A novel method for modelling the existence of fault fracture zones within 3D weathered rock slopes

Manyu Wang, Yuxiang Xia, Yong Liu*
State Key Laboratory of Water Resources and Hydropower Engineering Science, Institute of Engineering Risk and Disaster Prevention, Wuhan University, 299 Bayi Road, Wuhan 430072, P. R. China
* Corresponding author. Email: liuy203@whu.edu.cn

Abstract. High-steep weathered rock slopes are often encountered in vicinity of the large-scale hydropower engineering projects. A variety of fault fracture zones may exist inside the weathered rock mass due to the complexity of geological activities. However, few publications have considered the state of fault fracture zones within a rock slope in a realistic way. For this goal, this study proposes a new approach to modelling the existence of fault fracture zones inside rock slopes based on 3D Gaussian random field, in which the basic features of fault fracture zones can be well established in terms of the need of site conditions. The results demonstrate that the inclination of weak fractured zones has pronounced effects on the development of the failure mode of a rock slope. The degree of connectivity of the resultant irregular slip surfaces at each cross section of the 3D model significantly affects the system stability of a weathered slope. In addition, using a 3D numerical model for the analysis of a fractured slope gives a more reasonable and reliable estimation of the slope stability than the 2D one. The presented results can offer a new insight for the stability investigations of weathered rock slopes with fault fracture zones, aiming to reduce the risk of landslides.

Keywords. Weathered rock slope, Fault fracture zones, Landslide, Risk, Random field.

1. Introduction
Constructing large hydropower engineering projects inevitably passes through areas with poorly geological conditions [1]. The diversity of geological environment may bring challenges to the engineering safety [2]. However, the case of weathered rock mass are often encountered in vicinity of these projects [3]. Many field investigations revealed that a variety of fault fracture zones (FFZs) could be embedded inside the rock mass due to complex geological activities [1,4,5,6], which may result in a great risk of inducing landslides. As an example, Figure 1 shows a typical distribution of FFZs within weathered rock slopes in the region near the middle route of the South-to-North Water Transfer Project, located in Shijiazhuang City, Hebei Province, China. Once the landslide occurs, a heavy loss to the safety of diversion channel will be posed. As such, representing the state of internal FFZs in a relatively realistic way is an issue of worthy when performing the stability analysis of fractured rock slopes.

In general, the orientation of FFZs inside weathered rock slopes can easily be measured but its distribution throughout the whole slope is often unknown in terms of surficial observations [4]. This requires a new technique to numerically simulate the existence of FFZs in a reliable way. Many researchers have made attempts to achieve this goal [4,7,8,9]. For example, Kim et al. [4] applied the photogrammetry method to investigate the stability of a weathered rock slope based on the use of the GSI system and the Hoek-Brown strength criterion. Gao et al. [9] proposed a new theoretical method
based on fracture mechanics to study the effect of initial cracks on rock slope failure. However, most of studies considered a single FFZ or crack in the framework of a 2D slope, but a real slope is often not as the case. Few works simulate the FFZs within a 3D rock slope and consider its random features reasonably, which forms the motivation of this study.

From literatures, the concept of random field is widely used for reflecting the spatial variability of geo-materials in geotechnical applications [10,11,12]. Based on this fact, the current study attempts to represent the FFZs using a random field indirectly. For modelling the FFZs embedded in a 3D slope, the requirement on the mesh size of a slope model analysed is grossly high to reach a reasonable state. Therefore, a suitable 3D random field generation program with high efficiency is needed in this study. Details on the representation method of FFZs within rock slopes are described in the next section.

**Figure 1.** Typical distribution of fault fracture zones (FFZs) within weathered rock slopes in the region near the middle route of the South-to-North Water Transfer Project, located in Shijiazhuang City, Hebei Province, China.

**2. Methodology**

2.1. **Numerical Modelling of a rock slope with FFZs**

This study considers a geometrically simplified 3D rock slope as the engineering case. Figure 2a shows the profile of the slope model analysed, consisting of 457,409 elements. A fine mesh scheme (i.e., an element size of 0.3 m) is herein adopted to allow a more smooth representation of FFZs within the rock mass. For the boundary conditions, the bottom of the slope model is fixed in all directions, and the four lateral sides are constrained by rollers to prevent a deformation in its vertical direction. The rock and FFZs are modelled as elastic-perfectly plastic materials in the numerical model. The used parameter of Young’s modulus is 100 MPa and the Poisson’s ratio is 0.35. The shear strengths of the weathered rock and FFZs are set to 34.12 kPa and 10.73 kPa, respectively. The strength reduction technique is employed to perform the slope stability analyses [12], and a scenario of non-convergence of the finite element program is considered as the judgement condition of slope failure.

In general, the attitude of rock formation is usually characterized by using the three elements of strike, dig and inclination. In this study, the strike of FFZs is assumed to be spatially identical to the slope surface, as illustrated in Figure 2b. The inclination $\beta$ of FFZs within the rock slope is herein redefined at a new location for convenience of expression. Parametric studies on the inclination of FFZs within 2D and 3D rock slopes are conducted to investigate its effects on the overall performance of these slopes analysed, in which the value of $\beta$ used ranges from 0° to 180° with an interval of 30°.
2.2. Representation method of FFZs using 3D Gaussian Random Field

Regarding the novel method of modelling the FFZs proposed in this study, a stationary 3D Gaussian random field \( G(x,y,z) \) is first required, which is controlled by a zero-mean, unit variance, and an auto-correlation function. Due to the numerous numbers of finite elements for a 3D slope (see Figure 2a), the efficiency in the random field generation is a crucial issue worthy of concern. Liu et al. [13] proposed the modified linear estimation method that is able to generate a multi-dimensional Gaussian random field applicable for a model with more than one million elements. In addition, it has a high adaptability with any shapes of mesh. Herein, a squared exponential autocorrelation function \( \rho(x,y,z) \) employed is expressed as:

\[
\rho(x,y,z) = \exp \left\{ -\pi \left( \frac{\Delta x}{\theta_x} \right)^2 - \pi \left( \frac{\Delta y}{\theta_y} \right)^2 - \pi \left( \frac{\Delta z}{\theta_z} \right)^2 \right\}
\]  

(1)

where \( \theta_x, \theta_y \) and \( \theta_z \) are the correlation lengths of materials in the \( x- \), \( y- \) and \( z- \)directions, respectively; \( \Delta x, \Delta y \) and \( \Delta z \) are the absolute distances between two points in space along the \( x- \), \( y- \) and \( z- \)directions, respectively. In this study, the values of \( \theta_x = 20 \) m and \( \theta_y = 20 \) m are taken as the critical parameters to control the average length and width of FFZs. With respect to an inclined FFZ relative to the horizontal as depicted in Figure 2b, this requires a rotation around the \( Y- \)axis with an angle of \( \beta \) for the Gaussian random field, which can be transformed through the relationship:

\[
\begin{bmatrix}
x' \\
y' \\
z'
\end{bmatrix} =
\begin{bmatrix}
\cos \beta & 0 & \sin \beta \\
0 & 1 & 0 \\
-\sin \beta & 0 & \cos \beta
\end{bmatrix}
\begin{bmatrix}
x \\
y \\
z
\end{bmatrix}
\]

(2)

Figure 2. (a) Geometric and mesh size of the numerical slope model analysed in this study, consisting of 457,409 elements; (b) sketching for the inclination definition of a reconstructed FFZ within a rock slope.
where $x'$, $y'$ and $z'$ are the new coordinates of a rotated Gaussian random field $G(x', y', z')$. The next step is to define the regions of FFZs in a generated random field, which can be implemented by selecting a few intervals in the probability density function of a 3D Gaussian random field as explained in Figure 3. The judged criterion can be written as:

$$M(x', y', z') = \begin{cases} 
\text{Fault fracture zones (FFZs), } G(x', y', z') \in \Omega \\
\text{Rock, } G(x', y', z') \notin \Omega 
\end{cases}$$

(3)

where $\Omega$ represents the regions of FFZs. If the generated random value is belong to $\Omega$, it is reassigned a strength value of FFZs (10.73 kPa); otherwise, it is reassigned a rock strength value (34.12 kPa).

![Figure 3. Schematic diagram of the region definition of FFZs based on the probabilistic density function of a 3D Gaussian random field.](image)

Figure 4a shows a typical existence of FFZs within the rock slope in which the FFZs average inclination is equal to 30°, being accomplished by using the proposed method as mentioned above. From the sectional views presented in Figure 4b, it demonstrates that the proposed method has a good capability of reflecting the random features of FFZs distributed inside rock slopes.

![Figure 4. (a) Full view of a typical realization of the combined structures of both the rock mass and FFZs, in which the average inclination of FFZs is 30°; (b) corresponding details of FFZs distribution at each cross section of the slope model shown in Figure 4a.](image)
3. Results and Discussion

3.1. Analysis of a weathered rock slope without FFZs

Figure 5 shows the results of a deterministic analysis performed with a constant rock strength value of 34.12 kPa, which is taken as a reference case in this study. A regular circular slip surface is observed throughout the width direction of the model (i.e., Y-axis). Such a result is essentially identical to that of a 2D homogeneous rock slope, but a real slope project is often not as same as this case.

![Figure 5](image_url)

3.2. Failure mechanism of 3D rock slopes containing FFZs under different inclinations

Figure 6 presents the typical realizations of FFZs inside rock slopes under different average inclinations, and the corresponding failure mode for each case is also provided. Four major types of failure mode can be inferred from the irregular critical slip surfaces of all these given models. When the FFZs are basically horizontal (see Figure 6a), an obvious shallow failure is developed along the paths of FFZs located below the slope surface. This scenario is mainly because such horizontal FFZs offer a favourable condition for the development of the bottom part of a potential slip surface. As the inclination increases further but not exceeds 90° (see Figures 6b and 6c), a smooth component of the slip surface at the back parts of the slope is clearly observed. The FFZs at these regions directly form the irregular sliding paths, resulting in an accelerated tendency for the sliding of the upper fractured rock masses. At the front part of these two slopes, although various bands of shear failure having a certain angle with the critical slip surface are formed, it leads to insignificant effects on preventing the system failure of the slope. When the FFZs are almost vertical (see Figure 6d), the volume of the sliding masses reduces throughout the entire slope and a shallow slope failure occurs. Except for these FFZs at the back parts of the slope, the other parts of FFZs are basically perpendicular to the potential slip surface, which is unfavourable for the development of the slip surface and then results in a relatively stable condition. For these cases in which the inclination continues to increase (see Figures 6e and 6f), regarding the evolution of slip surfaces, opposite scenarios are observed compared with the cases shown in Figures 6b and 6c. It is more easily to lead to a local failure in the regions near the slope toe because of the highly close interfaces between the FFZs and the sliding rock masses. In contrast, for such a scenario the upper parts of rock mass remains relatively stable.

The results from Figure 6 indicate that a large deficiency in failure mechanism exists for the rock slopes with FFZs under different inclinations. The existence of FFZs significantly reduces the slope stability. These results can serve as a suggestion for the reinforcement of fractured rock slopes in terms of actual geological conditions.

3.3. Comparison of factor of safety for 2D and 3D rock slopes with FFZs

Without loss of generality, for comparisons the analyses for 2D weathered rock slopes with FFZs under different inclinations are also performed using the same input parameters as adopted in the corresponding 3D slope models. As an illustration, Figure 7 shows the results of a 2D weathered rock slope containing FFZs where the average inclination of FFZs is 30°. It can be seen that the failure mode...
is similar to that of the 3D one shown in Figure 6b as a whole. Figure 8 depicts the rose diagram of the average factors of safety of 2D and 3D slopes containing FFZs for all the cases. A general conclusion

Figure 6. Typical realizations of FFZs inside the rock slope under different FFZs inclinations and the corresponding failure modes. FoS = factor of safety.
**Figure 7.** Results of a 2D rock slope containing FFZs with an average inclination of 30°: (a) realization of combined structures of both the rock mass and FFZs; (b) the corresponding critical slip surface; (c) contours of the deformed displacements.

**Figure 8.** Comparison of the average factors of safety (FoS) for 2D and 3D rock slopes containing FFZs under different inclinations.

It can be inferred that the stability of a fractured rock slope from a 2D analysis is generally higher than that from a 3D analysis under the same inclination of FFZs, but the factors of safety of all of them are much lower than that of the case of a weathered rock slope without FFZs. To a certain extent, a 2D fractured slope model is essentially a cross section of a 3D slope and the distribution of FFZs on this section just represents a typical situation. An explanation for the phenomenon shown in Figure 8 is that the connectivity of these irregular slip surfaces at each cross section of the 3D slopes may reduce the system stability of the whole slope. This indicates that using a 3D numerical model is more reasonable than the 2D one when performing the stability analysis of a fractured rock slope.
4. Conclusions
This study proposes a novel method for modelling the existence of fault fracture zones (FFZs) within weathered rock slopes based on 3D Gaussian random field, in which the features of FFZs can be well established in the numerical model. This study mainly focuses on the effects of FFZs inclination on the slope stability. The results show that different inclinations of FFZs may lead to large deficiency in the failure mechanism of fractured rock slopes, which is mainly attributed to the different locations in which the FFZs directly form the components of the sliding paths. The connectivity of the resultant irregular slip surfaces at each cross section of the 3D slope may also affect the slope stability to different degrees. In addition, the analysis using a 2D slope model can overestimate the performance of real slopes containing FFZs. These results presented in this study can serve as a useful suggestion for the reinforcement of fractured rock slopes to make it maintaining a stable state and to avoid the risk of potential landslides.

Acknowledgments
This research is supported by the National Natural Science Foundation of China (Grant No. 51879203 and 52079099).

References
[1] Yin Q, Jing H, Su H, Zhao H 2018 Experimental study on mechanical properties and anchorage performances of rock mass in the fault fracture zone International Journal of Geomechanics 18 (7): 04018067
[2] Shen J, Karakus M 2014 Three-dimensional numerical analysis for rock slope stability using shear strength reduction method Canadian Geotechnical Journal 51 (2): 164–172
[3] Amit S 2012 Spatial variability modelling of geotechnical parameters and stability of highly weathered rock slope Indian Geotechnical Journal 42 (3): 179–185
[4] Kim D H, Gratchev I, Balasubramaniam A 2015 A photogrammetric approach for stability analysis of weathered rock slopes Geotechnical and Geological Engineering 33 (3): 443–454
[5] Wang Y, Jing H, Su H, Xie J 2016 Effect of a fault fracture zone on the stability of tunnel-surrounding rock International Journal of Geomechanics 04016135
[6] Zhang W, Wang J, Xu P, Lou J, Que J 2020 Stability evaluation and potential failure process of rock slopes characterized by non-persistent fractures Natural Hazards and Earth System Sciences 20 (11): 2921–2935
[7] Jiang M, Jiang T, Crosta G B, Shi Z, Chen H, Zhang N 2015 Modeling failure of jointed rock slope with two main joint sets using a novel DEM bond contact model Engineering Geology 193: 79–96
[8] Huang D, Cen D, Ma G, Huang R 2015 Step-path failure of rock slopes with intermittent joints Landslides 12 (5): 911–926
[9] Gao Wei, Dai S, Xiao T, He T 2017 Failure process of rock slopes with cracks based on the fracture mechanics method Engineering Geology 231: 190–199
[10] Griffiths D V, Fenton G A 2004 Probabilistic Slope Stability Analysis by Finite Elements Journal of Geotechnical and Geoenvironmental Engineering 130 (5): 507–518
[11] Liu Y, Zhang W, Zhang L, Zhu Z, Hu J, Wei H 2018 Probabilistic stability analyses of undrained slopes by 3D random fields and finite element methods Geoscience Frontiers 9 (6): 1657–1664
[12] Wang M Y, Liu Y, Ding Y N, Yi B L 2020 Probabilistic stability analyses of multi-stage soil slopes by bivariate random fields and finite element methods Computers and Geotechnics 122: 103529
[13] Liu Y, Lee F H, Quek S T, Beer M 2014 Modified linear estimation method for generating multi-dimensional multi-variate Gaussian field in modelling material properties Probabilistic Engineering Mechanics 38: 42–53