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Comparison of In-situ and Numerical Shear strength analysis of Sandstone at Nalagad Hydropower Site

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Abstract

The shear strength of rock is a critical factor influencing the stability and safety of hydropower structures, particularly in underground powerhouse sites. This study investigates the shear strength behavior of sandstone at the underground powerhouse site of the Nalagad Hydropower Project through a comparative analysis of in-situ direct shear tests and numerical simulations performed in Abaqus/CAE 2020. A dynamic explicit approach with quasi-static conditions is employed to simulate stress distribution. Additionally, a mesh sensitivity analysis is conducted to evaluate the influence of element size on numerical shear strength predictions. The results indicate that the numerical model converges at a 20 mm mesh size, ensuring accuracy without excessive computational cost.
In in-situ testing, the shear stress of sandstone was measured as 1.15 MPa and 1.80 MPa under normal stresses of 0.25 MPa and 0.65 MPa, respectively. Corresponding numerical modeling results yielded shear stresses of 1.10 MPa and 1.47 MPa under the same normal stress conditions. This indicates that the numerical model underpredicted shear stress values by approximately 4.3% at 0.25 MPa and 18.3% at 0.65 MPa compared to in-situ measurements. The observed discrepancies highlight the influence of material heterogeneity, boundary conditions, and constitutive model assumptions in numerical simulations. This research paper helps to understand the shear behavior of sandstone under specific loading condition and contribute in rock engineering. The paper can be useful for model enhancement and future research. The paper only focuses on shear behavior of sandstone but future research can be extended to other rock masses.

Keywords: Sandstone, Shear Behavior, Direct Shear Test, Abaqus, Quasi-Static

1. Background:

The Nalagad Hydropower Project, located in a seismically active region with complex geological conditions, presents an ideal case for studying the shear behavior of sandstone. The proposed hydropower site lies in the Nalagad River in Jajarkot District, Karnali Province, Nepal. The project includes key features such as a 200-meter-high dam, an 8,215-meter-long headrace tunnel with a 5.7-meter diameter, and a 171.97-meter-high surge shaft with a 12-meter diameter.

Additionally, it features a 990-meter-long pressure shaft and an underground powerhouse. The powerhouse, designed with an installed capacity of 410 MW (4×102.5 MW), utilizes a net head of 612 meters and is strategically positioned at the confluence of the Nalagad and Thuli-Bheri River. This region consists of extensive river terraces, while the slopes above contain interlayered sandstone, siltstone, and mudstone.

To evaluate the site's geological conditions, detailed geological mapping, a 320-meter-long test adit along the proposed CTVT, drilling, and geophysical surveys have been conducted. In-situ Test, including hydro-fracture tests, plate jack tests, and direct shear tests, were carried out to assess the rock's mechanical properties and overall stability. The sandstone properties were obtained from Detail design report geological and geotechnical report, June 2023 of Nalagad hydropower project.

2. Site Description

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Table 1. Description of Project

S.N.	Name of Project	Nalagad Hydropower Project
1	District	Jajarkot
2	Name of the River	Nalagad River
3	Types of Scheme	Storage
4	Region	Lesser Himalaya
5	Dam Site	Dolomite with frequent intercalation of black Shale
6	Headrace Tunnel	Limestone, Dolomite and Shale
7	Power house	(underground PH) Sandstone

3. Objective

The main objective of this study is to:

- Analyze and compare the shear strength and failure mechanisms of direct shear.
- Develop a numerical model using the finite element software Abaqus.

4. Literature review

Singh and Lone (2023) examined the properties of Upper Murree sandstones from Jammu and Kashmir through laboratory testing. Their research provided key insights into sandstone properties relevant to construction and slope stability, emphasizing its engineering applications. The mechanical behavior of rock masses has also been explored through numerical modeling approaches. Lin et al. (2010) simulated the direct shear test of rock joints using finite element methods (FEM), demonstrating that numerical simulations accurately predict shear strength and deformation trends. This was further reinforced by Dirgeliene et al. (2017), who combined experimental and numerical approaches to analyze direct shear test outcomes. Their study enhanced the understanding of shear behavior by integrating laboratory tests with FEM modeling.

Researchers have explored sandstone behavior under different conditions. Studies highlight how sandstone transitions from brittle to ductile, its permeability changes, and its response to axial loads. Numerical and experimental analyses, including direct shear tests, help understand its mechanical properties. The Mohr-Coulomb failure criterion to calculate the shear stress parameters also used for further process of numerical analysis. The Mohr-Coulomb model is well-suited for analyzing direct shear test results since it is based on shear strength parameters (cohesion c and friction angle φ), which are directly obtained from such tests.

The study of dynamic explicit quasi-static behavior in materials, especially rocks like sandstone, has been gaining traction due to its ability to simulate complex real-world scenarios involving both rapid and slow processes. This approach combines the benefits of dynamic analysis, which can capture rapid responses to stress, and quasi-static modeling, which is ideal for analyzing slow or gradual loading behaviors.

Overall, these studies collectively deepen our understanding of sandstone mechanics, providing valuable insights that can be applied to geoengineering projects. They enhance the ability to assess structural stability, predict the behavior of rock masses under various conditions, and refine modeling techniques in rock mechanics.

5. Methodology

During in-situ test Direct Shear Test is used to determine the behavior of sandstone in my research which is provided from Nalagad hydropower company limited (NHCL). The test procedure for direct shear test as per "IS:7746-1991: Insitu-Shear Test on Rock-code of practice".

A 25 mm thick mild steel plate of 700 mm X 700 mm size is placed on the block centrally for uniform distribution of normal load. If necessary, a series of reducer plates may be placed on the top of this plate to be appropriate with the size of the jack. A remote-controlled hydraulic jack of sufficient capacity shall be placed centrally on the top of the plates. A roller arrangement is centrally located on the piston of the jack. Packing plates placed concentric with the plunger of the jack between the beam and the jack may be used. The contact between the block and the beam is made by operating the jack. The hydraulic jack of suitable capacity for applying shear force.

Direct shear tests were conducted to measure shear stress-displacement behavior. Shear stress (τ) was calculated using the Mohr-Coulomb failure criterion:

$$\tau = c + \sigma \cdot \tan(\phi) \qquad \text{(equation 1)}$$

whereas,

τ = Shear stress (MPa)
σ = Normal stress (MPa)
c = Cohesion (MPa)
φ = Angle of internal friction (degrees)

6. Field Data and Analysis

Table 2. Normal stress and Shear stress (Peak)

DST1-Peak			
Test No.	**Normal stress (MPa)**	**Shear Stress (MPa)**	**Remarks**
1	0.25	1.15	
2	0.35	1.3	
3	0.55	1.6	In-situ Direct shear test
4	0.65	1.8	
5	0.75	1.85	

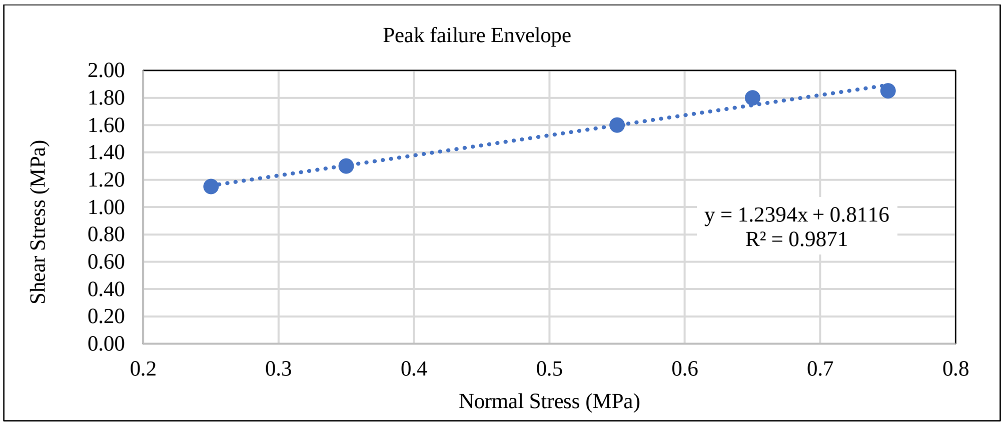

Figure 1. Direct Shear Test Peak Failure Envelope

Table 3. Normal stress and Shear stress (Residual)

DST1-Residual			
Test No.	**Normal stress (MPa)**	**Shear Stress (MPa)**	**Remarks**
1	0.10	0.78	
2	0.20	0.85	In-situ Direct shear test
3	0.50	1.15	

4	0.60	1.25
5	0.65	1.40

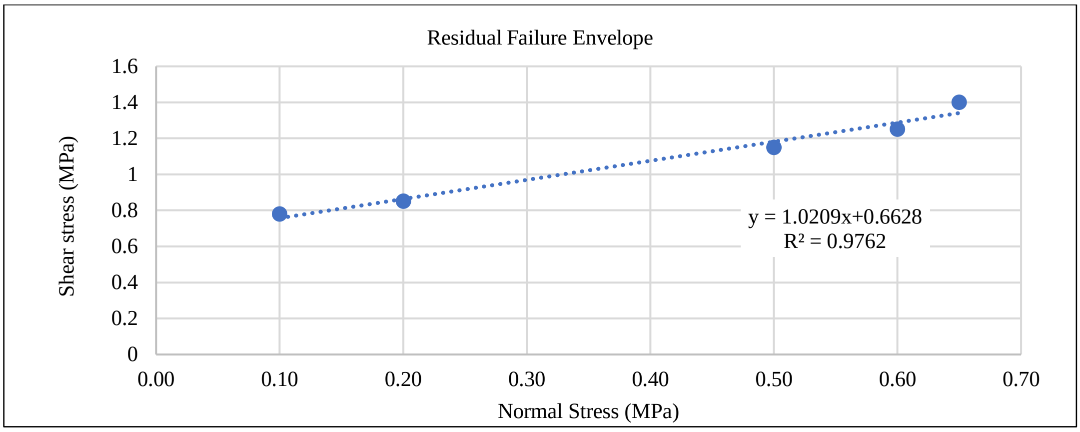

Figure 2. Direct Shear Test Residual Failure Envelope

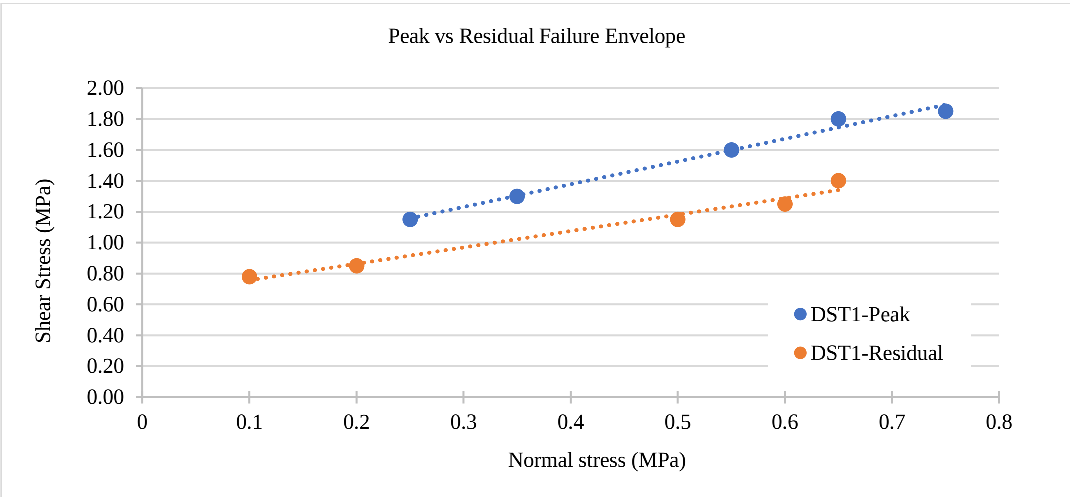

Figure 3. Peak and Residual Failure Envelope

7. Numerical Modeling

7.1. Geometry of the Specimen

The sandstone sample used in the numerical simulation of shear strength behavior at the Nalagad Hydropower Site measures 700 × 700 × 350 mm, matching the dimensions of the field test specimen to ensure consistency in comparison.

7.2. Creating the Model in Abaqus

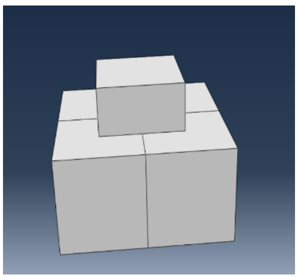

Figure 4. Sandstone Model

7.3. Material Definition

The material properties used in the numerical simulation were selected based on experimental data and established literature to ensure an accurate representation of sandstone at the Nalagad Hydropower Site. The Young's modulus (19.9 GPa) and Poisson's ratio (0.25) were taken from the study by Xu et al. (2016). The cohesion (0.812 MPa) and friction angle (51.10°) were obtained directly from experimental direct shear tests as presented in the Detail Design Report Geological and Geotechnical Report June 2023, ensuring site-specific accuracy. The density of 2.63 g/cm³ was adopted from Khanlari et al. (2014).

The selection of these parameters ensures that the numerical model closely represents the in-situ rock behavior while maintaining consistency with both experimental findings and established literature.

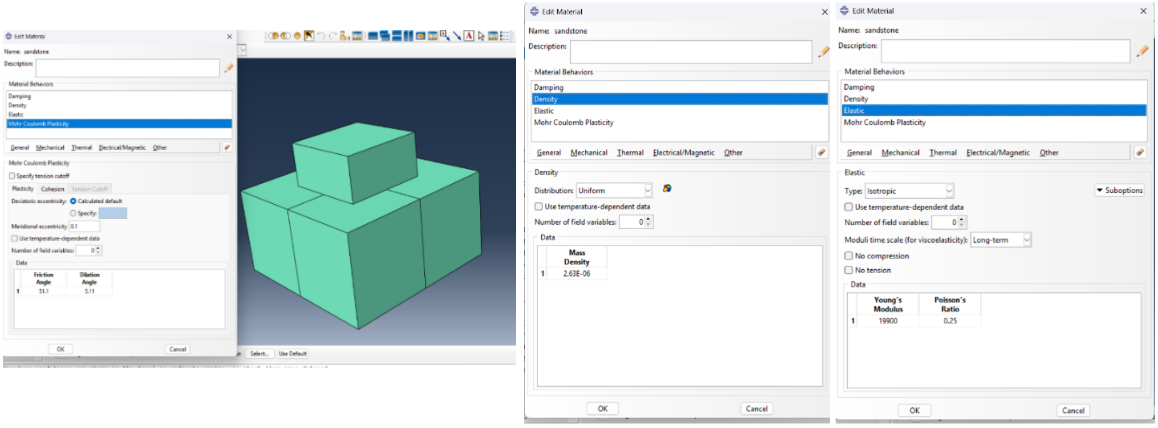

Figure 5. Material Properties used for FEA.

7.4. Mesh Generation

For the mesh generation, C3D8R elements were used to discretize the geometry of the parts into smaller, manageable elements in Abaqus.

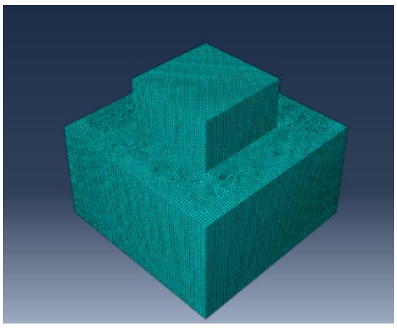

Figure 6. Fine Meshing (C3D8R)

A mesh sensitivity analysis was conducted to evaluate the influence of mesh refinement on shear stress results in the numerical simulation. The analysis was performed under a normal stress of 0.25 MPa, using mesh sizes of 40 mm, 25 mm, and 20 mm, and the corresponding shear stress values were recorded. Mesh sensitivity studies are essential in finite element modeling to ensure that numerical results are independent of mesh discretization while maintaining computational efficiency. The results of the analysis are summarized in Table 2.

Table 4. Mesh Sensitivity analysis

Mesh Size(mm)	Shear Stress (MPa)
40	1.15
25	1.10
20	1.10

The results indicate that refining the mesh from 40 mm to 25 mm led to a slight decrease in shear stress. However, further refinement to 20 mm did not alter the shear stress values, demonstrating that the numerical solution had converged. Since the 20 mm mesh size was adopted for the analysis, it ensures a balance between accuracy and computational efficiency. This confirms that the selected mesh provides reliable results without unnecessary computational expense.

7.5. Boundary Conditions

In order to properly model the lower face was encastred (U1=U2=U3=UR1=UR2=UR3=0). To impose a horizontal displacement on the upper face shear box to induce shearing. Vertical compressive load is applied to simulate normal stress.

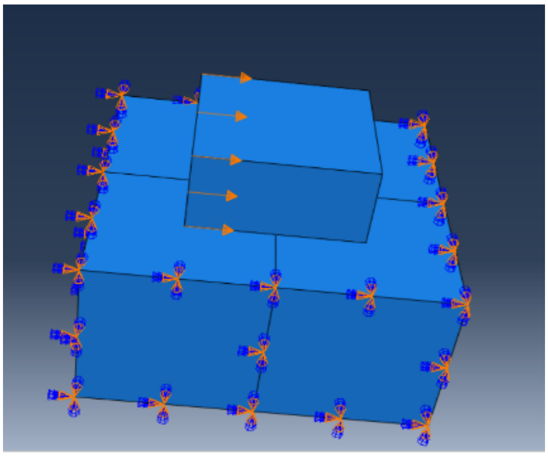

Figure 7. Boundary Condition

7.6. Analysis Process for Dynamic Explicit with Quasi-Static Behavior

Quasi static analysis was performed to make the simulation computationally inexpensive. Various trails were performed to achieve an appropriate combination of loading rate and mass scaling .Appropriate condition is achieved when the ratio of KE to IE of whole model (ALLKE/ALLIE) <5%. The first trail is done by applying mass scaling and Load rate as mention below.

MS-10^7 with 3 LR 0.5mm/s, 1mm/s, 1.4mm/s

At lower loading rates local deformations significantly decreased than higher loading rate but KE was still higher (>5%)

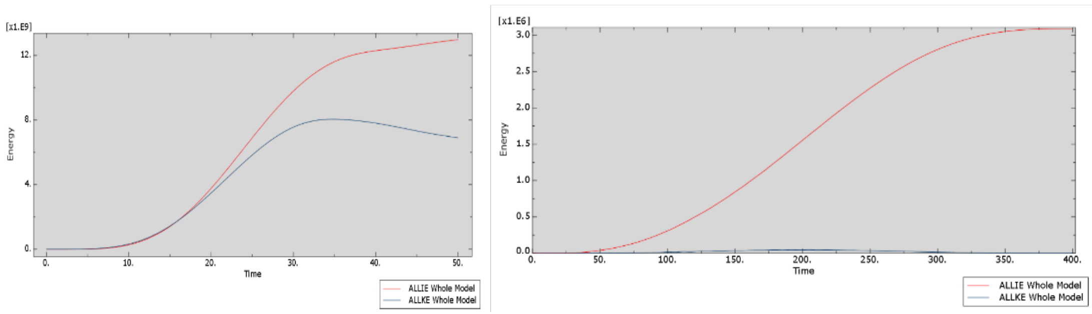

Figure 8. Energy time relationship with LR=1.4 & MS = 10^7 & LR = 0.025 & MS = 10^5 respectively

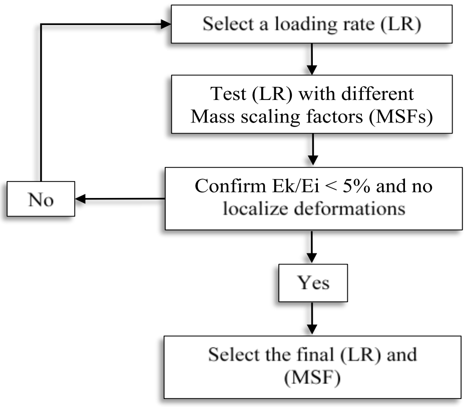

Figure 9. Procedure for selecting appropriate LR and MSF

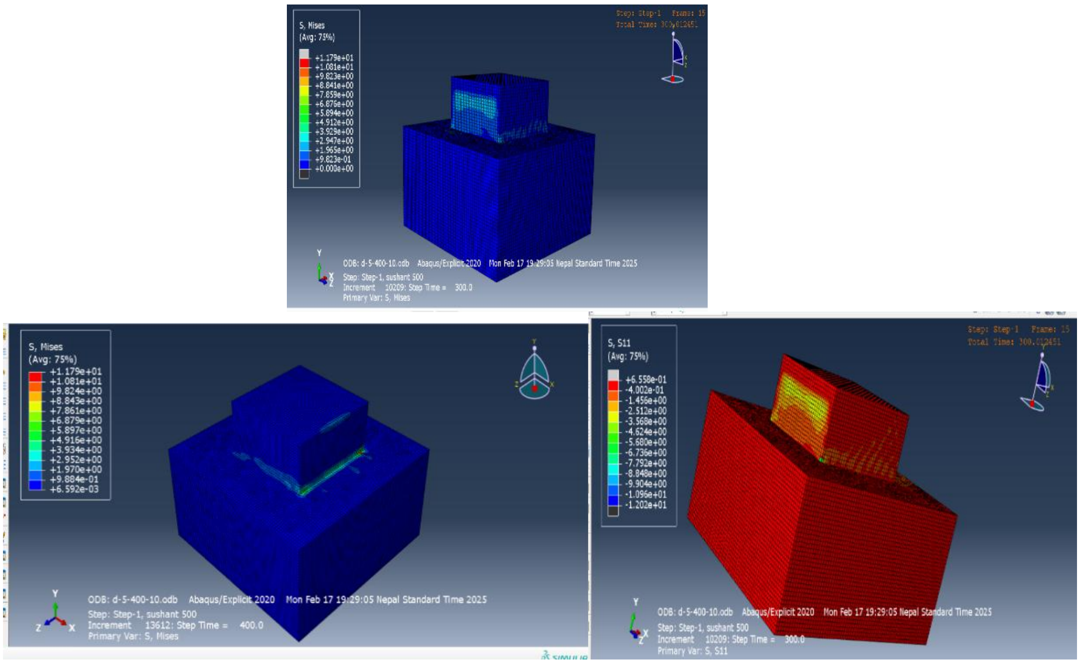

Figure 10:.Stress Propagation during simulation

8. Result and Discussion

The failure mechanism during numerical analysis is shear failure mechanism where the horizontal force and vertical normal stress was applied as shown in above figure. In numerical modeling the research wants to make sample and testing procedure as in field procedure.

In in-situ testing, the shear stress of sandstone was measured as 1.15 MPa and 1.80 MPa under normal stresses of 0.25 MPa and 0.65 MPa, respectively. Corresponding numerical modeling results yielded shear stresses of 1.10 MPa and 1.47 MPa under the same normal stress conditions. This indicates that the numerical model underpredicted shear stress values by approximately 4.3% at 0.25 MPa and 18.3% at 0.65 MPa compared to in-situ measurements. The observed discrepancies highlight the influence of material heterogeneity, boundary conditions, and constitutive model assumptions in numerical simulations.

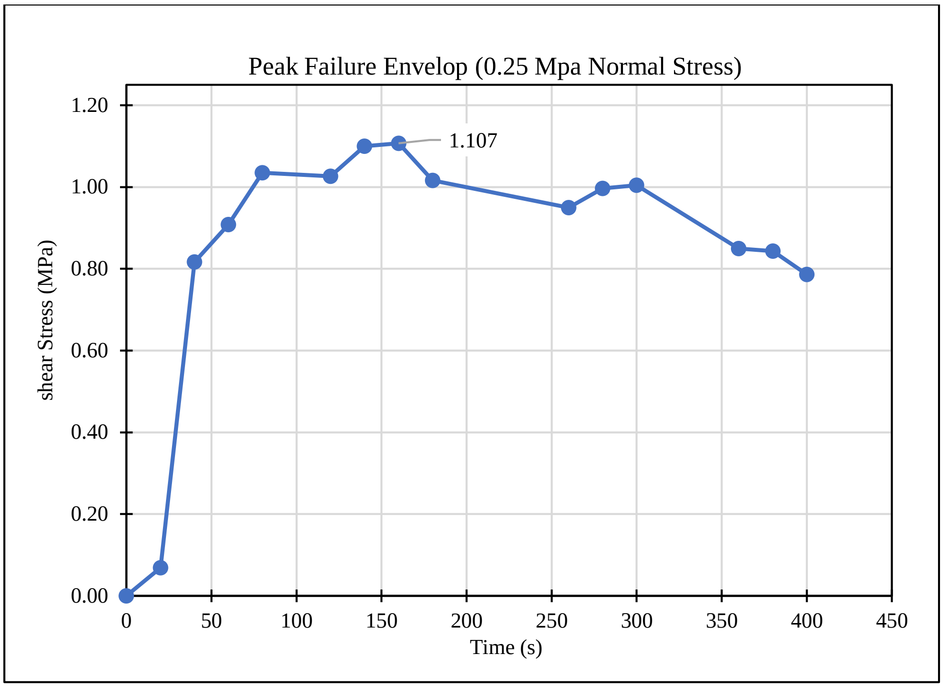

Figure 11. Numerical analysis results of peak failure envelope under 0.25 MPa normal stress.

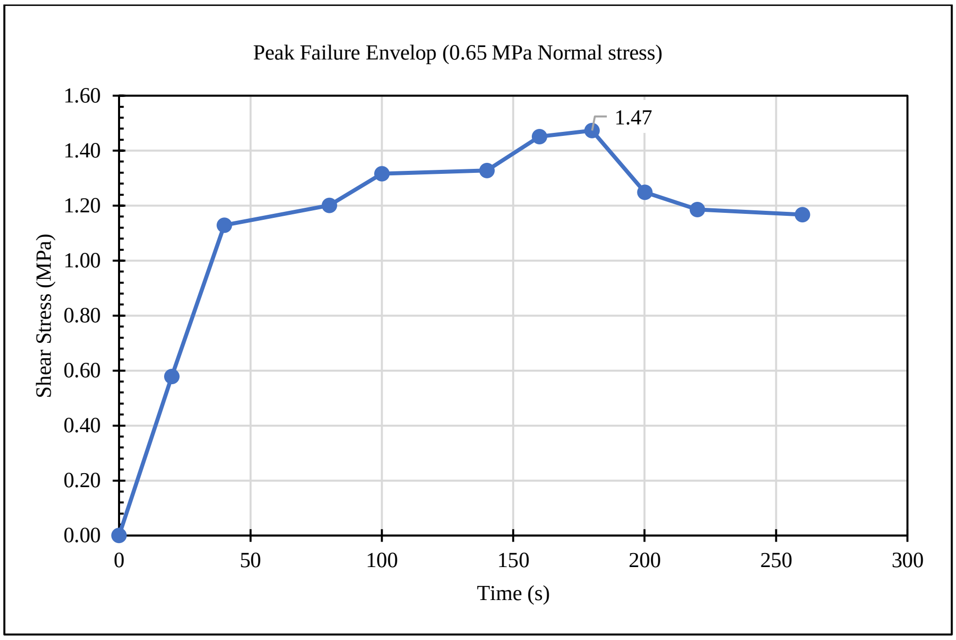

Figure 12. Numerical analysis results of peak failure envelope under 0.65 MPa normal stress.

9. Conclusion

The main objective of this research paper is to analyze and compare the shear strength of sandstone by analytical and numerical analysis. The numerical model provides a 4–18% lower estimation of shear stress compared to in-situ measurements, indicating a more conservative assessment of shear strength. This difference can be attributed to variations in boundary conditions, material heterogeneity, and simplifications in numerical assumptions. Specifically, under a normal stress of 0.25 MPa, the in-situ shear stress was recorded as 1.15 MPa, whereas the numerical model predicted 1.10 MPa (4.3% lower). Similarly, for a normal stress of 0.65 MPa, the in-situ shear stress was 1.80 MPa, while the numerical model estimated 1.47 MPa (18.3% lower). These results suggest that the numerical approach provides a safer estimate, making it suitable for conservative geotechnical design in high-seismic regions.

Further refinement under model such as improved material modeling, more precise loading conditions and high mesh resolution of model could enhance the model's accuracy by bringing the numerical result even closer to in-situ test result.

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