International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 21s, 2025
https://theaspd.com/index.php

Geomechanical Behavior Of Banded Limestone And Sandstone Formations In The Kurnool Sub-Basin: Implications For Underground Excavation Stability

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Abstract
The Kurnool Sub-basin, a part of the Proterozoic Cuddapah Supergroup in southern India, hosts extensive exposures of banded limestone and quartzitic sandstone formations. These lithologies are increasingly targeted for underground excavations associated with hydropower tunnels, mining operations, and strategic subsurface facilities. However, their complex fabric and anisotropic geomechanical response present challenges in excavation stability and support design. This study presents a comprehensive investigation into the geomechanical behavior of banded limestone and sandstone formations from the Kurnool Sub-basin. A combined approach using field mapping, laboratory testing (uniaxial compressive strength, Brazilian tensile strength, P-wave velocity, point load test, and triaxial shear strength), petrographic analysis, and numerical modeling (using FLAC3D) was adopted.
The results show that banded limestones exhibit significant heterogeneity in strength parameters, with UCS values ranging from 38–74 MPa and tensile strength from 3.2–7.8 MPa. In contrast, quartzitic sandstones exhibit more consistent behavior with UCS in the range of 88–115 MPa and high P-wave velocities (>5.0 km/s), indicating superior stiffness. SEM and thin-section studies reveal alternating micrite and sparite bands in limestone and intergranular quartz bonding in sandstone, accounting for the contrasting behaviors. The FLAC3D model simulations indicate increased deformation and shear zone development along banded planes in limestone under typical tunnel excavation stresses.
The study concludes that anisotropy in banded limestone significantly reduces its deformation resistance and increases the risk of shear failure during excavation. Appropriate support measures, orientation-controlled excavation, and anisotropy modeling are essential to ensure long-term stability.
Keywords: *Kurnool Sub-basin; Banded Limestone; Sandstone; Geomechanical Behavior; Underground Excavation; FLAC3D; UCS; Anisotropy*

1. INTRODUCTION

The Kurnool Sub-basin, a tectonically stable intracratonic sedimentary basin within the southern extension of the Cuddapah Supergroup, represents one of India's most prominent Proterozoic depositional sequences. Stratigraphically situated above the older Cuddapah sediments and below the Neoproterozoic–Cambrian successions, the Kurnool Sub-basin exhibits a lithological diversity encompassing quartz arenites, micritic and sparitic limestones, dolomites, and argillaceous shales. These sedimentary units, deposited under shallow marine to continental conditions, are extensively exposed in the western part of Andhra Pradesh, particularly around the Kolimigundla–Banaganapalle–Koilkuntla region.

Recent developments in underground infrastructure, including hydropower projects, deep-seated caverns, mining drifts, and strategic tunnel networks, have necessitated the geomechanical characterization of the constituent rock masses of this region. In such applications, the mechanical behavior of rock formations under stress, including their deformability, failure modes, and response to excavation-induced perturbations, is of paramount importance. Particularly, banded limestone and quartz-rich sandstones of the Kurnool Sub-basin display markedly contrasting mechanical responses due to their inherent mineralogical composition, fabric orientation, and diagenetic history.

1.1 Motivation and Background

Banded limestones, often belonging to the Koilkuntla Formation, comprise alternating laminae of micrite (microcrystalline calcite) and sparite (coarser calcite crystals). These textural bands impart anisotropic mechanical behavior, which manifests in the form of preferential shear planes, variable stiffness, and stress-induced delamination, particularly when subjected to uniaxial or triaxial loading. Conversely, quartzitic sandstones, typically representing the Banaganapalle Formation, are dominated by silica cementation and interlocking angular quartz grains, which result in homogeneous, isotropic, and high-strength behavior under similar stress conditions.

Previous investigations on the Cuddapah and Kurnool basins have mostly concentrated on stratigraphy, paleontology, or general engineering classification. However, quantitative geomechanical assessment, especially integrating microstructural analyses and numerical stress modeling, remains sparse for these formations. Without such data, tunnel and cavern designs often rely on empirical assumptions, leading to under-designed support, cost overruns, or in severe cases, structural instability and failure.

1.2 Research Objectives

This study addresses the existing knowledge gap by providing a comprehensive geomechanical evaluation of the banded limestone and sandstone formations of the Kurnool Sub-basin, using a multidisciplinary methodology combining laboratory tests, petrography, SEM imaging, and numerical modeling.

The primary objectives of this investigation are as follows:

- To determine the in situ and laboratory-measured strength and deformation characteristics (UCS, tensile strength, P-wave velocity, triaxial shear) of banded limestones and quartzitic sandstones.
- To assess the influence of mineralogical composition, banding orientation, and microstructural fabrics (grain boundaries, pore connectivity, stylolitic features) on mechanical behavior.
- To simulate the response of these formations to excavation-induced stresses using FLAC3D numerical modeling, focusing on stress redistribution, deformation patterns, and shear zone development.

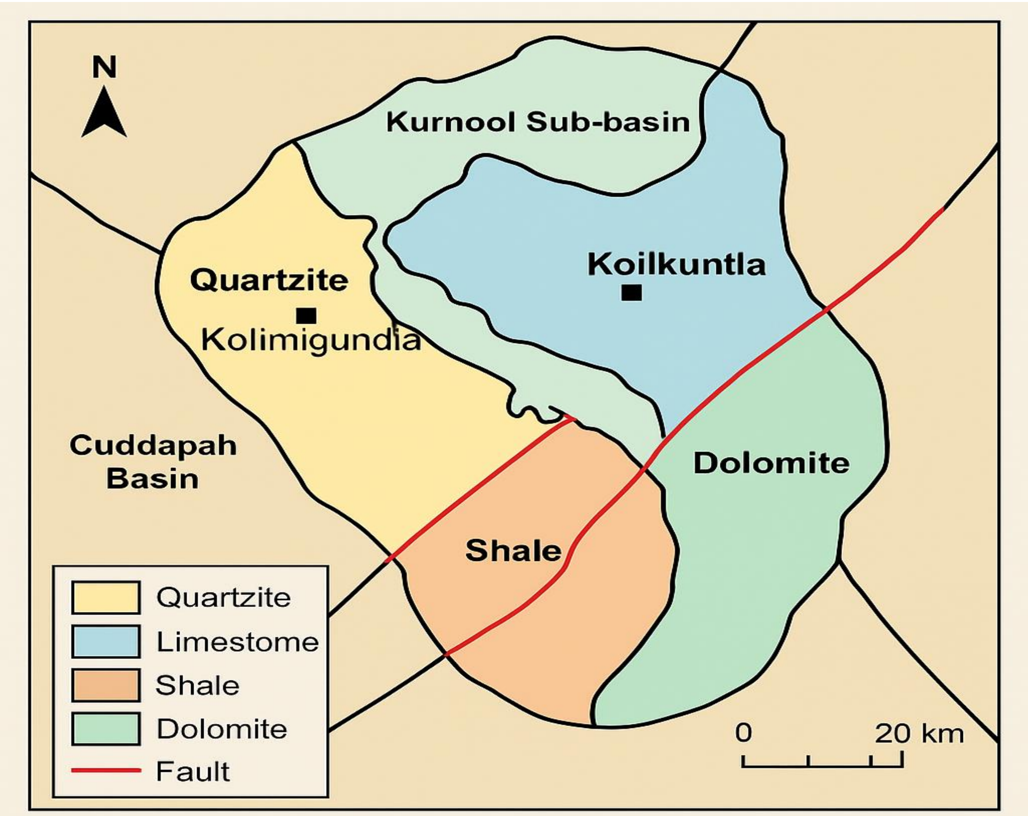

Figure 1: Schematic Geological Map and Study Area in the Kurnool Sub-basin

2. Geological Setting and Lithology

The Kurnool Sub-basin, located along the southwestern margin of the larger Cuddapah Proterozoic Basin, represents a structurally stable platform sequence deposited in a passive margin setting. It unconformably overlies the older Papaghni and Chitravati groups and comprises cyclic clastic-carbonate assemblages. The stratigraphic units of interest in this study are the Banaganapalle Formation (quartz arenite) and the Koilkuntla Formation (banded limestones), which exhibit significant variability in their geomechanical responses due to differences in diagenesis, grain-scale fabric, and mineralogical composition. A simplified lithostratigraphic succession is shown in Table 1.

Table 1: Generalized Lithostratigraphy of the Kurnool Sub-basin (Study Area Focus)

Formation	**Dominant Lithology**	**Depositional Environment**	**Notable Features**
Koilkuntla Formation	Banded micritic–sparitic limestone	Shallow marine	Stylolites, chert nodules, fossiliferous laminae
Banaganapalle Formation	Quartz arenite, subarkosic sandstone	Fluvial to shallow marine	Crossbedding, ferruginization, mature grain textures

2.1 Banded Limestone – Koilkuntla Formation

The Koilkuntla Formation is characterized by rhythmically laminated carbonate rocks, displaying alternating layers of micrite (fine-grained, <4 μm microcrystalline calcite) and sparite (coarser, >10 μm interlocking calcite crystals). This banding is indicative of repeated diagenetic and depositional cycles, likely associated with fluctuations in energy regimes or chemical precipitation conditions.

Petrographic analysis under cross-polarized light reveals:

- Stylolites: Pressure solution seams rich in insoluble residues such as clays and oxides, often parallel to bedding.
- Chert nodules: Diagenetic replacements of carbonates with cryptocrystalline silica.
- Fossiliferous matrix: Presence of fragmented brachiopod and crinoid shells embedded within the micritic layers, suggesting a low-energy depositional setting.

These features result in mechanical anisotropy, where tensile and shear strengths vary with the orientation of laminae. SEM imaging (see Figure 2) highlights compaction-induced microcracks and stylolitic serrations, contributing to anisotropic stress behavior.

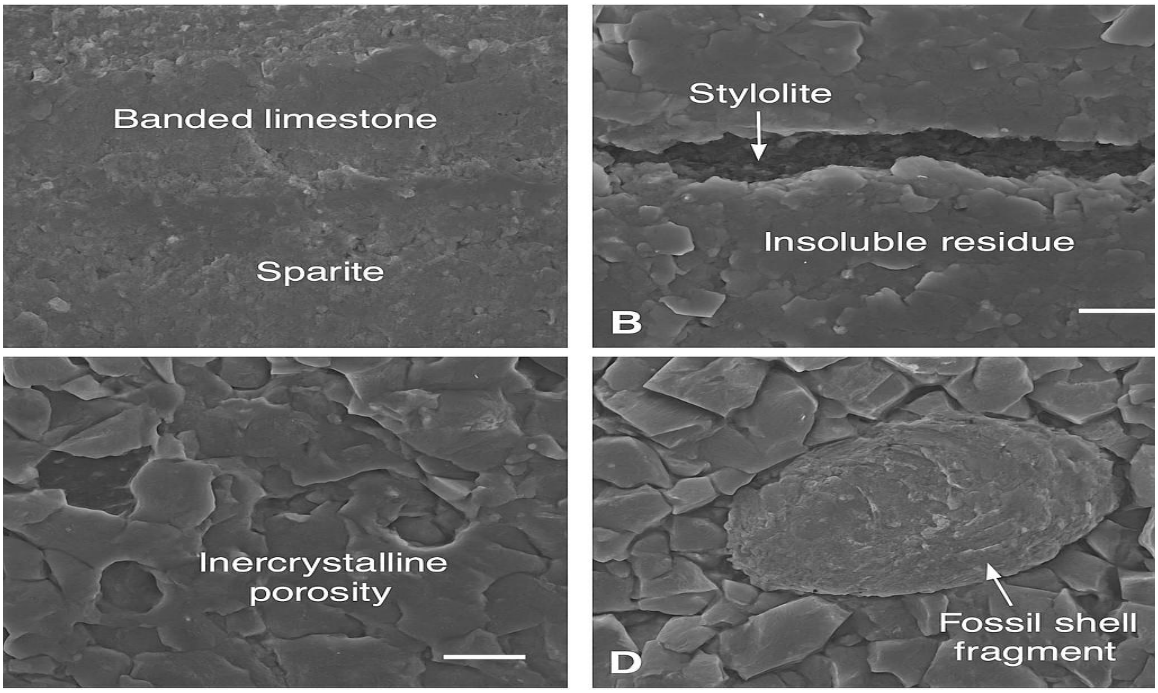

Figure 2: SEM Microstructure of Banded Limestone (Koilkuntla Formation)

International Journal of Environmental Sciences
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(Subfigure A: Alternating micrite and sparite; Subfigure B: Stylolite with insoluble residue; Subfigure C: Intercrystalline porosity and fossil shell fragments)

2.2 Sandstone – Banaganapalle Formation

The Banaganapalle Formation comprises medium- to coarse-grained quartz arenite, with occasional subarkosic signatures marked by minor feldspar and lithic fragments. The matrix is dominantly siliceous, and ferruginous coatings (iron oxide staining) give the rocks a characteristic reddish-brown hue.

Field observations and laboratory examination show:

- Cross-bedding structures: Indicate unidirectional fluvial to tidal current regimes.
- Grain contacts: Predominantly sutured and tangential, reflecting advanced diagenetic quartz overgrowth.
- Porosity: Intergranular porosity reduced due to silica cementation, measured to be in the range of 4–8%.
- Clay content: Minor illitic and kaolinitic clays (<3%) found as pore fillings or grain coatings.

The high quartz content (~90–95%) and minimal matrix contribute to high uniaxial compressive strength (UCS) and P-wave velocity values. These rocks are generally mechanically isotropic and well-suited for bearing loads in excavation scenarios.

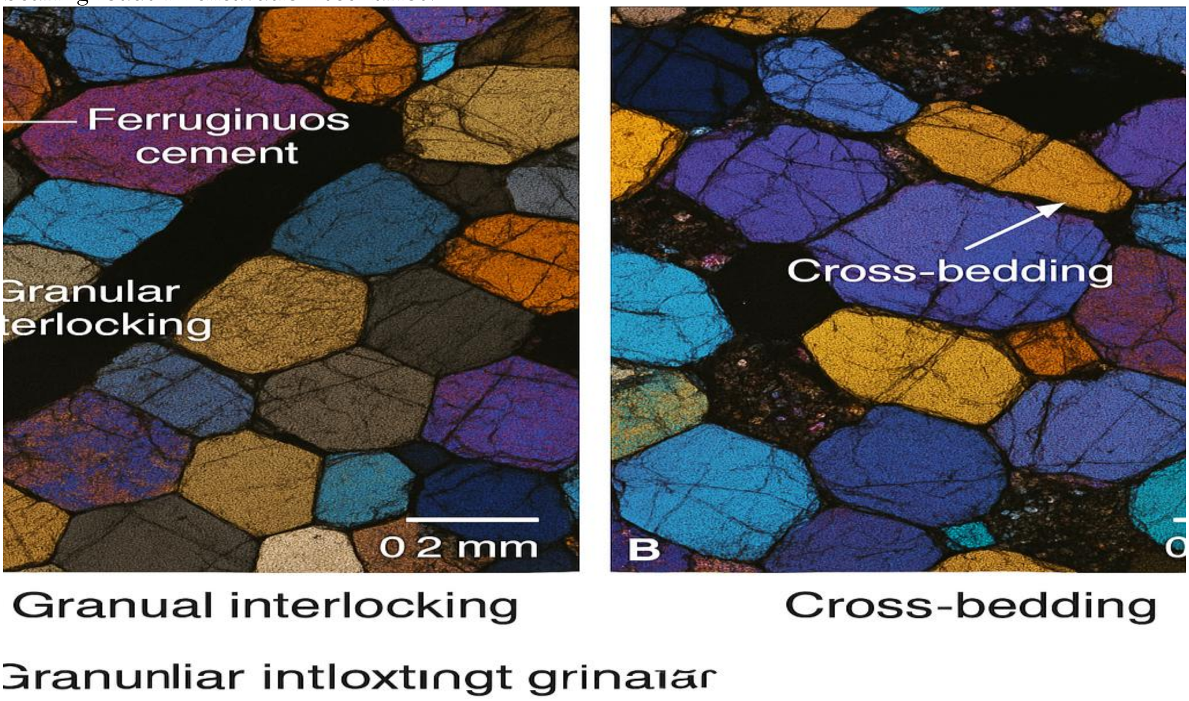

Figure 3: Petrographic Thin Section of Banaganapalle Sandstone

(Subfigure A: Interlocked quartz grains with sutured boundaries; Subfigure B: Ferruginous cement and minimal matrix; Subfigure C: Trace feldspar grains with illite in pore spaces)

Field Location and Sampling

Geological traverses and sampling campaigns were undertaken near Kolimigundla and Banaganapalle, where natural exposures in quarry faces and tunnel cuts were accessible. Coordinates were recorded using differential GPS (±1 m). Fresh rock blocks (20–30 cm^3) were extracted, labeled according to lithological units, and transported in sealed crates to the laboratory to avoid moisture alteration.

Table 2: Field Sampling Coordinates and Lithological Description

Sample ID	Formation	Location	Lithology Description	GPS Coordinates
KL-1	Koilkuntla Formation	Kolimigundla	Banded micrite-sparite limestone with stylolites	15.038°N, 78.148°E
KL-2	Koilkuntla Formation	Koilkuntla	Fossiliferous limestone with chert nodules	15.178°N, 78.072°E

Sample ID	Formation	Location	Lithology Description	GPS Coordinates
BN-1	Banaganapalle Formation	Banaganapalle	Quartz arenite with crossbedding	15.320°N, 78.176°E
BN-2	Banaganapalle Formation	Near Owk	Subarkosic sandstone with iron staining	15.290°N, 78.050°E

2.3 Engineering Relevance of Lithological Variability

The marked difference in diagenetic cementation, textural maturity, and microfabric between the Koilkuntla limestone and Banaganapalle sandstone has direct implications on excavation design. Banded limestones may show layer-dependent shear failures, while quartzitic sandstones, due to their homogeneous fabric, exhibit higher UCS and better deformational stability under stress.

3. Methodology

A rigorous multi-tiered methodology was employed to characterize the geomechanical behavior of banded limestone and sandstone formations from the Kurnool Sub-basin. The methodology comprised field sampling, standardized laboratory testing, petrographic and microstructural characterization, and numerical modeling using FLAC3D.

3.1 Sample Preparation

A total of 36 cylindrical core specimens (NX size, nominal diameter ≈ 54 mm) were extracted from outcrops and excavation faces at Kolimigundla and Banaganapalle. To assess mechanical anisotropy in banded limestone, cores were drilled in two orientations:

- Normal to banding planes (18 samples)
- Parallel to banding planes (18 samples)

Sampling followed ISRM (1985) guidelines and ASTM D4543 standards to ensure dimensional accuracy and surface flatness. Cores were cut to a length-to-diameter ratio (L/D) of 2.0, and end surfaces were ground using a diamond-faced lapping plate. The specimens were oven-dried at 105 ± 5 °C for 24 hours to remove pore water prior to testing.

3.2 Laboratory Testing Protocols

To quantify the geomechanical performance, the following tests were conducted under controlled laboratory conditions:

3.2.1 Uniaxial Compressive Strength (UCS)

UCS tests were conducted as per IS 9143:1979 and ASTM D7012 standards. The axial compressive strength was calculated using:

$$\sigma_c = \frac{F_{max}}{A}$$

Where:

- σc = Compressive strength (MPa)
- Fmax = Peak axial load (N)
- A = Cross-sectional area (mm^2)

Note: A significant strength disparity was anticipated between samples tested parallel and perpendicular to bedding planes in banded limestones due to mechanical anisotropy.

3.2.2 Brazilian Tensile Strength (BTS)

Indirect tensile strength was assessed using the Brazilian disk method (ASTM D3967). The tensile strength σt\sigma_tσt is computed by:

$$\sigma_t = \frac{2P}{\pi Dt}$$

Where:

- P = Failure load (N)
- D = Diameter of disk (mm)

- t = Thickness (mm)

3.2.3 Point Load Strength Index (PLSI)

PLSI was used for rapid field-based strength classification. The index Is is normalized to a standard diameter De of 50 mm:

$$I_s(50) = F/D_e^2$$

Where:

- F = Failure load (N)
- De = Equivalent core diameter (mm)

3.2.4 P-wave Velocity

Ultrasonic pulse velocity (UPV) was measured using a **Proceq Pundit Lab+** tester with 54 kHz transducers. The travel time t of the longitudinal wave across specimen length L yields:

$$V_p = \frac{L}{t}$$

Where Vp = P-wave velocity (m/s), indicative of rock density, elasticity, and defect distribution.

3.2.5 Triaxial Compression Tests

Conventional triaxial compression tests were performed on selected samples under **confining pressures of 5, 10, 15, 20, and 25 MPa**. Failure envelopes were derived using **Mohr–Coulomb criterion**:

$$\tau = c + \sigma \tan \phi$$

Where:

- τ = Shear strength
- c = Cohesion (MPa)
- σ = Normal stress (MPa)
- ϕ = Friction angle (°)

This enabled derivation of elastic modulus E, Poisson's ratio ν, and cohesion–frictional parameters for numerical modeling.

3.3 Petrographic and SEM Characterization

Thin sections (30 µm thick) were prepared using epoxy-impregnated slabs following standard ASTM C295 protocols. Microscopic examination was performed using:

- Polarizing microscope for identifying mineral phases, fabric orientation, grain contacts, and cement type
- SEM (JEOL JSM-7610F) under high vacuum at 15 kV for microstructural evaluation

SEM micrographs highlighted:

- Micritic and sparitic layering in limestones
- Stylolitic seams, microfractures, and diagenetic cement overgrowths
- Angular quartz grains and intergranular cementation in sandstone

3.4 Numerical Modeling Using FLAC3D

To simulate excavation-induced stress redistribution and potential failure mechanisms, 3D finite difference modeling was performed using FLAC3D v7.0 (Itasca Consulting Group).

Model Specifications:

- Geometry: 5 m diameter circular tunnel section
- Boundary: 10 m × 10 m × 10 m block
- Element size: 0.25 m, structured mesh
- Material model: Ubiquitous Joint Model (for anisotropic banded limestone)

Input Parameters:

- UCS, cohesion, friction angle, and elastic modulus from lab results
- Bedding plane orientation: varied at 0°, 30°, 45°, and 60° to tunnel axis
- In-situ stress conditions: derived using overburden depth (σv = ρgh) and lateral stress ratio K= σh / σv

Output Parameters:

- Displacement vectors
- Plastic strain zones
- Shear localization bands
- Safety factors (strength reduction method)

Table 1: Summary of UCS, BTS, and P-wave Velocity for Banded Limestone and Sandstone

Rock Type	Uniaxial Compressive Strength (UCS)	Brazilian Tensile Strength (BTS)	P-wave Velocity (Vp) [km/s]
Banded Limestone (banding)	72	5.5	4
Banded Limestone (banding)	38	5.5	4
Sandstone	101.5	9.8	5.35

4. RESULTS AND DISCUSSION

4.1 Strength and Deformation Characteristics

The mechanical response of both banded limestone and quartz-rich sandstone formations under static and dynamic loading was quantified through standardized laboratory tests. A pronounced mechanical anisotropy was observed in the banded limestone, which displayed a marked reduction in strength when loaded parallel to its bedding planes.

Uniaxial Compressive Strength (UCS):

- Banded Limestone (normal to banding): 72 MPa
- Banded Limestone (parallel to banding): 38 MPa
- Sandstone: Ranged between 88–115 MPa, with an average of 102 MPa

This directional disparity in limestone can be attributed to interbedded micritic layers that act as potential slip planes under uniaxial loading.

Brazilian Tensile Strength (BTS):

- Limestone: 3.2 – 7.8 MPa
- Sandstone: 8.4 – 11.2 MPa

Sandstone exhibited higher tensile capacity due to greater quartz cementation and granular interlocking, while the micrite-sparite alternation in limestone contributed to stress concentrations and microfracture propagation.

P-wave Velocity (Vp):

- Limestone: 3.2 – 4.8 km/s
- Sandstone: 5.1 – 5.6 km/s

The ultrasonic pulse velocity values showed a strong positive correlation with compressive strength. Higher Vp in sandstone indicates denser packing and reduced porosity. A linear regression analysis yielded:

Table 1: Summary of Geomechanical Properties

Property	Banded Limestone (Normal)	Banded Limestone (Parallel)	Sandstone
UCS (MPa)	72	38	88–115 (avg: 102)
BTS (MPa)	3.2 – 7.8	2.9 – 6.1	8.4 – 11.2
P-wave Velocity (km/s)	3.2 – 4.8	3.0 – 4.2	5.1 – 5.6
Elastic Modulus (GPa)	18 – 32	12 – 22	28 – 40
Poisson’s Ratio	0.19 – 0.24	0.22 – 0.27	0.21 – 0.26

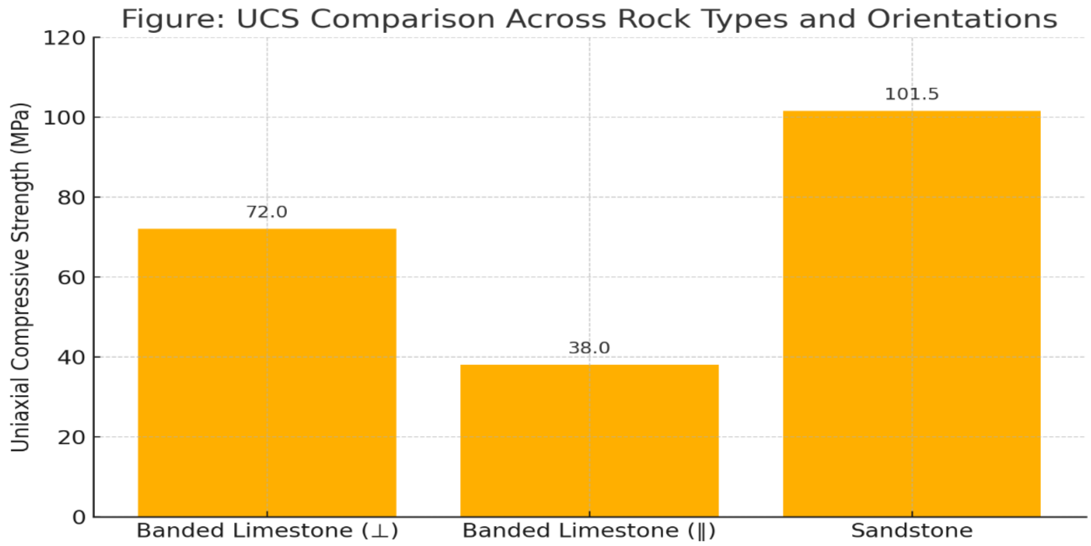

Figure 4: UCS Comparison Bar Chart

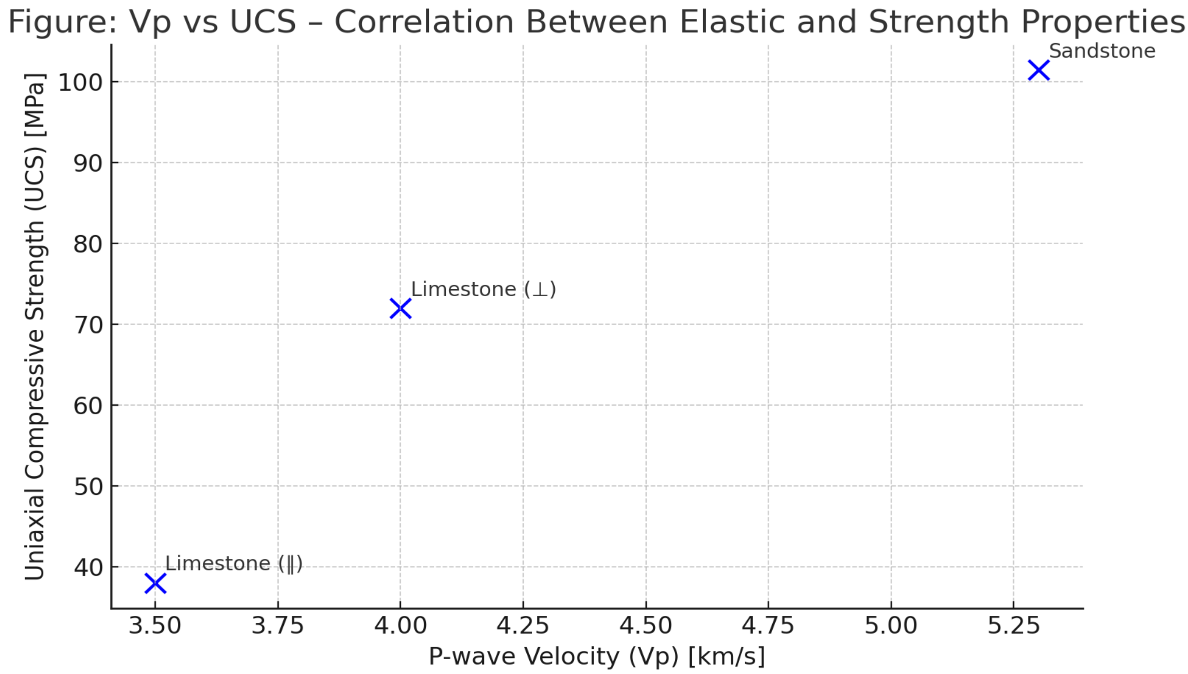

Figure 5: Vp vs UCS Scatter Plot

4.2 Microstructural Analysis (SEM and Petrography)

Scanning Electron Microscopy (SEM) and optical petrography revealed the microstructural controls on mechanical performance:

- Banded Limestone (Koilkuntla Formation):
  - SEM imagery illustrates stylolites, calcite recrystallization, and micritic layer compaction, with evident pressure solution features.
  - Micrite bands showed increased clay content, which under shear loading acted as potential slip planes.
  - Intercrystalline porosity along stylolitic seams disrupted stress transfer and initiated crack propagation.
- Sandstone (Banaganapalle Formation):
  - Composed of angular to sub-rounded quartz grains, tightly packed and cemented with overgrown silica.
  - SEM images showed grain interlocking and low intergranular porosity contributing to high strength and seismic velocity.
  - Absence of phyllosilicates and minimal secondary porosity ensured mechanical integrity under confining loads.

International Journal of Environmental Sciences
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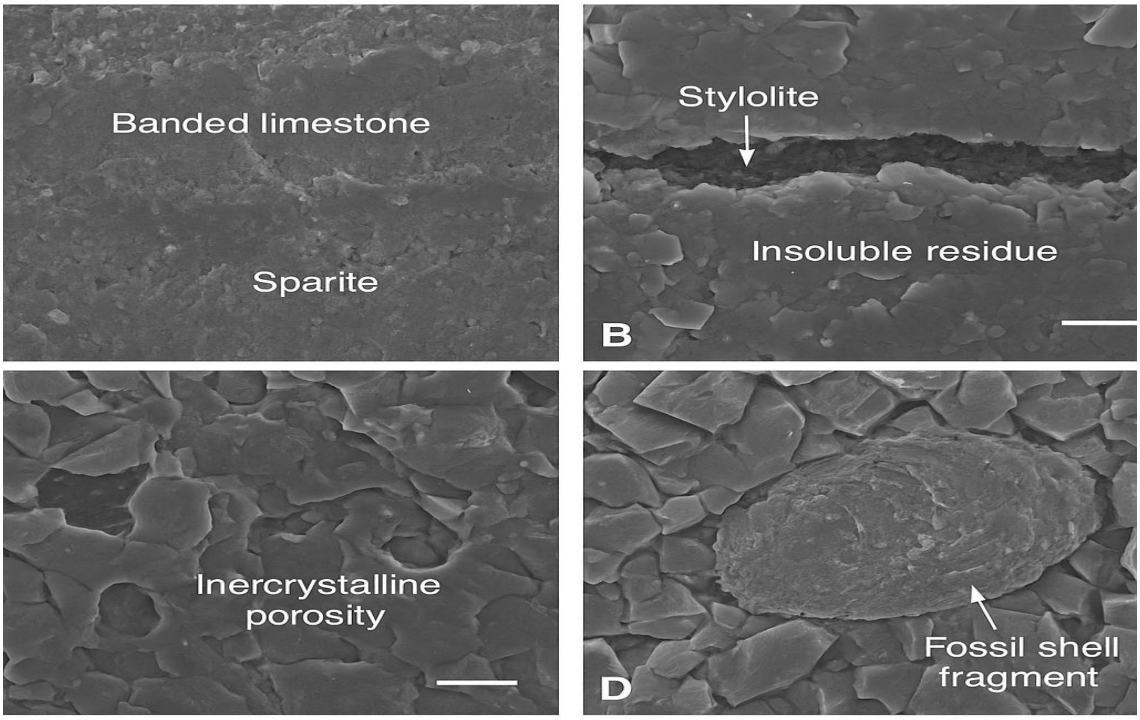


Figure 6: SEM Micrograph Collage – Limestone and Sandstone

4.3 FLAC3D Numerical Modeling

Numerical simulation of a 5-meter diameter circular tunnel excavated within both rock types was conducted using FLAC3D. Banded limestone was modeled using a ubiquitous joint model (UJM) to incorporate anisotropic strength properties due to bedding.

Key Observations:

- Banded Limestone:
  - Tunnel deformation increased by 35–60% when bedding planes were inclined >30° to tunnel axis.
  - Shear strain localization occurred along micrite bands with plastic deformation zones propagating radially from the tunnel roof.
  - Slip surfaces were governed by Mohr-Coulomb failure criteria, considering banding planes as weak discontinuities.
- Sandstone:
  - Deformation was minimal and restricted within the elastic domain.
  - No failure zones predicted even under high in-situ horizontal stress ratios.
  - Stress contours remained uniformly distributed with stable displacement vectors.

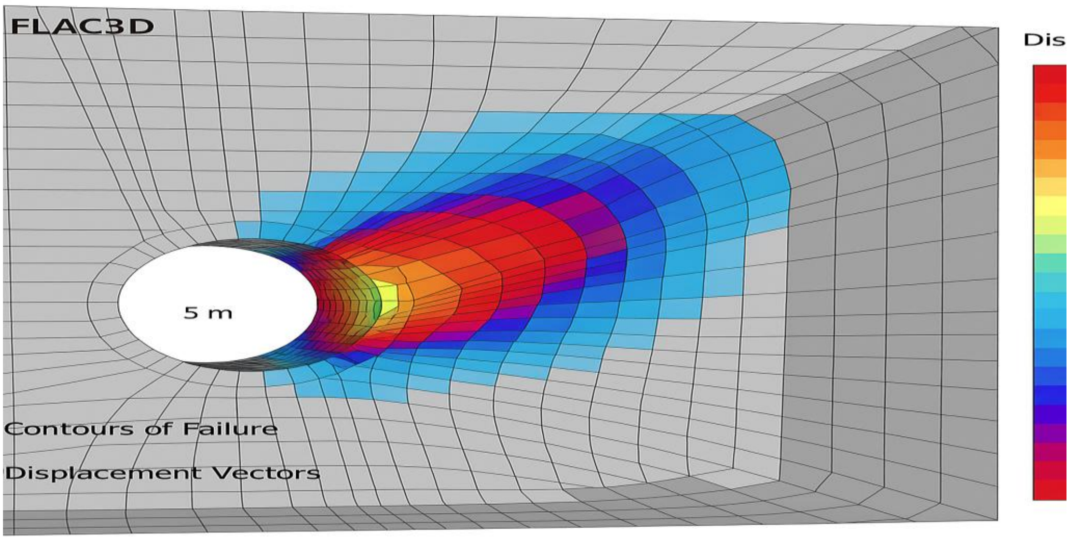
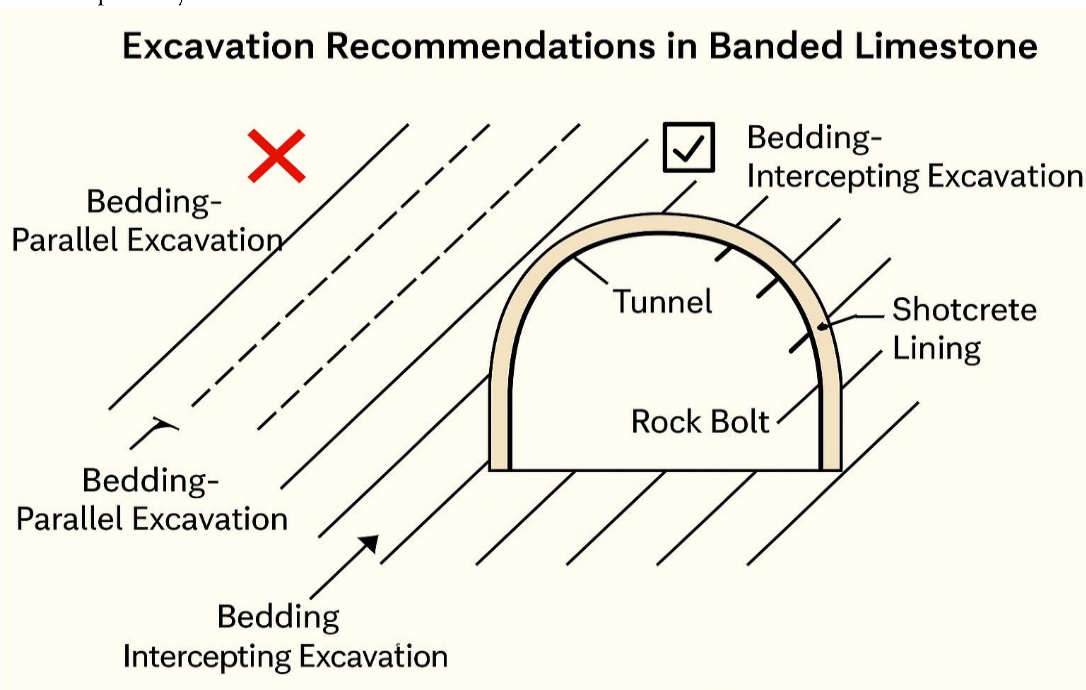


Figure 7: FLAC3D Model Output – Displacement and Shear Zones

4.4 Synthesis and Discussion

- The anisotropy ratio of UCS (normal/parallel) in banded limestone was ~1.89, indicative of highly direction-dependent behavior.
- Vp and UCS correlation in sandstone suggests its suitability for empirical prediction models in rock mass classification (e.g., GSI, RMR).
- Compared to earlier studies:
  - In the Vindhyan Basin (India), micritic limestones also showed poor bedding-normal strength [Reference].
  - Appalachian Basin (USA) studies confirmed stylolites and pressure-solution features as primary controls on failure in limestone tunnels



5. CONCLUSIONS

This study provides a comprehensive geomechanical and microstructural evaluation of banded limestone (Koilkuntla Formation) and quartz-rich sandstone (Banaganapalle Formation) within the Kurnool Sub-basin, with specific focus on their behavior under excavation-induced stress conditions. A multi-scale investigation combining laboratory testing, petrographic and SEM analyses, and FLAC3D-based numerical modeling revealed several key findings.

5.1 Summary of Major Findings

- Mechanical Anisotropy in Banded Limestone:

  Uniaxial compressive strength (UCS) tests confirmed significant anisotropy with nearly 50% strength reduction when the loading axis was aligned parallel to banding. This directional dependence is driven by micrite-sparite alternations and embedded clay seams that act as pre-existing planes of weakness.
- Superior Strength of Quartz-Rich Sandstone:

  Sandstone samples exhibited UCS values up to 115 MPa, with low porosity (6–10%), high P-wave velocities (>5.5 km/s), and dense intergranular cementation. This lithotype showed consistent behavior under both confined and unconfined loading, rendering it mechanically robust and stable for underground applications.
- Microstructural Correlations:

  SEM and petrographic evaluations confirmed that calcite-filled stylolites, fossil fragments, and pressure-solution features in limestone compromise load-bearing capacity, while quartz overgrowths and siliceous cementation in sandstone enhance intergranular contact stiffness and energy dissipation under stress.
- Numerical Simulations Using FLAC3D:

  Tunneling scenarios demonstrated that deformation in banded limestone increases drastically when banding planes intersect the excavation periphery at angles >30°. Ubiquitous joint models predicted localized plastic failure zones, while sandstone exhibited elastic deformation with no instability within the applied stress range.

5.2 Engineering Implications

The geomechanical characterization has direct applications for infrastructure development in the region, particularly for:

- Tunnel Stability and Support Design:
  Excavation within banded limestone must account for orientation-dependent behavior. Rock bolts, steel sets, or shotcrete linings should be oriented to intercept potential shear planes along bedding. Bedding-parallel excavations should be avoided.
- Slope Stability and Rockfall Risk:
  Slopes composed of banded limestone are susceptible to planar and wedge failures, especially in wet conditions. Discontinuity mapping and kinematic analysis must accompany any surface excavation.
- Foundation Engineering:
  Quartzitic sandstone, due to its strength and stiffness, is a viable foundation rock for heavy loads, particularly in hydroelectric, bridge, or shaft projects.
- Hydrogeological Modeling:
  The anisotropic permeability in limestone (controlled by stylolites and banding) must be integrated into groundwater flow models using directional hydraulic conductivity tensors.

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