Original Article
ISSN (Online): 2454-1907

International Journal of Engineering Technologies and Management Research
April 2024 11(4), 47–64

EVALUATION OF SAFETY MANAGEMENT DURING TUNNELS CONSTRUCTION IN SAUDI ARABIA

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Received 14 March 2024
Accepted 15 April 2024
Published 30 April 2024

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DOI
10.29121/ijetmr.v11.i4.2024.1449

Funding: This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

ABSTRACT

Tunnel construction projects are complex engineering projects that pose numerous safety challenges. Accordingly, prioritizing the protection of workers, the public, and the environment is imperative. This study aimed to comprehensively analyze the most significant risks associated with tunnel construction projects in Saudi Arabia. Twenty-nine hazards were identified through site inspections and interviews with engineers and managers engaged in various tunnel projects in Saudi Arabia. These risks were categorized into six groups, namely, Confined Spaces, Air surveillance & ventilation, Fires, Physical and chemical hazards, Electricity, and Personal safety and emergency plans. Data were acquired from 108 respondents completing a questionnaire. The data were statistically analyzed using the SPSS V20 package. The Total Importance Index Impact (TIII) application determined the most crucial risks affecting tunnel construction safety management. As a result, the most significant risk identified are Musculoskeletal disorder due to heavy manual handling, prolonged use of hand tools, or standing, Oxygen shortage brought on by the narrow tunnel, and Constant exposure to high noise; are the most effecting risks. The findings demonstrate that risk analysis facilitates project managers in identifying and focusing on principal risks, which supports the implementation and evaluation of safety management plans. By providing practical guidelines, risk analysis enhances the success rate of tunnel construction projects. Implementing measures to mitigate exposure to elevated noise levels, air supply hazards, fires, and oxygen deficiency is anticipated to result in numerous benefits, including improved worker health and performance, reduced time and expenses, enhanced productivity, and an improved reputation among staff and clients.

Keywords: Risk Management, Safety Management, Tunnels, Risk Assessment, Safety Analysis, Saudi Arabia

1. INTRODUCTION

Modern infrastructure relies indispensably on tunnels for the efficient transportation of people, the supply of utilities, and the execution of numerous subterranean operations. However, the tunnel construction process poses inherent risks due to complex engineering processes, confined spaces, and challenging geological conditions. Effective safety management is essential for maintaining tunnel structural integrity, protecting the environment, and ensuring worker safety

Ardeshana et al. (2015), Hung et al. (2009), Wu et al. (2019). In response to the necessity of navigating Makkah's steep terrain, the Saudi government constructed 58 tunnels to facilitate easier access for residents and tourists to the Grand Mosque and other sacred sites outside the holiest Islamic city. Official statistics report that these tunnels, extending over 30 km, are equipped with more than 66,935 lighting units, 599 jet fans, and 42 backup generators, in addition to computers, fire extinguishers, water pumps, and sensory devices. This state-of-the-art infrastructure positions the holy city as one of the world's most sought-after destinations that offers year-round accommodation to residents and tourists. Furthermore, Neom has awarded two contracts for the drill and blast construction of two separate tunnels, each 28 km long, intended for freight and high-speed rail services within the 170-km line project in northwest Saudi Arabia.

The Line forms a part of the ambitious Neom megacity—a futuristic development supported by USD 500 billion in government funding—set to occupy 26,500 km2 in northwest Saudi Arabia, bordered by the Red Sea and the Gulf of Aqaba. Tunnel construction significantly contributes to the demand for new transportation projects Liang et al. (2016). The first tunnel was constructed in 1896 and comprised submerged segments that were later joined underwater Lotysz (2010).

The international collaboration group on safety management delineated a safety management system (SMS) as "a series of organization-wide established processes facilitating effective risk-based decision-making connected to daily operations." The advantages of implementing a safety management system in construction include reducing injuries, controlling workplace hazards, and minimizing the risk of severe accidents, among others Alkaissy et al. (2020), Jazayeri et al. (2017). Tunnel construction risk mitigation is pivoted on the analysis and evaluation of tunnel stability Liu, et al. (2018), Xu et al. (2021). Given the direct impact on individuals' lives and property safety, engineers and scholars studying underground engineering prioritize the stability of rock masses during construction. Previous research has demonstrated that failures in rock masses during subterranean construction projects lead to significant casualties and property damage, especially in densely populated urban environments. For instance, the collapse of a massive metro tunnel support system in Singapore resulted in the sinking of the adjacent Nicoll Highway, claiming four lives Committee of Inquiry (COI) (2005), Whittle (2006).

Additionally, a severe accident in São Paulo during metro construction resulted in seven fatalities Barton (2008). Factors such as the geological environment, stability of surrounding rock, linear deformation, and stress in surrounding rock are paramount in assessing the risks of tunnel construction Yu et al. (2017), Li et al. (2019). The stability of large tunnel complexes is influenced by the degree of rock fracture and shear strength, with the selection of appropriate rock strength underpinning tunnel stability calculations. Extensive research has been undertaken to assess rock strength accurately. To elucidate the shear behavior of infilled rock joints, Zhao et al. (2020) employed the direct shear method to conduct experiments on sand-filled joints by replicating the standard joint roughness coefficient (JRC) profiles of rock-like materials with a fill material in the joints. Owing to the discrete nature of rock strength, a novel model was developed to characterize the strength of natural rock formations using the shear-related roughness classification through a fuzzy integrated evaluation Whittle (2006). Additional methodologies have also been explored for measuring rock strength Barton (2008), Yu et al. (2017). The significance of rock mass stability has been well-recognized, which has prompted numerous studies in recent years to ensure the safety of subterranean engineering projects Li et al. (2019), Zhao et al. (2020), Zhao et al. (2021b), Whittle (2006).

The scarcity of above-ground space has significantly spurred the development of subterranean spaces, exemplified by adjacent transport tunnel projects Barton (2008), Yu et al. (2017), Li et al. (2019) and complex tunnel initiatives Zhao et al. (2020), Zhao et al. (2021b). In recent years, this trend has resulted in a notable improvement in underground infrastructure construction within urban environments. The increasing complexity of urban subterranean excavations underscores the critical significance of the challenging stability analysis of rock masses. Moreover, construction risks have improved considerably. A targeted analysis of various construction scenarios is imperative for formulating effective risk control measures in tunnel construction. Identifying risks before construction and issuing risk warnings during construction comprise the two primary facets of safety risk control Zhao et al. (2021a).

The risk identification stage faces several challenges: traditional methods demand considerable labor, materials, and time; qualified risk identification specialists are scarce; and time and space limitations hinder the timely sharing of knowledge. Upon project completion, the disbandment of the tunnel construction team leads to a paucity of security risk knowledge. Nevertheless, the quality of risk warnings is contingent upon the monitoring data collected during construction. Establishing control standards based on monitoring data is crucial Cao et al. (2016).

This study aimed to comprehensively analyse the most significant risks associated with tunnel construction projects in Saudi Arabi, since this area has not been looked before in literature.

2. TUNNEL CONSTRUCTION RISKS

The categorization of risks facilitates safety management, thereby minimizing and controlling accidents and injuries at tunnel construction sites. This categorization enables managers and engineers to focus on the most critical risks impacting tunnel construction projects' cost, schedule, and safety. Previous research has organized tunneling construction risks into eight categories: technical, geological, environmental, social, human, political, contractual, and cost-related risks. These categories are detailed in Table 1, which illustrates the risks related to tunnel safety management.

Table 1

Table 1 Risks Affect the Tunnel Safety Management

Risk categories	Risks affect tunnel safety management	Previous study
Technical risks	• Tunnel Boring Machines: arrival and launch of TBM • Tunnel digging • Later revisions to the specification • Not adhering to design guidelines • Site entry • Collaboration with surrounding neighbors and utilities.	Liu et al. (2018) and Liu et al. (2011)
Geological risks	• Inadequate results from geotechnical studies	Feng et al. (2012)
Environmental risks	• Adverse Weather • Climate change	Qian & Lin (2016)

Social risks	• Geographical and ethnic restrictions • Absence of general agreement • Workplace unrest and strikes • Increased unemployment rate	Kim (1996)
Human risks	• Productivity and skills • Employee Access • Wages, salaries, labor rights, violations, and salaries	Liu et al. (2009)
Political risks	• Changes in government policies • Threats from the inside and outside, elections • Shifting perceptions of political events such as coups, revolutions, and wars	Kim (1996)
Contractual risks	• A delay in settling conflicts • A payment late • Difference between contract and actual work volume	Hu et al. (2021)
Cost and schedule risks	• Irrational cost projections • Improper methods of financing • Distribution of budgets	Zhao et al. (2021b), Zheng et al. (2009), Duan & Li (2012)

3. METHODOLOGY

The effectiveness of safety management in tunnel construction offers considerable scope for enhancement. Accordingly, this study provides insights into the safety evaluation of tunnel-building projects in Saudi Arabia. The current methodology encompasses five essential steps designed to fulfill the objectives of the study: identifying causes of accidents and risks from prior research, categorizing common significant risks, developing questionnaires, analyzing collected questionnaire data using SPSS and EXCEL, examining the top ten risks.

A questionnaire was developed to achieve the study's aims and objectives, comprising two sections to present information systematically and clearly. The first section solicited information from respondents regarding their age, years of experience in the tunneling field, level of education, and job title. The second section gathered data on 29 risks identified through site surveys and interviews with engineers and managers involved in tunnel projects in Saudi Arabia. These 29 risks were organized into six groups, as listed in Table 2.

Table 2

Table 2 Risks Categorization

Category	Code	Risks
Confined Spaces	R1	Dangerous or obstructed pedestrian walkways that could be hurt
	R2	Increased number of people inside the narrow tunnel
	R3	Burst/fall of rocks
	R4	Overtime and longer hours combined with diligence
	R5	Sporadic vacuuming/cleaning inside the tunnel
	R6	Sporadic vacuuming/cleaning inside the tunnel
Air surveillance & ventilation	R7	Inadequate ventilation system air supply
	R8	Sporadic ventilation system testing
	R9	Oxygen shortage brought on by the narrow tunnel
	R10	Fires brought on by welding or combustible gases

Fires	R11	Utilizing traditional firefighting tools, like portable fire extinguishers
	R12	Disruption of the fire detection and alarm systems
Physical and chemical hazards	R13	Symptoms such as fever, thirst, headaches, exhaustion, sluggishness, and unconsciousness
	R14	Dermatitis, allergies, and respiratory problems
	R15	Exposure to radiations
	R16	Constant exposure to high noise
	R17	Musculoskeletal disorder due to heavy manual handling, prolonged use of hand tools, or standing
	R18	Vibration due to hydraulic tools
Electricity	R19	Inadequate illumination within the tunnel makes it difficult to get to emergency locations.
	R20	Working close to exposed electrical equipment or supply lines increases the risk of electric shock exposure
	R21	Incorrect placement of electrical tools, equipment, cables, and connections
	R22	Inadequate inspection of the machine, equipment, and electrical connections
Personal safety and emergency plans	R23	Absence of safety orientation and induction training for staff
	R24	Absence of PPE, warning signs, and general guidelines
	R25	Lack of ease in utilizing one's own oxygen resources
	R26	Lack of emergency services and rescue team members
	R27	Inadequate number of ambulances or first aid kits in the ambulances.
	R28	Delayed emergency response times and inconsistent reporting
	R29	Inadequate material labeling and storage

4. DATA COLLECTION AND ANALYSIS METHOD

Appropriately executed data collection provides considerable benefits in terms of accuracy and reliability, which can offer definitive solutions to research queries. Moreover, its applicability and utility are immediate and relevant. The validation of this research relied on the data acquired from the questionnaire. The initial strategy involved rating risks using a structured questionnaire. The sample size was determined using a formula devised by Krejcie and Morgan (1970):

$$\text{Sample Size} = \frac{X^2 NP(1-P)}{d^2 (N-1)+X^2 P(1-P)} = 84, \qquad (1)$$

where X^2 denotes the table value of Chi-square for one degree of freedom at the desired confidence level (95%) = 3.841, N refers to the size of the population = 108, P refers to the population proportion of 0.5, and d is the degree of accuracy expressed as a proportion of 0.05. as shown in (Table 3). The respondents were interviewed via e-mail, personal visits, and interviews. Their responses to the questionnaire were analyzed to identify the most influential factors.

Table 3

Table 3 Population Sample

Title	HSE Manager	HSE Deputy	HSE Supervisor	HSE Inspector	HSE Trainer	HSE Advisor	Ambulance Driver	Assistant HSE	Total
No.	2	7	21	66	5	2	3	2	108

After calculating the Frequency Index (FI), Severity Index (SI), Importance Index Impact (III), and Total Importance Index Impact (TIII) for each risk, the risks were finally ranked overall based on the TIII for each risk both individually and among groups. The reliability analysis was completed at the end using the following equations.

Important Index (II) of health, performance, or productivity impact % = [FI% × SI%]/100 (2)

where FI and SI represent the Frequency Index and Severity Index, respectively.

FI: A formula ranks causes of delay based on their frequency of occurrence, as identified by the participants Zhang et al. (2018), Zheng et al. (2021).

$$FI\ (\%) = \sum a\ (n/N) \times 100/5 \tag{3}$$

SI: A formula is used to rank delay causes based on severity as indicated by the participants.

$$\text{Severity Index (S.I.) } (\%) = \sum a\ (n/N) \times 100/5, \tag{4}$$

where a denotes the constant expressing weighting given to each response (ranges from 1 for very low to 5 for very high), n denotes the frequency of the response, and N indicates the total number of responses Zheng et al. (2022) .

The II of safety and time impact (IISI)/(IITI) can be evaluated as a function of FI and SI, which signifies the impact of each risk on worker safety and the project schedule Yu et al. (2017), as follows:

$$(IISI)/(IITI)\ \% = (FI\% \times SI\%)/100 \tag{5}$$

After that, the TIII can be calculated as follows:

$$TIII = [IISI + IITI]/2 \tag{6}$$

The ranking was determined by the highest value of the Total Importance Index Impact (TIII); in cases of identical values, rankings were assigned based on the lowest standard deviation value.

The questionnaire data were analyzed using the TII technique in the Statistical Package for the Social Sciences (SPSS V20, IBM, IL, USA) software and EXCEL (Microsoft, SA, USA). The data from respondents were categorized according to the applicable risk before analysis using four principal statistical measures: FI, SI, II, and TII.

5. RESULTS AND DISCUSSION

5.1. RESPONDENTS' STATISTICS

The results of the questionnaire are discussed herein. The final questionnaire was distributed among 108 specialists and professionals engaged in tunnel construction at the Otaybiya Holy Mosque Tunnel in Mecca, Saudi Arabia. The respondents were categorized into five groups based on their roles: organization type, Health, and Safety Environment (HSE) managers, HSE deputies, HSE supervisors, HSE inspectors, HSE trainers, and HSE advisors, as shown in Table 1. The data were further segmented according to organization type, as depicted in Figure 1.

The age-wise distribution of respondents included 55 individuals aged 20–30, 37 within the 31–40 bracket, 13 aged 41–50, and three over 50 years, as illustrated in Figure 2. As discussed in Figure 3, their experience levels were categorized as 1–10 years (74 respondents), 11–20 years (25 respondents), and 21–30 years (15 respondents), whereas educational backgrounds—high diploma, BSc, MSc, and PhD—were reported by 18, 60, 16, and 4 respondents, respectively, as portrayed in Figure 4.

Figure 1

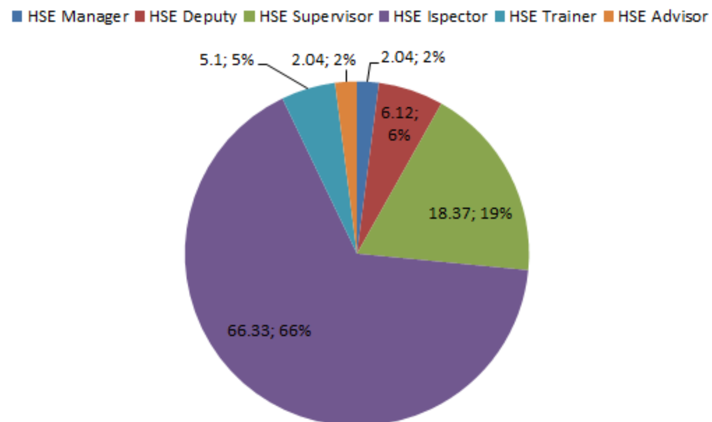

Figure 1

Figure 2

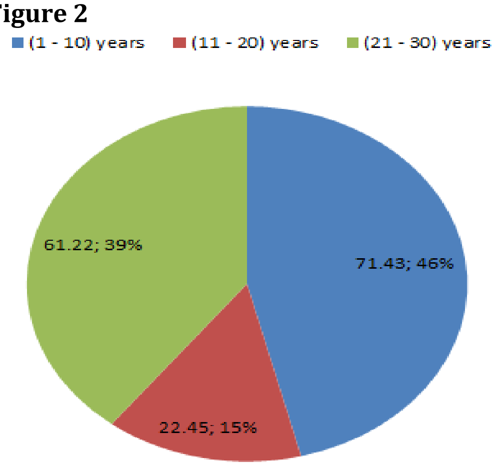

Figure 2

Figure 3

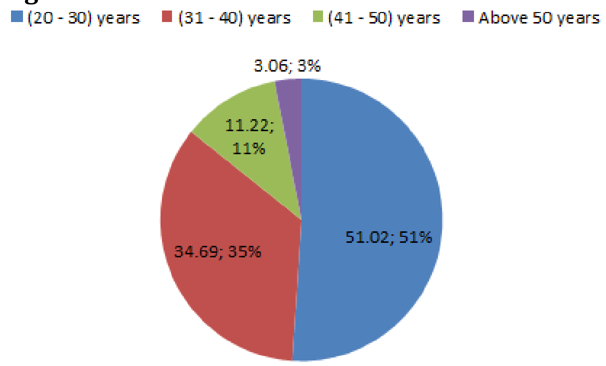

Figure 3

Figure 4

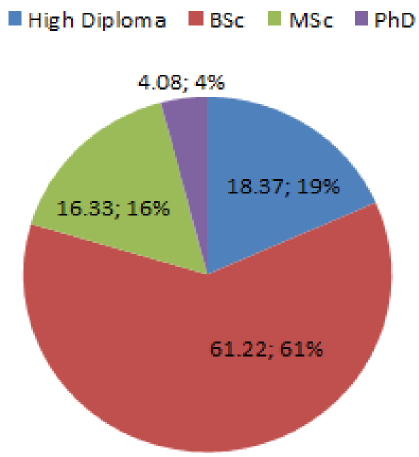

Figure 4

The information received from the 108 respondents was conducted using the TIII. A discussion on the six risk categories revealed the following findings.

5.2. CONFINED SPACES

Confined spaces, characterized by hazardous air conditions or increased risk of severe accidents such as falls or entrapment, present unique dangers. The confinement poses risks, with workers being more susceptible to hazards, such as the moving components of machinery in tight spaces. The most critical risks associated with confined spaces are outlined in Table 4, which highlights the six risks impacting worker safety and project timelines. The survey results indicated the risk of "Worker injuries caused by erratic vehicle movement and restricted entry and exit" as the foremost concern in this category, ranking fourth among the 29 risks with a TIII of 27.02%.

Tunneling and underground construction operations are significantly hindered by safety challenges caused by blind spots and limited visibility surrounding large vehicles and equipment. This environment increases the likelihood of collisions involving vehicles, pedestrians, and construction elements, leading to accidents Kim (1996). Such challenges can amplify the risk of vehicle-pedestrian incidents, diminish production quality and efficiency, and result in workplace accidents.

Table 4

Table 4 Confined Spaces Group Risks Ranking

Risk Code	**R1**	**R2**	**R3**	**R4**	**R5**	**R6**
Risk ID	Dangerous or obstructed pedestrian walkways that could be hurt	Increased number of people inside the narrow tunnel.	Burst/fall of rocks	Overtime and longer hours combined with diligence	Sporadic vacuuming/cleaning inside the tunnel	Worker injuries brought on by erratic vehicle movement and constricted entry and exit
TIII (%)	26.1	18.18	19.34	22.61	22.14	27.02
Overall Rank	6	26	24	12	16	4

The risk associated with "Dangerous or obstructed pedestrian walkways that could lead to injury" ranked second in this category and sixth out of the total twenty-nine risks, with a TIII of 26.1%. Research Hu et al. (2021) highlighted that the introduction of elevated walkways in train tunnels could significantly enhance evacuation conditions. However, only some studies have explored walkway design from an evacuation perspective. Evacuation aids such as handrails and tactile edge markers are widely appreciated for their convenience and safety. The findings demonstrated a correlation between walkway width and flow rate.

The risk related to "Overtime and extended hours coupled with high levels of diligence" emerged as the third risk in this category and twelfth among the twenty-nine risks, with a TIII of 22.61%. Extended work hours were defined as exceeding 48 hours per week or eight-hour shifts Duan & Li (2012). These conditions could influence social and biological outcomes, with individuals struggling to adapt to irregular sleep, rest, and work schedules, potentially facing adverse health effects.

The risk of "Sporadic vacuuming/cleaning within the tunnel" was identified as 4th in this category and 16th out of the 29 risk categories, with a TIII of 22.14%. Employers are obligated to ensure that materials or equipment on a construction site are not positioned, stored, or stacked near any opening or edge of a floor, scaffold, platform, or other structure where they could pose a direct risk to individuals below.

The risks of "Burst/fall of rocks" and "Increasing the number of people within the narrow tunnel" were ranked 5th and 6th in this category, respectively, placing 24th and 26th out of the 29 risks with TIII scores of 19.34% and 18.18%. The high velocities of rockfall incidents often prevent individuals from considering protective measures, substantially increasing the risk of injury and fatality.

5.3. AIR SURVEILLANCE AND VENTILATION

Atmospheric hazards are inherent when working in tunnels, necessitating air monitoring to identify potentially dangerous air pollutants within an underground tunnel, thereby enabling the implementation of appropriate safety measures for tunneling operations. Tunnel construction involves risks such as exposure to hazardous gases or oxygen deficiency. Consequently, it is imperative to install efficient mechanical ventilation systems to supply workers with adequate respirable air and eliminate air pollutants from the tunnel. This category contains three risks and significantly impacts worker safety and project timelines, as outlined in Table 5.

According to expert responses, the most critical risk within this group was "oxygen shortage due to the narrow tunnel," with a TIII of 28.98%, positioning it as the second of 29 risks. Research has indicated that low oxygen content and air pressure at high altitudes significantly affect bodily functions. Numerous undesirable physiological reactions may occur at high altitudes, which potentially lead to various high-altitude illnesses and, in extreme cases, death. This particularly concerns individuals in physically demanding roles such as tunnel construction.

The "inadequate ventilation system air supply" risk was identified as the second highest in this category, ranking ninth among the twenty-nine risks with a TIII of 23.73%. A prior study Zhao et al. (2020) reported that mines, tunnels, hydropower stations, and storage facilities, among others, have undergone significant research. Mechanical ventilation has been recognized as an effective method of controlling environmental conditions in underground spaces. Factors such as the dimensions of the chamber door, airflow angle, installation position, and structural features influence the efficiency of a system barrier against hazardous gases, known as barrier efficiency.

"Sporadic ventilation system testing" was identified as the third risk in this category, ranking 22nd out of the twenty-nine risks with a TIII of 19.89%. This finding underscores the importance of regular and systematic testing of ventilation systems to ensure the safety and well-being of workers in tunnel environments.

Table 5

Table 5 Air Surveillance and Ventilation Group Risks Ranking

Risk Code	**R7**	**R8**	**R9**
Risk ID	Inadequate ventilation system air supply	Sporadic ventilation system testing	Oxygen shortage brought on by the narrow tunnel
TIII (%)	23.73	19.89	28.98
Overall Rank	9	22	2

5.4. FIRES RISKS GROUP

The risks associated with burning, welding, gas cutting, and other heat-related activities are considerable. These activities not only present fire hazards but also contribute to the emission of harmful gases, vapors, dust, or fumes, which can reduce atmospheric quality and lead to oxygen scarcity. These three risks have significant implications for project timelines and worker safety during tunnel construction, as depicted in Table 6.

According to the analysis of results, the foremost and most significant risk in this category was "fires caused by welding or flammable gases," ranking 5th among 29 risks with a TIII of 26.59%. The involvement of flammable gases in fires or explosions can lead to rapid and severe damage, even if these gases are not primarily used in the tasks. Such incidents can propagate flames and cause flashbacks. Cylinders containing flammable gases may leak or rupture violently and swiftly in the event of a fire.

Within this category, "the use of traditional firefighting tools, such as portable fire extinguishers," and "disruption of fire detection and alarm systems" were identified as the second and third significant risks, respectively, ranking 8th and 17th out of the total 29 risks, with TIII values of 24.04 and 21.8. Prior research Yu et al. (2017) established that the identification of at least one fire product is crucial for fire detection. Fire detection systems are engineered to be responsive to various fire signatures, including heat, flames, smoke, and gases.

Table 6

Table 6 Fires Group Risks Ranking			
Risk Code	**R10**	**R11**	**R12**
Risk ID	Fires brought on by welding or combustible gases	Utilizing traditional firefighting tools, like portable fire extinguishers	Disruption of the fire detection and alarm systems
TIII (%)	26.59	24.04	21.8
Overall Rank	5	8	17

5.5. PHYSICAL AND CHEMICAL HAZARDS

Psychological distress, boredom, and fear are common physiological and psychological effects experienced in subterranean environments. Table 7 states the six risks associated with this category, which highlights the impact of underground conditions on mental health and well-being.

Table 7

Table 7 Physical and Chemical Hazards Group Risks Ranking						
Risk Code	**R13**	**R14**	**R15**	**R16**	**R17**	**R18**
Risk ID	Symptoms such as fever, thirst, headaches, exhaustion, sluggishness, and unconsciousness	Dermatitis, allergies and respiratory problems.	Exposure to radiations	Constant exposure to high noise	Musculoskeletal disorder due to heavy manual handling, prolonged use of hand tools or standing	Vibration due to hydraulic tools
TIII (%)	24.7	22.56	15.04	27.06	30.61	19.92
Overall Rank	7	13	29	3	1	21

The risks of "musculoskeletal disorder due to heavy manual handling, prolonged use of hand tools or standing" and "Constant exposure to high noise" were identified as the first and second in this category, with TIII of 30.61% and 27.06%, respectively, ranking them first and third among the 29 assessed risks. Excessive noise pollution from tunnel construction significantly jeopardizes workers' health. There is a critical need to improve occupational health conditions and address the health risks associated with noise in tunnel construction, which includes noise from metal collisions, material cutting, and mechanical operations, all of which are detrimental to human health.

Conversely, the risks of "Symptoms such as fever, thirst, headaches, exhaustion, sluggishness, and unconsciousness" and "Dermatitis, allergies, and respiratory problems" were ranked 3rd and 4th in this category, with TIII of 24.7% and 22.56% respectively, placing them 7th and 13th overall among the 29 risks. Commonly, during the construction phase, pollutants such as CO, CO2, NO2, SO2, dust, and exhaust gases from construction machinery are detected.

The risk associated with "Vibration due to hydraulic tools" was classified as the fifth risk in this group and twenty-first overall, with a TIII of 19.92%. Vibrations and electrical hazards are deemed high-risk Zhao et al. (2020). Consequently, preventive and control measures are imperative within one to two days. After exposure to vibrations, the hands, wrists, and arms should be massaged with appropriate oil and vibration absorbers should be utilized whenever possible. The final risk in this category and among the overall twenty-nine was "Exposure to radiations," with a TIII of 15.04%.

5.6. ELECTRICITY RISKS GROUP

The primary sources of electricity risk include digging tools, electrical plants, tunneling equipment, and underground power cables, as detailed in Table 8 below.

Table 8

Table 8 Electricity Group Risks Ranking

Risk Code	**R19**	**R20**	**R21**	**R22**
Risk ID	Inadequate illumination within the tunnel makes it difficult to get to emergency locations.	Working close to exposed electrical equipment or supply lines increases the risk of electric shock exposure	Incorrect placement of electrical tools, equipment, cables, and connections	Inadequate inspection of the machine, equipment, and electrical connections
TIII (%)	20.96	22.15	18.3	19.15
Overall Rank	19	15	28	25

The research findings highlight "Working close to exposed electrical equipment or supply lines" as a significant hazard in tunnel construction, ranking 15th among 29 identified risks with a Total Identified Importance Index (TIII) of 22.15%. This risk is underscored by the alarming statistic that electrical exposure has led to the deaths of 739 workers, which translates to nearly three fatalities every week. The gravity of this risk is further emphasized by literature that identifies contact with overhead and underground electric lines as a cause of fatal or severe electric shock and burn injuries Li et al. (2018), Zhou et al. (2015) . The Health and Safety Executive (HSE) notes that such contact can result in severe burns to hands, face, and body, even when protective clothing is worn Li et al. (2018). The Electricity Networks Association (ENA) also provides guidance on avoiding the dangers associated with underground electric cables, reinforcing the need for caution when working near such hazards Zhou et al. (2015) . Inadequate illumination within tunnels is another critical risk, ranking 19th with a TIII of 20.96%.

Adequate lighting is essential for performance and safety and plays a pivotal role in risk recognition and mitigation. The research findings align with industry standards that stipulate minimum lighting requirements for various areas of operation within construction sites, including tunnels Siang et al. (2017). OSHA standard 29 CFR 1926.56 outlines these requirements, emphasizing the need for sufficient lighting to prevent accidents and ensure safe egress Siang et al. (2017). The significance of lighting is further supported by the American National Standard A11.1-2965, R1970, which provides additional guidance on industrial lighting for areas such as tunnels Siang et al. (2017). The third and fourth risks, "Inadequate inspection of machinery, equipment, and electrical connections" and "Incorrect placement of electrical tools, equipment, cables, and connections," are also notable concerns, ranking 25th and 28th, respectively. These risks highlight the importance of regular inspections and proper placement of electrical components to prevent accidents. The HSE's guidance on working near power lines and cables emphasizes the need for competent advice and safe systems of work when working near electrical apparatus Li et al. (2018). This includes ensuring that machinery and equipment are inspected and correctly positioned to avoid electrical hazards.

5.7. PERSONAL SAFETY AND EMERGENCY PLANS

Emergencies or disasters are seldom anticipated, especially those affecting individuals, employees, or businesses directly. Nonetheless, they can strike anyone at any moment, as detailed in Table 9 below.

Table 9

Table 9 Personal Safety and Emergency Plans Risks Ranking

Risk Code	R23	R24	R25	R26	R27	R28	R29
Risk ID	Absence of safety orientation and induction training for staff	Absence of PPE, warning signs, and general guidelines	Lack of ease in utilizing one's own oxygen resources	Lack of emergency services and rescue team members	Inadequate number of ambulances or first aid kits in the ambulances.	Delayed emergency response times and inconsistent reporting	Inadequate material labeling and storage
TIII (%)	21.17	20.13	22.88	23.14	22.48	18.3	20.13
Overall Rank	18	20	11	10	14	27	23

The research identified critical risks associated with emergency services and personal safety equipment. The Total Identified Importance Index (TIII) highlighted "Lack of emergency services and rescue team availability" and "Lack of accessibility to personal oxygen resources" as the foremost risks, ranking 10th and 11th respectively, with TIII values of 23.14% and 22.88%. These risks are particularly significant in confined spaces, where the availability of emergency services and personal safety equipment is crucial for the safety of workers.

The selection of optimal respiratory protection and escape devices is a critical consideration in tunnel construction. This selection must consider the local exposure limits of potential hazards, such as silica dust, which is a prevalent risk in tunnel construction due to its severe health implications, including silicosis and other lung-related diseases Bravo-Paez & Arboleda (2016). The importance of effective respiratory protective equipment (RPE) is underscored by the need to prevent long-term health issues among workers Boudaghpour (2018). Furthermore, the availability of emergency services and rescue teams is essential for immediate response in case of incidents. The lack of such services can lead to severe consequences, including fatalities, especially in confined spaces where escape and rescue operations are inherently challenging. This aligns with global safety standards which emphasize the necessity of having trained emergency response teams readily available Health and Safety Executive. (2024).

Other identified risks include "Insufficient number of ambulances or inadequately equipped first aid kits in ambulances," "Lack of safety orientation and induction training for staff," "Absence of PPE, warning signs, and general guidelines," "Inadequate material labeling and storage," and "Delayed emergency response times and inconsistent reporting." These risks were ranked 4th to 7th in this category, highlighting a broader issue of inadequate safety management practices in tunnel construction projects. The insufficient number of ambulances and the lack of essential equipment in them compromise the ability to provide immediate medical attention during emergencies, potentially increasing the severity of injuries or health impacts. Similarly, the absence of proper safety orientation and training for staff contributes to a lack of awareness and understanding of potential risks, thereby increasing the likelihood of accidents Health and Safety Executive. (2024). The absence of personal protective equipment (PPE) and clear safety guidelines further exacerbates the risk to workers, as these are fundamental to preventing injury and ensuring safe working conditions. Moreover, inadequate material labeling and storage can lead to hazardous exposures and accidents, emphasizing the need for stringent safety protocols.

5.8. TOP TEN HAZARDS IMPACTING SAFETY MANAGEMENT DURING TUNNEL CONSTRUCTION

The most significant risk identified is "Musculoskeletal disorder due to heavy manual handling, prolonged use of hand tools, or standing," with a TIII of 30.61%. This finding is consistent with extensive literature indicating that manual handling and the use of hand tools are predominant risk factors for musculoskeletal disorders (MSDs) in construction work. These activities often require repetitive motion, forceful exertions, and maintaining awkward postures, which are well-documented risk factors for MSDs Batchiyska (2020). The ergonomic risk factors, including the design of tools and the organization of work tasks, significantly contribute to the development of these disorders Pro Choice Safety Gear. (2024). The second most impactful hazard, "Oxygen shortage brought on by the narrow tunnel," with a TIII of 28.98%, highlights the unique challenges related to environmental conditions in tunnel construction. Limited oxygen availability can occur due to inadequate ventilation systems and the confined nature of tunnel spaces, posing severe health risks to workers Industrial Scientific. (2024). Ensuring adequate ventilation and monitoring air quality are essential strategies to address this risk, aligning with safety standards that mandate environmental controls in confined work areas [58].

Table 10

Table 10 Top Ten Hazards Impacting Safety Management during Tunnels Construction

Risk Code	**R17**	**R9**	**R16**	**R6**	**R10**	**R1**	**R13**	**R8**	**R7**	**R26**
Risk ID	Musculoskeletal disorder due to heavy manual handling, prolonged use of hand tools, or standing	Oxygen shortage brought on by the narrow tunnel	Constant exposure to high noise	Sporadic vacuuming/cleaning inside the tunnel	Fires brought on by welding or combustible gases	Dangerous or obstructed pedestrian walkways that could be hurt	Symptoms such as fever, thirst, headaches, exhaustion, sluggishness, and unconsciousness	Sporadic ventilation system testing	Inadequate ventilation system air supply	Lack of emergency services and rescue team members
TIII (%)	30.61	28.98	27.06	27.02	26.59	26.1	25.28	24.04	23.73	23.14
Over-all Rank	1	2	3	4	5	6	7	8	9	10

"Constant exposure to high noise" ranks closely with a TIII of 27.06%. High noise levels in tunnel construction can result from the use of heavy machinery and blasting operations. Prolonged exposure to high noise can lead to hearing loss and other health issues. Implementing noise control measures, such as the use of sound barriers and hearing protection devices, is critical. The literature supports the effectiveness of these interventions in reducing noise exposure and protecting worker health PIARC. (2024). The risk associated with "Sporadic vacuuming/cleaning inside the tunnel," which has a TIII of 27.02%, underscores the importance of regular and effective cleaning practices to control dust and debris, which can contribute to respiratory problems and other health issues. Regular cleaning schedules and the use of appropriate cleaning technology are recommended to manage this risk effectively PIARC. (2024). Lastly, the "Lack of emergency services and rescue team members," with a TIII of 23.14%, points to a critical gap in emergency preparedness. The availability of trained emergency personnel is vital for immediate response to incidents, which can significantly reduce the severity of accidents and fatalities LRQA. (2024).

6. CONCLUSIONS

Safety management assessment during tunnel construction constitutes a pivotal component of infrastructure advancement. Given the distinctive challenges tunnels pose, emphasizing worker safety, environmental safeguarding, and structural integrity of the tunnel is essential. However, the study is aimed to enhance construction site safety in tunnel projects by pinpointing the most critical risks impacting worker safety and scheduling. The findings reveal that, the most significant risks identified are Musculoskeletal disorder due to heavy manual handling, prolonged use of hand tools, or standing, Oxygen shortage brought on by the narrow tunnel, and Constant exposure to high noise; are the most effecting risks. A statistical analysis of questionnaire data, conducted using the SPSS V20 package, identified the most significant risks to tunneling construction safety management regarding the total importance index impact (TIII). This analysis facilitates the provision of practical guidelines, enhancing tunnel construction projects' success rate. Implementing strategies to mitigate exposure to elevated noise levels, air supply hazards, fires, and oxygen deficiency is expected to confer multiple benefits, including improved worker health and performance, reduced time and costs, increased productivity, and an enhanced reputation among staff and clients.

By effectively managing identified hazards and risks, accidents and injuries at tunnel construction sites can be mitigated and regulated. This study's significance lies in its potential to promote a safer working environment by utilizing current findings and expert assessments to formulate a risk prioritization list for tunnel construction projects. Moreover, by providing practical guidelines, risk analysis enhances the success rate of tunnel construction projects. Additionally, implementing measures to mitigate exposure to elevated noise levels, air supply hazards, fires, and oxygen deficiency is anticipated to result in numerous benefits, including improved worker health and performance, reduced time and expenses, enhanced productivity, and an improved reputation among staff and clients.

CONFLICT OF INTERESTS

None.

ACKNOWLEDGMENTS

None.

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