Journal of Geomine (2023), 1(1), 1-6
DOI: 10.22077/jgm.2023.6345.1002

Investigating the effect of Beecher type fractures on tunnel displacement using the finite element method

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Recived: 2023 May 03, Revised: 2023 May 29, Online Published: 2023 May 31

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ABSTRACT

It is very important to study the displacement of underground spaces in mining, civil and environmental projects. Investigating the rock mass behavior depends on the relative fracture knowledge joints in the rock mass. From another point of view, uncertainty and variability in the behavior of rock masses, which are a combination of natural and heterogeneous materials, are inevitable in engineering geology studies. In this article, using Phase2 software, the effect of different distributions of joints and fractures of the Beecher type on the displacement of tunnels and underground spaces was investigated using numerical modeling. Hence, by varying the geometrical parameters of the tunnel, joints and different distributions of normal, log normal, uniform and exponential fracture, its effect on the stability of the tunnel was simulated in 640 models. The results show that in all these simulations, the exponential distribution of fractures in Beecher's model has less effect than other distributions in the maximum displacement of the tunnel. While normal and log-normal distributions have the greatest effect on tunnel stability in most of the simulated models. On the other hand, with the increase of the density of the joints from the value of 0.8, the displacement of the tunnel does not depend on the density of the joints. According to the sensitivity analysis of different parameters and their investigation based on different distributions of Beecher-type fracture joints in connection with the stability of tunnels, it can be stated that only an average difference of 19% of the types of distributions is effective in the stability and displacement of tunnels, and it is suggested that experts And tunnel engineers and excavators in this field should focus studies on other parameters of tunnel stability and underground spaces.

KEYWORD

Fracture distribution, displacement, tunnel, Beecher model.

I. INTRODUCTION

Fractures are surface cuts in macroscopic dimensions that can occur due to shape change or physical diagenesis in rocks. A fracture that has been displaced is called a fault, and where there is no displacement or it is so small that it is not clearly defined, the fracture is called a joint. Most of the fractures have little displacement or do not show displacement at all and are classified as joint. Fractures in underground spaces and tunnels play a significant role in displacement. Regarding the recognition of fractures, this basic point should be kept in mind; The geometry of fractures, which includes the slope, direction of slope, length of the joint line, intensity of the joint, location and openness, is among the influential factors in determining the rock mass behavior (Priest, 1993). Achieving a realistic model of fractures to investigate the rock mass behavior around underground excavations such as tunnels, underground caves, oil tanks and nuclear waste disposal tanks can increase the accuracy of design and safety studies. Finally, a correct understanding of rock failure in engineering projects can lead to more knowledge of mineral slopes, dam foundations, underground spaces, Geothermal resources, and radioactive waste burial areas, and access to this requires knowledge It is the fractures and discontinuities in rock mass (Adler and Thovert, 1999; Farhadian et al., 2021).

For the modeling of very complex fractures, various methods have been presented in the last four decades. Kulatilak modeled the fracture geometry randomly for the eastern part of a tunnel located in California. First, he recorded the data that included 16 harvest lines and was 300 meters long along the tunnel and analyzed with FRACNTWK software (Kulatilake et al., 2004; Moeini et al., 2018). In 2004, Riley proposed a rule-based statistical method for generating rock fracture patterns (Riley, 2004). Jan et al. in 2009 proposed a comprehensive engineering method to analyze the stability of vertical drilling in hard rock. They first produced a separate fracture network of the rock mass to record the structural complexity. Then, to analyze the stress of the fracture system produced, it was combined with a discrete element method (Hadjigeorgiou et al., 2009). Gettinoni et al. (2009) numerically investigated

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the flow of water entering the tunnel due to the fracture system in the rock mass. Gethinoni's main goal study was to investigate some structural effect ground parameters (slope and slope direction of discontinuities) on the tunnel drainage process (Gattinoni et al., 2009; Farhadian et al., 2016). Qinghua Li et al. in 2017 on natural role fracture in degradation around tunnel excavation in fractured rocks researched that one of the important results of this research was the effect of in situ stress conditions on the reactivation of natural fractures. Fig. 1 shows a 2D view of a fractured rock that was modeled in Phase 2 software with three-node triangular meshing (Lei et al., 2017).

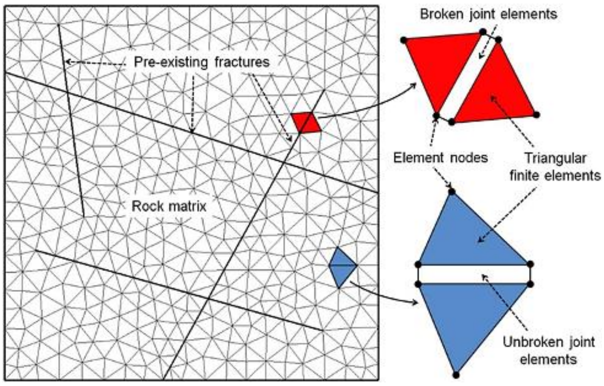

Fig. 1. 2D view of fractured rock modeled in Phase 2 software (Lei et al., 2017)

Zeyu Li et all in 2023 used the point material method (MPM) to simulate the failure responses of a rock tunnel surface during excavation through the FFZ. They found that the depth of the tunnel lining can magnify the failure responses and that the thickness of the FFZ greatly affects the volume of the moving rock mass when the FFZ consists of a weak rock mass (Li et al., 2023).

Guang Li et al in 2023 did a research on the failure process of road tunnel deformation in the mass of broken rock caused by mine excavation.studied the rock failure characteristics and mechanism around straight-walled arch tunnels. They obtained the important result that the failure modes of road deformations, including collapse, rock bursting, and floor heave, were similar regardless of depth (Li et al., 2022). In this study, the effect of different distributions of joints and fractures of the Beecher type on the displacement of tunnels and underground spaces was investigated using numerical modeling.

II. NUMERICAL MODELING

Numerical modeling in Phase2 software for fractures on tunnels involves using mathematical models and algorithms to simulate the behavior of a tunnel system that contains fractures. This type of modeling can be used to study the response of the tunnel to various types of loading and boundary conditions, such as changes in temperature, pressure, or stress, and to evaluate the stability of the tunnel in the presence of fractures.

In practical terms, the modeling process usually involves dividing the tunnel and surrounding rock mass into a series of interconnected elements, each with its own properties such as elastic modulus, Poisson's ratio, and strength properties. The software then uses numerical algorithms to solve the equations that describe the behavior of each element and how they interact with each other. The resulting model can simulate the deformation and stress distribution in the rock mass and the tunnel, as well as the potential for failure and the effects of support systems.

When it comes to modeling fractures, the software can simulate the geometry and orientation of the fractures, as well as their properties such as aperture, roughness, and stiffness. The model can also take into account the properties of the surrounding rock mass and the interaction between the fractures and the tunnel support systems.

Overall, numerical modeling in Phase2 software for fractures on tunnels allows engineers and geologists to better understand the behavior of fractured tunnel systems and to design more effective support systems to ensure their stability and safety. It can also be used to evaluate the potential for new fractures to form and the effects of changes in the surrounding rock masson the tunnel stability.

Numerical methods are complex and accurate methods that include finite element method, discrete element method, etc. Among the most widely used numerical methods, the finite element method is widely used in solving complex engineering problems. These methods provide more realistic results in contrast to the complexity of the need for specific initial information from the modeled environment.

In the finite element method, the model made of the studied environment is divided into smaller parts called elements, which elements can have different shapes depending on the complexity and needs of the problem. Each of these parts consists of a number of nodes that connect the elements to each other. During finite element analysis, all elements are analyzed simultaneously but separately from each other. In this article, Phase2 software provided by Rocscience Company is used to check the stability of the tunnel. Phase2 software is a 2D software, With the possibility of being used in various parts of engineering services such as trenching, slope stability, water leakage, probability analysis, consolidation and dynamic analysis, using the finite element method. One of the main features of Phase2 software is slope stability analysis using element method. This feature is automatically implemented in the software and can be used together with Moore-Columb or Hooke-Brown parameters.

Beecher model: Beecher model is a flexible algorithm that can generate complex joints. In this model, which follows some statistical distributions, it is assumed that the group of joints has a limited effect. The centers of the joint are located in space according to the Poisson point trend. The orientation of joints in Beecher's model can be different according to the directional distribution or fixed. The number of joints produced in the Beecher model is controlled by the joint intensity index. In order to avoid boundary effects for a specified region of the model, the Beecher algorithm first enlarges the region before creating joints. Then, after generating the joints, according to the desired seam intensity criterion, the algorithm limits the network with the border of the main area. Beecher model joints are generally limited in healthy rock (Baecher et al., 1977; Farhadian et al., 2017).

Joint intensity: Joint intensity values describe the amount of joint formation that occurs in a volume of rock mass:

P = number of effect joints per unit area of effect plate

Selection of distribution: The normal distribution is mostly used for statistical comparison in geotechnical engineering. If the true distribution of a variable is not known, it is usually assumed to be normally distributed. According to the explanation of normal variance section, standard deviation can be estimated by getting the best estimate from the minimum and maximum values of the variable. Other distributions may have the following uses: Variables with positive values (such as stability) often have probability density functions that cannot be well modeled by a normal distribution. For these variables, often asymmetric distributions such as exponential or log normal distribution are used instead of normal distribution. The uniform distribution is useful when considering the equal probability of a variable having any value between the minimum and maximum values. The Fisher distribution for joint orientation data is used for Beecher and Veneziano joint batch models.

Normal distribution: Gaussian distribution is the most common type of probability density function (PDF) and is often used for probabilistic studies in geotechnical engineering. For a normal distribution, approximately 68% of observations should fall within one standard deviation of the mean, approximately 95% of observations should fall within two standard deviations of the mean, and more than 99% should fall within three standard deviations. The normal probability density function shows the range of the standard deviation.

Incomplete normal distribution: An incomplete normal distribution can be defined by specifying an assumed minimum or maximum value for the variable. If the min/max values are less than 3, the standard deviation from the mean of the distribution is greatly reduced. This means that if the minimum and maximum values are at least 3, the standard deviation will be different from the mean and a perfect normal distribution will be obtained. For the theoretical normal distribution, 99.73% of all samples fall within 3 standard deviations from the mean. This fact leads to the "rule of three sigma", which allows you to estimate a random variable that is normally distributed with one standard deviation. Estimate the highest value (HCV) and lowest value (LCV) of the random variable and divide the difference between them by six:

$$\sigma = \frac{HCV - LCV}{6} \tag{1}$$

The answer to the above formula can be considered as the standard deviation of a normally distributed random variable. This method is used when real data is not available. This and other standard deviation estimation methods in (Duncan and Chang, 1970). has been thoroughly discussed.

Uniform distribution: The distribution is used to simulate random variations between two values, where all values in the range are equally likely. This distribution is characterized by mean, minimum and maximum values. For a uniform distribution, the definition of standard deviation is not needed.

Exponential distribution: This function is often used to define random variables such as joint or stability. The range of values of the exponential distribution must always be positive, that is, it cannot be used for variables that have negative values. The mean value will always be equal to the standard deviation for an exponential distribution. The range of the original exponential distribution is from zero to infinity. The exponential distribution is truncated by entering the desired minimum and maximum values.

Log-normal distribution: A random variable that has a normal logarithm distribution will be the normal logarithm of that normal distribution. Log normal distribution is only applicable for positive variables. The log-normal distribution is used to model variables that have a distribution close to zero and gradually decrease for higher values. It is useful for modeling the spacing and stability of joints.

Fisher distribution: This distribution is used to model the distribution of joint directions (polar vectors) on a sphere. This function describes the mean of the angular distribution of the orientation vector and is symmetric about the mean. The probability density function is expressed by the following relation:

$$f(\Theta)= \frac{k\ sinsi\ n(\Theta)\ e\hat{}(k\ cos(\Theta))}{e^{k}-e^{-k}} \quad (2)$$

In this regard, Θ is the angle of deviation from the mean vector (in degrees) and K is the Fisher dispersion coefficient (Fisher, 1953).

In the software, the orientation of the seam can be defined for the Beecher or Veneziano seam models using the Fisher distribution.

III. THE EFFECT OF DIFFERENT FRACTURE DISTRIBUTIONS ON THE MOVEMENT OF TUNNELS AND UNDERGROUND SPACES

For this purpose, finite element numerical modeling was used with the help of Phase2 software. In this type of simulation, the dimensions of the blocks were considered to be 50x50 square meters and the minimum number of elements was chosen to be 7000, which in tunnel stability issues, the number of elements should not be less than 1500 elements. The elements were selected from the graded three-node triangular type with a grading index of 0.1, which are among the standards of tunnel stability analysis in Phase2 software. The failure index used for stability analysis is Mohr-Columb type and the information required for simulating density, cohesion and friction angle, elastic modulus and Poisson's ratio are presented in Table 1.

Table 1. Values of geomechanical parameters for tunnel wall stability analysis (Fisher, 1953)

Poisson's ratio	Young's modulus (MPa)	Cohesion (MPa)	Friction angle (°)	Tensile strength (MPa)	Density (MN/m³)
0.3	20000	10.5	35	0	0.027

The value of the maximum displacement in the elements limited to the tunnel in the numerical model with changes in each of the different parameters such as the radius of the tunnel, *r*, (1, 3, 5 and 10 meters), the fracture length, *L*, (1, 3, 5 and 10 m) and different types of fracture distribution: normal, log normal, uniform and exponential with different degrees of joint density, P, were studied. Fig. 2 shows examples of simulated models to investigate the maximum displacement in different fracture distributions for a joint density of 0.4. Also, Fig. 3 shows different fracture distribution models with different joint density in the exponential distribution of joint and fracture.

Due to the uncertainties in the results of the measurements and characterization of the rock mass, conducting research on the impact of these uncertainties on the stability of tunnels seems inevitable. This necessity has caused a more accurate understanding of the effect of different types of fracture distributions on tunnel displacement with sensitivity analysis on the parameters affecting the stability of the tunnel. Therefore, by changing one parameter and keeping other parameters constant, maximum displacements based on different parameters of tunnel radius, r, length of fracture, L and different types of fracture distribution were obtained by numerical modeling (Fig. 4). According to the result, with the increase in fracture length, the difference in fracture distribution increases and becomes closer to reality. According to the exponential distribution of fractures in the Beecher model (Fig. 2) and the results of the simulation of different models (Fig. 4), it can be definitely said that in this type of distribution the maximum displacement value is less than other distributions and on the other hand in most cases, this value will be higher in normal and log-normal fracture distribution. In other words, with the increase of the density value from 0.1 to 1, the log-normal distribution in the case where the tunnel radius is 1 meter and the average length of the joints is 10 meters has the highest displacement with 83.18%, and in contrast, the exponential distribution in the case where the tunnel radius is 10 meters and the average length of the joints is 1 meter with 0.3%, it has the lowest amount of movement. Regarding the effect of fracture length of joints on the amount of total displacement, in the category of joints with an average length of 5 meters, regardless of the size of the tunnel radius, the effect of length of fracture of joints on the amount of displacement does not depend on the density of the joints, in other words, on the values of the density of the joints values greater than 0.8 are the same as the total displacement value (max). Also, in the group of joints with an average length of 10 meters, this happened in density values greater than 0.5. As can be seen, the more the radius of the tunnel increases, the more homogeneous the total displacement process will be in different distribution of fractures. In other words, when the tunnel radius is very small, the amount of total displacement does not follow a particular trend with respect to the increase in joint density for most of the different fracture distributions. Also, with the increase in the density of the joints, the difference in the amount of displacement in different fracture distributions increases, so that at the value of 1 density of the joints, the average difference in the distributions is 19%, and the largest difference is related to the log-normal and exponential distribution in the radius of 1 meter and The average length of the joint is 10 meters with 85.5% and the lowest difference is related to log normal and exponential distribution in the radius of 10 meters and the average length of the joint is 1 meter with 2.13%.

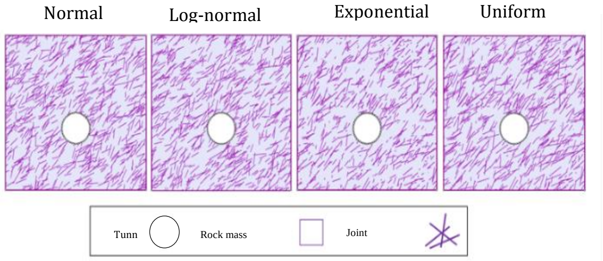

Fig. 2. Simulated models to investigate the maximum displacement in different distributions of Beecher type fracture (uniform, exponential, normal and log-normal) for a joint density of 0.2.

Therefore, according to the sensitivity analysis of different parameters and their investigation based on different distributions of Beecher-type fracture joints in connection with the stability of tunnels, it can be stated that only the average difference of 19% of the types of distributions is effective in the stability and movement of tunnels. and it is suggested that experts and tunnel engineers and diggers in this field focus their studies on other parameters of tunnel stability and underground spaces.

IV. Conclusions

In this article, using Phase2 software, the effect of different distributions of joints and fractures of the Beecher type on the displacement of tunnels and underground spaces was investigated using numerical modeling. The results of 640 simulated models on the effect of different types of Beecher fracture distribution on tunnel displacement show that:

1. In the exponential type distribution, the maximum displacement value is lower than other distributions, and on the other hand, in most cases, this value will be higher in the fracture normal and log normal distribution.
2. As the fracture length of the joints increases, regardless of the radius of the tunnel, the amount of total displacement will be the same at high densities of the joint bundle.
3. With the increase in the density of the joints, the difference in the amount of displacement in different fracture distributions increases, so that at a density of 1 of the joints, the average difference between the distributions is 19%.

In a fractured rock mass with a high joint density, the interaction between fractures can lead to a process known as "stress shadowing". This means that as the tunnel is drilled through the rock mass, the deformation and displacement of the rock around the tunnel is affected by the presence of adjacent fractures. When the joint density is high, the stress shadow effect can lead to the redistribution of stresses and strains in the rock mass, so that the total tunnel displacement is not significantly affected by the tunnel radius.

The choice of failure distribution can have a significant effect on the predicted tunnel displacement, with different distributions resulting in significantly different displacement values.

Furthermore, it is important to carefully consider the choice of fracture distribution when modeling a specific rock mass, taking into account the available data and the underlying assumptions of the distribution. Each distribution has its own advantages and limitations, and the choice of distribution should be based on a careful analysis of the data and the specific application.

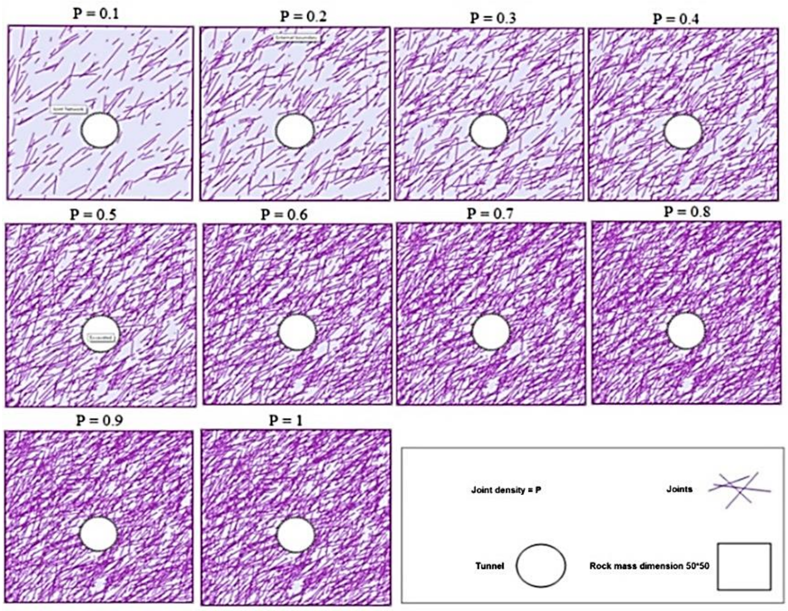

Fig. 3. Display the distribution of fractures based on joint density from 0.1 to 1 for exponential distribution.

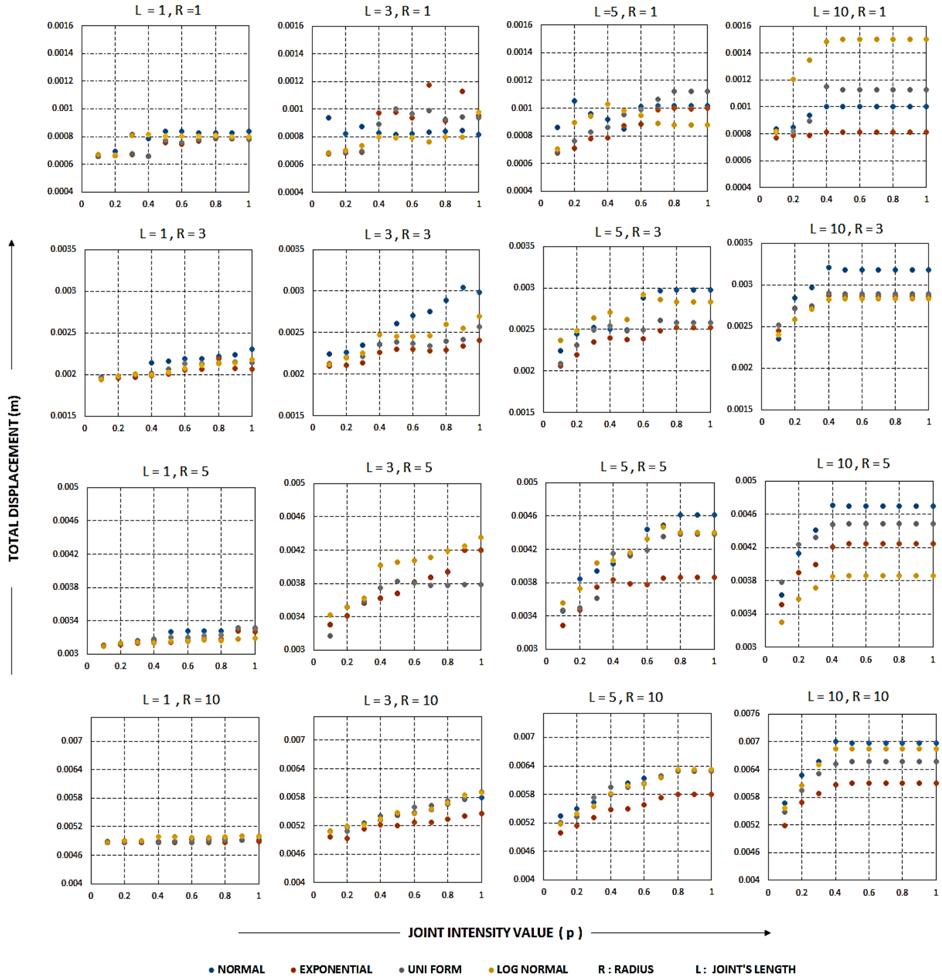

Fig. 4. Effect of tunnel radius parameters, fracture length and different fracture distributions on tunnel stability and underground spaces (maximum displacement) using finite element numerical simulation.

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