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The Crack Propagation in Different Rock Types: A Comparative Seismic Simulation

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Abstract

The presence of a preexisting crack in a rock can affect its stability during seismic events, leading to reduced strength and stiffness. This study, which aims to examine how different types of preexisting fracture angles and the mechanical properties of the rock impact real-time cracking propagation modes and crack propagation shape, has practical implications. The researchers used ABAQUS software to apply simulated seismic loading to their model and studied crack propagation using the extended finite element method (XFEM). They found that the crack propagation shape and real-time cracking propagation vary based on the preexisting fracture angles and the mechanical properties of the rock. Additionally, they observed a significant relationship between strain leading to nonlinear deformations and the mechanical properties and fracture seismic toughness mechanism. These findings can be applied to improve the prediction of failure mechanisms in rocks with different crack shapes and could potentially enhance seismic response simulation and geotechnical earthquake engineering codes. The numerical simulation results were validated and compared to existing literature, further highlighting the practical applications of this study's findings.

Keywords: Preexisting Fracture; Mechanical Properties; Shearing Strength; Stress; Deformations.

1. Introduction

Various types of discontinuities can appear in rock masses, and the fissures can exist in different types and sizes [1]. The engineering properties of rock have been classified and applied in relation to the normal stress magnitude required for crack propagation [2]. A uniaxial compression test was conducted on limestone containing preexisting cracks, and displacement was observed using digital image correlation [3]. Cracks can extend in various shapes [4], and seismic loading complicates the prevention of crack propagation [5]. Suitable mathematical techniques are used for crack and displacement simulation [6]. However, the displacement of the rock with preexisting cracks is still a topic of consideration. This study underscores the need for further research on the displacement that accelerates the crack propagation of the model in order to gain a deeper understanding of its impact. Rocks with preexisting cracks exhibit varying crack growth patterns under uniaxial, biaxial, and triaxial loading [7]. When loading is applied to a model, the

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damage grows due to the fracture angle path [8], and the crack propagation complex process appears if other factors govern the crack propagation. The impact of crack propagation in different rock types must be investigated in terms of rock materials and seismic loading. Complications due to rock crack propagation necessitate simplifying the investigation with a cost-effective method that simulates any single stage of the model's crack propagation. In addition, applicable numerical simulation is required for collapse prediction to identify the relationship between crack propagation and model morphological modification under seismic loading. Therefore, the XFEM has been proposed in this study.

The fracture has been classified in the cracking process of the rock using acoustic emission and the photographic system, and the real-time cracking process of the cracking specimens has been monitored. Classification of the tensile and shear cracks has been introduced [9, 10]. In addition, in the experimental work on material like rock, the flexural, shear, and intermediate flexural-shear crack propagation has been classified for identifying failure mechanisms by observing the strain and stress relationship and shearing strength behavior of specimens during crack propagation [11]. The cracking classification is a complicated task; the crack occurs at three main stages: initiation, propagation, and coalescence. Generally, rock fracturing takes place in three forms: tensile, shear, and mixed-mode cracks [12]. Also, the crack may result in a devastative collapse or reduction of the structural service life [13], and the crack propagation types have different paths [14]; this phenomenon is clearly explained using Digital Image Correlation [15], acoustic emission (AE) rate-process theory [16], and extended finite element method [17]. During cracking, advanced monitoring methods must analyze the model's strength, deformation, and strain mechanism to identify active damage modes. The deformation of the rock with preexisting cracks under seismic loading in subjecting elastic deformation and the numerical simulation can be explained clearly.

The preexisting fracture on the rock is a widespread geological defect that appears in many regions [18, 19]. The mechanical properties of rock mass are vital parameters for predicting disaster and estimating stability analysis [20]. Consequently, several researchers have investigated using theoretical concepts, experimental laboratory performance, and numerical simulation based on variations in the mechanical properties of rock that lead to failure modes of parallel fracture mechanisms [21, 22]. This kind of geological defect can be used to predict the failure mechanism of the rock that may lead to landslides or unacceptable infrastructure settlement hazards.

Numerical simulation with suitable boundary conditions has commonly been applied in solving geotechnical engineering problems [23]. In predicting rock crack propagation, many previous studies rely on the final results of the parallel-fractured rock failure due to inaccurate numerical simulation boundary conditions, unsuitable experimental work analysis results, and ignoring other practical factors. Considering this limitation of the previous investigation, a suitable numerical simulation that provides a model-load response at any stage of the simulation is required to predict the real-time cracking modes in different types of rocks. In addition, when rocks with preexisting cracks are subjected to seismic acceleration, investigation of the impact of the mechanical properties of the rock on crack propagation aspects is still relatively insufficient. In addition, statistical analysis of the numerical simulation results needs to be conducted in association with the literature analysis.

ANN is applied to understand the impact of experimental work in geotechnical engineering [24-27]. Artificial Neural Networks (ANNs) consist of training, testing, and validation stages through different layers. XFEM has been used to maintain the quality of the primary data integrated with the prediction quality of the simulation. The maximum stress related to the end of the preexisting crack angle was predicted using ANN.

The main objectives of the present numerical simulation are as follows;

- To assess the impact of the preliminary status of the preexisting crack angle in different types of rocks.
- To predict the real-time cracking propagation modes in different types of rocks subjected to the seismic acceleration that leads to the model failure.

To estimate the impact of the mechanical properties of the rock on crack propagation aspects.

2. Material and Methods

The parameter variations affect the crack propagation toughness. The specific influence of fracture inclination was simulated with a quantified numerical simulation method. The developing failure mechanism of the simulated model was examined through strain evolution using the XFEM technique, and the main failure modes of models were classified considering the mechanical properties of the rock.

Figure 1 indicates the types of rock, the research method, and the factors considered in crack classification. The numerical simulation uses three types of rocks: sandstone, mudstone, and granite. A single rock type was selected for any of the simulated models. These three types of rocks have dissimilar mechanical properties. The mechanical properties of rocks used in the numerical simulation and the dimensions of the model subjected to the seismic acceleration are presented in Table 1. The mechanical properties and fracture angle are two main research parameters in crack propagation classification. The seismic acceleration applied to the model was constant for all numerical simulations to analyze the impact of mechanical properties in crack propagation. The real-time crack propagation for each model subjecting to the failure mechanism was studied. Based on the preexisting (primary) crack simulation, the propagated (secondary) cracks are simulated. The flexibility, damping, and inertia are related to the mechanical properties of the rock. Therefore, three types of rocks have been used to examine the relationship between crack propagation and the mechanical properties of the rock. Table 1 shows that the elastic mechanical properties of sandstone, mudstone, and granite have dissimilar values. The results of this simulation study have been compared to those of the available literature to confirm the results.

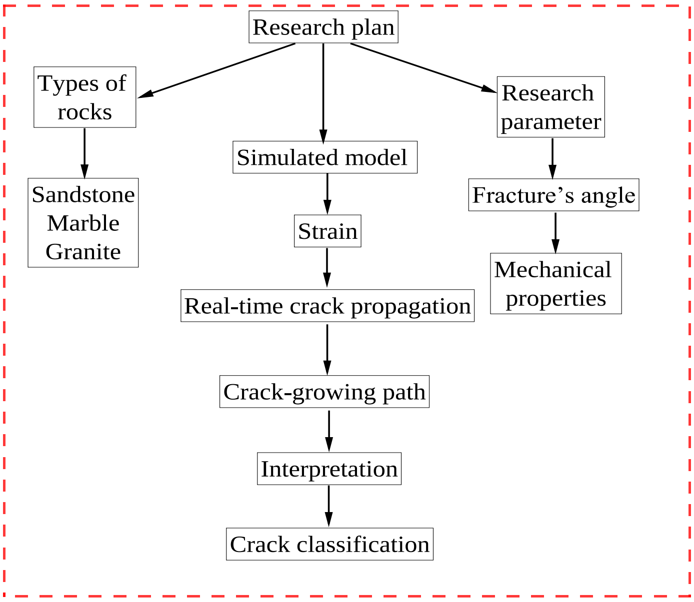


Figure 1. The Research Plan

Table 1. Mechanical properties of rocks used in the numerical simulation [28-30] and the dimension of the model subjected to the seismic acceleration

Rock type	Poisson's ratio, ν	Unit weight, γ (kN/m^3)	Modulus elasticity E (MPa)	Length (L) (mm)	Width (W) (mm)	Thickness (h) (mm)	Ref.
Granite	0.26	26.70	67500	400	400	40	Li et al. (2023) [28]
Sandstone	0.25	24	35000	400	400	40	Li et al. (2019) [29]
Mudstone	0.27	28	10000	400	400	40	Yu & Liu (2015) [30]

Figure 2 illustrates the ground acceleration of the Florina earthquake, which occurred in 2022 with a magnitude of 5.5 MWW at a depth of 10.0 km from the ground surface.

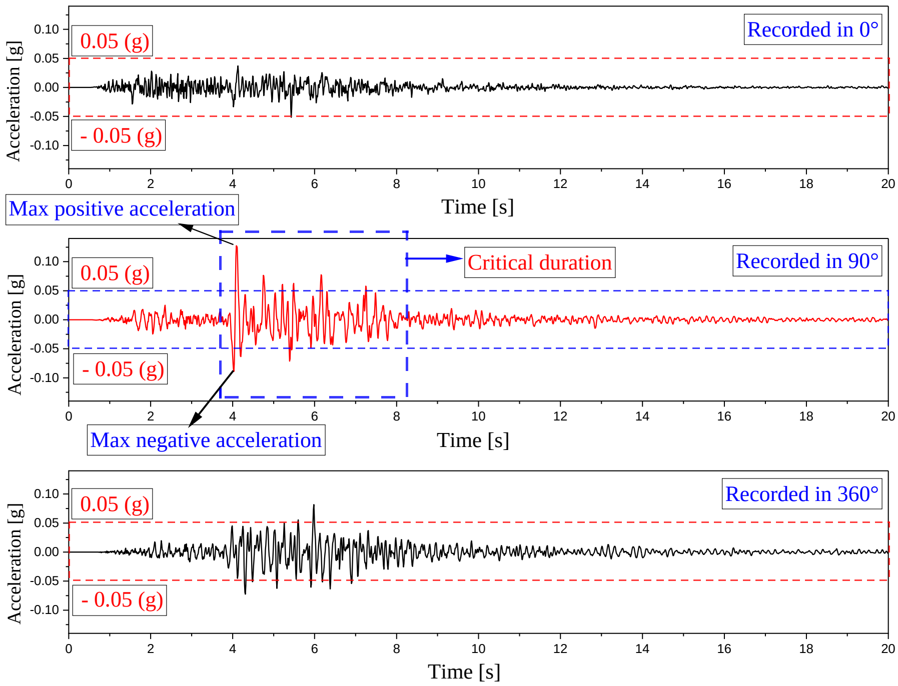


Figure 2. Ground acceleration of earthquake [31]

The depth of earthquake occurrence is very close to the surface compared to other earthquakes, due to which strong ground acceleration is released. The ground acceleration energy in the 0°, 90°, and 360° directions exhibits different tolerances in creating the vibration mechanism. In this study, the ground acceleration of the earthquake observed in the 90° direction has been used in the numerical simulation. The critical time of the earthquake's ground acceleration was used in the numerical simulation to minimize the simulation process.

Figure 3 explains the dimensions of models 1, 2, and 3 with the size of 400 (mm) × 400 (mm) × 40 (mm). In terms of the preexisting crack, three types of models were simulated. All the models were simulated with equal crack lengths to avoid the impact of the crack length on the crack propagation speed and mechanism. The preexisting crack's angles of 30°, 45°, and 60° were created with equal lengths for the crack. In addition, types of crack propagation in connection with rock materials were simulated.

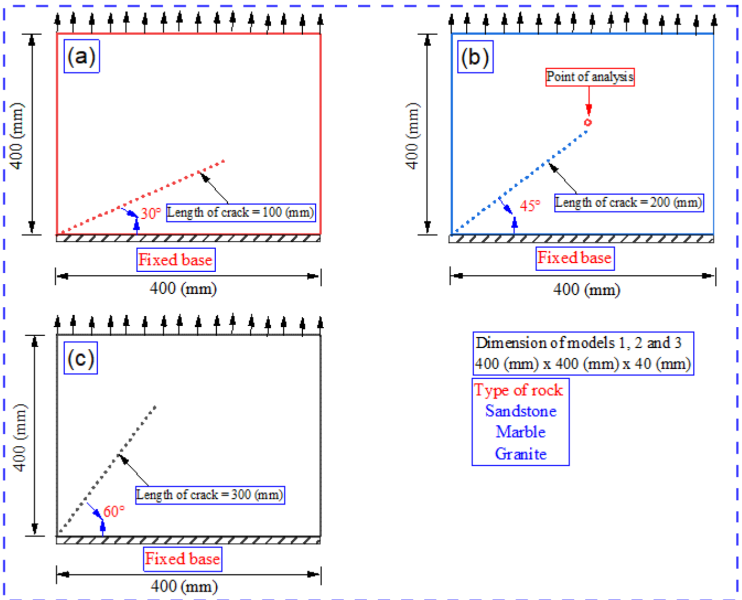


Figure 3. Simulated models 1, 2, and 3, considering types of rocks

Figure 3 demonstrates that the base of the model is rigid. Seismic acceleration is applied to the model in positive and negative directions. The model's boundary condition for all models is similar.

The boundary condition used in this study, previously verified and reported in the literature for analyzing crack propagation of the rock model, is subjected to seismic acceleration [8]. Two critical points in the models were selected to investigate the strain variation for classifying real-time crack propagation.

Figure 4 demonstrates the boundary condition of the node subjected to compression and shear waves in the positive and negative directions. The compressional wave (cp) and shear wave (cs) are the loadings that develop the crack propagation on the model [32]. The dashpot boundary condition was suggested and applied in simulation to solve several engineering problems [33].

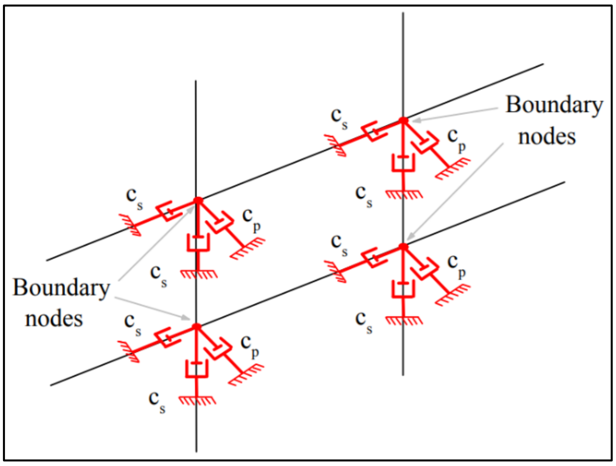


Figure 4. The boundary condition for each node [32]

In this simulation work, the above method is applied to the data to predict tensile, shear, and mixed-mode crack propagation during applied seismic acceleration on three types of rocks.

3. Numerical Modeling Steps

Step 1: Develop the geometry of the model. The geometry of the model has been built according to Figure 3. The boundary condition depicted in Figure 3 has been simulated. The preexisting crack angle was made according to the objective of the study.

Step 2: The mechanical properties of rocks are used, along with those presented in Table 1. Granite, sandstone, and mudstone are used in the simulation. The aim is to identify the impact of the rock's mechanical properties on crack propagation.

Step 3: Step for modeling. The natural frequency, seismic load, and self-weight application are three steps in performing numerical simulation that have been introduced to the model.

Step 4: The mesh of the same was selected for all models.

Step 5: The model was set to simultaneously be subjected to seismic loading in three directions.

Step 6: The numerical analysis was run in ABAQUS software.

Step 7: The results were assessed and interpreted considering the objectives. The ABAQUS software can produce various results. In this study, the results coincide with the objectives produced

4. XFEM and Traction and Cohesive Law

Due to the need for crack growth simulation for prediction and solving several engineering problems, XFEM was replaced with the traditional method of FEM. In the finite element method (FEM), the crack was applied to the model, while in using XFEM, the crack is predicted by considering several factors introduced to the model.

Using XFEM, the maximum traction and cohesive law is applied to simulate brittle and ductile material characteristics [34]. In this investigation, XEFM was employed to assess real-time cracking modes, the pattern of crack propagation, and strain at two specified model points. Furthermore, applying maximum traction and cohesive law facilitated fatigue crack propagation simulation. Figure 5 shows that the divided surfaces model presents cohesive law. The fracture energy in cohesive or traction separation law has been employed for crack growth simulation. In this process, the stiffness reduction of each node and element occurs the same as of the cohesive zone [35]. In this study, the boundary condition of the model was simulated, and the numerical simulation was carried out to perform cohesive law or traction separation law for the prediction of crack propagation. The crack opening and extending have been simulated using the XFEM's ability to recognize the model's cohesive zone and fracture principle. The Abaqus software performs crack growth simulations using XFEM for elastic-plastic fracture mechanics (EPFM).

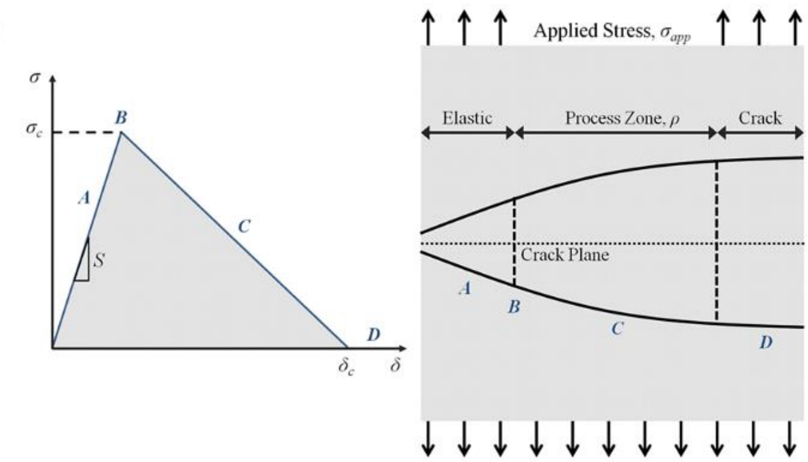


Figure 5. Graphical representation to explain the cohesive zone of the simulated model with the crack traction-separation constitutive performance [35]

The phantom node method was used in the crack propagation. The nodes and elements are adjusted with crack propagation [5]. This study uses the phantom node method to simulate the crack propagation in the Abaqus software.

The mesh size impacts the numerical simulation results in the mesh design for performing the numerical simulation [36]. This study used a single type of mesh for all models.

5. Statistical Integration for Data Processing

When the mechanical properties of the soil are governed by the safe bearing capacity of the mixed soil, the artificial neural network and linear regression methods are applied to assess the mixed soil characteristics [24, 26]. In addition, advanced mathematical models of artificial neural networks are proposed to forecast the compaction characteristics of fine-grained soils, considering physical properties [25] and the occurrence of liquefaction [27]. The artificial neural network has been executed by designing a single hidden layer, leading to accurate results [36]. In this simulation study, a single hidden layer was proposed in the architectural design of ANN.

Figure 6 presents the typical architectural design of ANN structure and operation. The ANN process starts from the input layer. At this stage, the networking corrects its weights on the performance of a training data set. It applies a learning regulation to discover a set of weights that will generate the input/output mapping that contains the minimum potential error for the prediction [37]. According to prediction and assessment, by using the statistical analysis available in the literature and applied in geotechnical engineering [8], Equations 1and 2 are applied to evaluate the prediction quality that ANN has done.

$$RMSE = \frac{1}{n}\sum_{i=1}^{n}(d - d_p)^2 \tag{1}$$

$$R^2 = 1 - \frac{\sum_{i=1}^{n}\sum(d - d_p)^2}{\sum_{i=1}^{n}\sum(d - \bar{D}_o)^2} \tag{2}$$

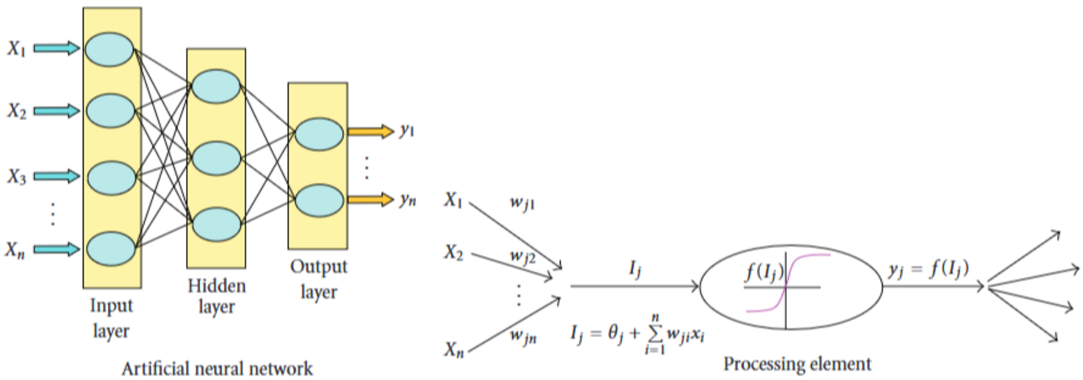


Figure 6. Typical architectural design of ANN structure and operation [37]

In Equations 1 and 2, d and dp are referred to as nonlinear stress simulated by XFEM and the predicted nonlinear stress by ANN, respectively. $\bar{D}_o$ is the mean of nonlinear stress from XFEM. MATLAB was used to execute training, testing, and validation phases in ANN through the back-propagation (BP) algorithm, with an assessment of the error and improving prediction quality.

6. Results and Discussion

The preexisting (primary) and propagated (secondary) cracks were simulated using XFEM. The fracture seismic toughness mechanism was observed during the crack propagation, which caused the model's failure. The model's failure initiation and the crack propagation angle were simulated with reasonable errors. The specimen's failure was relevant to the characteristics of the primary and secondary cracks. The mechanical properties of the rock and the angle of preexisting fracture are two parameters in the numerical simulation. According to the numerical simulation results, the mechanical parameter variations of samples govern the application of simulated seismic acceleration and changing crack propagation mechanisms. The shape and directions of the tensile crack have been changed in association with preexisting fracture angles and mechanical properties of the rock specimen. The direction and speed of crack propagation were related to the mechanical properties of the rock model. The fracture seismic toughness mechanism of the crack produces morphology and speed of fracture for each model at different stages of cracking modes. When the model is subjected to seismic loading, the mechanical properties of the rock govern its strength and stiffness. In the different types of rocks with a preexisting fracture angle of 45°, the interface strength of the crack was associated with the mechanical properties of the rock. If no growth is observed in the preexisting crack, the strain energy causes the deformation of the model in the form of model displacement.

The mechanical properties of the rock mitigate the crack propagation of the rock mass and impact the crack initiation, crack propagation, strength, stiffness, deformation, displacement, and failure mechanism of the model. When applied loading seismic acceleration reaches the peak strength of the rock, crack propagation appears. The growth of the crack shape leads to a change in the displacement mechanism of the model. The crack speed was associated with stress fluctuation linked with the specimen's stiffness.

Figure 7 illustrates the preexisting fracture angle of 45°and propagation of the fracture in sandstone, mudstone, and granite. The crack propagation in the sandstone and mudstone occurred in the two stages, while the crack propagation in the granite occurred in the three stages. For all models, the crack grew in different shapes by changing the mechanical properties of the rock. The mechanical properties of the rock change the speed, shape, and stage of developing crack.

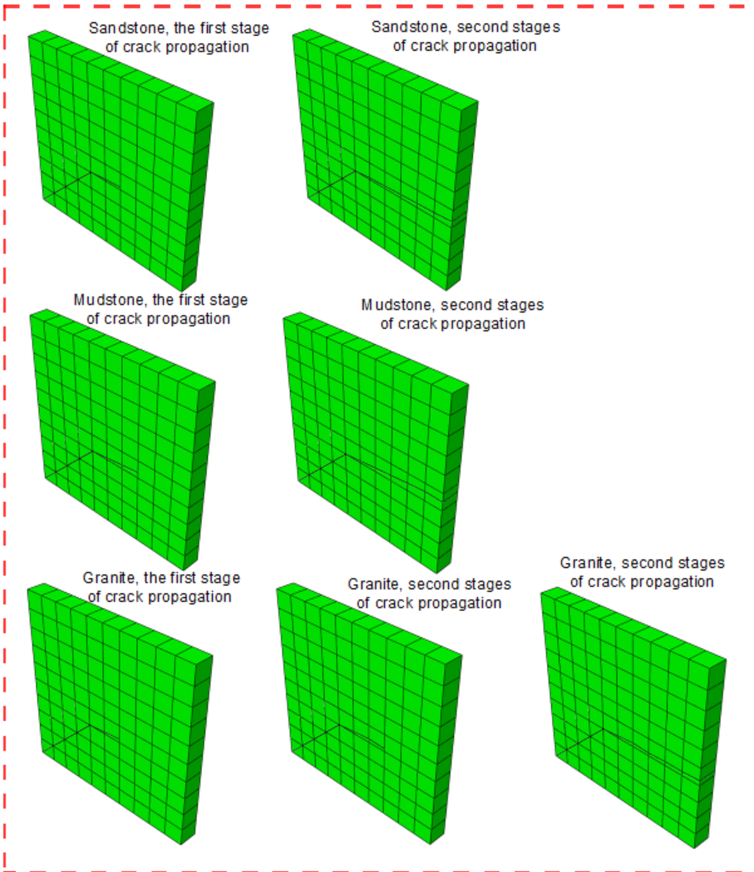


Figure 7. The preexisting fracture angle at 45°and propagation of the fracture in sandstone, mudstone, and granite

Figure 8 depicts the displacement in the vertical direction of all models in the final stage of crack propagation with a preexisting fracture angle of 45° for granite, sandstone, and mudstone. The fracture propagation in granite is complicated with minimum displacement compared to sandstone and mudstone. According to the modulus elasticity of all rocks, granite has higher brittleness than sandstone and mudstone, which causes granite to be subjected to crack propagation with a lower level of displacement.

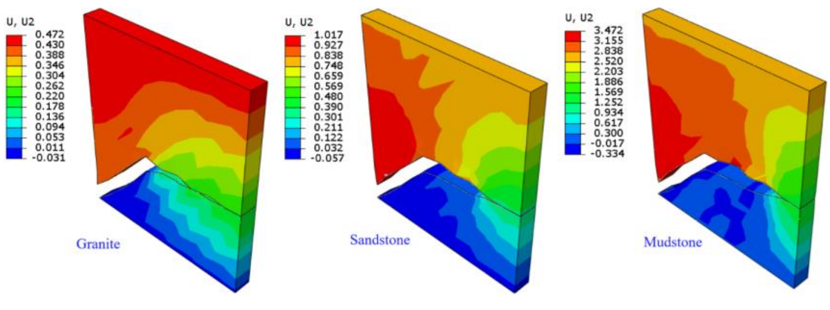


Figure 8. Displacement in the vertical direction of all models in the final stage of crack propagation with a preexisting fracture angle of 45° for granite, sandstone, and mudstone

The brittleness characteristics of a rock are highly associated with its failure mechanism. A rock's fracture performance can be equal to its brittleness behavior [38, 39]. The findings of the XFEM simulation align with those available in the literature.

In the crack propagation, modeling was used to simulate brittle and ductile fractures. Considering the fracturing zone of the model, deformations of the model without crack propagation and those with crack propagation can be distinguished. Crack propagation due to damage to the material occurs in response to the strength of the type of rock. The crack mechanism produced by the stress impacts the deformation of the rock [40], and the elastic modulus is one of the deformation parameters of rock [41]. In comparing the fracture mechanism with the deformation in granite, sandstone, and mudstone, there is a direct relationship between the fracture seismic toughness mechanism and the deformation of the model. In the rock model, when the fracture seismic toughness mechanism increases, the stages for the crack propagation increase. The ground acceleration of the earthquake generates the elastic stress wave through the seismic energy release, which creates crack propagation. Significant distinctions between the tensile strength of different types of rocks have been observed. The rock's increase in strength results from decreasing crack propagation time. As stress declines, a low-strain-hardening zone is formed differently for each type of rock.

Figure 9 depicts the stress and strain relationship for granite, sandstone, and mudstone. The model under the seismic loading condition has been subjected to deformation due to the seismic energy application, dissipation, and finally release of the energy. This process causes the crack propagation and the two sides of the crack coalescence. The stress-strain graph demonstrates that granite exhibits higher brittleness. Figure 8 shows the relationship between rock damage, crack propagation, and energy released due to rock brittleness. In addition, the stress-strain curve indicates that the rock model's deformation and failure mechanism occurrence is subjected to an equal level of seismic loading.

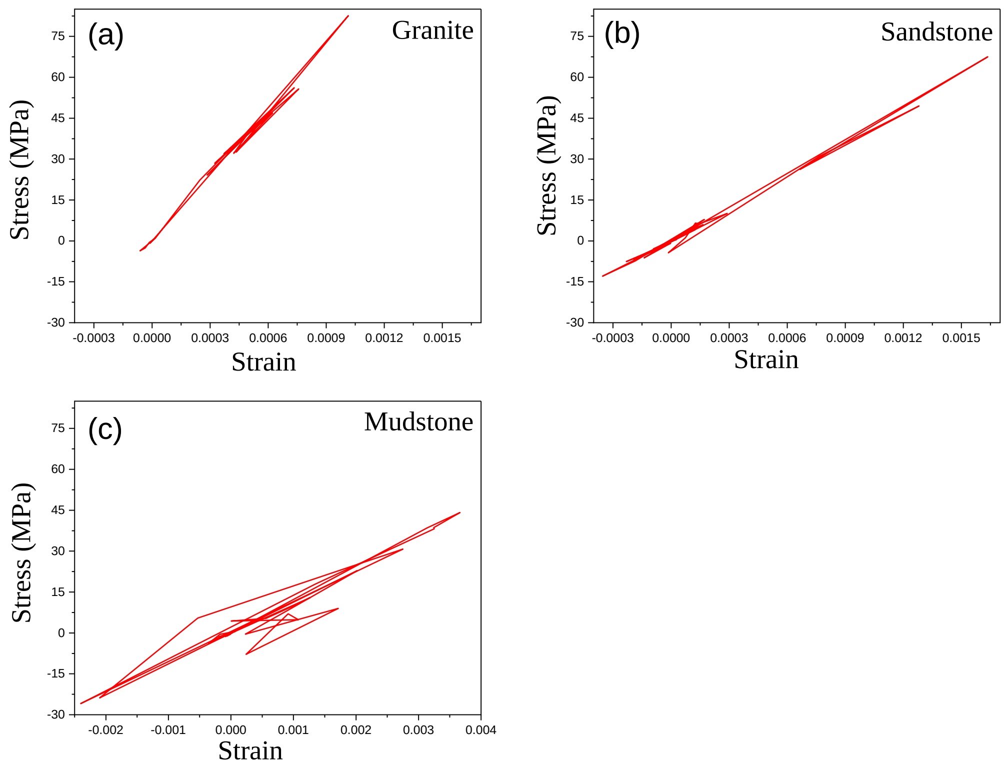


Figure 9. Stress-strain for granite, sandstone, and mudstone

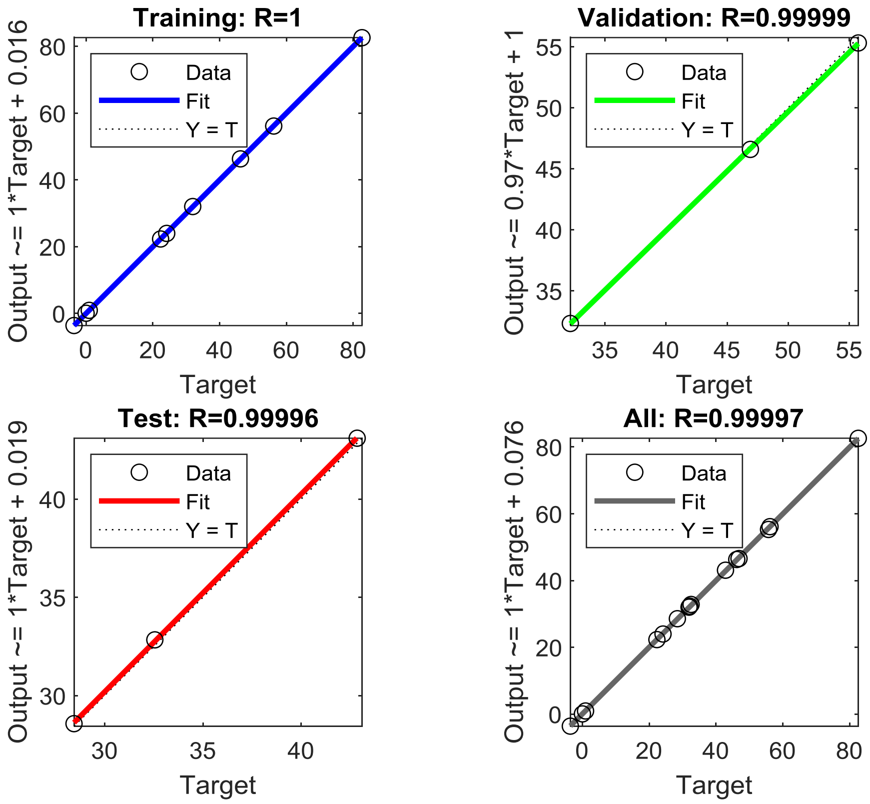
To predict stress in the vertical direction of the model, the input data for the ANN are Mises stress, maximum principal stress, maximum principal absolute stress, middle principal stress, minimum principal stress, and stress in the vertical direction. The point analysis is depicted in Figure 3.

Table 2 presents the outcome of the ANN for analysis accuracy of the prediction through R2 and MSE outcomes of models for preexisting fracture angles of 45°. Figure 10 depicts the regression analysis for stress prediction at sandstone, mudstone, and granite during crack propagation at a selected point. Based on the ANN prediction, the findings of this work can be applied in structure health monitoring.

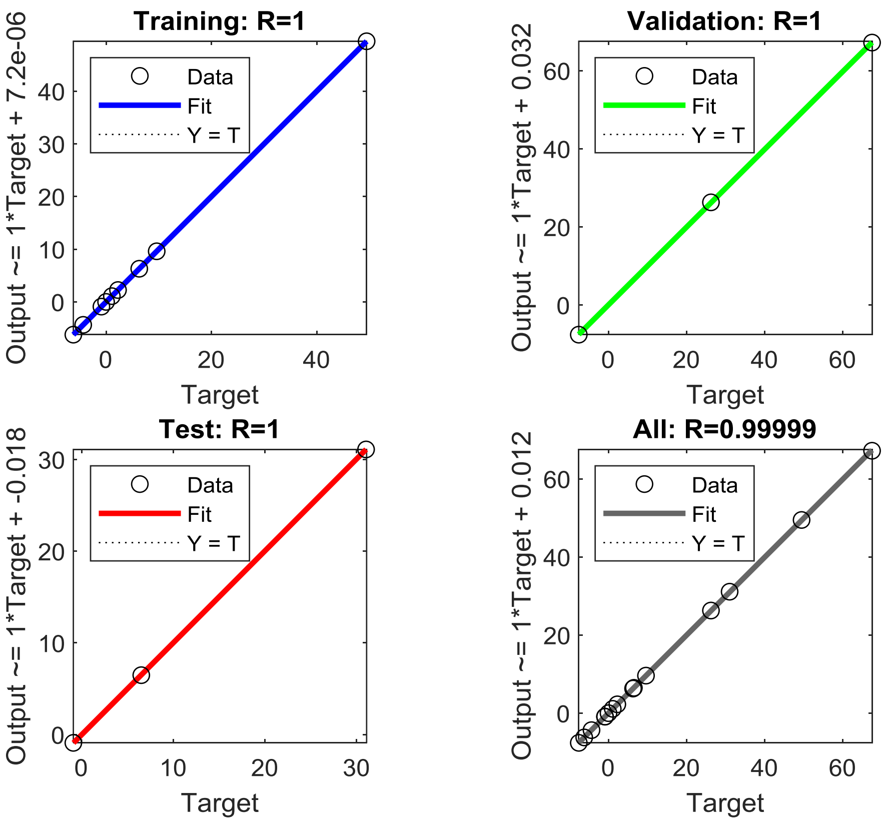
Table 2. R^2 and MSE outcomes of models for preexisting fracture angles of 45°

	-	Training	Validation	Test	Number of layers in ANNs
Granite	R^2	1	0.99999	0.99996	1
	RMSE	0.0055	0.1088	0.052	1
Sandstone	R^2	1	1	1	1
	RMSE	0.00	0.0378	0.0015	1
Mudstone	R^2	1	1	1	1
	RMSE	0.00	0.001	0.0014	1

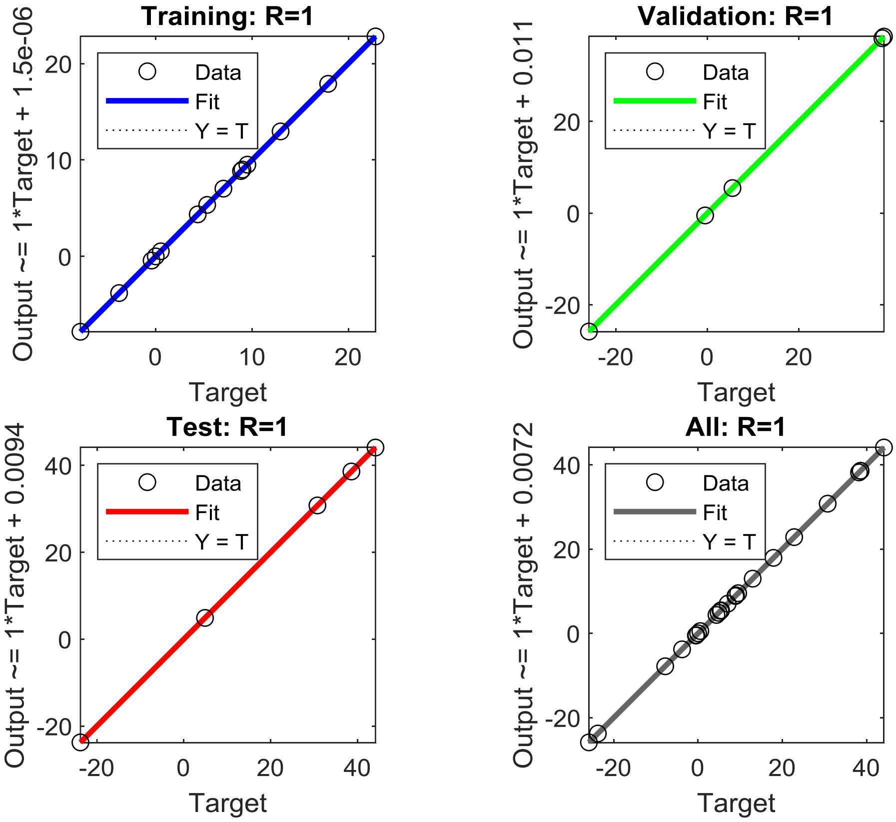
Figure 10 shows regression analysis for the overall stress prediction of all models. Predictions are presented during training, testing, and validation. In addition, all combined predictions are present separately. Accurate predictions using FEM results end with acceptable quality performance. The regression analysis for ANN outcome compared the overall results for different predictions. In the present work, in comparing the training, validation, and testing depicted by the regression analysis results, the ANNs made an acceptable prediction.



Granite rock



Sandstone rock



Mudstone rock

Figure 10. Regression analysis for stress prediction

In limited available data from the numerical simulation, ANN has generated adequate data to predict trustable results without modifying the main data quality and accuracy. The process takes place based on the random data selection for prediction. A regression analysis was adopted to predict the magnitude of stress fluctuation. The suitable association between finding data from the numerical simulation and observation is essential to minimize errors in the prediction.

7. Validation of Results

The XFEM simulation has been validated by employing the scale test results [42]. A crack is created if the direction of applied nonlinear loading is changed from axial to lateral [43]. The preexisting crack governs the resultants of the stress applied to the model. The preexisting fracture angle of 45° on the rock model reduces the strength interface and causes crack propagation due to changing axial seismic loading to the lateral direction. The regression analysis was applied in geotechnical engineering with a successful outcome using the experimental results [26]. In the present study, the regression analysis was applied by considering the numerical simulation results.

The displacement mechanism and crack shape of the materials are changed by their mechanical properties [5]. Understanding the shape and paths of the crack propagation concerning the types of rock helps improve the geotechnical earthquake engineering code, especially for case studies that need to be strengthened. The displacement mechanism of the model subjected to seismic loading changes in association with the mechanical properties of the materials [6]. In a model with a preexisting crack, differential displacement develops due to mechanical properties that change the crack speed. This phenomenon changes the crack propagation speed in a different type of rock subjected to seismic loading.

The brittleness characteristics correlate with a rock's fracture performance [38, 39]. This study's results are in good agreement with those available in the literature.

8. Conclusions

A suitable simulation of preexisting (primary) and propagated (secondary) cracks is simulated to predict the impact of seismic loading on a rock with preexisting cracks. Three types of rock with preexisting fracture angles of 45° are simulated by applying equal seismic loads. The preexisting (primary) crack length was simulated equally. The models' crack propagation, shearing strength, volumetric strain, nonlinear deformations, and failure mechanism were simulated. The seismic response for all models has been simulated.

When equal seismic acceleration is applied to the simulated model, the mechanical properties of the rock and the angle of the preexisting crack govern the shape of the crack propagation and develop the shearing strength, volumetric strain, and nonlinear deformations of the model, which lead to different types of failure mechanisms.

- The seismic simulation method classified the crack propagation in the tensile and shear/mixed modes for specimens with a preexisting fracture angle of 45°.
- The mechanical properties of the rock change the speed, shape, and stage of the developing crack. There is a direct relationship between the fracture seismic toughness mechanism and the deformation of the rock model.
- The health monitoring process of rock engineering requires recognizing the impact of classifying the type of rock propagation considering the primary crack, mechanical properties, and types of seismic loading applied in the model. A single type of seismic acceleration was applied to the model to simplify the investigation. Further studies can investigate the impact of types of seismic acceleration on the crack propagation of the model.
- The outcome of the present study, compared to those available in the literature, shows promising results for the prediction failure mechanism of the model. In addition, the research presented in this paper can further assist in deciding whether the critical preexisting crack leads to the failure of the structure. This study also helps comprehend several essential factors for future research.

9. Declarations

9.1. Author Contributions

Conceptualization, O.M. and A.K.; methodology, O.M., S.J.A., Y.L., M.A., and A.K.; software, A.N., and A.K.; validation, O.M., Y.L., S.J.A., and O.M.; formal analysis, A.N.; investigation, M.A.; resources, A.K.; data curation, A.N.; writing—original draft preparation, O.M.; writing—review and editing, M.A.; visualization, Y.L.; supervision, A.K.; project administration, A.N.; funding acquisition, O.M. All authors have read and agreed to the published version of the manuscript.

9.2. Data Availability Statement

The data presented in this study are available in the article.

9.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

9.4. Conflicts of Interest

The authors declare no conflict of interest.

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