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Research Progress on Multi-Hazard Disaster Mechanisms, Monitoring, Early Warning and Control in Underground Engineering

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Abstract: Underground engineering is increasingly exposed to complex geological conditions, intensive urban constraints, and long service periods. Disasters rarely arise from a single defective component; they usually develop through interactions among geological uncertainty, excavation disturbance, groundwater migration, support response, construction organization, and delayed deterioration. This paper presents a critical review of the mechanisms, monitoring methods, and prevention strategies associated with major underground-engineering hazards, including collapse, water and mud inrush, squeezing deformation, rockburst, ground settlement, harmful-gas and fire events, and structural deterioration. A source–pathway–response framework is used to explain how local damage evolves into system-level failure and cascading consequences. Analytical, numerical, physical-model, field-monitoring, and data-driven approaches are compared with respect to applicability, interpretability, and uncertainty. The review shows that conventional single-index warning and static safety assessment are inadequate for rapidly changing ground conditions. More reliable practice requires multi-source geological prediction, continuous deformation and seepage sensing, physics-informed data fusion, and decision thresholds linked directly to construction actions. An integrated closed-loop framework is therefore proposed that connects investigation, scenario analysis, monitoring, diagnosis, adaptive control, emergency response, and post-event model updating. The principal research needs are uncertainty-aware prediction, transferable warning models, coupled multi-hazard simulation, resilient support systems, and life-cycle digital twins. The review provides a structured basis for transforming underground disaster control from isolated hazard treatment to adaptive, risk-informed, and resilience-oriented management.

Keywords: Underground engineering, tunnel disaster, multi-hazard coupling, monitoring and early warning, grouting, digital twin, resilience.

1. Introduction

Underground infrastructure has become a central component of modern transportation, energy, water, mining, and urban-service systems. Greater burial depth, longer alignments, larger excavation sections, and stricter constraints on surface disturbance have expanded both the technical capability and the risk exposure of underground construction. Unlike above-ground structures, underground works are built within a medium whose properties are incompletely observed and may change abruptly over short distances. The engineering response is therefore controlled not only by structural capacity, but also by uncertain rock or soil fabric, groundwater connectivity, in-situ stress, excavation sequence, construction quality, and time-dependent degradation.

Accident investigations consistently show that unexpected ground conditions and incomplete risk control remain dominant contributors to severe events. Sousa and Einstein [1] grouped construction accidents into collapse, rockfall, flooding, excessive deformation, spalling, and location-specific failures, emphasizing the value of learning from observed failure processes. Zhu et al. [2] examined 48 major tunnel-construction accidents in China between 2010 and 2020 and argued that isolated treatment of individual hazards should be replaced by a monitoring–mitigation–rescue system with stronger resilience. These findings imply that disaster prevention cannot be reduced to the design of a single support member or the installation of a single sensor.

The original body of underground-disaster literature is highly fragmented. Collapse studies often emphasize limit analysis or support failure; water-inrush studies focus on seepage channels and grouting; settlement studies are dominated by empirical troughs, numerical models, and machine learning; and operational safety studies address gas, fire, leakage, and lining deterioration separately. Such specialization is necessary, but it can conceal common mechanisms. Excavation-induced stress redistribution can open fractures, increased permeability can accelerate softening and erosion, material loss can produce voids, and the resulting deformation can damage support and create additional flow paths. A local hydro-mechanical process may thus evolve into a collapse–inrush–settlement disaster chain.

This review reorganizes representative research around that shared evolution process. Its objectives are to: (1) classify the principal hazards and their precursors; (2) clarify the coupled mechanisms that connect geological disturbance to structural failure; (3) compare analytical, numerical, experimental, monitoring, and intelligent prediction methods; (4) evaluate current prevention and mitigation technologies; and (5) propose an adaptive, resilience-oriented framework for future underground engineering. The emphasis is on tunnels and related underground openings, while the framework is also relevant to deep excavations, caverns, underground stations, and utility spaces.

2. Review Scope and Analytical Framework

2.1. Scope and Organization of The Review

A structured critical-review approach was adopted rather than a purely bibliometric one. Foundational analytical studies and representative peer-reviewed work published mainly during the last two decades were organized according to hazard mechanism, observation method, and intervention stage. The review gives priority to studies that connect mechanism interpretation with field evidence or engineering control, because a model that reproduces a failure pattern but cannot guide monitoring or construction decisions has limited practical value.

The hazards considered here are grouped into five families: (i) gravity- and stress-driven instability, including face collapse, roof fall, progressive support failure, squeezing, and rockburst; (ii) hydro-geological hazards, including water, mud, sand, and soil inrush; (iii) ground and environmental response, especially surface settlement and damage to adjacent assets; (iv) atmosphere-related hazards, including methane or harmful-gas accumulation, fire, and explosion; and (v) service-stage deterioration, including leakage, corrosion, lining cracking, joint opening, and loss of structural performance. These categories overlap by design because the interaction between categories is often more important than the isolated hazard.

The literature is assessed using four questions: What initiates the hazard? Through what pathway does damage propagate? Which variables provide useful precursors? Which intervention can interrupt the pathway? This logic forms the basis of the source–pathway–response framework used throughout the paper.

2.2. Hazard-chain Representation

Fig. 1 summarizes the proposed multi-hazard evolution chain. Geological and environmental uncertainty defines the initial susceptibility of the system. Excavation, dewatering, blasting, machine operation, cyclic traffic, or aging then acts as a disturbance. The disturbance produces coupled changes in stress, pore pressure, fracture aperture, permeability, strength, and support demand. Once deformation or damage localizes, the system may release stored elastic energy, groundwater, soil particles, gas, heat, or detached blocks. Consequences propagate beyond the excavation boundary to workers, equipment, nearby buildings, utilities, groundwater systems, and transport networks.

For a time-dependent hazard H, a conceptual risk measure can be written as

$$R(t) = P[H(t) \mid G, C, M] \times L[H(t)] \quad (1)$$

Where G denotes geological and environmental conditions, C represents construction or operational actions, M denotes monitoring evidence, P is the conditional probability of the hazard, and L is the associated loss. Equation (1) is intentionally general: its value lies in making risk dynamic. Monitoring data should update P, while emergency planning and resilient design reduce L. A warning system that reports deformation without changing either term is not a complete risk-control system.

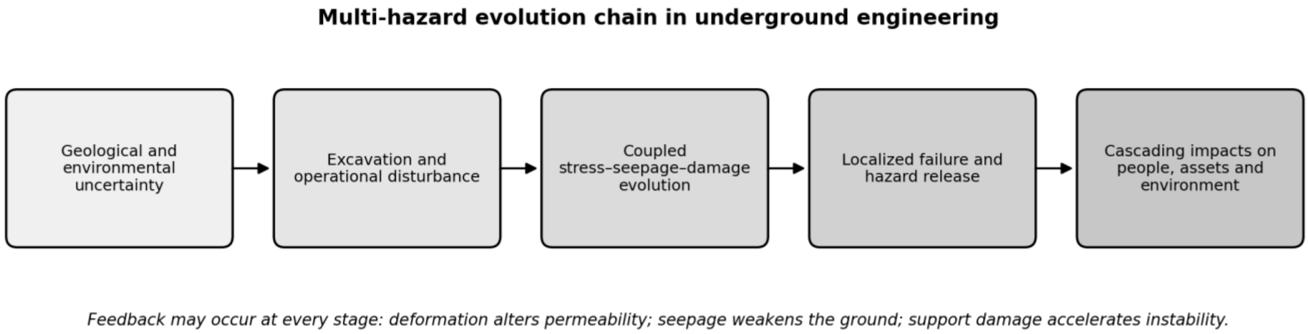

Figure 1. Multi-hazard evolution chain in underground engineering

Table 1. Principal underground-engineering hazards, precursors, and consequences

Hazard family	Typical initiating conditions	Dominant evolution process	Observable precursors	Potential consequences
Collapse and progressive instability	Weak or blocky ground; delayed closure; over-excavation; rainfall; support defects	Stress redistribution, loosening, block detachment, progressive support overload	Accelerating convergence; crown settlement; shotcrete cracking; bolt-load change; acoustic activity	Burial of workers or equipment; portal/daylight collapse; surface sinkhole
Water/mud/sand inrush	Karst cavity; water-rich fault; sandy aquifer; high hydraulic head	Seepage concentration, hydraulic fracturing, internal erosion, particle migration, channel breakthrough	Rising pore pressure; increased inflow; turbidity; resistivity anomaly; microseismic events	Flooding; material loss; face collapse; ground settlement; environmental drawdown
Squeezing deformation	High stress-to-strength ratio; weak or swelling rock; creep-prone ground	Time-dependent plastic flow and repeated support loading	Persistent convergence; invert heave; support yielding; stress redistribution	Section loss; support replacement; schedule disruption; secondary-lining damage
Rockburst/ dynamic failure	High in-situ stress; brittle hard rock; excavation-induced concentration	Crack coalescence and sudden release of elastic strain energy	Microseismic clustering; acoustic-emission acceleration; ejection sounds; stress change	Violent ejection; equipment damage; casualties; local support failure
Ground settlement and adjacent damage	Volume loss; groundwater drawdown; face instability; grouting imbalance	Ground-loss propagation, consolidation, void migration, building–ground interaction	Surface/utility settlement; building tilt; pore-pressure decline; shield parameter anomaly	Building cracking; utility rupture; road deformation; service interruption
Gas, fire, and explosion	Coal-bearing or gas-rich strata; inadequate ventilation; ignition source	Gas migration and accumulation; ignition; flame and pressure-wave propagation	Gas concentration rise; ventilation loss; temperature/smoke; electrical abnormality	Blast and fire damage; toxic exposure; evacuation difficulty
Service deterioration	Leakage; chemical attack; corrosion; cyclic loading; joint defects	Material degradation, crack growth, stiffness loss, water–structure interaction	Leakage rate; crack width; strain drift; corrosion potential; joint opening	Reduced durability and capacity; local failure; high maintenance cost

3. Major Hazard Types and Disaster Mechanisms

3.1. Collapse and Progressive Instability

Collapse is not a single failure mode. It may involve face extrusion, roof fall, wedge detachment, sidewall shear, invert heave, support buckling, or progressive failure extending to the ground surface. Limit-analysis studies provide upper- and lower-bound estimates for face and roof stability [8–10], whereas field cases reveal that real collapses are commonly governed by spatial variability, construction sequence, and incomplete support closure. For layered or discontinuous ground, partial failure may precede global collapse; the affected zone therefore depends on the orientation, persistence, and strength of weak interfaces rather than only on average rock-mass parameters.

Progressive collapse develops when the initial deformation alters the load path faster than the support system can adapt. In weak rock, loosening increases the effective span and transfers load to a limited portion of shotcrete, ribs, bolts, or segments. Cracking and debonding then reduce confinement, which further enlarges the loosened zone. The 'closed-door' collapse documented by Chen et al. [6] illustrates simultaneous failure of ground and support, while rainfall-induced collapse cases show that hydraulic weakening can transform a marginally stable slope–portal–tunnel system into a rapid failure [7]. The engineering lesson is that support capacity must be evaluated together with installation timing, closure distance, connection details, and the possibility of changing ground conditions.

Collapse prediction benefits from combining deformation trends with mechanism-specific observations. Absolute convergence is useful, but acceleration, spatial coherence, asymmetry, and the relation to excavation advance are often more diagnostic. Sarna et al. [11] showed the potential of continuation-length concepts for predicting upcoming collapse incidents. In practice, warnings should be linked to observable failure modes: increasing crown settlement may indicate loosening; asymmetric convergence may suggest wedge or fault-controlled movement; and repeated local shotcrete cracking may reveal concentrated load transfer.

3.2. Water, Mud, Sand, And Soil Inrush

Water and material inrush requires a source, a pathway, and a loss of resistance. The source may be a karst cavity, a confined aquifer, a fault zone, a weathered trough, or a surface-water body. The pathway may pre-exist as a fracture or may be created by excavation-induced damage, hydraulic fracturing, internal erosion, or progressive collapse. The resisting structure may be a rock bridge, a soil plug, a grouted zone, the tunnel face, or the lining. Xue et al. [4] reviewed genesis, evolution, and prevention mechanisms and emphasized that inrush is an evolving process rather than an instantaneous hydraulic event.

Hydro-mechanical coupling is central. Increased pore pressure lowers effective stress, while saturation and chemical interaction can reduce strength and stiffness. Deformation opens fractures and increases permeability; the resulting concentrated flow causes erosion and further strength loss. In water-rich fractured zones, Shi et al. [5] observed that sequential excavation and multiple fracture zones generated several stress- and deformation-concentration regions, while pore-water migration concentrated near the upper bench, face, arch foot, and lower positions. This feedback explains why apparently moderate inflow can precede a sudden increase in discharge or a combined collapse–inrush event.

In sandy aquifers, fine-particle migration is especially important. A small leakage path may enlarge through internal erosion until the face or lining can no longer retain the ground. Case histories from Qingdao and other metro projects demonstrate that water inrush, soil loss, ground collapse, and building damage can occur as a connected sequence [14,15]. Consequently, discharge alone is an incomplete warning indicator; turbidity, particle concentration, pore-pressure redistribution, ground loss, and surface response should also be considered.

3.3. Squeezing Deformation and Rockburst

Squeezing and rockburst represent different responses to high-stress conditions. Squeezing is dominated by large, time-dependent plastic deformation in weak or highly stressed ground, whereas rockburst involves brittle fracture and sudden release of elastic strain energy. Both hazards are sensitive to excavation geometry, face distance, stress orientation, and support interaction, but they require fundamentally different control philosophies.

For squeezing ground, an excessively stiff support may attract large loads before the ground has mobilized a stable arch. Yielding supports permit controlled deformation while maintaining confinement. Wu et al. [18] reviewed energy-absorbing bolts, compressible layers, segmented shotcrete with deformable elements, and sliding steel arches, and highlighted the need to coordinate the yield capacities of different components. The critical design task is not merely to maximize strength, but to match support resistance, deformation capacity, and installation sequence to the ground-response curve.

Rockburst control, by contrast, requires reduction of stress concentration, early identification of damage localization, and energy-absorbing support. Microseismic and acoustic-emission observations can identify changes in event rate, energy, spatial migration, and source mechanism. However, fixed thresholds are rarely transferable between projects because sensor geometry, background noise, rock type, and excavation rate differ. A reliable warning therefore combines local baseline learning with stress analysis and excavation context.

3.4. Tunnel-induced Ground Settlement and Adjacent-Asset Damage

Ground settlement is a system response to volume loss, stress relief, groundwater change, and soil–structure interaction. In shield tunnelling, important sources include face-pressure imbalance, over-excavation, tail void, grouting deficiency, steering correction, and soil loss around joints or interventions. In mined tunnels and deep excavations, settlement may result from face instability, crown relaxation, dewatering, basal heave, or wall movement.

Empirical settlement troughs remain useful for preliminary assessment, but their parameters are project dependent. Analytical and numerical models improve mechanism representation but require reliable constitutive parameters and construction details. Zhou et al. [22] reviewed empirical, analytical, numerical, and intelligent methods and noted a growing shift toward integrated monitoring, artificial intelligence, and sensor technology. Physics-informed neural networks offer a promising compromise between black-box prediction and purely numerical simulation by embedding physical constraints in the learning process [30].

Risk to adjacent assets depends on more than maximum settlement. Differential movement, curvature, horizontal strain, building stiffness, foundation type, utility joint capacity, and construction sequence determine damage. Over-control can also create problems: excessive or poorly distributed grouting may produce heave and building damage [24]. Settlement management should therefore use a response envelope that includes settlement, heave, tilt, and structural response, not a single downward-displacement limit.

3.5. Gas, Fire, Explosion, And Service-Stage Deterioration

Gas hazards are commonly associated with coal-bearing strata, organic-rich formations, abandoned workings, or shallow biogenic gas. Methane becomes dangerous when migration, accumulation, ventilation deficiency, and ignition coincide. The three tunnel explosion cases reported by He et al. [20] demonstrate that gas risk is not limited to coal mines. Geological prediction, probe drilling, ventilation design, continuous gas monitoring, explosion-proof equipment, and strict hot-work control must be integrated because eliminating only one element of the fire triangle may not be reliable under changing conditions.

During operation, fire risk interacts with ventilation, evacuation distance, lining temperature, cable and equipment performance, and smoke propagation. At the same time, slow deterioration mechanisms—leakage, corrosion, sulfate or chloride attack, freeze–thaw action, fatigue, joint opening, and repeated traffic loading—can reduce the reserve against extreme events. Service-stage management should therefore connect structural health monitoring with inspection and maintenance planning rather than treat fire safety and structural durability as separate domains.

The common feature of these hazards is delayed detectability. Damage may accumulate behind the lining or within joints before visible signs appear. Long-term sensing, robotic inspection, thermography, image-based crack detection, distributed fiber-optic sensing, and leakage monitoring can reduce blind zones, but only if data quality and maintenance of the monitoring system are controlled.

4. Research and Prediction Methods

4.1. Analytical and Empirical Methods

Analytical and empirical methods remain indispensable because they provide transparent relationships among geometry, material properties, load, and safety margin. Limit equilibrium, limit analysis, convergence–confinement, effective-stress consolidation, and empirical settlement-trough methods allow rapid screening and sensitivity analysis. They are particularly valuable during preliminary design and for checking complex numerical models.

Their limitations arise from idealized geometry, homogeneous or isotropic material assumptions, simplified boundary conditions, and difficulty representing progressive damage or changing construction states. Analytical models should therefore be treated as structured hypotheses rather than exact forecasts. Their greatest value is often to identify controlling dimensionless groups and to define the expected range of behavior.

4.2. Numerical Simulation

Finite-element and finite-difference methods are widely used for stress redistribution, support interaction, seepage, consolidation, and settlement. Discrete-element and discontinuum methods are better suited to block detachment, joint-controlled failure, and large movement. Material-point, peridynamic, and coupled particle–continuum methods can represent extreme deformation and evolving flow channels, although they require high computational effort and careful calibration.

The reliability of simulation is governed less by software sophistication than by model-form uncertainty and parameter identification. A three-dimensional coupled model may still be misleading if fracture connectivity, permeability evolution, excavation timing, or support installation are poorly represented. Validation should include multiple response variables—such as deformation, pore pressure, inflow, support load, and failure location—rather than calibration to a single curve.

4.3. Physical Modelling, Field Investigation, And Back Analysis

Physical model tests reveal mechanisms that are difficult to observe in the field, including face failure geometry, fracture propagation, hydraulic erosion, and load transfer. Centrifuge tests improve stress similitude for soil problems, while true-triaxial and seepage tests support research on rock damage and inrush. Nevertheless, scaling particle size, permeability, fracture roughness, time, and support stiffness remains challenging.

Field investigation and back analysis provide the strongest evidence of engineering relevance. High-quality case studies combine geological mapping, drilling, geophysics, monitoring, construction records, numerical reconstruction, and observed treatment effectiveness. The value of a case history increases when it reports unsuccessful actions and uncertainty, because these details allow transfer of lessons rather than retrospective confirmation.

4.4. Data-driven and Hybrid Methods

Machine-learning models are increasingly used to predict settlement, classify risk, detect anomalies, and fuse heterogeneous monitoring data. Their advantages are speed and capacity to represent nonlinear interactions. Their weaknesses are dependence on data coverage, vulnerability to distribution shift, limited interpretability, and difficulty extrapolating to rare extreme events.

Hybrid approaches are more promising than unrestricted black-box models. Physics-informed neural networks, Bayesian updating, surrogate models calibrated by numerical simulation, and digital twins can combine prior engineering knowledge with field observations. The goal should not be to replace mechanics, but to update uncertain parameters, identify deviations from expected behavior, and support decisions in near real time.

Table 2. Comparison of principal research and prediction approaches

Approach	Main outputs	Strengths	Key limitations	Best use
Empirical/statistical	Settlement troughs, risk scores, classification rules	Fast; low data and computation demand; easy communication	Project dependence; weak extrapolation; limited mechanism representation	Screening, preliminary design, benchmark checks
Analytical mechanics	Safety factors, collapse loads, ground-response relationships	Transparent assumptions; sensitivity analysis; physical interpretation	Idealized geometry/material; limited progressive-failure capability	Conceptual design and independent verification
Continuum numerical models	Stress, deformation, seepage, lining response	Flexible staging and constitutive modelling; widely available	Parameter and model-form uncertainty; mesh and boundary effects	Detailed design and scenario comparison
Discontinuum/ large-deformation models	Block movement, fracture growth, erosion channels	Represents discontinuities and extreme deformation	High calibration and computation demand; uncertain scaling	Jointed rock, collapse, inrush-channel evolution
Physical/model tests	Failure geometry, crack evolution, hydraulic response	Direct observation; controlled variables	Similarity constraints; boundary and scale effects	Mechanism validation and comparative studies
Field monitoring/back analysis	Actual performance and parameter updates	Highest practical relevance; captures construction effects	Incomplete coverage; sensor failure; confounding variables	Observational method and model calibration
Machine learning/hybrid models	Rapid prediction, anomaly detection, data fusion	Nonlinear mapping; real-time capability	Data bias; poor transferability; explainability concerns	Dynamic updating when paired with physics and uncertainty

5. Monitoring, Diagnosis, and Early Warning

5.1. Advanced Geological Prediction

Advanced geological prediction reduces uncertainty ahead of the excavation face. Common tools include geological mapping, probe drilling, tunnel seismic prediction, ground-penetrating radar, transient electromagnetics, electrical resistivity, induced polarization, borehole imaging, and water-pressure tests. No single method performs reliably under all geological conditions. Seismic methods may delineate interfaces but struggle to distinguish water content; electromagnetic methods are sensitive to conductive water but may be affected by equipment and clay; drilling provides direct evidence but samples only a small volume.

A rational program therefore uses sequential information fusion. Regional geology and surface investigation define prior scenarios; non-destructive geophysics identifies anomalies; targeted drilling verifies the highest-risk zones; and the excavation response updates the model. The result should be a decision-oriented geological model that specifies likely hazard type, location range, confidence, and required construction action.

5.2. Deformation, Seepage, Stress, And Dynamic Monitoring

Conventional monitoring includes convergence points, extensometers, total stations, inclinometers, piezometers, load cells, strain gauges, and flow meters. These instruments are mature and interpretable, but point measurements may miss localized damage. Three-dimensional laser scanning and photogrammetry provide spatial deformation and surface-condition information; InSAR supports regional settlement monitoring; microseismic and acoustic-emission systems detect dynamic cracking; and distributed fiber-optic sensing provides quasi-continuous strain, temperature, vibration, or acoustic information over long distances.

Cheng et al. [27] reviewed fiber-optic tunnel monitoring and highlighted the advantage of spatiotemporally continuous information in reducing blind zones. Continuous sensing does not automatically produce reliable warning, however. Installation strain, temperature cross-sensitivity, sensor debonding, data dropout, and long-term drift must be separated from structural response. Monitoring plans therefore require redundancy, calibration, health checks, and explicit data-quality flags.

A composite warning index may be expressed as

$$W(t) = \Sigma\, w_i\, z_i(t), \text{ with } z_i = f(\text{value, rate, acceleration, spatial pattern, data quality}) \quad (2)$$

The weights and transformation functions in Equation (2) should be mechanism dependent. A water-inrush warning may prioritize pore pressure, discharge, turbidity, and electrical anomalies; a collapse warning may prioritize convergence acceleration, support cracking, and acoustic activity. Thresholds should trigger predefined actions such as reducing advance length, increasing support, drilling verification holes, changing face pressure, evacuating personnel, or activating emergency drainage.

5.3. Intelligent Warning and Digital Twins

Digital twins link a physical project to a continuously updated virtual representation. Ye et al. [26] developed a tunnel-construction platform that integrated multi-source data, simulation, warning levels, and emergency response, and demonstrated its use in predicting a face-collapse event. The key contribution of a digital twin is not three-dimensional visualization; it is bidirectional updating between observed behavior and the construction model.

For practical deployment, a digital twin requires a stable data architecture, sensor metadata, synchronized construction records, uncertainty representation, and human-readable decision logic. The model should state why a warning is issued, which evidence is missing, and how the recommended action changes risk. Transfer learning and physics-informed models may reduce data requirements, but project-specific calibration remains essential.

The future warning system will likely combine rule-based safety constraints with probabilistic models and learned anomaly detectors. Rule-based limits protect against known unacceptable states; probabilistic models quantify uncertainty; anomaly detectors identify unfamiliar behavior. This layered architecture is more robust than relying on a single algorithm.

Table 3. Monitoring technologies for underground-engineering disaster control

Technology	Primary variables	Advantages	Limitations	Typical hazard applications
Total station / convergence monitoring	Displacement, convergence, settlement	Mature; accurate; directly interpretable	Discrete points; line-of-sight; manual workload	Collapse, squeezing, settlement
Piezometer / flow and turbidity monitoring	Pore pressure, water level, discharge, suspended solids	Direct hydrogeological evidence	Local measurement; clogging; delayed response in remote zones	Water/mud/sand inrush, dewatering impact
Load cells / strain gauges	Bolt, rib, lining, segment, or support demand	Links ground response to structural capacity	Installation sensitivity; local coverage	Support overload, lining damage, squeezing
Laser scanning / photogrammetry	Full-profile geometry, cracks, surface change	High spatial coverage; non-contact	Occlusion; dust/water; data-processing burden	Deformation, overbreak, lining inspection
Microseismic / acoustic emission	Fracture location, event energy, source mechanism	Sensitive to hidden cracking; dynamic precursor potential	Noise; location uncertainty; project-specific thresholds	Rockburst, collapse, fracture-channel evolution
Distributed fiber-optic sensing	Continuous strain, temperature, vibration, acoustics	Long-distance and dense coverage; electromagnetic immunity	Installation, bonding, interpretation, and data-volume challenges	Deformation, leakage, cracking, fire, long-term health
InSAR / GNSS / leveling	Regional or local surface displacement	Wide-area settlement surveillance; high precision when combined	Temporal decorrelation; atmospheric effects; limited underground diagnosis	Settlement basin, regional subsidence
Gas / smoke / thermal sensors	Gas concentration, airflow, smoke, temperature	Direct life-safety information; automatic interlocking	Sensor poisoning and drift; ventilation dependence	Methane, toxic gas, fire, explosion

6. Prevention and Mitigation Technologies

6.1. Collapse Prevention and Support Adaptation

Collapse control begins with reducing unsupported span and exposure time. Common measures include shorter excavation rounds, staged excavation, rapid ring closure, face bolts, forepoling, pipe roofs, spiles, canopy tubes, reinforced shotcrete, ribs, systematic bolts, and temporary invert closure. The correct combination depends on failure mode. Face extrusion requires face reinforcement and pressure control; block fall requires support that crosses discontinuities; loosening and progressive failure require rapid confinement and a closed load path.

Adaptive support design should define both resistance and deformation capacity. In variable ground, support classes alone are insufficient unless transition rules are specified. Observational design uses measured convergence, face behavior, support load, and geological mapping to modify advance length and support. Yielding elements are appropriate for severe squeezing, while energy-absorbing bolts and mesh are needed for dynamic conditions.

6.2. Water Control, Drainage, And Grouting

Water-hazard control should distinguish drainage, sealing, reinforcement, and pressure relief. Drainage lowers hydraulic head but may cause regional drawdown and settlement. Sealing preserves groundwater but transfers pressure to the lining and surrounding rock. The optimal strategy depends on environmental constraints, aquifer connectivity, lining capacity, and long-term maintenance.

Grouting remains the principal treatment for fractured or permeable ground. Li et al. [12] reviewed protection against water or mud inrush and emphasized the need to match grout material and method to fracture aperture, flow velocity, and ground type. Cement-based grout is economical and durable for larger openings; microfine cement improves penetrability; chemical grout can treat fine pores but raises durability and environmental concerns. Dynamic-water conditions require quick-setting or staged materials and carefully controlled pressure.

Grouting should be designed as a verifiable ground-improvement process. Parameters include hole geometry, sequence, pressure, volume, grout take, return flow, lifting or heave, and post-grouting permeability. Verification drilling, water-pressure testing, geophysics, and monitored excavation response are necessary because injected volume alone does not prove continuity of the treated zone.

6.3. Control of Squeezing and Rockburst

Squeezing control combines excavation geometry, stress release, reinforcement, and yielding support. Measures include pilot headings, stress-relief slots, long energy-absorbing bolts, deformable layers, yielding ribs, staged lining, and early invert closure. The support components should yield in a coordinated sequence; otherwise a weak connection can fail before the intended energy-dissipation mechanism is mobilized.

Rockburst mitigation includes stress-relief drilling or blasting, optimized excavation sequence, destress slots, surface retention, energy-absorbing bolts, cable bolts, mesh, and rapid re-entry rules. Monitoring must be integrated with exclusion zones and work planning. A warning that does not change personnel exposure or excavation activity provides little risk reduction.

6.4. Settlement and Adjacent-Asset Protection

Settlement control aims to reduce ground loss and manage the response of vulnerable assets. Shield projects use face-pressure control, controlled advance rate, steering limits, synchronized tail grouting, secondary compensation grouting, and strict management of interventions. Mined tunnels use forepoling, staged excavation, early support, groundwater control, and local ground improvement.

Protection of adjacent structures may include underpinning, isolation piles, compensation grouting, utility strengthening, temporary unloading, or controlled jacking. Trigger-action-response plans should use asset-specific limits. For a brittle masonry building, angular distortion may govern; for a pipeline, joint rotation or tensile strain may be critical. Monitoring should continue after excavation because consolidation or grout shrinkage may produce delayed movement.

6.5. Gas, Fire, And Life-Cycle Maintenance

Gas control requires geological screening, probe drilling, continuous concentration measurement, forced ventilation, drainage or extraction where necessary, explosion-proof electrical equipment, ignition-source control, and automatic shutdown or evacuation logic. Fire safety requires detection, communication, ventilation control, evacuation, compartmentation, fire-resistant materials, emergency access, and recovery planning.

Life-cycle maintenance should combine risk-based inspection with condition monitoring. Leakage and cracking should be traced to their mechanisms rather than repeatedly sealed at the surface. Maintenance databases should record defect location, growth rate, repair material, environmental condition, and recurrence. This information allows transition from periodic reactive repair to predictive maintenance and resilience planning.

Table 4. Mechanism-oriented prevention and mitigation measures

Hazard	Primary objective	Representative measures	Verification indicators	Common failure in practice
Collapse	Maintain confinement and a continuous load path	Short rounds; face reinforcement; canopy/pipe roof; rapid shotcrete/ribs/bolts; early closure	Convergence stabilization; support-load distribution; crack control; verified face condition	Delayed support, open invert, unsupported transitions, reliance on nominal support class
Water/mud/ sand inrush	Interrupt pathway and control hydraulic gradient	Probe drilling; drainage; pressure relief; pre/post-grouting; cutoff or freezing	Reduced permeability/inflow; stable pore pressure; low turbidity; verified treated zone	Unverified grout spread, excessive pressure, treating discharge without source/pathway analysis
Squeezing	Accommodate controlled deformation while retaining confinement	Yielding ribs, deformable layers, energy-absorbing bolts, staged lining, stress relief	Convergence within deformation allowance; synchronized yielding; residual capacity	Overly stiff support, mismatched component capacities, premature secondary lining
Rockburst	Reduce stress concentration and absorb released energy	Destress drilling/blasting; energy-absorbing bolts; mesh; exclusion zones; adaptive sequence	Microseismic response; reduced ejection; support energy capacity; controlled exposure	Static support designed only for load, warning not linked to work stoppage
Settlement	Minimize volume loss and protect sensitive assets	Face-pressure and grouting control; compensation grouting; underpinning; utility protection	Settlement/heave/tilt; building strain; grout pressure/volume balance	Single settlement limit, excessive grouting, delayed response to differential movement
Gas/fire/ deterioration	Prevent accumulation/ignition and maintain long-term functionality	Ventilation; gas extraction; interlocks; fire detection; inspections; predictive maintenance	Gas and airflow trends; thermal/smoke data; defect growth; repair performance	Sensor drift, poor ventilation zoning, repeated cosmetic repair without root-cause treatment

7. Integrated Framework for Multi-Hazard Resilience

The preceding review shows that prevention is most effective when it is organized as a closed loop rather than a sequence of independent technical tasks. Fig. 2 presents a six-stage framework. First, investigation establishes a baseline geological and structural model with explicit uncertainty. Second, scenario analysis identifies credible hazard chains and vulnerable receptors. Third, multi-source monitoring tests whether the system is following the expected response. Fourth, diagnosis distinguishes normal construction effects from emerging instability. Fifth, targeted control and emergency response interrupt the hazard pathway and reduce exposure. Sixth, field evidence is used to update the model and transfer knowledge to later stages or future projects.

Resilience extends the objective beyond avoiding initial failure. A resilient underground system should resist disturbance, limit propagation, maintain critical functions where possible, and recover rapidly. Chang et al. [31] emphasized multi-field monitoring, risk assessment, and rapid recovery as components of rock-engineering resilience. In practice, this requires redundancy in drainage and communication, replaceable or yielding support elements, access for inspection and repair, emergency storage or pumping capacity, and documented recovery procedures.

The framework also clarifies organizational responsibilities. Designers define credible scenarios and response limits; contractors maintain the link between observations and construction actions; monitoring teams ensure data quality and interpretation; owners define acceptable functional loss and recovery objectives; and emergency teams prepare for low-probability, high-consequence events. Shared data and decision records are necessary because fragmented responsibility can convert a detectable anomaly into an unmanaged disaster.

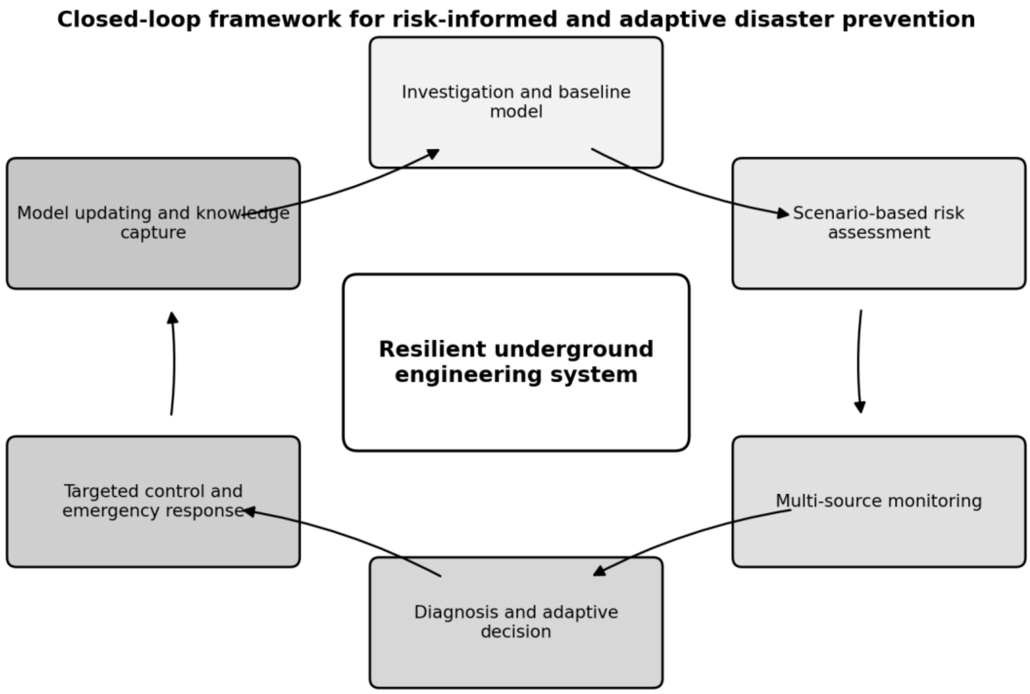

Figure 2. Closed-loop framework for adaptive disaster prevention and resilience

8. Research Gaps and Future Directions

First, uncertainty is still treated inadequately. Many studies report a deterministic prediction based on a single geological model, even though spatial variability and hidden discontinuities dominate underground risk. Future work should quantify uncertainty in geometry, parameters, boundary conditions, and model form, and should communicate prediction intervals rather than only mean values.

Second, multi-hazard coupling requires more attention. Existing models frequently analyze seepage, collapse, settlement, fire, or deterioration separately. Research should focus on transition conditions between hazards—for example, when seepage-induced erosion becomes a face collapse, when deformation creates a preferential flow path, or when fire damage reduces the residual capacity of a deteriorated lining.

Third, intelligent models need transferability and explainability. A model trained on one tunnel may fail when geology, construction method, sensor layout, or operational regime changes. Benchmark datasets, standardized metadata, physics-based constraints, domain adaptation, and uncertainty calibration are necessary before machine-learning warnings can be trusted in safety-critical decisions.

Fourth, monitoring should be designed around decisions rather than instrument availability. Research should link sensor placement to observability of failure modes and quantify the value of information. The most advanced sensor is not necessarily the most useful if it does not reduce uncertainty in a decision variable or trigger a timely action.

Fifth, resilience and recovery remain underdeveloped. Most studies end when the hazard is controlled. Future work should evaluate residual capacity, safe re-entry, emergency repair, functional recovery, and the long-term performance of treated zones. Digital twins should include maintenance history and recovery states, not only construction-stage geometry.

Finally, human and organizational factors should be integrated with geotechnical models. Work pressure, communication, competence, inspection quality, and response authority strongly influence whether warning evidence is acted upon. A complete disaster model must therefore include both physical evolution and decision-system performance.

Table 5. Priority research gaps and recommended directions

Research gap	Why it matters	Recommended direction	Expected benefit
Deterministic treatment of uncertain ground	Hidden structures and parameter variability control failure location and timing	Probabilistic geological models; Bayesian updating; interval prediction; robust design	More honest forecasts and better contingency planning
Single-hazard analysis	Hazards often transform and cascade through hydro-mechanical or thermal-structural feedback	Coupled multi-physics and event-chain modelling validated by field cases	Earlier identification of transition points and secondary consequences
Poor transferability of AI models	Project-specific data distributions cause unreliable extrapolation	Physics-informed learning; domain adaptation; standardized data and uncertainty calibration	Safer use of real-time prediction across projects
Monitoring disconnected from action	Large data volumes do not guarantee risk reduction	Decision-oriented sensor design; value-of-information analysis; trigger-action-response plans	Faster and more defensible construction decisions
Limited recovery and resilience research	Failure avoidance alone does not ensure continuity or rapid restoration	Residual-capacity assessment; replaceable systems; emergency repair and recovery metrics	Reduced downtime and life-cycle loss
Fragmented organizational learning	Lessons are lost between design, construction, operation, and different projects	Integrated incident databases; digital records; post-event model updating and governance review	Institutional learning and prevention of repeated failures

9. Conclusions

Underground-engineering disasters are best understood as evolving system failures rather than isolated events. Geological uncertainty and construction or operational disturbance initiate coupled changes in stress, seepage, damage, and support response. Localized damage can then release ground, water, gas, heat, or stored strain energy and generate cascading impacts at the surface and across connected infrastructure.

The review identifies four practical conclusions. First, mechanism-based hazard chains provide a better basis for prevention than lists of independent risk factors. Second, analytical, numerical, experimental, monitoring, and data-driven methods are complementary; reliability comes from cross-validation and uncertainty updating rather than model complexity alone. Third, monitoring must combine value, rate, acceleration, spatial pattern, and data quality, and warnings must be tied to predefined construction actions. Fourth, effective prevention requires a closed loop connecting investigation, risk scenarios, multi-source monitoring, diagnosis, adaptive control, emergency response, and knowledge capture.

Future progress will depend on coupled multi-hazard modelling, continuous sensing, physics-informed data fusion, transferable warning systems, resilient support and drainage, and digital twins that extend through maintenance and recovery. These developments can shift underground disaster management from reactive treatment toward adaptive and resilience-oriented engineering.

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