GEORGE BROWN PRESS
JOURNALS, BOOKS & PROCEEDINGS

International Journal of Engineering Advances

Article

Research on Identification and Analysis of Hazards in High Altitude Tunnel Construction Operations

Defeng Duan [1,*], Baofeng Sun [1] and Hai Liu [1]

[1] CCCC-SHB Fourth Engineering Co.,Ltd., Luoyang, Henan, 471002, China
* Correspondence: Defeng Duan, Fourth Engineering Co., Ltd., Second Highway Engineering Co., Ltd., Luoyang, Henan, 471002, China

Abstract: Tunnel construction is an important safety control scenario in transportation engineering construction. Due to its own characteristics, such as high weight of terrain and landforms, complex geological conditions, numerous environmental factors, and difficult management, tunnel construction safety management has attracted much attention. In different tunnel constructions, the difficulty of managing high-altitude tunnel construction is particularly prominent. This article focuses on the high-altitude areas represented by the Qinghai Tibet Plateau. Taking the Laze Tunnel as the research objective, a combination of on-site investigation, interview, and screening methods were used to identify the hazards of high-altitude tunnels from four aspects: personnel, equipment, environment, and management. Analyzed its existing problems and provided countermeasures and suggestions. This study lays a theoretical foundation and practical significance for the safety management of high-altitude tunnel construction operations.

Keywords: plateau; tunnel construction; human machine environment system analysis; hazard identification

Received: 11 June 2025
Revised: 20 June 2025
Accepted: 28 June 2025
Published: 10 July 2025

1. Introduction

1.1. The Growing Importance of Safety in Transportation Infrastructure

With the continuous development of the global economy, the acceleration of technological progress, and the rising public awareness of occupational safety, safety production has become a fundamental component of infrastructure planning and execution. In particular, the field of transportation engineering — which involves large-scale, high-risk, and long-duration projects — faces increasingly complex safety challenges. Ensuring safety is not only a legal requirement but also a critical determinant of project sustainability and social responsibility.

In recent years, the Chinese transportation industry has significantly strengthened its focus on risk prevention and control in engineering projects. A comprehensive legal and regulatory framework has gradually taken shape, encompassing laws, administrative regulations, technical standards, industry guidelines, and procedural codes. These instruments collectively aim to enhance the systematic, procedural, and standardized management of construction safety. Emphasis has been placed on the establishment of clear safety responsibility systems, proactive hazard identification, efficient risk mitigation strategies, and real-time supervision mechanisms to reduce the frequency and severity of workplace accidents.

1.2. Tunnel Construction: A High-Risk Scenario in Transportation Projects

Among various sectors of transportation construction, tunnel engineering stands out as one of the most technically demanding and safety-critical domains. Tunnel construction often involves working in confined spaces, dealing with geological uncertainties, and executing high-intensity tasks in hazardous conditions. The working environment is frequently unstable due to factors such as rock stress, groundwater infiltration, gas accumulation, and blasting operations. These challenges are further amplified in projects conducted in complex terrains, such as mountainous regions or high-altitude areas.

Safety management in tunnel construction is particularly intricate. Not only does it require strong engineering expertise and experience, but it also demands effective coordination among contractors, safety officers, government regulators, and frontline workers. Inadequate attention to hazard control in this context can lead to catastrophic accidents including collapses, flooding, gas explosions, and human casualties.

1.3. Safety Challenges Unique to High-Altitude Tunnel Construction

This paper focuses on tunnel construction in high-altitude regions, with a specific emphasis on the Qinghai-Tibet Plateau. This region presents a uniquely hostile environment for large-scale engineering projects. With an average elevation exceeding 4,000 meters, the atmospheric pressure is reduced to 60–70% of that at sea level. The lower partial pressure of oxygen results in chronic hypoxia among workers, which can significantly impair cognitive function, reduce physical endurance, and elevate the risk of human error. Long-term exposure to such conditions also increases the incidence of altitude sickness and cardiovascular complications among construction personnel.

In addition to hypoxia, workers must contend with strong ultraviolet radiation — 2 to 3 times higher than in low-altitude regions — sharp diurnal temperature fluctuations exceeding 20°C, frequent sandstorms, and extended periods of high winds. These environmental stressors, combined with the demanding physical nature of tunnel construction, create a compound risk scenario where the likelihood of accidents and occupational illness is significantly increased. It is thus imperative to adapt safety management practices to the specific conditions of high-altitude environments, particularly in tunnel projects where the consequences of safety lapses are severe and far-reaching [1].

1.4. Review of Current Research on Tunnel Safety Risk Identification

Over the past two decades, domestic and international researchers have conducted extensive investigations into tunnel safety management. Much of this research has focused on identifying the root causes of common tunnel accidents such as rockfalls, roof collapses, landslides, water and mud inrushes, and gas explosions. As a result, a number of comprehensive databases of safety risk factors have been established, serving as critical references for safety assessments and control planning in tunnel construction [2].

Zhang et al. developed a sophisticated expert risk identification system that combines Building Information Modeling (BIM) technology with a structured knowledge base and automated risk factor identification algorithms. This system significantly reduces reliance on human expertise and enhances the speed and accuracy of risk detection [3]. Similarly, Wu Han and colleagues applied the Integrated ISM-HHM method to identify and analyze the multi-layered causes of safety hazards in the Donghu Deep Tunnel project [4].

Human factor analysis approaches have also played a pivotal role in understanding tunnel accidents. By applying classification models, researchers have identified key behavioral and organizational elements — such as insufficient training, poor implementation of safety protocols, and inadequate communication — that contribute to accident causation. Among these, the "implementation of safety responsibilities" has emerged as a critical node in the causal chain of many accidents, suggesting that improvements in organizational accountability can yield substantial safety benefits [5].

Building on these findings, scholars have proposed comprehensive analytical frameworks for tunnel safety management. One such framework categorizes risks using six object elements (e.g., entrance operation zones, excavation faces), five driving factors (e.g., personnel, equipment, environmental, management), and ten outcome elements (e.g., collapse, gas leak, or sudden water inrush). This structured classification provides an effective tool for identifying safety control points, facilitating targeted interventions, and designing better risk monitoring systems [6].

1.5. Research Gaps and Motivation for High-Altitude Tunnel Studies

Despite these advances, most existing research has focused on lowland or mountainous tunnels located in temperate or subtropical climates. There is a conspicuous lack of targeted studies on tunnel construction risks in high-altitude environments, where the interplay between environmental stressors and operational hazards creates a distinctly different risk profile.

Given the increasing number of infrastructure projects being planned and implemented in high-altitude regions such as western China, Central Asia, and parts of South America, this research gap poses a challenge for both academic inquiry and engineering practice. The Qinghai-Tibet Plateau, in particular, serves as a valuable testbed for studying the combined impact of altitude, geology, and climate on construction safety.

Addressing the unique safety challenges of high-altitude tunnel construction is therefore both theoretically significant and practically urgent. A systematic investigation of hazard types, risk propagation mechanisms, and control strategies in these environments will not only enrich the existing body of safety management literature but also offer practical guidance for policy makers, engineers, and project managers working in extreme terrains.

2. Basic Concepts and Research Methods

2.1. Basic Concepts

In the context of construction safety, particularly in tunnel engineering, the concept of hazard sources plays a foundational role. A hazard source refers to any location, device, facility, or process within a system that possesses the potential to release hazardous energy or substances, thereby triggering accidents under certain conditions or external stimuli [7]. In practical terms, hazard sources are the concentrated zones where mechanical, chemical, electrical, or gravitational energies exist in unstable or uncontrolled forms.

These sources do not necessarily lead to accidents in isolation; however, when coupled with initiating events — such as operational errors, equipment failures, or environmental disturbances — they can rapidly escalate into incidents causing injury, damage, or disruption. Hence, identifying and managing hazard sources is the first and most crucial step in any effective safety risk control system, especially in complex and dynamic environments like high-altitude tunnel construction sites.

2.2. Research Methodology

To comprehensively analyze and manage risks in high-altitude tunnel construction, this study adopts a combination of system analysis and empirical investigation methods. The primary methodologies include the Human-Machine-Environment System Analysis and a multi-tiered hazard identification framework, each of which contributes to a more nuanced understanding of the risk landscape.

2.2.1. Human-Machine-Environment (HME) System Analysis

The Human-Machine-Environment (HME) System is a foundational model used in ergonomics and safety engineering to study the complex interplay between three critical components: human operators, mechanical equipment, and the working environment. In the context of high-altitude tunnel construction, each component is affected by unique constraints:

1) Humans may suffer from hypoxia, fatigue, or impaired judgment due to altitude stress.

2) Machines may face performance degradation under low-pressure and low-temperature conditions.
3) The Environment includes unpredictable geological structures, poor visibility, and temperature fluctuations.

The interdependence among these three components means that any hidden hazard or failure in one element can propagate through the entire system, resulting in compounded risks. Therefore, this method emphasizes integrated safety design, continuous monitoring, and systemic mitigation strategies to maintain overall operational efficiency and safety performance.

2.2.2. Hazard Identification Methods

A robust hazard identification process is essential for developing an accurate risk profile of tunnel construction sites, especially those in extreme environments. This study employs a three-pronged approach to hazard identification, combining both qualitative and quantitative techniques to ensure comprehensiveness and reliability.

1) On-Site Investigation Method

The on-site investigation method involves conducting field inspections to directly observe the construction environment, equipment, operational procedures, and worker behavior. This method typically includes the following steps:

a) Defining the investigation objective and scope.
b) Delimiting the physical area of investigation.
c) Preparing standardized inspection checklists or questionnaires.
d) Conducting visual inspections, photographic documentation, and real-time data collection.
e) Summarizing findings and reporting identified hazards.

By immersing researchers in the actual work environment, this method allows for the timely identification of visible and latent hazards, contributing to a practical and context-sensitive understanding of safety risks.

2) Interview Method

The interview method is a qualitative research tool aimed at capturing subjective insights and professional judgments from individuals directly involved in tunnel construction. This includes one-on-one interviews, focus group discussions, and semi-structured conversations with project managers, safety supervisors, frontline workers, and technical staff.

The goal is to uncover hidden risks not immediately apparent through observation — such as psychological stress, organizational safety culture, and procedural non-compliance. Interview data can reveal discrepancies between formal safety procedures and actual practices on-site, offering valuable input for risk assessment and corrective planning.

3) Screening Method Based on National Standards

To enhance the standardization and comparability of hazard identification, this study incorporates a screening method based on the Chinese national standard GB/T 13861-2022, titled Classification and Codes of Hazardous and Harmful Factors in Production Processes. According to this framework, 164 types of hazardous and harmful factors are classified into four major dimensions:

a) Human Factors (e.g., fatigue, inexperience, behavioral errors).
b) Material Factors (e.g., equipment failure, structural instability, explosive materials).
c) Environmental Factors (e.g., poor lighting, extreme temperature, limited ventilation).
d) Management Factors (e.g., inadequate supervision, policy violations, emergency planning gaps) [8].

Using this taxonomy, site-specific hazards can be systematically categorized and prioritized for intervention. This also facilitates benchmarking against industry best practices and compliance with safety regulations.

3. Identification and Analysis of Hazards in High-Altitude Tunnels

This article takes the Laze Tunnel as the research object. The highest peak of the tunnel route is located near K21 + 252m, with an altitude of about 5342m. The lowest point is located at the tunnel exit, with an elevation of about 4110m and a relative elevation of about 1232m. It belongs to the middle to high mountain area of the plateau desert in the middle cut. A combination of on-site investigation, interview, and screening methods was used to identify the hazards of high-altitude tunnels from four aspects: personnel, equipment, environment, and management.

3.1. Personnel Factors

Unsafe behavior of a person can be doing something wrong that was not supposed to be done, or not doing something that needed to be done. The unsafe factors of people on the construction site mainly include as shown in Table 1:

Table 1. Identification of Personnel Factors Hazards.

Factor	Dangerous source	Possible accidents
human factor	Physical health	Sudden personnel collapse and decreased production efficiency
	psychological pressure	Operational and judgment errors
	Weak safety awareness	Multiple accidents
	altitude sickness	Personnel suddenly collapse, coma, etc
	Operating in violation of relevant laws and regulations	Multiple accidents
	Operation error	Equipment damage, personnel injury
	Entering hazardous areas without following regulations	Multiple accidents
	Incorrect handling of dangerous goods	fire and explosion

3.2. Equipment Factors

Mainly involving safety hazards related to machinery, electrical or other equipment used in construction or production processes. Equipment factors usually include equipment failures, equipment maintenance, insufficient safety protection measures, and electrical equipment issues, as shown in Table 2.

Table 2. Identification of Equipment Factors and Hazards.

Factor	Dangerous source	Possible accidents
Equipment factors	mechanical failure	Multiple accidents
	Insufficient maintenance	Equipment damage, shutdown, and decreased production efficiency
	Defects within the device itself	Frequent malfunctions and equipment malfunction
	Unreasonable placement of equipment	Difficulty in operation, equipment damage, and personnel injury

	Equipment not regularly maintained	Sudden equipment failure and increased risk of accidents
	circuit aging	Short circuit, fire, equipment malfunction
	Electrical component malfunction	Equipment cannot start, electrical system failure
	Poor insulation	Electric shock accidents, fires, and damage to electrical equipment

3.3. Environmental Factors

Environmental factors refer to the natural or man-made conditions that exist in the work environment, which may have an impact on the safety, health, and efficiency of the workplace. Environmental factors mainly involve external influences on workers, equipment, and work processes, which may originate from physical, chemical, or biological environmental characteristics, as shown in Table 3.

Table 3. Identification of Environmental Hazard Sources.

Factor	Dangerous source	Possible accidents
environmental factor	oxygen deficiency	Personnel are unconscious and have difficulty breathing
	low temperature	Frostbite, operational errors, equipment damage
	Strong ultraviolet radiation	Skin burns, visual impairment
	pressure change	High altitude sickness, physical discomfort
	Sudden change in plateau climate	Sudden snowstorm and construction interruption
	Improper lighting	Operational errors, personnel injuries
	harmful gas	Poisoning, respiratory system damage
	Chemical Spills	Poisoning, environmental pollution, fire
	industrial dust	Suffocation and pneumoconiosis
	Bacteria and viruses	Disease transmission and personnel infection
	allergen	Skin allergies, respiratory allergic reactions

3.4. Management Factors

Management factors refer to problems caused by intellectual errors during the construction process, which can lead to human errors or unsafe conditions of machinery and objects, as shown in Table 4.

Table 4. Identification of Management Factors and Hazards.

Factor	Dangerous source	Possible accidents
Management factors	Insufficient safety training	Operational errors, personnel injuries, equipment damage
	The safety system is not sound	Violation of regulations and frequent accidents
	Defects in safety protection technology	Work injury and equipment accidents
	The accident reporting mechanism is not smooth	Delay in accident handling and risk escalation
	Chaotic on-site management	Multiple accidents and low production efficiency
	Improper command	Misoperation and frequent accidents
	Inadequate monitoring and management	Accidents not detected and handled in a timely manner

Professional security personnel lack sufficient mastery of safety knowledge	Improper handling of accidents and delayed investigation of hidden dangers
No warning or monitoring around the device	Personnel injuries, equipment damage

4. Existing Problems and Countermeasures Suggestions

4.1. Existing Problems

1) Some personnel have a weak sense of safety responsibility

Due to the significant environmental impact on high-altitude tunnel construction operations, personnel turnover is severe, and job transfers and transfers are frequent, resulting in some managers and workers having weak safety awareness and neglecting safety hazards, leading to a decline in safety management level.

2) There is a phenomenon of incomplete equipment inspection and rectification

The project is required by the company to conduct weekly equipment safety inspections, but there are many cases of incomplete equipment inspection and rectification.

3) Some special operation personnel lack special operation personnel certificates with different specifications

Although some special operation personnel (electricians, welders) have certificates, they are not uniformly issued certificates by the State Administration of Work Safety. They are not proficient in operating special types of work, resulting in repeated safety hazards in temporary electricity use and improper operation by welders.

4.2. Countermeasures and Suggestions

1) Strengthen macro control over project construction, provide technical guidance, and offer advanced management experience and methods for project safety production.
2) The phenomenon of full-time safety management personnel turnover is serious. Relevant policies can be introduced at the company level to increase the emphasis on safety personnel, while also increasing the frequency of training and assessment. Fully cover safety education and training for newly hired workers, and make full use of experiential education models.
3) Highlight key points, continue to deepen the special rectification of safety and health accident hazards, further promote standardized on-site management of safety and quality, regularly organize safety inspections, strengthen on-site inspection efforts, and eliminate accident hazards in their infancy.
4) According to the actual situation of the construction site, improve emergency rescue plans, develop emergency drill plans, and increase the frequency of emergency drills.

5. Conclusion and Discussion

This study centered on the safety challenges of high-altitude tunnel construction, with the Laze Tunnel project on the Qinghai-Tibet Plateau serving as a representative case. Given the region's harsh environmental conditions — characterized by extreme altitude, hypoxia, low pressure, ultraviolet radiation, and volatile climate — the research systematically identified safety hazards across four critical dimensions: personnel, equipment, environmental, and managerial factors.

Through the application of Human-Machine-Environment (HME) system theory and multi-method hazard identification techniques — including field investigations, expert interviews, and standardized screening protocols — this study provided a detailed account of the potential risk sources associated with high-altitude tunnel construction. It further analyzed the underlying causes of these risks and offered targeted countermeasures and safety management recommendations aimed at reducing accident likelihood, protecting worker health, and improving overall project resilience.

The findings not only contribute to theoretical understanding by expanding the scope of tunnel construction safety research into underexplored high-altitude contexts, but also offer practical guidance for engineers, project managers, and policy-makers working in similarly extreme environments. In particular, the identification of altitude-specific human and environmental stressors supports the development of localized safety protocols, including modified work-rest cycles, specialized equipment selection, and contingency planning tailored to plateau construction conditions.

However, it is important to note that this research also has its limitations. The scope of investigation was limited to a single case study, which may constrain the generalizability of the findings. Additionally, while qualitative methods such as interviews provide rich insights, they are subject to subjective bias and may lack statistical rigor. Future research could incorporate longitudinal data collection, simulation modeling, or cross-regional comparative studies to validate and extend the conclusions drawn here.

In summary, this study lays a foundational framework for understanding and managing construction safety risks in high-altitude tunnel projects. As infrastructure development continues to expand into ecologically and topographically challenging regions, there is an urgent need for more comprehensive, evidence-based safety strategies. This paper provides a stepping stone toward that goal and calls for continued interdisciplinary collaboration in this vital field of research.

Funding: This research was supported by grants from Project of Second Highway Engineering Co., Ltd. Fourth Engineering Co., Ltd (G16LZSD010-QT166).

References

1. Y. Cao and B. Yun, “Tunnel construction worker safety state prediction and management system based on AHP and anomaly detection algorithm model,” *Heliyon*, vol. 10, no. 16, 2024, Art. no. e36450, doi: 10.1016/j.heliyon.2024.e36450.
2. X. Wang, L. Gao, X. Song, L. Zhang, Y. Zhao and J. Liu, “Geohazards, reflection and challenges in mountain tunnel construction of China: a data collection from 2002 to 2018,” *Geomatics, Nat. Hazards Risk*, vol. 11, no. 1, pp. 766–785, 2020, doi: 10.1080/19475705.2020.1747554.
3. L. Zhang, X. Deng, J. Wu, Y. Zhao, F. Wang and Y. Li, “BIM-based risk identification system in tunnel construction,” *J. Civil Eng. Manag.*, vol. 22, no. 4, pp. 529–539, 2016, doi: 10.3846/13923730.2015.1023348.
4. H. Wu, Y. Liu, L. Li, X. Zhang, J. Zhang and Z. Wang, “HSE risk assessment of major sewage transport tunnel projects at the construction stage based on the structural entropy weight method and the cloud model,” *Adv. Civil Eng.*, vol. 2020, Art. no. 8882903, 2020, doi: 10.1155/2020/8882903.
5. Y. Yang, J. Zhao, H. Chen, W. Xu, C. Liu and X. Zhou, “Risk factors influencing tunnel construction safety: Structural equation model approach,” *Heliyon*, vol. 9, no. 1, 2023, Art. no. e12924, doi: 10.1016/j.heliyon.2023.e12924.
6. Y. Yang, C. Liu, X. Zhou, W. Xu, H. Chen and J. Zhao, “Factors affecting road tunnel construction accidents in China based on grounded theory and DEMATEL,” *Int. J. Environ. Res. Public Health*, vol. 19, no. 24, Art. no. 16677, 2022, doi: 10.3390/ijerph192416677.
7. R. J. Anderson, *Security Engineering: A Guide to Building Dependable Distributed Systems*, 2nd ed. Hoboken, NJ, USA: Wiley, 2010. ISBN: 9781118008362.
8. S. Abikenova, A. Serikbekova, B. Seitzhanova, A. Zhakipbekov, A. Akhmetov and A. Omarova, “Assessing occupational risk: A classification of harmful factors in the production environment and labor process,” *Int. J. Saf. Secur. Eng.*, vol. 13, no. 5, 2023, doi: 10.18280/ijsse.130511.