



Title	Structural Reliability Analysis of NATM Tunnel Face Stability in Soft Ground
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Publication date	2013-03-20
Publication information	Moradabadi, Ehsan, and Aliakbar Golshani. "Structural Reliability Analysis of NATM Tunnel Face Stability in Soft Ground." CIR Publishing, March 20, 2013. https://doi.org/10.13140/RG.2.1.2007.7920 .
Conference details	TU-Seoul 2013: Tunnelling and Underground Space Construction for Sustainable Development, Seoul, Korea, March, 2013
Publisher	CIR Publishing
Item record/more information	http://hdl.handle.net/10197/7464
Publisher's version (DOI)	10.13140/RG.2.1.2007.7920

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Structural Reliability Analysis of NATM Tunnel Face Stability in Soft Ground

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ABSTRACT: In spite of enhancement in modeling techniques as well as site investigation methods, uncertainty exists seriously in the process of construction of underground structure in soft soils. These uncertainties arise from limited data of geological data, measurement errors, interpolation of spatially geological properties, and extrapolation of results of experiments and natural analogue studies over times and conditions relevant to the project. Robust and optimize design of tunnel support pattern consists many important parameters including advance rate and excavation method. However, quantitative definition of these parameters is difficult because of restricting in site investigation data and uncertainties related to them. Furthermore, erroneous evaluation in these parameters can affect in incorrect projection of tunnel stability or economic loss. In this study, a probabilistic hypothetical elasticity modulus approach, based on Monte Carlo simulation algorithm (Latin Hyper Cube sampling), has been employed to evaluate the uncertainty in lining design of a NATM tunnel located in Tehran region. A parametric finite element model based on ABAQUS and a MATLAB interface program has been introduced to evaluate the performance of supporting system to limit the settlements induced by tunnel excavation in the different magnitudes of lifetime probability of failure. The tunnel has a horseshoe shape, excavating in a soft soil for subway purpose.

Keywords: Reliability/Uncertainty Analysis, Monte Carlo Simulation, Parametric Finite Element Model, Settlement Control, Hypothetical Elasticity Modulus

1 INTRODUCTION

In spite of enhancement in modeling techniques as well as site investigation methods (to predict the settlements induced), uncertainty seriously exists in the process of construction of underground structures in soft soils.

These uncertainties arise from limited geological data, measurement errors, interpolation of spatially geological properties, and extrapolation of experimental results and natural analogue studies over times and conditions relevant to the project (You, Park et al. 2005). Robust and optimize design of tunnel supports pattern consists of many important parameters including advanced rate and excavation method. However, quantitative definition of these parameters is difficult because of restricting in site investigation data and uncertainties related to them.

Furthermore, erroneous evaluation in these parameters can affect in incorrect projection of tunnel stability or economic loss (You, Park et al. 2005). Meanwhile, the probabilistic (or reliability) approach, as a more reasonable and realistic treatment for the uncertainties, has been invoked to achieve current requirements in many fields of geotechnics these years (Su, Li et al. 2011). A probabilistic approach, when it is possible to have sufficient data on the quality of the material, leads to better understanding of the project risks; more efficient geomechanical zoning; and a more reliable estimation of the costs (Oreste 2005).

In this study, a probabilistic approach, Monte Carlo simulation algorithm (Latin Hyper Cube sampling), has been employed to evaluate the uncertainty in lining design of a NATM tunnel located in Tehran region. A parametric finite element model based on ABAQUS and a MATLAB interface program has been introduced to evaluate the performance of supporting system in projection of settlements induced by tunnel excavation in the different magnitudes of lifetime probability of failure.

2 AMIRKABIR EXPRESS WAY TUNNEL

2.1 Location of the project

Amirkabir tunnel with approximately 1.5Km long in each line (north and south) is located between 17 Shahrivar street and Imam Ali highway in Tehran. In Kerman square, the tunnel is divided into two branches (Fig 1). The north branch (T4 section), the objective of this paper, is located under Doroodian street.

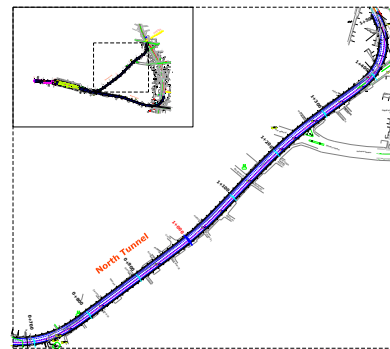


Figure 1. Plan of Amirkabir Tunnel

2.2 Geology and Material Characteristic of the site

The study area is located on sedimentary basin mainly composed of recent alluvial. Based on in-situ and lab analysis, the stochastic characteristics of the site are summarized in Table 1.

Table 1. Probabilistic parameters of the soil

Parameter		Mean	STD	Lower Bound	Upper Bound	Dist.
Cohesion(Pa)	C_{soil}	3.12E4	6.21E3	2.7e4	1.19E5	logN
Friction angle(Degree)	ϕ_{soil}	32.45	1.72	29	35.3	N
Young's modulus (Pa)	E_{soil}	8.41E+7	2.90E+7	1.68e7	9.66e7	N
Poisson ratio(-)	ν_{soil}	0.3	0.03	0.285	0.315	Beta
Density(Kg/m ³)	γ_{soil}	1960	120	1720	2090	N

2.3 Geometry of the Tunnel Section and Construction Phases

Regarding the construction phases of the north branch of the tunnel, the geometrical cross section of the T4 division includes one type of cross sections as shown in Figures 2.

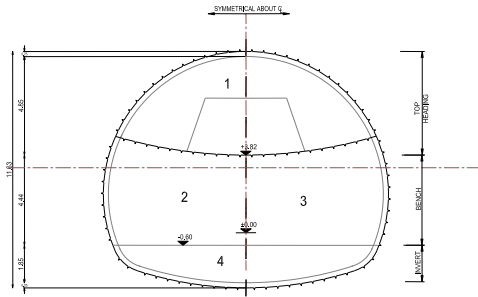


Figure 2. T4 Tunnel Cross Section

The excavation and support of the T4 tunnel will be carried out using the New Austrian Tunneling Method (NATM), combining a horizontal and a vertical operation sequence. In this method partial driving and sufficient face, support with shotcrete is required to provide safe tunneling conditions. The length of an excavation round is limited to maximum 1 meter. The advance rate is restricted to 3 - 4 m in 24 hours to limit deformations of the early age shotcrete lining according to the shotcrete guideline.

3 Reliability analysis and performance limit function

In the context of reliability analysis, failure is defined as the conditions where a predefined limit state is reached. Load and resistance factors are selected to insure that each possible limit state has an acceptably small probability of occurrence (FHWA 2001). Each reliability analysis requires a limit state function, which defines failure or safe performance. Limit states could relate to strength failure, serviceability failure, or anything else that describes unsatisfactory performance. The limit state function, f , is defined (Griffiths, Fenton et al. 2007):

$$\begin{aligned} f(X) \geq 0 &\rightarrow \text{Safe} \\ f(X) < 0 &\rightarrow \text{Failure} \\ X &= [x_1, x_2, \dots, x_N] \end{aligned} \quad (1)$$

Where X is the vector of model input and N is the number of random variables. For the Service Limit State, f is characterized as (FHWA 2001; Hung, Monsees et al. 2009):

$$y = f(X) = \delta_n - \delta_i \quad (2)$$

where δ_i is the estimated displacement and δ_n is tolerable displacement established by designer.

In this research, based on a MATLAB (Matlab 2010) interface program and a generic tool for uncertainty analysis, Eikos (Ekström 2005), 2000 Latin Hypercube simulations were performed on each of the non-circular surface to determine the probabilistic limit state function (Equation 1) of ABAQUS-based finite element model (ABAQUS 2010) which is described in next sections.

4 TIME-DEPENDENT SPRAYED SHOTCRETE MODEL

Aging makes the task of modelling sprayed concrete considerably more complicated than is the case for other

lining materials (Thomas 2009). According to (Chang 1994), a modified empirical exponential model is used in this research to model the changing of elasticity modulus of the sprayed concrete:

$$E_{ij} = 1.062 E_{28} / CR \cdot e^{-0.446 T_{ij}^{0.7}}$$

where E_{ij} and T_{ij} (day) are the Elasticity modulus and the average age of shotcrete of the part i of lining in phase j of excavation process, respectively; and E_{28} is the 28-day elasticity modulus of concrete.

In addition, CR is the calibration ratio derived from comparison of 3D model with current 2D, averagely is equal to 1.25 for this project. The assumptions of HEM-values for this research adopted with real excavation phases are fully presented in table 2.

5 PARAMETRIC FINITE ELEMENT MODEL

A finite Element analysis was conducted using the ABAQUS pre- and post-processing finite element program. Simulation of the NATM tunnelling process was commenced with the selection of the tunnel geometry and the model geometry in two-dimensions. Plane strain analysis was used in the analysis. Amirkabir's soil was modelled using the undrained material properties with the Mohr-Coulomb failure or strength criterion.

The water table is assumed to be 40m below the ground surface. Shotcrete used as a preliminary support measure in the trial tunnel has been modeled using elastic beam elements in the FEM analysis. In order to estimate the surface settlement, the Hypothetical Modulus of Elasticity (HME) soft lining approach (Potter 1990; John and Mattle 2003; Karakus and Fowell 2003; Karakus 2007), has been used in this research due to its flexibility when applied to multistage tunnel excavations.

The model geometry used in this work is 120 m wide and 40 m high. The selected tunnel size is approximately 11.53 m high and 14.03 m wide (Fig. 3).

Eight-node biquadrate reduced integration plane strain elements, CPE8R, were used for the continuum body and three-noded quadratic curved beam elements, B22, for the lining. There has been no interface introduced between the shotcrete and the ground because shotcrete is believed to provide a perfect interlock between the ground and itself.

The detailed analysis procedures employed during this parametric sequential excavation model (PSEM) are as follows:

Geostatic step: Introducing the initial stress state to reach equilibrium before tunnel excavation begins. The beam elements representing the lining were deactivated, as there was no lining at the beginning of the analysis.

The existing road and buildings over the tunnel considered by two different linear distribution loads with the parametric value of ROADLOAD and BUILLOAD, respectively.

1st cycle excavation step: Excavation of the top heading was achieved using the model change options in ABAQUS. Meanwhile, the lining elements for the top heading with lower elasticity modulus were activated.

A parametric HEM-value (TOPHEM1) was used for the Young Modulus of lining.

1st cycle lining step: The stiffness of the beam element for the top heading, i.e. the HME value, was increased to TOPHEM2, which is the assumed Time dependent elasticity modulus of the lining.

Table 2. Probabilistic parameters of the HEMs

Variable No.	Parameter	T_{ij} average(h)	T_{ij} Lower Band(h)	T_{ij} Upper Band(h)	Distribution	Variable's Name
Var1	$E_{1,1}$	6	5	7	Uniform	TOPHEM1
Var2	$E_{1,2}$	30	27	33	Uniform	TOPHEM2
Var3	$E_{1,3}$	87	80	95	Uniform	TOPHEM3
Var4	$E_{1,4}$	129	115	140	Uniform	TOPHEM4
Var4	$E_{1,5}$	215	195	235	Uniform	TOPHEM5
Var5	$E_{2,1}$	6	5	7	Uniform	LEFTHEM1
Var6	$E_{2,2}$	30	27	33	Uniform	LEFTHEM2
Var7	$E_{2,3}$	87	80	95	Uniform	LEFTHEM3
Var7	$E_{2,4}$	129	115	140	Uniform	LEFTHEM4
Var8	$E_{3,1}$	6	5	7	Uniform	RIGHTHEM1
Var9	$E_{3,2}$	30	27	33	Uniform	RIGHTHEM2
Var10	$E_{3,3}$	87	80	95	Uniform	RIGHTHEM3
Var11	$E_{4,1}$	6	5	7	Uniform	INVERTHEM1
Var12	$E_{4,2}$	30	27	33	Uniform	INVERTHEM2

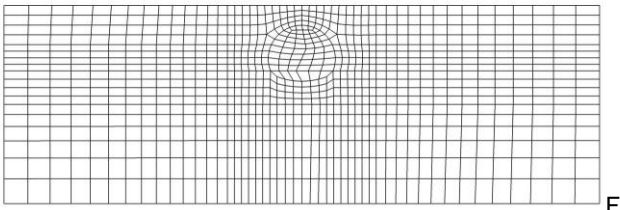


Figure 3. Finite element model adopted for the model

2nd cycle excavation step: The continuum elements in the left invert were removed and the beam elements with an LEFTHEM1 value for sidewall were activated.

2nd cycle lining: The HME value for the lining on the left periphery and top heading increased to LEFTHEM2 and TOPHEM3, respectively.

3rd cycle excavation step: The solid elements representing the right bench were removed and the beam elements representing the lining with an RIGHTHEM1 value for the wall were activated.

3rd cycle lining step: The HEM value for the lining for the right bench, left bench and top heading increased to RIGHTHEM2, LEFTHEM3 and TOPHEM4, respectively.

4th cycle excavation step: The continuum elements in the invert were removed. This is followed by the activation of the beam elements representing the lining with INVERTHEM1 value for the invert.

4th cycle lining step: Increasing the value of HME for invert, the right bench, left bench and top heading to INVERTHEM2, RIGHTHEM3, LEFTHEM4 and TOPHEM5, respectively and simulation was completed.

Providing the probabilistic properties of the parameters, full characterization of the system and the other related information are described in Table 3.

6 RESULTS AND DISCUSSION

6.1 Latin Hyper Cube Simulation (LHCS) Results

Performing 2000 LHCS, a set of stratified probabilistic

Table 3. Probabilistic parameters of the system

Parameter	Symbol	COV	Lining Parameters Distribution				Distribution	Unit	Variable's Name
			Mean	STD	Lower Bound	Upper Bound			
Density	γ_{con}	10%	2400	240			Kg/m ³	DENCON	
Young's modulus	$E_{28} = 4.7E6 \times \sqrt{f'_c}$						Pa	ELBEAM	
28-day Compressive Strength	f'_c	16%	2.5E7	4E+6	1.4E7	Normal	Pa	COMPST	
Poisson ratio	ν_{con}	10%	0.2	0.02	0.18	Beta	-	POIBEAM	
Thickness	t	10%	0.27	0.03	0.24	Uniform	m	TBEAM	
Loading Parameters Distribution									
Road Load	LL	25%	30000	7500		Normal	Pa	ROADLOAD	
Building Load	DL	25%	20000	5000		Normal	Pa	BUILLOAD	

distribution functions (PDF) and a cumulative distribution functions (CDF) of Maximum surface settlement are derived.

The statistics result indicates that the settlements are in the range between 19mm and 76mm with the average and standard deviation of 36mm and 7mm, respectively.

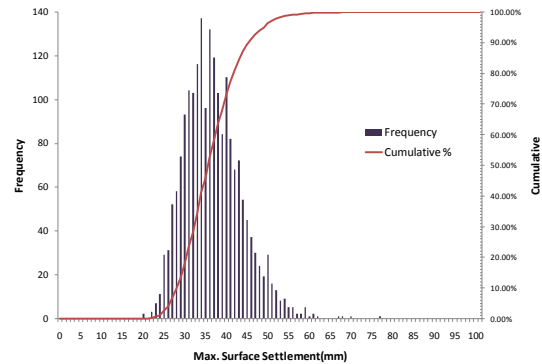


Figure 4. PDF and CDF of the settlements

6.2 Stochastic results

As the results of Monte Carlo simulation, the scatter plots of 6 principle variable of the system and regression line depending to each one are given in graphs of Figure 5. Regarding the changing trends of variables versus the output, it can be seen that the model is more sensitive to the variable of the soil as well as active loading, excepting the load of building, than the factors depending to the structure. However, it is crucial to note that this result is related to the serviceability of the system; and the probability of the failure of the lining system considering other limit state condition should be considered separately which is not in the scope of this paper.

6.3 Serviceability Failure

Assuming the accepted δ_n to be equal to 50mm, the limit

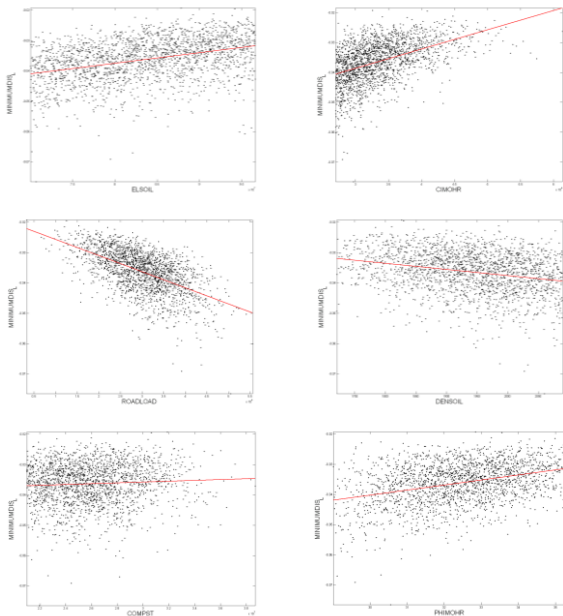


Figure 5. Scatter plots of different variables versus the settlement

state function and subsequently the probability of serviceability failure is derived by CDF of figure 4. With limit confidence of 96.34%, it could be result that all of predicted settlements are less than 50 mm; and they are less than 49mm for 95% confidence limit. This shows that the proposed sequential excavation method is certain enough to limit the settlements induced by tunnel excavation.

6.4 Comparing results with monitoring data

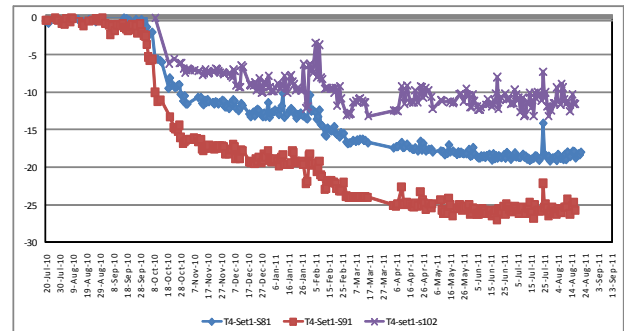
During the construction phase, the transversal settlement of surface of the road above the tunnel has been monitored to avoid the worse settlements or occurrence of serviceability failure. A sample of monitoring results, a worse case one, obtained during the 20 July 2010 to 13 September 2011 in Km-728 of the tunnel has been shown in Figure 6. Considering the statistics analysis of monitoring data along the length of the studied tunnel, it is considerable to report that the maximum settlement observed was 52mm, less than predicted by the LHCS performed in this research. However the average result was 18mm mere half of the average results of the LHCS. Thus, it is resulted that the simulation was confidence enough, being an accurate safe prediction of surface settlements.

7 CONCLUSIONS

Regarding uncertainties related to system, the model was more sensitive to the variable of the soil as well as active loading than the factors depending to the structure. Comparing monitoring data with stochastic outcomes of the model demonstrated that the method used in this research to simulate the uncertainty of the system gave real judgment on the consequences of the excavation phase of the project.

ACKNOWLEDGEMENT

The authors would like to express his deep gratitude to the Tehran Municipality for providing financial support during the research at Tarbiat Modares University.



T4-Set1-S81, T4-Set1-S91 and T4-Set1-S102 have been benched above the tunnel on middle and both sides of the pavement of the road, respectively.

Figure 6. Continuous observation of surface settlement for a benchmark above the tunnel

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