# Intelligent risk management for TBM hard rock tunnelling based on Knowledge Graph

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ABSTRACT: Tunnel construction using TBM involves various factors that increase risks to the structure, including workers, machinery, operation, structure and surrounding environment. These factors interact in complex ways, making risk management rather complicated and challenging. To achieve a better risk management, state-of-the-art technologies such as knowledge graph (KG) can help manage construction risk by storing, managing and mining risk concepts and construction entities. In the paper, a risk management knowledge graph was created for the TBM hard rock tunnel constructed in West China using Neo4j graph database. Work breakdown tree (WBS) and risk breakdown tree (RBS) were created to subdivide the complex TBM tunnelling process and risk sources. WBS and RBS entities were then integrated into the knowledge graph, making the attributes and relations of various entities clear to engineers. The case study demonstrated that knowledge graph is effective, reliable and advanced in TBM hard rock tunnelling risk management.

*Keywords: TBM tunnelling, hard rock, risk management, knowledge graph, work breakdown structure, risk breakdown structure.*

## 1 INTRODUCTION

Nuclear energy, a prominent source of clean energy, finds widespread application in power production, medical, and industrial sectors. Currently, nuclear power plants generate approximately 10% of the world's electricity, highlighting its significance. Notably, China has undertaken commendable initiatives in developing nuclear energy for power generation, nuclear medicine technology and industrial nuclear radiation processing.

China's progress in nuclear energy industry has brought the challenge of disposing nuclear waste to the forefront. Beishan underground laboratory project in Gansu represents China's pioneering effort towards addressing this problem. As the country's first underground field research and development platform dedicated to high-level waste disposal technology, the project is slated to become the world's largest, most functional, and inclusive underground laboratory upon completion. Its state-of-the-art facilities will provide a crucial testing platform and foundation for tackling the global challenge of geological disposal of high-level waste.

The laboratory is situated in wild Gobi, characterized by geological conditions dominated by slightly weathered granite with a quartz content of 25% to 30%. The platform is situated at a significant depth of 560 meters underground, representing a challenging hard rock project. Given the local construction site's unique features and associated needs, the structural plan comprises a spiral rampway-multi-shaft-two-level flat tunnel, as depicted in Figure 1.

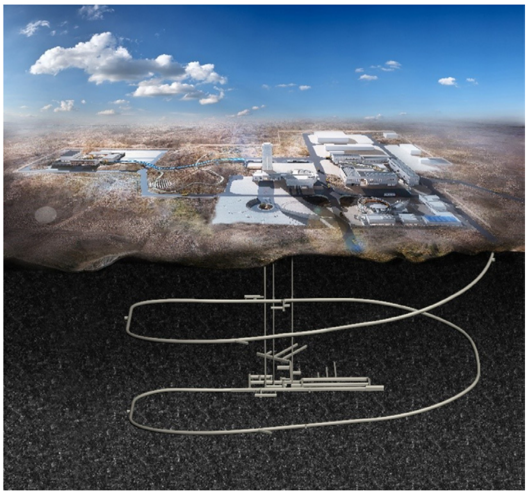

Figure 1. Laboratory construction site layout.

The ramp road, measuring 7.2km in length, constitutes a critical project that significantly impacts the laboratory's construction. A TBM machine is deployed for the excavation of the ramp, which measures 7m in diameter, with a turning radius of 400m in the curved section. The ramp road has a slope of 10% and rotates clockwise twice from the surface downwards, connecting with two flat lanes at -240 level and -560 level, respectively.

Hard rock tunnelling presents several engineering challenges, mainly including cracking of hard rock blocks, cutter damage and lining breakage. Thus, the laboratory project is a complex undertaking characterized by high construction requirements, a long service period, high TBM tunnelling risks at significant depths and high safety levels. Additionally, it is China's first large depth nuclear waste laboratory, which lacks relevant technical standards and practical construction experience. The absence of corresponding safety risk management may result in incalculable negative social impacts and significant losses, severely hindering the laboratory's construction.

Thus, a TBM hard rock tunnelling risk management method is proposed. In the paper, the second section provides a risk analysis of TBM tunnelling process and proposes the overall framework of risk management. The third section constructs a risk knowledge graph and stores a set of existed risk accident cases. The final section summarizes the paper and proposes future research directions.

## 2 TBM TUNNELLING RISK MANAGEMENT

Long service time of underground projects increase the likelihood of diseases, greatly impacting the structure's safety performance, thus risk management is quite essential for large underground projects (Xue & Li, 2018). However, traditional risk analysis methods are prone to subjective biases and may require a significant amount of data and model assumptions. Qualitative assessment, represented by the expert survey method, is subject to subjective factors, while quantitative assessment, represented by the hierarchical analysis method, may require a substantial amount of data and model assumptions (Modarres, 2006).

A novel approach to risk assessment that utilizes a dynamic methodology is proposed. The proposed method involves the construction of work breakdown structure (WBS) and risk breakdown structure (RBS). The WBS subdivides the continuous TBM tunnelling process into traceable sub-tasks. Similarly, the tunnelling- related risk sources at the construction site are also subdivided into assessable sub-risk sources in the RBS. Then, a priori risk fault tree unit is constructed for each sub-task in the WBS using existing engineering accident data sets and expert experience, forming a risk fault tree unit database. The risk management method can be adapted to other large-scale underground projects.

## 2.1 *Work breakdown structure*

Work Breakdown Structure (WBS) is a project management tool used to simplify complex projects or processes by breaking them down into manageable sub-tasks that can be completed independently. It organizes sub-tasks into a hierarchical structure, ensuring that each sub-task will be fully considered and executed (Siami-Irdemoosa, Dindarloo, & Sharifzadeh, 2015).

TBM hard rock tunnelling is a complex system process that involves a range of tasks, including rock breaking, rock ship discharge, lining installation, and power propulsion. To simplify this complex process, a tree structure is created using WBS approach. Each node in the tree represents a task, with the upper nodes representing larger tasks and the lower ones representing smaller tasks.

TBM hard rock tunnelling is then decomposed into four main parts: rock breaking, rock ship discharging, lining installation and power propulsion. Each part is further subdivided into smaller tasks, partly illustrated in Figure 2. The bottom sub-tasks are relatively independent of each other and are directly performed by workers, such as disc cutter wear & tear checking and disc cutter replacing. By using WBS, the complex TBM hard rock tunnelling is broken down into smaller, more manageable sub-tasks, making it easier to execute and manage.

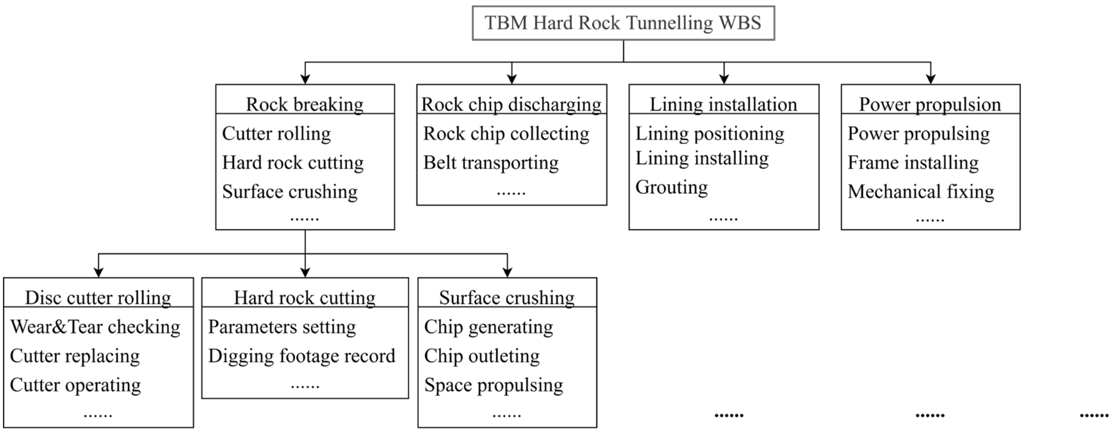


Figure 2. TBM hard rock tunnelling WBS.

## 2.2 *Risk breakdown structure*

RBS is a risk management method that breaks down risk sources into multiple levels and subdivides them into directly identifiable and assessable sub-risk sources (Jeong & Jeong, 2021). It bears resemblance to WBS. In the context of tunnelling construction sites, RBS is typically constructed based on four categories: personnel, machinery, environment and management.

The TBM tunnelling site entails multiple intricate risk sources, which are categorized and further subdivided into an RBS structure. The engineer can directly identify and evaluate the bottom specific risk sources. The risk sources were subdivided based on personnel, machinery, environment, and management. These risk sources can be further categorized deeper based on construction sites. For instance, personnel risk can be further broken down into designers, workers, engineers and project managers based on roles. Environment can be classified into geology, hydrology, and climate due to location. Similarly, machinery can be classified into TBM, slag transport machines, and cutter discs. Figure 3 provides part of the RBS content. Whenever possible, all associated risk sources should be integrated into the RBS framework to make the risk management and analysis more comprehensive.

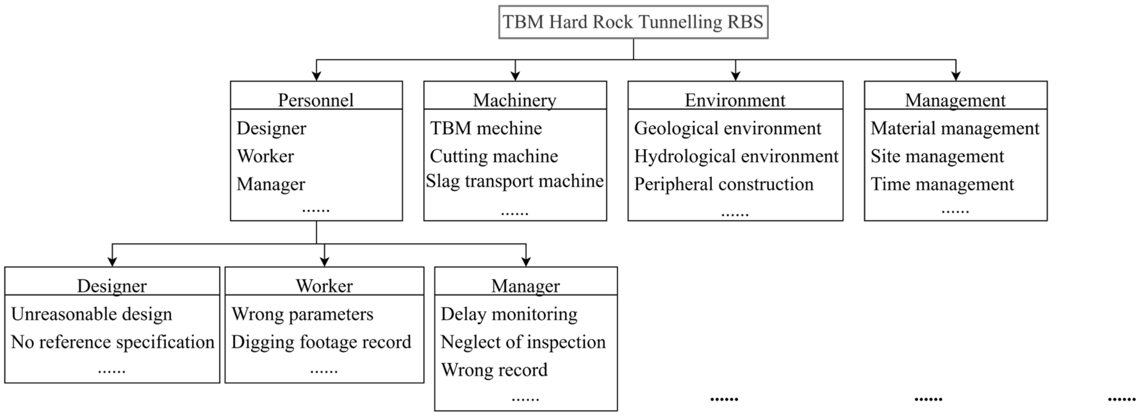


Figure 3. TBM hard rock tunnelling RBS.

## 2.3 *Fault tree unit database*

Multiple risk sources can lead to various risk faults, creating a many-to-many influence relationship. For instance, hard rock cutting process may lead to a rock collapse fault, with structural surface of the rock being the risk source. Similarly, the lining installation process may cause lining damage, originating from imprecise positioning during installation or incorrect lining design. To facilitate a detailed analysis of each risk fault, fault tree method is employed. Fault Tree Analysis (FTA) is a systematic approach to analyzing the causes of accidents. The method involves representing events as nodes and using logical relationships and Boolean algebra to construct a tree structure that systematically identifies the root causes and possibilities of accidents (Wessiani & Yoshio, 2018). Undesirable soft rock geology often leads to large deformation of rock formations, which is a common contributing factor. Soft rock deformation zones would cause initial support deformation, cracking, destabilization, overrun, collapse, and other damages (Ou et al., 2021). Figure 4 shows a fault tree for rock collapse hazard during hard rock cutting.

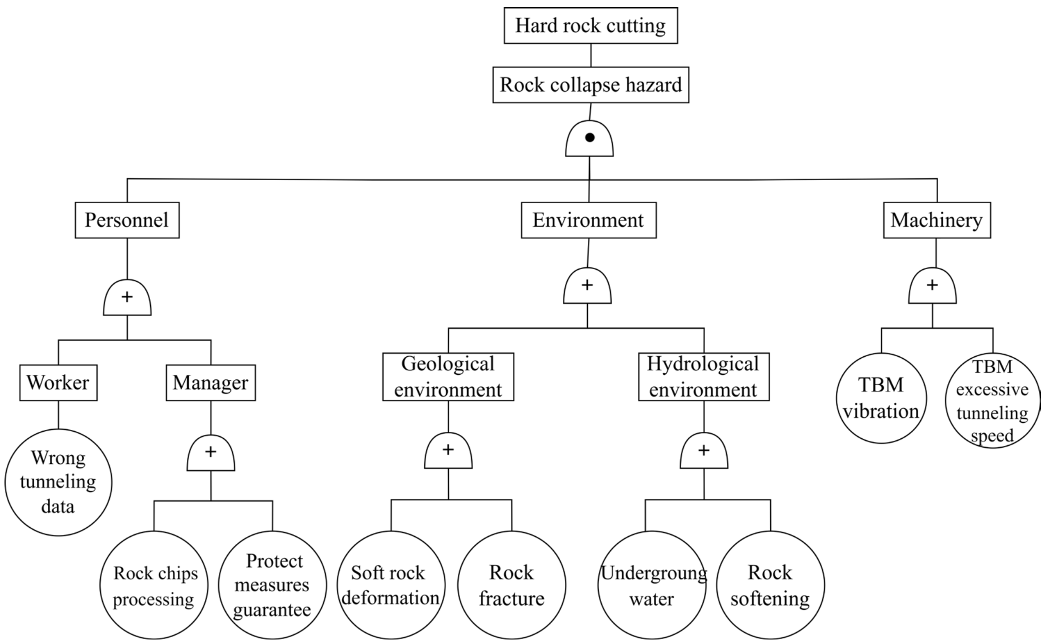


Figure 4. Hard rock cutting fault tree.

The example illustrates a risk-fault tree analysis of potential rock collapse risks during the sub-task rock cutting. Conducting fault tree analyses for each sub-task of WBS yields a database of risk-fault tree units that provides valuable prior risk knowledge for TBM tunnelling. The historical risk data guides project construction and supports risk management.

## 3 RISK KNOWLEDGE GRAPH

Knowledge graph is an effective tool for storing entities and their relationships. These entities can be people, places, events, organizations, cultures, artifacts and so on (Zou, 2020). Relationships capture the interactions or connections between entities. As introduced in Section 2, risk management is a mesh structure composed of various entities and their relationships, making knowledge graph rather an ideal approach to storing risk-related information. In the risk knowledge graph, nodes represent sub-tasks at each level of WBS, sub-risks sources at each level of RBS, and various risk faults, while relationships represent inclusion relationships between these nodes and occurrence relationships between sub-risk source nodes.

Figure 5 shows the model layer of the risk knowledge graph. It clearly illustrates the whole framework of the risk knowledge graph. WBS and RBS data are linked by risk fault nodes, with one side connected to WBS bottom sub-task nodes and the other side connected to the risk fault tree unit.

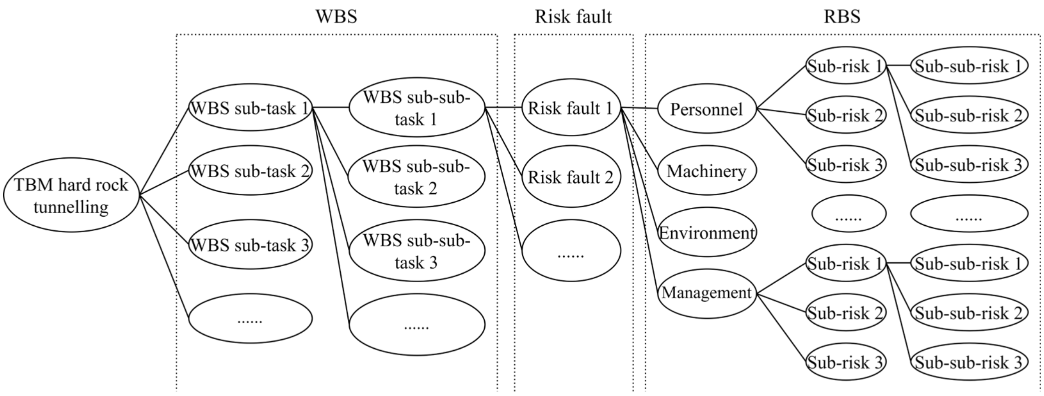


Figure 5. The model layer of the risk knowledge graph.

Neo4j is utilized as a graph database for constructing risk knowledge graph. WBS and RBS of TBM hard rock tunnelling and the risk fault tree units based on historical experience are imported into neo4j to form the instance layer, forming the construction of a priori risk knowledge graph. The final risk knowledge graph is displayed in Figure 6, showing one fault tree example.

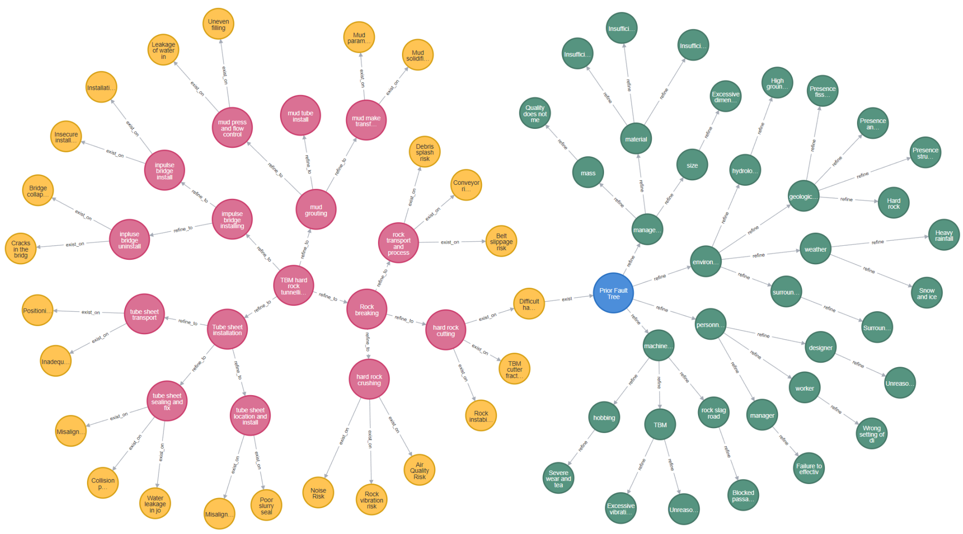

Figure 6. The instance layer of the risk knowledge graph.

Updating the existing risk knowledge graph in a timely manner is crucial as the construction of the underground laboratory progresses and the previous risk knowledge graph may not be applicable to new situations. To ensure the map remains relevant, new risk fault tree can be added to the risk knowledge graph after expert analysis. Each new risk fault on a sub-task undergoes fault tree analysis by an expert. A new fault node is added to the corresponding risk node, creating a fault tree node. As the project progresses, the sub-task accidents become more detailed and comprehensive, resulting in more fault tree units in the risk database. This prepares historical data for future risk prediction. The risk management method is universal and can be applied to other types of risk management work.

## 4 CONCLUSION AND FUTURE RESEARCH

The paper proposes a risk management method for TBM hard rock tunnelling by breaking down complex continuous TBM tunnelling work into controllable sub-tasks through WBS and manage risk sources through RBS. The method connects WBS and RBS nodes through risk fault and then constructs a risk knowledge graph by neo4j graph database. The risk knowledge graph processes existing risk experience into structured information by fault tree to guide construction and updates dynamically as newly encountered faults are added after expert analysis. The method ensues that the risk knowledge graph is suitable for managing risks in engineering construction under different circumstances.

While the paper successfully achieved the storage and updating of the risk knowledge graph, it lacked data-based reasoning by graph algorithm. In fact, the knowledge graph consists of entities and relations, which are connected by relations to form a series of triads. Through semantic analysis and reasoning of these triads, the implicit relationships between entities can be discovered and new knowledge can be derived (Chen, Jia, & Xiang, 2020). In future, the researchers aim to explore statistical patterns embedded within big data using knowledge graph and to mine potential risk faults and sub-risk sources based on these patterns.


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