Spring 2017

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Recommended Citation

Michael, Powers, "Structural Reliability Analysis of Tunneling-Induced Ground Settlement and Damage to Adjacent Buildings: A Case Study using Moment Methods and FLAC2D" (2017). *Graduate Theses & Non-Theses*. 128.
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Structural Reliability Analysis of Tunneling-Induced Ground Settlement and Damage to Adjacent Buildings: A Case Study using Moment Methods and FLAC2D[1]

Michael Powers, Lei Wang, and Zhe Luo

Abstract: Tunnels are widely used for underground space development in urban areas such as mass transit. However, tunneling in heavily congested areas is a very risky operation that can impose significant damage to adjacent buildings. In the traditional analysis of tunnel structures, the deterministic approach is commonly used. The owners or regulatory agencies establish the limiting ground surface settlement value and angular distortion value for buildings as a means of preventing tunneling-induced failure and damage to adjacent buildings. In addition, significant uncertainties in geotechnical parameters exist in the prediction of tunneling-induced ground settlement and damage to adjacent buildings. Design and analysis found through the deterministic approach is often prone to violate the limiting deflection values due to these uncertainties. In this paper, a probabilistic assessment methodology is proposed to account for the stochastic nature of geotechnical parameters for tunneling-induced ground settlement and damage to adjacent buildings. This method combines both moment methods and finite difference analysis for probabilistic assessment since the performance function for tunneling analysis is usually a numerical model without an explicit function. A series of moment methods were used to evaluate the failure probability based on the solutions obtained from FLAC 2D, a commercially available finite difference code. The efficiency of the probabilistic assessment framework for tunneling-induced ground settlement and damage to adjacent buildings is demonstrated using a case study and the results provide engineers with the appropriate data to make risk based decisions.

Keywords: tunnel; probability; uncertainty; point estimate method.

1. INTRODUCTION

Subsurface excavations, such as tunneling in urban areas, can cause significant damage to adjacent structures. Therefore, it is important to predict the effects of tunneling-induced ground settlement and angular distortion to assess the serviceability of the adjacent buildings and other structures. In this paper, a probabilistic approach for failure probability assessment was used to assess the risk to the buildings caused by the effects of tunneling. A Mohr-Coulomb model integrated in FLAC 2D is used as the deterministic model for evaluating the maximum ground settlement and the angular distortion induced by tunneling in urban areas.

Moment methods are proposed for the reliability analysis of serviceability failure problems using numerical modeling of tunnel excavations based on the finite difference method. Higher order moments of the performance function are employed (third and fourth moments) to overcome the limitations of approximating the performance function. By evaluating the performance function at selected points, moment methods using the advanced point estimate method (PEM) can be utilized to calculate the first four moments. This method is much more computationally effective because it does not involve a significant amount of iterative evaluations of the numerical model such as the Monte Carlo simulation (Zhao and Ono 2001; Wang et al. 2014). This paper will provide an example to demonstrate the moment methods as an effective approach for reliability analysis of tunneling-induced ground settlement and building damage assessment using numerical methods.

This analysis was presented at the 6th Asian-Pacific Symposium on Structural Reliability and its Applications (APSSRA6) on 28-30 May 2016 in Shanghai, China and has been slightly revised from its original version (Powers et al. 2016).

2. FINITE DIFFERENCE METHOD USING FLAC 2D

In this model, ground settlement and angular distortion are analyzed using numerical methods such as the finite difference code FLAC 2D ver. 7.0 (Itasca 2011). This code allows large strain calculations to be computed while also retaining good numerical stability. In this analysis, the subsurface soil layers are generated and the proper soil behavior under the tunnel construction is modelled to simulate soil and rock behavior accurately. The main purpose of this study is to analyze the effects of tunnel boring machine (TBM) tunneling on the foundations of the adjacent buildings.

The elasto-plastic behavior of the subsurface strata (including soil and rock layers) was simulated using the Mohr-Coulomb constitutive model. The Mohr-Coulomb shear strength properties of the soft ground are based on limited testing data while the Mohr-Coulomb shear strength properties for rock mass I and II are attained by estimating the average Hoek-Brown properties of the rock masses.

In 1982, Panet proposed the Convergence-Confinement Method which is used to simulate the effects of an advancing TBM face. In FLAC 2D a dedicated subroutine (programmed in Itasca's FISH programming language) regulates the gradual stress relief of the tunnel boundary from its initial K_o condition to the pre-set value of relaxation (30%). A complete unloading schedule is programmed to run from 0% to 100% relaxation. This yields a complete convergence (relaxation) curve at selected boundary points (i.e, crown), which can be used to derive significant data on the plastic yielding in the surrounding material during unloading. For this analysis, relaxation is set at a constant 30%, which

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[1] *Earlier Version Published in: 6th Asian-Pacific Symposium on Structural Reliability and its Applications (APSSRA6), 28-30 May 2016, Shanghai, China, H.W. Huang, J. Li, J. Zhang & J.B. Chen (editors)*

generally corresponds to support installed very close to the face.

3. MOMENT METHODS FOR RELIABILITY ANALYSIS

The advanced point estimate method (PEM) formulated by Zhao and Ono (2000) is used to estimate the moments of the performance function in terms of a finite difference model. This PEM method uses five points to estimate the four moments of the performance function to produce accurate results.

PEM uses a weighted sum of the function assessed at a finite number of points, which are used to satisfy the equation (Zhao and Ono 2000; Zhao and Ono 2001):

$$\sum_{j=1}^{m} P_j (x_j - \mu_x)^k = M_{kx} \tag{1}$$

M_{kx} is the k^th^ moment of x. x_j are the estimating points for j = 1, …, *m*. P_j are the corresponding weights for for j = 1, …, *m*. μ_x is the mean.

In this PEM procedure, the estimated points are obtained in the standard normal space, and the Rosenblatt transformation is used to correlate the estimating points in the original space (x_j) into corresponding points in standard normal space (u_j) (Zhao and Ono 2000; Wang et. al. 2014). Hermite integration is then used to estimate points and their corresponding weights in standard normal space. When the five-point estimate in the standard normal space is used, the estimating points and weights are achieved by (Zhao and Ono 2000):

$$u_0 = 0 \tag{2a}$$

$$P_0 = 8/15 \tag{2b}$$

$$u_{1+} = -u_{1-} = 1.3556262 \tag{2c}$$

$$P_1 = 0.2220759 \tag{2d}$$

$$u_{2+} = -u_{2-} = 2.8569700 \tag{2e}$$

$$P_2 = 1.12574 \times 10^{-2} \tag{2f}$$

After obtaining the PEM estimating points (u_0, u_{1+}, u_{1-}, u_{2+}, and u_{2-}) and their weights (P_0, P_1, and P_2), the k^th^ central moment of the function y= y(x) can then be calculated as (Zhao and Ono 2000):

$$\mu_y = \sum_{j=1}^{m} P_j y[T^{-1}(u_j)] \tag{3}$$

$$M_{ky} = \sum_{j=1}^{m} P_j (y[T^{-1}(u_j)] - \mu_y)^k \tag{4}$$

where T^{-1} is the inverse Rosenblatt Transformation and y is the point at which the mean or the moment is taken.

The soil parameters including cohesion (c_T), friction angle (φ_T), and Young's Modulus (E_T) of the Transition Group, and the rock parameters including cohesion (c_R), friction angle (φ_R), and Young's Modulus (E_R) for Rock II are treated as random variables for the numerical model (more details are descried in the next section). The performance function can then be written as G = G(Z) = G(Z_1=c_T, Z_2=φ_T, Z_3=E_T, Z_4=c_R, Z_5=φ_R, Z_6=E_R), where G is the maximum ground settlement or the angular distortion predicted by the numerical model.

The four moments of G = G(Z_1, …, Z_6) can be determined using a lists of equations as follows formulated by Zhao and Ono (2000):

$$\mu_G = \sum_{i=1}^{n} (\mu_i - G_\mu) + G_\mu \tag{5}$$

$$\sigma^2{}_G = \sum_{i=1}^{n} \sigma^2{}_i \tag{6}$$

$$\alpha_{3G}\sigma^3{}_G = \sum_{i=1}^{n} \alpha_{3i}\sigma^3{}_i \tag{7}$$

$$\alpha_{4G}\sigma^4{}_G = \sum_{i=1}^{n} \alpha_{4i}\sigma^4{}_i + 6\sum_{i=1}^{n-1} \sum_{j>1}^{n} \sigma^2{}_i \sigma^2{}_j \tag{8}$$

where G_μ is the function G = G(Z_1, …, Z_6) calculated at the mean of variables (Z_1, …, Z_6); μ_1, σ_1, α_{31}, α_{41} are the mean value, standard deviation, skewness coefficient and kurtosis coefficient of G(Z_1, Z_2-Z_6 = mean), which were attained using PEM with one random variable per Eq. (3) and Eq. (4). Likewise, μ_2, σ_2, α_{32}, α_{42} are the mean value, standard deviation, skewness coefficient and kurtosis coefficient of G(Z_1 = mean, Z_2, Z_3-Z_6 = mean), which were attained using PEM with one random variable per Eq. (3) and Eq. (4). Similarly, all the rest of the variables can be derived using similar procedures.

Various moment methods can be employed for reliability analysis based on the four moments obtained from the performance function. The detailed formulations for the three moment methods used in this paper (second, third, and fourth moment methods) are summarized in Zhao and Ono (2001).

4. CASE STUDY: MODELING SETTLEMENT AND ANGULAR DISTORTION USING FLAC 2D

A plan-view for the case study of tunneling-induced building assessment in an urban area is presented in Figure 1 and used for this analysis. As depicted in Figure 1, twin tunnels (green lines) are planned to be excavated beneath a street in an urban area with one building situated on each side of the street. Line A-A' depicts the cross-section used in this analysis to simulate the excavation and it is 300 ft in length. Ground settlement and angular distortion were then computed to analyze the effects of tunneling.

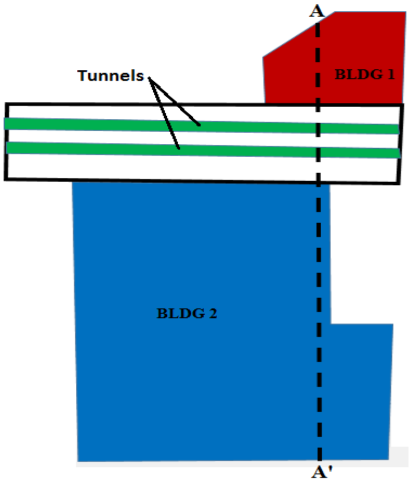

Figure 1. Plan-view of the case study and relative location of buildings and tunnels

4.1 Geological Materials &Properties

The geological strata in this model consist of three separate soil layers (from top to bottom: Fill, Cretaceous Group, and Transition Group) as documented in Table 1, and two layers of rock (from top to bottom as Rock II and Rock I) as documented in Table 2. For convenience of illustration, the Cretaceous Group can be denoted as GCC and the Transition Group can be denoted as TransSat.

As depicted in Figure 2, soil properties of the Transition Group and rock properties of Rock II have the most significant influence on the tunnelling-induced settlement analysis since these are the two stratigraphic units being excavated during tunnelling. In this analysis, the strength and modulus parameters of these two strata are modelled as random variables in the analysis. The mean values of these parameters are based on limited testing data and empirical relationships. The coefficient of variation (COV) used for the cohesion (c) of soil and rock is assumed to be 20% (Phoon and Kulhawy 1999, Low and Phoon 2015). The COV for the friction angle (φ) of soil and rock is assumed as 7% (Phoon and Kulhawy 1999; Xu et al. 2014). The COV of Young's Modulus (E) for soil and rock is assumed as 20%. The statistical values (mean and COV) for the uncertain parameters of Transition Group and Rock II are summarized in Table 3.

Table 1. Soil parameters for the subsurface strata (Fill, Cretaceous Group, and Transition Group).

	Fill	Cretaceous Group	Transition Group
Unit Weight (pcf)	120	130	125
Friction Angle (°)	28	36	27
Cohesion (psf)	0	0	200
Young's Modulus (psf)	2.16E+05	1.44E+06	1.44E+06
Poisson's Ratio	0.3	0.3	0.3

Table 2. Rock parameters for the subsurface strata (Rock I and Rock II).

	Rock I	Rock II
Unit Weight (pcf)	183	183
Friction Angle (°)	50	45
Cohesion (psf)	43200	25900
Young's Modulus (psf)	1.01E+09	7.34E+08
Poisson's Ratio	0.2	0.25

Table 3. Statistics of Soil and Rock Parameters.

	Mean	COV (%)
c_T (psf)	200	20
φ_T (deg)	27	7
E_T (psf)	1.44E+06	20
c_R (psf)	25900	20
φ_R (deg)	45	7
E_R (psf)	7.34E+08	20

Note: All the random variables are assumed as normally distributed.

4.2 Groundwater

The groundwater table for this case study is assumed to be constant at 14 ft below the ground surface. Anything below this surface is wet.

4.3 Structural, Interface & Traffic Loading Assumptions

After the stress-relaxation stage, a 12-inch continuous structural concrete liner was used as support. When analyzing the interface between the liner and the ground, both building structures are represented as uniform loads applied to the entire footprint. A traffic load of 300 psf has also been included along the roadway. The loads from two adjacent buildings have been estimated by the structural engineers. For buildings at each side, the foundation load is represented as uniform loads applied to the entire footprint (representing the shallow foundation case). The footing pressure of Building 1 is applied 30 ft below the ground surface (foundation depth of left building in Figure 2 and Figure 3) and the footing pressure of Building 2 is applied at 24.1 ft below the ground surface (foundation depth of right building in Figure 2 and Figure 3).

5. RELIABILITY ANALYSIS RESULTS

5.1 FLAC 2D Case Modeled

The geologic profile and the FLAC 2D model geometry can be seen in Figures 2 and 3. The case examined in FLAC 2D represents both structures as uniform loads applied to the entire footprint (Building 1 and Building 2). In this model, two tunnels are excavated beneath a city street with 30% relaxation.

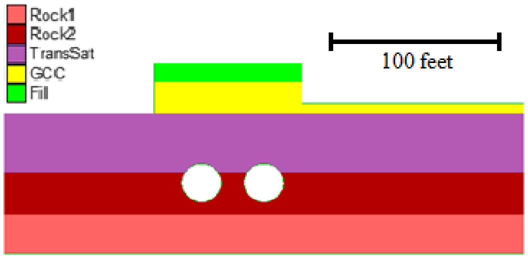

Figure 2. FLAC model: geological strata + tunnels

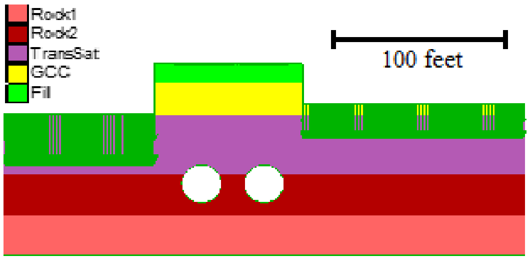

Figure 3. FLAC model: geological strata + tunnels + applied loads

5.2 Reliability Analysis Results with Different Moment Methods

With the deterministic model from the FLAC 2D solution, three moments are used to conduct the reliability analysis for tunnelling-induced ground settlement as well as building damage.

The probability of serviceability failure in terms of tunnelling-induced ground surface settlement can be expressed as a probability of exceedance. This is done by first calculating the reliability index, which is then used to calculate the probability of exceedance. The maximum ground settlement (y) computed from the FLAC 2D model can be used to define the limit state or performance function (Wang et al. 2012):

$$g_1() = y_{\text{lim}} - y \tag{9}$$

where y_{lim} is the limiting ground settlement specified by the designer or design code. A design is considered to have serviceability failure if the $g_1()$ is less than 0. The probability of failure is expressed as the probability of exceedance of a specified limiting ground settlement value.

Following the procedures for moment methods, the probability of exceedance under different limiting ground settlement can readily be calculated. Figure 4 illustrates the results from the reliability analysis using the second moment method, third moment method and fourth moment method, respectively. As can be observed in Figure 4, the probability of exceedance depends significantly on the chosen limiting ground settlement value by the designer. The greater the limiting settlement value, the lower probability of exceedance. It can also be observed that the results from different moment methods are very close to each other with similar trends. Based on the results from these three moment methods, a reasonable estimation for the probability of exceedance can be confidently determined for a specified limiting ground settlement value.

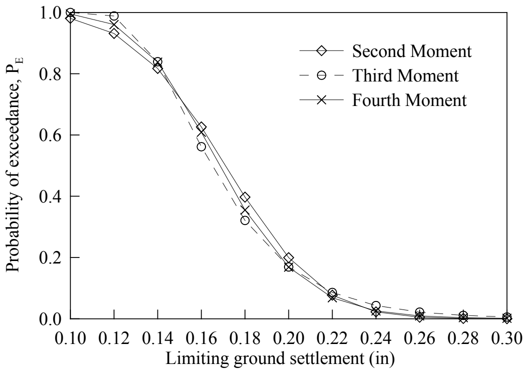

Figure 4. Probability of exceedance at various levels of limiting ground settlement

The probability of serviceability failure for a specific building can be determined in terms of the angular distortion. Similarly, the angular distortion (z) computed from the FLAC 2D model can be used to define the limit state or performance function as follows:

$$g_2() = z_{\text{lim}} - z \tag{10}$$

where z_{lim} is the limiting angular distortion value specified by the designer. A design is considered to cause the serviceability failure of a specific building if the $g_2()$ for a specific building is less than 0. The probability of exceedance of a specified limiting ground settlement value is used to measure the probability of serviceability failure for a given building.

Based on the procedures for different moment methods, the probability of exceedance at different levels of limiting distortion for each of the two buildings (building 1 and building 2 as shown in Figure 1) can be determined. The limiting angular distortion value is set to increase from 1/3000 to 1/1000. The limiting angular distortion 1/3000 represents the most stringent requirement while the limiting angular distortion 1/1000 represents the least stringent requirement. As can be seen in Figure 5 and Figure 6, with less stringent requirement from 1/3000 to 1/1000, the probability of exceedance gradually decreases for each of the buildings. Also the results from different moment methods are very similar and these two figures provide a reasonable estimation for the probability of exceedance for a given limiting angular distortion value specified by the designer.

6. DISCUSSION

In this analysis, several assumptions are made. Values for the random variables were based on limited testing data and empirical relationships. However, these values can easily be changed and implemented into the model. Therefore, data obtained in the field can be implemented into this analysis with little difficulty.

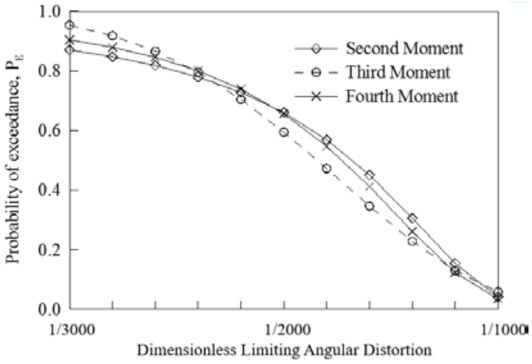

Figure 5. Probability of exceedance at various levels of limiting angular distortion for building 1

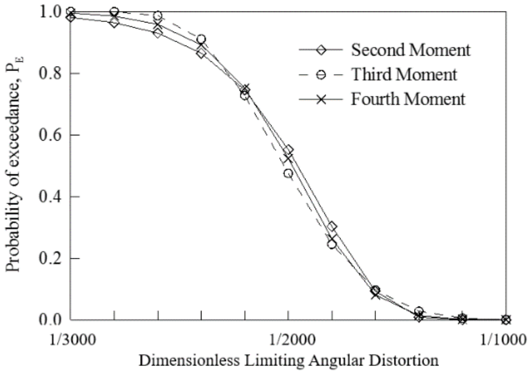

Figure 6. Probability of exceedance at various levels of limiting angular distortion for building 2

Model geometries and parameters can also be changed easily. FLAC 2D code can be manipulated to change geometries, boundary conditions, material parameters, and many more of the model parameters. However, if the geometry of the model is change significantly, an entirely new model should be generated.

This analysis can be applied to many types of geotechnical models. When uncertain geologic parameters are involved in a geotechnical analysis, moment methods can be applied to account for their stochastic nature. Combining the point estimate method with moment methods allows for engineers to produce reliability based results that can then be used to make risk based decision.

7. CONCLUSIONS

This paper presents a study of reliability analysis of tunnelling-induced ground settlement and building damages combing moment methods and finite difference analysis with a commercially available numerical code. A case study of TBM tunnel construction in the urban environment is used to illustrate the significance of the proposed methods. From the analysis results, it is found that different moment methods (second, third and fourth) yield similar results. The moment methods based on the five-point estimate method combined with finite difference analysis improve the computational efficiency in the reliability analysis significantly. The resulting probability of exceedance in terms of either specified ground settlement or angular distortion of a building provides a useful reference for engineers to make risk-based decisions for tunnel design and construction.

ACKNOWLEDGEMENTS

This research was partially supported by the Faculty Development Grant Initiative from Montana Tech of the University of Montana in which the second author is the Principal Investigator. The support from General Engineering Department and this financial assistance were greatly appreciated. The Geological Engineering Department also provided the FLAC2D software necessary to complete this project.

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