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Safety in NATM tunnel construction: A systematic review of incidents, causes and prevention measures

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ABSTRACT:

The New Austrian Tunnelling Method (NATM) is one of the most widely adopted techniques for tunnel construction in complex geological conditions, applied extensively in road, metro, and hydropower projects. NATM construction entails significant occupational hazards owing to confined working spaces, an unsupported excavation face, and intensive construction cycles. This paper presents a systematic review of NATM construction safety based on international incident databases, technical reports, and multidisciplinary peer-reviewed studies. Three principal findings emerge: collapses and daylight collapses account for 69% of all recorded incidents; unpredicted ground conditions — the most frequently cited external cause — typically reflect inadequate site investigation rather than truly unforeseeable geology; and management and supervision failures contribute to the majority of incidents. An integrated three-dimensional safety management framework — technical, organisational, and individual — combined with the Observational Method and modern monitoring technologies is proposed and discussed.

1. Introduction

The rapid urbanisation of recent decades has substantially increased demand for underground space. Tunnels play an indispensable role in transport, utility distribution, and hydraulic infrastructure, with the global stock of road and urban tunnels now exceeding hundreds of thousands of kilometres and still growing rapidly in developing economies, particularly across Asia [1], [2]. Tunnel construction is widely recognised as one of the highest-risk activities in the civil engineering sector; incident records have been documented from Japan [3], South Korea [4], [5], Europe [6], and numerous other regions [7]. The International Labour Organisation (ILO) consistently identifies construction as among the industries with the highest rates of occupational injury and fatality worldwide [8].

Among modern tunnelling methods, the New Austrian Tunnelling Method (NATM) stands out for its adaptability to diverse ground conditions. Since its introduction by Rabcewicz in the 1960s

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[9], [10], [11], NATM has been applied to thousands of kilometres of tunnels globally, from mountain road tunnels to deep urban metro systems [12]. Its defining characteristic — an unsupported or lightly supported excavation face that relies on the ground's own load-bearing capacity — creates specific safety challenges that warrant systematic investigation.

A substantial body of literature now addresses tunnel construction safety, including international incident databases [7], [2], [13], [14], statistical analyses of causes and consequences [15], [6], [16], [17], technical guidance from safety authorities [18], [19], and multidisciplinary studies incorporating human and organisational factors [20]. Regional analyses cover Japanese [3], [21], South Korean [4], [5], and German rail-tunnel [6], [22] experience. However, a review that simultaneously integrates technical, organisational, and individual dimensions of NATM safety management remains lacking.

This paper is structured as follows: Section 2 reviews the historical development and technical principles of NATM. Section 3 analyses the global incident database. Section 4 synthesises failure mechanisms by construction stage. Section 5 examines causes and causal chains. Section 6 proposes an integrated prevention framework. Section 7 discusses limitations and emerging directions. Section 8 presents conclusions.

2. Historical development and technical principles of NATM

2.1 Origin and evolution

NATM was introduced by Rabcewicz through three consecutive papers in 1964–1965 [9], [10], [11], building on experience from Alpine railway construction dating to the nineteenth century. Müller-Salzburg [23] identified the fundamental reasons for unsuccessful NATM applications, laying the groundwork for procedural standardisation. The defining distinction from conventional methods is the principle of continuous monitoring of ground behaviour and iterative adjustment of the support system — NATM is not a specific excavation or lining technique but a set of principles [24], [25].

NATM spread widely across Europe from the early 1970s. Its extension to urban metro construction in soft ground during the 1980s–1990s brought substantially greater technical challenges and a cluster of serious incidents [18], [26]. Following the 1994 Heathrow Express collapse, the UK Health and Safety Executive (HSE) undertook a comprehensive review and issued technical guidance [18], [26] that became an international reference standard. Critical analyses of NATM's conceptual boundaries were published by Haack [27] and Kovari [28], clarifying appropriate application scope. The DAUB committee [24] formalised definitions and classification of NATM construction methods. From the early 2000s, NATM was adopted broadly across Asia [3], [4], [5], [21] and South America [7], and integration of digital technologies — IoT sensors and Digital Twins [29], [86] — into NATM monitoring has emerged as a leading trend of the 2020s.

2.2 Technical principles and construction cycle

NATM rests on three core principles: (1) mobilising the natural load-bearing capacity of the surrounding ground; (2) controlling deformation through a flexible support system installed immediately after excavation; and (3) continuous monitoring with real-time design adjustment [18], [25]. Karakus and Fowell [25] provide a comprehensive analysis of stress redistribution and deformation mechanisms in NATM. The Ground Reaction Curve (GRC) illustrates the equilibrium between ground deformation and support resistance, allowing the lining to accept load at larger deformation levels and thus exploit the ground's residual strength. The Observational Method formulated by Peck [30] and revisited by Muir Wood [31] constitutes the philosophical backbone of NATM; ITA [32] codified it within international tunnel design guidelines.

The standard NATM construction cycle comprises sequential partial-face excavation (top heading, bench, invert); immediate face stabilisation with initial shotcrete; installation of support (shotcrete, rock bolts, lattice girders, forepoling where required); continuous deformation monitoring; and design adjustment based on monitoring feedback [18], [12]. Barbole and Pawar [12] describe a 13-step standard sequence for urban conditions. The importance of early ring closure — invert completion within approximately 2D of the face — is consistently emphasised in both technical literature [18], [23], [33] and field records [34], [35]. Broms and Bennermark [36] quantified face instability risk through the stability number N, a tool that has been embedded in NATM design practice ever since. Mair and Taylor [37] analysed tunnel–structure interaction in urban environments, while Barton et al. [38] systematised Q-system rock mass classification for support design. Hoek and Marinos [39] highlighted the specific challenge of squeezing ground, where large sustained deformations can exceed conventional support capacity.

3. Incident database and classification

3.1 Sources and scope

Systematic tunnel incident databases began emerging in the late twentieth century across several regions independently. In Japan, Inokuma et al. [3] reported 71 incidents in 65 tunnels between 1978 and 1991, complemented by the Japan Labour Standards Bureau technical handbook [21]. In South Korea, Park and Lee [4] analysed collapse modes and causes in metro tunnels, supplemented by a national consultancy report [5]. In Germany, Leichnitz [6] analysed NATM collapses on the new Federal Railway lines; Bindow and Wagner [22] documented early contractor experience from the 1970s.

In the UK, following the October 1994 Heathrow Express triple-tunnel collapse, HSE assembled 39 NATM incidents from 1973–1994 [18] and in 2006 published a supplementary report covering 108 incidents [19]. Seidenfuss [13] compiled 110 incidents and Stallmann [14] assembled 33 detailed collapse case studies. Vlasov et al. [2] published a database particularly rich in cases from Russia and Eastern Europe.

The most comprehensive compilation is the MIT study by Sousa and Einstein [7], conducted in 2007–2009, which assembled 206 cases from technical literature and correspondence with 113 specialists worldwide. The database spans railway (26%), road (21%), hydraulic/hydropower (34%), metro (18%), and other projects (1%), with geographic distribution: Europe 49%, Asia 30%, South America 14%, North America 6% [7]. This remains the only database enabling systematic comparison between NATM/drill-and-blast and TBM/shield methods [7]. Sousa and Einstein [16] subsequently developed quantitative risk assessment using Bayesian networks, applied to the Porto Metro project. Einstein [15] established the theoretical foundation for geotechnical risk analysis.

3.2 Incident classification and frequency

Following the phenomenological classification of Sousa and Einstein [7], incidents are grouped into seven types, summarised in Table 1. Collapses and daylight collapses together account for 69% of all incidents — not necessarily because they are the most frequent in absolute terms, but because they produce the most severe consequences and are more completely reported [7]. Rockburst mechanisms are classified by Kaiser et al. [40], with case studies from Lee et al. [41] and Ortlepp and Stacey [42].

Table 1. Incident distribution in the MIT database (n = 206) [7].

Incident type	n	%	Location and key characteristics
Collapse	78	41	75% at the excavation face; volume 10–250 m^3 (NATM/D&B) [7]
Daylight collapse	52	28	Mainly at face; when H/D < 5; volume 10–3,000 m^3 [7]
Excessive deformation	19	10	65% behind the face; associated with squeezing/swelling [7]
Flooding / inundation	12	6	37% at face; 47% unspecified; more frequent in TBM drives [7]
Rock fall	12	7	43% at crown/sidewalls; 36% at face [7]
Rockburst / spalling	4	2	At crown, walls, floor; high stress and brittle rock [7], [40], [41], [42]

Special locations (portal, junction, shaft)	10	5	Stress concentrations at portals, junctions, and shafts [7]
Other (fire, gas, equipment)	~19	~9	Great Belt TBM fire (1991) [43][44]; Baku metro gas explosion [7]

Spatially, 56% of all incidents occurred at or near the excavation face and 18% behind it [7] — consistent with the NATM characteristic of an unsupported heading. Proportionally, daylight collapses are more common in NATM/drill-and-blast than TBM drives; flooding is more prevalent in TBM tunnelling [7]. Collapse volumes range from 10–250 m^3 for collapses to 10–3,000 m^3 for daylight events; the latter occur when $H/D < 5$, typically when $H/D < 3$ [7]. Notably, the Hai Van Pass Tunnel in Vietnam (Project ID 62) appears in the database with a daylight collapse in September 2001 [7].

3.3 Selected landmark incidents

The Heathrow Express collapse (UK, October 1994) exemplifies a cascading failure in a multi-tunnel system: approximately three months of incorrect excavation sequence, sub-standard work at a junction section, and improper remediation [18], [26], [45]. Total losses: USD 141 million; programme delay: 14 months [7]. Wallis [46] documented analogous lessons from earlier NATM incidents in Germany. The Seoul Metro Line 5 experience (South Korea, 1991–1993) recorded five successive daylight collapses — a stark illustration of the consequences of failing to transfer lessons between incidents [7], [4], [5]. The Montemor Tunnel (Portugal, 1994) demonstrated that correctly specified rock bolts installed in the wrong sequence can loosen rather than reinforce the ground [47]. The Lisbon Olivais Sul collapse (1996) resulted from overestimated geomechanical parameters in design [51]. Weber [50] and Friedrichsen [49] documented the Munich Metro failures in urban clay.

3.3.1 Pinheiros Station, São Paulo (January 2007)

The most severe urban underground incident in Brazilian history: a daylight collapse on 12 January 2007 during NATM construction caused seven fatalities and extensive infrastructure damage. The station comprised a 40 m-diameter, 36 m-deep shaft and two 18.6 m-wide platform tunnels in weathered gneiss with four joint sets [52].

The investigation identified two independent causal chains converging simultaneously [52], [53]. On the design side, an oversimplified geomechanical model omitted an axis-parallel fault, and warning thresholds were never defined. On the construction side, the bench excavation sequence was reversed, bench height was increased, and shotcrete quality control was severely deficient. Critically, monitoring data showed accelerating deformation from December 2006 — yet excavation speed increased through January 2007 [52]. This provides direct documentary evidence of schedule pressure overriding technical judgment. Barton [53] further analysed the geological factors contributing to the sudden, catastrophic failure mechanism.

4. Failure mechanisms in NATM Tunnelling

Synthesising across verified technical sources [7], [18], [25], [34], [35], [54], failure mechanisms in NATM construction are grouped by construction stage — an approach with direct practical value because it links each mechanism to corresponding prevention measures [18]. Schubert and Riedmüller [54] provide post-collapse field investigation data; Schubert and Vavrovsky [34] systematise monitoring data interpretation; Schubert and Richardson [35] document Seoul Metro experience.

Table 2. NATM failure mechanisms by construction stage [7], [18], [25], [34], [35], [54].

Construction stage	Main failure mechanisms	Governing factors
Unsupported excavation face [7], [18], [25], [36]	Face instability in soft ground (N > 6); wedge failure in jointed rock; viscoplastic flow in saturated soft soils; pressurised groundwater ingress through face	Stability number N [36]; C/D ratio; groundwater pressure; ground anisotropy [18]
Post-excavation, before ring closure [18], [34], [54], [55]	Excessive deformation in squeezing ground; bending failure of lining due to overloading; invert heave; uneven loading causing lining fracture	Cover ratio; ring-closure delay; early-age shotcrete thickness and strength [18][56]
Long-term, after ring closure [18], [35], [57]	Surface settlement from excessive dewatering; long-term deformation from creep and swelling; flood damage; additional loading from surface surcharge	Groundwater level; adjacent loading; long-term material quality [18], [37], [57]

At the unsupported face stage, Broms and Bennermark [36] established that a stability number N > 6 typically leads to uncontrolled face instability in soft clay — a quantitative tool integrated into NATM practice ever since. Karakus and Fowell [25] extended the analysis to plasticity-based failure modes in rock.

Between excavation and ring closure, Müller-Salzburg [23], [33] stressed the primacy of ring-closure timing — one of the earliest lessons from NATM practice. Kovari and Staus [55] and Einstein [58] provided quantitative treatments of squeezing and swelling. Schubert [56] and Barla [57] prescribed engineering solutions for severe squeezing. Hoek [59] synthesised experience from large tunnels in difficult ground; John et al. [60] recorded monitoring experience from the Channel Tunnel.

Long-term mechanisms after ring closure involve groundwater changes, creep in cohesive soils, swelling in expansive clays [57], and time-dependent surcharge loading — particularly critical in dense urban environments. Mair and Taylor [37] provided a comprehensive treatment of tunnel–structure interaction effects.

5. Incident causes and causal chains

5.1 Classification and characteristics

Drawing on multiple international sources [2], [7], [16], [17], [18], NATM incident causes are classified into two groups: external causes related to hydrogeological and environmental conditions, and internal causes related to planning, design, and construction management. No incident has a single cause — all result from chains of events and concurrent contributory factors [7], [18]. Einstein [15] formalised causal chain concepts and proposed influence diagrams as an analytical tool. Sousa and Einstein [16], [17] constructed incident-specific influence diagrams for each failure type, providing a systematic framework for risk assessment.

5.2 External causes

Unpredicted ground conditions constitute the most common external cause, encompassing faults, weak zones, saturated sand/gravel lenses, and karstic features [7], [18]. Sousa and Einstein [7] and the HSE [18] both emphasise that this typically reflects inadequate site investigation rather than genuinely unforeseeable conditions — a conclusion consistent across regional analyses from Germany [6], [22], Japan [3], and South Korea [4], [5]. Barton [61] provides an in-depth analysis of fault-zone contributions to both TBM and NATM incidents.

Groundwater is a particularly severe amplifying factor: it transforms failure from unsaturated sliding to saturated flow — faster and substantially larger in volume [7]. Nakagawa and Torii [62] documented four major water-ingress incidents in the Seikan Tunnel (Japan) with 34 total casualties. Earthquakes are rare but catastrophic: Dalgic [63] analysed the 1999 Bolu

Tunnel collapse triggered by the Duzce earthquake, supplemented by Ghasemi et al. [64]. Gas hazards are recorded at the Los Angeles Metro [43]; TBM fire risk is illustrated by the 1991 Great Belt event [44], [7].

5.3 Internal causes

Four internal cause groups are consistently identified [7], [18], [20]. Planning and design errors include the Olivais Sul case (1996) with overestimated geomechanical parameters [51]. Construction errors encompass the Montemor case (out-of-sequence bolting [47]) and Pinheiros (reversed bench sequence and poor shotcrete quality [52]). Wallis [46] documents the financial history of NATM failures in Germany and Europe; Bindow and Wagner [22] record the earliest field experience with NATM construction errors in the USA.

Management and monitoring failures appear as contributing factors in the majority of incidents [7], [18], [20]: failure to act on clear monitoring signals, as at Shanghai Metro Line 4 in 2003 [65] and Pinheiros in 2007 [52], [53], represents the most preventable failure mode. Face stability under challenging conditions requires additional measures: Anagnostou and Kovari [66] address stability under high water pressure; Pelizza and Peila [67] and Lunardi [68] cover ground reinforcement comprehensively.

Table 3. NATM incident cause groups and corresponding prevention measures.

Cause group	Typical manifestations	Primary prevention measures
EXTERNAL		
1. Unpredicted ground conditions [7], [18], [6]	Faults, weak zones, saturated sand/gravel lenses, karst voids, unmapped buried structures — usually reflecting inadequate investigation rather than truly unforeseeable conditions	Adequate borehole density; continuous probe drilling ≥10 m ahead of face; combined TSP and GPR [7], [18], [69], [70]
2. Groundwater and pore pressure [7], [18]	Water transforms failure mechanism from dry sliding to saturated flow — faster and larger in volume; sudden inflow from faults, aquifers, or karst (Lausanne M2 2005; Seikan 1969–1976 [62])	Continuous piezometric monitoring; pre-grouting; standby pumping; probe drilling ahead of face [7], [18]
3. External events: earthquake, surcharge [7], [63], [64]	Duzce 1999 earthquake collapsed both Bolu Tunnel headings at NATM–fault intersection [63]; sudden groundwater change from intense rainfall	Seismic risk assessment in design; post-earthquake monitoring; emergency plan [7], [64]
INTERNAL		
4. Planning and design errors [7], [18], [54]	Insufficient ground investigation leading to under-designed support; 3D effects ignored at tunnel junctions; warning thresholds not defined (Pinheiros 2007 [52])	Thorough pre-design investigation; 3D analysis in complex zones; pre-defined warning thresholds and contingency plans [7], [5], [16], [18]
5. Construction errors [7], [18], [22], [47]	Rock bolts installed out of sequence causing ground loosening (Montemor [47]); delayed invert closure; reversed bench sequence (Pinheiros [52]); poor shotcrete quality control	Strict adherence to design sequence; invert closure within ~2D of face [18], [23], [33]; field shotcrete quality control [7], [18], [20]

Cause group	Typical manifestations	Primary prevention measures
6. Management and monitoring failures [7], [18], [20]	Failure to act on monitoring signals despite available data: Shanghai 2003 [65] (faulty equipment unreported; USD 60 M, 47 months delay); Pinheiros 2007 [52] (accelerating deformation over 2 months; excavation rate increased)	Quantitative alert thresholds with clear stop-work authority; no-blame reporting culture [71]; independent audits; continuous training [7], [18], [20], [72]

5.4 Consequences and economic losses

Consequences are classified as in-tunnel (structure, personnel, equipment) and at surface (buildings, persons, urban infrastructure) [7]. In the period 1990 to the early 2000s, cumulative Construction All-Risk insurance losses exceeded USD 750 million in property damage alone [73]. Average programme delay was six months, with seven cases exceeding twelve months [7], [73]. Munich Re Group [74] estimates total costs of urban tunnel incidents globally in the billions. Grandori et al. [75] document lessons from the Evinos-Mornos tunnel on risk management in exceptionally challenging ground. Weber [50] questions the applicability limits of shotcrete-based construction in urban railway conditions.

6. Integrated prevention framework

6.1 Observational method and geotechnical monitoring

Peck's Observational Method [30], revisited by Muir Wood [31] and codified by ITA [32], is the technical foundation of NATM. It requires: pre-construction definition of expected and most unfavourable behaviour envelopes; quantitative alert and action thresholds; and pre-prepared contingency plans [30], [32]. The geotechnical monitoring programme typically includes 3D displacement monitoring, shotcrete stress measurement, rock bolt load cells, surface settlement monitoring, and groundwater level measurement [18], [34]. Habernicht [76] described an early field implementation of NATM monitoring feedback. Schubert and Vavrovsky [34] systematised monitoring data interpretation. Measurement frequency must match excavation rate — at minimum twice per shift in soft ground conditions [18].

Ahead-of-face probing is the key measure to mitigate risk from unpredicted ground conditions. Dickmann and Sander [69] developed the Tunnel Seismic Prediction (TSP) system with a detection range of 100–150 m ahead. Cardarelli et al. [70] assessed the effectiveness of combined geophysical methods including GPR (high resolution over 5–30 m) for tunnel stability evaluation. Sousa and Einstein [7] characterise continuous probing during construction as both "feasible and necessary" — the primary countermeasure against the leading external cause.

6.2 Support system and stability control

Steel-fibre shotcrete is the primary technical measure: early-age strength (6–8 hours) must reach at least 2 MPa for immediate post-spray protection [18]. Hoek and Brown [77] provide the fundamental quantitative tool — the Hoek-Brown failure criterion — for rock mass strength classification. Kovari and Descoeudres [78] synthesise international experience from Swiss tunnel construction. Barla and Pelizza [79] analyse TBM performance in difficult ground, providing systematic comparison with NATM.

Early ring closure is the single most fundamental technical requirement of NATM [18], [23], [33]. Anagnostou and Kovari [66] quantify face stability under high water pressure and soft-ground conditions. Pelizza and Peila [67] synthesise ground reinforcement techniques. Lunardi [68] systematises tunnel design and construction methods, emphasising the ADECO approach of pre-face deformation analysis. Barton et al. [38] provide Q-system-based support design for varied ground conditions. Bindow and Wagner [22] document the earliest practical experience with NATM support measures.

6.3 Organisational safety management

ILO [72] provides a comprehensive code of practice for safety and health in underground construction, covering pre-construction risk assessment, emergency planning, and response procedures with clearly assigned responsibilities. The safety culture concept — originating in post-Chernobyl research [71] — is increasingly integrated into tunnel construction safety management. Without a no-blame reporting culture, early-warning signals will not be acted upon in time, as demonstrated by Shanghai 2003 [65] and Pinheiros 2007 [52]. ILO [80] recommends mandatory professional certification for tunnel construction supervisory personnel. Inokuma et al. [3] and the Japan Labour Standards Bureau [21] document Japan's specific training requirements.

6.4 Underground environmental safety

PIARC [81] provides authoritative guidance on fire and smoke control in road tunnels — the international reference standard for fire protection in tunnel construction. OSHA [82] specifies ventilation requirements, permissible concentrations of hazardous gases (CO < 50 ppm, NOx < 3 ppm post-blast), and hydrocarbon detection requirements. Experience from the Los Angeles Metro [43] and the 1991 Great Belt TBM fire [44] established higher standards for automatic fire detection systems.

6.5 Advanced monitoring technologies

Pelecanos et al. [83] demonstrated that Distributed Fibre Optic Sensing (DFOS) enables continuous strain profiling along structural elements, detecting local anomalies that point-based monitoring systems may miss — a technology with particular promise for NATM lining surveillance. Wang et al. [29] reviewed Digital Twin applications in underground engineering; Zhao et al. [86] developed an integrated Digital Twin simulation system for NATM tunnelling that models geological uncertainty through Markov Random Fields and assesses construction accident risk via AHP–DEMATEL, achieving schedule prediction error of only 0.5% in a full-scale validation project in Yunnan Province, China. Du et al. [87] proposed a data-as-a-service (DaaS) framework that integrates multi-source sensor data from distributed NATM monitoring networks, using Gaussian Process models to identify associations among geological, deformation, and structural load parameters, enabling real-time early warning and construction scheme adjustment. Wu et al. [88] presented an interpretable AI framework combining convolutional neural networks with Bayesian inference to automatically identify NATM work-cycle activities from CCTV surveillance images, achieving 81.3% overall accuracy — a proof-of-concept for AI-assisted construction safety monitoring. Pu et al. [84] proposed a risk assessment model combining game theory and multi-dimensional cloud modelling to handle simultaneous uncertainty and fuzziness in complex geological conditions. He et al. [40] built a rockburst database applying data mining techniques, laying groundwork for AI-based deep-tunnel risk assessment. As Bektašević et al. [20] caution, however, the value of any advanced monitoring technology is entirely contingent on its integration into a decision-making system with clearly assigned response responsibilities.

Table 4. Integrated three-dimensional safety management framework for NATM tunnel construction [7], [18], [20].

Dimension	Component	Measures and tools	References
Technical	Investigation and probing	Adequate borehole density; TSP (100–150 m ahead); GPR (5–30 m); continuous probe drilling in complex zones	[7], [18], [69], [70]
	Support system	Steel-fibre shotcrete ≥2 MPa at 8 h; correctly sequenced rock bolts; forepoling; FRP face reinforcement; early ring closure within ~2D	[18], [23], [33], [66], [67], [68]

Dimension	Component	Measures and tools	References
	Monitoring and surveillance	3D displacement monitoring; shotcrete stress; DFOS distributed sensing; IoT automated alert systems; Digital Twin [29][86]; AI-based work progress identification [88]; data-as-a-service integration [87]	[7], [18], [20], [34], [76], [83], [86], [87], [88]
	Underground environment safety	Post-blast ventilation (CO < 50 ppm); hydrocarbon detection; automatic TBM fire detection; evacuation planning	[18], [20], [43], [44], [81], [82]
Organisational	Risk management	Pre-construction risk assessment updated when conditions change; emergency plans with clear responsibilities; evacuation drills	[7], [18], [20], [15], [16]
	Training and competence	Stage-specific risk awareness training; mandatory professional certification; supervisory engineer training	[20], [3], [72], [80]
	Safety culture and oversight	No-blame reporting culture; independent inspection; effective stop-work authority; timely processing ofonitoring a	[7], [18], [20], [71]
Individual	PPE	Hard hat; safety footwear [85]; high-visibility vest; respiratory protection; life jacket in flood-risk zones	[20], [82], [85]
	Awareness and behaviour	Hazard identification; right to refuse unsafe work; workload and mental health management; long-term silicosis prevention	[20], [72], [80]

7. Discussion

Three convergent findings emerge consistently from the international evidence base [7], [18], [20], [2], [3], [6], [4]. First, multi-causality is a structural characteristic of NATM incidents: no incident has a single cause [7], [18], and this demands systemic intervention rather than isolated technical fixes. Second, unpredicted ground conditions — the most frequently cited external cause — typically reflect insufficient investigation, meaning the majority of incidents are in principle preventable [7], [18], [15]. This conclusion is corroborated independently by regional analyses from Japan [3], South Korea [4], [5], Germany [6], [22], and the global dataset [7], [16], [17]. Third, management and monitoring failures — present in the majority of incidents as contributing factors — represent the most tractable internal cause group [7], [18], [20].

Several limitations warrant acknowledgement. The MIT database [7] was compiled through approximately 2009 and is geographically skewed toward Europe (49%) and Asia (30%), so it does not capture incident patterns of the 2010–2025 period, which has seen substantially expanded NATM use in Southeast Asia. Some advanced monitoring technologies reviewed here [29], [83], [84], [86], [87], [88] lack sufficient long-term field validation to permit quantitative effectiveness assessment. Vietnam-specific information in the international literature is limited to the Hai Van Tunnel incident (2001) [7]; a more complete picture of regional incident patterns requires dedicated data collection.

8. Conclusions

A systematic review of NATM construction safety, drawing on international incident databases, multi-regional technical reports, and peer-reviewed multidisciplinary research, yields the following conclusions.

On incident distribution: collapses and daylight collapses account for 69% of all recorded incidents; 56% occur in the vicinity of the excavation face — directly consistent with the NATM characteristic of an unsupported heading. Daylight collapses develop when $H/D < 5$ and involve the largest displaced volumes. Groundwater is the most severe amplifying factor, transforming dry sliding into saturated flow with markedly greater velocity and volume.

On failure mechanisms: mechanisms are systematically grouped into three construction stages — unsupported face (most critical when $N > 6$ or with significant seepage); pre-ring-closure (requiring invert completion within approximately 2D of the face); and long-term post-ring-closure (creep, swelling, and unpredicted surface loading).

On incident causes: multi-causality is a structural feature — no single-cause incident exists in the dataset. Unpredicted ground conditions, the most commonly reported external cause, typically reflect inadequate site investigation rather than genuinely unforeseeable geology, as confirmed consistently across independent sources and regions. Management and monitoring failures appear as contributing factors in the majority of incidents.

On prevention: effective risk management requires an integrated three-dimensional approach — technical (adequate investigation, continuous ahead-of-face probing, appropriate support, early ring closure, continuous monitoring), organisational (ongoing training, emergency planning, safety culture, effective stop-work authority), and individual (risk awareness, appropriate PPE). IoT, Digital Twin, and AI technologies open significant potential for improved monitoring effectiveness, but their value depends entirely on integration into a decision system with clearly assigned response responsibilities.

On future research directions: the following priorities are identified, with particular relevance for Vietnam and Southeast Asia.

(i) Regional incident database for Vietnam and Southeast Asia. The international literature contains only one documented Vietnamese NATM incident (Hai Van, 2001) [7]. Vietnam is now actively constructing metro lines in Hanoi and Ho Chi Minh City through heterogeneous alluvial deposits and weathered rock profiles that combine characteristics of both European soft-ground and Asian mountainous contexts. A dedicated incident database — structured analogously to the MIT database but capturing local conditions, institutional frameworks, and contractor experience — is urgently needed as a foundation for evidence-based safety regulation;

(ii) Characterisation of Vietnamese and Southeast Asian ground conditions for NATM risk. The geological profiles encountered along urban metro alignments in Vietnam — laterite, residual soils, alluvial sequences with buried palaeochannels, and karst in the northern limestone highlands — present specific hazard combinations not fully represented in European-derived guidance documents. Systematic characterisation of these profiles, including probabilistic hydrogeological modelling, would enable more reliable application of tools such as influence diagrams [16], [17] and vulnerability frameworks [86] to local conditions;

(iii) Adaptation and validation of advanced monitoring technologies to local constraints. DFOS [83], Digital Twin platforms [86], and AI-based monitoring [87], [88] have been validated primarily in European and East Asian project environments with high instrumentation budgets and established data infrastructure. Research into lower-cost deployment configurations, wireless data transmission under tropical humidity conditions, and adaptation of AI training datasets to Southeast Asian equipment types and construction workflows is required before these technologies can be reliably transferred;

(iv) Development of national technical standards and institutional frameworks. Vietnam currently relies primarily on adapted international codes for tunnel construction safety. A research programme addressing the development of national NATM guidelines — incorporating local geological classification, contractor competence certification requirements, and mandatory incident reporting — would provide the institutional preconditions for systematic safety improvement. Comparative analysis of Japan's [3], [21] and South Korea's [4], [5] experience in developing national tunnelling safety frameworks offers directly transferable procedural lessons for this process.

Contributions of authors in this article

Truong Van Y: Methodology, Data management, Formal analysis, Investigation, Validation, Visualization, Grant acquisition, Feedback on peer review, Writing – original manuscript. **Nguyen Tien Thuy, Nguyen Tuan Anh, Nguyen Trong Tam, Pham Ngoc Thach:** Data compilation, Data analysis, Investigation, Verification, Writing – original manuscript. **Nguyen Tan Dong, Bui Hong Dang:** Methodology, Supervision, Grant Acquisition, Manuscript Editing.

Declaration of competing interest and dedication to copyright

The authors declare the absence of any potential conflicts of interest from this study and affirm that the paper has not been previously published.

Data available

Data will be provided upon request.

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