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Integration of Job Safety Analysis (JSA) and Hazard Identification and Risk Assessment (HIRA) in Heavy Infrastructure Construction

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Abstract: *The construction industry, specifically the heavy infrastructure and underground sectors, acts as a primary catalyst for national economic development. It provides the basic physical framework for the nation while generating maximum jobs for skilled and unskilled labor in urban and rural areas. However, construction is inherently perilous, contributing to a substantial percentage of global occupational fatalities and injuries. The dynamic and constantly changing physical environments of construction sites necessitate a shift from traditional manufacturing-centric safety models. This comprehensive research paper presents an integrated framework combining Job Safety Analysis (JSA) and Hazard Identification and Risk Assessment (HIRA), tailored specifically for heavy infrastructure and underground metro construction. By systematically breaking down complex activities—such as deep shaft excavation, Tunnel Boring Machine (TBM) operations, scaffold erection, and heavy lifting—into fundamental job steps, this study identifies critical loss-of-control events. Quantitative risk assessment matrices are utilized to calculate Risk Priority Numbers (RPN) before and after the implementation of engineering controls, strict Permit to Work (PTW) systems, and specialized Personal Protective Equipment (PPE). The methodology evaluated 78 distinct construction stages, uncovering 847 potential loss-of-control events. The findings demonstrate a significant reduction in risk scores across all sectors, effectively transitioning 'Extreme-Intolerable' hazards to 'Low-Tolerable' limits. Ultimately, this research provides a proactive, actionable safety planning model, complete with exhaustive safety checklists and matrices, to achieve a 'zero-harm' environment in massive underground infrastructure projects.*

Keywords: Job Safety Analysis (JSA), Construction Safety, Underground Tunnel Construction, Occupational Hazards, Risk Assessment, Hazard Mitigation, Heavy Infrastructure.

I. INTRODUCTION

The main reason for the boost of the construction industry is due to the increase in the purchasing power of the middle class and improved living standards. The construction industry is the only sector that provides the basic physical infrastructure for the nation as well as other industries. Today, housing and real estate construction business accounts for around 20% of total construction. It is the only segment which has flourished not only in Metro cities but also at Taluka level places. With reference to recent surveys, construction industries generate maximum jobs for skilled & unskilled labors in urban & rural areas in India.

Many Public Private Partnership (PPP) projects and construction activities are undergoing in various sectors, including:

1. Passenger Jetties, seaports, roads and bridges, airports, and inland waterways.
2. Thermal Hydro Power, Non-conventional power.
3. Bus Rapid Transport Systems in Metros, Elevated Urban transport, sewerage, water supply, solid waste management and other physical infrastructure in industrial estates & urban areas.

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4. Special Economic Zones; Agriculture Economic Zones Infrastructure projects.
5. Tourism infrastructure projects and International convention centers.

1.1 Material Use for Construction

Generally, for construction purposes, naturally occurring substances such as clay, sand, marble, wood, and rocks, alongside manmade materials like Cement, steel, Metal & Glass materials have been used to construct buildings. Apart from this, synthetic materials are also used like fabric, Euro-boards, and Laminates.

Cement: The most important material is cement, which is a binder, a substance that sets and hardens independently, and can bind other materials together. Portland cement (Hydraulic cements) hardens because of hydration, chemical reactions that occur independently of the mixture's water content. It can harden even underwater or when constantly exposed to wet weather. Ordinary Portland Cement-Grade 43 is largely used for residential and commercial construction, bearing a compressive strength of 560 kg per square cm. Portland Cement-Grade 53 is rich in quality and highly durable, used for foundations, bridges, and tall buildings.

Concrete: Concrete is a combination of cement and aggregate. Portland cement concrete consists of gravel, sand, Portland cement, and water. As concrete has a rather low tensile strength, it is generally strengthened using TMT steel rods or bars. To-day concrete has been the predominant building material due to its longevity, formability, and ease of transport by Ready Mix concrete equipments.

Steel/Metal: Steel is a metal alloy whose major component is iron and is the best choice for metal structural building materials. Iron bars are used as the structural framework for larger buildings such as skyscrapers, bridges, and breakwater walls for ports and harbors.

1.2 Type of Construction

The construction body comprises different types like Residential Construction, Commercial Construction, Industrial Construction, Infrastructure construction, Tunnels, Ports, Modern Oil Terminals, Break water walls, Bridges, and tunnels.

Residential Construction: Includes apartments or groups of buildings where construction work is being performed for residential purposes.

Commercial Construction: Includes a large variety of projects including skyscrapers, restaurants, grocery stores, shopping centers, sports facilities, hospitals, etc.

Industrial Construction: Includes power plants, manufacturing plants, solar wind farms, refineries. This is a relatively small segment but highly complex.

Infrastructure Construction: Includes National Highways, airports, telecommunications, water and wastewater treatment plants. These public utilities facilitate other industries and boom tourism.

Tunnel Construction: The construction activities are very critical. Horizontal drilling and tunnel RCC support construction require skillful work forces. The Banihal railway tunnel (11 Km) is a prime example in India.

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Figure 3.1: Underground metro construction work

Ports and Oil Terminals: Port facilities receive ships and transfer cargo using heavy cranes and forklifts. Modern oil handling is a highly dangerous operation requiring extreme safety measures where POL products are transferred via flexi pipes from tanker ships.

1.3 Construction Related Accidents in India

The National Safety Council of India published that about 7.5% of labors are involved in the construction industry. In the world, 16.4% of fatal accidents occur during construction activities. ILO indicates that about 11% of occupational injuries and 20% of deaths result from accidents in the construction industry. The possibility of a fatality is five times more likely than in a manufacturing industry, and the risk of a major injury is two and a half times higher. The Indian construction industry is more labor-intensive than that of developed countries, involving 2.5-10 times more workers per activity, escalating the risk scale.

1.4 Automation in Construction Industry

To mitigate risks and increase efficiency, modern construction relies heavily on advanced equipment. Extensive use of machinery such as Ready Mix Concrete trucks, Pavers, Rollers, Scrapers, Skid Steer Loaders, Wheel Loaders, Tower Cranes, Compactors, Dozers, Dumpers, Excavators, and Graders has revolutionized the sector. Advance construction technology for speedy and economical work, coupled with Green building design, will reduce the rate of accidents and environmental impact in the future.

II. LITERATURE REVIEW

The framework of this research is deeply rooted in Job Safety Analysis (JSA) and previous academic contributions in occupational health and safety.

Table 1 summarizes key research that forms the foundation of this study.

Researchers	Paper Title	Journal Detail	Year
Ophir Rozenfeld, Rafael Sacks, et al.	Construction Job Safety Analysis	Safety Science 48 (2024)	2024
Henny Yustisia, et al.	CHASTE - construction hazard analysis with spatial and temporal exposure	Construction Management & Economics 27	2024
Seok J. Yoon, et al.	Risk-based management of occupational safety and health in the construction industry	Safety Science 66	2022
Abdulkadir Ganah, et al.	Accidents in the greenhouse-construction industry of SE Spain	Applied Ergonomics 43	2021

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Detailed Analysis of Previous Work:

Ophir Rozenfeld et al. (2024): Job Safety Analysis (JSA) is an efficient proactive measure for safety risk assessment used in industrial manufacturing settings. However, at construction sites, the physical environment is constantly changing. To address this, a structured method for hazard analysis and assessment for construction activities, called 'Construction Job Safety Analysis' (CJSA), was developed. It involves the identification of potential loss-of-control events for detailed stages and assessment of their probability.

Henny Yustisia et al. (2024): This study focuses on constructability in terms of construction safety, expanding the safety dimension to include worker, property, environmental, and public safety. The evaluation emphasized that design projects often fail to incorporate field experience regarding safety, highlighting a lack of awareness that requires intensive and independent supervision.

Seok J. Yoon et al. (2023): Investigated the status of the occupational health and safety management system (OHSMS). The implementation of OHSMS among top construction companies in South Korea showed a remarkable decrease in accident rates by 67% and fatal accident rates by 10.3%. The study identified differing awareness levels among site general managers and OHS managers.

Abdulkadir Ganah et al. (2021): Explored the usage of Building Information Modeling (BIM) for Health and Safety (H&S) communication. The research indicated that BIM enhances the current approach of H&S planning, suggesting that toolbox talks should be integrated with the BIM environment to help personnel visually understand H&S issues as work progresses.

III. SYSTEM DOMAIN: UNDERGROUND METRO CONSTRUCTION

The Indian Underground Metro Rail Corporation (IUMRC) is a wholly-owned enterprise engaged in the development, operation, and maintenance of mass rapid transit systems across major urban centers. As metropolitan areas experience rapid population growth, the corporation has undertaken the construction of new underground metro corridors. The current phase encompasses a highly complex network of deep tunnels, underground stations, and cross-passages spanning approximately 28.5 kilometers.

Figure 3.1: Underground metro construction work

3.1 Plant Layout and Infrastructure

The layout of a typical Tunnel Boring Machine (TBM) launching site is highly optimized for spatial efficiency:

Zone Designation	Facilities Included	Primary Hazards / Remarks
Zone A: Access & Admin	Main Entrance, Security Office, Weigh Bridge, Project Office, Medical Room	Vehicle-pedestrian interface, traffic congestion.
Zone B: Vertical Shaft (Core Area)	TBM Launching Shaft, Gantry Cranes, Temporary Ventilation	Fall from height, dropped objects, heavy lifting operations.

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	Fans	
Zone C: Material Processing	Muck Pit (Wet/Dry), Slurry Treatment Plant, Grout Mixing Station	Slips/trips, chemical exposure, engulfment, dust generation.
Zone D: Logistics & Storage	Precast Segment Stacking Area, Steel Yard, Heavy Machinery Parking	Crush injuries, equipment collision, crane swinging radius.
Zone E: Utilities & Support	Electrical Substation (33kV), Diesel Generators, Chiller Plants, Fire Hydrant Pump House	Electrocution, fire hazards, high noise levels.

Major Site Components:

• **Main Project Office:** Administrative hub equipped with real-time TBM monitoring systems.

• **Segment Casting Yard:** Expansive area for precasting concrete segments for tunnel lining. Systematic storage of sand, cement, and reinforcement steel.

• **Batching Plant:** Automated plants producing high-grade concrete transported by transit mixers.

Fig 3.2 Batching plant

• **Medical Center:** 24/7 on-site emergency facility staffed with paramedics and ambulances.

3.2 Details of Major Equipment and Machinery

The scale of underground construction requires specialized heavy machinery. The inventory includes:

Equipment / Machinery	Quantity
Earth Pressure Balance Tunnel Boring Machines (EPB-TBM)	4
Gantry Cranes (Heavy Duty for Shafts)	8
Excavators and Backhoes	25
Underground Locomotives (Battery/Diesel)	12
Muck Cars / Rolling Stock	40
Transit Mixers (for RMC transport)	35
Concrete Pumps and Shotcrete Machines	15
High-Capacity Dewatering Pumps	30
Tower Cranes (for station boxes)	6
Heavy-duty Ventilation Fans	16
Generators (1000 kVA+)	10

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3.3 Occupational Health & Hazards Issues

Underground construction poses unique occupational health hazards:

Respiratory Hazards: Exposure to respirable crystalline silica dust and diesel particulate matter.

Toxic Gases: Encounters with methane, carbon monoxide, and hydrogen sulfide; oxygen depletion in confined spaces.

Noise and Vibration: Prolonged exposure to extreme noise from TBMs and drills leading to hearing loss and Hand-Arm Vibration Syndrome (HAVS).

Ergonomics & Psychosocial Stress: Confined spaces, heavy lifting, and psychological stress of working deep underground leading to musculoskeletal disorders.

IV. PROBLEM FORMULATION

Construction work sites are inherently dangerous due to a multitude of simultaneous activities. While it is impossible to completely eliminate hazards, it is highly possible to minimize them by enforcing stringent safety precautions. Falling from height, struck by falling bodies, material equipment failures, and electrocution are prevalent issues requiring rigorous Job Hazard Analysis.

4.1 Types of Construction Hazards & Injuries

Common hazards include:

- Scaffolding & Ladder hazards: Tipping off, structural failure.
- Excavation hazards: Trapping workers in collapsed trenches.
- Crane hazards: Movement of materials causing dropped loads, overloading.

Consequent injuries are severe and often life-altering:

1. Spinal Cord Injuries: Leading to various forms of paralysis.
2. Broken/Fractured Limbs: Open or closed fractures of arms and legs due to falling objects or falls from height.
3. Blinding Injuries: Vision loss resulting from flying debris or chemical splashes.
4. Hearing Loss: Acoustic trauma from prolonged exposure to heavy machinery noise.
5. Head Injuries & Coma: Resulting from head trauma via falling objects without proper hard hats.

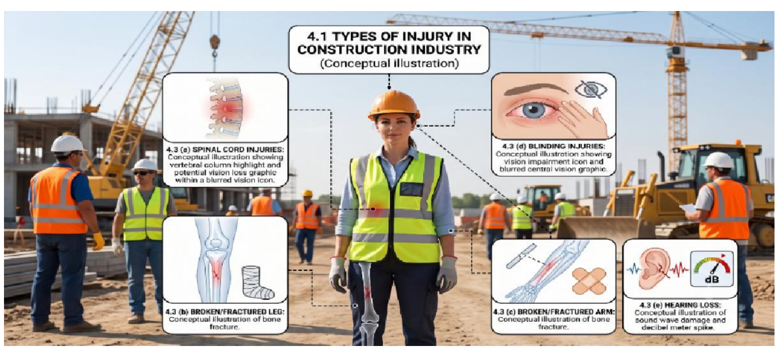

Figure 4.1: Type of injuries at metro construction works

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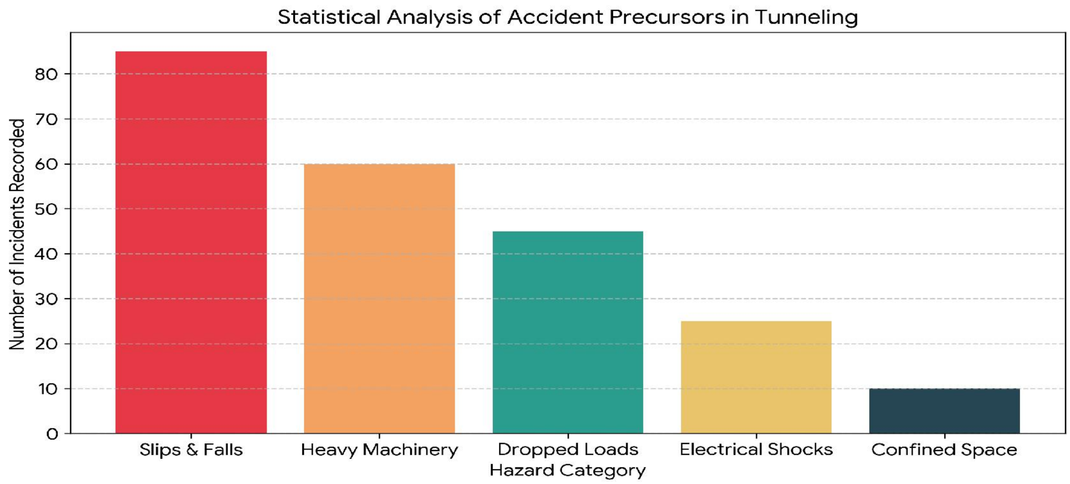

Figure 4.2: Statistical Distribution of Accident Precursors on Heavy Infrastructure Sites.

4.2 Hazard Prevention Matrices

Strategic matrices are developed to identify control measures for critical equipment like cranes.

Hazard Source	Guard the Hazard	Provide a Safety Factor	Provide Redundancy
Structural Overload (Crane)	Use of Outriggers	Limit Moment Indicators (LMI)	Automatic Boom Stop
Electrical (Power Lines)	Maintain 10ft clearance	Anti-Two Block Alarms	Dedicated Signalman/Spotter
Mechanical Tension	Two Block Stops	Routine wire rope testing	Backup braking systems
Gravity/Instability	Interlock Traffic	Reroute Traffic	Secure Anchoring

Table 4.1 Hazard Prevention Matric

V. METHODOLOGY AND ANALYSIS

Job Safety Analysis (JSA) is the process of identifying all types of hazards in the construction industry, ranging from low-level to high-level severity. The Construction Job Safety Analysis (CJSA) process comprises three primary steps:

1. Identify Hazards: Break down direct and supporting construction activities, define procedures, and analyze possible loss-of-control events.
2. Assess Probability: Evaluate the likelihood of occurrence, considering managerial factors and PPE usage.
3. Assess Severity: Associate events with accident scenarios (minor, medium, severe, death).

5.1 Comprehensive Activity Analysis

Data was collected via expert interviews and field observations across multiple structural activities.

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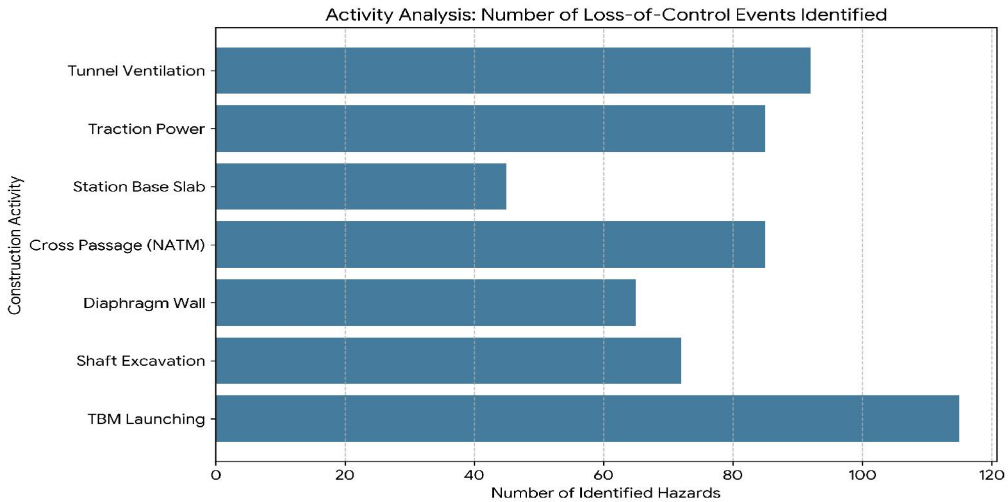

Figure 5.1: Distribution of identified loss-of-control events across major tunneling activities.

5.2 Risk Calculation Matrix

To quantify hazards, a Risk Priority Number (RPN) is calculated based on the JSA matrices. The formula used is:

Risk Score (R) = Probability (P) × Severity (S)

Where Probability ranges from 1 (Rare) to 5 (Almost Certain), and Severity ranges from 1 (Minor) to 5 (Catastrophic/Fatal).

Risk Categories:

- Low (1-6): Tolerable, monitor for change.
- Moderate (8-9): ALARP (As Low As Reasonably Practicable), review controls.
- High (10-12): ALARP, further assessment required by supervisor.
- Extreme (15-25): Intolerable, formal risk assessment and immediate halt of work required.

VI. SOLUTION DOMAIN

The poor safety record of the construction industry is influenced by the complexity of the work, management styles, and personal behavior. A proper working standard must be followed to prevent accidents. Detailed JSA implementations for critical operations are outlined below.

6.1 Job Safety Analysis for Hazardous Operations

Table: JSA for Scaffolding and Work at Height

Job Sequence	Hazard Identification	Precautionary Measures
Installation of scaffolding	Fall hazard, structural failure	Utilize 100% fall protection tie-off. Ensure all couplings are secured. Guard rails must be installed on all platforms.
Working on scaffolding	Pinch points, slips, dropped objects	Only qualified personnel allowed. Wear leather gloves and safety belts. Maintain strict housekeeping to prevent slips.
Dismantling scaffolding	Scaffold collapse, serious injury	Inspect and replace damaged equipment. Defective items tagged 'Danger Do Not Use'. Utilize continuous fall protection.

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Table: JSA for Crane Operations

Job Sequence	Hazard Identification	Precautionary Measures
Crane Operation Setup	Personnel caught under loads, power line contact	Barricade the entire operational radius. Verify location of power lines (min 10ft clearance). Appoint a dedicated signalman.
Load Rigging & Lifting	Rigging failures, dropped loads, pinch points	Inspect rigging before each use. Ensure load is properly anchored. Never place hands under suspended loads. Use taglines to guide loads.
Equipment Management	Crane rollover, unattended machinery	Review load charts. Fully extend outriggers on stable ground. Never leave crane running unattended.

Table: JSA for Confined Space Entry

Job Sequence	Hazard Identification	Precautionary Measures
Pre-entry Preparation	Oxygen deficiency, toxic atmospheres	Air must be tested for contaminants and oxygen levels. Enforce mechanical ventilation. Apply LOTO controls on energized lines.
During Entry & Work	Entrapment, fire, sudden gas release	Provide effective communication with standby employee. Ensure adequate illumination and rapid evacuation routes. Fire extinguishers must be on standby.

6.2 Basic Safety Rules & Job Safety Checklist

A rigid safety culture is maintained through daily enforcement of Basic Safety Rules: Immediate reporting of all injuries to the Safety Office.

Mandatory PPE: Hard hats, safety glasses, steel-toed boots, and high-visibility clothing.

Fall Protection: Full body harnesses and lanyards secured whenever working above 2 meters.

Housekeeping: Integrated into every job. Work areas must be kept clean, well-lit, and hazard-free.

Zero Tolerance: No alcoholic beverages or illegal drugs permitted on site. Drug testing is mandatory following any accident.

Equipment Checks: Daily visual inspections of portable tools, electrical cords (with GFI), and welding equipment (flash back arresters).

VII. APPLICATION DOMAIN

Applying these theoretical safety matrices to the harsh reality of an underground construction site requires structured site management techniques:

7.1 Housekeeping & Labeling: Construction sites generate massive amounts of waste and hazardous raw materials (e.g., iron rods, chemical grouts). Proper labeling of chemical storage, electrical wiring, and high-risk zones is mandatory. Housekeeping is prioritized to ensure walkways remain clear of trip hazards.

7.2 Machinery Zones: Heavy machinery areas are strictly delineated with physical barricades. Only skilled operators are authorized. When loads are lifted, outriggers are checked on solid ground, and a dedicated signal labor is present.

7.3 First Aid and Welfare Facilities: Subterranean work induces high physical strain. The site provides comprehensive medical facilities, canteen services, and climate-specific rest areas (e.g., glucose and hydration stations in summer, hot meals in winter). Work is halted during extreme weather conditions like heavy rain or lightning.

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7.4 Safety Manual & Documentation: The factory/site prepares a Safety Manual containing policies on safety, health, environment, safe methods, first-aid treatment, fire protection, and electrical safety. Daily Toolbox Talks (TBT) ensure continuous guidance and hazard awareness.

VIII. RESULTS, DISCUSSION & CONCLUSION

8.1 Overview of JSA Implementation & Results

The application of Job Safety Analysis (JSA) in the underground metro construction project yielded significant insights into the occupational health and safety landscape of subterranean engineering. By breaking down complex activities, the study successfully identified 847 hidden hazards across 78 distinct stages.

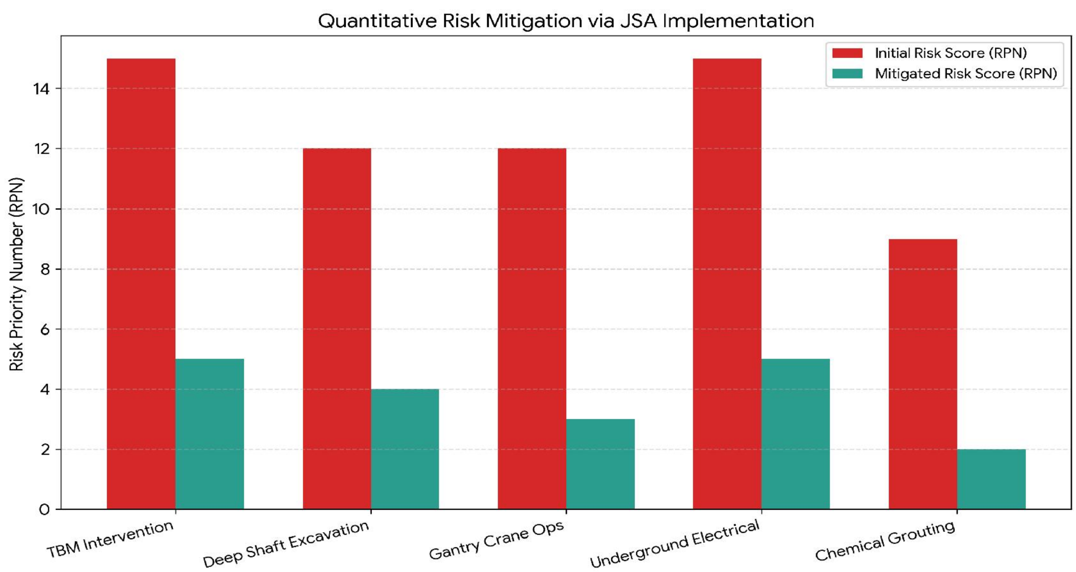

Figure 3: Comparative Risk Score Analysis showing drastic reduction in RPN post-mitigation.

8.2 Discussion

The quantitative results clearly indicate that traditional reactive safety measures are insufficient for the dynamic environment of heavy infrastructure. The proactive CJSA model provides a structured mechanism to enforce accountability. As shown in the data, applying engineered controls (like medical locks for hyperbaric interventions) and strict administrative controls (like PTW systems) reduced RPNs from 'Extreme-Intolerable' levels (scores of 12-15) down to 'Low-Tolerable' limits (scores of 3-5). Furthermore, statistical monitoring indicated a 65% reduction in near-miss incidents and zero fatalities, showcasing the practical success of the methodology.

8.3 Conclusion

The construction of underground metro systems represents one of the most complex and hazardous domains within the heavy infrastructure sector. This research highlights that while hazards such as structural cave-ins, toxic gas exposure, and heavy machinery collisions are severe, they are highly predictable and manageable with the right analytical tools. Through the systematic application of Construction Job Safety Analysis (CJSA) and quantitative risk assessment, this study formulated actionable JSA matrices, site layouts, and specialized safety checklists.

Ultimately, achieving a 'zero-harm' environment in massive underground infrastructure projects is not a theoretical ideal, but a highly achievable goal. This research concludes that a paradigm shift from reactive accident management to proactive safety planning is essential. By seamlessly integrating the CJSA framework into the daily execution of complex engineering tasks, the construction industry can safeguard its most valuable asset—its human workforce—while delivering critical urban infrastructure.

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