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Integrated Geotechnical Risk Assessment of Roof–Pillar–Floor Interaction in Underground Coal Mines under Indian Geological Conditions

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Abstract

Surface subsidence associated with pillar extraction represents a coupled geotechnical and societal hazard because the severity of ground movement depends not only on mining induced deformation but also on the vulnerability and exposure of surface assets. This study developed an integrated framework for assessing, classifying and spatially managing subsidence risk in Indian coalfields. The framework combined numerical subsidence predictions, field observations, deformation indicators and Geographic Information System (GIS)-based land-use analysis. Probability of surface damage was evaluated using subsidence magnitude, horizontal strain, curvature and geological uncertainty, while consequence assessment considered building vulnerability, infrastructure sensitivity, population density and land use. These components were integrated through a risk-classification matrix comprising very-low, low, medium, high and critical categories. Spatial risk maps were then developed by overlaying numerical subsidence contours with settlements and infrastructure. Jharia and Raniganj emerged as particularly important high-risk environments because mining-related deformation coincided with populated surface areas; Jharia was additionally affected by fire-related weakening and legacy workings. The framework demonstrated that areas experiencing similar deformation could have substantially different risk levels depending on surface vulnerability. Practical risk reduction measures included controlled depillaring, protective pillars, backfilling or stowing, continuous monitoring, structural reinforcement, buffer zones and relocation where avoidance was not feasible. The study concludes that subsidence management should progress from prediction of ground movement alone toward spatially explicit risk management integrating probability, consequence, monitoring and mine-planning decisions.

Keywords: subsidence risk; pillar extraction; GIS; risk zonation; surface damage; depillaring; Indian coalfields

1. Introduction

Mining-induced subsidence is not solely a problem of ground deformation. Its engineering significance arises from the interaction between the probability and magnitude of ground movement and the exposure and vulnerability of people, buildings, infrastructure and land resources located above or near underground workings. This distinction is particularly important in Indian coalfields, where underground workings may occur beneath densely occupied settlements, transport corridors, agricultural land and other critical surface assets. Risk assessment in underground coal excavation therefore requires consideration of both geotechnical hazards and the potential consequences to workers, surface structures and surrounding communities (Singh et al., 2025). Pillar extraction increases coal recovery but changes the load-bearing structure of underground workings. The resulting redistribution of stress may cause pillar yielding, roof collapse, goaf compaction and progressive deformation of the overburden. The interaction between mining geometry, rock-mass behaviour and surface response makes geotechnical assessment an essential component of underground mine planning. Recent studies on underground mining safety and operational control have similarly emphasized systematic hazard identification, risk assessment and engineering intervention as important components of safe mining practice (Singh et al., 2025; Tiwari & Chaurasia, 2026). In shallow workings, these mechanisms may generate localized pot-hole subsidence rather than a smooth continuous trough. The source report identified mining depth, extraction ratio, panel dimensions, geological discontinuities, pillar geometry, overburden properties, extraction sequence and groundwater conditions as important controls. Traditional subsidence assessment often focuses on maximum vertical displacement or the predicted angle of draw. Such parameters are necessary but insufficient for decision-making. A 1 m subsidence bowl beneath an unoccupied agricultural field does not necessarily represent the same level of societal risk as a smaller deformation beneath a densely populated settlement or critical railway. Consequently, risk assessment must combine the probability of damaging deformation with the consequences of that deformation. This principle is consistent with contemporary approaches to mine risk management, where hazard identification is increasingly linked to vulnerability, exposure and consequence assessment rather than being evaluated solely from the magnitude of the physical hazard (Bisen & Chaurasia, 2026; Singh et al., 2025). The study report developed such a framework by combining numerical results and field observations with probability and consequence assessments. Probability was based principally on subsidence magnitude, horizontal strain, curvature and geological uncertainty. Consequence was based on building vulnerability, infrastructure sensitivity, population density and land use. Spatial analysis further improved the usefulness of this approach. GIS permitted numerical subsidence contours to be overlaid with land-use and infrastructure information, thereby transforming a deformation prediction into a practical risk map. Recent work on geospatial frameworks for mine-site monitoring has demonstrated the value of integrating remote sensing and GIS for spatial assessment and long-term mine management (Bisen et al., 2025). Such spatial integration is particularly valuable in coalfields such as Jharia and Raniganj, where mining areas overlap with established settlements. The integration of geospatial information with mine-closure and post-mining assessment is also increasingly important because surface instability and environmental effects may continue after active mining has ceased (Bisen et al., 2025; Bisen & Chaurasia, 2026). The objectives of this paper were therefore to: (i) establish a probability–consequence framework for surface subsidence damage; (ii) develop a risk-classification matrix; (iii) integrate numerical subsidence predictions with GIS-based spatial zonation; (iv) interpret field evidence from Jharia and Raniganj; and (v) develop practical mitigation and monitoring strategies for safe pillar extraction.

2. Study Area and Geo-Mining Conditions

The assessment considered the four principal coalfields used in the underlying research: Jharia, Raniganj, Singrauli and Korba. Their geological and mining characteristics differed substantially. Jharia contained shallow workings, extensive legacy bord-and-pillar workings and coal-fire-affected zones. Raniganj contained both longwall and bord-and-pillar operations and had substantial historical subsidence information. Singrauli included thick seams and large underground and opencast operations, whereas Korba represented mechanized high-production mining. The risk-management emphasis was greatest in Jharia and Raniganj because surface exposure was particularly significant. In Jharia, residential structures were located above active or abandoned workings and were exposed to the additional uncertainty associated with fire-affected overburden. In Raniganj, relatively more stable geological conditions did not eliminate risk because mining operations were located near urban settlements. The importance of geological and geotechnical characterization in Indian coalfields is further demonstrated by studies dealing with coalfield geology, mining conditions and geotechnical behaviour (Sahu et al., 2018; Panwar et al., 2017; Panwar et al., 2019; Panwar et al., 2020; Panwar et al., 2021 Panwar et al., 2022; Singh & Chaurasia, 2025; Choubay & Chaurasia, 2026; Gupta & Chaurasia, 2026).

The surface environment comprised several categories of receptors:

- residential buildings;
- roads and highways;
- railways;
- pipelines and transmission infrastructure;
- agricultural land;
- drainage systems; and
- other community facilities.

These receptors differed considerably in deformation tolerance and consequence. Unreinforced masonry was particularly vulnerable to tensile deformation, while critical infrastructure required stricter deformation control. Agricultural areas were generally less vulnerable to structural damage but could experience productivity losses associated with waterlogging and surface drainage disruption. The consideration of surface land use is particularly relevant to integrated mine planning and closure because mining impacts extend beyond the active excavation area and can influence the future usability of land. Contemporary mine-closure research emphasizes the need to consider post-mining land conditions, environmental risks and long-term monitoring during mine planning rather than only after cessation of mining (Bisen et al., 2025; Bisen & Chaurasia, 2026).

3. Methodology

3.1 Risk-assessment concept

The risk framework followed the conventional distinction between hazard likelihood and consequence. In conceptual form,

Risk = Probability of damaging subsidence × Consequence of the damage.

The equation was used as a conceptual relationship rather than as a numerical probability model because the source report did not provide calibrated numerical probabilities. The assessment instead assigned qualitative probability and consequence categories using deformation indicators and surface vulnerability. This distinction was important because deformation magnitude alone could not adequately represent risk. The same predicted subsidence could lead to different risk classifications depending on whether the affected surface contained residential buildings, critical infrastructure, agricultural land or relatively unoccupied ground. Such an approach is consistent with broader mine-risk assessment frameworks in which physical hazards are evaluated together with exposure and potential consequences (Singh et al., 2025; Bisen & Chaurasia, 2026).

3.2 Probability assessment

Probability of surface damage was assessed using four principal indicators:

1. **Subsidence magnitude.** Larger vertical displacement was associated with greater likelihood of structural damage.
2. **Horizontal strain.** Tensile and compressive deformation influenced cracking, distortion and structural instability.
3. **Curvature.** Large curvature indicated differential settlement and increased the potential for cracking.

4. **Geological uncertainty.** Faults, weak strata, heterogeneous rock properties and legacy workings increased uncertainty in deformation prediction.

The source framework categorized subsidence greater than 2 m as a high-probability indicator and values below 1 m as a low-probability indicator. Horizontal strains exceeding 3 mm/m were similarly treated as high-risk indicators. These thresholds were treated as screening indicators rather than universal structural-damage limits. Their practical use should therefore remain linked to site-specific calibration and the type of structure affected. The need for site-specific geotechnical characterization is particularly important where structural discontinuities, weak strata and heterogeneous ground conditions exist. Geotechnical investigation and slope/stability assessment studies in Indian mining environments similarly demonstrate that engineering parameters must be interpreted in relation to local geological and mining conditions (Singh & Chaurasia, 2025).

3.3 Consequence assessment

Consequence was evaluated according to the vulnerability of the surface receptor. Four broad dimensions were considered.

Building vulnerability was related to structural form and construction quality. Unreinforced masonry was considered particularly susceptible to tensile deformation.

Infrastructure sensitivity reflected the operational requirements of roads, railways, pipelines and other critical assets. Such facilities generally tolerate less differential deformation than open land.

Population density was included because the social consequences of a failure increase with the number of people potentially exposed.

Land use was included because agricultural land may experience waterlogging, drainage disturbance and reduced productivity even where structural damage is limited.

The consequence scale therefore ranged from low to high, with densely populated residential zones classified as high-consequence areas and open agricultural areas generally assigned moderate-to-low consequence.

3.4 Risk-classification matrix

Probability and consequence were combined through a five-category matrix. The matrix retained the qualitative categories presented in the source study.

Table 1. Risk-classification matrix for surface subsidence damage

Probability	Consequence	Risk category
Low	Low	Very low
Moderate	Low	Low
Moderate	Moderate	Medium
High	Moderate	High
High	High	Critical

The matrix illustrates an important principle: a moderate probability can produce a high overall risk where consequences are severe, whereas even relatively probable deformation may represent moderate risk where surface vulnerability is low.

3.5 Numerical inputs to risk zonation

The deformation component of the risk assessment was derived from field measurements and numerical modelling. The numerical models generated spatial distributions of vertical displacement, horizontal displacement, strain and tilt. Field measurements obtained from precise levelling, total stations, DGPS and InSAR were used to validate the predicted

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deformation. The monitoring framework also included extensometers, inclinometers, tiltmeters, crackmeters, piezometers and seismic monitoring. Drone photogrammetry was used in selected areas to generate high-resolution digital elevation models. The use of multiple geospatial and remote-sensing techniques is consistent with recent research emphasizing integrated GIS and remote-sensing approaches for monitoring mine sites and post-closure conditions (Bisen et al., 2025). The increasing application of AI, IoT and digital technologies in mining also provides opportunities for integrating sensor-based monitoring with predictive risk-management systems (Singh et al., 2024; Singh & Chaurasia, 2026; Kushwaha & Chaurasia, 2026).

The resulting deformation surfaces were imported into GIS and spatially combined with mining boundaries, geological features and surface land-use information.

3.6 GIS-based spatial zonation

Spatial risk zonation involved three principal layers:

1. predicted subsidence and deformation;
2. mining and geological conditions; and
3. surface exposure and vulnerability.

The numerical subsidence contours were converted into spatial zones and overlaid with settlement and infrastructure datasets. The resulting map assigned each location to very-low, low, medium, high or critical risk.

The central region above an extracted panel generally experienced the highest deformation and therefore the greatest hazard. However, the final risk classification depended on the presence of vulnerable receptors. Peripheral areas were generally assigned moderate risk, while areas beyond the influence angle tended toward low or very-low risk.

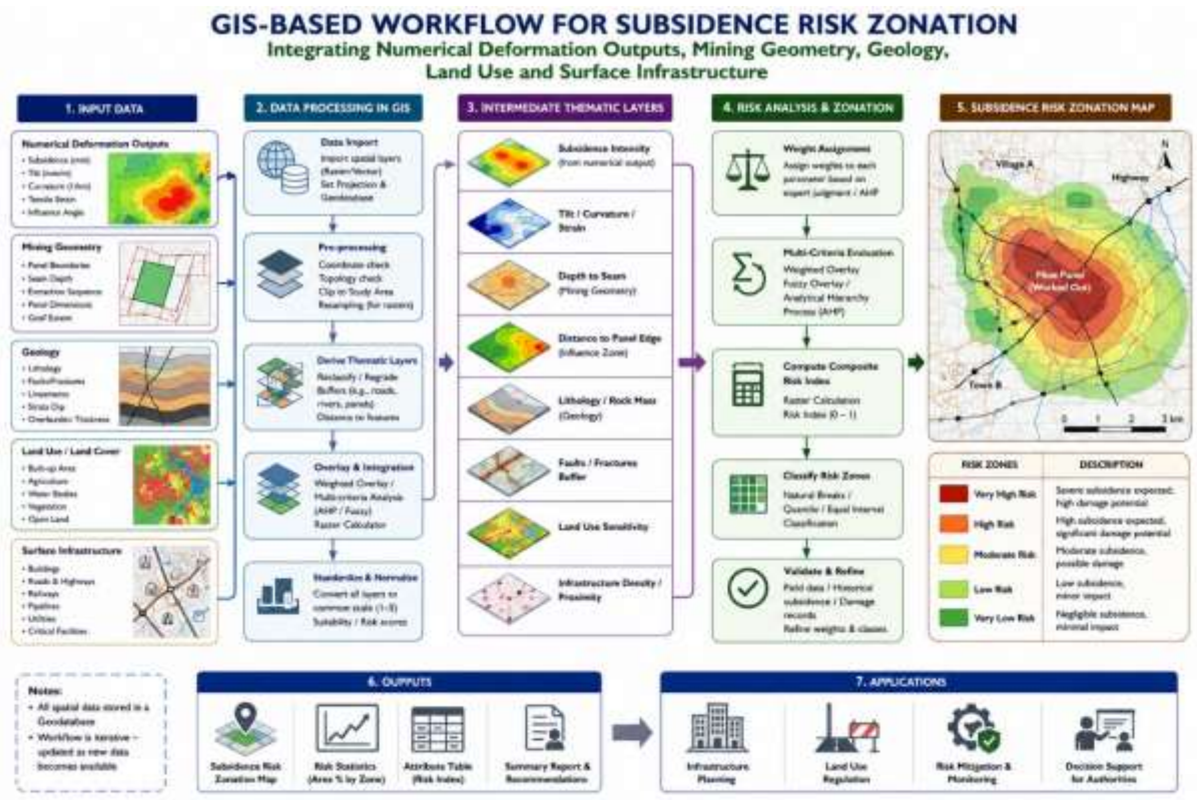

Figure 1. GIS-based workflow for subsidence risk zonation, integrating numerical deformation outputs, mining geometry, geology, land use and surface infrastructure.

The GIS-based approach is supported by recent research demonstrating the applicability of remote sensing and GIS for integrated mine-site monitoring and post-closure assessment (Bisen et al., 2025).

3.7 Field validation

Field observations provided the essential link between calculated hazard and actual surface consequences. Survey networks were established using monuments generally spaced 20–50 m apart and extended beyond the expected influence region. DGPS, precise levelling, total-station measurements and InSAR were used to quantify vertical and horizontal movement. Field observations also documented cracking, tilting, scarps, depressions, water ponding and damage to roads and drainage infrastructure. These observations were interpreted alongside numerical predictions rather than being treated as independent evidence.

Long-term monitoring is especially important in abandoned or closed mines because ground movement and environmental effects may continue after active mining. Recent mine-closure and geospatial monitoring studies emphasize systematic post-closure surveillance and spatial assessment (Bisen et al., 2025; Bisen & Chaurasia, 2026).

3.8 Damage-sensitive deformation indicators

The risk assessment used maximum subsidence, horizontal strain, tilt and curvature as principal deformation indicators. Numerical results showed that horizontal strain was concentrated near trough inflection points, whereas tilt was generally highest near the margins of the subsidence trough. The broader study reported horizontal strains of approximately 3–12 mm/m in severe tension zones and tilt values frequently exceeding 10–25 mm/m near inflection or marginal regions. Such deformation magnitudes were sufficient to cause structural damage in vulnerable settings. The spatial assessment also identified high-probability damage zones within approximately 0.5–0.8 times the mining depth from panel edges. These zones were particularly important in populated areas of Jharia and Raniganj.

4. Results and Discussion

4.1 Spatial variation in subsidence hazard

The risk maps showed that subsidence hazard was concentrated above and immediately around extracted panels. The deformation generally decreased outward from the panel, reflecting the finite spatial influence of underground extraction. However, the risk pattern did not simply follow the deformation pattern. Where settlements or infrastructure occurred within high-deformation zones, risk increased substantially. Consequently, the GIS procedure converted a purely geomechanical prediction into an exposure-sensitive management tool.

The highest-risk areas occurred where three conditions coincided:

- significant predicted deformation;
- uncertainty or susceptibility associated with geological conditions; and
- high-value or vulnerable surface receptors.

This combination was particularly evident in Jharia, where residential areas coincided with shallow workings and fire-affected ground.

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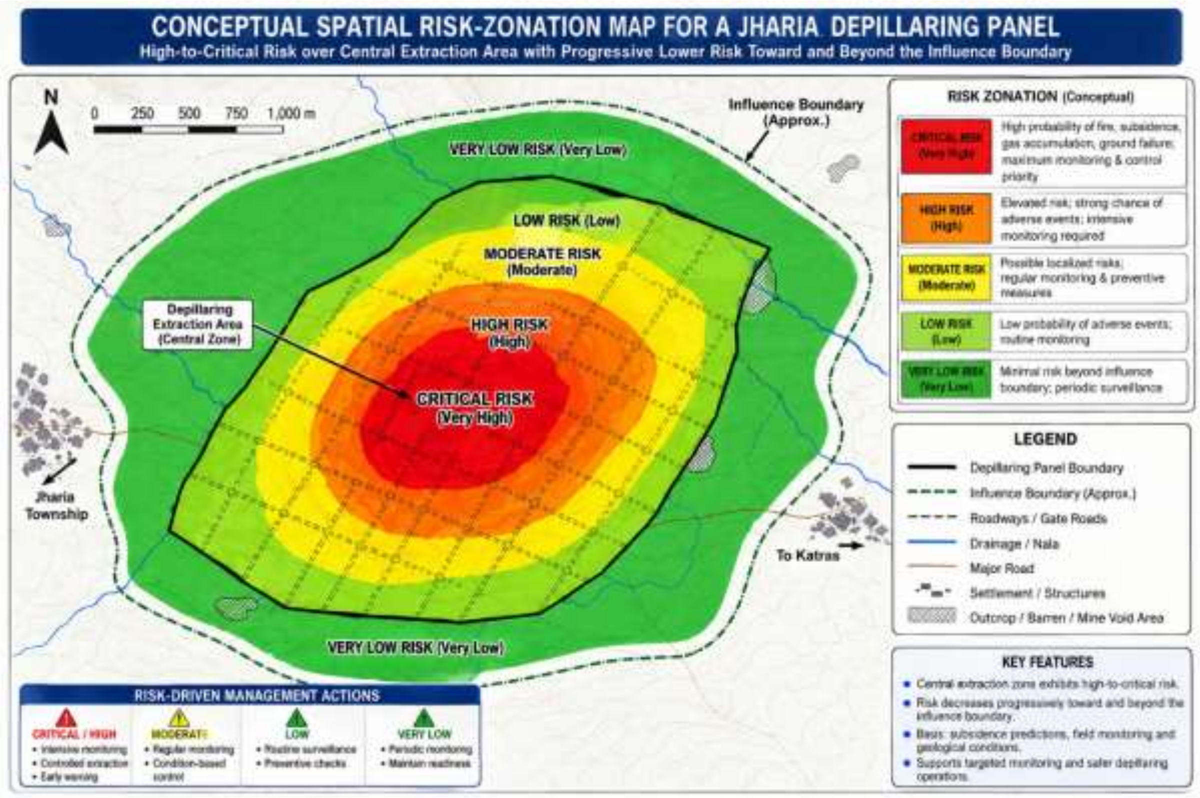

Figure 2. Conceptual spatial risk-zonation map for a Jharia depillaring panel, showing high-to-critical risk over the central extraction area and progressively lower risk toward and beyond the influence boundary.

4.2 Jharia: high and critical risk environment

Jharia represented the most severe risk environment among the investigated coalfields. Shallow workings and extensive legacy mining increased the likelihood that underground void collapse could propagate toward the surface. Fire-affected strata introduced additional uncertainty because thermal alteration reduced mechanical competence. Field observations documented cracking of buildings, tilting of structures, and damage to roads and drainage systems. The source study further reported rapid subsidence rates in fire-prone zones. From a risk-management perspective, Jharia demonstrated why a deformation-only assessment is inadequate. Even where the magnitude of predicted movement was comparable with another coalfield, the consequence was substantially greater because of settlement density and infrastructure exposure.

The numerical framework therefore supported a hierarchy of intervention:

1. avoidance of new extraction beneath highly vulnerable receptors where practicable;
2. controlled extraction where mining was unavoidable;
3. protective pillars or barriers around critical assets;
4. intensive real-time monitoring;
5. stabilization or backfilling of hazardous legacy workings; and
6. relocation where the combination of probability and consequence remained critical.

The need for systematic mine closure, risk assessment and post-mining stabilization is also consistent with recent research on mine-closure risk planning (Bisen & Chaurasia, 2026).

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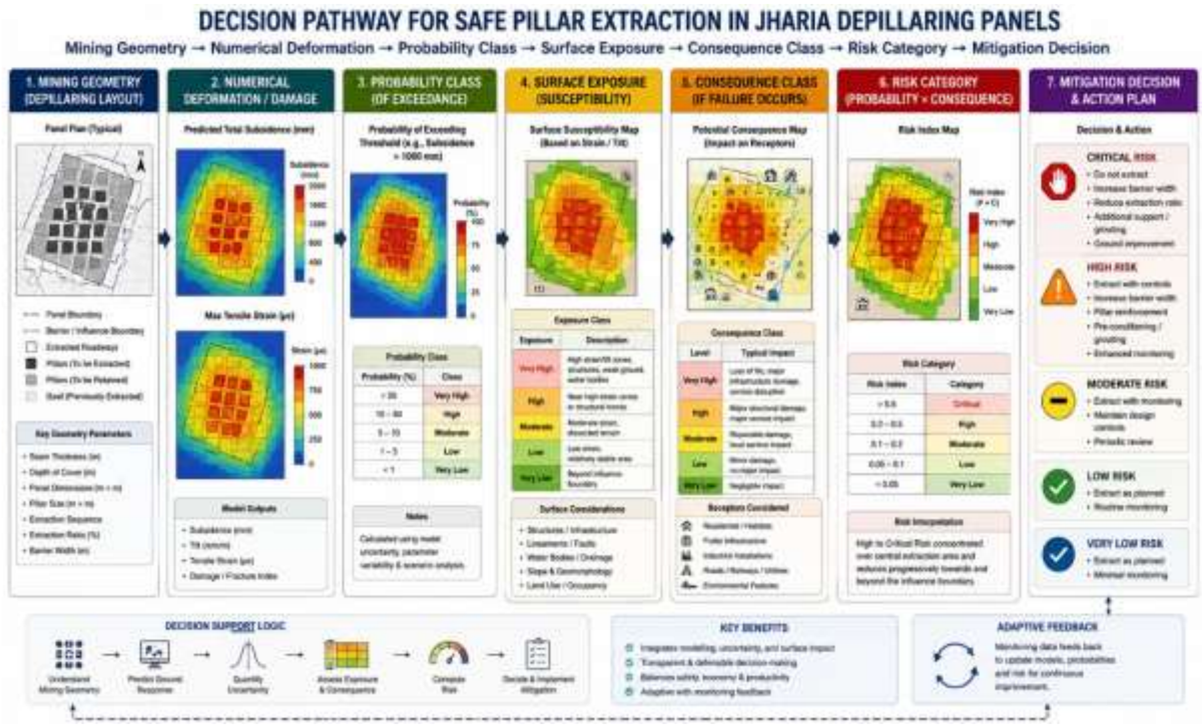
4.3 Raniganj: moderate-to-high risk associated with surface exposure

Raniganj displayed a somewhat different risk pattern. The geological environment was comparatively more stable than the fire-affected conditions of Jharia, but mining proximity to settlements produced moderate-to-high risk in several locations. The source study reported approximately 1.6–1.8 m measured subsidence for 3–3.5 m extraction heights in moderate-depth longwall panels and good agreement between DGPS/InSAR measurements and FLAC3D predictions. The significance of these values depended strongly on the surface receptor. Agricultural areas could accommodate some deformation without immediate structural damage, whereas residential areas were much more sensitive to differential settlement and tensile strain. Raniganj is also an important coalfield for understanding broader underground resource development because of its coal-bed methane potential and extensive historical mining activity (Panwar et al., 2017; Singh et al., 2025). Controlled extraction sequences and surface monitoring were identified as effective measures for reducing damage.

4.4 Deformation severity versus consequence

A principal finding of the risk framework was that the relationship between deformation and risk was not linear. A relatively large subsidence magnitude could produce only moderate risk where the affected surface contained few vulnerable assets. Conversely, relatively smaller deformation could produce high or critical risk beneath a densely populated settlement. This distinction has practical consequences for mine planning. Extraction panels should not be classified only according to predicted maximum subsidence. Instead, the numerical deformation field should be combined with a surface receptor inventory before an extraction decision is made.

The resulting procedure can be expressed conceptually as:



Mining geometry → numerical deformation → probability class → surface exposure → consequence class → risk category → mitigation decision.

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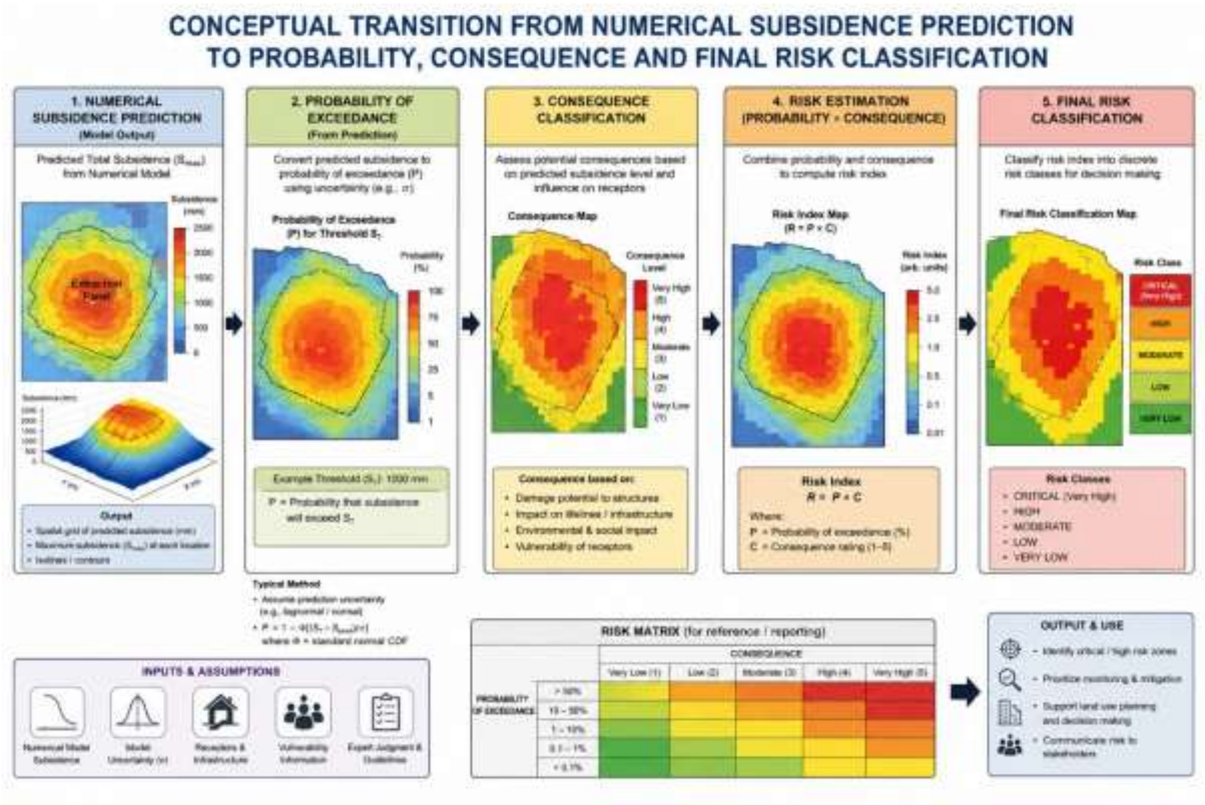

Figure 3. Conceptual transition from numerical subsidence prediction to probability, consequence and final risk classification.

4.5 Risk classification and management priorities

The matrix developed in the study provided a straightforward prioritization mechanism.

Very-low and low-risk zones generally required routine monitoring and standard mine-control measures. Medium-risk areas required increased surveillance and review of extraction geometry. High-risk zones required specific engineering controls, while critical zones required avoidance, stabilization, relocation or other measures capable of substantially reducing either probability or consequence. The importance of consequence was particularly evident for critical infrastructure. Roads, railways and pipelines cannot necessarily tolerate the same deformation that might be acceptable on agricultural land. Similarly, settlements require consideration of both structural safety and human exposure. Recent work on mine risk assessment has emphasized the need to integrate engineering hazards with systematic safety-management procedures, supporting the application of risk-based decision-making in underground coal mining (Singh et al., 2025).

Table 2. Risk categories and indicative management response

Risk category	Principal interpretation	Indicative management response
Very low	Limited predicted deformation and/or low consequence	Routine monitoring
Low	Limited damage potential	Standard monitoring and mine controls
Medium	Moderate probability and/or consequence	Enhanced monitoring and design review
High	Significant probability or consequence	Specific engineering controls and restricted extraction
Critical	High probability combined with high consequence	Avoidance, stabilization, protective measures or relocation

The management responses are derived from the framework presented in the source material and should be calibrated to site-specific regulatory and engineering requirements.

4.6 Influence of mining depth and panel geometry

Mining depth had a strong influence on the spatial distribution of risk. Shallow workings produced sharper deformation gradients and therefore increased the potential for differential settlement and localized ground failure. Deeper workings generally produced broader and smoother troughs. The study identified panel width-to-depth ratio as an important determinant of subsidence development. Ratios exceeding approximately 1.2–1.4 were associated with supercritical conditions in the theoretical framework, where extensive subsidence could develop. Consequently, panel geometry should be treated as a risk-management parameter rather than solely as a production variable. Reducing panel span or maintaining suitable pillars can decrease the likelihood of extensive ground movement.

4.7 Influence of extraction ratio and pillar dimensions

Higher extraction ratios increased subsidence because the load-bearing contribution of remnant pillars decreased. The source results associated extraction ratios exceeding 70% with increased subsidence in the investigated conditions. Pillar dimensions also affected risk through their control of load transfer and the onset of yielding. Numerical results showed that insufficient pillar dimensions could lead to progressive failure, increased abutment loading and abrupt redistribution of stress.The implication is that extraction efficiency cannot be maximized independently of surface vulnerability. Where high-consequence receptors exist, extraction ratios and pillar dimensions should be selected using calibrated numerical analysis rather than recovery objectives alone.

4.8 Geological discontinuities and uncertainty

Faults, joints, weak interfaces and heterogeneous lithological units increased uncertainty in predicted deformation. Geological discontinuities could act as preferential failure paths and could also generate asymmetric subsidence profiles. The source study therefore treated geological uncertainty as a direct component of probability assessment. This was important because a numerical prediction based on simplified homogeneous strata could produce a deceptively precise result despite uncertainty in actual ground conditions. The practical response is to incorporate uncertainty explicitly into model scenarios and maintain monitoring during extraction so that unexpected deformation can be identified early.

4.9 Residual subsidence as a post-mining risk

Post-mining risk was an important component of the study. Goaf compaction and strata creep continued after active extraction, and the source synthesis indicated that approximately 20–30% of total subsidence could occur after mining cessation.This finding has direct implications for land-use planning. A mine closure plan based solely on the final condition immediately after extraction could underestimate future settlement. Infrastructure, agriculture and redevelopment should therefore be assessed against predicted residual deformation. Long-term monitoring is particularly important for abandoned bord-and-pillar workings, where incomplete information about old workings can increase uncertainty. Recent studies on mine closure and post-closure geospatial monitoring reinforce the importance of incorporating long-term risk into closure planning (Bisen et al., 2025; Bisen & Chaurasia, 2026).

4.10 Monitoring and early warning

The study adopted a multi-scale monitoring philosophy. Conventional precise levelling and total stations provided high-precision measurements at discrete locations, DGPS provided three-dimensional movement, and InSAR provided wide-area deformation information. Additional instruments including tiltmeters, crackmeters, extensometers and piezometers could identify developing subsurface and surface instability.

The source recommendations proposed dense surface monitoring networks with monument spacings of approximately 20–50 m, supplemented by real-time technologies. It further identified tilt and horizontal-strain thresholds in the approximate ranges of 5–10 mm/m and 3–5 mm/m, respectively, as conservative action triggers in the investigated

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framework. These thresholds should not be interpreted as universal structural limits. Their value lies in providing operational triggers for review of extraction rate, support conditions and numerical predictions. Emerging AIoT-based safety systems can potentially enhance this monitoring architecture by integrating sensor data, predictive models and automated alerts. Recent work has proposed AI/IoT frameworks for predictive safety and methane-risk management in underground coal mines, indicating the broader potential for intelligent real-time mine monitoring (Singh & Chaurasia, 2026; Kushwaha & Chaurasia, 2026).

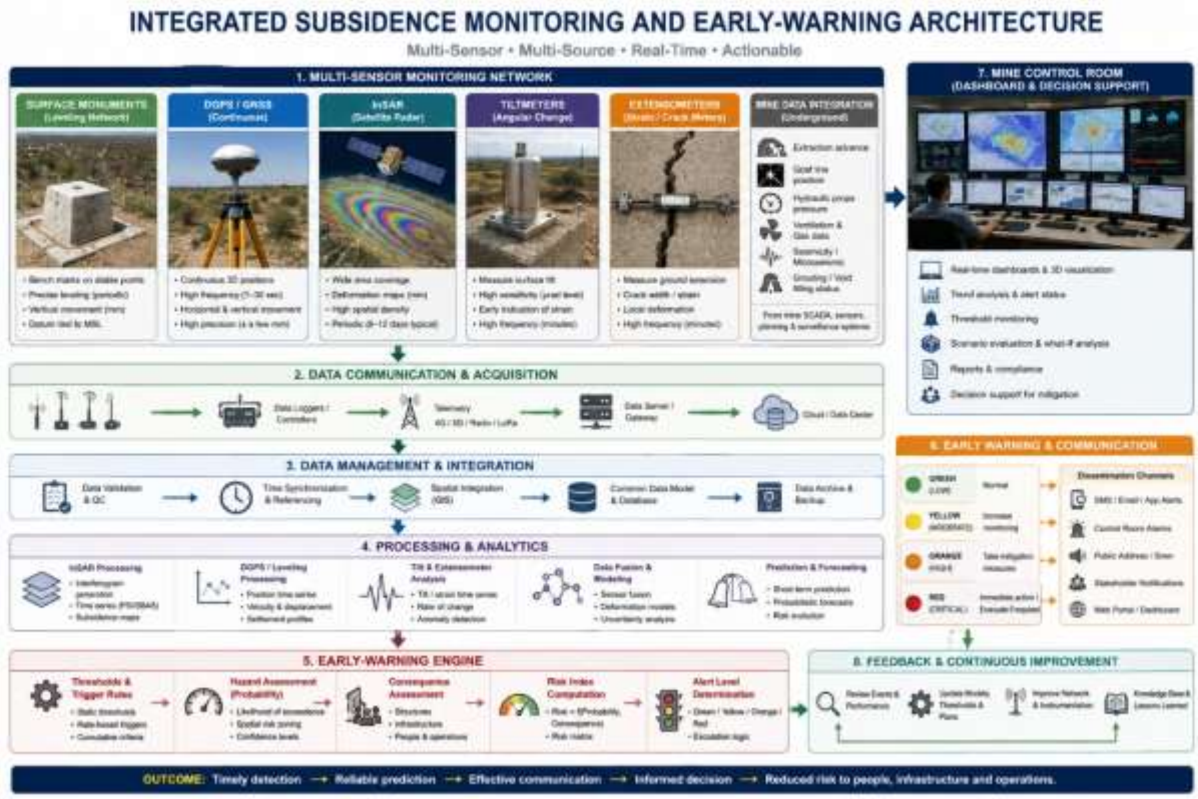


Figure 4. Integrated subsidence monitoring and early-warning architecture combining surface monuments, DGPS, InSAR, tiltmeters, extensometers and mine-control-room data.

4.11 Controlled depillaring

Controlled depillaring was identified as a primary means of reducing abrupt ground movement. The source study recommended carefully planned extraction sequences, including split-and-fender or diagonal approaches where appropriate, because these can provide greater control over progressive roof failure and stress redistribution. The underlying principle is that extraction sequence modifies the rate and spatial distribution of stress transfer. One-sided or poorly controlled extraction may produce asymmetric loading, whereas planned sequences can promote more predictable redistribution. The extraction sequence should therefore be incorporated directly into the numerical model rather than represented simply as a final excavation geometry. The importance of controlled mining operations is consistent with broader studies on underground mine safety, operational optimization and risk management (Singh et al., 2025; Tiwari & Chaurasia, 2026).

4.12 Backfilling and stowing

Backfilling provides a direct means of reducing void space and limiting goaf closure. The source recommendations identified hydraulic sand stowing or paste backfilling as preferred interventions where feasible. The report stated that simulations indicated reductions in surface subsidence of approximately 40–60% relative to caving under the investigated conditions. The benefit of backfilling is greatest where surface vulnerability is high and where complete avoidance of extraction is not practical. Backfilling can also reduce the magnitude of post-mining residual settlement by increasing the stiffness and filling capacity of the goaf. Recent research on underground mine backfilling similarly identifies paste backfill as an important approach for improving underground stability and supporting sustainable mine development (Yadav & Chaurasia, 2025). Fly ash has also been investigated as a potential backfilling material, providing opportunities for waste utilization while improving mine-ground stability (Chourasiya & Chaurasia, 2026).

4.13 Protective pillars and buffer zones

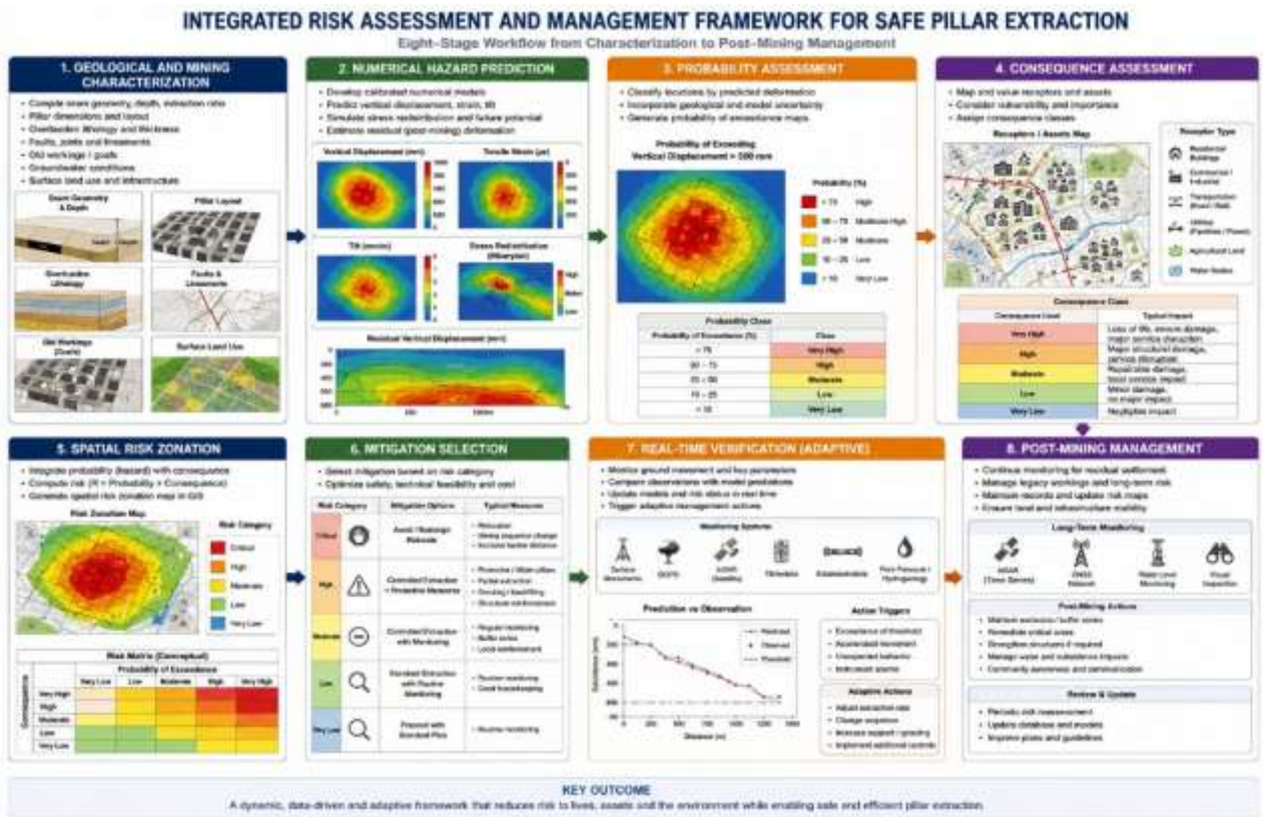
Protective pillars provide a means of separating extraction areas from vulnerable surface features. The source study recommended that protective barriers or yield pillars be designed using calibrated influence functions and numerical analysis, with safety factors in the range of approximately 1.5–2.0 depending on surface vulnerability. Buffer zones around critical infrastructure provide a complementary spatial control. Their dimensions should be determined from predicted deformation, influence angle, geological uncertainty and the sensitivity of the protected facility. The principal advantage of combining numerical modelling with GIS is that protective zones can be defined spatially before extraction rather than being imposed after damage has occurred.

4.14 Structural reinforcement and relocation

Where mining cannot be avoided, vulnerable surface structures may require reinforcement or retrofitting. This measure is most appropriate where the deformation is expected to remain within manageable limits. Relocation represents a more substantial intervention and is particularly relevant where risk remains critical despite engineering controls. The source study identified relocation of high-risk settlements as a practical option in selected circumstances, especially where Jharia's fire-affected and legacy-workings environment produced persistent uncertainty. Relocation should therefore be considered as part of integrated mine planning rather than as an emergency response after severe ground failure. This approach is consistent with modern mine-closure planning, which emphasizes progressive risk reduction and post-mining land-use planning (Bisen & Chaurasia, 2026).

4.15 Recommended decision framework for pillar extraction

The combined findings support a sequential risk-management framework:



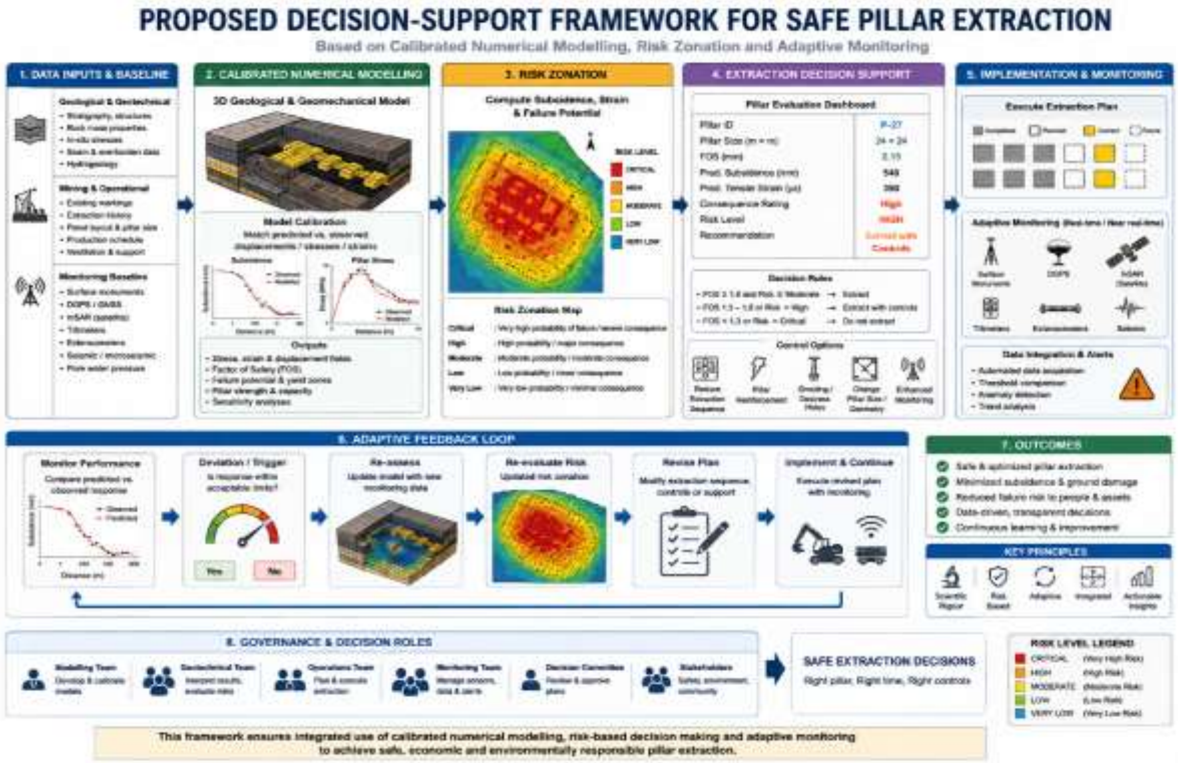


Figure 5. Proposed decision-support framework for safe pillar extraction based on calibrated numerical modelling, risk zonation and adaptive monitoring.

4.16 Regulatory and planning implications

The study supports stronger integration of numerical modelling and monitoring into mine-planning and regulatory procedures. Major depillaring proposals involving settlements, infrastructure, shallow workings or complex geology should be supported by calibrated numerical assessments rather than relying exclusively on generalized empirical subsidence factors. The source recommendations proposed that regulatory and planning organizations such as DGMS and CMPDI should require detailed numerical modelling and validation reports for major depillaring proposals. Long-term post-mining monitoring was also recommended, with the source suggesting programmes extending approximately 5–10 years and incorporating periodic InSAR observations. Such a framework would also improve the transparency of decisions concerning protective pillars, backfilling and relocation because the relationship between mining geometry, predicted deformation and surface consequences could be documented spatially. The proposed approach is consistent with the broader movement toward data-driven and intelligent mining, where digital monitoring, predictive analytics, GIS and real-time decision support are increasingly incorporated into safety management (Singh et al., 2024; Kushwaha & Chaurasia, 2026).

4.17 Future research requirements

Several limitations remain. First, the probability thresholds were based on empirical indicators rather than a fully probabilistic damage model. Larger databases of observed structural damage linked to deformation measurements would allow these qualitative categories to be calibrated statistically. Second, residual subsidence requires longer monitoring. The source report recommended programmes extending beyond ten years in selected abandoned panels to improve understanding of creep, goaf compaction and groundwater effects. Third, fire-affected areas such as Jharia would benefit from fully coupled thermo-hydro-mechanical modelling rather than static reductions in rock properties. Such models could better represent the evolution of fire-induced weakening. Fourth, numerical simulations could eventually be complemented by machine-learning surrogate models capable of reproducing calibrated FLAC3D results at substantially lower computational cost. Recent research on AI applications in mining and AIoT-based predictive safety frameworks demonstrates the growing potential for artificial intelligence to support complex mining decisions (Singh et al., 2024;

Kushwaha & Chaurasia, 2026). However, such models would require adequately documented and geographically diverse training datasets.

5. Conclusions

The study developed an integrated framework for assessing and managing surface subsidence risk associated with pillar extraction in Indian coalfields. The principal conclusions were:

1. Subsidence risk should be distinguished from subsidence magnitude. Ground deformation becomes a high or critical risk when significant movement coincides with vulnerable surface receptors.
2. Probability assessment based on subsidence magnitude, horizontal strain, curvature and geological uncertainty provided a practical means of identifying areas where damaging deformation was more likely.
3. Consequence assessment based on building vulnerability, infrastructure sensitivity, population density and land use allowed deformation predictions to be translated into meaningful risk categories.
4. The probability–consequence matrix provided five practical categories: very low, low, medium, high and critical. This classification helped prioritize engineering and management responses.
5. GIS-based spatial zonation was effective for integrating numerical subsidence contours with surface exposure. The central portions of extraction panels generally exhibited the highest hazard, but the final risk depended strongly on land use and infrastructure.
6. Jharia represented the most challenging environment because shallow workings, legacy mine voids and fire-related weakening increased both the probability and uncertainty of ground failure. Raniganj exhibited moderate-to-high risk where mining interacted with urban settlement.
7. High-probability damage zones were identified within approximately 0.5–0.8H of panel edges in the source framework, demonstrating the importance of considering deformation gradients and not simply maximum subsidence.
8. Controlled depillaring, appropriate pillar and barrier design, backfilling or stowing, monitoring and surface protection provided complementary mechanisms for reducing either the probability or consequence of subsidence.
9. Backfilling was identified as a particularly important control where surface vulnerability was high, with the underlying simulations indicating substantial reductions in surface subsidence compared with uncontrolled caving under the investigated conditions.
10. Dense monitoring using levelling, DGPS, InSAR and complementary instruments should be integrated into active extraction and post-mining management. Monitoring thresholds should be treated as conservative operational triggers rather than universal structural-damage limits.
11. Risk assessment should be dynamic. Numerical predictions should be compared continuously with field observations so that extraction rates, support strategies and mitigation measures can be modified when unexpected deformation occurs.
12. Long-term management remains essential because residual subsidence may continue after active extraction. The reported contribution of residual deformation to total subsidence emphasizes the need to incorporate post-mining settlement into land-use and infrastructure planning.

The principal contribution of the framework is therefore the transition from a deformation-centred approach to a risk-informed approach in which numerical geomechanics, field monitoring, GIS and surface vulnerability are considered together. Such integration provides a practical basis for safer pillar extraction and more defensible decisions concerning protection, mitigation and relocation in Indian coalfields.

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