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Geotechnical Challenges and Failure Mechanisms in Indian Underground Coal Mines: Roof Stability, Pillar Design and Floor Behaviour under Complex Geological Conditions

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Abstract

Underground coal mining in India is constrained by complex Gondwana geology, variable rock-mass quality, increasing extraction depths, and heterogeneous stress conditions. Weak laminated shale, jointed sandstone, high horizontal stresses, pillar degradation, floor instability, and mining-induced deformation frequently interact during underground extraction. This paper synthesizes the geotechnical evidence presented in the source report, focusing on roof and rib stability, pillar behaviour, floor response, stress redistribution, and associated failure mechanisms. Major Indian coalfields including Jharia, Raniganj, Singrauli, Talcher, Wardha Valley, and Godavari Valley are considered within the broader geological framework. Representative coal-measure rocks commonly exhibit fair-to-poor rock-mass quality, with RMR values generally ranging from 35 to 60. The reported high horizontal-to-vertical stress ratio of 1.5–3.0 at greater depths changes the dominant failure response from gravity-controlled instability toward stress-driven deformation. Field observations indicate roof convergence of 0.5–5 mm/day during development, increasing during depillaring. Numerical analyses demonstrate substantial reductions in roof sag and plastic-zone development following systematic reinforcement. Case studies from Jharia and Singrauli illustrate how delamination, wedge failure, rib spalling, interface shearing, moisture weakening, and abutment loading can combine into progressive instability. The synthesis indicates that site-specific characterization, calibrated numerical modelling, appropriate pillar dimensions, reinforcement, extraction sequencing, and continuous monitoring are necessary for reliable ground control under Indian conditions.

Keywords: Indian coalfields; roof stability; pillar design; floor heave; stress redistribution; rib spalling; rock mass classification; underground mining

1. Introduction

Coal remains a major component of India's energy supply. India's underground reserves include extensive deep-seated Gondwana coal resources. Surface extraction becomes less suitable as mining depth increases. Underground extraction consequently remains strategically relevant for resource recovery. The continuing importance of underground coal mining is also reflected in recent Indian research addressing underground excavation, mine safety, continuous-miner productivity, methane emissions, blasting, and smart-mining applications (Gopal Singh & Chaurasia, 2024; Singh et al., 2025; Tripathi & Chaurasia, 2025a, 2025b; Tiwari & Chaurasia, 2026a). The source report identifies underground production below five percent nationally. This limited contribution contrasts with India's substantial underground coal resource base. Greater underground production requires improved understanding of ground behaviour. Indian underground mines operate within unusually heterogeneous geological environments. Coal seams occur between shale, siltstone, sandstone, and clay-rich horizons. Rapid lithological changes produce strongly variable roof and floor responses. Tectonic structures introduce additional joints, faults, shear zones, and discontinuities. Historical workings further modify the present stress and deformation fields. Multiple-seam extraction creates interactions between adjacent excavations and old workings. These conditions complicate direct application of generalized design relationships. Roof instability remains one of the principal underground hazards. Laminated shale roofs can separate along persistent bedding planes. Joint intersections may generate wedges around roadways and intersections. Massive sandstone can behave differently from weak laminated shale. Competent sandstone may bridge openings and delay natural caving. Delayed caving subsequently increases abutment loading near extraction areas. Weak immediate roofs can then fail progressively beneath stronger strata. Pillar stability represents another central geotechnical design problem. These interacting geological and operational factors emphasize the need for systematic risk assessment and site-specific ground-control planning in underground coal excavations (Singh et al., 2025). Pillars carry redistributed overburden loads after excavation. Extraction progressively increases stress concentrations around remaining pillars. Rib spalling reduces the effective pillar load-bearing width. Pillar strength consequently depends upon geometry and damage development. Seam inclination can further modify pillar stress distribution. High depth and horizontal stress intensify these effects. Floor behaviour receives comparatively less attention during routine roadway design. Soft shale and clay-rich floor materials can deform substantially. Swelling and moisture sensitivity may accelerate roadway closure. Floor instability can reduce effective roadway dimensions and equipment clearance. Floor response also interacts with pillar loading and roof convergence. Consequently, floor behaviour should form part of integrated ground-control design. Backfilling and stowing can provide additional control over stress redistribution and post-extraction deformation, particularly where weak strata and subsidence are significant concerns (Yadav & Chaurasia, 2025). The source report combines theoretical analysis, field investigations, laboratory testing, classification, and numerical modelling. Its methodology uses RMR, Q-system assessment, stress analysis, and constitutive modelling. FLAC3D, RS2, and UDEC provide complementary numerical approaches. The models were calibrated against laboratory and field observations. Reported calibration errors for roof convergence remained within 10–18%. Recent developments in artificial intelligence and digital mining further indicate the potential for real-time geotechnical monitoring, predictive assessment, and intelligent safety management in underground mines (Singh & Chaurasia, 2024; Kushwaha & Chaurasia, 2026a, 2026b). The present paper reorganizes the source material around failure mechanisms. The emphasis remains on Indian coal-measure ground conditions and their implications for underground excavation stability, pillar design, extraction planning, support selection, and monitoring.

2. Geological and Geo-Mining Setting of Indian Coalfields

2.1 Gondwana coal-measure geology

Indian coal-bearing sequences predominantly belong to Gondwana formations. These sequences contain cyclically interbedded coal, shale, sandstone, and siltstone. Individual lithological units can change substantially over short distances. Such layering creates composite roof and floor behaviour. Mechanical contrasts between adjacent beds promote differential deformation. Weak bedding contacts can provide preferred separation surfaces. Indian coalfields exhibit considerable geological and geotechnical variability. Studies of Indian coal and coal-bearing formations have demonstrated the importance of mineralogical composition, petrographic characteristics and depositional conditions in determining coal and associated strata behaviour (Sahu et al., 2018; Panwar et al., 2017, 2019, 2020, 2021, 2022; Nath et al., 2023a, 2023b). The source report describes coal seams generally between 2–20 m thick. Shale partings commonly occur between stronger sandstone horizons. The resulting stratigraphic architecture controls roadway and pillar performance. Tectonic history has further modified the rock-mass structure. Faulting increases discontinuity density and creates locally disturbed ground. Igneous intrusions occur within some coalfield sectors. Jharia contains documented dykes and extensive tectonic disturbance. Historical extraction also produces secondary fractures and damaged zones. These features reduce the reliability of intact-rock strength alone.

2.2 Representative geomechanically properties

Coal generally exhibits lower strength than competent sandstone. Reported coal UCS ranges between 15 and 40 MPa. Young's modulus for coal ranges between 2 and 8 GPa. Roof shale exhibits UCS values between 20 and 60 MPa. Laminated shale can possess strengths below 25 MPa. Sandstone generally exhibits UCS values between 40 and 120 MPa.Its Young's modulus ranges between 15 and 35 GPa.

Table 1. Representative geomechanically properties of Indian coal-measure rocks

Rock type	UCS (MPa)	Tensile strength (MPa)	Density (g/cm³)	E (GPa)	Poisson's ratio	Slake durability Id_2 (%)
Coal	15–40	1–3	1.3–1.6	2–8	0.25–0.35	—
Shale	20–60	2–6	2.0–2.5	5–15	0.20–0.30	20–85
Sandstone	40–120	5–15	2.1–2.6	15–35	0.15–0.25	85–98

These ranges indicate substantial contrasts between adjacent strata. Such contrasts influence stress transfer around underground openings. They also affect support anchorage and failure localization. Rock-mass quality commonly falls within fair-to-poor categories. Reported RMR values generally range between 35 and 60. Q values in the broader analysis range from 0.3 to 8. The source identifies decreasing RQD with increasing mining depth. The significance of geological characterization is also evident from Indian studies dealing with coal characterization, washability and geochemical variability. Such variations may indirectly influence mining response because changes in coal and associated strata properties affect excavation geometry, fragmentation, loading and stability (Sahu et al., 2018; Panwar et al., 2021).

2.3 Depth-dependent deterioration

Depth affects both stress magnitude and rock-mass damage. Raniganj generally retains higher RQD at shallow depths. Reported shallow-depth RQD values range from 75% to 90%. At 250–300 m, values decrease toward 55–70%. Jharia exhibits stronger deterioration with increasing depth. At depths exceeding 350–400 m, RQD commonly reaches 40–60%. Localized faulted and fire-affected zones can exhibit lower values. This deterioration reflects several interacting mechanisms. Increasing stresses promote damage around existing discontinuities. Repeated extraction generates additional fractures around excavations. Adjacent seams can interact through intervening rock layers. Old workings modify the current load-transfer system. Consequently, depth alone cannot adequately predict ground quality. The increasing significance of depth, stress and underground working conditions is consistent with recent Indian studies emphasizing systematic risk assessment and safety management for underground coal excavation (Singh et al., 2025). At greater depths, the interaction between geological uncertainty and mining-induced stress requires increasingly site-specific assessment.

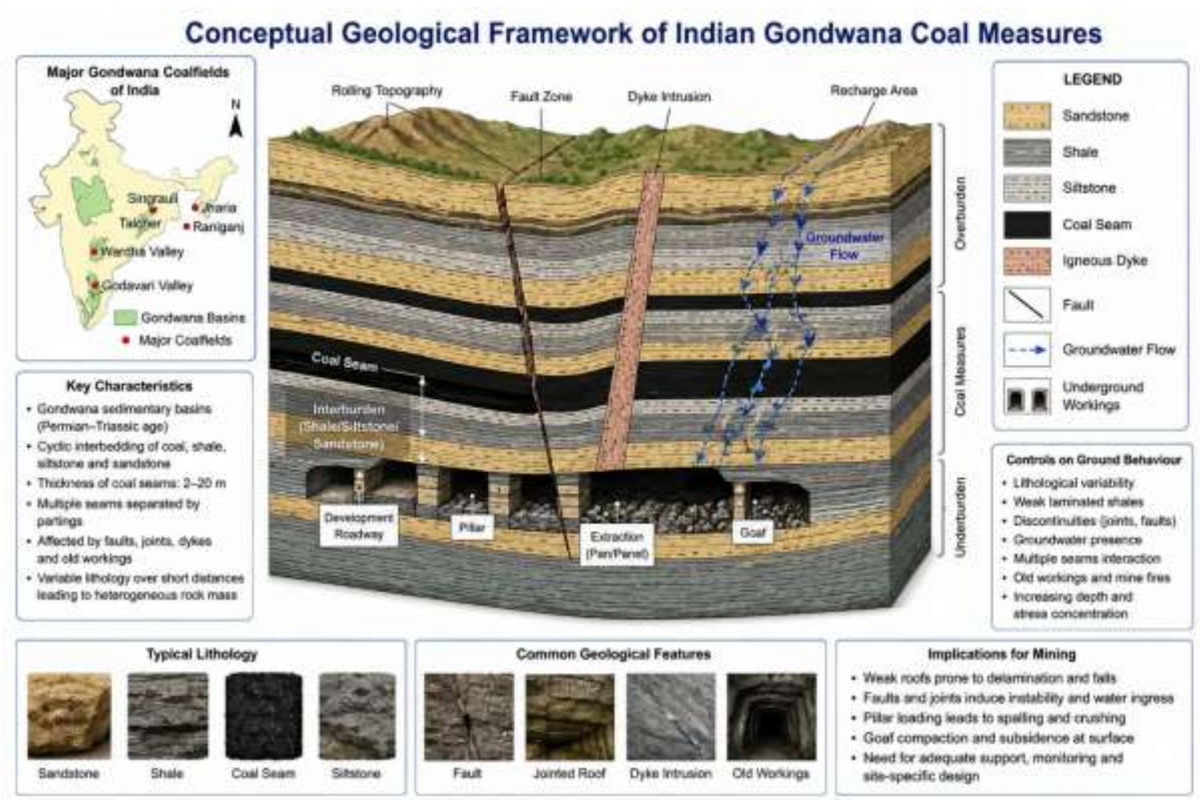

Figure 1. Conceptual geological framework of Indian Gondwana coal measures

Suggested schematic showing interbedded coal, laminated shale, siltstone, sandstone, faults, old workings, and underground roadways, with representative stress-transfer pathways.

3. Methodology and Analytical Framework

The source study follows an integrated geotechnical methodology. The framework combines theory, field observations, laboratory testing, and numerical modelling. RMR and Q classifications establish initial rock-mass quality estimates. Stress analysis evaluates excavation-induced redistribution around mine openings. Laboratory testing provides intact strength and deformation parameters. Field monitoring supplies convergence, stress, and failure observations. Numerical models integrate these datasets for site-specific interpretation. Such an integrated approach is consistent with the broader transition toward data-driven and intelligent mining systems. Artificial intelligence has increasingly been proposed for prediction, monitoring, decision support and safety management in mining operations (Singh et al., 2024; Kushwaha & Chaurasia, 2026a).

3.1 Rock-mass classification

RMR incorporates intact strength, RQD, discontinuity spacing, discontinuity condition, groundwater, and orientation. The Q-system provides a complementary classification for jointed rock. Both systems help organize support requirements and excavation conditions.
Classification values should be updated as geological conditions change. Geological mapping should therefore be considered a continuing activity rather than a one-time input during mine planning.

3.2 Laboratory characterization

The methodology includes UCS and triaxial compression testing. Point-load tests supplement strength characterization for difficult specimens. Brazilian testing provides indirect tensile strength estimates. Density and porosity support stress and geophysical interpretations. Slake durability testing evaluates moisture-sensitive argillaceous rocks. Laboratory characterization is particularly important where coal and associated strata exhibit significant mineralogical and geochemical variability. Studies on Indian coal have demonstrated substantial differences in mineralogical and geochemical characteristics between coalfields and seams (Sahu et al., 2018; Panwar et al., 2019, 2021).

3.3 Numerical modelling

FLAC3D was used for three-dimensional excavation and stress analysis. RS2 supported two-dimensional roadway and pillar sensitivity studies. UDEC addressed discontinuum behaviour in highly jointed domains. Models incorporated excavation sequence, material properties, and in-situ stresses. Support elements were included to evaluate reinforcement effectiveness. Calibration compared simulated and observed deformation behaviour. Parameter adjustment remained within physically reasonable laboratory-derived ranges. Reported convergence predictions achieved errors within approximately 10–18%. Sensitivity analysis identified horizontal stress and joint cohesion as important controlling parameters.

Numerical modelling should therefore be treated as a complementary decision-support tool rather than a substitute for field observation. Recent developments in AIoT, digital twins and predictive safety frameworks offer opportunities to integrate numerical modelling with continuous monitoring and real-time decision support (Kushwaha & Chaurasia, 2026a, 2026b).

4. Results and Discussion

4.1 Roof stability under laminated strata

The immediate roof frequently contains thin laminated shale. Reported shale bands range approximately from 0.3 to 2.5 m. These layers may behave as individual beams after excavation. Differential deformation can separate adjacent layers along bedding. Weak bedding contacts further reduce composite roof strength. Roof failure can occur through several linked mechanisms. Delamination develops when bedding shear resistance becomes insufficient. Wedge failure occurs where discontinuities intersect unfavourably. Tensile cracking develops under high horizontal stress conditions. Beam instability can follow progressive loss of interlayer confinement. Field convergence provides an indicator of this progression. Development convergence commonly ranges between 0.5 and 2 mm/day. Depillaring can increase rates toward 3–5 mm/day. Poor ground may reach 4–12 mm/day. Total convergence can exceed 150 mm in weak ground.

Table 2. Reported roof convergence characteristics

Mining stage	RMR range	Convergence rate (mm/day)	Total convergence (mm)	Principal mechanism
Development	45–55	0.5–2.0	20–60	Gravity and delamination
Depillaring	35–50	2.0–5.0	80–200	Stress and wedge failure
Poor ground	<40	4.0–12.0	>150	Crushing and buckling

The transition from development to extraction is especially critical. Pillar extraction changes the surrounding load-transfer configuration rapidly. Roof deformation accelerates as abutment loading develops. Monitoring must consequently intensify during depillaring. Underground mining risk assessment should therefore incorporate both static geological conditions and changing operational conditions. This is consistent with recent Indian work on risk assessment and safety management in underground coal excavation (Singh et al., 2025).

4.2 Jharia roof-collapse mechanism

The Jharia case provides a representative layered-roof failure. The development gallery was approximately 5.5 m wide. The reported depth was approximately 420 m. RMR was approximately 38 and Q approximately 0.8. The immediate roof contained 1.8 m carbonaceous shale. Jointed sandstone occurred above the immediate roof.

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Convergence accelerated from 1.2 to above 8 mm/day. Total closure reached approximately 180 mm before collapse. Two joint sets intersected weak bedding surfaces. The resulting wedges became potentially detachable from the roof. Horizontal stress generated tensile cracking within laminated shale. Moisture reduced joint cohesion during the failure process. The reported pillar stress reached approximately 20 MPa. Existing 1.8 m bolts failed to anchor into sandstone. The case demonstrates the importance of anchorage depth. Short reinforcement can remain ineffective beneath thick weak layers. Longer reinforcement should penetrate competent strata where feasible. The case also demonstrates why underground mine safety cannot be separated from geotechnical characterization. Recent Indian research on underground coal excavation emphasizes systematic hazard identification and risk-based safety management (Singh et al., 2025).

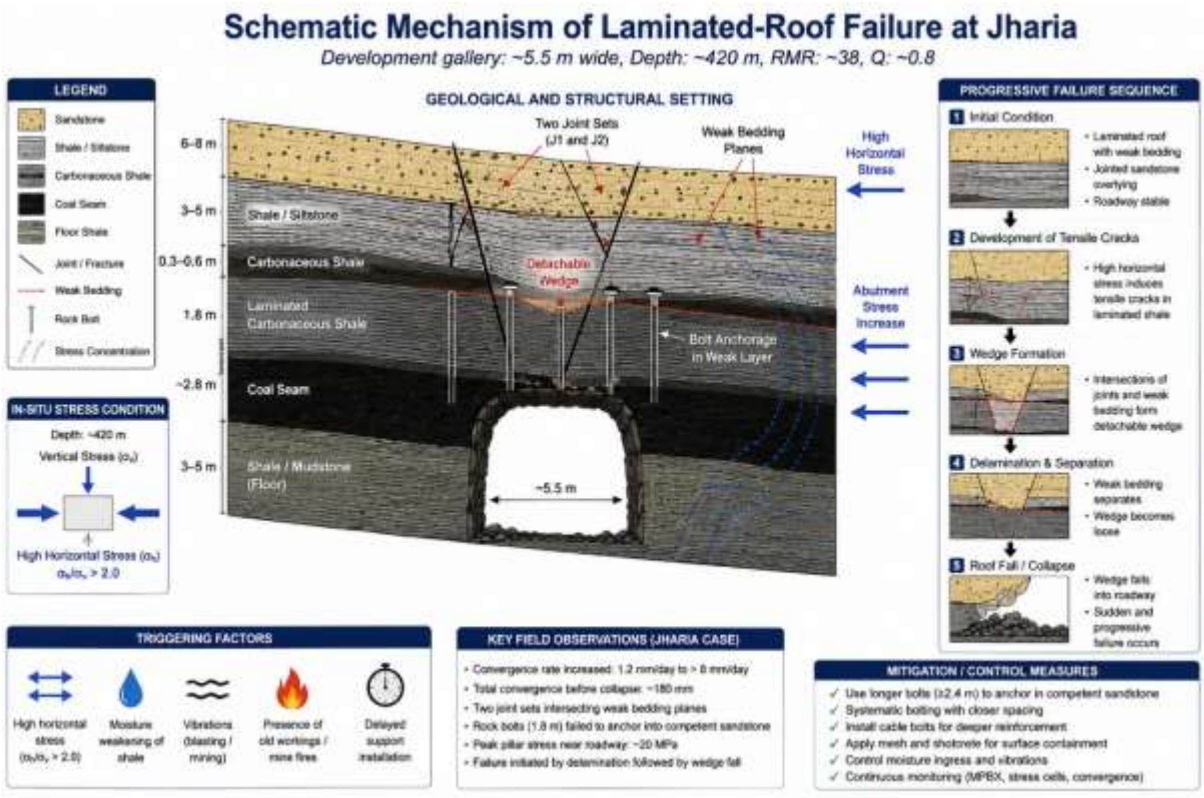

Figure 2. Schematic mechanism of laminated-roof failure at Jharia

Suggested schematic showing laminated carbonaceous shale, overlying jointed sandstone, intersecting joint sets, abutment loading, delamination, wedge formation, and roof-bolt anchorage.

4.3 Rib spalling and pillar degradation

Pillar ribs experience increasing tangential stress during extraction. Spalling removes coal from exposed pillar surfaces. The effective pillar width consequently decreases progressively. Reduced width increases stress concentration within the remaining pillar. This produces a potentially unstable feedback mechanism. Reported spalling depths range between 0.5 and 1.8 m. Mechanized panels may experience larger localized spalling depths. Moisture and blasting vibrations can accelerate rib deterioration. Coal-shale interfaces can provide additional weakness planes. The Singrauli case illustrates this mechanism clearly. The gallery was approximately 4 m wide. Pillars measured approximately 18 m by 18 m. Rib spalling reached 1.2–1.8 m on both sides. Effective pillar width consequently decreased by approximately 30%. Gallery convergence exceeded 120 mm. Stress-cell measurements indicated tangential stresses near 18–24 MPa. These stresses exceeded the strength of weak coal-shale interfaces. Plastic strain initiated around pillar corners. Damage subsequently propagated inward through the pillar mass. Delayed reinforcement further contributed to progressive degradation. Blasting-induced ground disturbance should also be considered where drilling and blasting are used near critical pillars and roadways. Recent studies have emphasized optimization of blasting parameters and reduction of blast-induced seismic disturbance in mining environments (Sahu & Chaurasia, 2025a, 2025b; Tiwari et al., 2025a, 2025b).

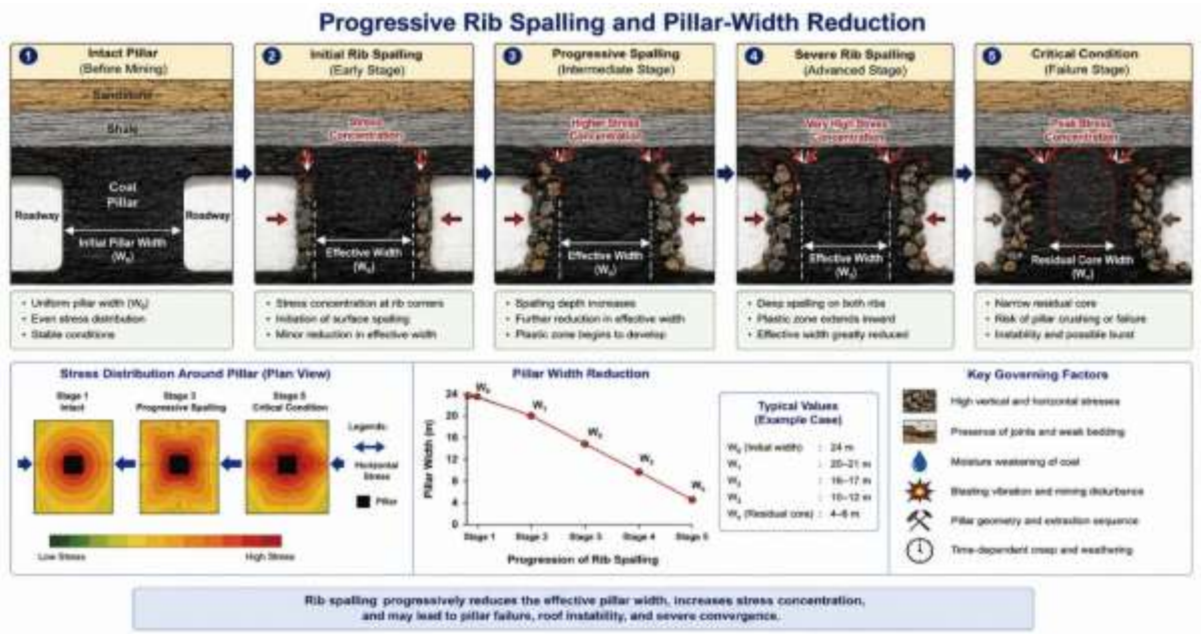

Figure 3. Progressive rib spalling and pillar-width reduction

Suggested diagram showing an intact pillar, initial rib spalling, progressive width reduction, stress concentration, plastic-core contraction, and potential pillar instability.

4.4 Pillar stress redistribution

Excavation transfers overburden loads toward remaining pillars. Stress concentration becomes greatest near pillar corners and ribs. The resulting stress distribution is strongly non-uniform. Outer pillar regions may yield before central regions. A relatively elastic core can remain within wider pillars. Complete yielding occurs when opposite plastic zones merge. The FLAC3D model illustrates this stress-transfer process. Representative pillars measured approximately 20 m by 20 m. The model depth was approximately 350 m. Horizontal stress ratios ranged from 1.8 to 2.5. Peak pillar stresses reached 2.2–3.1 times virgin levels. Roof plastic zones extended 1.8–3.2 m. At approximately 500 m depth, vertical stress was higher. Peak pillar stresses reached approximately 28–32 MPa. Stress concentration factors reached approximately 2.3–2.6.

Table 3. Numerical predictions for representative pillar-gallery conditions

Support condition	Maximum roof sag (mm)	Plastic-zone depth (m)	Maximum pillar stress (MPa)	FoS
Unsupported	55–85	1.8–3.2	18–25	0.9–1.2
Systematic bolting	15–28	0.8–1.4	16–22	1.6–1.9
Bolting + cables	8–18	0.5–1.0	15–20	1.8–2.3

The numerical results demonstrate strong support sensitivity. Systematic bolts reduce roof deformation and plastic-zone development. Cable reinforcement further improves structural stability. The results also support deeper anchorage beneath weak immediate roofs.

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4.5 Pillar design considerations

Pillar design cannot rely solely upon intact coal strength. Geometry, depth, stress ratio, seam inclination, and discontinuities matter. Width-to-height ratio strongly influences the retained elastic core. Rib degradation must also be incorporated into design assessment. The source identifies limitations in conventional pillar-strength equations. These limitations become important for deeper locked-up pillar extraction. Large width-to-height coal masses behave differently under high stress. Inclined seams introduce further complexity into load distribution. A site-specific safety factor remains necessary for extraction planning. The report recommends safety factors between 1.5 and 2.0. These values should be adjusted using site-calibrated design relationships.

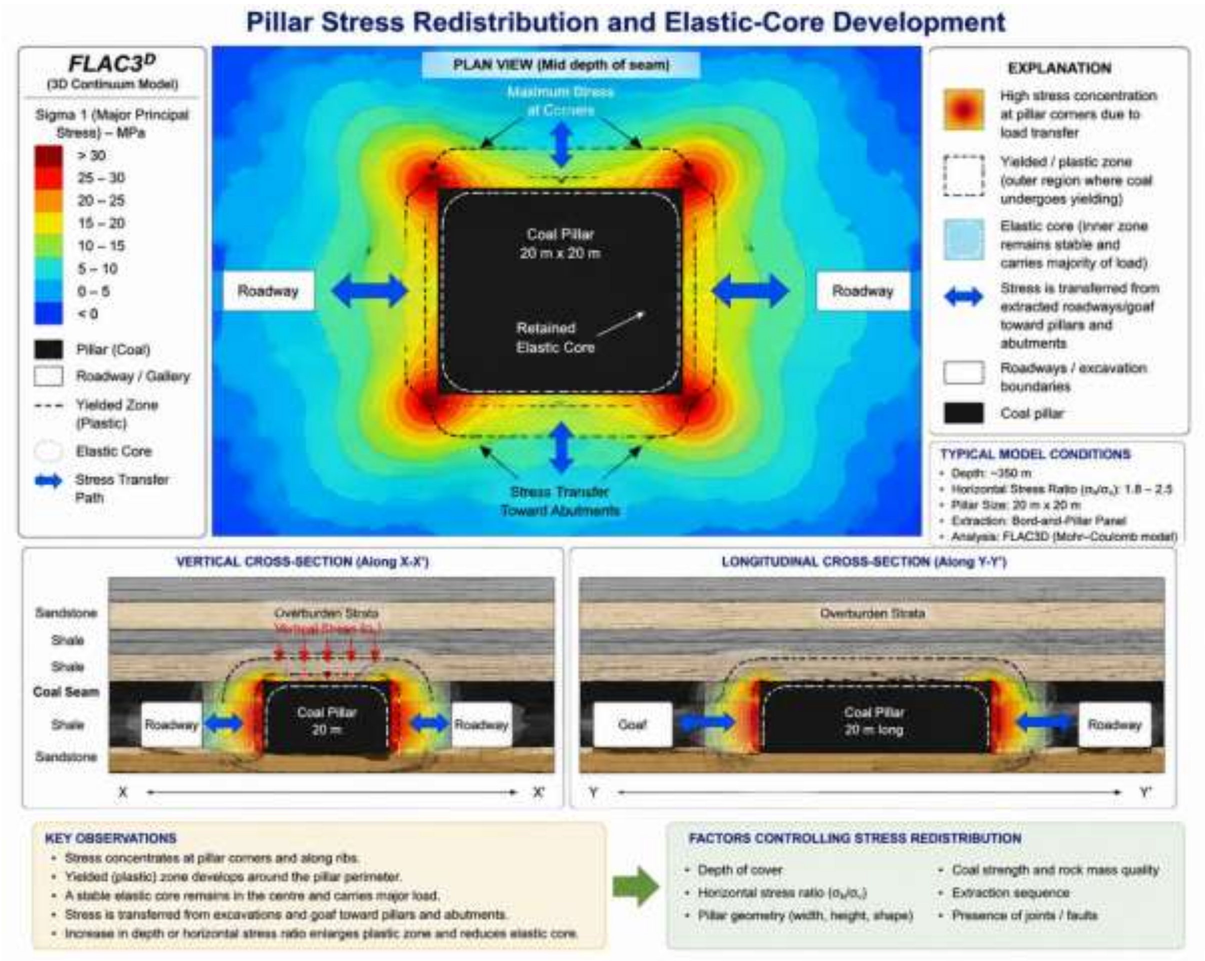

Figure 4. Pillar stress redistribution and elastic-core development

Suggested FLAC3D-style contour illustrating stress concentration around pillar corners, yielded outer zones, retained elastic core, and stress transfer toward abutments.

4.6 Floor behaviour and floor heaving

Floor instability is associated with weak and moisture-sensitive strata. Clay-rich shale can soften after groundwater exposure. Swelling materials can generate additional closure pressures. Pillar loading can also induce floor punching and extrusion. The source reports swelling pressures of 0.5–2 MPa. These pressures can contribute to roadway closure and bolt loading. Groundwater also reduces shale strength through slaking. Reported saturated-condition strength reductions reach 30–60%. Floor response should consequently be linked with hydrogeological conditions. Water management is not merely a drainage requirement. It also represents a geotechnical stability measure. Drainage and grouting can limit moisture-related degradation. Backfilling and stowing provide additional mechanisms for controlling deformation and stress redistribution. Indian research has examined underground mine backfilling, paste backfill and fly-ash utilization as alternative approaches for improving post-extraction stability and resource utilization (Yadav &

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Chaurasia, 2025; Chourasiya & Chaurasia, 2026). The source also identifies floor coal destressing as relevant. Hole-bottom fracturing has been proposed for selected high-stress conditions. Such interventions seek to modify stress concentrations around working areas.

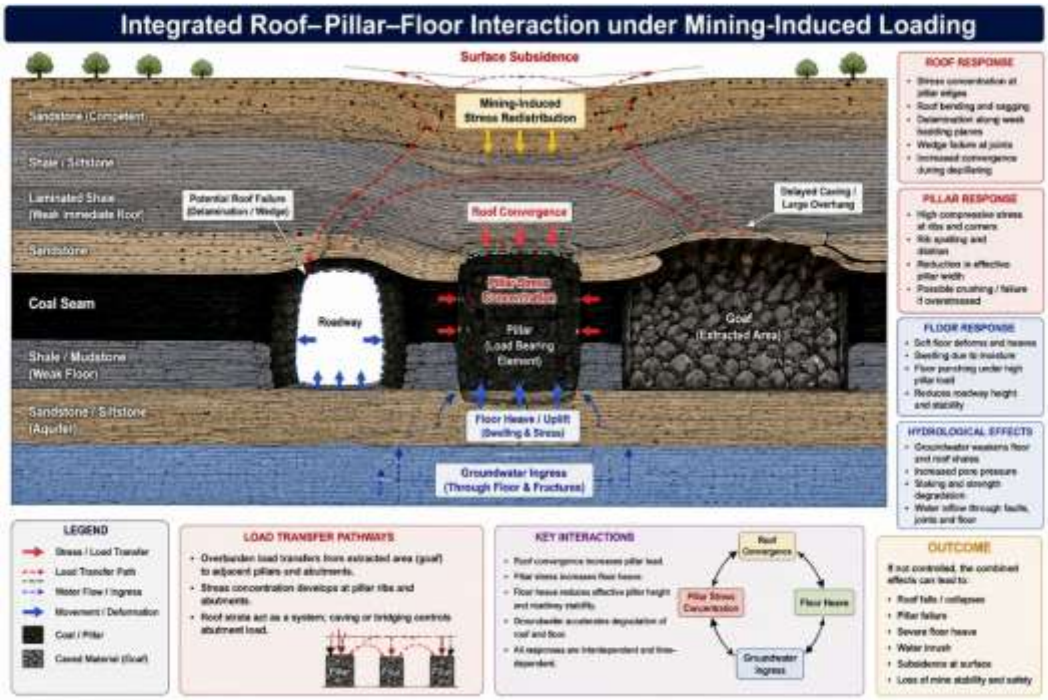

Figure 5. Integrated roof-pillar-floor interaction under mining-induced loading

Suggested cross-sectional schematic showing roof convergence, pillar stress concentration, floor heave, groundwater ingress, and load-transfer pathways.

4.7 High horizontal stress and abutment loading

Horizontal stress becomes increasingly influential at greater depth. Reported stress ratios reach 1.5–3.0 beyond approximately 300 m. High horizontal stresses can induce tensile roof cracking. They can also promote rib spalling and pillar dilation. Roadway orientation relative to maximum horizontal stress matters. Depillaring creates additional abutment loading around active extraction fronts. Remaining pillars receive load transferred from extracted coal. Roof strata can bridge above the goaf before failure. Delayed caving can produce concentrated loading near extraction lines. Massive sandstone roofs are especially difficult to cave. Longwall mining produces broader abutment stress zones. Reported modelled zones extend 50–60 m ahead of faces. Face convergence can reach 150–300 mm in simulations. Bord-and-pillar mining generates more localized stress concentrations. Its flexibility can be advantageous within disturbed geological conditions. However, pillar failure remains a significant extraction-stage hazard.

4.8 Common failure mechanisms under Indian conditions

Indian underground coal failures commonly involve multiple mechanisms. Purely single-mode failures are less representative of complex workings. Gravity-driven deformation can transition toward stress-driven instability. Geological discontinuities can then localize the final failure.

The principal mechanisms include:

1. **Bedding-plane delamination** within laminated immediate roofs.
2. **Wedge failure** at intersecting discontinuity sets.
3. **Tensile cracking** under elevated horizontal stress.

4. **Rib spalling** under concentrated pillar loading.
5. **Pillar crushing** following progressive width reduction.
6. **Floor heave** within weak or swelling strata.
7. **Buckling** within thinly bedded roof sequences.
8. **Interface shearing** between coal and weak shale.
9. **Goaf instability** under poor caving conditions.
10. **Dynamic failure** under severe stress concentration.

The source characterizes these failures as hybrid mechanisms. Gravity effects dominate some development-stage failures. Stress effects become stronger during extraction and greater depth.

Table 4. Principal failure mechanisms and controlling factors

Failure mechanism	Principal controlling factors	Typical consequence
Delamination	Bedding, weak shale, span	Roof fall
Wedge failure	Joint orientation and persistence	Localized roof collapse
Rib spalling	Abutment stress, coal strength	Pillar-width reduction
Pillar crushing	Geometry, stress, rib damage	Loss of load capacity
Floor heave	Weak floor, swelling, moisture	Roadway closure
Buckling	High horizontal stress, thin beds	Roof deformation
Interface shear	Weak coal-shale contacts	Pillar degradation
Goaf instability	Massive roof, poor caving	Abutment loading
Dynamic failure	High stress and rapid redistribution	Bumps or violent failure

5. Mining-Method Implications

5.1 Bord-and-pillar mining

Bord-and-pillar remains widely adaptable within Indian conditions. It accommodates irregular seams, faults, and variable geological quality. The method permits selective development around disturbed ground. Its principal geotechnical weakness concerns pillar loading during depillaring. Reported recovery commonly ranges from 40% to 60%. Recovery can decline further in thick seams. Depillaring increases abutment stresses around remaining pillars. Roof and rib instability consequently intensify during extraction. The increasing use of continuous miners also makes the relationship between excavation geometry, production rate and ground stability important. Studies of continuous-miner production emphasize the need to optimize operating parameters while maintaining safe underground working conditions (Tripathi & Chaurasia, 2025a, 2025b).

5.2 Longwall mining

Longwall provides substantially higher potential recovery. Reported recovery ranges between 70% and 85%. However, broad abutment zones develop ahead of the face. Weak roofs may not cave predictably behind powered supports. Overhangs can generate periodic weighting and sudden loading. The source reports face convergence between 200 and 500 mm. Longwall therefore requires favourable roof caving characteristics. Uniform seams and competent strata provide more suitable conditions.

Table 5. Comparison of Bord-and-Pillar and Longwall mining

Parameter	**Bord-and-Pillar**	**Longwall**
Recovery	40–60%	70–85%
Typical convergence	40–150 mm	200–500+ mm
Stress field	Localized	Broad abutment
Geological flexibility	High	Lower
Capital requirement	Lower	Higher
Principal hazard	Pillar and roof instability	Face and goaf instability
Suitable setting	Variable geology	Uniform competent blocks

The source favours geotechnical selection rather than technology alone. Modified bord-and-pillar with stowing can suit weak strata. Selective longwall remains appropriate within competent, predictable blocks.

6. Ground-Control Measures

Systematic reinforcement remains the primary roof-control strategy. Fully grouted resin bolts provide reinforcement within weak roofs. The source recommends 1.8–2.4 m bolts for RMR 40–55. Poorer ground requires longer 2.4–3.0 m reinforcement. Cable bolts provide deeper anchorage into competent strata.

Table 6. Source-based support framework

RMR	**Bolt length**	**Bolt spacing**	**Supplementary support**	**Expected convergence reduction**
>55	1.8 m	1.2 × 1.2 m	Mesh optional	40–60%
45–55	2.0–2.4 m	1.0 × 1.0 m	Mesh and straps	60–75%
35–45	2.4–3.0 m	0.8 × 0.8 m	Cables and shotcrete	70–85%
<35	3.0+ m	0.8 × 0.8 m	Cables, shotcrete, stowing	>80%

Surface reinforcement can contain small detached blocks. Wire mesh and shotcrete also protect weathered roof surfaces. Shotcrete can reduce moisture-driven slaking in exposed strata. Rib straps and channels improve confinement around stressed pillars. Stowing provides another mechanism for controlling load transfer. Sand or fly-ash stowing reduces void volume after extraction. Recent Indian work specifically considers paste backfill and fly ash as mine-backfilling materials, supporting their potential role in sustainable ground-control and mine-waste utilization strategies (Yadav & Chaurasia, 2025; Chourasiya & Chaurasia, 2026).

The broader Indian research literature also emphasizes sustainable management of mine waste and post-mining areas, which provides additional justification for evaluating backfilling and stowing as integrated mine-management strategies (Bisen et al., 2025; Bisen & Chaurasia, 2026). The source reports substantial reductions in surface subsidence through stowing. Stowing also limits goaf closure and abutment loading.

7. Monitoring and Numerical Validation

Ground control should operate as an observational process. MPBX instruments provide information on roof deformation. Stress cells identify changing load conditions around pillars. Convergence stations track roadway deformation rates. Microseismic systems can identify dynamic activity and event clustering. Trigger levels provide decision thresholds for intervention. The source identifies convergence above 30 mm as one trigger. A rate exceeding 3 mm/day also warrants intervention. Numerical models can support interpretation of monitoring data. Model outputs should be updated as field behaviour changes. This approach reduces dependence on fixed empirical assumptions. The future of underground

ground-control monitoring is likely to involve integration of conventional instrumentation with AI, IoT sensors, digital twins and predictive analytics. Recent Indian research has proposed AIoT-enabled safety frameworks using wearable sensors, physics-informed neural networks and digital-twin concepts for underground coal mining (Kushwaha & Chaurasia, 2026a). AI-based mining applications have also been identified as an important emerging direction for the broader mining industry (Singh et al., 2024).

Methane monitoring and carbon-footprint studies further demonstrate the potential for integrating real-time environmental and operational datasets within underground mine management systems (Singh & Chaurasia, 2025; Singh & Chaurasia, 2026). Although methane and carbon emissions are distinct from geotechnical stability, the same sensor and data infrastructure can contribute to an integrated smart-mine monitoring architecture.

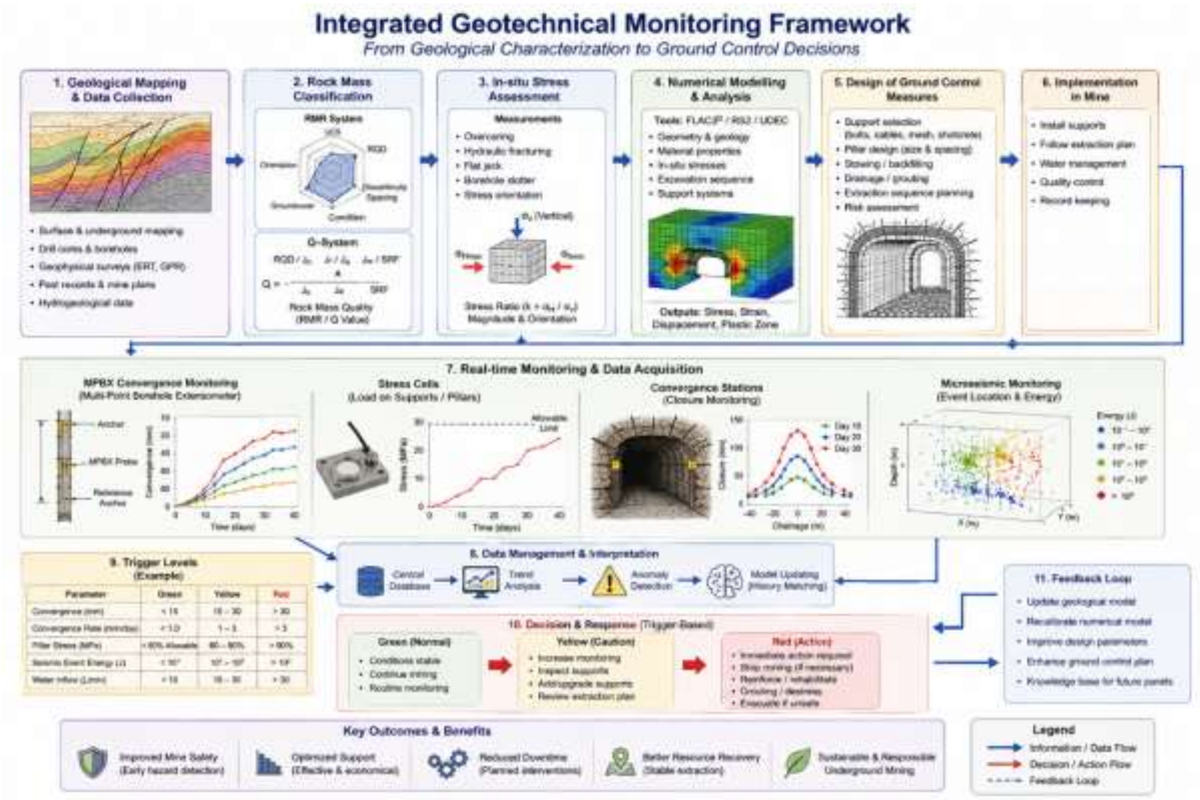

Figure 6. Integrated geotechnical monitoring framework

Suggested diagram linking geological mapping, RMR/Q classification, MPBX convergence, stress cells, microseismic monitoring, numerical modelling, trigger levels, and support decisions.

8. Conclusions and Recommendations

Indian underground coal mines operate within heterogeneous Gondwana formations. Weak laminated roofs remain a principal stability constraint. Jointed sandstone creates additional wedge and caving problems. High horizontal stresses increasingly control deeper mine behaviour. Pillar loading becomes severe during extraction and depillaring. Rib spalling progressively reduces the effective pillar width. Soft floors and moisture-sensitive strata create roadway closure problems. These mechanisms frequently interact rather than occur independently.

Reported RMR values commonly indicate fair-to-poor rock masses. Depth-dependent RQD reduction further increases support requirements. Field convergence accelerates significantly during extraction stages. Jharia and Singrauli demonstrate representative compound failure mechanisms. Numerical modelling reproduces major field deformation trends. Systematic bolting substantially reduces roof deformation and plastic yielding. Cable reinforcement provides deeper anchorage within competent strata. Stowing can reduce subsidence and moderate abutment loading. Recent

Indian research on mine backfilling and sustainable mine management supports further investigation of paste backfill and fly-ash-based materials as integrated ground-control solutions (Yadav & Chaurasia, 2025; Chourasiya & Chaurasia, 2026).

The following recommendations emerge from the source synthesis. Site-specific RMR and Q mapping should precede panel design. In-situ stress measurements should accompany deeper mining assessments. Pillar design should retain a stable elastic core. Rib degradation should be incorporated into effective pillar dimensions. Longer bolts should penetrate competent roof horizons where necessary. Extraction sequences should minimize abrupt stress concentration. Monitoring intensity should increase during depillaring and face approach.
Numerical models should be calibrated against actual monitoring data. Stowing should receive preference within thick weak-roof conditions. Geotechnical databases should be standardized across Indian coalfields.

The source recommends extending investigations beyond 600–800 m depths. Dynamic loading and long-term creep require further investigation. Artificial intelligence could support real-time rock-mass assessment. Hybrid mechanized methods also warrant systematic evaluation.

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