Shahrood University of Technology

Journal of Mining and Environment (JME)

Journal homepage: www.jme.shahroodut.ac.ir

Iranian Society of Mining Engineering (IRSME)

The Effect of Non-persistent and Persistent Joint Angles on the Representative Elementary Volume Rock Mass Based on Strength

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Article Info

Received 16 June 2024

Received in Revised form 22 July 2024

Accepted 25 August 2024

Published online 25 August 2024

DOI: 10.22044/jme.2024.14677.2774

Keywords

Representative elementary volume

Persistent, Non-persistent

Jointed rock masses

Joint angles

Discrete element method

Abstract

Unlike the mechanical properties of intact rock, which can be obtained on a laboratory scale, estimating the mechanical properties of the jointed rock mass is very difficult due to the presence of different joints and the complexity of the joints. Therefore, to calculate the mechanical parameters of the jointed rock mass and use the continuous media theory of the jointed rock mass, it is necessary to calculate the Representative Element Volume (REV) of the rock mass. In this study, the Discrete Element Method (DEM) and the mechanical index of strength were used to investigate the effect of persistent and non-persistent joint angles, as well as model size on the REV in x, y, and z directions. The numerical results showed that by changing the joint angles and side length, both the strength and the REV of the rock mass were affected. The maximum representative side length for the persistent joint in the x and z directions occurred at angles of 60° and 75°, respectively. The minimum strength was obtained for joints in the x and z directions at a 45° angle. Finally, the REV for persistent and non-persistent joints is calculated as 10*0.5*8m and 4*0.5*4m, respectively.

1. Introduction

The mechanical parameters of rock mass, influenced by the presence of natural joints, exhibit complex behavior. These parameters' values vary with the jointed volume of the investigated rock and these variations stabilize above the critical value, known as the Representative Elementary Volume (REV) [1].

Alejano et al. [2] have demonstrated that the mechanical properties of rock mass are considerably affected by rock mass size. As the dimensions of the model increase, substantial changes are created in these properties. However, beyond a certain dimension, these properties are no longer influenced by sample size. This specific size is termed the REV, and it is crucial to consider this volume to obtain accurate results of the rock mass properties [2]. The presence of the REV allows for replicating the representative mechanical behavior of jointed rock mass. With this understanding, continuous media theory can be aptly employed in the analysis of jointed rock masses [3, 4]. Figure 1 shows the concept of the REV of rock mass properties.

Researchers have suggested various indicators to estimate the size of the REV. These indicators can be categorized into three groups: hydraulic, geometrical, and mechanical.

Hydraulic indicators are used for projects related to water flow conditions. Permeability tensor, average block permeability, permeability coefficient and hydraulic conductivity are hydraulic indicators provided by researchers [5-10].

Geometrical and mechanical indicators are also applicable to a wide range of engineering endeavors. Deformation modulus, Poisson's ratio, uniaxial compressive strength, damage coefficient, shear modulus of fracture intensity, blockiness,

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ratio of micro-cracks, GSI and Geometrical connectivity are among the geometric and mechanical indicators provided by the researchers [4, 5,11-22].

Obtaining real results regarding the mechanical properties of jointed rock mass through laboratory tests proves immensely challenging, if not impossible. This difficulty arises due to the limitation related to the model size in laboratory tests [23]. The interpretation of in-situ tests poses additional challenges, primarily due to the hidden nature of fractures and the absence of precise boundary conditions. Moreover, time and economic constraints make the process more difficult [24].

Therefore, numerical simulations have been widely used to determine the properties of large-scale rock masses. This involves an upscaling procedure where variations in mechanical properties are estimated as the size of the analyzed rock volumes increases, ultimately reaching the REV size.

Figure 2 shows three types of joints: intermittent, persistent and non-persistent [25]. Intermittent joints are geologically improbable and intermittent joints should be considered persistent during mechanical analysis [26]. Additionally, the persistent joints do not match the real and natural conditions of the rock mass [27, 28]. Therefore, the most appropriate approach is to consider the persistent characteristics of the rock mass joints as non-persistent joints [26, 29].

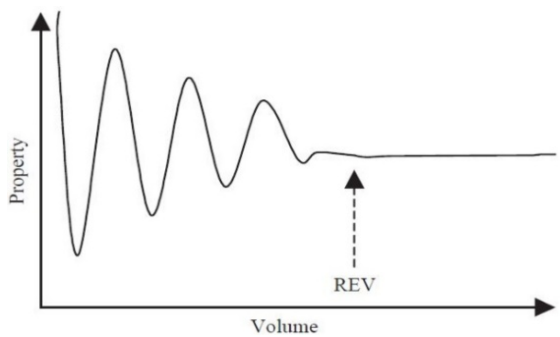

Figure 1. Representative elementary volume [1]

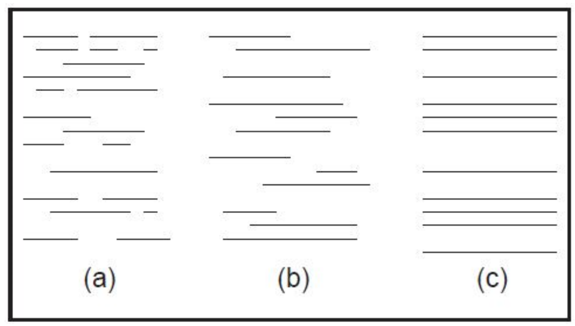

Figure 2. Traces of (a) intermittent, (b) non-persistent (c) persistent joints [25]

The purpose of this paper is to investigate the effect of different persistent and non-persistent joint angles on the REV using the mechanical index of uniaxial compressive strength. Previous studies have not investigated the effect of different persistent and non-persistent joint angles on the REV of the rock mass. The previous studies conducted have focused on the modeling of joints using the DFN-DEM method, in which the joints are applied randomly in the modeling, so it is not possible to investigate the effect of the joint angles. In this paper, the effect of joint angles of 0°, 15°, 30°, 45°, 60°, 75° and 90°, and the effect of persistent and non-persistent joint angles on the REV was investigated using the mechanical index of uniaxial compressive strength, and finally the anisotropy of the REV was investigated. For this purpose, the widely used numerical method of Discrete Element (DEM) has been used due to the explicit representations of both the fracture system geometry and constitutive relations of intact rock and fractures. In a 3DEC analysis, the domain of interest is represented as an assemblage of rigid or deformable blocks, and the contacts between the blocks are identified and updated continuously during the entire deformation process.

2. Numerical Modeling

2.1. Loading procedure and model calibration

To determine the stress-strain curve and compute the maximum strength of jointed rock masses, a constant loading velocity (CLV) was imposed on the model boundaries (Figure 3a). In this study, to apply the suitable velocity in the modeling, the intact rock model underwent calibration using back analysis techniques under uniaxial compressive conditions. The results of the stress-strain curve were then adjusted to align with those obtained from uniaxial compressive strength (UCS) tests conducted in laboratory tests. Figure 3b illustrates the stress-strain curve derived from the numerical uniaxial compressive test for an intact rock model.

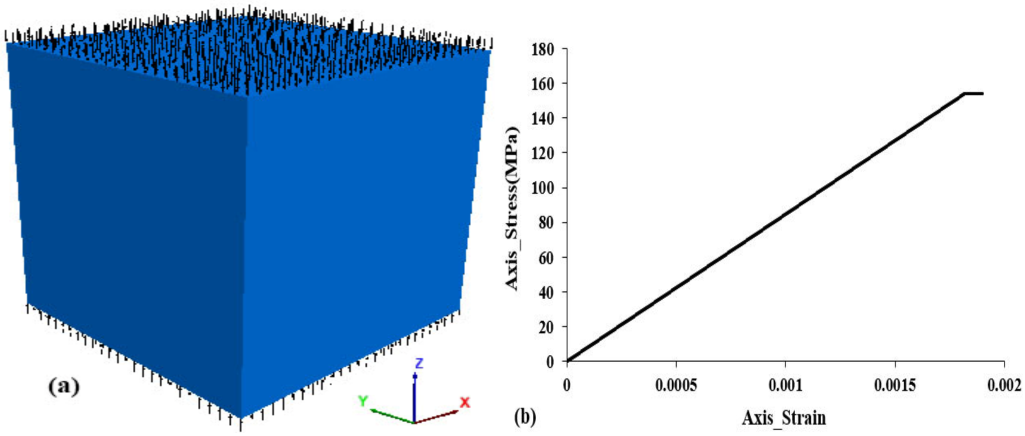

Figure 3. a) Intact rock numerical model under constant velocity loading; b) Stress-strain curve of intact rock in the UCS numerical simulation

2.2. Mechanical parameters and behavioral models

The physical and mechanical parameters about the intact rock, the granite matrix, and mechanical properties of joints that were used for modeling in 3DEC is shown in Table 1 and 2. This information was based on the laboratory test results reported in Sellafield site investigation, which was used in ref. [22]. Considering that the selection of input parameters in modeling plays a significant role in modeling results, in this study, input parameters have been selected, which have been used in many papers to conduct research. [5, 17, 20, 22, 23, 30, 31].

Table 1 presents the values of density (ρ), elastic modulus (E), Poisson's ratio (ϑ), uniaxial compressive strength (σ_c), cohesion (c), friction angle (φ) and dilation angle (ψ) of intact rock. Table 2 shows the values of parameters related to joints, such as normal stiffness (JKn), shear stiffness (JKs), joint cohesion (c_j), joint friction angle (φ_j), and joint dilation angle (ψ_j). It is assumed that all the joints possess identical mechanical properties.

As failure in jointed rock masses can occur not only in the joints but also in the intact rock, and then it may reach the joint, it is important to consider a behavior model for the intact rock that considers for the possibility of failure. In this study, the Mohr-Coulomb elastoplastic behavior model was used to determine the ultimate strength of the intact rock, which is expected to yield answers with less uncertainty. The Coulomb Slip Model was also used as the behavior model for the joints.

Table 1. Mechanical and Physical parameters of intact rock [22]

$\rho\,(kg/m^3)$	2750
E (GPa)	84.6
ϑ	0.24
σ_c (MPa)	157
C (MPa)	28
φ(deg)	50
ψ(deg)	8

Table 2. Mechanical parameters of joints [22]

$JKn\,(GP/m)$	434
$JKs\,(GP/m)$	434
c_j(MPa)	5
φ_j(deg)	24.9
ψ_j(deg)	5

2.3. DEM models

To investigate the effect of joint angles on the REV of rock masses, the mechanical parameters in Tables 2 and 3 were used to generate DEM models. The joint angles were generated from 0° to 90° and each step increased by 15°, and the dip direction was fixed at 90° for all modeling steps, also the joint spacing was 5 cm. The model dimensions were chosen 0.5, 1, 2, 4, 6, 8, 10, 12, 14, and 16 m, as shown in Figure 4.

To investigate the effect of non-persistent joint angles on the rock mass REV, the joints generated only increased up to 1 m in length, and the joint length did not increase with the dimensions of the model (Figure 5).

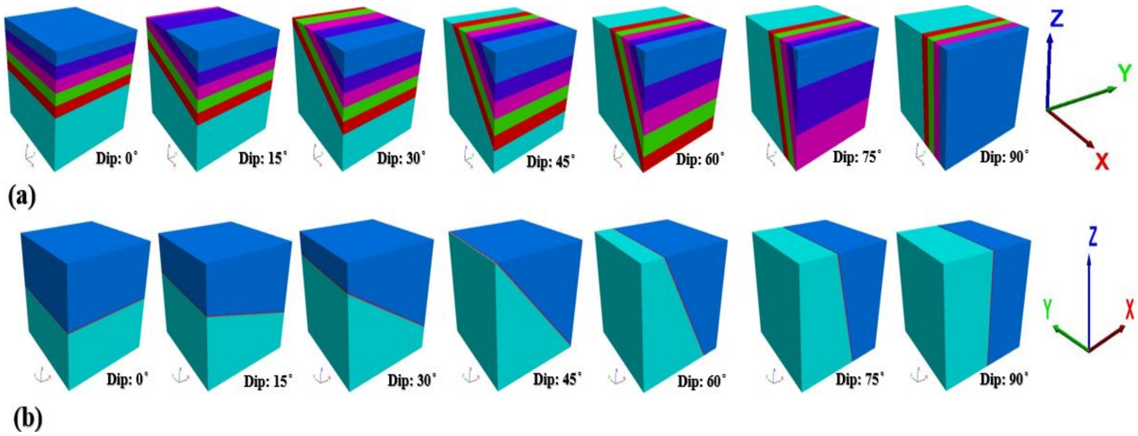

Figure 4. Specimens used to study the REV of persistent joint; a) model size 0.5m; b) model size 16m

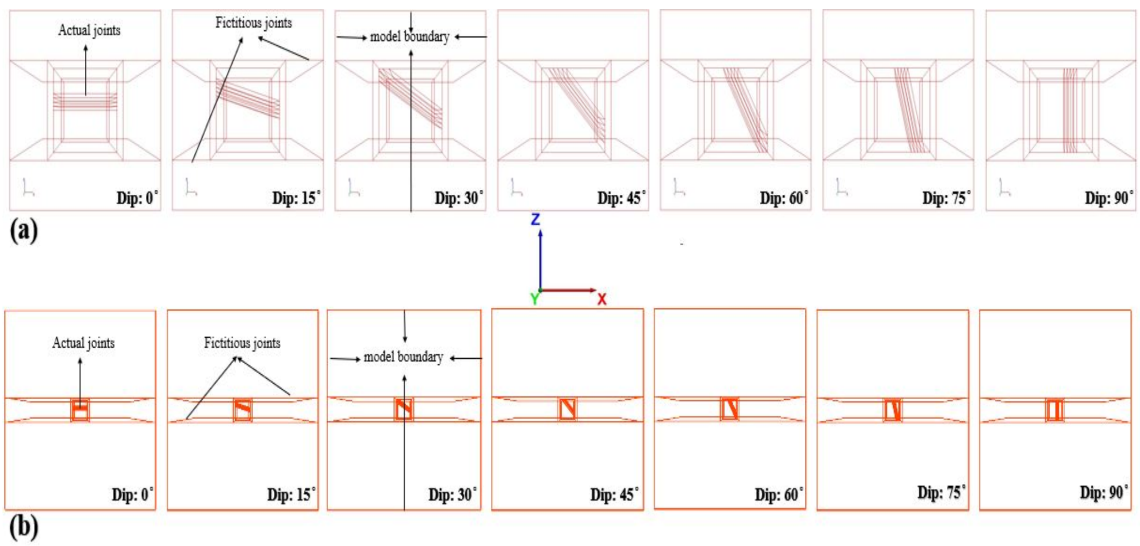

Figure 5. Specimens used to study the REV of non-persistent joint; a) model size 2m; b) model size 16m

2.4. Model monitoring and stress and strain measurement

To create the stress-strain curve and compute the peak strength of jointed rock masses where the velocity is applied, it is essential to record the displacements and stresses of the monitoring points on all faces during the application of velocity. For this purpose, a FISH function was developed and integrated into the discrete element models. This function records the normal stress in all block areas and calculates its average as the applied stress. Additionally, to calculate the displacement of the points and the rate of normal strains, the points were symmetrically placed on each face of the model, with one point every 25 cm on each side of the cube. Figure 6 illustrates the positioning of the monitoring points in a 1m model for the use of velocity monitoring techniques during compression tests.

3. Results and Analysis

3.1. Determining the REV of persistent joints based on UCS

Figure. 7 shows the effect of model size and joint angles on the uniaxial compressive strength (UCS) in the x direction. Based on Figure 7, at joint angles of 0° and 90°, the REV of the rock mass is 0.5 m. With the increase in the model size, the UCS increases in the x direction and after a certain size, the UCS remains constant. For joint angles of 15°, this size is 8m. The REV can be considered 6m for joint angles of 30° and 45°. For joint angles of 60° and 75°, the REV is 10 and 1m, respectively.

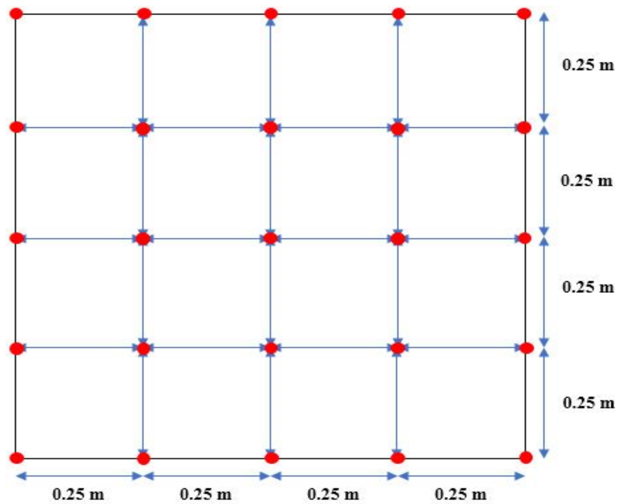

Figure 6. model with size of 1m×1m and position of monitoring point

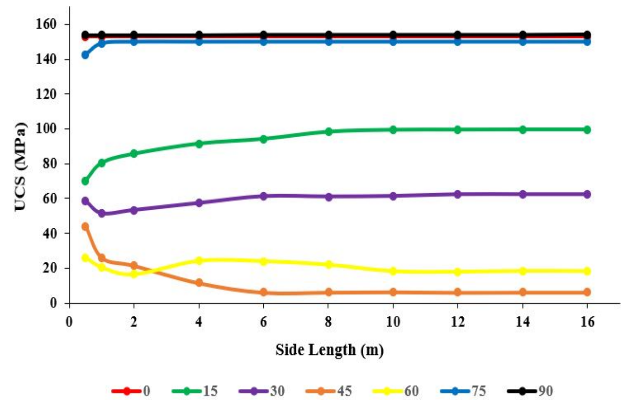

Figure 7. Effects of model size and persistent joint angles on the UCS in the x direction

The effect of joint angles on the REV was investigated in the z direction. According to Figure 8, at joint angles of 0° and 90°, the REV of the rock mass is 0.5 m. At the joint angle of 15°, the REV can be considered 1m in the z direction. For angles of 30°, 45°, and 60°, the side length was calculated 6m as the REV. The side length of the 8m can also be considered for the joint angle of 75°. The effect of joint angles was also investigated in the y direction. The results showed that the dip and dip direction of the joints had no effect on the UCS, and for all dimensions, the REV 0.5m was obtained.

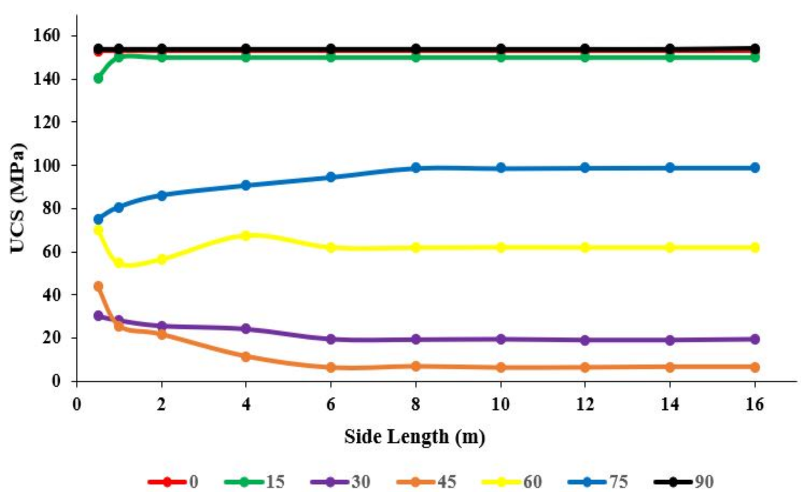

Figure 8. Effects of model size and persistent joint angles on the UCS in the z direction

Based on the results of REVs of the UCS for various joint angles, curves have been created as shown in Figure 9 and 10. Investigations show that the maximum REV is 10m in the x direction, which occurs at the joint angle of 60°, and the minimum REV was calculated at the angles of 0° and 90°, as shown in Figure 9.

As shown in Figure 10, the joint angle of 45° has the maximum effect on the UCS in the x direction, decreasing the rock mass strength by 25 times compared to the intact rock. Joint angles of 0° and 90° also have the minimum effect on the UCS in the x direction. According to Figure 11, the maximum REV in the z direction is 8m, which occurs at the joint angle of 75°. The minimum REV occurs at the angles of 0° and 90°, which is 0.5m. Similar to the x direction, the minimum effect of the joint angle on the UCS is related to the angles of 0° and 90°, and the maximum effect occurs at an angle of 45°, as shown in Figure 12.

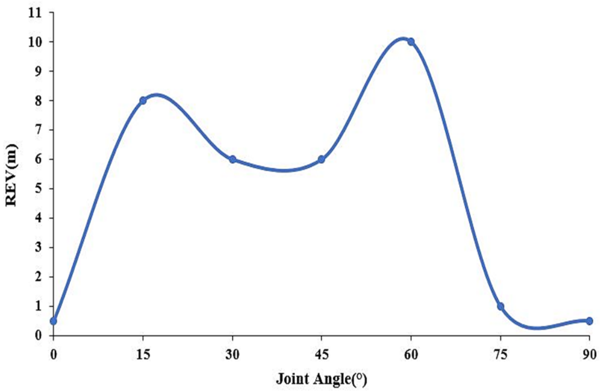

Figure 9. The effect of the persistent joint angles on the REV in the x direction

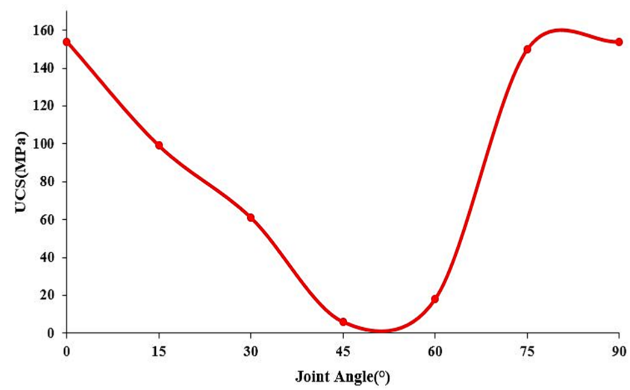

Figure 10. The effect of the persistent joint angles on the UCS in the x direction

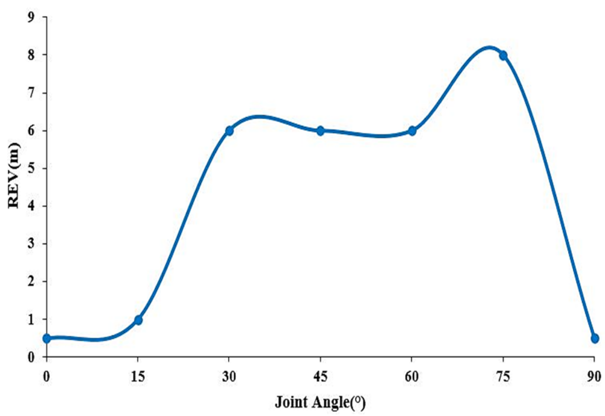

Figure 11. The effect of the persistent joint angles on the REV in the z direction

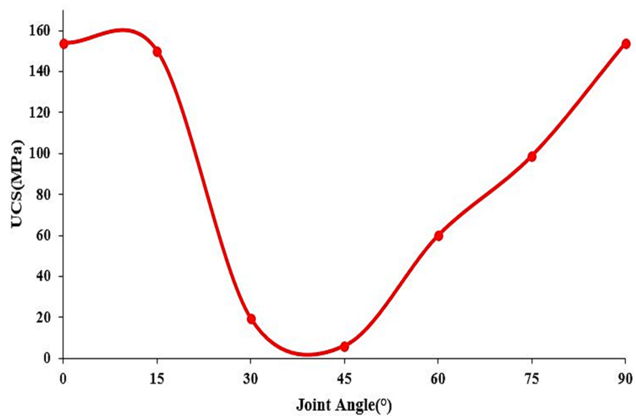

Figure 12. The effect of the persistent joint angles on the UCS in the z direction

3.2. Determining the REV of non-persistent joints based on the UCS

According to the Figure 5, the persistence of joints for all the models generated in this study is considered to be 1m. However, a typical non-persistent joint network in 3D may not discretize the block into a polyhedron. Therefore, it was necessary to create some fictitious joints. By combining these fictitious joints with the actual joints, the block was discretized into a polyhedron. The values of the fictitious joints were set to high, so that slipping and failure would not occur in these fictitious joints. The characteristics of Table 3 were used to add fictitious joints to the model.

Similar to persistent joints, the REV of 0.5 m is suitable for the joint angle of 0° and 90°. An increase in the side length of more than 4m at a joint angle of 15° has little effect on the UCS; therefore, the REV is considered to be 4m. For joint angles of 30°, 45°, and 60°, the REV is also 4m in the x direction. For an angle of 75°, this value is 1m in the x direction (Figure. 13). Figure 14 shows the effect of non-persistent joints on the REV in the z direction. According to the figure, the REV is 1m for joint angles of 15°. An increase in the dimensions of more than 4m at joint angles of 30°, 45°, 60° and 75° has little effect on the UCS; therefore, the REV is 4m. The REV of the model is 0.5m for angles of 0° and 90° in the z direction. The effect of joint angles in the y direction in the case of the non-persistent joint is obtained like persistent joints and the same value was calculated for all dimensions and the REV was 0.5m.

Table 3. Fictitious joints mechanical Parameters

JKn(GP / m)	5000
JKs(GP / m)	2000
c_j(MPa)	70
t_j(MPa)	50

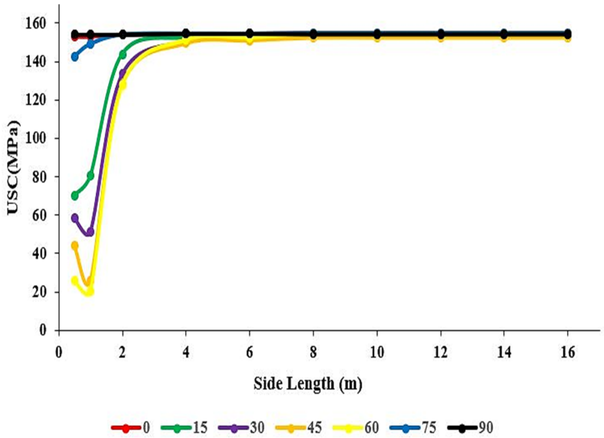

Figure 13. Effects of model size and non-persistent joint angles on the UCS in the x direction

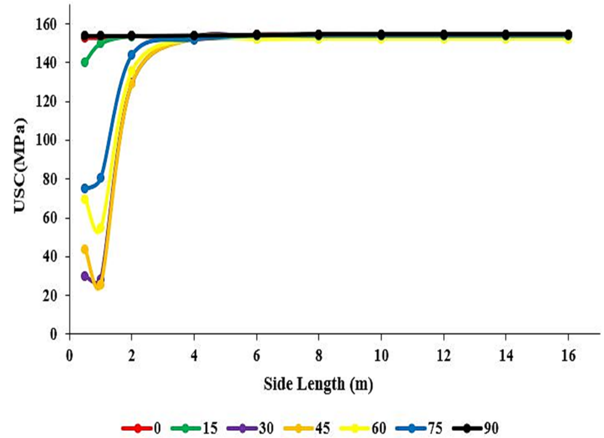

Figure 14. Effects of model size and non-persistent joint angles on the UCS in the z direction

Based on the results of REVs of the UCS for various joint angles, the maximum REV in the x direction is 4m, which occurs at joint angles of 15°, 30°, 45°, and 60°. In comparison, the minimum REV is 0.5m, occurring at angles of 0° and 90°, as shown in Figure 15. Considering that the persistence of joints is only 1m and with the increase of the model size, the trace length of the joint does not increase, the UCS of jointed rock mass has not decreased significantly, and the UCS at the angle of 45° was calculated 148 MPa (Figure. 16).

In the z direction, the maximum REV is also 4m, occurring at angles 30°, 45°, 60° and 75° and the minimum REV is 0.5m, occurring at angles of 0° and 90°, as shown in Figure 17. Similar to the x direction, the UCS was also investigated, and the results showed that the minimum UCS is 151 MPa, which occurs at an angle of 45° and does not have a significant effect on the rock mass strength (Figure. 18).

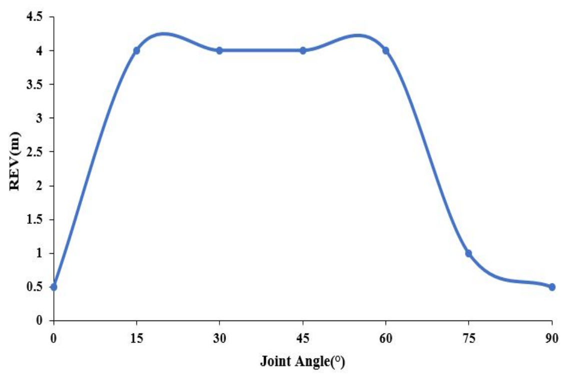

Figure 15. The effect of the non-persistent joint angles on the REV in x direction

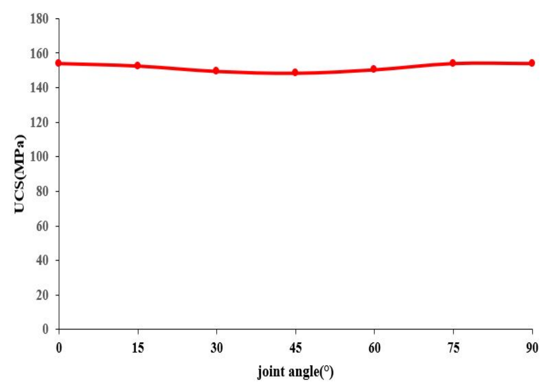

Figure 16. The effect of the non-persistent joint angles on the UCS in the x direction

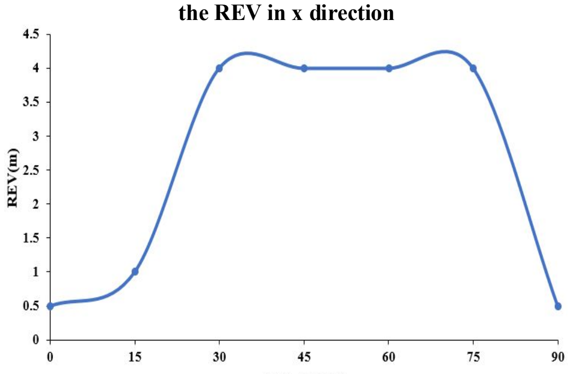

Figure 17. The effect of the non-persistent joint angles on the REV in the z direction

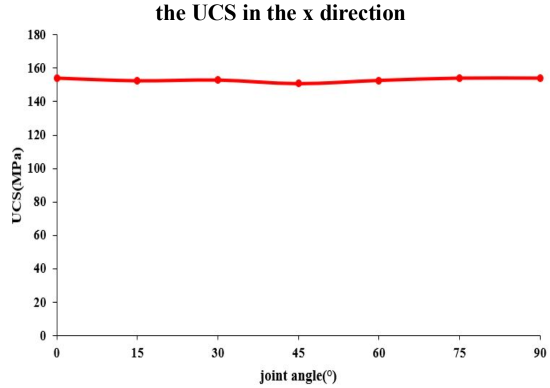

Figure 18. The effect of the non-persistent joint angles on the UCS in the z direction

4. Conclusions

The model size and joint angles are two key characteristics of jointed rock masses. The effects of model size on the presence of REV are significant for the uniaxial compressive strength of jointed rock masses. Additionally, the UCS is influenced by joint angles and the direction of study. Consequently, the evaluation of REV based on joint angle and study direction may vary accordingly. The DEM was employed for numerical simulation of UCS tests with sizes of model 0.5, 1, 2, 3, 4 to 16m and joint angles of 0°, 15°, 30°, 45°, 60°, 75° and 90° and for persistent and non-persistent states. The results indicate that the UCS and REV of jointed rock masses are interdependent on both the model size and joint angles. The investigations carried out on 210 models for the persistent joint showed that the joint angles of 0° and 90° had the minimum effect on the REV of the jointed rock mass and are not affected by the loading direction. On the other hand, at the joint angle of 15°, when the sample is loaded in the x direction, the REV is of 8 m, while at this joint angle, when the loading is in the z direction, the REV of the rock mass is 1m; similar to this situation, it is observed in the joint angle of 75°, and the REV in the joint angle is 1m in loading in x direction, and 8m in loading in the z direction. For the joint angles of 30° and 45°, the REV of the rock mass, regardless of the loading direction, was calculated as 6 m. For the joint angle of 60°, the effect of the loading direction on the REV was also observed. Loading in the y direction for the joint angles in this study had the minimum effect on the REV of the jointed rock mass, and the REV in this direction was calculated for all angles of 0.5m.

Investigations carried out on the UCS in the persistent joints showed that the joint angles of 0° and 90° had the minimum effect on the UCS of the jointed rock mass in the x and z directions, and the strength at these angles is approximately equal to the UCS of intact rock. The results of the UCS modeling in the REV showed that the joint angle of 15° in the x direction, decreasing the UCS by 1.6 times compared to the intact rock, while for the z direction, this strength decrease value is obtained at an angle of 75°. By increasing the angle of the joint to 30°, the strength of the jointed rock mass decreased by 2.6 times compared to the intact rock in the x direction, while this decrease was obtained for the joint angle of 60° in the z direction. Based on the results of modeling the UCS of the jointed rock mass, at the joint angle of 60° in the x direction, the UCS decreases by 8.2 times compared to the intact rock, while this decrease is at the angle of 30° in the z direction. The joint angle of 45° had the maximum effect on the UCS in the x and z directions, resulting in the minimum strength values. The UCS in this joint angle also decreased by 25 times compared to the intact rock, which showed the maximum decrease among the joint angles. Loading in the y direction showed the same effect on the UCS for all joint angles and dip direction investigated in this study. Therefore, the REV of the jointed rock mass was considered 10*0.5*8 m, based on different study directions and different joint angles.

In the case of non-persistent joints, the trace length of the joint is considered to be 1m. The investigation of 126 models for non-persistent joints showed that the REV for the joint angles 15°, 30°, 45° and 60° in the x direction and 30°, 45°, 60° and 75° in the z direction were considered 4 times the length of the joint. The UCS of these angles is approximately 153MPa. This value is approximately equal to the strength of intact rock. This means that as the model size increases more than 4 times the joint trace length, the strength of the jointed rock mass approaches the value of the intact rock. Therefore, the REV of the jointed rock mass was considered 4*0.5*4m, based on different study directions and different joint angles.

In general, the investigations of the persistent joint angles showed anisotropy in the REV of the rock mass, while for the non-persistent joint angles, Because of the UCS of the rock mass reaches the strength of intact rock at 4 times of the trace length, and in this value, the REV of the rock mass is obtained, so anisotropy in the direction of in x and z was not observed for the non-persistent joint angles. the peak strength of the specimens shows a "U" shape change for the persistent joint angles and reach the minimum value when the angle is 45°.

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تأثیر زوایای درزه پایا و ناپایا بر حجم المان معرف توده سنگ براساس شاخص مقاومت فشاری تک محوره

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ارسال ۲۰۲۴/۰۵/۱۶، پذیرش ۲۰۲۴/۰۸/۲۵

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چکیده:

برآورد خواص مکانیکی توده سنگ درزه دار بر خلاف خواص مکانیکی سنگ بکر که در مقیاس آزمایشگاهی قابل محاسبه است؛ به دلیل ماهیت پیچیده درزه ها بسیار دشوار است. بنابراین برای محاسبه پارامترهای مکانیکی توده سنگ درزه دار و استفاده از روش پیوسته معادل توده سنگ درزه دار لازم است حجم المان معرف توده سنگ درزه دار محاسبه شود. در این مطالعه، از روش المان گسسته و شاخص مکانیکی مقاومت فشاری تک محوره برای بررسی تاثیر ابعاد مدل و زوایای درزه پایا و ناپایا بر حجم المان معرف توده سنگ درزه دار استفاده شد. نتایج عددی نشان داد که با تغییر زوایای درزه و افزایش طول مدل، مقاومت و حجم المان معرف توده سنگ تحت تأثیر قرار می‌گیرد. حداکثر طول المان معرف برای درزه پایا در جهت x و z به ترتیب در زوایای ۶۰ درجه و ۷۵ درجه محاسبه شد. برای جهت های x و z حداقل مقاومت نیز در زاویه ۴۵ درجه به دست آمد. در نهایت، حجم المان معرف برای درزه های پایا ۱۰ متر در جهت x، ۰/۵ در جهت y و ۸ متر در جهت z محاسبه شد. برای درزه ناپایا نیز حجم المان معرف در جهت x و z ، ۴ متر و در جهت y ۰/۵ متر محاسبه شد

کلمات کلیدی: حجم المان معرف، درزه های پایا، درزه های ناپایا، توده سنگ درزه دار، زوایای درزه، روش المان گسسته.