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RESEARCH PAPER

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Geometric model Construction of the main discontinuities using the Discrete Fracture Network method, A Case Study of the Pirtaghi dam site, Northern Iran

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Abstract
Accurate characterization and geometric modeling of rock mass discontinuity networks are fundamental for assessing the strength, mechanical, and hydraulic behavior of jointed rock masses. This is particularly crucial for infrastructure projects like dams, where discontinuities profoundly influence stability and seepage. At the Pirtaghi Dam site, understanding the main discontinuity network is essential for abutment stability evaluating and predicting potential seepage paths. This research focused on constructing a three-dimensional (3D) stochastic geometric model of the main fracture network using the discrete fracture network (DFN) method at the Pirtaghi Dam site. For this purpose, detailed geological mapping of fractures was conducted in the dam abutments to collect comprehensive data on fracture location, orientation, trace length, and density. Based on this data, appropriate probability distribution functions (PDFs) were determined for these key geometric parameters. A 3D fracture network model was then simulated using the Monte Carlo method and a custom code developed within 3DEC (3-Dimensional Distinct Element Code) software, incorporating the derived PDFs. Goodness-of-fit tests revealed that the geometric parameters of the main joint sets at the Dam site follow uniform (for orientation), exponential-lognormal (for spacing), and power (for trace length) probability distributions. The 3D density values (P_{32}=1.5 to 2.3 m^2/m^3) and the exponent values (a = 2.3 to 2.5) of the joint sets were also quantified. The developed DFN model, along with the derived quantitative geometric parameters, provides reliable, site-specific input data for advanced numerical modeling, such as distinct element method simulations, using software like 3DEC. This detailed model significantly enhances the ability to analyze and predict the complex hydraulic and mechanical behavior of the discontinuous rock mass at the Pirtaghi Dam site, offering a critical tool for engineering design and risk assessment.

Keywords: Geometric Model, Discrete Fracture Network, Probability Distribution, 3D Density, Joint.

Introduction

Studying the characteristics of discontinuity sets in rock masses, including the number, orientation, spacing, location, shape, and size, is significant because these features determine the geomechanical and hydrological properties of the rock mass. The presence of major fractures in rock masses can lead to inhomogeneous stress fields, significant fluid flow paths in geological formations, and instability in rock blocks (Lang et al., 2014). Therefore, accurately simulating rock mass characteristics, particularly the geometry of fractures, is crucial for creating a random network of fractures and generating a two-dimensional or three-

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dimensional numerical model of the discontinuities. Such simulations can enhance the accuracy of detailed designs, reduce uncertainty in estimating rock mass behavior, and potentially lower implementation costs (Pine et al., 2006). Various researchers have proposed methods to simulate fractures and construct joint models in rock masses. Snow (1969) developed the first model to represent discontinuity sets based on the assumption that all discontinuities are defined by three sets of perpendicular joints of infinitely parallel planes with constant spacing. Long et al (1985), refined this approach by defining a finite length for each fracture with more realistic orientations. The disk model, proposed by Baecher et al (1977), became a prominent discrete discontinuity model, assuming circular discontinuities based on the Poisson distribution. The geometric parameters used to describe this discontinuity network are density, directional distribution, size, shape, and their equivalent hydraulic opening. Veneziano (1978) introduced a polygonal discontinuity plane model with Poisson-distributed discontinuity planes, where the effect lengths of discontinuities are generated according to an exponential distribution**.** Dershowitz and Einstein (1987) proposed a more accurate model for forming discrete rock blocks based on Veneziano's model. This model has the advantages of the orthogonal model in defining discrete rock blocks and variable directional distribution. Priest (1993) then developed a three-dimensional stochastic model assuming circular disk joints with random diameter sizes generated by algorithms with appropriate distributions. Kulatilake et al (2003) modeled the fracture geometry randomly using FRACNTWK software based on scan line data from a California tunnel. With the advancement of science, discrete fracture network (DFN) models emerged, allowing for the creation of fractures with limited length and arbitrary orientation. Baghbanan and Joolaei (2010) developed a DFN model based on probability distribution functions of geometric parameters of discontinuities retrieved from the surface of boreholes using a Monte Carlo algorithm and the FracIUT computer code**.** Lang and Zimmerman (2014) developed the discrete element method (DEM-DFN) to simulate the permeability tensor integrating fracture geometry, stress-flow coupling, and deformation within the model using Monte Carlo simulation. This method created an equivalent fracture network geometric model using the Monte Carlo simulation technique, which is based on random realizations of fracture systems. Fereshtenejad et al (2016) presented a model of DFN that can be used to model the discontinuity network in folded rock layers.

Despite these advancements, accurately characterizing and modeling complex fracture systems in specific geological settings, such as the Pirtaghi dam site, remains a significant challenge. Conventional methods often struggle to capture the full stochastic variability of discontinuity parameters from limited field data, leading to uncertainties in geomechanical and hydrological assessments. This study addresses this challenge by presenting an integrated Discrete Fracture Network (DFN) modeling approach. Its primary purpose is to develop a robust methodology for the stochastic modeling of discontinuity characteristics using probability density functions (PDFs) derived from geological mapping at the Pirtaghi Dam site. A key advantage of our approach is the use of the fish code developed in 3DEC software to create a 3D DFN based on the stochastic simulation of fracture systems. Unlike some conventional approaches that oversimplify fracture geometries, 3DEC software, as a discrete element modeling (DEM) program (Itasca, 2016), enables the creation of complex geometric structures in rock masses using the DFN. This general stochastic DFN approach assumes fractures are straight lines (in 2D) or flat disks/polygons (in 3D) and considers other geometric parameters, such as position, density, size, and orientation, as independent random variables (Lei et al., 2017). This integrated methodology aims to provide a more accurate and comprehensive representation of the fracture network, thereby improving the reliability of subsequent analyses for dam seepage flow and dam stability.

Study Area and Site Characterization

Geographical location and dam specifications

The Pirtaghi Dam site is located in the Qezel Ozan River valley in northwestern Iran, approximately 45 kilometers southwest of Khalkhal in Ardabil Province (Figure 1). Regionally, the study area lies within the West of the folded and thrust Alborz zone, a significant morphotectonic unit characterized by a general NW-SE trend and complex geological structures (Alavi, 1996). Preliminary geological and geotechnical investigations confirmed the feasibility of constructing a dam at this site. According to phase one studies, the proposed dam is a double-arched structure with a height of 160 meters and a reservoir capacity of 320×10^6 m3. This dam is designed to control the upstream flow of the Ghezel Ozan River, generate 165 MW of energy, and support agricultural initiatives (Toossab Consulting Engineers Company, 2015). The location of the dam site is shown in Figure 1.

The Geological and Geotechnical study of Dam Site

The local geology of the Pirtaghi Dam site is dominated by the Tertiary magmatic Alborz complex. Geological investigations indicate that the oldest exposed units at the dam and reservoir site are Eocene and Oligocene volcanic rocks. To characterize the geotechnical and geomechanical properties of the rock mass and alluvial river deposits, extensive geological and geotechnical studies were conducted. These studies included the drilling of 48 exploratory boreholes, totaling approximately 5300 meters, across the riverbed, abutments, spillway, and diversion tunnel. Complementary investigations involved in-situ and laboratory tests on rock and soil samples, trial cement grouting, and geophysical surveys (Toossab Consulting Engineers Company, 2015). Figure 2 shows the location of the exploratory boreholes and galleries in the geological map of the dam site.

The borehole drilling revealed a maximum thickness of alluvial material in the dam foundation ranging from 35 to 40 meters. The dam foundation alluvial materials consist of coarse-grained gravel with clay (GP-GC), fine-grained sand with clay (SW-SC), and boulder and cobble materials. Based on the petrographic studies' results, Eocene volcanic tuff rocks are the oldest geological units exposed in the reservoir and dam foundation. The primary rock mass comprising the dam foundation and abutments consists of Oligocene-aged volcanic rocks, including andesitic tuffs, breccia andesite, andesite, rhyolite, and basaltic andesite.

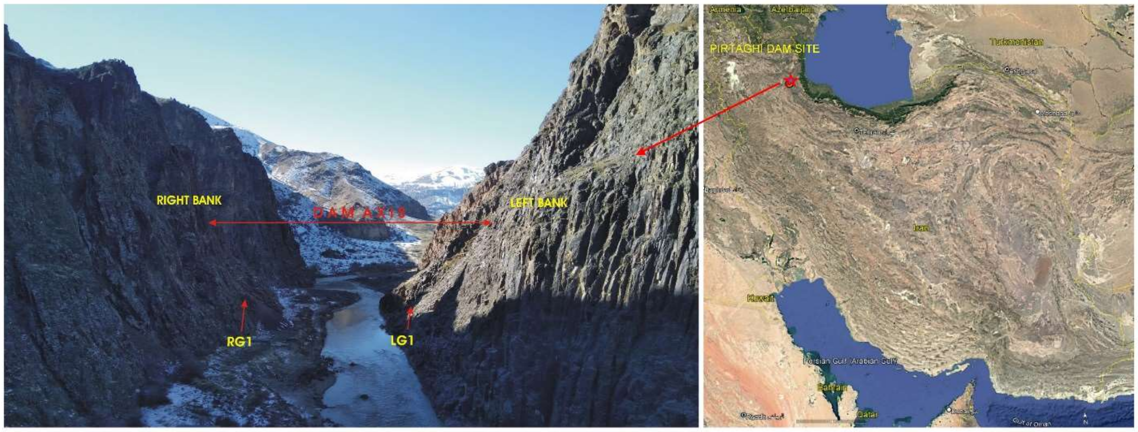

Figure 1. a) Location of Ghezel Ozan dam site in NW Iran (image courtesy of Google Earth/Landsat/ Copernicus). b) Outcrop of andesitic rock mass in the Ghezel Ozan dam abutment. Southeast view (X = 254558.39, Y = 4150281.13, Zone 39s)

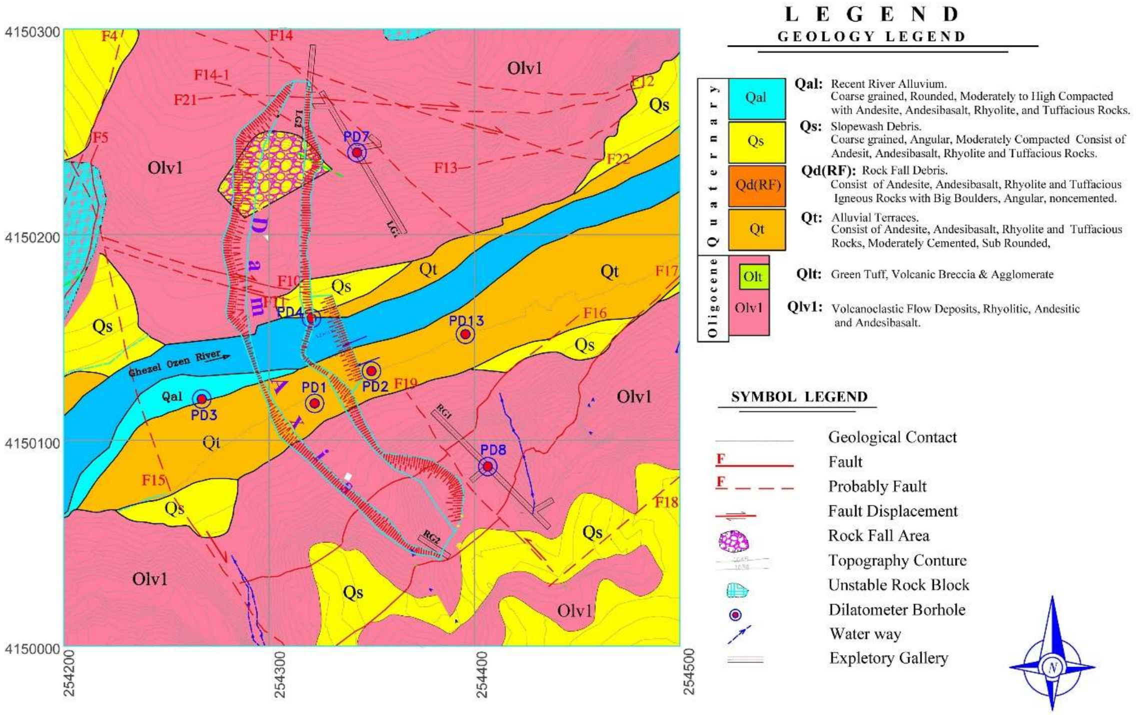

Figure 2. Geological map and the location of borehole in foundation and abutments of Pirtaghi dam site (Toossab Consulting Engineers Company, 2015)

An angular unconformity, marked by a 1 to 3-meter-thick layer of obsidian rocks, separates the Eocene and Oligocene units (Motamed-Shariati et al., 2023; Toossab Consulting Engineers Company, 2015).

Materials and Methods

A comprehensive methodology was employed to characterize the stochastic characteristics of discontinuities using PDFs and subsequently generate a three-dimensional discrete fracture network (DFN) model for the Pirtaghi Dam site. This methodology involved two main stages: (1) statistical analysis of discontinuity parameters derived from geological field studies and (2) stochastic simulation of fracture systems to construct the DFN model. The geometry of fractures in a rock mass was defined by key parameters including orientation, density, trace length, and geometric center. These parameters were essential for creating a representative discrete fracture network model (Jing & Stephansson, 2007; Wittke, 2014). The most significant parameters and their theoretical definitions are detailed below.

Fracture orientation

Fracture orientation was typically defined by two independent components: dip direction and dip angle. Research indicates that while dip direction often follows a uniform distribution, dip angle is commonly described by a Fisher distribution. The Fisher distribution is characterized by a Fisher Constant (κ), which determines the deviation value of the orientation angle relative to the mean value (θ). For a population of fracture orientations, the probability density function of the Fisher distribution for K is given by (for $\mathbf{0} < \boldsymbol{\theta} < \frac{\boldsymbol{\pi}}{\mathbf{2}}$):

$$f(\theta) = \frac{kSin\theta e^{kcos\theta}}{e^{k}-e^{-k}} \qquad \text{(Equation 1)}$$

Where θ is the angle between the fracture normal and the mean direction vector, and ϕ is the angle of rotation about the mean direction vector (Jing & Stephansson, 2007).

Fracture frequency

Fracture frequency (λ) quantifies the average number of fractures per unit length, area, or volume. It was defined as one-dimensional frequency (linear frequency, per unit length), two-dimensional frequency (per unit area), or three-dimensional frequency (per unit volume). One-dimensional and two-dimensional frequencies are dependent on the orientation of the measurement line or plane. The inverse of the linear frequency (s=1/λ) is commonly referred to as spacing. Studies have shown that spacing often follows various probability distribution functions, including normal, log-normal, and negative exponential distributions (Jing & Stephansson, 2007; Priest, 1993).

Fracture Length

The discontinuity size represents the extent of the discontinuity plane (Xu & Dowd, 2010). In 3DEC software, which models discontinuities as circular disks, the trace length was used to infer the diameter of the circular joint (Itasca 2016). Generally, log-normal, negative exponential, and power-law probability distribution functions are used to analyze the actual discontinuity trace length data (Karimzade et al., 2017). Cumulative frequency distribution and frequency density distribution was commonly used to describe fracture size data**.** For a population of fractures that follows a power law, the density distribution *n(l)* corresponds to the number of fractures *N(l)* belonging to an interval divided by the bin size *dl* is calculated by the following equation:

$$n(l) = \alpha l^{-a} \qquad \text{(Equation 2)}$$

Where C is a constant and α is the power-law exponent. A log-log plot of *N(l)* or *n(l)* versus l typically shows a straight line whose slope gives the power law exponent (a). The power law exponent determines the ratio between the smallest and largest fracture size (Darcel et al., 2004). The exponent generally varies between 1 and 3.5, with a “typical value” around 2. Factors such as stress history, linkage and connectivity, scale, and sampling bias affect the value (Zimmerman & Paluszny, 2023). The value of (α), also known as the density factor depends on exponent value (Bour et al., 2002; Lei et al., 2017).

Fracture Density

The volumetric intensity of fractures (P_{32}) was defined as the mean total area of fractures per unit volume of rock mass (m^2/m^3). This is a three-dimensional measure of fracture density, distinct from one-dimensional (linear density, P_{10}) or two-dimensional (areal density, P_{21}) frequency measurements which are dependent on the orientation of the sampling line or plane. P_{32} was calculated considering the size and frequency distribution of fractures, often through Monte Carlo simulation (Jing & Stephansson, 2007). In isotropic conditions, where the Fisher constant (κ) is relatively small (κ<1), the joint orientation distribution is close to uniform distribution, and the three-dimensional fracture density can be related to P_{10} ($P_{10}=P_{32}/2$) and P_{21} ($P_{21}=\pi/4P_{32}$). Wang (2005) derived the P_{32} value for fractures with constant size, non-connected, and under non-isotropic conditions (κ>1) according to the following equation:

$$P_{10} = P_{32}\int_0^{\pi}|cos\alpha|f_A(\alpha)d\alpha = P_{32}.(C_{13})^{-1} \qquad \text{(Equation 3)}$$

Where α is the angle between the scan line direction and the fracture normal vector (figure 3), $f_A(\alpha)$ is the probability density function α and C13 is a conversion factor (1<C< ∞) (Wang, 2005).

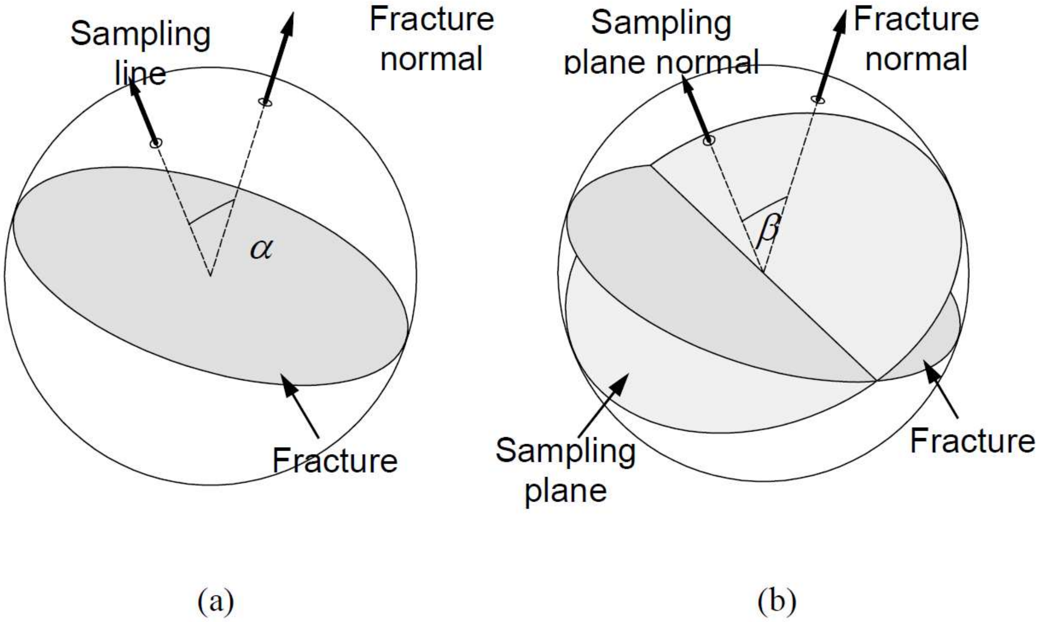

Figure 3. Determining angles α and β from orientations of the sampling line (a) or sampling plane (b) (Wang, 2005)

Results and discussion

Statistical Analysis of Fracture Parameters

A statistical study of the main fracture sets at the Pirtaghi Dam abutments was conducted to define their geometry properties, which were crucial for constructing the DFN model. This analysis was based on studying the main discontinuity characteristics of 2700 fractures (including the dip and dip direction, spacing, and trace length) using the Scan Line method at the dam abutments. The stereographic projection of these discontinuities is presented in Figure 4, which illustrates the major fracture sets identified at the site.

To determine the most appropriate probability density functions (PDFs) for each random variable (orientation, trace length, and spacing) associated with the main fracture set (JS_1, JS_2, and JS_3), a Kolmogorov–Smirnov test was performed at a 5% significance level (α=0.05) using Easy fit v5.6 software. The statistical characteristics and the best-fit PDFs for the main fracture sets are summarized in Table 1.

Table 1. Main fracture set characteristics at the Pirtaghi Dam site

Joint Set	**Dip** (deg)	**Dip Direction** (deg)	**Fisher Constant** (K)	**Spacing (cm)**		**Trace length (m)**	
				Mean	Std	Mean	St.d
JS1	28	144	23.47	51.47	49.64	2.65	2.55
PDF	Fisher	Uniform		Exponential		Power	
JS2	82	028	8.63	73.26	72.69	2.63	2.55
PDF	Fisher	Uniform		Lognormal		Power	
JS3	73	301	10.21	82.01	79.35	2.35	2.10
PDF	Fisher	Uniform		Exponential		Power	

Statistical analysis indicated that the dip direction of the identified main fracture sets (JS_1, JS_2, and JS_3) followed a uniform distribution, while their dip angles conformed to a Fisher distribution. Figure 5 visually illustrates the fitted uniform probability distribution for the dip direction of these main fracture sets.

The spacing of discontinuities, although not directly represented as an independent value in the 3DEC model, was vital for estimating the volumetric density of the fractures in the 3D model. According to the goodness-of-fit test results, the spacing of the fracture sets primarily followed exponential (JS1, JS3) and log-normal (JS2) distribution functions (Figure 6).

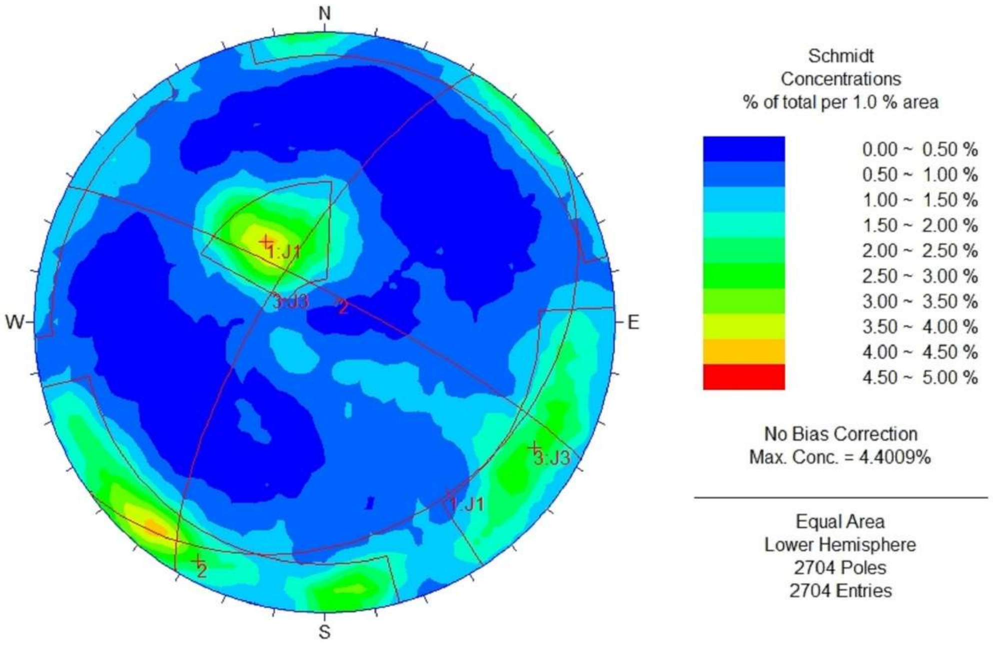

Figure 4. Stereonet constructed of main discontinuities set in the Pirtaghi Dam site

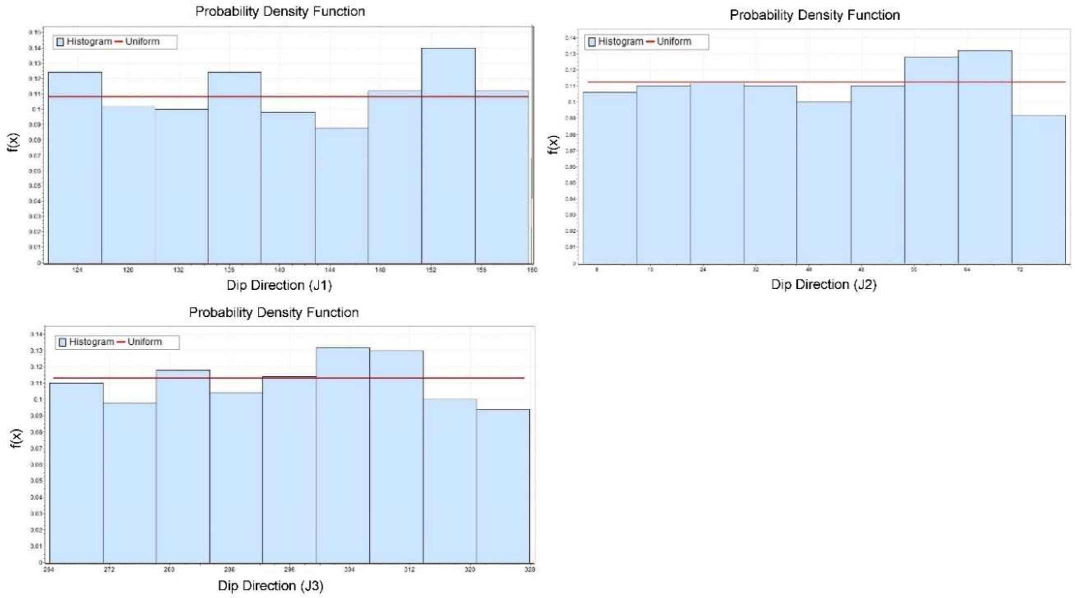

Figure 5. Uniform probability distribution function for the dip direction in the main discontinuity sets

Trace Length and Disc Radius

In this study, after determining the trace length of each main joint set, the data related to them were analyzed separately to identify the most appropriate probability distribution functions. The goodness-of-fit test results revealed that the trace length in all main fracture sets (JS1, JS2, JS3) consistently followed a power distribution function (Figure 7).

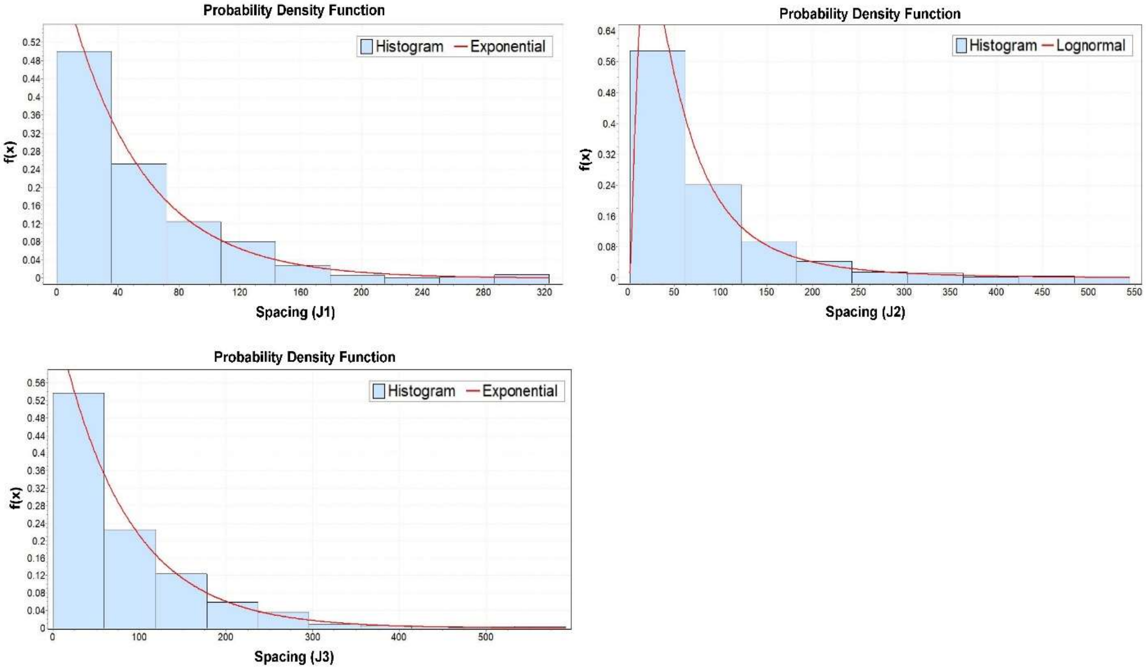

Figure 6. Probability distribution function for spacing in the main discontinuity sets

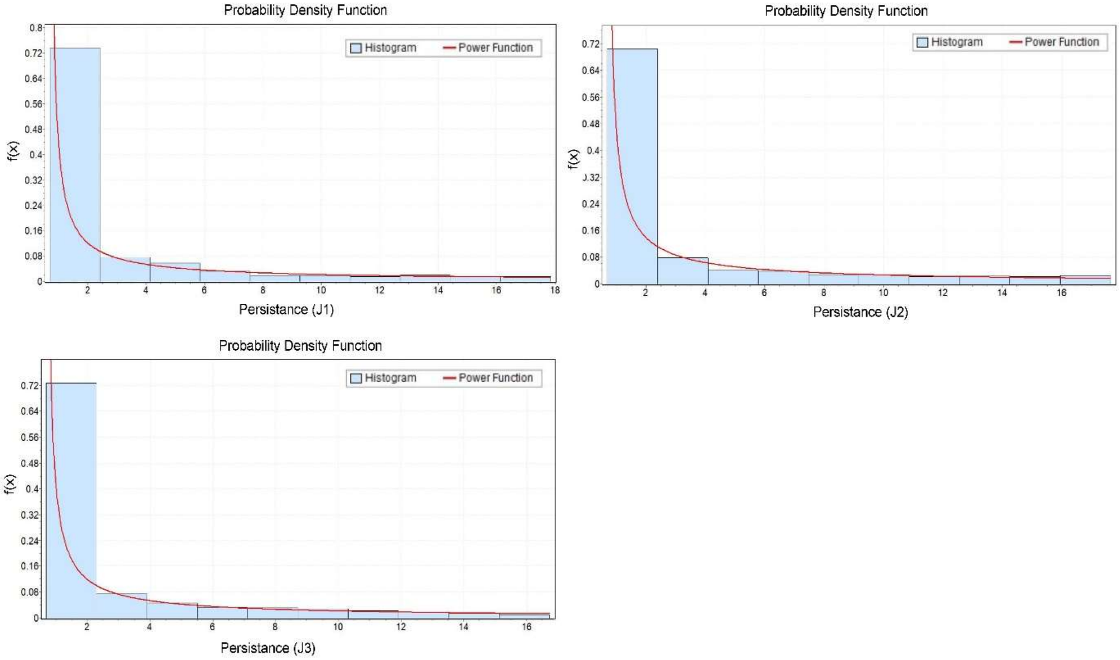

Figure 7. Power probability distribution function for trace length in the main discontinuity sets

To determine the fracture plane dimensions in the 3D model, the trace length *(l)* per unit area (m^2) in each main fracture set was plotted against the fracture size density distribution *n(l),* as shown in Figure 8. As depicted, the logarithmic plot of *n(l)* versus *l* exhibited a straight-line relationship, confirming the power probability distribution function. The slope of this graph determines the exponent scale (a), which defines the ratio between the model's smallest and largest fracture sizes. For fracture sets JS_1, JS_2, and JS_3, the calculated exponent scales for building the DFN model were 2.4, 2.3, and 2.5, respectively.

The finding that trace lengths follow a power distribution function for all major fracture sets is highly significant. This type of distribution is characteristic of many small and significant numbers of very large natural fracture systems (Itasca, 2016). This has profound implications for both the mechanical stability and hydrological connectivity of the rock mass. The calculated power-law exponents (a) of 2.4 (JS1), 2.3 (JS2), and 2.5 (JS3) are consistent with the generally accepted range for geological fracture networks (typically between 1 and 3.5, with a common value around 2). The slightly higher values for JS1 and JS3 (2.4, 2.5) suggest a relatively higher proportion of smaller fractures compared to very large ones within those sets; however, large fractures are still present and contribute significantly to overall connectivity and the potential for large-scale block formation. These exponents are critical inputs for accurately modeling the fracture network's heterogeneity and ensuring the DFN captures the full range of fracture sizes present at the Pirtaghi Dam site.

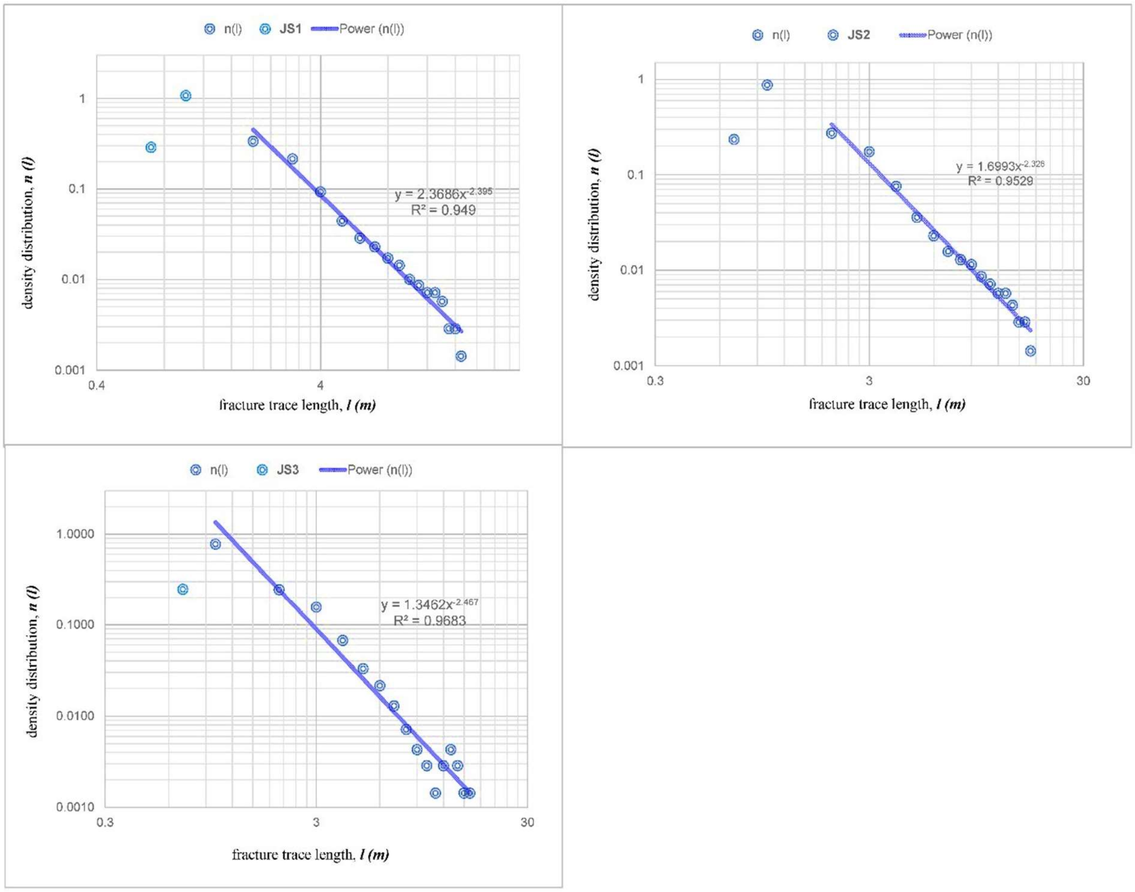

Figure 8. Fracture length density distribution function calculated for main fracture set (JS1, JS2 and JS3) using a power law length distribution with an exponent (a) = 2.4, 2.3, 2.5.

Density and Location of Joints

To create the DFN model within the rock mass abutments, the fracture volumetric intensity (P_{32}), expressed in m2/m3, was calculated for each main fracture set using Equation 3 (Wang, 2005), based on the determined orientation and spacing parameters. The calculated P_{32} values for discontinuity set JS_1, JS_2, and JS_3 were 2.3, 1.8, and 1.5 m2/m3, respectively. The detailed determination of P_{32} for each main fracture set is shown in Table 2.

The calculated P_{32} values represent the total fracture surface area per unit volume of rock, providing a quantitative measure of fracture intensity. The P_{32} values of JS_1, JS_2, and JS_3 indicated that JS_1 was the most pervasive fracture set in terms of overall area density, followed by JS_2 and JS_3. This aligned with the relatively smaller mean spacing observed for JS_1 in Table 1. These P_{32} values are crucial for generating a realistic 3D DFN model, as they directly control the overall "fracture density" in the simulated volume. Higher P_{32} values generally correlate with a higher degree of rock mass fracturing, potentially leading to more fragmented rock blocks and increased hydraulic conductivity. These site-specific values reflect the complex fracturing processes within the volcanic units of the Pirtaghi Dam site, serving as fundamental inputs for subsequent geomechanical and hydrological simulations.

Discrete Fracture Network Model Generation

The DFN method employed here is a specific discrete solution where the main fractures are explicitly represented in the model by specifying their location, dip, and dip direction. This method is based on two fundamental factors: the fracture geometry system and individual fracture extension (Jing & Stephansson, 2007). Figure 9 illustrates the overall procedure of the proposed DFN–DEM multi-scale modeling approach using 3DEC software.

The general stochastic DFN approach assumes fractures to be straight lines (in 2D) or planar discs/polygons (in 3D), treating their geometrical properties (e.g., position, frequency, size, orientation) as independent random variables (Lei et al., 2017). Fracture geometry was reproduced based on stochastic simulation of the fracture sets and their associated probability density functions, derived from field sampling results at the Pirtaghi Dam site (Tables 1 & 2), utilizing the Monte Carlo simulation method (Jing & Stephansson, 2007). In this model, each major discontinuity was represented as a disk-shaped plane with a limited number of discrete points. The same generation process was repeated for all main fracture sets, forming a comprehensive DFN model. Figure 10 visually presents the simulation of each main discontinuity and the resulting 3D fracture network developed for the Pirtaghi Dam site. The Monte Carlo algorithm, a computational method that uses random sampling, is employed to estimate numerical results. This simulation performed for problems where the role of the time factor is unimportant and offers a straightforward application compared to other probability analysis methods. In this method, the final function is simulated using the probability distribution of variables, and numerical results are estimated based on random sampling and statistical analysis (Baecher & Christian, 2005).

Table2. Determination of volumetric intensity in the main fracture sets in the dam site

Joint Set	**Dip**	**Dip Direction**	**Spacing (mean)** *d (cm)*	**1d intensity (m^{-1})** $P_{10}=1/d$	**Conversion Factors** $C_{13} = \frac{1}{a\cos(b\rho) + c}$	**3d intensity (m^3)** $P_{32}=C_{13}.P_{10}$
JS1	28	144	51.47	1.94	1.16	2.3
JS2	82	028	73.26	1.36	1.34	1.8
JS3	73	301	82.01	1.22	1.26	1.5

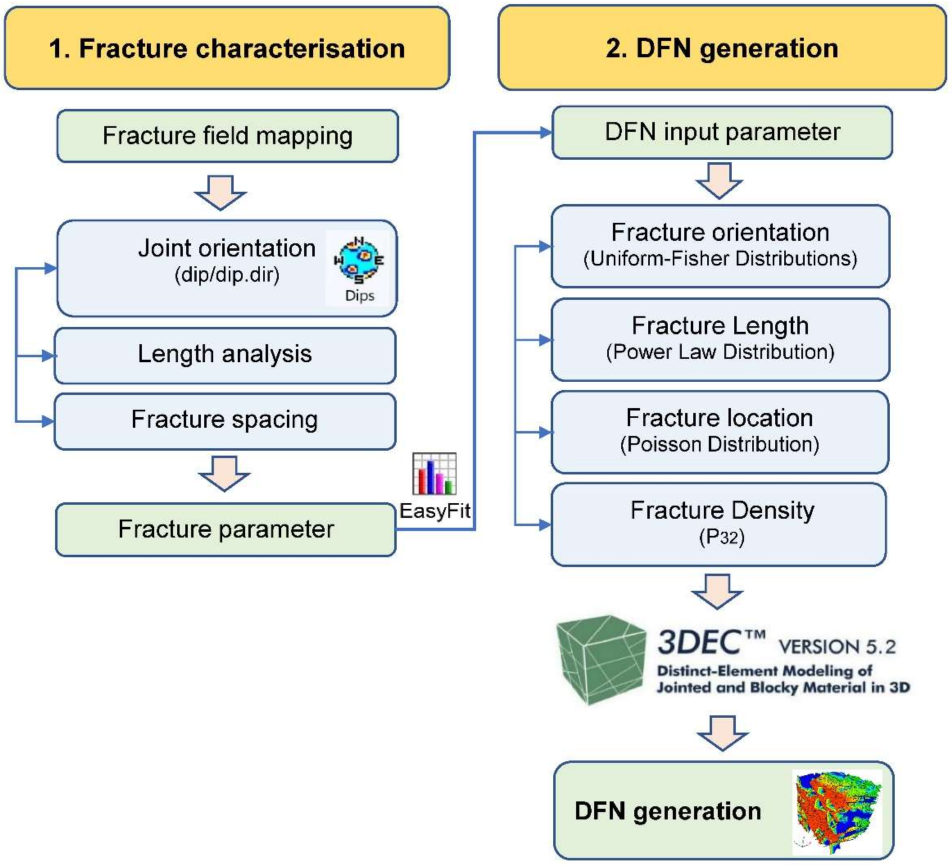

Figure 9. The main procedure of the proposed DFN–DEM multi-scale modeling approach

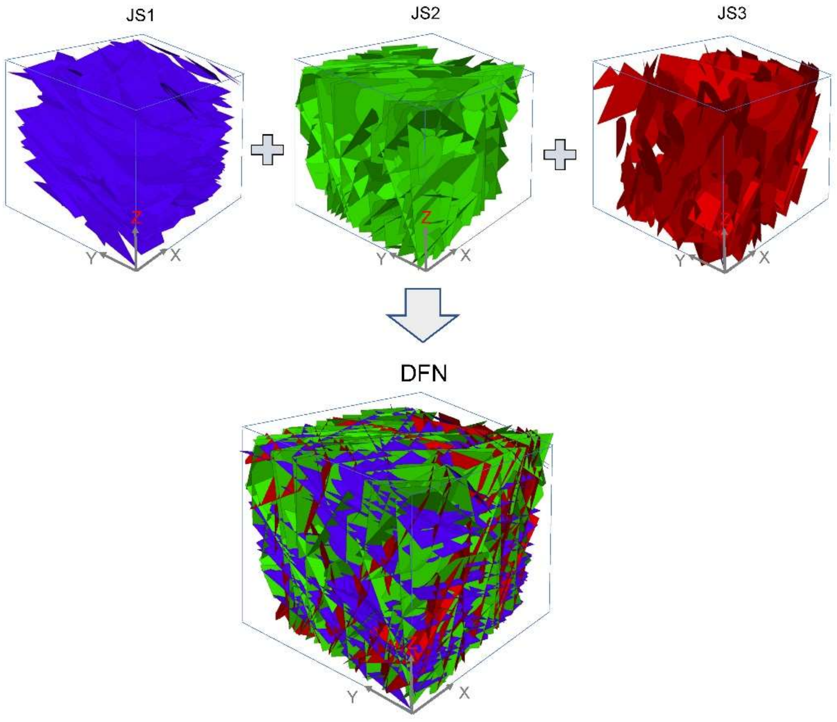

Figure 10. Assign Fractures characterization for DFN-DEM simulation with 3DEC code

The generated 3D DFN model for the Pirtaghi Dam site, built upon the statistically derived fracture parameters (Tables 1 and 2), provides a geometrically realistic representation of the rock mass's discontinuity network. The use of 3DEC software, which allows for explicit modeling of discrete fracture geometries as disk-shaped planes (Figure 10), is a significant advantage over simplified continuum approaches. This model accurately incorporates the observed stochastic variability in fracture orientation, length, spacing, and density. The accuracy of this DFN, driven by the site-specific PDFs, enables more reliable geomechanical analyses by accurately depicting potential block sizes and kinematics.

Model Validation

To ensure the representativeness and reliability of the generated DFN model, a comprehensive validation process was undertaken. This approach involved a comparison between the stochastic characteristics of the discontinuities generated within the DFN model and the field-measured statistical parameters (orientation, frequency, length, and density) that served as inputs. For fracture orientation, Stereonet plots of the modeled fracture sets visually confirmed the accurate reproduction of the dominant dip directions and dip angles observed in the field data (Figure 4). Furthermore, Kolmogorov-Smirnov (K-S) tests (as detailed in Section 4.1) were employed to quantitatively compare the probability density functions of the generated fracture lengths and spacings with their respective empirically derived distributions showed no statistically significant differences at a 95% confidence level, indicating a strong compliance. Therefore, the DFN model successfully replicates the statistical properties of the rock mass discontinuities at the Dam site, providing confidence in its ability to represent the actual geological conditions and geotechnical analyses. The developed DFN model for the Dam site offers significant practical applications for various engineering geological and geotechnical aspects.

This model primarily provides a statistically representative framework for conducting advanced stability analyses of the dam abutments, reservoir slopes, and any associated underground excavations such as tunnels. By accurately capturing the geometry and connectivity of the discontinuity networks, the DFN model can be integrated into numerical simulations to predict potential failure mechanisms, and optimize support system designs, thereby enhancing the overall safety and cost-effectiveness of construction and operation (Mensah et al., 2025). Moreover, the DFN model is invaluable for hydrogeological assessments, enabling more precise predictions of groundwater flow paths and seepage rates through the dam foundation and abutments. It allows for a more accurate assessment of hydraulic conductivity anisotropy and fluid flow pathways within the fractured rock mass, which is critical for dam seepage analysis (Zimmerman & Paluszny, 2023). The Monte Carlo simulation approach ensures that the model captures the inherent uncertainty and variability of natural fracture systems, providing a robust framework for subsequent detailed engineering analyses of the Dam foundation and abutments. This approach significantly enhances the reliability of predictions compared to models based on less detailed or generalized fracture characterization.

Conclusions

This research successfully developed a three-dimensional stochastic discrete fracture network (DFN) model for the main discontinuity sets within the rock mass of the Pirtaghi Dam site. This was achieved through a comprehensive study involving extensive geological field mapping, precise statistical analysis of discontinuity geometry, and subsequent Monte Carlo simulation for DFN generation within the 3DEC software environment. The detailed field investigation and statistical analysis revealed critical stochastic characteristics of the main discontinuity sets

(JS_1, JS_2, and JS_3). Our findings demonstrate that:

The orientation components (dip direction and dip angle) of the discontinuities consistently follow uniform and Fisher distributions, respectively.

The trace length of these fractures conforms to a power distribution characterized by scaling exponents ('a') of 2.4, 2.3, and 2.5 for JS_1, JS_2, and JS_3, respectively. These values are typical for natural fracture networks and were crucial inputs for accurately representing fracture size variability in the stochastic DFN model.

The three-dimensional volumetric intensity (P_{32}) values for the main discontinuity systems were quantitatively determined as 2.3 m^2/m^3 for JS_1, 1.8 m^2/m^3 for JS_2, and 1.5 m^2/m^3 for JS_3, that considering the measured spacing, linear density, Fisher distribution parameters, and conversion factors.

These findings underscore the critical importance of characterizing the stochastic nature of fracture geometric parameters. The derived probability density functions and quantitative parameters (P_{32} and scaling exponents) provide essential and reliable inputs for creating numerical models that realistically represent the complex, heterogeneous in-situ rock mass conditions at the Pirtaghi Dam site. The developed DFN model is therefore well-suited to serve as a fundamental concept for subsequent advanced numerical analyses, such as those required for assessing dam stability, evaluating potential failure mechanisms, and predicting stress-seepage coupled behavior in this jointed rock formation. This integrated approach and its resulting detailed characterization are expected to contribute significantly to more accurate and reliable geotechnical designs for dam projects and similar infrastructure in discontinuous rock masses.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors' contributions

All authors contributed to the study's conception and design. Material preparation, data collection, and analysis were performed by Ehsan Motamed-Shariati. The first draft of the manuscript was written by Ehsan Motamed-Shariati and other authors commented on previous versions of the manuscript. All authors read and approved the final manuscript and contributed equally to this work.

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