

Risk analysis in underground tunnel construction with tunnel boring machines using the Best–Worst method and data envelopment analysis

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ABSTRACT

Background: The use of tunnel boring machines is continuously increasing; however, this activity faces many risks, resulting in negative events.

Methods: A novel approach using the best–worst method and a data envelopment analysis model was proposed to analyze the risks of underground tunnel construction with tunnel boring machines. The proposed approach was validated using a realistic case study of metro construction in Thailand.

Results: The proposed approach efficiently analyzed the risks and produced more solid findings. The most critical and least affected risks can be identified according to risk scores in descending order.

Implication: This study contributes a new method of risk analysis that benefits project managers and stakeholders who design risk management plans to reduce the occurrence and mitigate the severity of metro works.

Originality: The new risk analysis can obtain the best compromise ranking of risks based on decision-makers' preferences, probabilities, and various consequences under different circumstances.

1. Introduction

Infrastructure development is one of the main factors for enhancing a country's connectivity, as new technologies start to play a major role in improving the convenience and quality of life of residents. With the increasing urban population density and traffic loads, governments have developed infrastructure and architecture to achieve accelerated growth [1]. Many development projects support rapid urbanization, such as the expansion of public transport networks, creation of new cities to accommodate increased populations, and installation of double-track railways [2–4]. Among the numerous projects for urban development, tunnel construction is necessary to alleviate congestion, promote healthier traffic flows, minimize disruptions in suburban areas, and bring immense benefits to rural and urban regions by connecting their transportation capabilities [5]. The Thai government has proposed several large-scale underground tunnel constructions such as drainage, subway, traffic, and public utility tunnel constructions. Underground tunnel

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constructions for mass rapid transits (MRTs) are being executed; these projects improve the usefulness and efficiency of public transit systems and increase business for commercial development, thus enhancing the economy of the country.

Tunnel building for metro systems is the most important activity because it involves the design of underground passages constructed to enable transportation between two points. Nowadays, metro paths are usually built using a tunnel boring machine (TBM), which excavates tunnels using a circular cross section through various soil and rock strata. Using this machine has many advantages, such as continuous processes, high safety with low overbreak, lower emissions in terms of vibration and gas release, low manpower, minimal ground disturbances, and higher advance rates [6]. However, the use of mechanized methods has encountered numerous risks that have led to sophisticated developments and difficult infrastructure constructions [7–9]. These risks directly affect the completion of tunnel construction, project delivery, safety, health, and work environment. Although the risks are unlikely to occur, they can happen anywhere and at any stage of underground construction and consequently affect anyone. Thus, it is in the best interest of project managers to prevent the occurrence of these unexpected events; however, it is challenging to identify the most critical risk to mitigate its consequences.

To the best of our knowledge, this is the first study to analyze and prioritize the risks of underground tunnel construction with tunnel boring machines using the best–worst method (BWM) and a data envelopment analysis (DEA)-based risk analysis. The BWM was adapted to assign relative weights to the criteria, whereas the DEA model of risk assessment was used to measure more reliable risk scores. The proposed approach was tested using a case study involving the construction of an MRT purple line. The findings and benefits of this study will help project managers and stakeholders assess and prevent uncertainties in infrastructure development projects.

The rest of this paper is organized as follows: Section 2 describes the literature review. Section 3 provides the research methodology. Section 4 presents the results. The discussion is provided in Section 5. Finally, Section 6 concludes this work.

2. Literature review

Risk analysis of underground construction has been extensively studied in numerous directions. One of the most popular existing techniques for addressing unexpected events in mechanized underground tunnel construction is the analysis of risks based on probabilities and consequences [10]. Many past studies conducted various risk analysis methods in metro network construction. For example, Moradi and Farsangi [11] applied the risk matrix method to evaluate the risks of merchandized tunnel construction and predict the advance rates of these risks. Yazdani-Chamzini [12] designed a risk assessment-based fuzzy inference system to prioritize the risks of tunneling construction. Liu et al. [13] computed the occurrence probabilities of tunnel construction risks using the hybrid bow-tie method-based Bayesian network. Chung et al. [14] presented a shield TBM risk analysis model (STRAM) to analyze risks of geology, design, and construction management. Arbabsiar et al. [15] created a risk modelling-based inference engine to determine the risk levels. Sharafat et al. [16] invented the bow-tie method to assign probabilities of risks and consequences of the risks. Although the risk assessment methods can analyze unexpected events, decision-makers cannot make a ranking result because of involvement of a large number of risks, conflicting data, and lack of important information [17].

To make a better decision, different MCDM methods integrated with other MCDM techniques or other methods have been employed to provide outranking of tunnel construction risks. The integrated approach is relatively simple, straightforward, does not require high expertise, and is in line with the psychological behavior of human beings. Few studies have used integrated MCDM approaches to analyze the risks of underground construction. Yazdani-Chamzini et al. [18] ranked the risks associated with underground construction by using the analytic hierarchy process (AHP) and elimination and choice expressing reality (ELECTRE). Hyun et al. [19] assessed the risks of subway construction using AHP and fault tree analysis (FTA). Nezarat et al. [20] employed fuzzy AHP to prioritize negative risks in mechanized tunneling construction. Ehsanifar and Hemesy [21] established a hybrid MCDM approach integrating Shannon's entropy, decision-making trial and evaluation laboratory (DEMATEL), and the complex proportional assessment of alternatives with gray relations (COPRAS-G) for ranking uncertainties of underpass construction. Hou et al. [22] categorized the risks of metro construction using credal networks and the improved evaluation based on distance from average solution (EDAS). The related literature is summarized in Table 1, and the abbreviations are listed in Appendix A.

Table 1
Related literature.

Author	Method
Moradi and Farsangi [11]	Risk matrix method
Yazdani-Chamzini [12]	Risk assessment-based fuzzy inference system
Liu et al. [13]	Bow-tie-Bayesian network
Chung et al. [14]	STRAM
Arbabsiar et al. [15]	Risk modelling
Sharafat et al. [16]	Bow-tie risk analysis
Yazdani-Chamzini et al. [18]	AHP + ELECTRE
Hyun et al. [19]	AHP + FTA
Nezarat et al. [20]	Fuzzy AHP
Ehsanifar and Hemesy [21]	Shannon entropy + DEMATEL + COPRAS-G
Hou et al. [22]	Credal networks + EDAS
The present study	BWM + DEA-based risk analysis

After reviewing the literature, the previous approaches were found to be insufficient. The integration of MCDM approach and risk analysis is a new trend for addressing uncertainties in underground tunnel constructions with TBMs. In most previous studies, AHP and fuzzy AHP have been used to prioritize decision-making attributes. Both methods involve significant complexities and unavoidable redundancies, and the BWM invented by Rezaei [23] can overcome these difficulties owing to its low data requirements and comparisons [24]. Hence, this study employed the BWM to prioritize the risk analysis criteria. With reference to a risk modeling method, the existing methods for computing risk levels cannot accommodate multiple inputs and outputs and neglect the increase or decrease in efficiency based on size and output levels despite past studies having developed risk analysis methods in multiple ways. These limitations can be eliminated using Wang’s DEA model [25], which evaluates the relative efficiencies of decision-making units when multiple inputs and outputs are involved. Thus, we employed this model to compute more relative risk scores.

Therefore, integrating the BWM and DEA is preferred, and the following reasons explain why these two approaches apply in risk analysis. The BWM was applied in this study because it requires fewer comparison data than other weighting methods, thereby providing a straightforward way for decision-makers to evaluate criteria based on their preferences and making the interpretation of results more intuitive and understandable. The DEA was utilized because it deals with multiple risk factors of performance and allows benchmarking against the best-performing entities, which can be useful in risk analysis to identify best practices. Hence, combining the BWM and DEA in risk analysis can offer a comprehensive approach, integrating stakeholders’ preferences and objective data to arrive at well-informed risk management decisions. Although BWM–DEA approaches have been proposed (see Huang et al. [26], Mei and Chen [27]), the DEA-based risk analysis developed by Wang et al. [25] has not been included in previous integrated risk analysis approaches. Therefore, the integration of the BWM and DEA in this study is completely new compared to other BWM–DEA approaches.

Based on the above literature, this study first proposed a new comprehensive risk analysis for mechanized underground tunnel construction. The proposed approach includes the BWM and DEA. The BWM was applied to calculate the weights of the criteria, whereas the DEA model of risk assessment was employed to estimate local risk scores based on the weights, including likelihoods and various aspects of severity. The obtained scores were used to prioritize the risks in descending order.

3. Research method and material

This section presents the proposed approach for analyzing risks of mechanized metro tunnel construction. There are two main

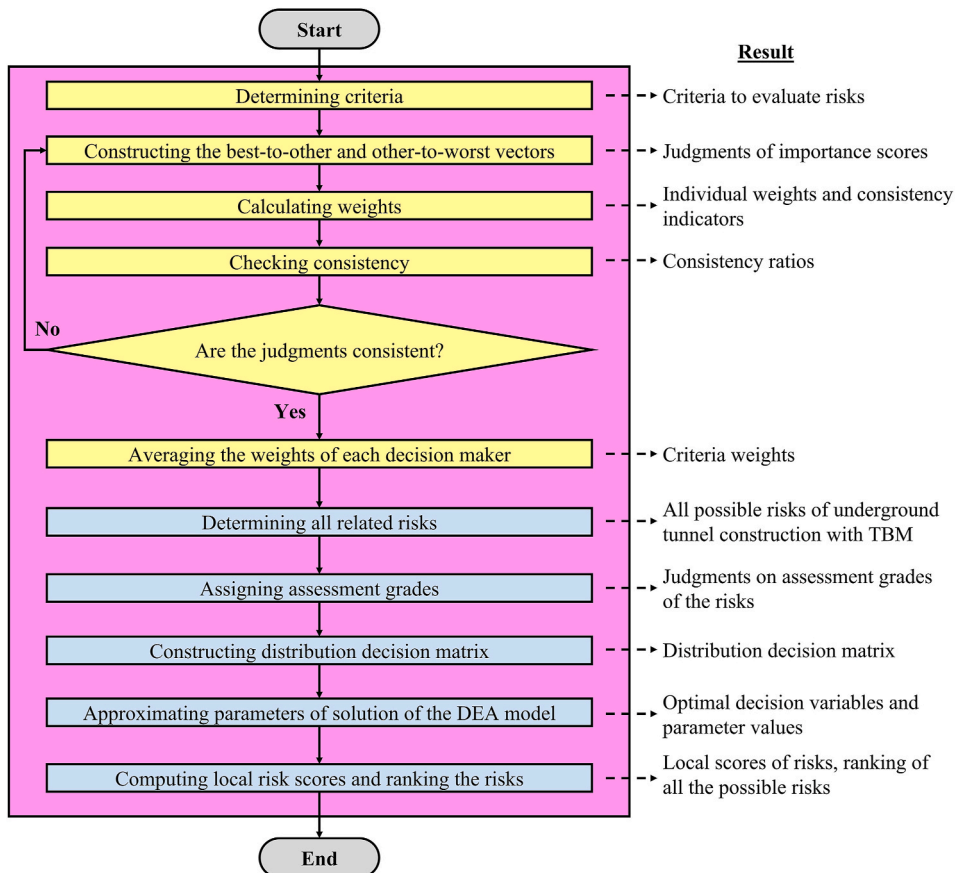


Fig. 1. Procedures of the proposed approach.

phases: (1) weight determination by BWM and (2) risk calculation by DEA model. The detailed computational procedures of each phase are shown in Fig. 1 and explained in the following subsections.

3.1. Phase 1: weight determination

This phase focuses on using the BWM to assign weights to the criteria for risk analysis in metro tunnel construction, as it is uncommon to assign equal importance to all criteria of risk assessment problems. The details of each step are given as follows:

Step 1. Let $C = \{C_1, C_2, \dots, C_m\}$ be the set of criteria, where m is the number of criteria and $j = 1, 2, \dots, m$. Experts as decision-makers then determine the best and worst criteria from the set of criteria [28].

Step 2. The decision-makers compare the best criterion with other criteria (best-to-other) and the remaining ones with the worst criterion (other-to-worst) using importance scales as shown in Table 2 (more details on the importance scales, please see Zare et al. [29], Orji et al. [30], Gupta [31], and Koohathongsumrit and Luangpaiboon [32]). The best-to-other and other-to-worst vectors are respectively written as $A_{BOd} = \{a_{B1d}, a_{B2d}, \dots, a_{Bmd}\}$ and $A_{OWd} = \{a_{1Wd}, a_{2Wd}, \dots, a_{mWd}\}$, where a_{Bjd} is the importance scale of the best criterion over criterion j , evaluated by decision-maker d ; a_{jWd} is the importance scale of criterion j over the worst criterion, evaluated by decision-maker d ; D is the number of decision-makers; $a_{BBd} = 1$; $a_{WWd} = 1$; $j = 1, 2, \dots, m$; and $d = 1, 2, \dots, D$.

Step 3. The optimum weights of the criteria are calculated by maximizing the maximum from set $\{|w_{Bd} - a_{Bjd}w_{jd}|, |w_{jd} - a_{jWd}w_{Wd}|\}$, which generates the following model: $\min \max_j = \{|w_{Bd} - a_{Bjd}w_{jd}|, |w_{jd} - a_{jWd}w_{Wd}|\}$, when its constraint is $\sum_j w_{jd} = 1$; and $w_{jd} \geq 0$ for all j . This model is converted into a linear model with a unique solution, as shown in Eq. (1) [33,34]:

$$\begin{aligned} & \text{Min } \xi^L \\ & \text{Subject to} \\ & |w_{Bd} - a_{Bjd}w_{jd}| \leq \xi^L, \text{ for all } j \\ & |w_{jd} - a_{jWd}w_{Wd}| \leq \xi^L, \text{ for all } j \\ & \sum_j w_{jd} = 1 \\ & w_{jd} \geq 0 \end{aligned} \tag{1}$$

where ξ^L means the consistency indicator of comparisons; w_{Bd} , w_{Wd} , and w_{jd} are weights of the best, the worst, and the j th criteria, obtained from decision-maker d .

Step 4. A crucial feature of the BWM is its ability to determine a consistency ratio. It is often impossible to achieve full consistency and subjective evaluation with a high level of accuracy. The existence of consistency cannot show the level of expertise; therefore, the decision accepts a slight inconsistency. The consistency ratio (CR) is calculated as shown in Eq. (2):

$$CR = \frac{\xi^{L*}}{CI} \tag{2}$$

where CI and ξ^{L*} refer to the consistency index and the optimal value of the consistency indicator, respectively; the consistency index can be obtained based on the importance scale between the best and worst criteria as shown in Table 3 [23,35]. The CR value derived from the ratio of ξ^{L*} to CI is used to check the consistency judgments. The lowest ξ^{L*} provides the optimal weights; meanwhile, the CI value should be high to indicate the importance score between the two criteria. When the denominator is extremely high, the CR value is low. Therefore, a low value or convergence to zero of CR indicates that the judgments are more consistent and vice versa. If the CR value is high, decision-makers must revise the comparisons until this value is accepted.

Step 5. The weights derived from each decision-maker are averaged to determine the group judgment of the weights as shown in Eq. (3):

$$w_j = \frac{\sum_{d=1}^D w_{jd}}{D} \tag{3}$$

Table 2
Detail of importance scale [29–31,36].

Intensity of importance	Definition	Explanation
1	Equal importance	Two criteria contribute equally to the objective.
3	Weak importance of one over another	Experience and judgment slightly favor one criterion over another.
5	Essential or strong importance	Experience and judgment strongly favor one criterion over another.
7	Demonstrated importance	A criterion is strongly favored and its dominance demonstrated in practice.
9	Absolute importance	The evidence favoring one criterion over another is of the highest possible order of affirmation.
2, 4, 6, 8	Intermediate values between the two adjacent judgments	Where compromise is needed.

Table 3
Consistency index [23,35].

a_{BW}	2	3	4	5	6	7	8	9
Consistency index	0.44	1.00	1.63	2.30	3.00	3.73	4.47	5.23

where w_j is the weight of criterion j ; $\sum_j w_j = 1$ [36]; and D is the number of decision-makers.

3.2. Phase 2: risk calculation

This phase aims to calculate risk levels using the DEA-based risk assessment. The details of each step are described as follows:

Step 1. All possible risks are identified through a literature review and interviews with experts. Let $A = \{A_1, A_2, \dots, A_n\}$ be the set of risks (alternatives), where n is the number of risks; $i = 1, 2, \dots, n$.

Step 2. The decision-makers individually assign grades to each risk with respect to all the criteria. The definition of each grade, which depends on the characteristics of the criteria, is known after determining the criteria.

Step 3. Suppose $G_j = \{H_{j1}, H_{j2}, \dots, H_{jK_j}\}$ be the set of risk assessment grades for criterion j , where H_{j1}, \dots, H_{jK_j} are the risk assessment grades from the most to least important grades of criterion j [37]. Assuming that $ND = \{ND_{ij1}, ND_{ij2}, \dots, ND_{ijK_j}\}$ be the number of decision-makers considering risk i in each grade under criterion j , where n and K imply the sets of possible risks and assessment grades; $i = 1, 2, \dots, n$; and $k = 1, 2, \dots, K$. The decision-makers evaluate risks with respect to all the criteria and construct a distribution decision matrix as shown in Table 4 [38].

Step 4. The DEA model is formulated to approximate the solution parameters, as presented in Eq. (4) [25]:

$$\begin{aligned}
 & \text{Maximize } \alpha_{ij} \\
 & \text{Subject to} \\
 & a_j \leq \sum_{k=1}^{K_j} S(H_{ijk})(ND_{ijk}) \leq 1 \\
 & S(H_{ij1}) \geq 2S(H_{ij2}) \geq \dots \geq K_{ij}S(H_{ijK_{ij}}) \geq 0
 \end{aligned} \tag{4}$$

where α_{ij} is the parameter of solution of risk i with respect to criterion j ; $S(H_{ijk})$ is the decision variable of risk i , criterion j in grade k ; and $S(H_{ij1}) \geq 2S(H_{ij2}) \geq \dots \geq K_{ij}S(H_{ijK_{ij}}) \geq 0$ is the strong ordering condition imposed on risk assessment grades [39].

Step 5. The local risk scores are calculated by multiplying the most optimal decision variables obtained from the lowest value of the parameter under each solution with the associated sets of decision-makers, as presented in Eq. (5):

$$x_i = \sum_{j=1}^m \left(\sum_{k=1}^{K_j} S^*(H_{jk})(ND_{ijk}) \right) \times w_j \tag{5}$$

where x_i is the local score of risk i ; and $S^*(H_{jk})$ is the most optimal decision variable under criterion j and grade k . The highest local risk score is assigned to the most critical risk. Therefore, the risks are ranked based on the local risk scores in descending order.

4. Results

This section describes the step-by-step application of the proposed approach to an actual MRT metro construction project, Tao Poon-Rat Burana section, Bangkok, Thailand. This metro network, which connects the center of Bangkok to its suburbs, plans to construct a 23.63-km sector line, covering an underground structure of 14.29 km with 10 stations and an elevated structure of 9.34 km with 7 stations. The details about the case study project are presented in Figs. 2–4. The overall construction progress of this project as of the end of May 2023 is 11.55 %. This project plans to utilize an earth pressure balance shield with a shield diameter ranging from 6.43 to 6.46 m and a face pressure ranging from 50 to 200 kPa [40].

We conducted a literature review and in-depth interviews with decision-makers (DMs) as experts. Four decision-makers, who hold

Table 4
Distribution decision matrix.

	C_1	...	C_j	...	C_m		
	H_{11}	...	H_{1K_1}	...	H_{m1}	...	H_{mK_m}
A_1	ND_{111}	...	ND_{11K_1}	...	ND_{1j1}	...	ND_{1mK_m}
\vdots	\vdots	...	\vdots	...	\vdots	...	\vdots
A_i	ND_{i11}	...	ND_{i1K_1}	...	ND_{ij1}	...	ND_{imK_m}
\vdots	\vdots	...	\vdots	...	\vdots	...	\vdots
A_n	ND_{n11}	...	ND_{n1K_1}	...	ND_{nj1}	...	ND_{nmK_m}

a doctorate degree in civil engineering, have at least ten years of strong academic background, relevant research publications, and practical experience in tunnel construction. The other three decision-makers work in different popular construction companies and hold at least a master’s degree in civil engineering, with at least ten years of experience in underground tunnel construction. The qualifications of each decision-maker are shown in Table 5.

Five criteria were determined to analyze the risks related to the metro construction system, namely “probability” (C₁), “increase in cost” (C₂), “late delivery of project” (C₃), “resource loss” (C₄), and “decrease in quality of working” (C₅). There are 68 possible risks, which can be classified into eight aspects as shown in Table 6. Most previous studies have considered many risk aspects related to geology, machines, technicality, finance, and facilities. Each aspect poses unique challenges that affect the safety, progress, and overall success of tunnel construction projects. The present study comprehensively considers various risks that affect tunnel construction using TBMs, particularly risks related to human, political, legal, and other aspects. Despite the advanced technology used in tunneling, human involvement remains essential for operating, managing, and overseeing the construction process. If workers prioritize safety, follow protocols, and maintain a safety-conscious mindset, the risk of accidents and injuries can be significantly reduced. Political and legal aspects often influence the planning, execution, and overall success of construction processes. Delays in obtaining permits from government agencies slow project development and increase costs. Moreover, legal disputes over contract terms can lead to project delays and cost overruns. Public opposition to tunnel construction, whether owing to environmental concerns, community impacts, or other reasons, can lead to legal challenges or delays. Other aspects include residents’ complaints, natural disasters, and epidemics.

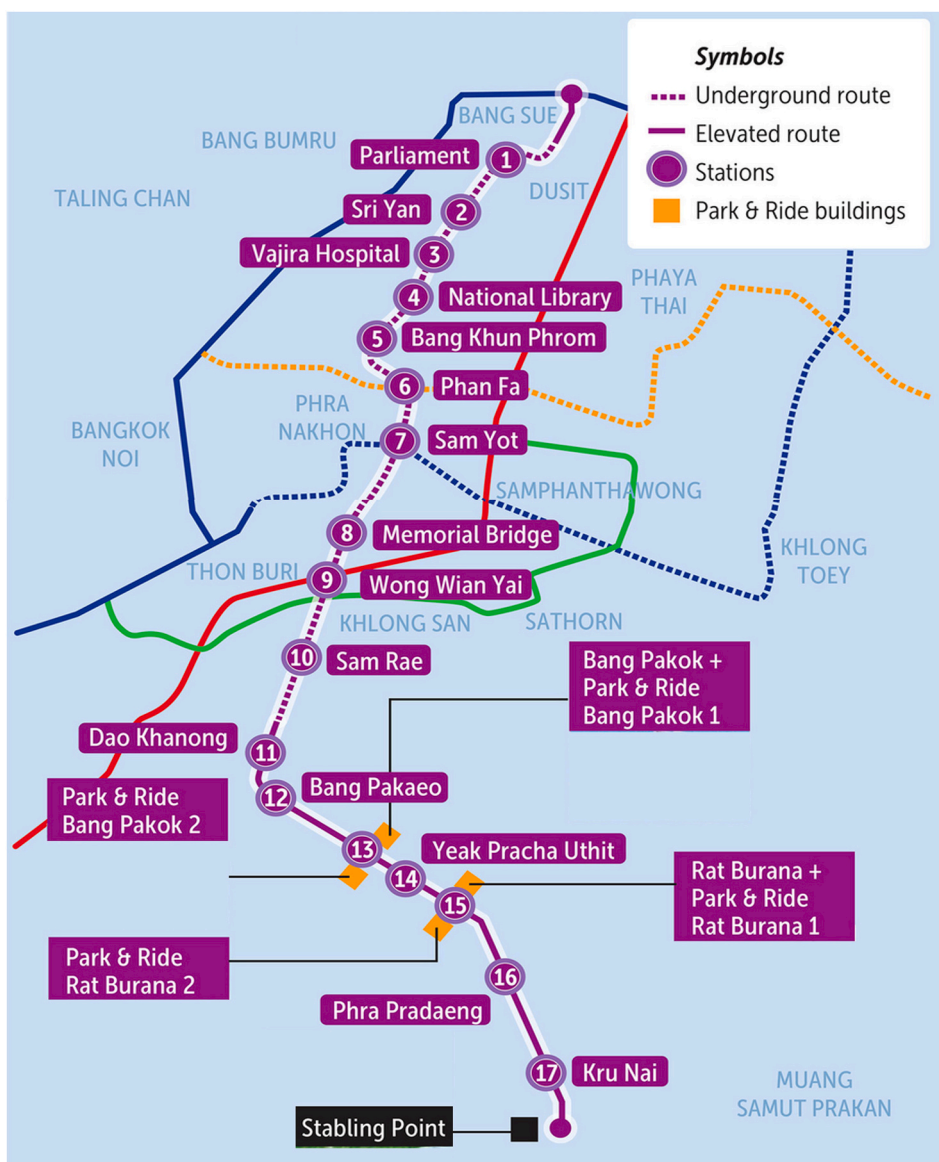


Fig. 2. Project map [40,41].

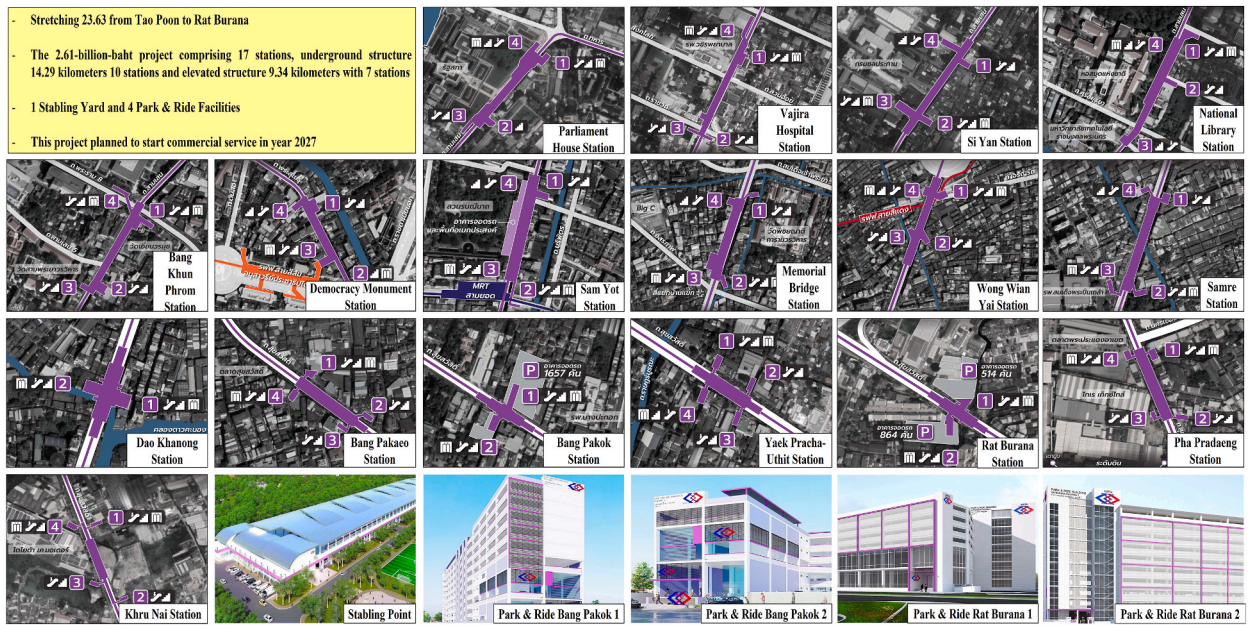


Fig. 3. Project details [40,41].

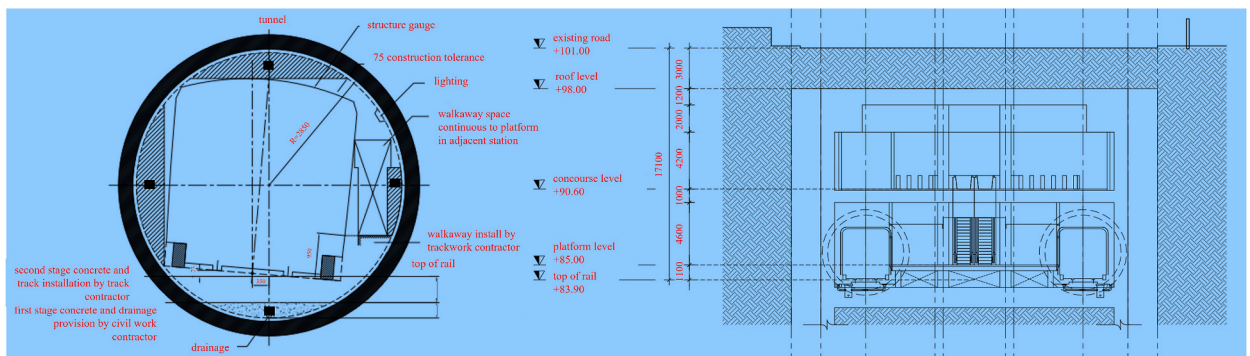


Fig. 4. Cross-section of tunnel [40,41].

Table 5
Decision-makers' qualifications.

DM	Experience (Years)	Position	Sector	Area of expertise
1	15	Associate professor	Academic	Risk analysis of tunnel construction
2	18	Professor	Academic	Geology for underground work
3	11	Assistant professor	Academic	Geotechnical engineering
4	17	Associate professor	Academic	Underground infrastructure design
5	13	Civil engineer	Private company	Tunnelling operation using TBM
6	12	Civil engineer	Private company	Tunnel construction in hard/soft rocks
7	12	Project engineer	Private company	Tunnelling operation using TBM

Serious complaints may result in legal actions to address the residents' grievances, and legal battles can be time-consuming and costly for all parties involved. Natural disasters can cause construction delays and damage tunnels and the surrounding infrastructure, requiring repairs and further delaying the construction process. An epidemic of infectious diseases can also disrupt construction activities, pose health and safety risks to workers, affect supply chains, and result in financial and scheduling challenges. Therefore, all the risk aspects were considered in this study.

The decision-makers were individually interviewed to collect the data for weight calculation. In-depth interviews that lasted an average of 1–1.5 h were conducted. Some sample questions that were asked of the DMs are as follows:

Table 6
 Descriptions of all possible risks in tunnelling construction.

Aspect	Risk	Description	References	
Geological aspect	Hardness of rock mass (A ₁)	Level of resistance exhibited by the rock mass when excavated during tunnel construction.	[14,19,42], DM ₂ , DM ₅ ,	
	Interface of different types of rock mass grades (A ₂)	A boundary or transition zone is where two or more distinct types or grades of rock masses come into contact.	[14,42], DM ₂ , DM ₅ , DM ₇	
	Rock burst (A ₃)	Sudden release of accumulated energy within the rock mass results in an ejection of rock fragments.	[12,16,43]	
	Squeezing or swelling ground (A ₄)	Surrounding rocks exhibit a tendency to deform, causing challenges during tunnel excavation	[11,12,15,19,20,42], DM ₂ , DM ₅ , DM ₇ ,	
	Large water inflow (A ₅)	Significant volumes of water enter tunnels during excavation.	[11,12,20,43], DM ₄ , DM ₅ , DM ₆	
	Fractured zone (A ₆)	Areas within rocks are disrupted by fractures and/or other types of discontinuities.	[14,19,21,42], DM ₂ , DM ₅	
	Confined aquifer (A ₇)	Groundwater-bearing geological formation is bounded above and below by layers of rock and soil.	[13,19,43], DM ₄	
	Insufficient bearing capacity of the ground (A ₈)	Soil and rock materials cannot provide sufficient support for the loads imposed by tunnel structures and the loads applied from above.	[19], DM ₂ , DM ₃ , DM ₄ , DM ₇ ,	
	A large amount of gravel and quartz in the ground (A ₉)	Small stones and mineral quartz are in the ground surrounding and beneath the tunnel excavation.	[11,14,15,20,42]	
	A large number of boulders and clays in the ground (A ₁₀)	Large-sized rocks and cohesive soil consist of fine particles within the ground surrounding and beneath the tunnel excavation.	[11,14,15,42], DM ₃ , DM ₅ , DM ₆	
	High water pressure in the ground (A ₁₁)	Elevated hydraulic pressure is caused by groundwater within the geological formation surrounding and beneath the tunnel excavation.	[14,42,43]	
	Surface subsidence (A ₁₂)	Downward movement of the ground surface is caused by tunnel excavation or ground disturbances.	[12,19,42,43], DM ₃ , DM ₇	
	Machinery aspect	Cutter abrasion (A ₁₃)	Erosive cutting tools of TBM are used to excavate tunnel faces.	[14,16,42,44], DM ₃
		Delay of cutter replacement (A ₁₄)	Scheduled replacement of cutting tools is postponed beyond the specified timeframes.	[19], DM ₃
Insufficient force and torque (A ₁₅)		Force and rotational torque exerted by machinery are inadequate.	[14,16,19,42,43], DM ₁ , DM ₃ , DM ₆	
Faulty design of the cutter head (A ₁₆)		Poor designs of configuration, structure, and components for cutter heads are used in TBMs.	[16,18,19], DM ₄	
Seal failure at the shield tail (A ₁₇)		Loss of integrity of the sealing system occurs at the rear or tail end of the TBM shield.	[13,43,44]	
Excessive cutter head torque (A ₁₈)		Rotational torque applied to the cutter heads of the TBM exceeds safe limits.	[13,43], DM ₂	
Improper face pressure (A ₁₉)		Inadequate and/or excessive pressure are exerted on the faces or front of tunnel excavations.	[13,19], DM ₃	
Use of inappropriate TBM and cutter types (A ₂₀)		TBMs and/or cutting tools are unsuitable for specific geological conditions.	[16,19,43], DM ₁	
Blockage in the conveyor belt (A ₂₁)		Materials and debris are trapped in conveyor belt systems.	[14,19,42], DM ₅ , DM ₆	
Insufficient capacity of the conveyor belt (A ₂₂)		Conveyor belt systems ineffectively handle required volumes or loads of material.	[14,43], DM ₁ , DM ₄	
Misalignment/off-route (A ₂₃)		Tunnel excavation deviates from the intended alignments.	[14,16,42]	
Technical aspect	Insufficient backfill grout (A ₂₄)	Amount of grout material used to fill the gaps behind tunnel linings is insufficient.	[13,14,19,43]	
	Uncontrollable transportation of the muck (A ₂₅)	Excavated materials are difficult to control during the transport process from tunnel excavation sites.	[14,16,19,42,43]	
	Excessive deviation from the axis (A ₂₆)	Actual tunnel alignment significantly differs from that of the desired alignments.	[13,43,44], DM ₈	
	Delay of material supply (A ₂₇)	Availability of the necessary material for construction processes is delayed beyond specific timeframes.	[12,16], DM ₅	
	Unavailability of materials (A ₂₈)	Necessary construction materials are not accessible within specific timeframes.	[12,45], DM ₂	
	Tight radius curve (A ₂₉)	Curved sections of a tunnel with a small radius are constructed in tunnel alignments.	[19], DM ₁ , DM ₃ , DM ₅ , DM ₆	
	Poor management of the amount of slurry and mucking (A ₃₀)	Controls of the slurry mixture and removal of excavated materials are inadequate.	[19,43], DM ₂ , DM ₃ , DM ₆	
	Improper excavation span (A ₃₁)	Width of tunnel excavation is not designed and executed correctly.	[44], DM ₂ , DM ₂	
	Inadequate specifications (A ₃₂)	Preparation, detailing, and documentation of specifications related to construction projects are inadequate.	[12,16], DM ₁ , DM ₃ , DM ₄	
	Human aspect	Poor workmanship (A ₃₃)	Construction workers with inadequate skills, techniques, and attentiveness are involved in construction projects.	[12], DM ₂
		Lack of experienced consultants (A ₃₄)	Highly skilled and knowledgeable experts do not work in the tunnel construction.	[12], DM ₁ , DM ₂ , DM ₆ , DM ₇
Change of key personnel (A ₃₅)		Crucial individuals in key positions within project teams are replaced.	[12]	
Lack of communication (A ₃₆)		Exchanges of information and feedback among various stakeholders are incomplete.	DM ₃ , DM ₄	

(continued on next page)

Table 6 (continued)

Aspect	Risk	Description	References
Financial aspect	Managerial inability (A ₃₇)	Managerial skills of managers and supervisors in construction projects are deficient.	[12,44]
	Inefficient labor (A ₃₈)	Workers in construction projects do not perform effectively.	[45], DM ₁ , DM ₃ , DM ₅
	Not following guidelines (A ₃₉)	Guidelines, regulations, and standards, which govern construction processes, are not adhered to by project teams.	DM ₁ , DM ₂ , DM ₆ , DM ₅
	Fluctuation (A ₄₀)	Changes in financial conditions impact project budget, cost estimates, and financial viability.	DM ₁ , DM ₄ , DM ₅
	Recession (A ₄₁)	Economic downturn negatively affects tunnel construction projects.	DM ₁ , DM ₂ , DM ₆ , DM ₇
	Inflation (A ₄₂)	Decrease in purchasing power of money results in higher costs for materials, labor, equipment, and resources.	DM ₄ , DM ₆
	Inflation of cost and price of materials (A ₄₃)	Costs of labor and construction materials increase over time.	[12]
	Inconsistent project budget (A ₄₄)	Allocated budget for tunnel construction projects is inconsistent throughout a project's lifecycle.	DM ₁ , DM ₄ , DM ₅
	Delay in the payment for ensuring contractual progress (A ₄₅)	Payment to contractors for completed work is postponed.	[12], DM ₁ , DM ₇
	Political and legal aspects	Financial difficulties of the owner (A ₄₆)	Owner encounters financial limitations to fulfill their financial obligations to tunnel construction projects.
Difficulty in cooperation with the related government (A ₄₇)		Collaboration and communication with the government are not easily conducted.	[12], DM ₄ , DM ₇
Public opposition (A ₄₈)		Objections are expressed by the general public toward the implementation of a tunnel construction project.	[12], DM ₆
Monetary or fiscal policy (A ₄₉)		Terms related to managing a country's economy impact to the overall economic environment of tunnel construction projects.	DM ₁ , DM ₃ , DM ₄ , DM ₇
Land acquisition problem (A ₅₀)		Difficulties are faced in acquiring necessary land and property rights for tunnel construction projects.	[12], DM ₂ , DM ₃
Nonconformance to occupational safety standards (A ₅₁)		Safety regulations and practices established for protecting the health and well-being of workers are ineffective.	[12,43]
Violations of laws related to underground working (A ₅₂)		Actions contravene the legal requirements designed to ensure safe operations in tunnel construction activities.	DM ₁ , DM ₃ , DM ₄ , DM ₅ , DM ₇
Protest (A ₅₃)		A way of expressing a community's causes objections to tunnel construction projects.	DM ₁ , DM ₂ , DM ₄
Coup (A ₅₄)		Interruptions of tunnel construction projects are caused by military action to overthrow the government.	DM ₁ , DM ₂ , DM ₄
Facility aspect		Instability of the power supply system (A ₅₅)	Electrical power supply to tunnel construction sites experiences disruptions and unreliable performance.
	Chipping at segments and joints (A ₅₆)	Dislodging, cracking, and stripping of concretes occur at segments and joints.	[19,43], DM ₂ , DM ₃ , DM ₄
	Improper reinforcement of the borehole (A ₅₇)	Reinforcement measures implemented in boreholes are inadequate in providing the necessary structural support.	[16,44]
	Poor ventilation (A ₅₈)	Airflow and air quality within tunnels are insufficient.	[16,21], DM ₁ , DM ₂ , DM ₃ , DM ₅ , DM ₆ , DM ₇
	Poor lighting at the workplace (A ₅₉)	Lighting conditions within tunnel construction sites are inadequate.	[21], DM ₁ , DM ₂ , DM ₃ , DM ₅ , DM ₆
	Installing improper segments (A ₆₀)	Inappropriate assembling and installing of critical segments are caused by failing to meet the necessary guidelines.	[13,19,43]
	Poor management of noise (A ₆₁)	Measures and practices implemented to control and mitigate excessive noise levels are inadequate.	[12,21]
	Water leakage at the workplace (A ₆₂)	Failures in controlling water ingress cause unwanted water entry into tunnel construction areas.	[19,42], DM ₆ , DM ₇
	Toxic gas leakage at the workplace (A ₆₃)	Unintended releases of toxic gases are caused by a failure to control and prevent the emission of harmful gases.	[11,12,20], DM ₁ , DM ₃
	Collapse of segments (A ₆₄)	Structural segments comprising roofs and overhead portions of tunnels collapse.	[18,21,42], DM ₁ , DM ₂ , DM ₃ , DM ₅ , DM ₆ , DM ₇
Other aspect	Fire in the tunnel (A ₆₅)	Fires within tunnel construction sites occur.	[16,21], DM ₂ , DM ₂
	Complaints from residents (A ₆₆)	Dissatisfactions and grievances are raised by individuals living in proximity to construction sites.	[12]
	Natural disasters (A ₆₇)	Natural forces trigger sudden and extreme events delaying the tunnel construction project.	[16], DM ₁ , DM ₄ , DM ₆
	Epidemic (A ₆₈)	A widespread contagious disease outbreak occurs within the construction site or among workers.	[16], DM ₁ , DM ₃

- What is the best criterion among all the criteria?
- Which is the best criterion compared to the other criteria?
- What is the worst criterion among all the criteria?
- Which is the worst criterion compared to the other criteria?

The best and worst criteria were determined as shown in Table 7. For example, DM₁ judged that the best and worst criteria are

respectively C_2 and C_5 .

Next, the decision-makers separately compared the best criterion to the other criteria and the remaining ones against the worst criterion using importance scales. The vectors of best-to-others and others-to-worst are shown in Table 8. Some sample questions for comparing the criteria pair were asked of DM_1 in the interview. These questions are as follows:

- How important is the best criterion of “increase in cost” (C_2) when it is compared with “decrease in quality of working” (C_5)?
- What is the importance of “increase in cost” (C_2) over the worst criterion of “resource loss” (C_4)?
- What scores do you assign for comparing “increase in cost” (C_2) and “late delivery of project” (C_3) on a rating of 1–9 scale?

For example, the best-to-other and other-to-worst vectors obtained from DM_1 were defined as follows $A_{BO1} = \{2, 1, 3, 2, 4\}$ and $A_{OW1} = \{3, 4, 2, 2, 1\}$.

Min ξ^L .

Subject to

$$|w_{21}-2w_{11}| \leq \xi^L \quad |w_{21}-3w_{31}| \leq \xi^L$$

$$|w_{21}-2w_{41}| \leq \xi^L \quad |w_{21}-4w_{51}| \leq \xi^L$$

$$|w_{11}-3w_{51}| \leq \xi^L \quad |w_{31}-2w_{51}| \leq \xi^L$$

$$|w_{41}-2w_{51}| \leq \xi^L$$

$$w_{11}+w_{21}+w_{31}+w_{41}+w_{51} = 1$$

$$w_{11}, w_{21}, w_{31}, w_{41}, w_{51} \geq 0$$

Subsequently, the weights of the criteria and the consistency ratios were calculated as presented in Table 9. For example, the weights and consistency value obtained from DM_1 were measured as follows: $w_{11} = 0.205$, $w_{21} = 0.370$, $w_{31} = 0.137$, $w_{41} = 0.205$, $w_{51} = 0.083$, and $CR = 0.041$. The results showed that the decision-makers’ judgments were consistent owing to all the values of the consistency ratio being close to zero.

Using Eq. (3), the average weights with respect to every criterion were computed as follows: $w_1 = 0.232$, $w_2 = 0.239$, $w_3 = 0.211$, $w_4 = 0.173$, and $w_5 = 0.145$. For example, the weight of C_1 was calculated as follows:

$$w_1 = \frac{0.205 + 0.424 + \dots + 0.188}{7} = 0.232$$

The risks must be evaluated after obtaining the weights of the criteria. This necessitates the development of details for each risk assessment grade with respect to the criteria. Herein, the assessment grades for evaluating the risks under the “probability” (C_1) were defined by adapting the probability grades of Gokler et al. [10], Moradi and Farsangi [11], Degn Eskesen et al. [46], and Benekos and Diamantidis [47], as follows: “*Improbable*” (I), “*Remote*” (R), “*Occasional*” (O), “*Probable*” (P), and “*Frequent*” (F), where the “I” and “F” denote the smallest and highest possible values. The assessment grades for evaluating the risks under the remaining criteria (C_2 , C_3 , C_4 , and C_5) were defined by adapting the consequence grades of Chung et al. [42], Hyun et al. [19], and Kumar Agrawal et al. [48], as follows: “*Very Low*” (VL), “*Low*” (L), “*Moderate*” (M), “*High*” (H), and “*Very High*” (VH). The grades of C_2 – C_5 are similar because the criteria consider the impact of the risks. Different descriptions were defined based on the characteristics of the criteria. The risks affecting the criteria less than or equal to 4%, 8%, 12%, and 16% of their properties were considered into VL, L, M, and H; however, they are categorized into VH if the risks affect more than 16%. The descriptions of each grade are listed in Tables 10–14.

We conducted in-depth interviews for 2–4 h to collect the data regarding the assessment grades. The following sample questions were asked of the DMs to evaluate the risks against the criteria:

- What is the risk assessment grade of “probability” (C_1) for evaluating “hardness of rock mass” (A_1)?
- What effect does the assessment grade of “fractured zone” (A_6) have on “resource loss” (C_4)?
- How does the risk assessment level on “abrasion of the cutter” (A_{13}) affect “late delivery of the project” (C_3)?

The decision-makers provided their own judgments of the risks under each criterion as shown in Supplementary Material Table S1. For example, considering A_1 under C_1 , two decision-makers assigned “P,” three decision-makers assigned “O,” and other two decision-makers designated “R.” The DEA models were formulated to estimate the values of the parameter solution based on the assessment

Table 7
Best and worst criteria.

	DM_1	DM_2	DM_3	DM_4	DM_5	DM_6	DM_7
Best	C_2	C_1	C_2	C_3	C_3	C_1	C_2
Worst	C_5	C_4	C_3	C_2	C_1	C_5	C_3

Table 8
Best-to-other and other-to-worst vectors.

	Best-to-others					Others-to-worst				
DM ₁	<i>a</i> ₂₁₁ 2	<i>a</i> ₂₂₁ 1	<i>a</i> ₂₃₁ 3	<i>a</i> ₂₄₁ 2	<i>a</i> ₂₅₁ 4	<i>a</i> ₁₅₁ 3	<i>a</i> ₂₅₁ 4	<i>a</i> ₃₅₁ 2	<i>a</i> ₄₅₁ 2	<i>a</i> ₅₅₁ 1
DM ₂	<i>a</i> ₁₁₂ 1	<i>a</i> ₁₁₂ 3	<i>a</i> ₁₁₂ 2	<i>a</i> ₁₁₂ 6	<i>a</i> ₁₁₂ 3	<i>a</i> ₁₄₂ 6	<i>a</i> ₂₄₂ 2	<i>a</i> ₃₄₂ 2	<i>a</i> ₄₄₂ 1	<i>a</i> ₅₄₂ 4
DM ₃	<i>a</i> ₂₁₃ 2	<i>a</i> ₂₂₃ 1	<i>a</i> ₂₃₃ 3	<i>a</i> ₂₄₃ 2	<i>a</i> ₂₅₃ 2	<i>a</i> ₁₃₃ 1	<i>a</i> ₂₃₃ 3	<i>a</i> ₃₃₃ 1	<i>a</i> ₄₃₃ 2	<i>a</i> ₅₃₃ 1
DM ₄	<i>a</i> ₃₁₄ 2	<i>a</i> ₃₂₄ 3	<i>a</i> ₃₃₄ 1	<i>a</i> ₃₄₄ 2	<i>a</i> ₃₅₄ 2	<i>a</i> ₁₂₄ 2	<i>a</i> ₂₂₄ 1	<i>a</i> ₃₂₄ 3	<i>a</i> ₄₂₄ 2	<i>a</i> ₅₂₄ 3
DM ₅	<i>a</i> ₃₁₅ 7	<i>a</i> ₃₂₅ 2	<i>a</i> ₃₃₅ 1	<i>a</i> ₃₄₅ 2	<i>a</i> ₃₅₅ 2	<i>a</i> ₁₁₅ 1	<i>a</i> ₂₁₅ 2	<i>a</i> ₃₁₅ 7	<i>a</i> ₄₁₅ 3	<i>a</i> ₅₁₅ 2
DM ₆	<i>a</i> ₁₁₆ 1	<i>a</i> ₁₂₆ 3	<i>a</i> ₁₃₆ 2	<i>a</i> ₁₄₆ 3	<i>a</i> ₁₅₆ 6	<i>a</i> ₁₅₆ 6	<i>a</i> ₂₅₆ 3	<i>a</i> ₃₅₆ 3	<i>a</i> ₄₅₆ 3	<i>a</i> ₅₅₆ 1
DM ₇	<i>a</i> ₂₁₇ 2	<i>a</i> ₂₂₇ 1	<i>a</i> ₂₃₇ 5	<i>a</i> ₂₄₇ 2	<i>a</i> ₂₅₇ 3	<i>a</i> ₁₃₇ 2	<i>a</i> ₂₃₇ 5	<i>a</i> ₃₃₇ 1	<i>a</i> ₄₃₇ 2	<i>a</i> ₅₃₇ 2

Next, the linear models of BWM concept were mathematically conducted. For example, the linear model based on the judgments of DM₁ was formulated as follows:

Table 9
Weights of criteria and consistency ratio.

	<i>w</i> _{1d}	<i>w</i> _{2d}	<i>w</i> _{3d}	<i>w</i> _{4d}	<i>w</i> _{5d}	CR
DM ₁	0.205	0.370	0.137	0.205	0.083	0.041
DM ₂	0.424	0.165	0.188	0.058	0.165	0.071
DM ₃	0.133	0.333	0.134	0.200	0.200	0.067
DM ₄	0.196	0.087	0.326	0.195	0.196	0.065
DM ₅	0.062	0.169	0.385	0.215	0.169	0.046
DM ₆	0.413	0.150	0.225	0.150	0.062	0.038
DM ₇	0.188	0.400	0.082	0.188	0.142	0.024

Table 10
Assessment grade for evaluating “probability” (*C*₁) [10,11,46,47].

Grade	Definition
Improbable (I)	Risk almost never occurs.
Remote (R)	Risk seldom occurs.
Occasional (O)	Risk sometimes occurs.
Probable (P)	Risk frequently occurs.
Frequent (F)	Risk certain or almost certain to occur.

Table 11
Assessment grade for evaluating “increase in cost” (*C*₂) [19,42,48].

Grade	Definition
Very Low (VL)	Risk increases the additional cost by 4 % or lower.
Low (L)	Risk increases the additional cost by 8 %.
Moderate (M)	Risk increases the additional cost by 12 %.
High (H)	Risk increases the additional cost by 16 %.
Very High (VH)	Risk increases the additional cost by more than 16 %.

Table 12
Assessment grade for evaluating “late delivery of project” (*C*₃) [19,42,48].

Grade	Definition
Very Low (VL)	Risk increases project delivery time by 4 % or lower.
Low (L)	Risk increases project delivery time by 8 %.
Moderate (M)	Risk increases project delivery time by 12 %.
High (H)	Risk increases project delivery time by 16 %.
Very High (VH)	Risk increases project delivery time by more than 16 %.

Table 13
Assessment grade for evaluating “resource loss” (C₄) [19,42,48].

Grade	Definition
Very Low (VL)	Risk decreases resources by 4 % or lower
Low (L)	Risk decreases resources by 8 %.
Moderate (M)	Risk decreases resources by 12 %.
High (H)	Risk decreases resources by 16 %.
Very High (VH)	Risk decreases resources by more than 16 %.

Table 14
Assessment grade for evaluating “decrease in quality of working” (C₅) [11,16,46].

Grade	Definition
Very Low (VL)	Risk has a negligible impact on the quality of work and can be ignored
Low (L)	Risk is insignificant and can be handled by routine processes.
Moderate (M)	Risk is significant but can be handled by additional controls and/or mitigations.
High (H)	Risk is severe and requires immediate attention and action.
Very High (VH)	Risks are intense and must be addressed before working.

grades of several decision-makers for each criterion. For example, the parameter values of C₁ are shown in [Supplementary Material Table S2](#). We found that the optimal decision variables of C₁ were S*(VH₁₁) = 0.214, S*(H₁₂) = 0.107, S*(M₁₃) = 0.071, S*(L₁₄) = 0.054, and S*(VL₁₅) = 0.043 because these variables generated the lowest α value of 0.300. The same method was used to find the optimal decision variables of the other criteria, which are presented in [Table 15](#).

The local risk scores, which were obtained by multiplying the optimal decision variables, criteria weights, and the number of decision-makers in each assessment grade, were ranked in descending order to determine the ranking of the risks. The local risk scores are shown in [Table 16](#). The following example shows how to calculate the local risk score of A₁ using the sum-product of the number of decision-makers in each grade with respect to every criterion and the associated optimal decision variables, multiplied by the associated weights.

$$x_1 = (((0.214)(0) + (0.107)(2) + (0.071)(3) + (0.054)(2) + (0.043)(0)) \times 0.232) + (((0.231)(0) + (0.115)(0) + (0.077)(0) + (0.058)(6) + (0.046)(1)) \times 0.239) + (((0.259)(1) + (0.129)(0) + (0.086)(0) + (0.065)(4) + (0.052)(2)) \times 0.211) + (((0.283)(0) + (0.142)(0) + (0.094)(3) + (0.071)(3) + (0.057)(1)) \times 0.173) + (((0.238)(0) + (0.119)(0) + (0.079)(4) + (0.060)(1) + (0.048)(2)) \times 0.145) = 0.513$$

[Table 16](#) shows that the most important risk of underground tunnel construction with TBM is “Installing improper segments” (A₆₀), which exhibits the highest risk score. The risk ranking is written as follows: A₆₀ > A₆₄ > A₆ > A₅₃ > A₄₈ > A₁₄ > A₁₅ > A₄₁ > A₂₉ > A₄ > A₅₂ > A₁₉ > A₄₇ > A₁₁ > A₃₅ > A₁₃ > A₈ > A₃₈ > A₄₃ > A₆₁ > A₁₀ > A₁₈ > A₃₉ > A₃₆ > A₃₂ > A₆₆ > A₅ > A₂₀ > A₂ > A₆₃ > A₃₄ > A₃₇ > A₂₄ > A₅₇ > A₆₈ > A₁₇ > A₁₆ > A₃ > A₅₄ > A₂₆ > A₅₅ > A₃₃ > A₅₀ > A₄₉ > A₂₃ > A₅₁ > A₆₇ > A₃₁ > A₉ > A₁₂ > A₂₂ > A₆₂ > A₂₁ > A₄₀ > A₅₉ > A₅₆ > A₂₇ > A₁ > A₇ > A₄₆ > A₂₈ > A₄₄ > A₄₅ > A₅₈ > A₂₅ > A₆₅ > A₃₀ > A₄₂.

5. Discussion

Based on the application results, we conclude that the integration of the MCDM approach and the risk assessment method effectively analyzes and prioritizes the risks of underground tunnel constructions with TBMs. The proposed approach facilitates decision-makers in expressing their preferences for criteria weights based on comparisons of the best and worst criteria against the others. The decision-makers can evaluate the probabilities of risk occurrence and the consequences of the risks regarding cost increase, project delay, resource depletion, and work quality. All these decision-making data were used to calculate the local scores, which prioritized risks from the riskiest to the least risky. The proposed approach not only produces an effective ranking of risks when dealing with multiple criteria and contradictory data but also provides the best compromise solution to identify the most important risk.

However, the risk ranking can change if one of the decision-making attributes varies. Therefore, it is necessary to verify the performance of the proposed approach. A sensitivity analysis based on the changes in the criteria weights was performed to monitor the validity and robustness of the ranking. The adjusted weights, which potentially reveal the judgments of the interviewed decision-makers, represent specific scenarios. The new weights reflect the judgments of the situations that are most relevant to the decision-

Table 15
Optimal decision variable and parameter value of criteria.

	S*(VH ₁₁)	S*(H ₁₂)	S*(M ₁₃)	S*(L ₁₄)	S*(VL ₁₅)	α
C ₁	0.214	0.107	0.071	0.054	0.043	0.300
C ₂	0.231	0.115	0.077	0.058	0.046	0.377
C ₃	0.259	0.129	0.086	0.065	0.052	0.375
C ₄	0.283	0.142	0.094	0.071	0.057	0.396
C ₅	0.238	0.119	0.079	0.060	0.048	0.333

Table 16
Local risk score and rank.

	x_i	Rank	x_i	Rank	x_i	Rank	x_i	Rank
A ₁	0.513	58	A ₁₈	0.591	22	A ₃₅	0.623	15
A ₂	0.583	29	A ₁₉	0.640	12	A ₃₆	0.590	24
A ₃	0.568	38	A ₂₀	0.587	28	A ₃₇	0.578	32
A ₄	0.649	10	A ₂₁	0.529	53	A ₃₈	0.601	18
A ₅	0.588	27	A ₂₂	0.531	51	A ₃₉	0.590	23
A ₆	0.672	3	A ₂₃	0.553	45	A ₄₀	0.529	54
A ₇	0.510	59	A ₂₄	0.575	33	A ₄₁	0.661	8
A ₈	0.606	17	A ₂₅	0.465	65	A ₄₂	0.433	68
A ₉	0.541	49	A ₂₆	0.568	40	A ₄₃	0.597	19
A ₁₀	0.592	21	A ₂₇	0.525	57	A ₄₄	0.484	62
A ₁₁	0.630	14	A ₂₈	0.493	61	A ₄₅	0.476	63
A ₁₂	0.535	50	A ₂₉	0.658	9	A ₄₆	0.503	60
A ₁₃	0.607	16	A ₃₀	0.462	67	A ₄₇	0.635	13
A ₁₄	0.663	6	A ₃₁	0.541	48	A ₄₈	0.668	5
A ₁₅	0.662	7	A ₃₂	0.590	25	A ₄₉	0.553	44
A ₁₆	0.571	37	A ₃₃	0.561	42	A ₅₀	0.559	43
A ₁₇	0.572	36	A ₃₄	0.579	31	A ₅₁	0.550	46
						A ₅₂	0.648	11
						A ₅₃	0.671	4
						A ₅₄	0.568	39
						A ₅₅	0.565	41
						A ₅₆	0.526	56
						A ₅₇	0.574	34
						A ₅₈	0.474	64
						A ₅₉	0.528	55
						A ₆₀	0.803	1
						A ₆₁	0.592	20
						A ₆₂	0.530	52
						A ₆₃	0.580	30
						A ₆₄	0.718	2
						A ₆₅	0.462	66
						A ₆₆	0.588	26
						A ₆₇	0.545	47
						A ₆₈	0.573	35

making process. By focusing on certain weights, decision-makers indicate where they believe resources should be directed. In this regard, the weight of C_2 was varied from 0.100 to 0.900 in increments of 0.100 because it had the highest weight and represented the input parameter with the largest influence on the output of the proposed approach. Meanwhile the other criteria weights were changed in optimal proportions as shown in Eq. (6) [49]:

$$w'_j = \frac{1 - w'_p}{1 - w_p} \times w_j \tag{6}$$

where w'_j is the new weight of criterion j ; w'_p denotes the new weight of criterion p ; w_p identifies the original weight of criterion p ; and p is the most important criterion in the “Normal” experiment.

Hence, nine experiments were conducted to verify the change in ranking based on the new weights as shown in Table 17. For example, in the experiment 1, the weight of the most important criterion ($w_2 = 0.239$) was changed into $w'_2 = 0.100$, whereas the new weights of the remaining criteria were calculated as follows:

$$w'_1 = \frac{1 - 0.100}{1 - 0.239} \times 0.232 = 0.274,$$

$$w'_3 = \frac{1 - 0.100}{1 - 0.239} \times 0.211 = 0.250,$$

$$w'_4 = \frac{1 - 0.100}{1 - 0.239} \times 0.173 = 0.205,$$

$$w'_5 = \frac{1 - 0.100}{1 - 0.239} \times 0.145 = 0.172.$$

For experiments 2 to 9, the new weight of the most important criterion ranged between 0.200 and 0.900, which were varied in increments of 0.1000. The same procedures were applied to calculate the new weights as shown in Table 17, where the weights under the “Normal” experiment were calculated by the BWM.

The new ranks of each risk were identified as shown in Supplementary Material Table S3 and Fig. 5. The sensitivity analysis results demonstrated that “Installing improper segments” (A_{60}) retained the highest local risk score in 6/10 experiments, with few interchanges of the other ranks. When the weight of the most important criterion increases between 0.600 and 0.800, the “Tight radius

Table 17
New weights of each experiment.

	Experiment									
	1	2	Normal	3	4	5	6	7	8	9
w_1	0.274	0.243	0.232	0.213	0.183	0.152	0.122	0.091	0.061	0.030
w_2	0.100	0.200	0.239	0.300	0.400	0.500	0.600	0.700	0.800	0.900
w_3	0.250	0.222	0.211	0.194	0.166	0.139	0.111	0.083	0.055	0.028
w_4	0.205	0.182	0.173	0.159	0.136	0.114	0.091	0.068	0.045	0.023
w_5	0.172	0.153	0.145	0.134	0.115	0.095	0.076	0.057	0.038	0.019

curve" (A_{29}) moved to the first place. In the last experiment, if the weight of C_2 equals 0.900, "A large number of boulders and clays in the ground" (A_{10}) took the first position in the ranking, with slight changes in other ranks. Furthermore, "Inflation" (A_{42}) and "Inconsistent project budget" (A_{44}) mostly occupied either the last or second last rank.

Based on the above findings, we conclude that the proposed approach provides reasonable robustness of risk ranking and further proposes a novel risk priority model when facing multiple risk events. Moreover, it effectively responds to decision-makers' preferences and appraisals of risk scores. Apparently, the ranks of the risks were altered based on the changes in weights; risks with scores in the criteria with high priorities were prioritized as top-ranked positions.

Although the sensitivity analysis provided numerous ranking results under different scenarios, the highest risk was determined based on real criteria data. Herein, a scenario using the real weight data obtained from the BWM was interpreted, and "Installing improper segments" (A_{60}) was determined to be the riskiest event in this case. To prevent the most important risk from occurring, we consulted with the authorities and project managers to design the risk management process and its various steps as follows:

- 1) Ensure that the design and engineering of the tunnel and its key segments are thoroughly reviewed and approved by qualified professionals.
- 2) Develop standardized assembly procedures specifically tailored to the key segments involved in the project. These procedures should outline the correct sequence, techniques, and tools required for the assembly.
- 3) Employ skilled and experienced personnel who have the necessary expertise in tunnel construction and segment assembly.
- 4) Establish a robust quality assurance and control program to ensure that each assembly meets the required standards.
- 5) If key segments are sourced from external suppliers, a stringent supplier management process must be established. Evaluate the potential suppliers based on their track record, reputation, quality control systems, and adherence to industry standards.
- 6) Maintain comprehensive documentation throughout the project, including detailed assembly instructions, technical specifications, and quality control records.
- 7) Encourage meetings, site visits, and collaborative problem-solving sessions to address any concerns or potential issues related to segment assembly.
- 8) Continuously monitor the project for potential risks related to segment assembly. Implement proactive risk management techniques, and promptly address any emerging issues to prevent the installation of improper assemblies.
- 9) Establish a process to capture and apply the lessons learned from previous projects and incorporate them into future endeavors. Encourage project teams to share their experiences, and identify the best practices in assembly processes and procedures.

By adopting these risk management processes, project managers can minimize the likelihood of installing improper assemblies of key segments in tunnel construction projects, thereby promoting successful and safe project execution.

For comparative analysis, the sum-method of the risk assessment grade with the same datasets was used to indicate the benefits of the proposed approach, as presented in Eq. (7):

$$x_{(c)i} = \sum_{j=1}^m \sum_{k_j=1}^{K_j} H_{jk_j} \tag{7}$$

where $x_{(c)i}$ denote the risk score of risk i calculated by the compared method; H_{jk_j} of the risk assessment grade of criterion j under grade k is replaced by crisp risk levels as follows: "Improbable" and "Very Low" = 1, "Remote" and "Low" = 2, "Occasional" and "Moderate" = 3,

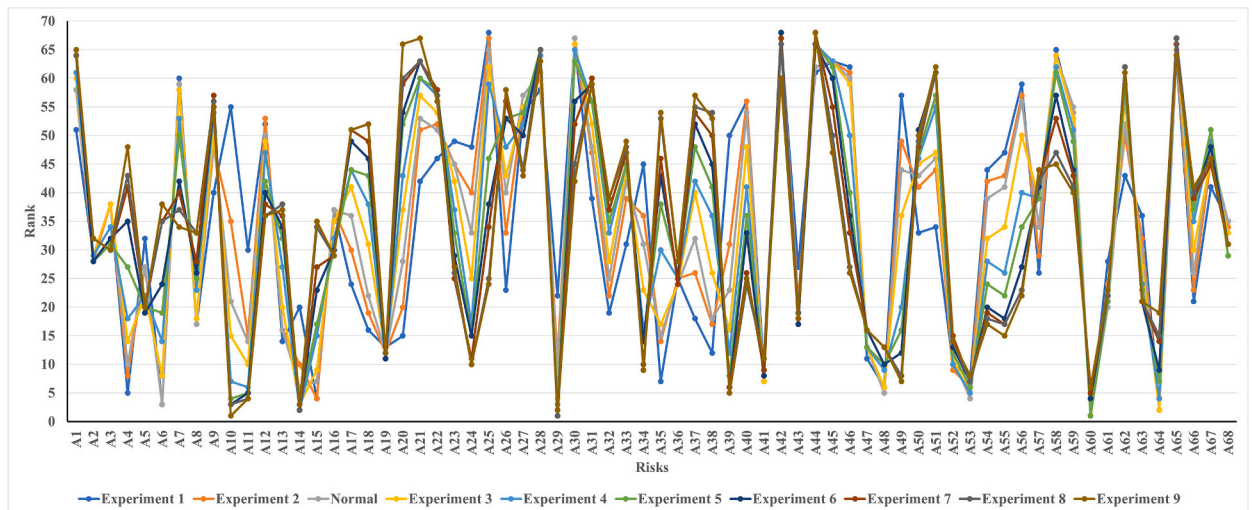


Fig. 5. Sensitivity analysis results.

“Probable” and “High” = 4, and “Frequent” and “Very High” = 5. The maximum and minimum risk scores of the compared method in this case were 175 and 35, respectively. The risk scores of the compared method were calculated based on the data in Table S1 and compared with the original scores, as shown in Table 18. For example, the calculation of the risk score of A_1 was conducted as follows:

$$x_{(c)1} = (4 + 4 + 3 + 3 + 3 + 2 + 2) + (2 + 2 + 2 + 2 + 2 + 2 + 1) + (5 + 2 + 2 + 2 + 2 + 1 + 1) + (3 + 3 + 3 + 2 + 2 + 2 + 1) + (3 + 3 + 3 + 3 + 2 + 1 + 1) = 81.$$

The most important risk did not change, but the other risks in the ranking changed significantly. The ranks of the compared method ranged between 1 and 37 because some risks had the same order. However, these results are unclear and inappropriate for real-life scenarios. With equal local risk scores, the decision-makers were unaware of which risks are more important; this presented a major difficulty in interpreting the results. Comparing the local risk scores and the risk scores, the results of the proposed approach are more precise and can prioritize all the risks with continuous scores, whereas the other method can rank some risks (26.47 % of all available attributes). The comparison results indicate that the proposed approach produces more reasonable and exact results than the other method.

The sensitivity and comparative analyses confirmed that our proposed methodology is consistent with the preferences and risk degrees of the decision-makers. Therefore, the proposed approach has many advantages: 1) providing continuous results to prioritize risks; 2) saving research time with fewer computation data for weight calculation, reducing to $2m - 3$ from $m(m - 1)/2$, where m is the set of criteria; 3) comprehensive evaluation of probabilities of risk occurrences and all dimensions of risk consequences; 4) reasonable analysis of risk scores based on conflicting data; and 5) ease-of-use as a tool for ranking the risk of underground tunnel construction. Project managers and stakeholders can use these findings to design risk policies and control plans. They can determine the risk tolerance for the corporate goal level, conduct a detailed analysis of areas of special interest, create diagrams showing risk profiles for monitoring performance reports according to the corporate plan, determine risk clauses, design risk assessment methods, and many others. Moreover, these guidelines can be used to detect incompatibilities in different dimensions of operations. The major benefit of the ranking results is the risk of requiring more attention and/or detailed response plans. This includes determining how to mitigate risk and ensuring that each risk is covered by appropriate mitigating responses.

6. Conclusion

Large-scale projects, particularly metro tunneling construction, are unique and involve various risks, including hazards, accidents, and uncertainties throughout the processes of planning, design, construction, and operation. These numerous risks, which have different properties, directly cause additional costs, delays in project delivery, and negative impacts on every aspect of project execution. Therefore, it is necessary to understand the most important risks and determine whether the impacts of the identified risks are acceptable. This study proposes a novel BWM-DEA methodology to analyze and prioritize the risks of mechanized underground tunnel construction. The proposed approach consists of the weight determination-based BWM and the DEA risk calculation model. Finally, the proposed methodology was validated by a metro construction in Bangkok, Thailand.

This study provides theoretical and practical implications for academic areas and the management of metro construction projects and develops a new methodology for integrating risk analysis and MCDM approaches. The proposed BWM-DEA approach is effective in analyzing the uncertainties of underground tunnel constructions with TBMs. This study demonstrates that both methods can effectively determine the best solution for risk ranking. Decision-makers can utilize the obtained results to comprehensively decide the most critical risk that must be eliminated first. Moreover, they can develop remedies to mitigate the risk impacts as much as possible. This implies that government agencies and project teams can design risk management and internal control manuals that identify and assess the potential risks that may affect project objectives. These are proactive actions rather than reactive operations and offer strategies to reduce the possibility of adverse events and their possible severities in the progress of metro construction projects. For example, the following questions must be answered: “How do we manage to reduce the likelihood of insufficient segment wall thickness, poor installation of the lining ring, poor location of the gasket groove axis, and extremely short ring segment diameter?” and “If the installations of improper assemblies of key segments still occur, how do project decision-makers prepare for potential impacts of losing resources, increasing hidden costs, and scheduled delays.”

However, the application of the proposed approach may be difficult for experienced/inexperienced individuals who are not knowledgeable in using the proposed approach to repeat the research or reproduce the results. As a guide, the following workflows can aid decision-makers in implementing the approach in real-world settings: 1) determine the criteria, 2) construct the importance vectors, 3) calculate the weights of the criteria using the BWM, 4) check for consistency, 5) calculate the average of the weight values, 6) determine all related risks, 7) define assessment grades, 8) create a distribution decision matrix, 9) formulate the DEA model, and 10) compute the local risk scores and rank them in descending order. Decision makers must check and consider the potential limitations and challenges of implementing the proposed methodology (e.g., tunnel alignment and profile, construction constraints, and types of TBM) that cannot be found in other common tunnel construction projects. These specific requirements must be included in the proposed approach. Furthermore, if the projects have different risk data, the details of the assessment grade must be improved according to the realistic data.

Although the proposed approach has numerous benefits, it also has some limitations: 1) interrelated relationships and interactions between criteria and risks for calculating the weight were not considered; 2) levels of tolerances were ignored in making importance judgments and risk assessments; and 3) the proposed approach can only operate with nonbeneficial criteria. These disadvantages suggest possibilities for future work. Two new weight calculation-based comparison vectors that can analyze the interdependences and relationships of decision-making attributes must be developed to calculate more rational criteria weights. Fuzzy logic can enhance the algorithms of the proposed method by providing flexible and objective evaluations, such as the fuzzy BWM of weight determination

Table 18
Comparison of local risk score and risk score.

	x_i	Rank	$x_{(c)i}$	Rank		x_i	Rank	$x_{(c)i}$	Rank
A ₁	0.513	58	81	27	A ₃₅	0.623	15	98	11
A ₂	0.583	29	90	18	A ₃₆	0.590	24	86	22
A ₃	0.568	38	92	16	A ₃₇	0.578	32	87	21
A ₄	0.649	10	104	6	A ₃₈	0.601	18	96	12
A ₅	0.588	27	90	18	A ₃₉	0.590	23	88	20
A ₆	0.672	3	107	4	A ₄₀	0.529	54	75	32
A ₇	0.510	59	76	31	A ₄₁	0.661	8	108	3
A ₈	0.606	17	101	8	A ₄₂	0.433	68	63	37
A ₉	0.541	49	79	29	A ₄₃	0.597	19	101	8
A ₁₀	0.592	21	81	27	A ₄₄	0.484	62	76	31
A ₁₁	0.630	14	90	18	A ₄₅	0.476	63	77	30
A ₁₂	0.535	50	84	24	A ₄₆	0.503	60	75	32
A ₁₃	0.607	16	104	6	A ₄₇	0.635	13	96	12
A ₁₄	0.663	6	94	14	A ₄₈	0.668	5	109	2
A ₁₅	0.662	7	101	8	A ₄₉	0.553	44	84	24
A ₁₆	0.571	37	85	23	A ₅₀	0.559	43	84	24
A ₁₇	0.572	36	83	25	A ₅₁	0.550	46	85	23
A ₁₈	0.591	22	93	15	A ₅₂	0.648	11	99	10
A ₁₉	0.640	12	95	13	A ₅₃	0.671	4	101	8
A ₂₀	0.587	28	100	9	A ₅₄	0.568	39	90	18
A ₂₁	0.529	53	83	25	A ₅₅	0.565	41	83	25
A ₂₂	0.531	51	75	32	A ₅₆	0.526	56	75	32
A ₂₃	0.553	45	89	19	A ₅₇	0.574	34	94	14
A ₂₄	0.575	33	89	19	A ₅₈	0.474	64	73	34
A ₂₅	0.465	65	65	36	A ₅₉	0.528	55	81	27
A ₂₆	0.568	40	80	28	A ₆₀	0.803	1	112	1
A ₂₇	0.525	57	82	26	A ₆₁	0.592	20	88	20
A ₂₈	0.493	61	80	28	A ₆₂	0.530	52	85	23
A ₂₉	0.658	9	102	7	A ₆₃	0.580	30	91	17
A ₃₀	0.462	67	69	35	A ₆₄	0.718	2	106	5
A ₃₁	0.541	48	85	23	A ₆₅	0.462	66	74	33
A ₃₂	0.590	25	95	13	A ₆₆	0.588	26	93	15
A ₃₃	0.561	42	96	12	A ₆₇	0.545	47	86	22
A ₃₄	0.579	31	82	26	A ₆₈	0.573	35	91	17

and fuzzy DEA of risk calculation with numerous benefit and nonbenefit criteria. The proposed approach can be enhanced to become a user-friendly decision support system using Python and/or R programming. Another direction is to use the proposed approach to analyze the risks of other underground works such as passageways, drainage systems, and pipeline constructions.

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Data availability statement

Data will be made available on request.

CRedit authorship contribution statement

Nitidetch Koohathongsumrit: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Validation, Visualization, Writing - original draft, Writing - review & editing, Software. **Warapoj Meethom:** Supervision, Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

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