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Effects of statistical distribution of joint trace length on the stability of tunnel excavated in jointed rock mass

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Abstract

The rock masses in a construction site of underground cavern are generally not continuous, due to the presence of discontinuities, such as bedding, joints, faults, and fractures. The performance of an underground cavern is principally ruled by the mechanical behaviors of the discontinuities in the vicinity of the cavern. During underground excavation, many surrounding rock failures have close relationship with joints. The stability study on tunnel in jointed rock mass is of importance to rock engineering, especially tunneling and underground space development. In this study, using the probability density distribution functions of negative exponential, log-normal and normal, we investigated the effect of joint trace length on the stability parameters such as stress and displacement of tunnel constructed in rock mass using UDEC (Universal Distinct Element Code). It was obtained that normal distribution function of joint trace length is more critical on the stability of tunnel, and exponential distribution function has less effect on the tunnel stability compared to the two other distribution functions.

Keywords: *joint trace length, statistical distribution functions, tunnel stability, UDEC.*

1. Introduction

Jointed rock masses are often encountered during underground excavation. Many failures of underground opening during excavation and in operation are reported closely related to joints. Joints usually occur in sets which are more or less parallel and regularly spaced; also there are usually several sets in very different directions so that the rock mass is broken up into a blocky structure [1]. Because of the low shear strength and tensile strength, as well as the looseness of rock mass due to the unloading by excavation, the rock masses are easy to slide along structural plane or to detach, flex, and break. Under some conditions, the joints may lead to big disasters for tunnel construction.

A general way to investigate the deformation and failure characteristics of tunnels is to carry out model test and numerical analysis. Everling [2] carried out a basic scale model test to investigate the stability of support of rock joint deformation. Goodman et al. [3] examined the behavior of deformation of tunnel in jointed rock mass using the scaled model test. Jeon et al. [4] performed scaled model tests to investigate the effect of a fault and grouting on the stability of a tunnel. Yeung and Leong [5] carried out a parametric study using two-dimensional discontinuous deformation analysis (DDA) to study the effects of the attribute of joints in a rock mass on the stability of a tunnel excavated in the rock mass. Hao and Azzam [6] investigated the influence of some parameters of a fault on tunnel stability by numerical method using UDEC software [7].

Jiang et al. [8] developed a multiple system for analyzing the feature of geometrical distribution of rock joints, and discussed the relationship between deformational behavior and fractal dimension and orientation of joint sets based on fractal analysis and numerical simulation of underground opening in the jointed rock masses. For the blocky structure cut by joints, Goodman and Shi [9] suggested blocky theory to analyze the stability of rock blocks around underground openings. After them, more analysis methods have been used to study the blocky stability.

Chan and Goodman [10] calculated the average number and volume of removable blocks using the Baecher disk model [11]. Hoerger and Young [12] applied the Baecher disk model with a bivariate normal distribution of joint orientation to the analysis of block occurrence around a tunnel. Song et al. [13] used a three dimensional statistical joint modeling technique to analyze the stability of rock blocks around a tunnel and concluded that the removable blocks occurred more frequently as joint persistence, degree of scatter in joint set orientation and volumetric frequency of the joints increased. Jia and Tang [14] investigated the influence of different dip angles of layered joints on the stability of tunnel in jointed rock mass and concluded that the existing of joints changes the failure mode of tunnel.

For horizontal layered joints, the failure mode is the break of ‘‘rock beam’’ and the spalling and crushing of sidewalls; for joints at dip angle of 30 and 45, the failure mode is sliding-in of sidewall and the detaching, flexing, and breaking of layered rock mass near the shoulder of tunnel. Wang et al. [15] studied effects of the discontinuity network, possible intact rock and discontinuity parameter variability, representation of rock masses as discontinum or equivalent continuum material and rock support system on the deformation and stability around the tunnel. It was concluded that under no rock support condition, the maximum deformations around the tunnel increased by about 2.4-4.4 times by adding discontinuities to the geo-mechanical model, which had only intact rock. The highest increase was observed on the walls of the tunnel.

Although the influences of rock joints and the stress state on the stability of underground structures have been studied, but investigating geometric properties of joints is less studied on the stability of tunnels. A well understanding about this is highly required and deemed important for a desirable support design and safe excavation. The main objective of the study presented herein is to investigate the influence of joint trace length on the stability of tunnel excavated in jointed rock mass.

2. Response of an unlined circular tunnel in a biaxial stress field

Crushing failure is an important mechanism by which unlined tunnels may fail. Crushing is treated as a static phenomenon and involves massive failure around the excavation due to large-scale plastic flow. The objective of this section is to describe the responses of a circular tunnel subjected to a non-hydrostatic static load and the non-linear deformational behavior of fully deformable blocks in UDEC.

The normalized stresses and displacements of the problem can be written in dimensionless form, as functions of independent variables and problem parameters, as follows:

$$\frac{\sigma_{ij}}{q} = \sigma_{ij}^{*}\left[\frac{r}{a},\theta,\frac{(\sigma_1+\sigma_2)}{q},\frac{(\sigma_1-\sigma_2)}{q},\varphi,\psi\right] \qquad (1)$$

$$2\frac{u_r}{a}\frac{G}{q} = U_r\left[\frac{r}{a},\theta,\frac{(\sigma_1+\sigma_2)}{q},\frac{(\sigma_1-\sigma_2)}{q},\nu,\ \varphi,\psi\right] \qquad (2)$$

where σ_{ij} = stresses

u_r = displacement

r = radial coordinate,

θ= angle,

a= tunnel radius,

q= uniaxial compressive strength,

σ_1, σ_2 = far-field principal stresses,

ν= Poisson's ratio,

G= shear modulus,

φ= internal friction angle, and

ψ= dilation angle.

Therefore, the normalized radial displacement of crown (i.e., r/a = 1, θ = π/2), of the tunnel excavated in the rock characterized by given friction angle φ_0, dilation angle ψ_0, and Poisson's ratio ν_0, can be written:

$$U_r^c = U_r\left[1, \frac{\pi}{2}, \frac{(\sigma_1+\sigma_2)}{q}, \frac{(\sigma_1-\sigma_2)}{q}, \nu_0,\ \varphi_0, \psi_0\right] \quad (3)$$

while the normalized radial displacement of spring line (r/a = 1, θ = 0), is

$$U_r^s = U_r\left[1, 0, \frac{(\sigma_1+\sigma_2)}{q}, \frac{(\sigma_1-\sigma_2)}{q}, \nu_0,\ \varphi_0, \psi_0\right] \quad (4)$$

Actual radial displacements u_r can be calculated from the normalized displacements U_r from:

$$u_r = \frac{a\,q}{2\,G} U_r \quad (5)$$

Alternatively, the percentage closure $\hat{u}_r$ = 100 (u_r /a) can be expressed as:

$$\hat{u}_r = \frac{50q}{G} U_r\,(\%) \quad (6)$$

The corrections for added external loading are:

At the crown:

$$\Delta U_r^c = (1-2\nu)\frac{\sigma_1+\sigma_3}{2q} + \frac{\sigma_1-\sigma_3}{2q} \quad (7)$$

At the springline:

$$\Delta U_r^s = (1-2\nu)\frac{\sigma_1+\sigma_3}{2q} - \frac{\sigma_1-\sigma_3}{2q} \quad (8)$$

The percentage closure for added external loading is then:

$$u_r^k = \frac{50\,q}{G}\left(U_r^k + \Delta U_r^k\right)(\%) \qquad k = c, s \quad (9)$$

3. Investigating the statistical distribution of joint trace length

Studying the rock joints is essentially required for many engineering works. For example, in road construction and mining works, when selecting the location of tunnels, the properties of rock joints should be investigated because the joints will affect the tunnel excavation process and make it difficult to support the tunnel. It is also necessary to investigate the region joints before the construction of dams.

Investigation of geometric characteristics of joints is important in terms of structural geology. Statistical studies of these characteristics can be used to specify the features of stresses that are applied to the region rock masses. Having a good recognition of probable functions of rock mass properties is required to make proper decision about the possible problems in the field of rock mechanics and an appropriate analysis. Although the possibility to predict and determine the exact behavior of the rock mass is not certainly feasible, but it is possible to determine the probability of a particular behavior of the rock mass based on previous observations. The probability distribution for all the properties of the rock mass (both mechanical and geometric properties) can be specified by distribution functions that are used to analyze the rock mass behavior.

Joints trace lengths are usually used as parameters to describe the geometrical characteristic of the fracture network of discontinuities. Joint trace length is randomly placed in rock masses and can be described by a number of probability density functions [16-18]. Considering the importance of the exponential, log-normal, and normal distribution functions in rock engineering, the current study aims to accomplish a parametric analysis of the stability of excavated tunnels in rock masses by using these functions.

4. Parametric analysis

In this study, data with known values of averages were created using normal, log-normal, and exponential distribution functions in the statistical software Easy Fit [19]. It is briefly listed below how to produce the data for each of these distribution functions.

The mean value of normal distribution function equals to Equation (10). In the production of data with known averages of normal distribution function for joint trace length, the parameter μ (i.e., location parameter), is needed. In the data production process, the parameter μ has variable values. After the production of these data, it was observed that the variance of these data is less than its value for the log-normal and exponential distribution functions, meaning that the difference between produced data and average value is small.

$$\mathrm{E}(\mathrm{x})=\mu \tag{10}$$

The mean value of log-normal distribution function equals to Equation (11). In the production of data with known averages of this distribution function for joint trace length, in addition to the parameters μ and σ (i.e., location and scale parameters, respectively), γ is also needed as another location parameter. Parameters γ and σ select to be constant value *1*, and μ have variable values.

$$\mathrm{E}(\mathrm{x})=e^{\mu+\sigma^2/2} \tag{11}$$

The mean value of exponential distribution function equals to Equation (12). In the production of data with known averages of this distribution function for joint trace length, in addition to the parameter λ (i.e., inverse scale parameter), γ is also needed. In the data production process, parameter γ select to be constant value *1*, and λ have variable values. After the production of these data, it was observed that the variance of these data is more than its value for the two other distribution functions, meaning that the difference between produced data and average value is large.

$$\mathrm{E}(\mathrm{x})=1/\lambda \tag{12}$$

These produced data for the three distribution functions were used as joint trace lengths in a rock mass with the specifications shown in Table 1. The jointed rock mass is modeled in UDEC software using Mohr-Coulomb constitutive model, the tunnel is placed in it and then, the model would be analyzed. The tunnel diameter, joints aperture, and their space selected to be 6m, 4cm and 0.5m, respectively and the other parameters are constant for all models. The obtained results are shown below for both vertical and horizontal joints.

4.1. Vertical joints

Evaluating the stability of the tunnel roof. In this case, the vertical displacement for all three distribution functions (normal, long-normal, and exponential) increases until it reaches a constant value. This increase of displacement for normal distribution function is more than the other ones. Whereas vertical stress decreases for all three distribution functions and this decrease of stress for normal distribution function is more than the two other functions. Graphs of displacement and stress are presented in Figures 1 and 2, respectively.

Evaluating the stability of the tunnel sides. In this case, the horizontal displacement of tunnel sides increases for all three distribution functions but this increases of displacement is very smaller than previous case. Horizontal stresses also decreases for all three distribution function while this decrease is less than previous case. Graphs of displacement and stress are presented in Figures 3 and 4, respectively.

Table 1. Material Propertiesof rock mass and joint

Parameter	Rock mass	Joint (weak layer)
Density, γ (Kg/m^3)	2720	220
Young's modulus, E (MPa)	800	500
Poisson's ratio, v	0.21	0.25
Bulk modulus, K (MPa)	459	333
Shear Modulus, G (MPa)	330	200
Cohesion, c (MPa)	1.0 E-1	1.0 E-3
Tensile strength (MPa)	0	0
angle of internal friction, φ (deg)	35	10

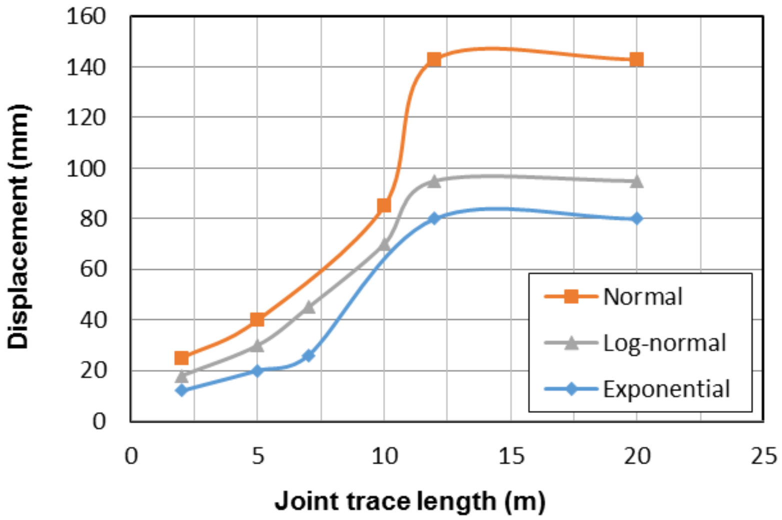

Fig. 1. Effects of joint trace length on vertical displacement of tunnel roof in vertical joint condition

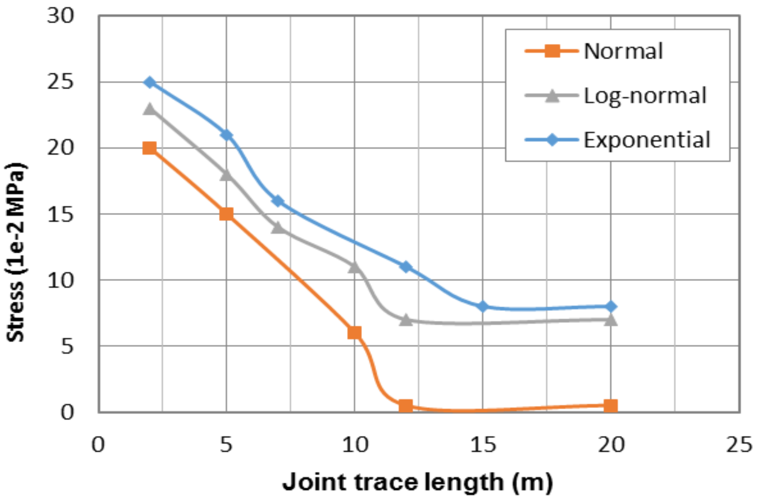

Fig. 2. Effects of joint trace length on vertical stress of tunnel roof in vertical joint condition

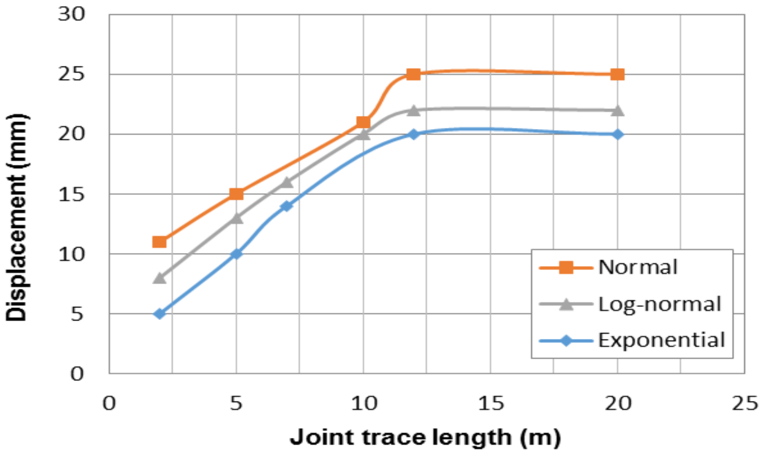

Fig. 3. Effects of joint trace length on horizontal displacement of tunnel side in vertical joint condition

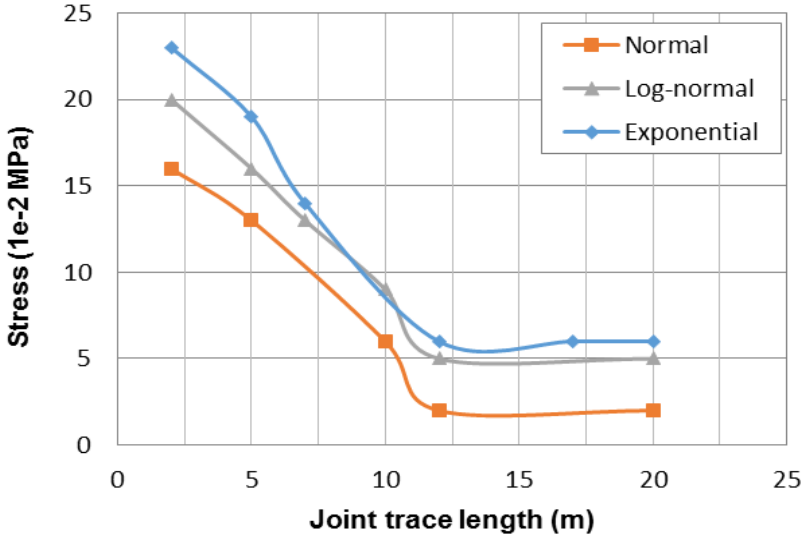

Fig. 4. Effects of joint trace length on horizontal stress of tunnel side in vertical joint condition

4.2. Horizontal joints

Evaluating the stability of the tunnel roof. In this case, the vertical displacement for all three distribution functions (normal, long-normal, and exponential), increases until it reaches a constant value. This increase of displacement for normal distribution function is more than the other ones. In this case, stress decreases for all three distribution functions and this decrease of stress for normal distribution function is more than the two other functions. Graphs of displacement and stress are presented in Figures 5 and 6, respectively.

Evaluating the stability of the tunnel sides. In this case, the horizontal displacement of tunnel sides increases for all three distribution functions and this increase of displacement for normal distribution function is more than the other ones. Horizontal stresses also decreases for all three distribution function while this decrease of stress for normal distribution function is more than the two other functions. Graphs of displacement and stress are presented in Figures 7 and 8, respectively.

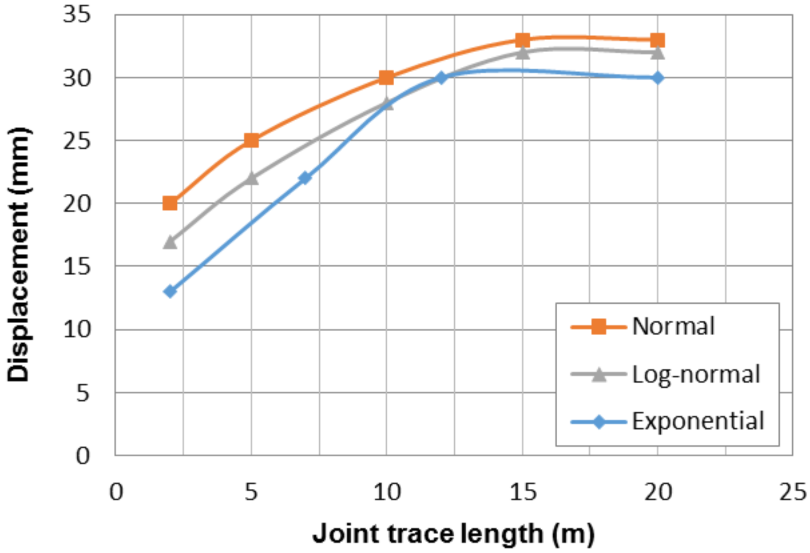

Fig. 5. Effects of joint trace length on vertical displacement of tunnel roof in horizontal joint condition

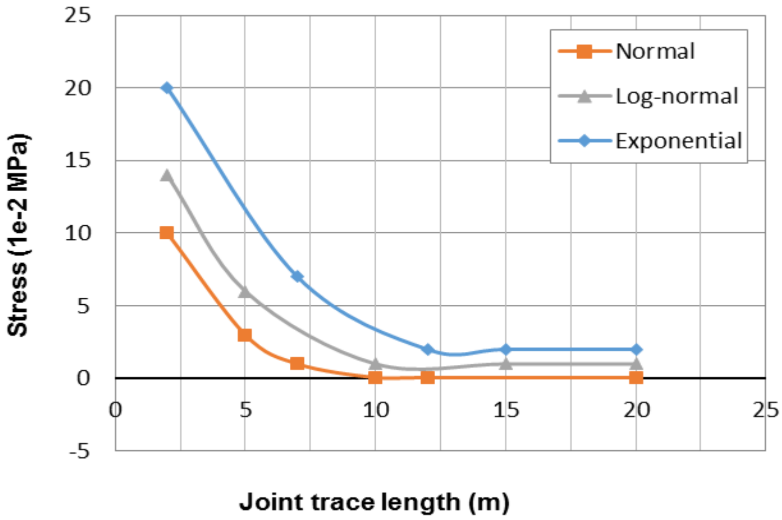

Fig. 6. Effects of joint trace length on vertical stress of tunnel roof in horizontal joint condition

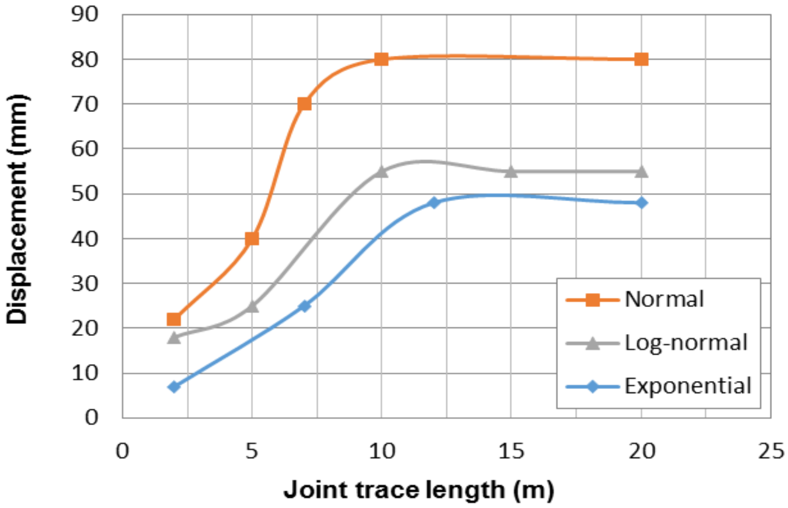

Fig. 7. Effects of joint trace length on horizontal displacement of tunnel side in horizontal joint condition

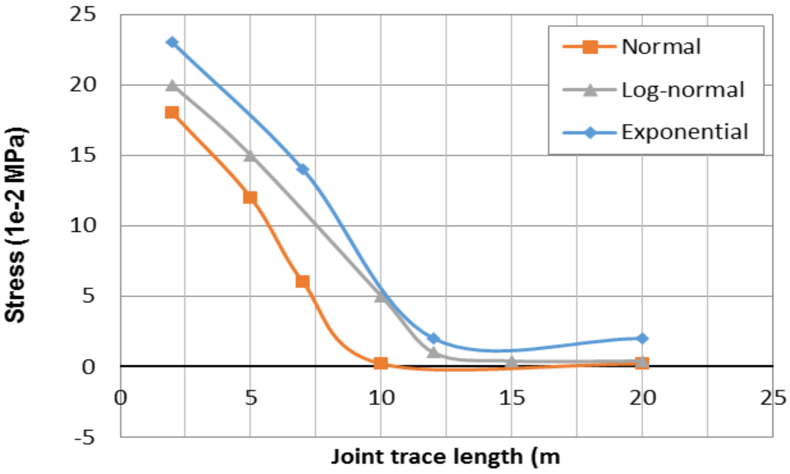

Fig. 8. Effects of joint trace length on horizontal stress of tunnel side in horizontal joint condition

5. Conclusion

In the construction of the underground structures, such as tunnels in jointed rock mass, evaluating the joints is one of the most important issues for designing. Studying the geometrical specifications of the joints such as trace length, aperture and distance have a great importance in the stability evaluation of structures in jointed rock mass. In the present study, the effects of joint trace length and aperture on the stability of excavated tunnels in jointed rock mass is evaluated and the following conclusion can be drown:

1. In the normal distribution function, because of less variance compared to exponential and log-normal distribution functions, the effects of joint trace length on the tunnel stability in both horizontal and vertical cases is more critical.
2. The changes of displacements and stresses for all the distribution functions (normal, log-normal, and exponential) become almost constant after a certain average.

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