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Hydro-Mechanical Behavior of Anisotropic Slate and Its Implications for Sustainable Slope Stability and Environmental Geo-Hazard Mitigation

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ABSTRACT

Hydro-mechanical behavior of anisotropic slate is quite significant in regulating the stability of slopes and geo-engineering structures in water sensitive environments. The paper looks at the interaction between structural anisotropy and hydrological environment on strength, deformation and failure of slate. The suggested method to fill the gaps in the existing research involves a multi-scale methodology that will incorporate laboratory testing with the numerical model and slope-scale analysis. The standardization of uniaxial and triaxial compression tests was done using slate samples at various bedding angles, under both dry and wet conditions. The experimental results indicate that compressive strength is highly directional because it is an ordinary U-shaped curve with bedding inclination. The hydro-mechanical coupling imposes large strength and stiffness losses because of the impact of pore pressure, interlayer debilitation and along discontinuity lubrication. It was found that the saturated conditions promoted more complicated crack propagation and premature failure as compared to dry conditions. It was established that there were clear changes in failure modes, tensile-slipping, shear-slipping, and composite failure, among different bedding orientations. To study micro-mechanical behavior further, a Discrete Element Method (DEM) model based on Particle Flow Code (PFC) was built and calibrated. Patterns of initiation, propagation and coalescence of cracks observed in laboratory experiments could be replicated in the numerical models. Experimental and numerical results were synthesized to give us the most important thresholds that run the mechanisms of failures in the coupled conditions. The insights were extrapolated in hydro-mechanically coupled stability modeling to the slope scale. The results prove that the dominant factors that define slope instability are the pore water pressure and structural anisotropy. The proposed framework enhances the predictive capability in the geo-hazard assessment of reservoir banks and slopes which get rainfalls. This study will aid in bridging this gap between the laboratory level observations and field-level engineering. It gives an in-depth insight into how anisotropic rocks behave in real environmental conditions. The results present feasible suggestions on safer and more sustainable infrastructure design. Besides, the study advocates the formulation of better risk mitigation measures in geologically complicated areas. On balance, the given work contributes to the further development of combining hydro-mechanical effects in rock mechanics and the study of geo-hazards of the environment.

1. Introduction

Foliated and layered rock masses, e.g., slate, are present in large amounts in slopes, tunnels, reservoir banks, and underground engineering systems where structural anisotropy controls their mechanical behavior strongly. Due to the existence of bedding and the directions of schistosity, the response to the strength, stiffness, and deformation properties is directional. It thus does not behave much the same as an isotropic rock material (Zamanian, Mollaei-Alamouti, and Payan 2020). Existence tests have indicated that the structural planes' position with respect to the loading direction is the conclusively dominant control of compressive strength and deformation patterns (Zhang et al. 2017). Specifically, it has been recently confirmed through research on slate that the compressive strength is dependent on the bedding inclination on a typical U-shaped curve, and the mechanisms of failure switch between composite tensile-shear, shear-slip, and tensile splitting (Wen et al. 2023).

Along with anisotropy, water is another severe environmental parameter that affects the mechanical performance of rock masses. The HMC processes, such as pore pressure action, discontinuity lubrication, and degradation of inter-layer bonds, play a significant role in strengthening weaknesses in the strength of the rock and changing deformation and discontinuity failure (Qian et al. 2024). Laboratory observations reveal a decrease in compressive strength and a longer and more complicated crack propagation of saturated slate specimens under wet conditions than under dry conditions because the cementitious slates soften and become more capable of becoming deformed along structural planes (Zheng et al. 2025). These dark-oil interactions are especially applicable in water-related engineering contexts, including the slope of the reservoir, tunnels of diversions, and areas with rainfall, where seepage and redistribution of stress take place as a pair (Tian et al. 2025).

Environmentally and in an engineering sense, slope instability and geo-hazards are increasingly becoming appreciated as coupled hydro-mechanical phenomena, as opposed to mechanical failures. The interaction between water infiltration, stress concentration, and gradual fracture growth in anisotropic rock masses often leads to landslides, rockfalls, and instabilities in the banks of reservoirs (Zhu et al. 2025). Consequently, recent studies have focused on the combination of a lab experiment, numerical modeling, and field-scale tests in order to gain a superior understanding of the interplay of complex processes that determine rock mass action in the environmental loading conditions (Heinze et al. 2016). The simulated crack initiation, propagation, and coalescence of anisotropic rocks in discrete element methods (DEM) and, in particular, particle flow code (PFC) have been proven to be effective, as discrete element methods can be used to investigate the mechanisms behind failure under different hydro-mechanical settings in detail (Sun et al. 2019).

In spite of improvements, there are still substantial research gaps. The available literature is divided between laboratory-scale characterization of anisotropic rock behavior and numerical models of slope stability, but there has been a lack of integration between the two. Moreover, the application of hydro-mechanical coupling to the regulation of the failure processes and the environmental geo-hazards in layered rocks like slate has not been fully studied (Li et al. 2024). Thus, this study shall examine the hydro-mechanical characteristics in anisotropic slate by applying a combined experimental-numerical setting, as well as define a multi-scale connection between the laboratory results and slope scale stability study. The results are likely to be used in better forecasting and managing geo-hazards in water-related engineering systems to aid in the sustainable construction of infrastructure and environmental resilience (Tsatsaris et al. 2021). The overall conceptual framework integrating hydro-mechanical interactions and geo-hazard mitigation in anisotropic slate is illustrated in Figure 1.

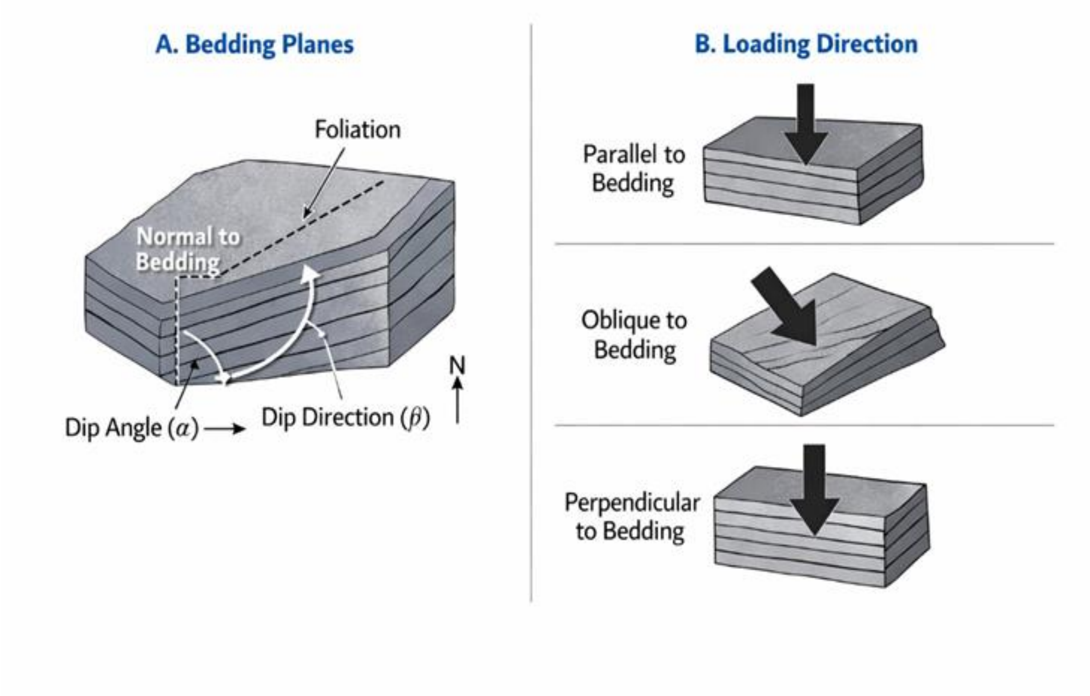

Figure 1. Integrated Hydro-Mechanical Framework for Anisotropic Slate Behavior and Geo-Hazard Mitigation

2. Literature Review

The mechanical effects of anisotropic rocks in the analysis of their mechanical behavior (Yan et al. 2020). Summary of key literature on anisotropic rock behavior, hydro-mechanical coupling, numerical modeling, and slope stability relevant to the proposed study in Table 1.

Table 1. Summary of Key Literature on Anisotropic Rock Behavior

Study	Rock Type	Key Focus	Methodology	Key Findings	Research Gap
Yan et al. (2020)	General anisotropic rocks	Mechanical behavior	Review	Direction-dependent strength	Lack of hydro-mechanical integration
Li et al. (2020)	Shale	Crack initiation thresholds	Experimental	Nonlinear deformation behavior	Limited environmental conditions
Hao et al. (2020)	Slate	Strength vs bedding angle	Lab tests	Weak interlayer bonding reduces strength	No coupling with water
Wen et al. (2023)	Layered rocks	Failure mechanisms	Dynamic testing	Tensile-shear and splitting modes	No slope-scale application
Zhao et al. (2023)	Rock masses	Hydro-mechanical coupling	Review	Water reduces effective stress	No anisotropic focus
Sun et al. (2019)	Fractured rocks	DEM modeling	Numerical	Crack propagation simulation	Limited validation with experiments
Xiang et al. (2020)	Jointed rock slopes	Stability analysis	Numerical	Structural planes control failure	No multi-scale framework

The mechanical behavior of anisotropic rocks has been of great interest to the mechanical engineering community, especially those that are in layered form like slate, schist, and shale, because of the importance in geotechnical engineering applications (Yan et al. 2020). In comparison to isotropic rocks, anisotropic rocks have direction-sensitive strength and deformation properties that are described by the planes of structure, including the bedding, foliation, and schistosity. It has also been shown that these structural characteristics have a substantial impact on the behavior of stress-strain, crack initiation, and strain behavior during loading (Li, Xie, and Wang 2020). Research on slate has found that the low strength is due to discontinuities and weak interlayer bonds, which result in poor deformability, especially when compressively loaded (Hao et al. 2020). Experiments in the laboratory and numerical analysis have also shown that in anisotropic rocks, the fracture process becomes complex with crack coalescence, propagation, interaction between pre-existing discontinuities, as well as induced fracture (Ismail and Azadbakht 2025). The effect of the interaction between intact rock bridges and structural planes in layered rocks frequently dominates the deformation of layered rocks to such an extent that the behavior of stress-strain is non-linear, and brittle failure occurs. The results obtained herein emphasize the need to consider anisotropy when examining and modeling the mechanics of rocks both in experiments and in computations (Yan et al. 2020). The structural anisotropy and loading configurations in slate are illustrated in Figure 2.

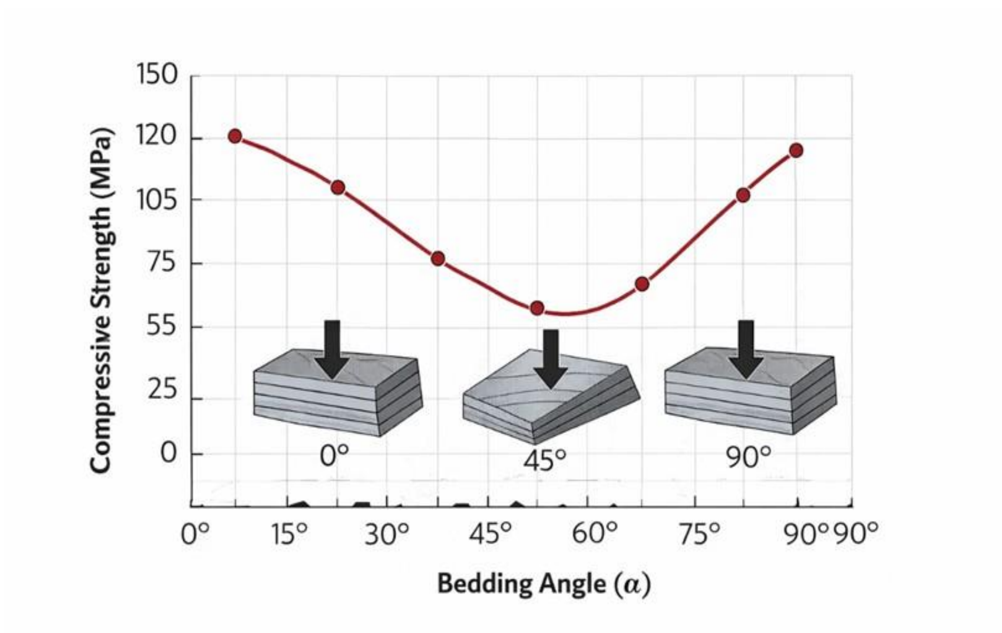

Figure 2. Structural Anisotropy in Slate: Bedding Orientation and Loading Direction

2.1 Influence of Bedding Angle on Strength and Failure Modes

It was observed that the strength and failure modes can vary depending on the angle of the bedding (Liu et al. 2023). One of the most important factors that affects the mechanical response of an anisotropic rock is the orientation of the structural planes with respect to the direction of loading. Several studies have demonstrated that compressive strength depends on the bedding inclination in a systematic manner; in many cases, there would be a U-shaped pattern with the bedding becoming weakest at the intermediate angles and becoming stronger at the higher angles (Si, Luo, and Luo 2024). Such a tendency is explained by the change of various failure mechanisms, such as tensile splitting, shear sliding, and composite failure modes. Latest research in slate confirms that failure modes can be divided into three major ones: composite tensile-shear failure at low angles, shear-slip failure at intermediate angles, and tensile splitting at high angles (Wen et al. 2023). Minimum strength is usually seen at the angle where the shear of the structural plane predominates, and this reflects the importance of interlayer adhesion and resistance to friction. Also, the bedding orientation has a great impact on crack propagation, whereby fractures either cut across or parallel with the structural planes based on the stress conditions (Suo et al. 2020). This relationship between bedding angle and compressive strength is schematically shown in Figure 3.

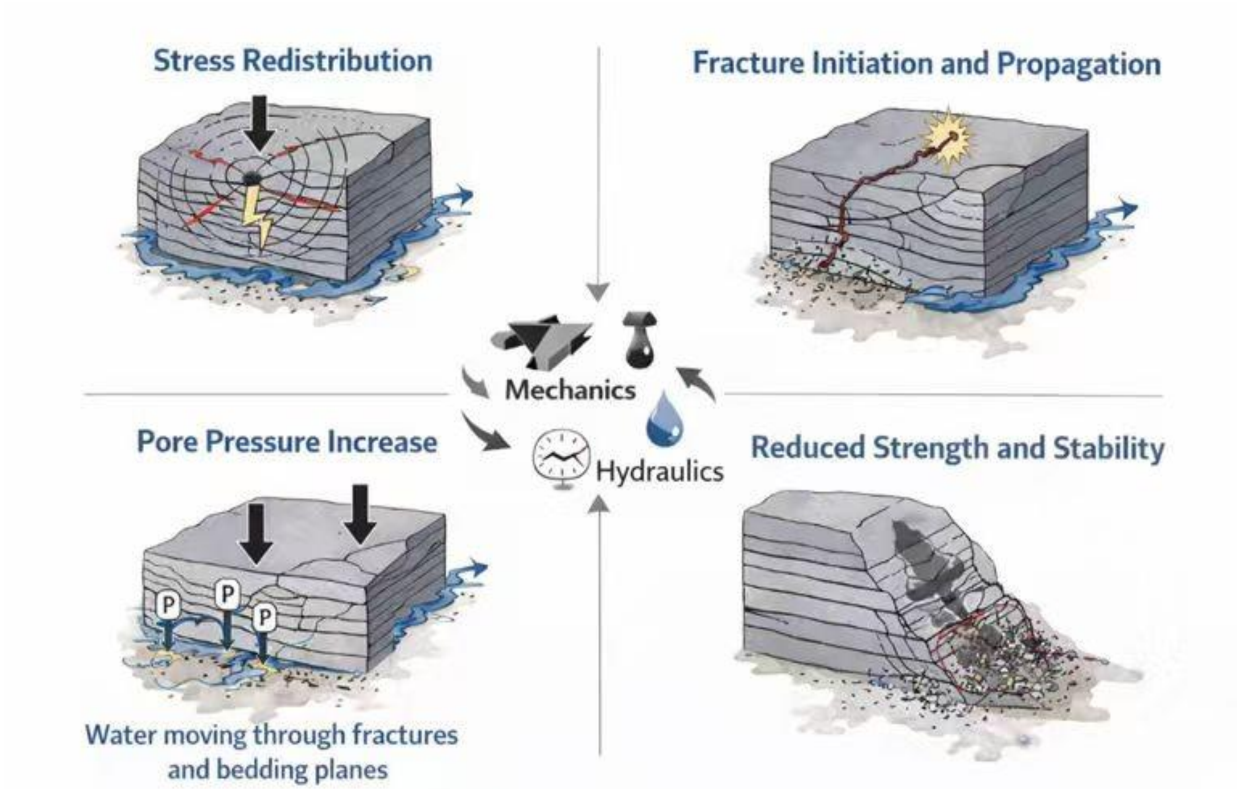

Figure 3. Relationship between Bedding Angle and Compressive Strength of Anisotropic Slate

2.2 Hydro-Mechanical Coupling in Rock Masses

Hydro-mechanical coupling is a basic factor in rock masses' behavior, especially in a setting where water infiltrations, seepage, and pore pressure variations take place. It is found that water diminishes effective stress, adversely impacts bonding between mineral particles, and favors discontinuity sliding, thus aiding the decrease in strength and the change in failure modes (Zhao et al. 2023). It has been experimentally demonstrated that saturated rocks tend to have lower compressive strength, lower elastic modulus, and higher deformability than in the dry condition (Teng and Gong 2020). Hydro-mechanical forces are more pronounced in anisotropic rocks such as slate since such rocks have weak interlayers besides the preferred flow directions across structural planes. The introduction of water may also encourage the creation of cracks and grain boundaries and cause more complex fracture systems and their premature breakage (Lynch 2019). Moreover, recent studies have been done regarding the issue of thermal-hydro-mechanical coupling that highlights the interaction of temperature, stress, and fluid flow on the behavior of rocks (Wang et al. 2025). These findings underline the need to use a combination of approaches in studying the hydro-mechanical mechanisms of layered rock systems. The most important hydro-mechanical coupling processes that control fracture initiation and strength decrease are introduced in Figure 4.

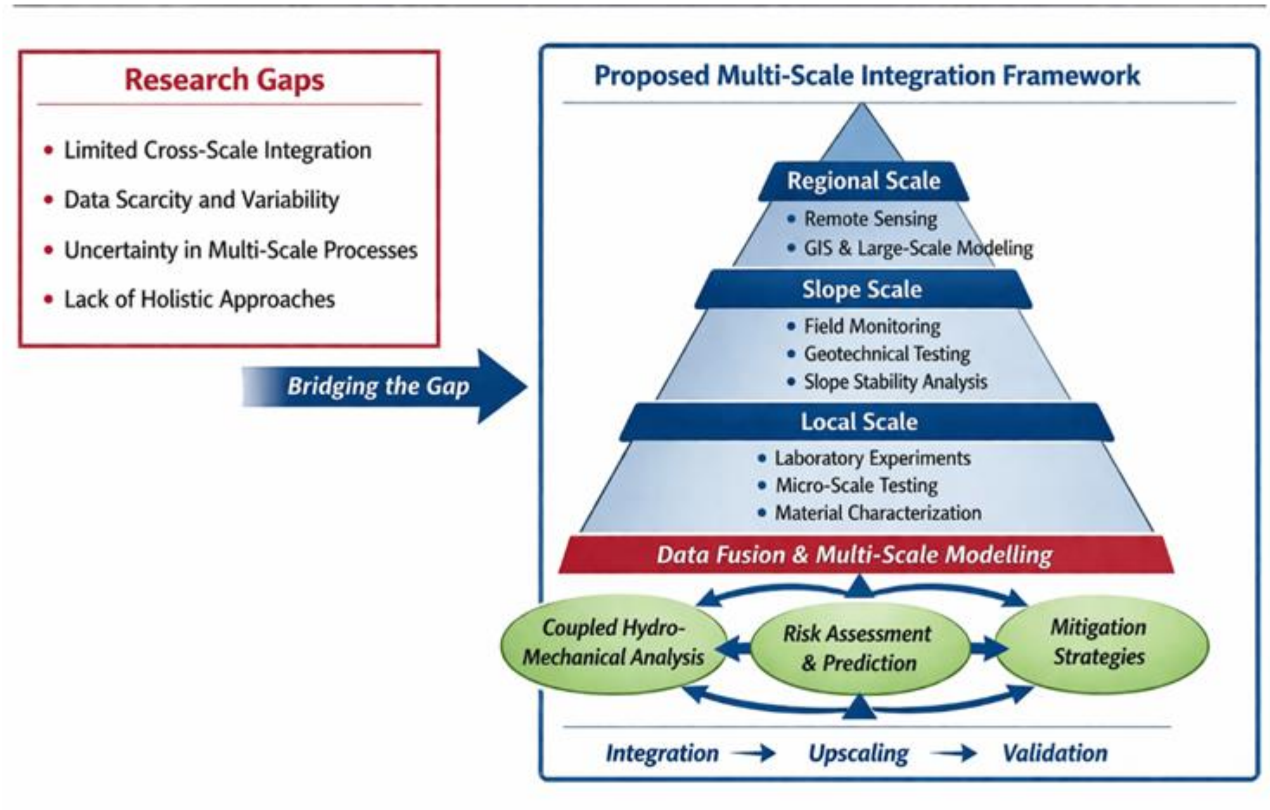

Figure 4. Hydro-Mechanical Coupling Mechanisms in Layered Rock Masses

2.3 Numerical Modeling (DEM, FEM, PFC)

Numerical modeling has been an essential technique of studying how rocks behave, particularly to learn the complicated fracture processes which are difficult to measure experimentally. Other methods that have been popular in the modeling of crack initiation, propagation, and coalescence in rock materials are the discrete element method (DEM) (Camones et al. 2013). Stress distribution and deformation in rock masses have also been analyzed by using finite element methods (Yang et al. 2014) and hybrid methods (FEM) particularly when it concerns large-scale engineering. Recent publications involving a combination of laboratory experiments and numerical calculations have demonstrated that there is a good correspondence between the simulated and observed failure patterns, which proves to be useful in the anisotropic behavior and hydro-mechanical coupling (Lisjak et al. 2014). Nevertheless, there are still difficulties in the correct modeling of the complex fracture networks and in the extrapolation of laboratory findings to the field (Taleghani, Gonzalez, and Shojaei 2016).

2.4 Slope Stability and Environmental Geo-Hazards

The problem of slope stability in rock masses is a problem of paramount importance in the sphere of engineering geology and environmental science, especially in the areas covered by water infiltration, seismic processes, and human activities. Anisotropic rocks, particularly rock slopes, are particularly vulnerable to failure because of the existence of weak structural planes and varying hydro-mechanical conditions (Xiang et al. 2020). The causes of landslides and rockfalls are usually a combination of factors that may include pore pressure that increases due to rain, weathering, and redistribution of stress.

Respondent research on the slopes of reservoirs and the water diversion has demonstrated that the slopes can become unstable due to the challenges of hydro-mechanical coupling of water level changes and seepage forces (Sadiq and Islam 2023). Sophisticated numerical modeling methods, such as coupled hydro-mechanical models, have been used to predict slope failure and to determine risk in varying environmental conditions (Zhao et al. 2023). Those methods permit the combination of parameters obtained in the laboratory with those in the field, giving a deeper insight into geo-hazard processes.

2.5 Research Gaps

Although a lot of research has been done regarding the behavior of anisotropic rocks and slope stability, there are several gaps. To begin with, there is a lack of integration between laboratory-scale experiments and numerical simulations, as most of the literature is dedicated to one or the other. Second, the hydro-mechanical coupling, because of its role in regulating failure mechanisms in anisotropic rocks, especially slate, is not fully understood. Third, multi-scale frameworks between field-scale slope stability and environmental geo-hazard mitigation to laboratory outcomes are absent. To fill the abovementioned gaps, a holistic method that involves experimental studies, numerical modeling, and environmental implementation is needed, which is the foundation of the current study. The research gaps and the proposed multi-scale integration framework are summarized in Figure 5.

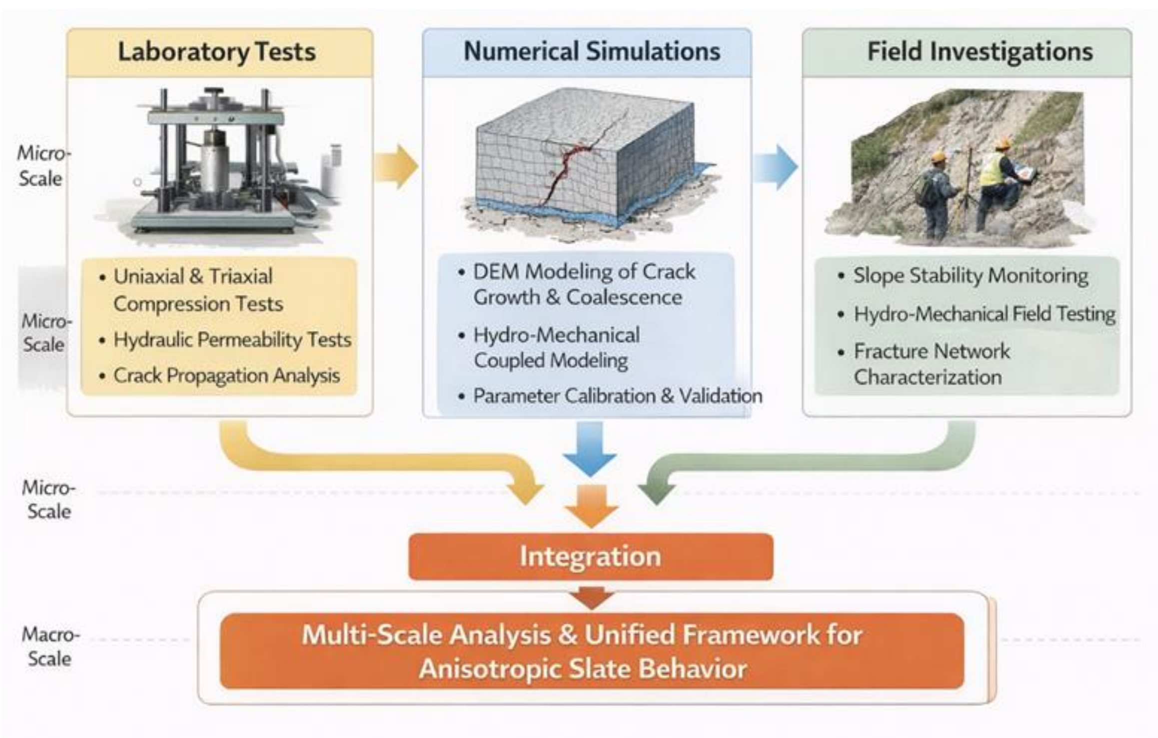

Figure 5. Research Gap and Proposed Multi-Scale Integration Framework

3. Research Objectives and Research Questions

3.1 Aim and Scope of Research

The overall aim of the research is to investigate the hydro-mechanical properties of the anisotropic slate and to establish a multi-scale model of linking the laboratory-scale processes with the slope-scale stability analysis and its geo-hazard management of the environment. The need to achieve a deeper insight into the interplay between structural anisotropy and water effects on the regulation of rock corrosion is driven by the requirement to understand the interaction between structural anisotropy and water in more detail, particularly in water-based engineering systems, such as reservoir slopes and diversion projects (Nadi et al. 2021). Previous studies have indicated that the change of strength and failure of transition of anisotropic rocks is complex at different bedding orientations and environmental conditions. Nevertheless, a detailed model that unites the two has not been developed.

3.2 Research Objectives

The study is organized into the following objectives to accomplish the overall aim and scope.

Objective 1: To experimentally define the behavior of anisotropic slate under different bedding angles and hydro conditions (dry and saturated) to define the behavior of the experiment in mechanical and deformation. This contributes to the previous results that compressive strength and mode of failure are highly dependent on the structural plane inclination and water content.

Objective 2: To examine the hydro-mechanical coupling processes affecting the crack initiation, crack propagation, and failure development in layered rock masses. Hydro-mechanical processes, including pore pressure influences and the lubrication across discontinuities, are proven to change the strength and deformation properties.

Objective 3: To construct and test a numerical model (DEM-based, e.g., PFC) that would be able to simulate the anisotropic rock failure in the coupled hydro-mechanical conditions. DEM methods have shown some success in the micro-mechanical behaviors of crack coalescence, fracture growth in anisotropic rocks.

Objective 4: To suggest a model of environmental geo-hazard mitigation, hydro-mechanical processes need to be included in the slope stability assessment and in the risk assessment. This is in line with recent studies that highlight the importance of coupled processes as predictors of landslides and slope failures.

3.3 Research Questions

According to the objectives mentioned above, the research questions of the study are as follows:

1. What is the effect of hydro-mechanical coupling on the strength, deformation, and failure modes of anisotropic slate? The existing literature reveals that water can considerably diminish strength and alter the behavior of crack propagation, yet the mechanisms behind the effect need to be studied in more detail.

2. Which are the critical bedding angles and hydro conditions that control the transitions between the various failure modes (tensile, shear, and composite)? There is experimental evidence that failure mode transitions take place within certain angular ranges, but these boundaries are not completely delimited in hydro-mechanical conditions.

3. What is the most effective way of numerically modeling the initiation and propagation of cracks in anisotropic rocks when subjected to a coupled hydro-mechanical load? The methods based on DEM offer promising methods, yet they need to be calibrated and tested against experimental data.

4. What model can be established to incorporate hydro-mechanical processes in sustainable slope stability and geo-hazard mitigation measures? The answer to this question is critical to enhance risk assessment and facilitate environmentally sustainable engineering practices.

4. Research Methodology

4.1 Research Framework

The suggested research is based on experimental-numerical-environmental combined research on the hydro-mechanical character of anisotropic slate and its implications on the slope stability. The research is structured into three steps that are highly related, i.e., (i) the laboratory study that defines anisotropic and hydro-mechanical properties, (ii) the numerical analysis of the crack propagation and failure modes, and (iii) the application in slope-scale stability and environmental geo-hazard. It is an inter-scale approach which is required to best optimize the disparity between the laboratory experiments and the field environment as seen in previous studies of rock mechanics and geotechnical modelling. The combination of laboratory experiments, numerical simulations, and field studies into a multi-scale research methodology is described in general Figure 6.

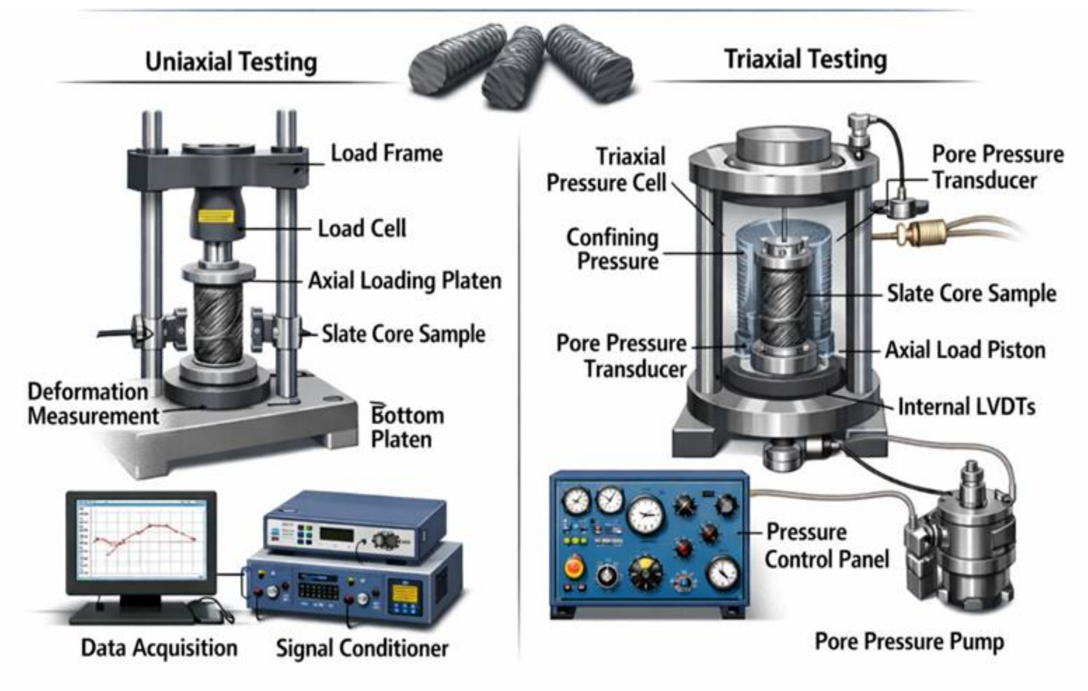

Figure 6. Multi-Scale Research Methodology Integrating Experimental, Numerical, and Field Approaches

4.2 Laboratory Experimental Program

The experiments will be conducted in a laboratory in order to quantify the mechanical behavior of anisotropic slate in a controlled experimental set up. To ensure directional dependence on strength and deformation, standard cylindrical specimens will be subjected to different bedding angles (e.g., 0°, 15°, 30°, 45°, 60°, 75°, and 90°). Proposed laboratory experimental program for investigating the hydro-mechanical behavior of anisotropic slate under different bedding orientations and moisture conditions in Table 2.

Table 2. Laboratory Experimental Design

Test Type	Parameter	Values	Purpose
Uniaxial Compression	Bedding Angle	0°–90°	Evaluate anisotropy
Triaxial Compression	Confining Pressure	5–30 MPa	Simulate field stress
Moisture Condition	Dry/Saturated	Controlled	Hydro-mechanical effect
Sample Size	Diameter/Height	Standard ISRM	Consistency

Loading Rate	Stress-controlled	Constant rate	Avoid dynamic effects
Measurements	Stress-strain	Continuous	Deformation analysis
Failure Analysis	Crack observation	Visual + imaging	Failure mechanism

Dry and saturated conditions will be taken into consideration to examine hydro-mechanical effects. Uniaxial compression tests will be conducted to get stress-strain curves, maximum strength, elastic modulus, and failure properties. Where practicable, triaxial compression tests will be carried out to determine the effect of confining pressure. The experimental design is in line with the traditionally accepted rock testing standards and methods common in past research (Zhang and Zhao 2014). Anisotropic strength difference and transition to failure mode in slate and other layered rocks can also be studied successfully using similar experimental methods (Tien, Kuo, and Juang 2006). The effects of hydromechanics will be researched through the comparison of the dry and saturated specimens. The saturation will be determined by using controlled water immersion, and the water absorption properties will be determined. The effect of water on strength degradation and deformation characteristics will be examined because it is already known that water decreases interlayer bonding and increases deformability (Wong, Maruvanchery, and Liu 2016). The laboratory setup for uniaxial and triaxial testing is illustrated in Figure 7.

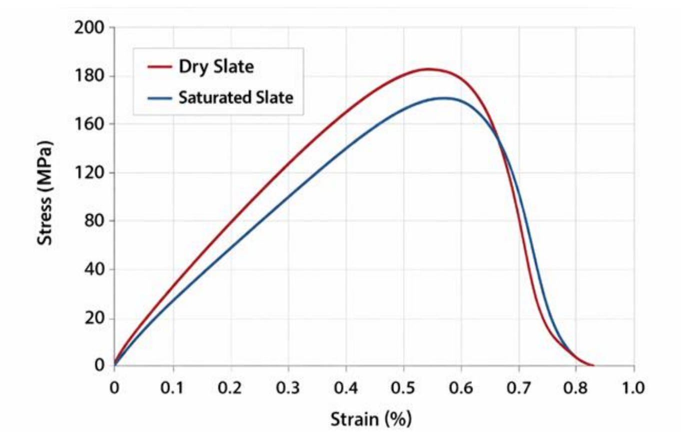

Figure 7. Laboratory Setup for Uniaxial and Triaxial Testing of Anisotropic Slate

4.3 Hydro-Mechanical Characterization

The hydro-mechanical behavior of anisotropic slate will be described with an in-depth examination of experimental data. Key stages of deformation will be identified through the use of stress-strain curves, such as compaction, elastic, elastoplastic, and failure stages. The mechanical parameters (compressive strength, elastic modulus, and strain characteristics) will be compared at varying bedding angles and moisture conditions. Consideration will be given to the determination of anisotropy in power as well as failure mode transitions, such as composite tensile shear failure, shear slip, and tensile splitting. It has been previously demonstrated that these failure modes are highly affected by the structural plane orientation and water content (Yao et al. 2019). The effect of hydro-mechanical coupling on crack initiation and propagation will also be evaluated, and it should focus on the contribution of pore water to the formation of the fracture (Zhao, Zhang, and Lei 2021). Typical stress-strain responses under dry and saturated conditions are shown in Figure 8.

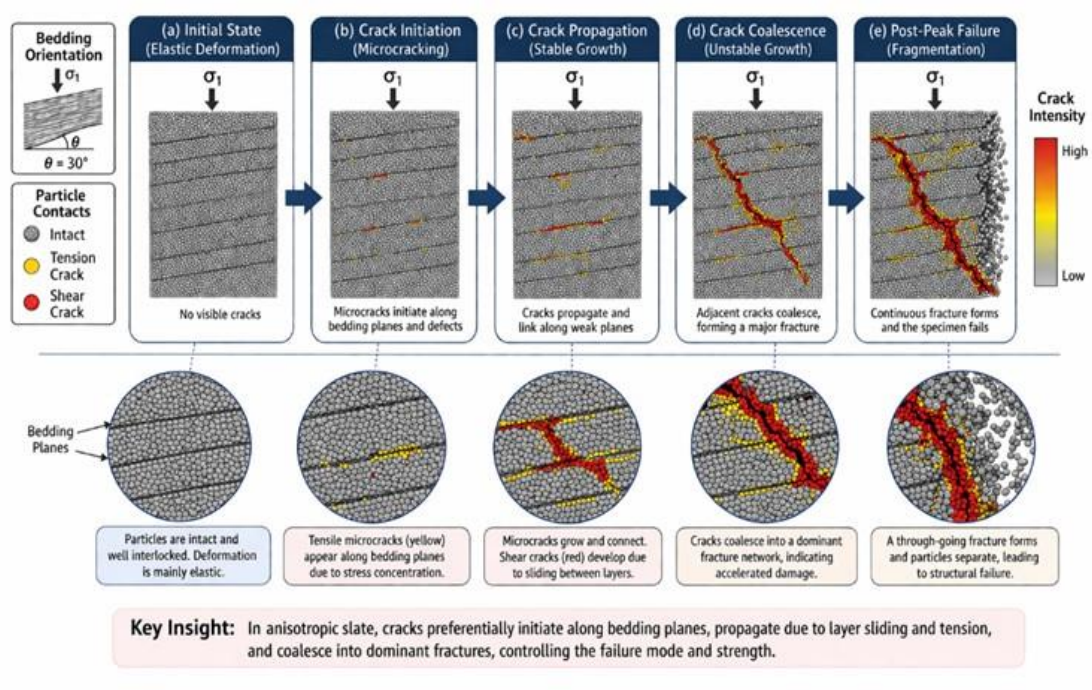

Figure 8. Stress-Strain Curves of Slate under Dry and Saturated Conditions

Proposed comparative framework for evaluating the influence of bedding angle and moisture condition on the mechanical properties and failure behavior of anisotropic slate in Table 3.

Table 3. Effect of Bedding Angle and Moisture on Mechanical Properties

Bedding Angle (°)	Condition	Compressive Strength	Elastic Modulus	Failure Mode	Crack Pattern
0°	Dry	High	High	Tensile splitting	Vertical cracks
15°	Dry	Moderate-high	Moderate	Composite	Mixed cracks
30°	Dry	Low	Moderate	Shear-slip	Inclined cracks
45°	Dry	Minimum	Low	Shear dominant	Sliding failure
60°	Dry	Increasing	Moderate	Composite	Mixed
75°	Dry	High	High	Tensile	Vertical
90°	Dry	Very high	High	Tensile splitting	Parallel cracks
0°	Saturated	Reduced	Reduced	Tensile	Extended cracks
45°	Saturated	Very low	Low	Shear-slip	Lubricated planes
90°	Saturated	Reduced	Moderate	Tensile	Wide fractures

4.4 Numerical Modeling (DEM PFC)

The Discrete Element Method (DEM) Particle Flow Code (PFC) will be used to do numerical simulations in order to complement the laboratory experiments. DEM in particular is particularly useful in the modeling of rock behavior because it is a micro-mechanical description of the behavior of fractures (Chen et al. 2023). A slate numerical model that is anisotropic will be developed and calibrated using experimental data. The parameters of the model such as particle rigidity, bond strength, and coefficient of friction will be varied to obtain observed stress-strain behavior and mode of failure. The crack initiation, propagation and coalescence will be examined by conducting simulations at different bedding angles and hydro conditions. Previous studies have already demonstrated that PFC can be used to simulate the behavior of anisotropic rocks and reproduce experimental failure modes (Yin et al. 2019). Numerical modeling parameters of the DEM/PFC model and their importance in the modeling of crack initiation, crack propagation, and the evolution of failure in anisotropic slate in Table 4.

Table 4. DEM Numerical Modeling Parameters (PFC)

Parameter	Symbol	Description	Role
Particle stiffness	kn, ks	Normal & shear stiffness	Controls deformation
Bond strength	σb	Inter-particle bonding	Crack initiation
Friction coefficient	μ	Sliding resistance	Shear failure
Porosity	n	Void ratio	Fluid flow behavior
Water pressure	Pw	Pore pressure	Hydro-mechanical coupling
Contact model	—	Linear/parallel bond	Behavior simulation
Calibration	—	Lab data matching	Model validation

The numerical model will be employed in this research to: find out the locations of stress concentration, trace crack growth and fracture networks, and determine failure mode transition critical thresholds. The technique gives a more intimate insight of micro-mechanical processes, which are experimentally not readily observed (Fu et al. 2024). The DEM-based simulation of crack initiation, propagation, and coalescence is illustrated in Figure 9.

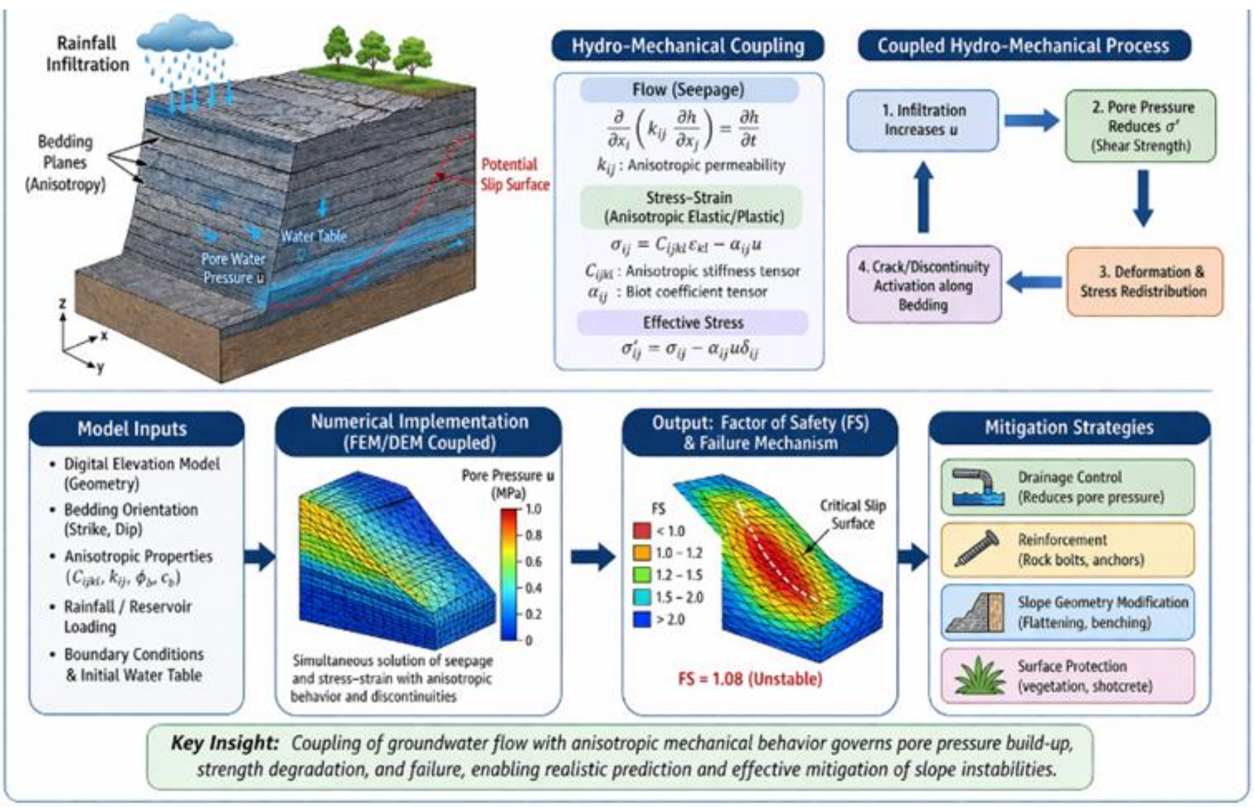

Figure 9. DEM Simulation of Crack Initiation, Propagation, and Coalescence in Anisotropic Slate

4.5 Slope Stability and Environmental Application

The laboratory and numerical results will be further applied to slope-scale applications to measure geo-hazards to the environment. Anisotropic mechanical properties and hydro-mechanical coupling effects will be included in the development of a slope stability model. Limit equilibrium (LEM) and numerical (FEM/DEM) methods can both be used to test slope stability under varying environmental conditions. The hydro-mechanically coupled slope stability modeling framework is presented in Figure 10.

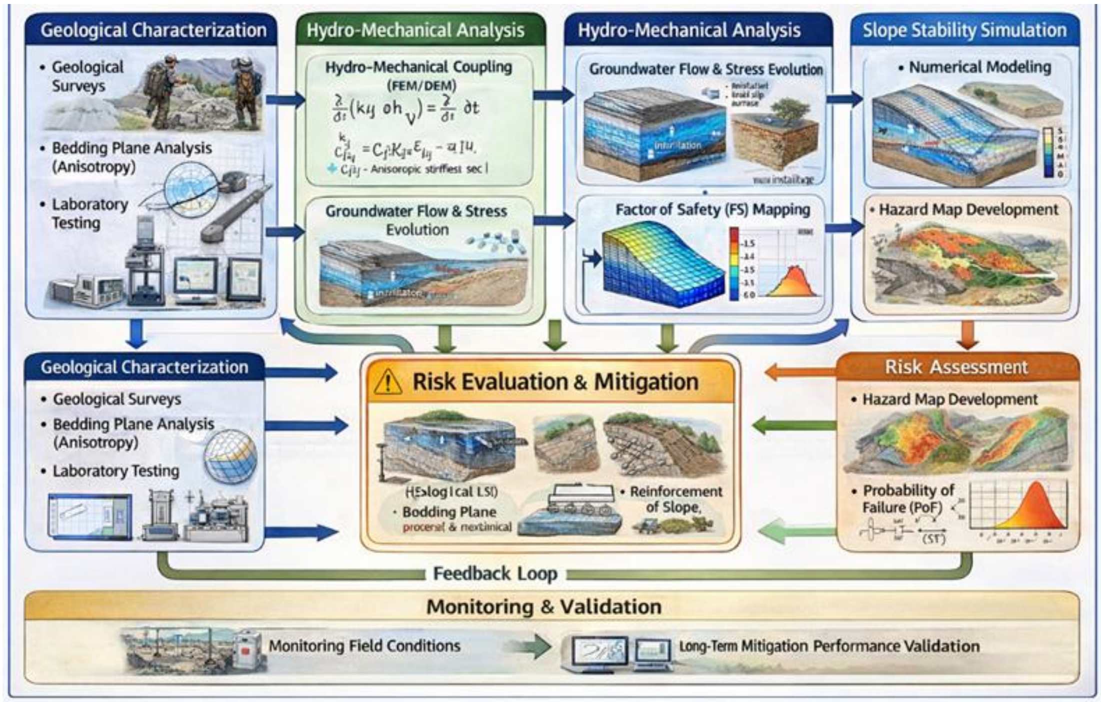

Figure 10. Hydro-Mechanically Coupled Slope Stability Model for Anisotropic Rock Masses

Principal geotechnical and hydro-mechanical parameters considered in slope stability assessment and geo-hazard evaluation of anisotropic rock masses in Table 5.

Table 5. Slope Stability Parameters under Hydro-Mechanical Conditions

Parameter	Description	Source	Influence on Stability
Cohesion (c)	Shear resistance	Lab tests	High impact
Friction angle (φ)	Shear strength	Lab tests	High impact
Bedding orientation	Structural anisotropy	Field/lab	Critical
Pore water pressure	Water effect	Hydro analysis	Reduces stability
Seepage force	Flow-induced force	Numerical	Triggers failure
Unit weight	Rock density	Lab	Moderate
Crack density	Fracture intensity	DEM	Weakens slope

The factors that will be taken into consideration in the model include: (i) bedding discontinuities and structural orientation, (ii) water forces and seepage, and (iii) redistribution of stress and fracture. The proposed framework will be tested using case studies that pertain to the topic of reservoir slopes, water diversion projects, or landslides that occur as a result of rainfall. It has been prioritized in previous studies that hydro-mechanical coupling contributes significantly to slope instability, especially in anisotropic rock masses (Song et al. 2024). Incorporation of laboratory-derived parameters in the slope models improves the accuracy of the prediction, and it creates a more realistic measure of geo-hazard risk (Tchuwa and Makande 2025). The integrated framework for geo-hazard risk assessment and mitigation under hydro-mechanical conditions is illustrated in Figure 11.

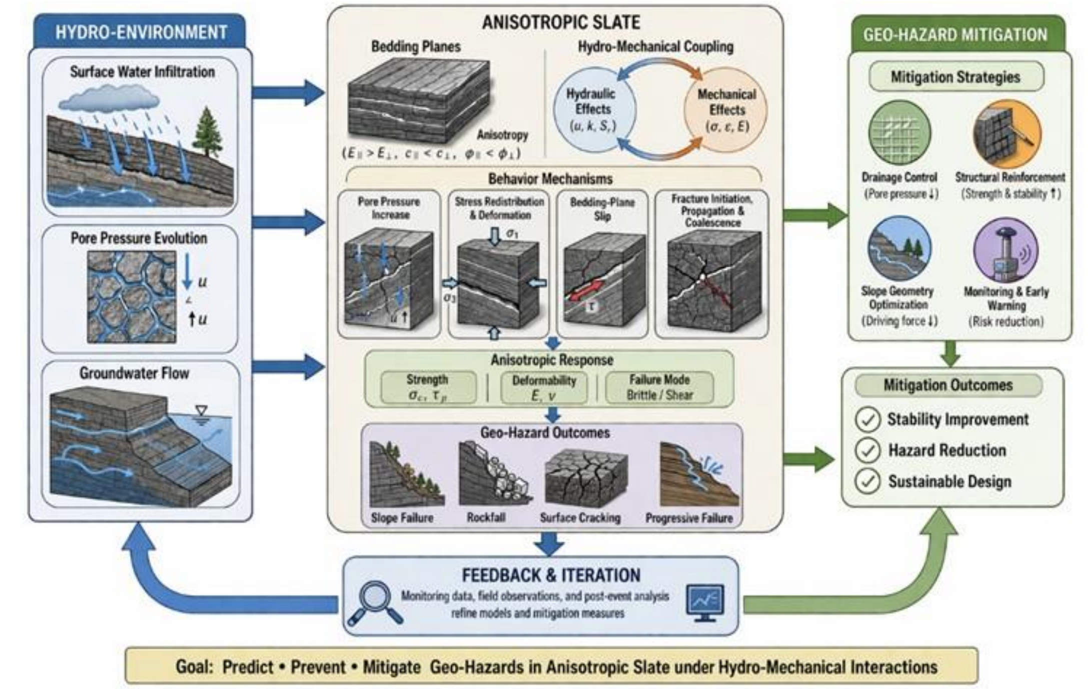

Figure 11. Framework for Geo-Hazard Risk Assessment and Mitigation under Hydro-Mechanical Conditions

4.6 Data Analysis Techniques

The analysis of data will be conducted both quantitatively and qualitatively. The correlation between the bedding angle, water content, and mechanical properties will be determined by statistical means. The key parameters that affect the behavior of rocks and slope stability will be realized through sensitivity analysis. The failure modes will be characterized according to the observed pattern of cracks and the results of numerical simulations. A comparative analysis of experimental and numerical data will validate the modeling method. This combined discussion will offer an equalized view of the hydro-mechanical procedures in anisotropic slate and its symbolism to environmental hazards of geo-hazards (Zargarbashi 2011).

5. Anticipated Conclusions and Contributions

5.1 Scientific Contributions

It is hoped that the present study will contribute to the knowledge about hydro-mechanical behavior in anisotropic slate, especially concerning the change in strength, the nature of deformation, and the failure processes. They expect to find, based on previous results, a strong dependence of compressive strength and elastic properties on the bedding orientation, with the typical U-shaped relationship between strength and inclination angle. The study will also measure the effect of water saturation on these relationships, which cause the decrease in strength and alteration in deformation stages caused by weakening interlayer bonding and enhanced by pore pressure. Moreover, the research will give a better insight into the failure mode transition under the conditions of hydro-mechanical coupling. It will be founded on previous sets of tensile shear, shear-slip, and tensile splitting failures of slate. It will determine crucial bedding angle and water conditions thresholds linked with the changes. Better constitutive models of anisotropic rocks will be formulated with these discoveries, and predictive capability in rock mechanics will be enhanced.

5.2 Engineering Contributions

The outcome of the current research will be very useful engineering-wise in designing and stability analysis of structures in which layered rock masses are taken into account. A set of analytical laboratory experiments with the appropriate computer-based simulation will probably lead to a validated DEM model structure that is able to model the exact crack propagation and the formation of cracks in anisotropic slate. Such a framework will enable the engineers to: (i) anticipate the reduction of strength under various conditions of hydro, (ii) determine significant planes of structural planes that may be unstable, and (iii) evaluate the impacts of infiltration of water on slope and underground structures. These skills are particularly required in infrastructure work such as tunnels, slopes, and reservoirs where the characteristics of the anisotropic rocks and hydro-mechanical connection are a significant contributor to stability. The result will then be applicable in the safer and more efficient engineering design practices.

5.3 Environmental and Geo-Hazard Contribution

The proposed study will further advance the science of the environment and mitigation of geo-hazards through the enhancement of knowledge on the mechanism of slope instability in anisotropic rock masses. It is also anticipated that the research will portray how the hydro-mechanical processes, such as infiltration of water and stress variations caused by seepage, play an important role in the development and advancement of slope failures. The study will have a predictive framework that can be used to determine the geo-hazard risk in water-related sites, such as the banks of reservoirs and slopes under rainfall, by incorporating laboratory-derived parameters in slope-scale models. With the help of this framework, it will be possible to: (i) early detection of unstable slope conditions, (ii) better evaluation of risk in landslides and rockfalls, and (iii) formulation of mitigation measures of sustainable infrastructure. Moreover, the research will lead to sustainable engineering activities because it will connect rock mechanics and geologically advanced geologies to environmental processes, thus helping to design an efficient infrastructure system that is resilient to geologically advanced geographies (Basu, Misra, and Puppala 2015).

5.4 Integrated Contribution

In general, the anticipated outcomes of this study will be a multi-scaled and comprehensive anisotropic slate behavior during hydro-mechanical coupling to fill the gap between the laboratory, numerical, and field scales. The combination of these strategies helps overcome major limitations of the existing literature. It provides a feasible way forward in enhancing scientific understanding as well as engineering practice in rock mechanics, engineering geology, and environmental geo-hazard control (Wang and Nanehkaran 2024).

6. Innovation and Novelty

The study presents a few original points that contribute to the development of the existing level of knowledge in the field of rock mechanics, engineering geology, and environmental science, especially when considering the anisotropic slate and hydro-mechanical interaction.

6.1 Overview of Hydro-Mechanical Coupling

One of the key discoveries of this paper is the clear incorporation of hydro-mechanical coupling in the study of anisotropic slate behavior. Although the effects of water on the strength of rocks or the study of anisotropic mechanical properties have been discussed independently in prior studies, very few studies have investigated the two factors in a comprehensive system. The current literature proves that water decreases compressive strength and changes the process of failure in layered rocks. Still, the relationship between structural anisotropy and hydro-mechanical processes is poorly comprehended. This gap is filled in the present study, which examined the interactions involving water infiltration, pore pressures, and interlayer weakening to affect strength anisotropy and changes in failure modes (Zhao et al. 2024).

6.2 Multi-scale Research Framework (Laboratory to Numerical to Field)

The other important innovation is the design of a multi-scale framework, which relates to both laboratory-scale observations and numerical modeling and field applications. Most of the past research is restricted to either laboratory experiments or numerical modeling, without a clear relationship of scale. The combination of experimental data, simulations of DEM-based models, and slope stability modeling through current research allows for the development of a more complete picture of rock behavior at varying scales. The simulation of the crack propagation and failure evolution using PFC further increases the capability of capturing the micro-mechanical processes that govern the macroscopic behavior (Li et al. 2022).

6.3 Determination of Critical Failure Thresholds in Hydro-Mechanical Conditions

The research will find the key bedding angle and the hydro conditions that are critical in defining changes between various failure modes. It has been established in previous studies that anisotropic rocks undergo different failure modes depending on the structural plane orientation. However, the boundaries between them under hydro-mechanical coupling are not well-defined. With the combination of experimental and numerical methods, this study will set up quantitative standards for predicting the transition of failure mode; this project will be of great importance for both theoretical and practical applications in rock mechanics (Stead, Eberhardt, and Coggan 2006).

6.4 Rock Mechanical Calibration with Environmental Geo-Hazard Reduction

One of the most significant novelties of this study is the explicit connection between the geo-hazard mitigation of environmental issues and rock mechanics. Although conventional studies emphasized mechanical behavior, this study has extended the study to environmental applications, such as slope stability, landslides, and reservoir bank failures. Hydro-mechanical processes are identified as some of the major causes of geo-hazards, especially in water-sensitive regions (Xue et al. 2026). These processes have been integrated into a predictive framework that makes the study a part of developing sustainable engineering solutions to hazards prevention and risk reduction.

6.5 Numerical Anisotropic Rock System Modeling

The suggested study also facilitates the use of numerical modeling methods, especially the DEM-based methods on the anisotropic rock systems. Though DEM has been extensively applied to simulate rock behavior, the usage of the method to model hydro-mechanical coupling in layered rocks is scarce. This work will improve the model calibration and validation, which will make the simulation more reliable in predicting the process of crack propagation and failure. These improvements are vital to the creation of powerful engineering design and hazard evaluation tools (Hardison and Hallowell 2019).

6.6 Novel Contribution in Research

This research is novel in that it applies a multi-disciplinary strategy, which integrates hydro-mechanical coupling, anisotropic rock behavior, multi-scale modeling, and environmental geo-hazard applications. This holistic formulation does not only fill major gaps in existing literature but also provides useful mechanisms to improve slope stability assessment and sustainability in the creation of infrastructure in not-so-simple geology. The suggested plan offers a reasonable chain of basic research and application, including the combination of experimental, numerical, and environmental factors. This systematic arrangement is consistent with the optimal practice of the research of rock mechanics. It offers an important way towards the attainment of the research goals in addition to sustainable geo-hazard mitigation. Mapping of research innovation, existing knowledge gaps, and the proposed study's original contributions to anisotropic rock mechanics and environmental geo-hazard mitigation in Table 6.

Table 6. Research Contribution and Innovation Mapping

Innovation Aspect	Existing Studies	Proposed Study Contribution
Anisotropy analysis	Studied separately	Integrated with hydromechanics
Hydro-mechanical coupling	Limited focus	Fully coupled framework
Experimental work	Isolated lab studies	Multi-condition experiments
Numerical modeling	DEM used	DEM + validation
Scale integration	Missing	Lab → Numerical → Field
Geo-hazard application	Limited	Full slope stability model

7. Conclusion

The study of the hydro-mechanical properties of anisotropic slate and its implications on sustainable slope stability and environmental mitigation geo-hazard will be done in this research proposal. The study fills major gaps in the current body of knowledge regarding the behavior of anisotropic rocks under coupled conditions by combining laboratory tests, numerical modeling and slope-scale techniques. The proposed work relies on the existing research that demonstrates that the bedding orientation and water significantly affect the strength, deformation, and failure of rock that is generated at the interface between a multi-scale and a multi-physics model. The method enables the representation of the behavior of rock masses in a more realistic way and provides superior tools in predicting instability in engineering as well as the environmental environment. Both the scientific and engineering worlds will use the expected findings and warrant more secure and sustainable infrastructure development in geologically intricate and water-sensitive environments. Besides, the addition of the hydro-mechanical processes to the slope stability assessment will enhance the predictive and mitigation potential of landslides or reservoir bank collapses geo-hazards. To sum up, the intended study provides an innovative application-oriented and interdisciplinary study that advances knowledge in rock mechanics, engineering geology, and environmental geo-hazard science while addressing the fundamental research gaps in the hydro-mechanical behavior of anisotropic rock.

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Data availability: The statistics supporting the outcomes of this research are accessible upon reasonable request from the first author.

Declarations

Ethical approval: Not applicable
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