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Reliability assessment on stability of tunnelling perpendicularly beneath an existing tunnel

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ABSTRACT

This paper presents a simplified procedure to evaluate the failure probability of crossing tunnels. Numerical package FLAC^{3D} (Itasca, 2017) was adopted to carry out a series of extensive parameter studies of crossing tunnels. Subsequently, two closed-formed limit state functions have developed via the logarithmic regression to estimate the global factor of safety as well as the induced maximum settlement of the existing tunnel. The developed surrogate models were implemented into the Monte Carlo Simulation to calculate the ultimate limit state failure and the probability that the threshold maximum settlement value is exceeded. This proposed method is an effective way to evaluate the safety and serviceability of tunneling perpendicularly beneath an existing tunnel.

Keywords: reliability assessment; crossing tunnels; safety factor; maximum settlement; MCS

1 INTRODUCTION

With development of urban subway construction and commercialization in the downtown areas, crossing metro tunnels are becoming more common. A simplified procedure is proposed to evaluate the failure probability of crossing tunnels. A series of numerical simulations by finite difference program FLAC^{3D} (Itasca, 2017) are carried out to investigate the influence of the various key design factors on the stability and the serviceability of the existing tunnel, such as the rock mass quality, the radius of the new and existing tunnels, the buried depth of the existing tunnel and the clearance between crossing tunnels. Based on the numerical results, surrogate models have been developed to assess the ultimate limit state in terms of the global factor of safety, as well as the serviceability limit state from aspects of the induced maximum settlement of the existing tunnel through the simple logarithmic regression. The Monte Carlo Simulation (MCS) is adopted to determine the ultimate limit state failure and the probability that the threshold maximum settlement value is exceeded.

2 NUMERICAL MODELING

This paper adopts finite difference analysis code FLAC^{3D} (Itasca, 2017) to numerically model the crossing tunnels and the construction procedures.

2.1 Assumptions

There are some assumptions of numerical analyses to simplify the calculation procedure. The rock mass behavior follows the Hoek-Brown failure criterion. The shield tunneling method is adopted in the numerical model. The cross section of existing tunnel and new constructed tunnel are circular. The support pressure ratio of tunnel face is 1. The tunnels are supported by shell elements, and the thickness of tunnel liner is 0.3m. C50 concrete is used in shield tunnel segment. The material parameters of C50 are shown in Table 1. Creep of surrounding rock is not considered. The construction parameters of tunnel boring machine, such as the face support pressure, grouting pressure and thrust force, etc., are not considered in the numerical model. Factor of safety is calculated for the existing tunnel liner.

Table 1. C50 material properties.

Young modulus/(N/m^2)	Poisson's ratio	Density/(kg/m^2)
3.5×10^{10}	0.2	2500

2.2 Geometrical parameters of crossing tunnels model

The layout of crossing tunnels is plotted in Fig.1. The burial depth of existing tunnel is H, varying between 10 and 40 m. The diameter of existing tunnel is D_1, and the new tunnel is D_2. Both D_1 and D_2 change from 6 to 15 m. The center-to-center spacing between the two tunnels h varies from 1 to 30 m. The different levels of each geometrical parameter is listed in Table 2.

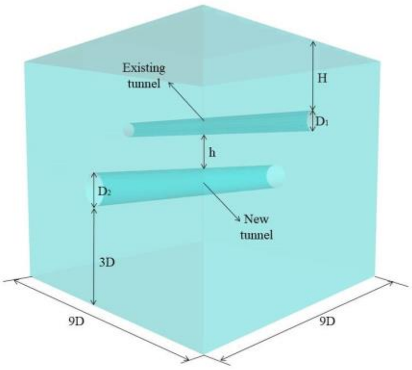


Fig.1. 3D view of crossing tunnels model

Table 2. Input geometrical parameters.

Geometrical parameters	Values
H (m)	10,20,30,40
D_1 (m)	6,9,12,15
D_2 (m)	6,9,12,15
h (m)	1,6,12,18,30

2.3 Rock mass properties

As mentioned above, the Hoek-Brown criterion is adopted in this paper. The input rock mass parameters in the crossing tunnels model are designed as in Table 3. For simplicity, density of 2400 kg/m^3 is assumed for rock mass of all the ranges of *GSI*.

Table 3. Rock mass parameters in crossing tunnels model

Input rock mass parameters	σ_i (MPa)	m_i	GSI
Values	10	5	10
	30	10	30
	50	15	50
	70	20	70

2.4 Modeling results

For the seven input parameters mentioned above, there are in all 20480 combinations for the perpendicularly crossing tunnels model. It would be a huge amount of work for computation of 3D model by FDM. In order to minimize the computational task, orthogonal test is employed. 32 groups were produced through orthogonal test based on the seven parameters.

The safety factor of existing tunnel liner FS_{FLAC} was calculated by Carranza-Torres's method, which is the load capacity of the liner in compression or tension(Carranza-Torres and Diederichs, 2007). The safety factor The maximum settlement of existing tunnel $S_{\max(FLAC)}$ is monitored in the new tunnel excavation. The calculation results are summarized in Table 4.

Table 4. Modeling results of crossing tunnels

Group	FS_{FLAC}	$S_{\max(FLAC)}/mm$	Group	FS_{FLAC}	$S_{\max(FLAC)}/mm$
1	4.35	0.24	17	5.51	1.01
2	3.55	3.083601	18	18.54	0.13
3	9.94	0.79	19	1.30	7.68
4	51.28	0.10	20	3.68	0.29
5	5.57	1.79	21	7.78	0.85
6	6.32	0.85	22	18.23	0.12
7	4.69	1.01	23	12.16	0.36
8	13.47	0.69	24	5.06	1.84
9	2.46	0.44	25	4.75	0.68
10	4.27	0.34	26	14.72	0.76
11	48.20	0.04	27	13.80	1.01
12	7.15	0.85	28	14.86	0.44
13	19.74	0.25	29	4.21	0.25
14	9.62	0.35	30	9.94	0.36
15	2.08	3.62	31	3.42	0.92
16	2.76	3.73	32	28.75	0.34

3 PREDICTIVE MODELS

Based on the above results, two surrogate models of tunnelling beneath an existing tunnel were developed via logarithmic regression, as represented in equations (1) and (2).

$$FS_{\text{regression}} = 3.3670\sigma_i^{0.3151} m_i^{0.0626} GSI^{0.8919} H^{-0.7470} D_1^{-0.5251} D_2^{-0.0135} h^{0.0184} \quad (1)$$

$$S_{\max(regression)} = 0.04135\sigma_i^{-0.3024} m_i^{0.0325} GSI^{-0.9131} H^{0.5719} D_1^{0.1070} D_2^{2.1218} h^{-0.0517} \quad (2)$$

A comparison between $FS_{\text{regression}}$ and FS_{FLAC} (the safety factor of existing tunnel liner obtained from FLAC^{3D}) is shown in Fig.3. Similarly the difference between $S_{\max(FLAC)}$ and $S_{\max(regression)}$ is plotted in Fig.4. The coefficient of determination R^2 between $FS_{\text{regression}}$ and FS_{FLAC} is 0.895 while R^2 between $S_{\max(FLAC)}$ and $S_{\max(regression)}$ is 0.902, indicating that the estimated results from the developed logarithmic regression models are in good agreement with the FDM values.

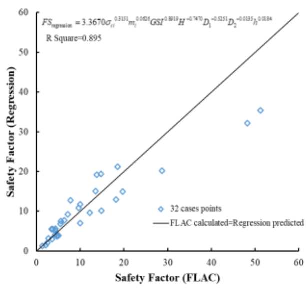


Fig.2. Comparison between FS_{FLAC} and $FS_{regression}$

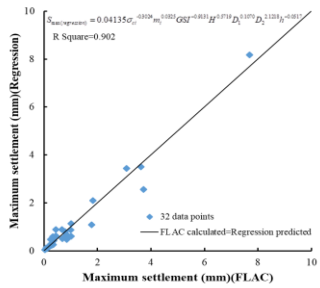


Fig.3 Comparison between $S_{\max(FLAC)}$ and $S_{\max(regression)}$

4 RELIABILITY ASSESSMENT

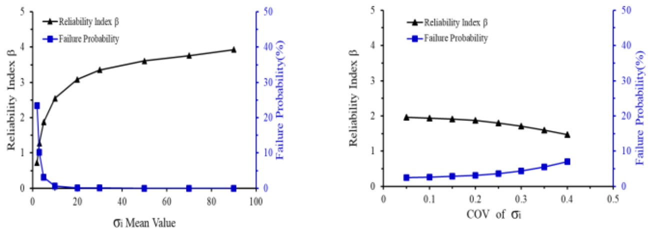
According to the relevant literature, the threshold safety factor of existing tunnel liner is generally set at 2.0 and the critical settlement of existing tunnel is taken as the warning/alarming value of 10mm (Jiang et al.,2012; Liu,2013; Zhang et al., 2017). If either of them exceeds the threshold value, the existing tunnel is considered to be failed (exactly, less satisfactory). The developed estimation models were implemented into the Monte Carlo Simulation accordingly to calculate the reliability index and the failure probability of the existing tunnel. For an example analysis of crossing tunnels, rock mass parameters selected from Hoek (1997) for poor quality rock mass at shallow depth as well as the geometrical parameters are listed in Table 5.

Table 5. Input parameters in an example analysis

Parameter	Mean value	COV
	Probabilistic	
σ_i (Mpa)	5	0.2
m_i	9.6	0.2
GSI	20	0.2
	Deterministic	
H(m)	20	——
D1(m)	9	——
D2(m)	15	——
h(m)	6	——

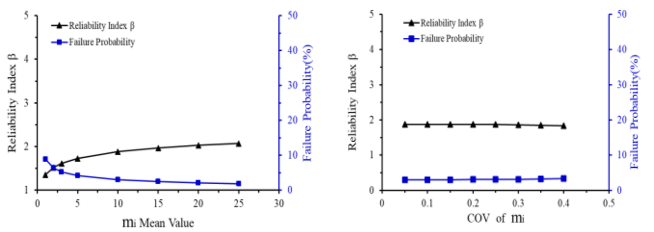
4.1 Influence of rock mass properties

As mentioned above, the Hoek-Brown criterion was assumed for the rock mass material. The determination of rock mass quality requires at least three parameters σ_i , m_i and GSI. These three parameters are not constants due to the inhomogeneity of rock mass and the error of visual observation in practical engineering. Therefore, it is necessary to consider the uncertainty of rock mass parameters in tunnel design. The influence of mean value and coefficient of variation (COV) of σ_i , m_i and GSI are illustrated in Fig.4 to Fig.6, respectively.



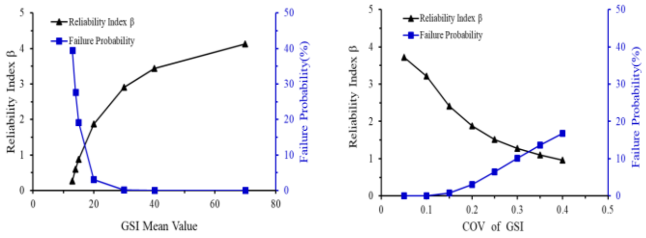
(a) (b)

Fig.4 Influence of: (a) mean value, and (b) COV of σ_i



(a) (b)

Fig.5 Influence of (a) mean value, and (b) COV of m_i



(a) (b)

Fig.6 Influence of (a) mean value, and (b) COV of GSI

As shown in Fig.4, the failure probability of existing tunnel decreases as the mean value of σ_i increases. Accordingly, the reliability index β increases as the mean value of σ_i is becoming even greater. On the contrary, with the increase of COV of σ_i , the failure probability increases and the reliability index β decreases accordingly. The influences of mean value and COV of both m_i and GSI for the existing tunnel follow the same trend as σ_i , as shown in Fig.5 and Fig.6, respectively. However, it is important to point out that the failure probability and reliability index β of existing tunnel are on low variations with the increasing of mean value and COV of m_i . Especially the COV of m_i on existing tunnel has little effect on the safety of existing tunnel from Fig.5b. The material constant of intact rock m_i directly affects the size of m_b and the Poisson's ratio of rock mass υ_{rm} . When other parameters are determined, the change of GSI caused by m_i within its range is small. Therefore, m_i has the least impact on the existing tunnel by comparing with GSI and σ_i . What is more, m_i is the property of intact rock. The geology strength index(GSI) is to measure the degree of intact rock deterioration. Therefore, the properties of surrounding rock of tunnel depend more on the geology strength index(GSI).

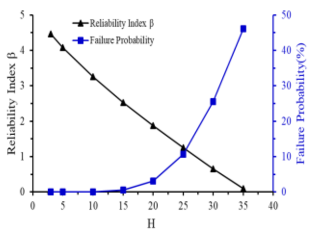


Fig.7. Influence of burial depth H

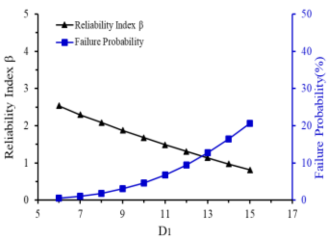


Fig.8. Influence of diameter D_1 of existing tunnel

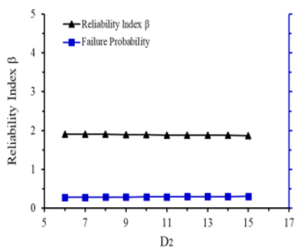


Fig.9. Influence of diameter D_2 of new tunnel

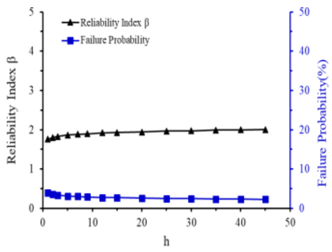


Fig.10. Influence of clear distance h

As shown in Fig.7, with the increasing of burial depth H, the failure probability of existing tunnel increases and the reliability index β decreases. The effect of diameter of existing tunnel D_1 and new tunnel D_2 on the safety of existing tunnel are the same as burial depth H as illustrated in Fig.8 and Fig.9. But the failure probability of existing tunnel decreases and the reliability index β of existing tunnel increases with increase of the clear distance h between existing and new tunnels, based on Fig.10. It should be noted that the diameter D_2 of new tunnel has marginal impact on the failure probability and reliability index β, as shown in Fig.9. The reason lies is that the material parameters of the existing liner selected for FDM computations are conservative and on the safer side. In other words, the segment designed in the engineering of shield tunnel has a large safety space. But even if we could assume that the conservative segments are supported immediately after the excavation of shield tunnel, the increase or decrease of the diameter of the new tunnel has little impact on the settlement and safety of the existing tunnel in some range of buried depth.

5 CONCLUSIONS

FDM numerical analyses have been carried out to assess the reliability of tunneling beneath an existing tunnel. Two surrogate models relating the liner safety factor and the maximum settlement of existing tunnel to rock mass properties and geometrical parameters were developed respectively by logarithmic regression, based on 32 sets of orthogonal experimental results. A comparison between the calculated and predicted safety factor and maximum settlement of existing tunnel showed good agreement. The developed surrogate models were implemented into the Monte Carlo Simulation (MCS) for calculation of the failure probability and the reliability index β.

In the part of reliability analysis of crossing tunnels, rock mass parameters were considered as probabilistic while the geometrical parameters of crossing tunnels were deterministic. The reliability analyses indicated that the probability of failure is significantly influenced by geological strength index GSI, the uniaxial compressive strength σ_i and the burial depth of existing tunnel H. It can be seen from reliability analysis that the uncertainty and variance of rock mass properties may have more influences on the safety and serviceability of existing tunnel than some geometry parameters in the design for crossing tunnel. Therefore, the uncertainty of rock mass parameters cannot be ignored in the new tunnel construction, especially the GSI and σ_i values. It is suggested that the safety factor FS, the maximum settlement and the failure probability of existing tunnel can be systematically considered in further research for system reliability analysis in the design for tunneling beneath an existing tunnel. In addition, the spatial variability of the GSI and σ_i parameters should also be taken into consideration, instead of the spatially-constant ground conditions in the current study.

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