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A Numerical Approach of Failure Mechanism of Transversely Isotropic Rocks

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ABSTRACT: Stress-induced rock failures occur during the construction of underground structures, which draws a considerable attention of geotechnical, mining, and petroleum engineers to understand the failure mechanism of rocks. This paper presents a numerical experiment for evaluating the strength and deformation characteristics of transversely isotropic rock specimen, 5 cm in diameter and 10 cm in height, using advanced finite element software PLAXIS. A mesh refinement study was conducted to select the appropriate finite element mesh for the proposed study to ensure that the computed responses are independent of the finite element mesh. Seven orientations of bedding plane (15, 30, 45, 60, 75 and 90^0) and four confining pressures (0, 2.5, 5 and 10 MPa) were considered in this study. The Mohr-Coulomb failure criterion was employed for each isotropic layer joined by an interface bonding. The results indicate that the failure strength is, in general, dependent on confining pressure and bedding plane orientation. The largest failure strength is obtained for case with maximum bedding plane, and the smallest strength is obtained when the bedding plane angle is between 40^0 and 60^0. The predicted ultimate strengths are compared with the experimental results of Yi Shao et al. (1999). A reasonable match between the numerical and experimental approaches is observed, especially at low confining pressure.

1. INTRODUCTION

Rocks found on the Earth's crust show well-defined fabric elements in the form of foliation, bedding, layering, stratification, fissuring or jointing. In general, these rocks have properties that vary with direction and are categorized as inherently anisotropic [1, 2]. The study of the mechanical behavior of sedimentary rocks, especially shale and mudstone, is of particular interest to the oil exploration industry as well as to civil and mining engineering.

Experimental efforts to capture the realistic transport and mechanical behaviors of such rocks are, therefore, dependent on sampling orientation with respect to loading directions and bedding plane. Collecting field samples that represent the realistic condition is time consuming and difficult. In such situations, advanced finite element models can be used to gain further insights with minimal effort. Studies have demonstrated that considering rock anisotropy has immense importance in civil, mining and petroleum engineering. This is certainly true when considering the effects of anisotropy of the stress strain properties in determination of in situ rock stresses. Anisotropy of rocks may be attributed to mineralogical, formation process or tectonic process (for stress induced anisotropy). Most rocks show transversely isotropic symmetry planes [1]. Studies show that the strength of rock is dependent upon the loading orientation and confining pressure [3, 4, 5].

The objective of this study is to evaluate the effect of anisotropy on the strength and deformation characteristic of transversely isotropic rocks. One of the widely used and advanced finite element software, PLAXIS, has been used to gain better understanding of the failure mechanism that may occur in actual rock and may be difficult to observe through experimental studies. The accuracy of the finite element predictions is validated with the experimental data found in the literature.

2. METHODOLOGY

Among different testing techniques and testing methods for determining the anisotropic parameters of rocks, the most classical experiment is the conventional triaxial compression test, with a number of loading orientations and confining pressures. Results of such studies are expressed in terms of strength anisotropy which can be represented using plots of stress-strain and compression strength versus orientation angle of the bedding plane, anisotropy curve [6,7,8].

The data for simulating transverse anisotropy for this study is extracted from Yi Shao et al.'s published work [4]; the specimens are composed of a cement kaolinite mixture and a cement micro silica mixture. Cylindrical specimens (diameter = 5 cm and height = 10 cm) having seven different inclination angles, 0, 15, 30, 45, 60, 75 and 90^0 were drilled from a bi-laminated block composed of alternating layers. Each of the layers is, therefore, an isotropic rock which can be described by Mohr-Coulomb criterion [4].

The interface between layers in the artificial triaxial specimens was modeled using an interface element available in PLAXIS. The interface allows achieving a reduced strength as compared to the friction in the soil; the reduction factor (R_{inter}) can be obtained in three ways: (1) using a rule of thumb value of 0.66 recommended by PLAXIS (PLAXIS, 2008); (2) the smaller of cohesion of the interface material/cohesion of material 1, or Cohesion of the interface material/ Cohesion of material 2 ($R_{inter-1}$ and $R_{inter-2}$, respectively); and (3) the smaller of Friction angle of the interface/ Friction angle of material 1, or Friction angle of the interface / Friction angle of material 2. The Mohr Coulomb model parameters of the constituent materials are presented in Table 1 and the maximum principal stresses obtained from laboratory experiments by Yi Shao et al. (1999) are shown in Table 2.

Table1: Mohr Coulomb parameters of constituent materials

	Cohesion C' (MPa)	Friction angle, Φ' (^{0})	Young's modulus E (MPa)	Poisson's ratio, ν
Material 1	10.2	25	7000	0.23
Material 2	6.34	15	2500	0.21
Interface	0.98	29		
$R_{inter-1}$	0.096	1.16		
$R_{inter-2}$	0.155	1.933		
PLAXIS R_{inter}	0.660	0.66		

Table2: Maximum principal stress from triaxial test on artificial rock by Yi Shao et al. (1999).

σ_3 (MPa)	σ_1 (MPa)						
	θ(^{0}) 0	15	30	45	60	75	90
0.0	14.3	12.9	12.6	4.4	3.6	6.7	21.4
2.5	21.3	20.5	17.0	10.8	10.4	13.0	26.5
5.0	25.4	24.2	22.1	20.5	18.8	20.1	33.1
10.0	29.3	29.3	27.1	25.0	26.9	30.5	44.0

The cases with bedding plane angles of 0 and 90^0 were represented by axisymmetric formulation in the finite element modeling. The bottom boundary of the numerical specimen was supported on vertical rollers (fixed in vertical direction and free to move in the horizontal direction) the symmetric vertical line was on horizontal rollers (fixed in horizontal direction and free to move in vertical direction). The confining pressure was applied on the other vertical side of the numerical specimen. Then the vertical load was applied at the top as a distributed load.

Although the cylindrical specimen subjected to vertical load with symmetric boundary conditions can be represented by axisymmetric formulation, it cannot be used for simulating samples with bedding plane angles of 15^0, 30^0, 45^0, 60^0 and 75^0. It is simply because the three-dimensional specimen cannot be produced by rotating the two-dimensional model through 360^0. At the same time, the plane strain formulation does not represent the actual material, loading and boundary conditions. In this study, the plane strain formulation was used to model the cases with plane angles of 15^0, 30^0, 45^0, 60^0 and 75^0.

The geometry is divided into a number of triangular elements using an automatic non – structured mesh generation program in PLAXIS. Higher order (15-node) triangular element formulation was used. The regions closer to the interface where large shear strain may occur was refined to capture the behavior more accurately. Further, a mesh refinement study was conducted to select the appropriate finite element mesh (fine mesh) to ensure the computed responses are independent of the finite element mesh.

In addition to the investigation of the effect of bedding planes on the failure strength, a parametric study was conducted to investigate the effect of confining pressure on the failure strength. In this study, four confining pressure values (0, 2.5, 5 and 10 Mpa) were applied.

3. RESULTS

Presented in Figs. 1-2 are selected loading arrangement, deformed mesh and incremental shear strains for the unconfined simulations (confining pressure of zero) with bedding plane angle of 30 and 75^0 . It is observed that the failure shapes, somehow, follow a typical triaxial failure.

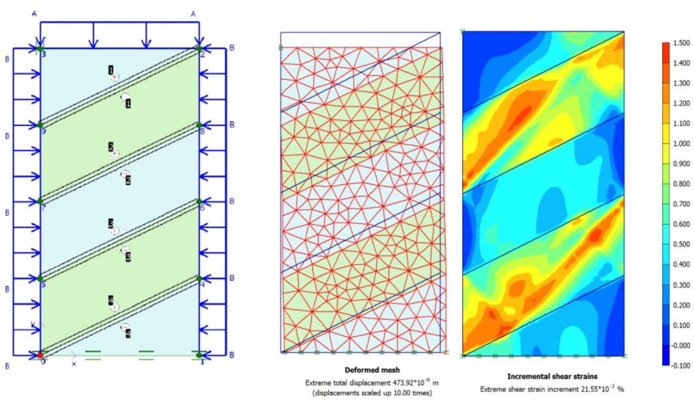

Fig. 1. Loading, deformed shape and incremental shear strain under σ_3 = 0 MPa, when the bedding plane angle = 30^0

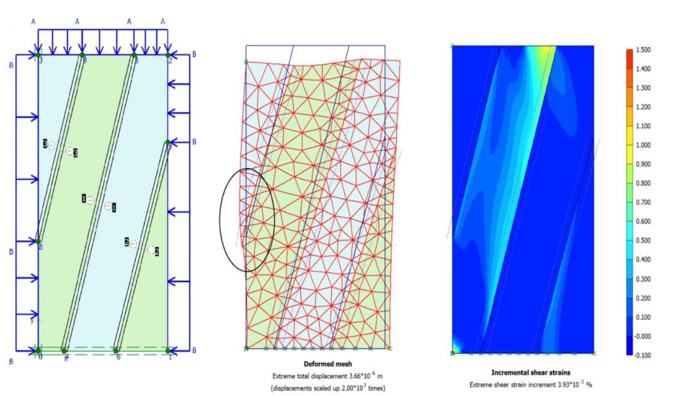

Fig. 2. Loading, deformed mesh and incremental shear strain under σ_3 = 0 MPa, when the bedding plane angle = 75^0

The comparison of predicted and measured [4] major principal stresses are shown in Fig. 3. A reasonable agreement is observed for all bedding plane orientations less than 80^0. It is noted that a transversely isotropic rock simulation using interface element can be reasonably applied in situations where experimental measurements are difficult to obtain along the shear plane. In addition, the minimum strength is observed at a joint plane angle between 45^0 and 65^0.

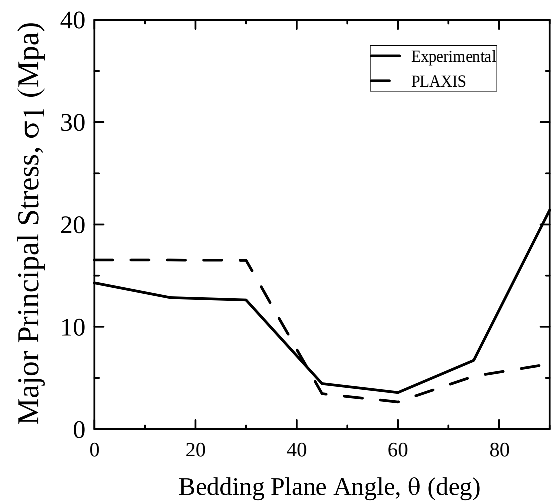

Fig. 3. Comparison of experimental and numerical results when σ_3 = 0 Mpa.

Displayed in Fig. 4 are the loading arrangement, deformed mesh and incremental shear strain plots for the cases with bedding plane angle of 30˚ and confining pressure of 2.5 MPa. In this case, the failure occurs along a plane in the soil matrix inclined at an angle close to 45˚ as clearly shown in Fig. 5, but not along the bedding plane as observed in Fig. 2. The comparison of the compressive strength values of this study with Yi Shao (1999) at σ_3 = 2.5 MPa is displayed in Fig. 5.

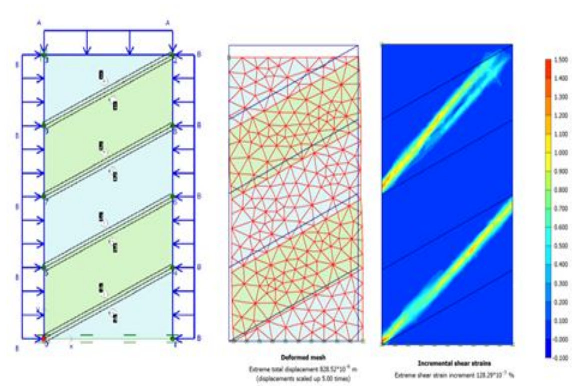

Fig. 4. Loading, deformed mesh and incremental shear strain under σ_3 = 2.5 MPa, when the bedding plane angle = 30^0.

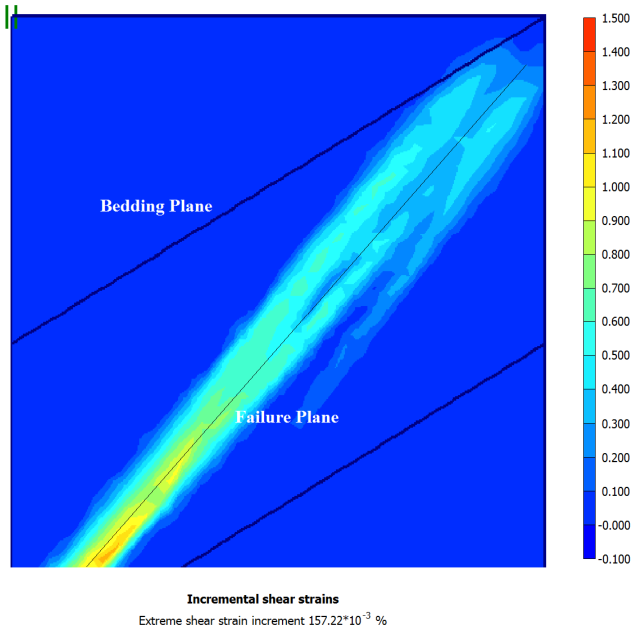

Fig. 5. Illustration of failure occurring in the soil matrix other than along the bedding plane.

From Fig. 6, it is observed that when the confining stress is limited to 2.5 Mpa, the PLAXIS results match the Yi Shao et al. (1999) measured values reasonable well for bedding plane angles less than 60˚.

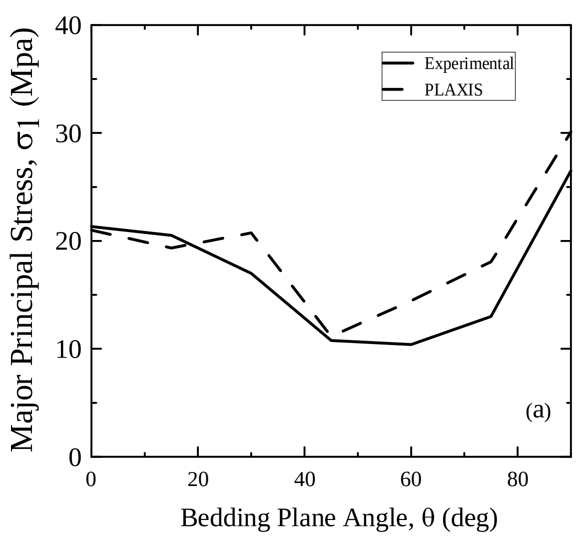

Fig. 6. Comparison of experimental and numerical results when σ_3 = 2.5 MPa.

Displayed in Figs. 7 and 8 are the loading arrangement, deformed mesh and incremental shear strain for bedding plane orientations of 30˚, confining pressures of 5 and 10 MPa, respectively. The failure planes was observed in the soil matrix at an angle close to 45 ˚. The comparison of the experimental and numerical compressive strength values at confining pressures of 5 and 10 MPa are displayed in Figs 9 and 10, respectively.

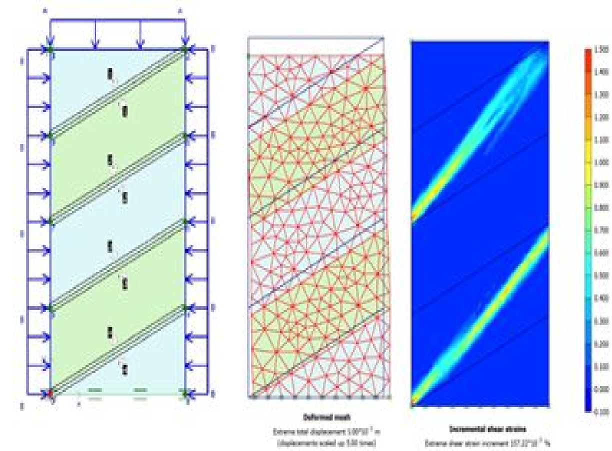

Fig. 7. Loading, deformed mesh and incremental shear strain under σ_3 = 5.0 MPa, when the bedding plane angle = 30°.

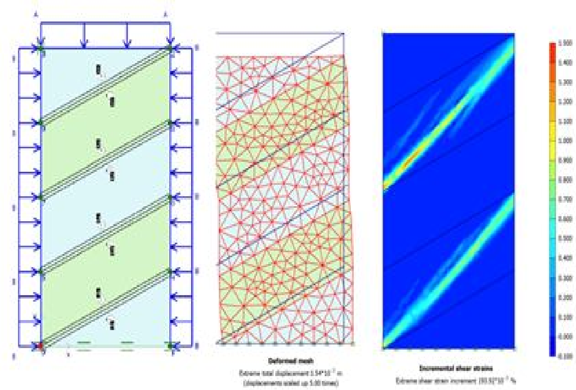

Fig. 8. Loading, deformed mesh and incremental shear strain under σ_3 = 10.0 MPa, when the bedding plane angle = 30°.

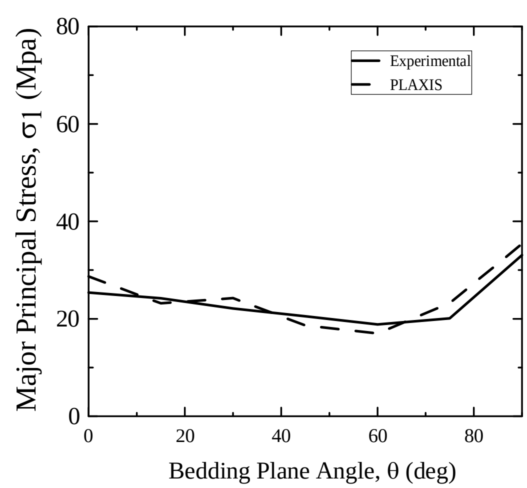

Fig. 9. Comparison of experimental and numerical results when σ_3 = 5.0 MPa.

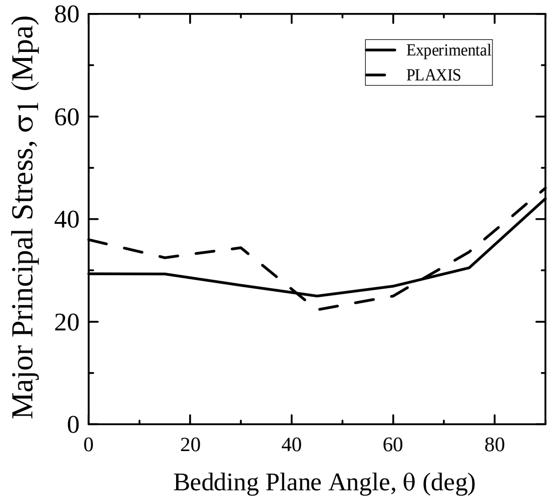

Fig. 10. Comparison of experimental and numerical results when σ_3 = 10.0 MPa.

4. CONCLUSION

A numerical approach of determining the major principal stress at failure of a bilaminated transversely isotropic rock is dealt in this study. The Mohr-Coulomb properties were taken from an experimental study by Yi Shao (1999). The finite element model that represents a laboratory triaxial specimen (5 cm in diameter and 10 cm in height) is constructed using higher order triangular elements and the numerical study was conducted using the PLAXIS finite element software. Each isotropic layer is assumed to follow the Mohr-Coulomb failure criteria joined by an interface bonding. It is shown that strength is generally dependent on confining pressure and bedding plane angle. The largest failure strength is obtained for case with maximum bedding plane, and the smallest strength is obtained when the bedding plane angle is between 40^0 and 60^0. The predicted ultimate strengths are compared with the experimental results of Yi Shao et al. (1999). A reasonable match between the numerical and experimental approaches is observed, especially at low confining pressure.

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