters. For the model, 10,000 iterations were performed with Latin Hypercube sampling. This means that every run of the simulation yields 10,000 different possible combinations of input variables, which are sampled randomly from the defined distributions.

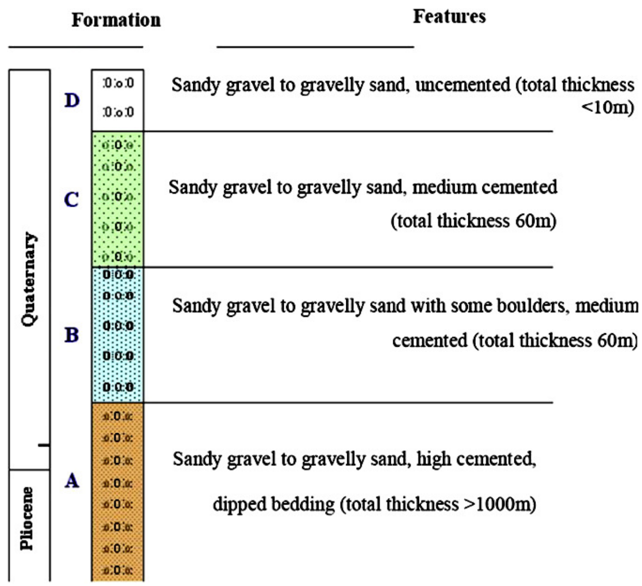


Figure 3 – Stratigraphy of Tehran alluvium

Table 2 – Soil parameters distribution of Tehran alluvium

Parameter	**Mean value**	**Standard deviation**	**Coefficient of variance**
C (MPa)	0.0179	0.008	0.462
Φ	34.563	5.827	0.168
E (MPa)	24.07	3.9	0.402

A sensitivity analysis was carried out for tunnel strain field in Tehran No. 3 subway line using the @Risk program. The obtained results show the importance of Deformation modulus, Poisson's Ratio, cohesion and friction angle (see Figure. 4). Based on obtained results from risk analysis point of view an underground opening should be concerned with the deformation modulus with the greatest effect. In this case, the cohesion has less influence in comparison to friction angle in the analysis, because the subway line is located in gravelly and sandy soils with a low cohesion value. In other words the calculated strain field of the soil is less dependent on cohesion in this case.

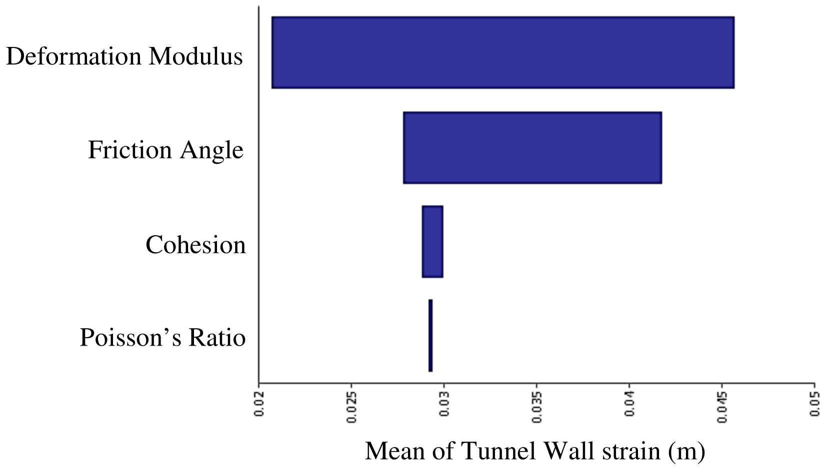


Figure 4 – Tornado diagram of sensitivity analysis using the @Risk program

CONCLUSIONS

The tunneling industry today faces unprecedented waves of additional costs, time and other challenges. A geotechnical risk assessment model is needed to minimize complexity and risks in such projects. This paper aims to describe a methodology for the development of a geotechnical risk model for underground development in particular tunneling operations. A risk model algorithm is proposed for Tehran No. 3 subway line design. In practice, however, there are uncertainties that exist in each one of the input variables. To overcome this deficiency a probabilistic model was developed for the tunnel strain field. The obtained results show that the Deformation Modulus and Friction Angle are the most critical geotechnical parameter in the design process of Tehran Line 3 subway tunnel. This approach can be used as a supplement in underground opening design for assessing risks associated with underground projects.

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