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Reliability-Based Design Method for Cut-and-Cover Tunnels

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Summary

The statistical results of geometrical and physical parameters for both backfill soil and structural material of cut-and-cover tunnels are given in this paper, while centrifugal model test is employed to figure out uncertainties in calculation formulae of backfill soil pressure. Then, uncertainties in load effect of structures under backfill soil pressure are determined with finite element-multiple response surface method. On the basis of above research, reliability indices for the 16 cut-and-cover tunnel structures in standard design drawing album are calculated and a target reliability index as well as partial coefficients in design equation are selected. Finally, a reliability-based design equation for cut-and-cover tunnel structures is developed.

1 Introduction

Cut-and-cover tunnel is an important type of tunnel constructions. Compared with other tunnels, cut-and-cover tunnel has more similarity with ground structures, so it is relatively more easier to make a reliability-based design for this type of tunnel than that of other tunnels.

In this paper, uncertainties in backfill soil and structural material, uncertainties in calculation formula of backfill soil pressure and probability characteristics of load effect of structures are discussed, following with reliability calculation of cut-and-cover tunnel structures as well as selection of target reliability index and partial coefficients in design equation.

The parameters affecting backfill soil pressure include thickness, slope angle, bulk density and internal friction angle, of the backfill soil. Centrifugal model test is used to help find uncertainties in calculation formulae of backfill soil pressure, by comparing experimental results with theoretical results of the earth pressure. 11 models, backfilled in both symmetric and asymmetric shapes of soil, are tested to achieve the uncertainty analysis. When small sample size occurs in statistics, statistical uncertainty is taken into consideration[1]. Accordance with so-called "structure-load" model, the uncertainties in load effect of cut-and-cover tunnel structures under backfill soil pressure are worked out with finite element-multiple response surface method[2], in which 16 structures from standard design drawing album are involved in calculation, and 4 random variables, modulus of elasticity of structural material, coefficient of rock mass reaction, backfill soil pressure on arch ring and backfill soil pressure on side wall, are taken into account in response surface. Based on the aforementioned work and the calibration method, we compute reliability indexes for the 16 structures with fractile method[3] and determine a target reliability index and partial coefficients in design equation, all being weighted with coefficients selected according to the rate of utilization of cut-and-cover tunnels. At the end of this paper, reliability-based design equation for cut-and-cover tunnel structures is given for application in practice.

2 Statistical analysis of basic random variables

The random variables influencing structural reliability of cut-and-cover tunnels could be divided into two groups. One group is on load, such as geometric shape of backfill soil (thickness and slope angle), material properties of backfill soil (bulk density and internal friction angle) and coefficient of rock mass reaction etc. Another group falls on structural capacity, for instance the bulk density, compressive strength, tensile strength, modulus of elasticity and Poisson's ratio, of structural material, etc. The statistical results of those basic random variables are shown in Table 1. Statistical data for variables on load are obtained by ourselves through in-situ investigation. To the load-relative variables, statistical uncertainties are thought over when their sample sizes are less than 50. Statistical data for capacity-related variables are mainly taken from ground structures. The capacity-related variables, having no bearing on backfill soil pressure, will play a role in load effect calculation and reliability computation of the structures.

Table 1 Statistical results of basic random variables

random variables	design value	sample size	mean	var. coeff.	distr. type
thickness of backfill soil (m)	1.5	31	1. 545	0.0906	normal
	2.0	40	1. 927	0.0610	
	2.5	10	2.516	0.0528	
	3.0	20	2.980	0.0601	
slope angle of backfill soil (°)	11.31(1:5)	40	11.07	0.0783	normal
	5.71(1:10)	12	5.79	0.0618	
	18.43(1:3)	15	19.17	0.1263	
bulk density of backfill soil (KN/m^3)	19.00	99	18.94	0.0551	normal
internal friction angle of backfill soil (°)	35.00	50	34.17	0.1216	normal
coeff. of rock mass reaction (MN/m^3)	rock mass of type II*		133	0.177	lognormal
	rock mass of type III		300	0.236	
	rock mass of type IV		733	0.225	
	rock mass of type V		1400	0.101	
bulk density of concrete (KN/m^3)			23	0.02	normal
compressive strength of concrete (MPa)	C20		20.67	0.308	lognormal
tensile strength of concrete (MPa)	C20		3.878	0.336	lognormal
modulus of elasticity of concrete (MPa)	C20		27000	0.0853	normal
Poisson's ratio of concrete	C20		0.2	0.05	normal

* The type of rock mass is from within the rock mass classification adopted by railway in China, the same blow.

3 Uncertainties in calculation formulas of backfill soil pressure

Backfill soil pressure can be verified by in-situ test, ordinary simulation model test and centrifugal model test. The in-situ test is quite expansive with results of high dispersity. In ordinary simulation model test, the model, required satisfying geometric and physical similarity rules, will be quite small in size and the backfill soil in the model will be unduly thin in thickness at the same time, which makes the measurement of backfill soil pressure uneasy. In comparison with the former two methods, centrifugal model test is relatively cheap in cost, easy in making, convenient in measuring, with a good representing of the prototype. Centrifugal model test has been widely used in geotechnical engineering and stability analysis of high slopes and hydraulic structures etc. It is the centrifugal model test that is appropriate to be employed in evaluation for uncertainties in calculation formulas of backfill soil pressure.

In this study, 11 model tests are completed. The model scale is 1:50 and structural material is C20 concrete in all tests. Other test parameters are listed in Table 2.

Table 2 Principal parameters in centrifugal model tests

type of cut-and-cover tunnel	slope of cutting	slope of backfill soil	thickness of backfill soil at crown (m)	type of backfill soil	number of survey points
type I in shape II*	1:0.75	1:5(symmetric)	1.5	clay	8
type I in shape II	1:0.75	1:5(symmetric)	2.0	clay	8
type I in shape II	1:0.75	1:5(symmetric)	2.5	clay	8
type I in shape IV	1:0.75	1:10(symmetric)	1.5	sand	8
type I in shape IV	1:0.75	1:10(symmetric)	2.0	sand	8
type I in shape IV	1:0.75	1:10(symmetric)	2.5	sand	8
type I in shape IV	no cutting	1:10(symmetric)	2.0	sand	8
type I in shape IV	1:0.75	1:10(symmetric)	2.0	clay	8
type II in shape IV	1:0.75	1:5(asymmetric)	1.5	sand	11
type II in shape IV	1:0.75	1:3(asymmetric)	1.5	sand	11
type II in shape IV	1:0.75	1:2(asymmetric)	1.5	sand	11

* Here "shape" denotes the shape of cross section of a lining, with I corresponding to symmetric cross section, II asymmetric cross section with vertical side wall, III asymmetric cross section with one inclined side wall and IV asymmetric cross section with one inclined side wall on which there is no earth pressure. "Type" means the type of rock masses in which a tunnel are constructed. The rock mass are classified from VI to I according to railway standard in China, in which the smaller the type, the worse the quality of the rock mass. For every shape, we have 4 types of structures from V to II.

The uncertainties in calculation formulas might be expressed with an uncertainty random variable of calculation formulas, which is defined as a ratio of experimental value to theoretical value of backfill soil pressure. Here, the theoretical value is calculated according to the formulas in appendix III of Design Code for Railway Tunnel in China.

Taking a look at the experimental results, we know that the backfill soil pressures at different location on arch ring have a smaller difference, between their experimental value and theoretical value, in contrast to side wall. The reason for this phenomena is suggested to be due to the lack of consideration of resistance of cutting slope in the formulas of the code. Therefore, we use two uncertainty random variables to express uncertainties in calculation formulae on arch ring and side wall separately. Statistical results of the uncertainty variable ξ on arch ring and η on side wall are given in Table 3. Here the statistical uncertainties of ξ and η are also considered.

Table 3 Uncertainties in calculation formulas on backfill soil pressure

random variables	sample size	mean	stand. dev.	var. coeff.	distr. type
ξ	42	1.0327	0.2190	0.2120	normal
η	37	0.8063	0.3123	0.3873	normal

4 Uncertainties in load effect of cut-and-cover tunnel structures

Section 2 gives probability characteristics of basic random variables, while section 3 proposes

the uncertainties in calculation formulae of backfill soil pressure. Following we come to uncertainties in load effect of cut-and-cover tunnel structures under backfill soil pressure.
We take in the uncertainty analysis of load effect 16 cut-and-cover tunnel structures, which cover all the structures from type V to type II in I-IV shapes in standard design drawing album. In load effect calculation below, thickness of backfill soil at crown is chosen as 2m and slope of cutting is 1:0.75 for all 16 cur-and-cover tunnels.
We treat the structures as a plane strain problem, being discreted into beam elements at backfill soil and beams element on elastic foundation at rock mass, respectively. 4 random variables with strong influence on internal forces of structures, modulus of elasticity of structural material, coefficient of rock mass reaction, backfill soil pressure on arch ring and backfill soil pressure on side wall, are taken into account in calculation. Other variables, for example structural gravity and geometric size etc., are regarded as constants due to their small variability.
The probability characteristics of modulus of elasticity of structural material and coefficient of rock mass reaction have been given in Table 1. The probability characteristics of backfill soil pressure on arch ring and backfill soil pressure on side wall could be brought out with Monte-Carlo method from random variables of thickness of backfill soil, slope angle, bulk density, internal friction angle and uncertainty variables of ξ and η. The probability characteristics for the 4 selected variables are obtained as in Table 4.

Table 4 Probability characteristics of basic variables in load effect computing

random variables		mean	var. coeff.	distr. type
modulus of elasticity of lining (GPa)		27	0.0853	normal
elastic coeff. of rock mass (MN/m^3)	rock mass of type V	1400	0.1770	log normal
	rock mass of type IV	733	0.236	
	rock mass of type III	300	0.225	
	rock mass of type II	133	0.101	
backfill soil pressure on arch ring (KPa)		39.347*	0.2258	normal
backfill soil pressure on side wall (KPa)		27.777#	0.4255	normal

* The value represents a mean of earth pressure at crown. The means of earth pressure at other positions on arch are different from the one at crown, while variation coefficients for all locations on arch are the same.
\# The value represents a mean of earth pressure at spring. The means of earth pressure at other positions on wall are different from the one at spring, while variation coefficients for all locations on wall are the same.

In interval $[-3\sigma,+3\sigma]$ of backfill soil pressures on arch ring and side wall, we divide whole the sampling area into 9 sub-areas to achieve a multiple response surface, which is used to calculate probability characteristics of load effect, axial force N and moment M. Here σ denotes the standard deviation of variables of interest. Calculation results at the most dangerous section of tunnel structures are shown in Table 5.

5 Target reliability index and partial coefficients

On the calculation results of load effect in section 4, it is known that the 16 cut-and-cover tunnel structures are all controlled for failure by tensile limit state, so we could, based on the tensile strength design equation of concrete in deterministic design, establish a limit state function for reliability-based design as follows

$$g=1.75\sigma_t d^2+Nd-6M \quad (1)$$

where N--axial force, KN; M--moment, KN-m; σ_t--tensile strength of concrete, KPa; d--section thickness, m.
In Eq.(1), only the variability of σ_t, M and N are considered, while d is looked upon as a constant.

According to Eq.(1), the design equation for cut-and-cover tunnel structures can be written as

$$\gamma_t^{-1} \cdot 1.75\sigma_t d^2 + \gamma_n^{-1} \cdot Nd \geq \gamma_m \cdot 6M \quad (2)$$

in which γ_t--partial coefficient on capacity; γ_n--partial coefficient on load effect(axial force); γ_m--partial coefficient on load effect(moment); other symbols in Eq.(2) are the same as in Eq.(1).

Table 5 Probability characteristics of load effect for 16 cut-and-cover tunnels

shape	type	location	load effect	mean	var. coeff.	distr. type
I	V	arch ring	axial force N (KN)	118.64	0.3366	lognormal
			moment M(KN-m)	14.03	0.3410	
	IV	arch ring	axial force N (KN)	127.86	0.3375	
			moment M(KN-m)	20.02	0.3414	
	III	arch ring	axial force N (KN)	130.45	0.3374	
			moment M(KN-m)	24.32	0.3424	
	II	side wall	axial force N (KN)	284.71	0.3327	
			moment M(KN-m)	105.85	0.4438	
II	V	arch ring	axial force N (KN)	106.71	0.3448	lognormal
			moment M(KN-m)	22.86	0.3497	
	IV	arch ring	axial force N (KN)	102.87	0.3468	
			moment M(KN-m)	24.64	0.3503	
	III	arch ring	axial force N (KN)	111.24	0.3473	
			moment M(KN-m)	27.74	0.3540	
	II	side wall	axial force N (KN)	332.48	0.3420	
			moment M(KN-m)	243.24	0.4463	
III	V	arch ring	axial force N (KN)	118.20	0.4015	lognormal
			moment M(KN-m)	24.82	0.4110	
	IV	arch ring	axial force N (KN)	111.84	0.4037	
			moment M(KN-m)	28.38	0.4164	
	III	side wall	axial force N (KN)	278.67	0.4002	
			moment M(KN-m)	50.87	0.4120	
	II	arch ring	axial force N (KN)	220.36	0.4348	
			moment M(KN-m)	79.09	0.4472	
IV	V	arch ring	axial force N (KN)	104.82	0.3523	lognormal
			moment M(KN-m)	26.76	0.3545	
	IV	arch ring	axial force N (KN)	116.08	0.3553	
			moment M(KN-m)	31.46	0.3589	
	III	arch ring	axial force N (KN)	118.36	0.3603	
			moment M(KN-m)	33.67	0.3611	
	II	arch ring	axial force N (KN)	223.82	0.4314	
			moment M(KN-m)	103.82	0.3459	

Barring limit state function and design equation, we also need weight coefficients in calculation of target reliability index and partial coefficients. Based on investigation data of 278 cut-and-cover tunnels in use, we figure out the weight coefficients as in Table 6.

Table 6 Weight coefficients relevant to the rate of utilization of cut-and-cover tunnels

shape \ type	V	IV	III	II
I	0.000	0.002	0.073	0.107
II	0.005	0.036	0.232	0.172
III	0.000	0.014	0.038	0.038
IV	0.009	0.047	0.141	0.086

Making use of the probability characteristics of properties of structural material and load effect, Probabilities of structural failure of 16 cut-and-cover tunnel structures are computed on the limit state function with fractile method. Then, weighting the probabilities of structural failure with the coefficients from Table 6 yields an average failure probability $P_f=8.916\times10^{-5}$, Which results in a reliability index $\beta=3.748$. Therefore the target reliability index for cut-and-cover tunnel structures can be chosen as

$$\beta=3.7 \tag{3}$$

Partial coefficients for the 16 structures can be brought about from the target reliability index. Again weighting the partial coefficients with the coefficients from Table 6 finally produces the partial coefficients for cut-and-cover tunnel structures as below

$$\gamma_t=1.35, \quad \gamma_n=1.12, \quad \gamma_m=2.74 \tag{4}$$

In partial coefficient computing, the nominal value of property parameter σ_t of concrete is taken as fractile of 5% probability, and the nominal values of load effect N and M as fractiles of 95% probability.

At the end, we come to the design equation for cut-and-cover tunnel structures relevant to tensile limit state function as

$$\frac{1.75\sigma_t d^2}{1.35}+\frac{Nd}{1.12}\geq 2.74\times 6M \tag{5}$$

6 Conclusions

This paper shows the statistical results of parameters of backfill soil and properties of structural material in cut-and-cover tunnels in China. Based on centrifugal model test, uncertainties in calculation formulas of backfill soil pressure are brought out. After figuring out probability characteristics of load effect of 16 cut-and-cover tunnel structures under backfill soil pressure with finite element-multiple response surface method, the author calculates the reliabilities of the 16 structures, and according to the calibration method, selects a target reliability index and partial coefficients in design equation.

Owing to the lack of statistical data, we just considered the load produced by backfill soil, neglecting other loads, e.g. load due to collapse of side hill etc. Otherwise, because the target reliability index and partial coefficients are all computed at the most dangerous sections, and all the most dangerous sections are controlled by tensile limit state, we can only propose a design equation relevant to tensile limit state. Generally speaking, the design equation relevant to compressive limit state could be written as

$$\gamma_c^{-1}\cdot\alpha\sigma_c d\geq\gamma_n\cdot N \tag{6}$$

where N--axial force, KN; σ_c--compressive strength of concrete, KPa; α--eccentric influence factor for axial force N ($\alpha=1+0.648(e/d)-12.569(e/d)^2+15.444(e/d)^3$); e--eccentricity (=M/N), m; d--section thickness, m; γ_c--partial coefficient on capacity; γ_n--partial coefficient on load effect.

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