Probabilistic analysis of roof deflection for multi-stage excavation using limited data – A case study of Lijiaping metro station in Chongqing City, China

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ABSTRACT

Multi-stage tunneling can play a significant role in reducing ground settlement and damage to surrounding structures. In fact, dividing the tunnel face to smaller sections can help with enhancing ground stability till the lining completion. In this paper, a three dimensional multi-stage excavation of the 9th Metro line project in Chongqing city, China, was modelled in Flac 3D software. The established model was then extended to a reliability model. The exceedance probability of the maximum deflection of tunnel roof was calculated by a simplified Monte Carlo algorithm. The results were then presented in the form of an exceedance probability curve for any desired value of tunnel deflection. Finally, application of the proposed exceedance probability curve for reliability-based evaluation and design of tunnels is described by a simple example.

Keywords: multi-stage excavation; maximum deflection; reliability analysis; exceedance probability

1 INTRODUCTION

Construction of large sections for subways, road tunnels, and railways is usually performed by multi-stage excavation. For this purpose, the tunnel face is divided into the side, top, and bench sections, and at each excavation stage, the rock bolts, supports, and shotcrete linings are installed (Gioda and Swoboda 1999). This excavation technique plays an important role in reducing the ground settlement and damage to adjacent structures in urban areas, especially if tunnel is planned to be excavated in shallow areas (Galli et al. 2004).

One of the most important issues in multi-stage excavation is the change of stress and displacement field around the tunnel section and also along the tunnel excavation progress (Gharti et al. 2012). Hence, multi-stage excavation should be studied by three dimensional modeling to consider the effects of displacement normal to the tunnel cross section. Another important issue is the uncertainty associated with the Geotechnical characteristics that is ignored in deterministic analyses (Khademian et al. 2017). In fact, the result of deterministic analysis only addresses one of the possible scenarios that is not necessarily the most critical case; hence, decision making and design process based on deterministic approaches may not be fully consistent with the expected risk (Ghasemi 2015, Li and Low 2010). Probabilistic models, however, require a comprehensive understanding of variability in geotechnical properties which is not usually available in real projects (Zhang et al. 2014). Hence, it is required to utilize a simple procedure that could work with limited data.

In this paper, the tunnel excavation project of metro line 9 located in Chongqing city, China, at Lijiaping station was used as the case study. First, a three-dimensional model of the project is simulated in Flac 3D software. The maximum deflection of the tunnel roof at different excavation stages is then calculated. Further, by defining the Geotechnical characteristics of the middle layer as random variables, the problem is defined as a reliability model. A simplified Monte Carlo method is adopted and the exceedance probability of maximum ground settlement at the roof of the tunnel is calculated. The results are presented in terms of exceedance probability versus maximum tunnel settlement. Finally, application of the exceedance probability curve for reliability-based evaluation and design is described using a simple example.

2 PROJECT OVERVIEW

Lijiaping Station is the ninth station of Chongqing metro line 9 project. The vertical plan of section A, investigated in this paper, together with geological condition around the tunnel are schematically shown in Fig. 1.

The geotechnical study report does not show any major geological issue, such as presence of the landslide, collapse, debris flow, and so forth around the project area. The overall geotechnical stability of the site seems to be fair. The material composition is mainly the cohesive soil, sandstone, and mudstone fragments, containing small amounts of the construction and domestic wastes. The structure is slightly dense to medium dense, and the thickness slightly varies.

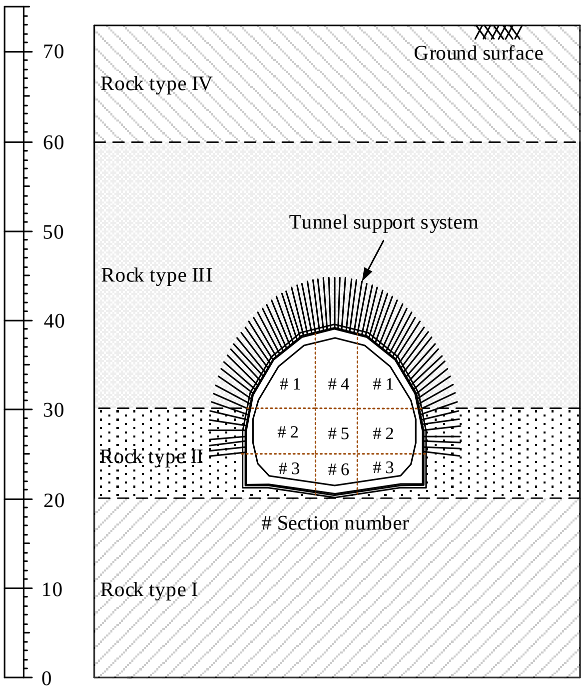


Fig. 1. A section view of Lijiaping station.

3 SOFTWARE SIMULATION

In the numerical simulation, four types of rock have been considered around the tunnel as shown in Fig. 1. The main Mohr-Coulomb parameters used in the numerical simulation are bulk modulus, shear modulus, friction angle, cohesion, and tension limit. The amounts of these parameters used in the software simulation are given in Table 1.

Table 1. The geotechnical characteristics of rock around the tunnel.

Rock Type	Bulk modulus (Pa)	Shear modulus (Pa)	Friction angle	Cohesion (Pa)	Tension limit (Pa)
I	200e6	100e6	20	25e3	1e3
II	400e6	150e6	20	50e3	5e3
III	500e6	200e6	20	60e3	5e3
IV	600e6	200e6	20	70e3	5e3

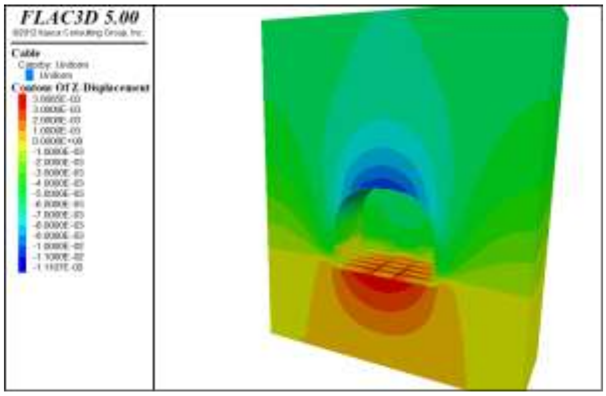
A multi-stage method was applied for drilling the tunnel section. In other words, each excavation step is completed in several stages. First, the tunnel roof on the right and left sides is drilled. Then, the middle section of the tunnel is removed. Next, the lower sides of the tunnel section are excavated. The middle-top section of the tunnel is then drilled, and finally, the excavation is completed by drilling the floor of the tunnel. It is worth noting that each of these drilling stages is accompanied by the installation of tunnel support system, and executing the lining, and rock bolt systems.

As previously mentioned, Flac 3D software was used for the numerical simulation of excavation at Lijiaping metro station. The vertical displacement contour and also the deflection of the tunnel roof were defined as the key parameters to judge the tunnel stability. As seen in Fig. 2, the maximum deflection induced at the tunnel crown is calculated as 1.1 cm. This value is in good agreement with the field monitoring measurement reporting the crown settlement to be around 10.93 mm.

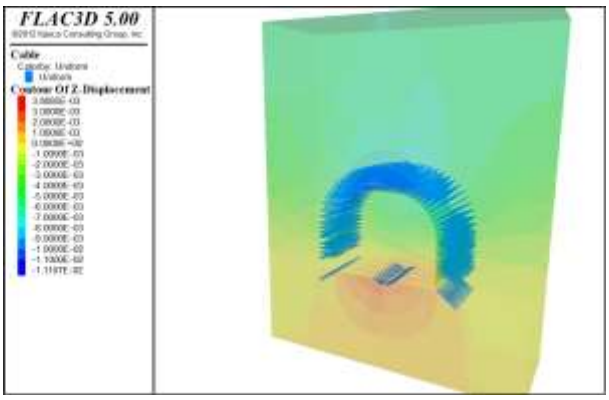
In continuation of study, the trend of the changes at each excavation stage and during the excavation steps, also the maximum deflection at the tunnel roof were calculated after each iteration. The values of these outputs are given in Table 2. In addition, these outputs are also depicted in Fig. 3.

Table 2. Roof deflection along the excavation, δ_z (m).

Step	Sec. 1	Sec. 2	Sec. 3	Sec. 4	Sec. 5	Sec.
1	2.41E-3	4.86E-3	6.31E-3	1.10E-2	1.08E-2	1.10E-2
2	3.40E-3	5.17E-3	7.56E-3	1.05E-2	1.09E-2	1.10E-2
3	4.03E-3	5.47E-3	9.70E-3	1.04E-2	1.09E-2	1.10E-2
4	4.58E-3	5.79E-3	1.13E-2	1.07E-2	1.10E-2	1.11E-2



(a) Contour plot of the vertical displacements



(b) Tunnel support system

Fig. 2. Analysis results at the last step of excavation.

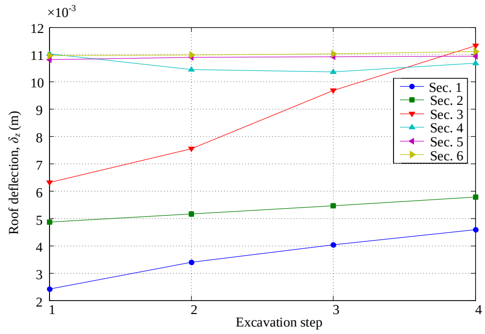


Fig. 3. Roof deflection at different steps of excavation.

4 RELIABILITY MODEL

To establish the problem as a reliability model, the involved parameters should be defined as random variables. In this paper, the characteristics of the middle rock layer (layer II), namely the shear modulus, cohesion, and friction angle were considered as random variables following lognormal distribution. Probabilistic characteristics of the variables are reported in Table 3. Mean values are different with deterministic values since they are calculated from different locations along the tunnel.

Table 3. Probabilistic characteristics of the random variables.

No.	Parameter	Mean	Std.	Par. 1*	Par. 2*
1	Shear modulus (MPa)	362	72.4	5.8720	0.1980
2	Friction angle (º)	23	4.6	3.11589	0.1980
3	Cohesion (Pa)	90000	18000	11.3879	0.1980

* Par. 1 and Par. 2 represent the first and second parameters of distribution function.

To perform the reliability analysis, uniformly distributed random numbers (between 0 and 1) were first generated for each random variable. The generated random numbers were then transferred to the target distribution function according to the probabilistic characteristics listed in Table 3. By substituting each set of the generated random numbers in the software model, the maximum deflection of the tunnel roof was calculated for each case. Thus, a databank of model outputs was created containing different values of the maximum tunnel deflection. The histogram of the outputs is shown in Fig. 4.

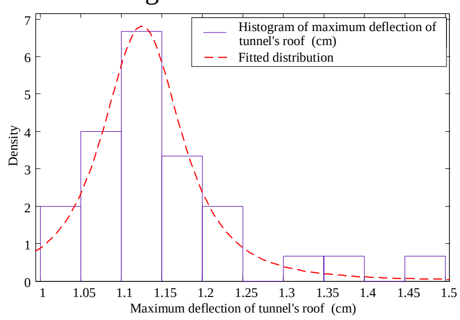


Fig. 4. Histogram of the maximum deflection values of the tunnel roof.

In the following, a limit state function (LSF) was defined as the difference between predicted maximum tunnel deflection (δ_{Tmax}) and desired tunnel deflection (δ_d) as follows:

$$\mathrm{LSF} = \delta_d - \delta_{T\max}. \quad (2)$$

First, assuming δ_d=1.2 cm, the problem was presented in the form of exceedance probability of tunnel deflection with respect to the above value. To solve this problem, different methodologies are available, such as the first- and second-order reliability analyses, Monte Carlo sampling method, and so forth. However, due to the complexity of the deterministic model governing the problem (i.e. software model), the response of the model is available for a limited caseloads. Thus, the above-mentioned conventional methods cannot be simply implemented and instead, a methodology is required which can work with limited data. For this purpose, the proposed method by Shadab Far and Wang (2016) is utilized in this paper. As such, by assuming δ_d=1.2 cm, the calculated values of δ_{Tmax} were substituted in Eq. 2 and the value of LSF function was calculated for all load cases. Then, LSF values were sorted in small to large order so that x_1 corresponds to the smallest value and x_n represents the largest value. Then, Gumbel probability was calculated for each x_i value as follows:

$$P_i = \frac{i}{N+1}, \quad (3)$$

where N is the total number of samples and i is the sample counter. Next, per each P_i, a z_i was calculated as $z_i=\Phi^{-1}(z_i)$, where $\Phi^{-1}(\bullet)$ is the inverse of the standard normal cumulative distribution function. In the next step, the z_i values were plotted versus x_i in Fig. 5.

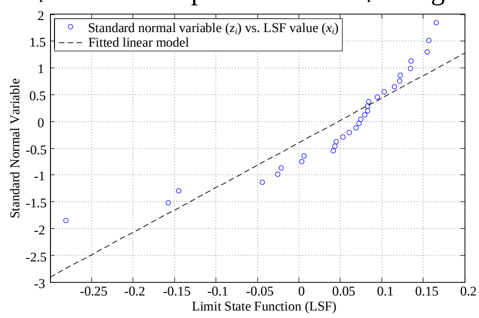


Fig. 5. Standard normal variable versus LSF.

Then, a first-order function (linear model) was fitted to the data. The equation obtained for the data studied in this paper is as follows:

$$z = 8.3643x - 0.3992. \quad (4)$$

As discussed in Shadab Far and Wang (2016), calculating the intersection of this curve with the axis x=0 (intercept), the exceedance probability can be calculated as follows:

$$P_f = \Phi(\text{intercept}) = \Phi(-0.3992) = 0.344873. \quad (4)$$

Thus, the probability of exceedance was estimated as 34.49%. This means that there is a 34.49% chance that the tunnel settlement could exceed 1.2 cm.

5 EXCEEDANCE PROBABILITY CURVE

So far, the exceedance probability of tunnel settlement for δ_d=1.2 cm was calculated. However, the target is to estimate the exceedance probability for any desired value of the tunnel settlement. Therefore, by changing the δ_d, a new reliability problem is presented and solved by the described algorithm, and the corresponding probability of exceedance was calculated. The results are shown in Fig. 6. This graph shows the exceedance probability for any possible value of target parameter (i.e. δ_d). As seen, by increasing δ_d, the exceedance probability falls sharply, so that for δ_d values larger than 1.35 cm the probability is less than 5%. The probability values directly calculated from the simulation results are also depicted in Fig. 6. As seen, the exceedance probability curve is in good agreement with the probability values calculated from model response.

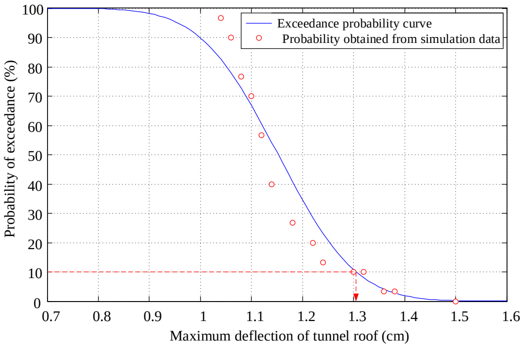


Fig. 6: Exceedance probability curve for the tunnel roof deflection.

The presented exceedance probability curve has practical application in the reliability-based evaluation and risk assessment of real projects (Shadab Far et al. 2018). For further explanation, assume that the project employer accepts a risk up to 10% for the excavation of the Chongqing metro tunnel. Thus, the corresponding settlement estimated from exceedance probability curve will be 1.3 cm, as shown in Fig. 6. A typical software analysis is then required to calculate the maximum tunnel settlement. If the calculated value is greater than 1.3 cm, the expected risk level has not been met. Therefore, further measures should be taken to increase the stability of the tunnel. Otherwise, the structure is safe and the excavation is in line with the expected risk level.

6 CONCLUSION

In this paper, a three dimensional model of Lijiaping station at line 9 of Chongqing metro tunnel was simulated and analyzed under different load cases. Then, by defining the geotechnical parameters as random variables, the problem was presented as a reliability model. A simplified algorithm was then used to solve the problem and estimate the exceedance probability.

The main contributions of this paper are as follows:

- The exceedance probability curve has been developed for the maximum deflection of the tunnel roof, providing the exceedance probability for any desired δ_d value.
- It was observed that, by increasing the δ_d value, the exceedance probability is sharply reduced, so that the exceedance probability for δ_d=1.35 cm is less than 5%.
- Given the target risk level of the project, the procedure to use exceedance probability curve to evaluate the structural safety is described by an example.

Finally, it is worth noting that the results of this paper can be updated by establishing a more comprehensive simulation database. Additionally, the effect of existing structures located on the ground surface has not been considered in this paper. This topic will be investigated by the authors in their future work.

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