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Evaluation of Procurement of Environment Monitoring Equipment for Tunnel Construction

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Railway and highway traffic projects inevitably require a large number of tunnels to pass through hills or mountains due to the complex topographic conditions. Accordingly, tunnel construction increases in proportion, scale, and number and becomes increasingly important. In this study, we reviewed the key factors of the monitoring system for the working environment in tunnel construction. The evaluation criteria for the procurement of environment monitoring equipment for tunnel construction were established and summarized on the basis of engineering cases and a literature review. Then, an evaluation scale to assess the weights of key factors was established through the Analytic Hierarchy Process (AHP), which includes four evaluation dimensions, 13 sub-level evaluation criteria, and their weights. Finally, three suppliers of construction environment monitoring equipment were selected for empirical analysis. The research results verified the effectiveness of the evaluation scale, which can provide a systematic evaluation mode for government engineering units to select the environment monitoring equipment for future construction.

1. Introduction

Owing to complex topographic conditions in mountainous areas with little flat land, major construction projects including railways, roads, pipelines, and hydraulic engineering projects inevitably require a large number of tunnels through hilly or mountainous areas, leading to the increasing proportion, scale, number, and importance of tunnels. Despite the continuous improvement of tunnel construction techniques, machinery, and equipment, stricter geological and hydrological surveys, and more complete safety and feasibility evaluation before excavation, construction disasters and accidents still occur frequently owing to complex geological structures, uncertain construction risk factors, and multiple disaster-induced potentials, which can even cause heavy casualties for on-site construction personnel.

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Compared with other industries, safety health management, personnel safety, safe work habits, and operating safety protection are particularly complex for personnel involved in tunnel construction. Therefore, more uncontrollable factors are involved in the compliance of tunnel construction personnel with safety regulations. Meanwhile, tunnel construction also has specific features, such as various types of engineering works, frequent changes of operating personnel, a poor operating environment, unstable operating sites, climatic factors, geometric and environmental factors, and the variation of hazards as a project progresses. In past research, there have been much discussion on landslides,(1) fires,(2) and floods(3) in construction projects but less discussion on the monitoring of harmful gases in tunnels during their construction. Therefore, it is especially important to choose a qualified supplier of systems for sensing hazardous gases.

Because of poor management, a multilayer contract system, and low-price bidding, it is difficult to implement health and safety policies in the construction industry; therefore, the incidence of major occupational accidents in the construction industry has remained high. In addition, workers in the construction industry need to move constantly during the operation, while the construction equipment and facilities are mostly temporary structures. Unsafe factors at the worksite or the negligence of equipment and personnel can lead to safety accidents or disasters, which not only delay the engineering schedule and cause financial loss but also have psychological and financial impacts on the families of victims.(4)

Government agencies consider many factors including product quality, contact implementation ability, and customer complaint management when selecting suppliers, but decision-makers and contractors have no accurate criteria for selecting appropriate suppliers. Therefore, it is important to construct a favorable evaluation mode to help decision-makers select suitable supplier partners and improve the government's purchasing performance through appropriate performance evaluation.

In this study, to comprehensively review the key factors of the monitoring system for tunnel construction, evaluation criteria for the procurement of environment monitoring equipment for tunnel construction were established and the procurement performance system was evaluated. Then, the latest trends of sensing and monitoring systems were investigated by combining the opinions of experts and a questionnaire survey. Finally, various evaluation criteria and properties were summarized by collecting the opinions of an expert group, and a set of objective evaluation criteria was established through the Analytic Hierarchy Process (AHP) to select the optimal supplier partner of environment monitoring equipment. We also investigated the disasters that have occurred in tunnel construction, summarized the gases harmful to construction workers during construction, and conducted multivariate data analysis to derive a selection mechanism for suppliers of hazardous gas sensing equipment. Therefore, relevant recommendations can be made on the basis of the results of this study.

2. Evaluation Criteria for Procurement of Environment Monitoring Equipment for Tunnel Construction

By analyzing engineering disasters and reviewing the historical literature, we found that AHP and grey correlation analysis are suitable for evaluating construction environment monitoring equipment. Grey correlation analysis can be used for quantitative analysis and comprehensive appraisal through comparison;[5] however, various factors are assigned with equal weights in the calculation of the grey correlation coefficient, which markedly differs from practical requirements. AHP is capable of determining objective weights based on group decisions,[6,7] which compensates for the shortcomings of grey correlation analysis. In this study, the literature on the criteria and characteristics of construction environment monitoring equipment was reviewed and analyzed by AHP to generalize appropriate selection criteria and evaluate characteristics.

2.1 Trend in development of environment monitoring equipment for tunnel construction

In a tunnel operating environment, construction personnel may be exposed to hazardous substances and abnormal effluent.

(1) Hazardous substances. The hazardous substances in a tunnel mainly include overflowing gas resulting from the excavation of carbonized land, harmful gases produced in concrete spraying and blasting, oxygen-deficient air generated by oxygen absorption by reductive components such as soil and rocks in excavation, and harmful gases produced during the construction of waterproof membranes.[8]

(2) Abnormal effluent. In mountainous areas with high precipitation or a high underground water level, abnormal effluent may be induced during excavation in fractured formations and fault fracture zones, which may lead to collapses, rockfalls, and a large volume of water at the excavation face. Workers may not be able to escape in time, and may drown or be buried alive.

During tunnel construction, automatic sensing and monitoring play an important role in preventing tunnel deformation and collapse, which also affect construction procedures. To ensure both safety and economy, a tunnel should be monitored during construction. Such monitoring is an important part of tunnel construction management. Through field monitoring, dynamic environmental data can be obtained during construction, providing reliable data for tunnel engineering design and construction guidance. Table 1 lists the sensors used for monitoring geological structures for disaster prevention and control during construction.

Table 1
Applications of various sensors for monitoring geological structures.

Type	Monitoring items
Structure safety monitoring	Inclinometer, water manometer, cycloid meter, load meter, extensometer, subsidence recorder, etc.
Tunnel safety monitoring	Subsidence recorder, extensometer, convergence gauge, crack meter, water manometer, soil pressure gauge, inclinometer, strain gauge, etc.
Safety monitoring in construction	Inclination tube, inclination disk, water manometer, water level gauge, subsidence recorder, strain gauge, etc.

With the development of high-technology industry, severe damage caused by accidents and occupational injuries have also increased. People can work in harsh conditions and prevent harm caused by gases by monitoring their concentration in the operating environment in real time.[9,10] Monitors for harmful gases have become important devices in the construction industry to ensure the health and safety of workers. The characteristics of gas monitors and the latest data can serve as a basis for system design. Currently, well-established analysis plans have been developed to select and install suitable gas monitors meeting the requirements of convenience, light weight, real-time monitoring, and accuracy. To ensure accuracy, gas monitors should be calibrated, maintained, and managed regularly. Table 2 lists the application ranges of various gas monitors and sensors.

A fully automatic monitoring, recording, and warning system can collect, organize, calculate, and analyze signals measured by various monitoring devices and automatically send alarms in case of danger.[11,12] The processes of such a system mainly consist of signal collection, signal transmission, and data processing.[13,14] Signals are collected by various monitoring devices installed at the construction site, which are transmitted by cable or wireless transmission and finally processed by the fully automatic monitoring, recording, and warning system. The system can automatically scan various types of signals, then record and analyze the signals with built-in programs, and finally plot, display, and print various types of charts. In addition, various warning values can be set so that the system can automatically send an alarm when a measured value is close to a dangerous level. Figure 1 shows the architecture of a fully automatic monitoring, recording, and warning system.

An automatic site monitoring and control system equipped with offline reading and monitoring functions has been developed. Through data acquisition cell units (Cells), the monitoring data can be wired or wirelessly connected to a computer in the monitoring station via

Table 2
Application ranges of gas monitors and sensors.

Item	Contents	Notes
Industrial safety	Monitoring of high-pressure and toxic gases	Monitoring leakage gases such as SiH_4, PH_3, and AsH_3 from gas cylinders, pipes, and storage tanks
	Tunnel engineering monitoring system	Safety monitoring in tunnel engineering including monitoring of CO and noise
	Mobile explosion detector	Monitoring emergency leakage and inspecting pipe leakage of, for example, combustible gases
	Detection at confined sites before work	Measuring contents of gases such as CO and O before entering confined spaces to work to ensure personnel safety
Industrial hygiene/health	Fixed detector of personal exposure	Measuring concentrations of various gaseous pollutants at fixed positions
	Portable detector of personal exposure	Evaluating exposure of various workers
Environmental protection	Discharge pipes	Monitoring types and concentrations of various pollutants in discharge pipes during tunnel construction
	Periphery of tunnel engineering	Monitoring gases escaping from perimeter of tunnel
	Atmospheric environment	Air pollution monitoring stations for detecting various standard pollutants and toxic pollutants
Others	Mobile pollution sources	Monitoring exhaust gases of tunnel engineering turbine trucks

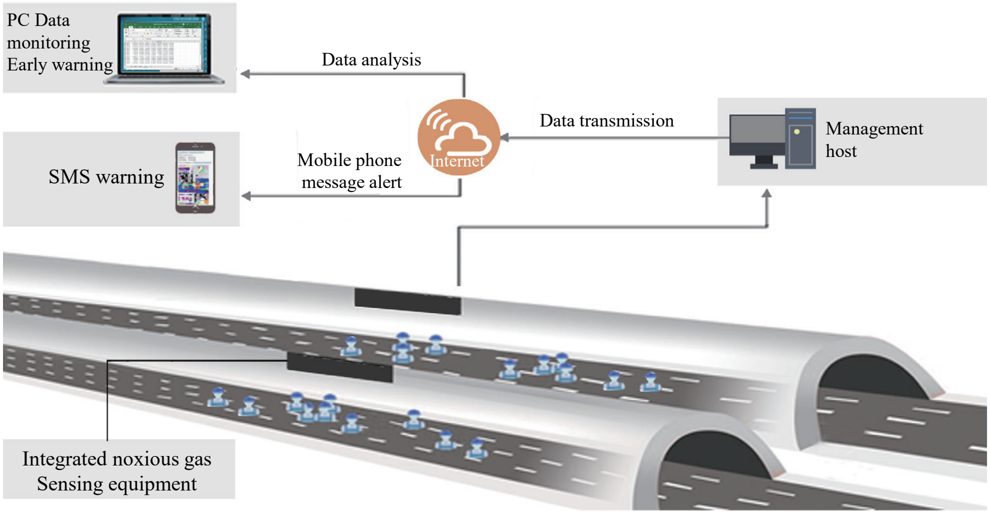

Fig. 1. (Color online) Illustration of fully automatic monitoring, recording, and warning system.

a network. A notebook computer can also directly read the monitoring data. Even in the case of transmission cable damage and signal interference, monitoring and reading are not affected. All the information at the monitoring station, including the data, video, and audio, can be aggregated in the central control room, which is equipped with databases consisting of high-volume hard-disk devices and CD-ROM drivers, and a telecom network server. The offices of decision-makers or consultant companies at the telemetering terminal can communicate various signals with the monitoring room through a telecommunication network.

2.2 Establishment of procurement evaluation criteria for monitoring equipment

In 1966, Dickson defined and proposed 23 criteria for the assessment and selection of suppliers.(15) He pointed out that the top three criteria in selecting suppliers are quality, delivery time, and past performance. For the case of a just-in-time management environment, Ansari and Modarress proposed six evaluation criteria for suppliers: quality, delivery time, price, attitude, geographic position, and packing capability.(16) O'Shaughnessy and O'Shaughnessy argued that the level of importance and criteria for procurement are different for different types of products.(17) For example, quality and prices should be the top priorities when purchasing routine consumer products, while delivery time and service are the main concerns when purchasing procedural products. Browning *et al.* believed that purchasers pay attention to five items while making procurement strategies, namely, delivery time, price, productivity, technical capability, and production equipment.(18) In practical supply chain management, the modern, intelligent, and sustainable decision-making criteria for supplier selection are twofold: the determination of standard weights and the ranking of suppliers.(19) In this study, the evaluation hierarchy and criteria for equipment procurement are established on the basis of past safety disasters in tunnel construction, a literature review, and in-depth interviews with senior engineers, scholars, and experts of tunnel construction.

The formal questionnaire designed in this study consists of three layers. The first layer reflects the evaluation theme of monitoring equipment procurement, the second layer reflects the evaluation of monitoring equipment procurement, and the third layer reflects the evaluation criteria. As shown in Fig. 2, the first layer represents the research object; the second layer consists of four evaluation dimensions for the procurement of environment monitoring equipment, i.e., quality evaluation, delivery time evaluation, cost evaluation, and management control evaluation; and the third layer includes 13 evaluation criteria under the four dimensions of the second layer, which are described in detail below.

A. Four evaluation criteria for quality: product yield rate, sensor precision, safety and stability, and sensing speed.
B. Three evaluation criteria for delivery time: emergency delivery capability, contractual capability, and reaction capability to order change.
C. Three evaluation criteria for cost: payment method of purchaser, negotiation space for purchase quantity, and quotation competitiveness.
D. Three evaluation criteria for management control: crisis management capability, the capability of dealing with defective products, and customer complaint handling capability.

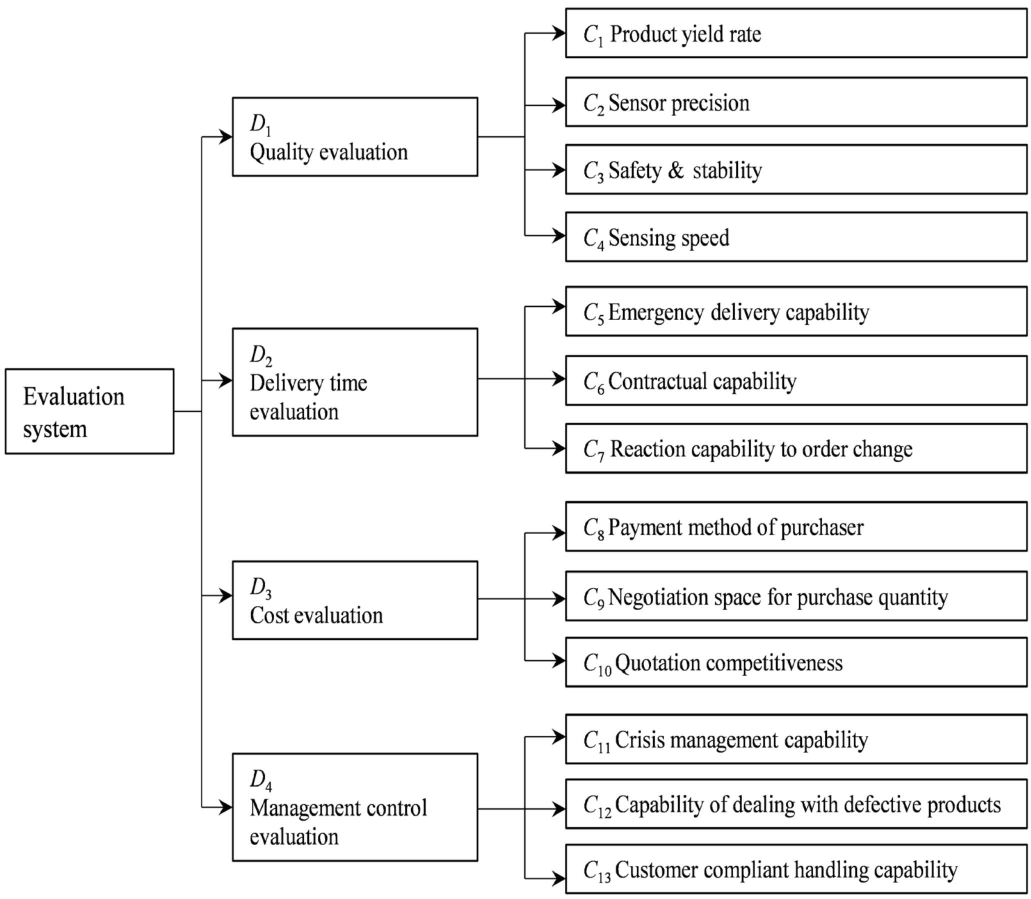

Fig. 2. Hierarchy of evaluation criteria for monitoring equipment procurement.

3. Methods

The multi-criteria decision-making method has been systematically investigated in academia since 1959. Adams and Fagot discussed the value function principle from an undifferentiated perspective.(20) Afterward, Krantz proposed an additive value function based on measure theory; accordingly, decision-making criteria were used to compare specific points between different schemes, measuring rules, or standards, and as a preference-measuring model.(21) The criteria generally include objectives and attributes. Multi-objective decision-making (MODM)(22,23) or multi-attribute decision-making (MADM)(24,25) can also be referred to as multi-criteria decision-making (MCDM).(26,27)

3.1 AHP

AHP, proposed by Thomas L. Saaty, a professor from the University of Pittsburgh, is a decision-making method that has been applied in the U.S. Department of Defense contingency planning investigation.(28) It has been extensively applied in many fields, mainly for decision-making in uncertain cases or with multiple evaluation criteria, particularly for the evaluation of qualitative information. Through AHP, decision-makers can establish different hierarchical structures for complex evaluation problems using the system structure method, and then decompose these problems at different levels. By facilitating quantitative judgment, AHP can help decision-makers gain in-depth knowledge and reduce the risk of decision-making errors.

In this study, key criteria were determined by analyzing documents on monitoring equipment in tunnel construction, summarizing sensing devices employing the latest technologies, and interviewing engineers with practical experience. Then, the weights of various criteria were calculated with AHP. Finally, a procurement evaluation system for environment monitoring equipment for tunnel construction was established, which can meet the requirements in the rapid development of sensor application technologies in the Internet of Things (IoT) era.

3.2 Implementation procedures of AHP

A. Definition of decision-making problem of construction environment monitoring system

For the procurement evaluation of environment monitoring equipment, all possible causes of impacts should be included in the questions. Also, a focus group consisting of scholars, experts, and engineers with practical experience should be established to determine the scope of the problem.(29)

B. Establishment of decision-making groups

In this study, a focus team including 11 experts was established to address the evaluation and decision-making problems of monitoring equipment procurement, which involved different domains and complexity degrees. Owing to the different preferences of various experts in the decision-making group, the feasible plans or schemes have different weights. Accordingly, the preferences of the experts should be integrated before or after the supplier is selected.

Specifically, pre-integration mainly includes the geometric mean and the majority decision, while the integration after the decision of the supplier adopts the geometrical mean.

C. Establishment of hierarchical structure

A hierarchical structure should be established and decomposed when dealing with complex problems. Assuming that it is not easy for humans to compare seven or more things simultaneously,[30] the number of factors in each level should not exceed seven. This stage includes three steps: defining problems, clarifying the definitions, and determining factors and hierarchies. The hierarchical structure is established to identify all the factors in the hierarchical structure and establish the hierarchical relationship among these factors, which connect questions and answers. Each level in the hierarchical structure is influenced only by the upper level, and the various factors are independent of each other. The hierarchical structure can show good consistency only if the above conditions are satisfied.

D. Questionnaire design, survey, and establishment of pairwise comparison matrix

Factors in each level were evaluated using the factors in the upper layer as the evaluation criterion. For the factors of the same level, a pairwise comparison was performed, and the evaluation scales (1–9) are listed in Table 3. Accordingly, the pairwise comparison matrix $\boldsymbol{A}$ can be obtained. For the comparison of n factors, $n \times (-1) / 2$ pairwise comparisons should be made. Assuming that a_{ij} denotes the ratio of factor i to factor j, the ratio of factor j to factor i equals the inverse of a_{ij}, that is, $1/a_{ij}$. Similarly, each factor in the lower triangular part of pairwise comparison matrix $\boldsymbol{A}$ is the multiplicative inverse of the corresponding factor in the upper triangular part, as shown by Eq. (1).

$$\boldsymbol{A} = [a_{ij}] = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ 1/a_{12} & 1 & \cdots & a_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ 1/a_{1n} & 1/a_{1n} & \cdots & 1 \end{bmatrix} \tag{1}$$

Given the weights of various factors, Eq. (1) can be rewritten as

Table 3
Evaluation scales between factors

Evaluation scale	Definition	Explanation
1	Equal importance	Equal contribution degrees of two comparison factors
3	Slight importance	Slight preference to a scheme based on experiences and judgment
5	Essential importance	Strong preference to a factor based on experiences and judgment
7	Very strong importance	Extremely strong preference to a factor in the reality
9	Absolute importance	Absolute preference to a scheme based on enough evidence
2, 4, 6, 8	Intermediate values	In case of compromise value

$$\boldsymbol{A}=[a_{ij}]=\begin{bmatrix} 1 & a_{12} & \dots & a_{1n} \\ 1/a_{12} & 1 & \dots & a_{2n} \\ \dots & \dots & \dots & \dots \\ 1/a_{1n} & 1/a_{2n} & \dots & 1 \end{bmatrix}=\begin{bmatrix} 1 & w_1/w_2 & \dots & w_1/w_n \\ w_2/w_1 & 1 & \dots & w_2/w_n \\ \dots & \dots & \dots & \dots \\ w_n/w_1 & w_2/w_n & \dots & 1 \end{bmatrix}. \tag{2}$$

where w_i denotes the weight of factor i (i = 1, 2, …, n), and a_{ij} denotes the ratio of the relative importance between any two factors (i = 1, 2, …, n; j = 1, 2, …, n).

3.3 Calculation of eigenvalues and eigenvectors

After obtaining the pairwise comparison matrix, eigenvectors or advantageous vectors were calculated using an eigenvalue solution by numerical analysis to determine the weights of various factors at different levels. The column-vector geometrical averaging normalization proposed by Saaty in 1980, also known as normalization of the geometric mean of the rows, is the most commonly used method for calculating eigenvectors. By multiplying the factors in various rows/columns, geometrical averaging, and normalization, the eigenvector matrix W_i can be calculated as

$$W_i=\frac{\left(\prod_{j=1}^{n} a_{ij}\right)^{\frac{1}{n}}}{\sum_{i=1}^{n}\left(\prod_{j=1}^{n} a_{ij}\right)^{\frac{1}{n}}}, \qquad i, j=1,2,\cdots,n. \tag{3}$$

A new eigenvector matrix W_i' is obtained by multiplying W_i by the pairwise comparison matrix $\boldsymbol{A}$. Each vector in the new eigenvector matrix W_i' is divided by the vector in the original eigenvector matrix W_i. After taking the arithmetic average, λ_{max} is obtained as

$$\lambda_{\max}=\frac{1}{n}\left(\frac{W_1'}{W_1}+\frac{W_2'}{W_2}+\ldots+\frac{W_n'}{W_n}\right). \tag{4}$$

3.4 Consistency test

The consistency index (*C.I.*) is used to determine whether the pairwise comparison matrix including the answers of decision-makers is a consistent matrix. In the case of an unqualified degree of consistency, there must be problems with the relationship between factors at different levels. Saaty suggested that the degree of consistency is optimal when *C.I.* < 0.1. The maximum allowable bias should be below 0.2, i.e., *C.I.* < 0.2, to ensure consistency.[29]

A. Consistency index (*C.I.*)

C.I. can be calculated as

$$C.I. = \frac{\lambda_{\max} - n}{n - 1}, \tag{5}$$

where λ_{max} is the maximum eigenvalue of matrix ***A*** and n is the number of the evaluation factors.

If *C.I.* = 0, then the judgment of the relative importance degrees of n factors under a single criterion is completely consistent; if *C.I.* > 0, the decision-makers or experts have inconsistent judgments. Saaty suggested that *C.I.* < 0.1 is optimal and that the maximum allowable bias should be *C.I.* < 0.2.[31]

For matrices with the same orders, the ratio of *C.I.* to the average random consistency index (*R.I.*) is referred to as the consistency ratio (*C.R.*):

$$C.R. = \frac{C.I.}{R.I.}. \tag{6}$$

C.R. < 0.1 indicates a satisfactory degree of consistency. For the positive inverse matrix generated on the basis of evaluation scales 1–9, different values of *C.I.* correspond to different ranks, also known as the *R.I.* In Saaty's study, different *R.I.* values were used to calculate matrices of different orders, e.g., a matrix of order four can be calculated using the *R.I.* value of 0.90 found in Table 4. The higher the order, the higher the tolerance error value.

B. Determination of optimal supplier of environment monitoring equipment for tunnel construction

After the judgments of experts on the evaluation dimension and criterion weights satisfying the consistency requirements, the weight combined with each scheme can be used to determine the priority index (*P.I.*) of each scheme in each evaluation index. *P.I.* can be calculated as follows from the weights (W_i) and the scores of various schemes relative to various indexes (X_{ij}) through simple weighting:

$$P.I. = \sum\nolimits_{j=1}^{n} W_i * X_{ij}. \tag{7}$$

4. Results and Discussion

The primary purpose of a safety monitoring system for all structures under construction and in operation is to ensure the safety of buildings, personnel, and properties in, outside, and around

Table 4
R.I. values.

Order	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
R.I.	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.58

the site. To comprehensively review the key factors of the monitoring system for tunnel construction, we established evaluation criteria for the procurement of environment monitoring equipment for tunnel construction and evaluated the procurement performance. The evaluation framework of the procurement was reviewed through monitoring feedback, enabling the project to meet both safety and economic objectives. The results of the analysis of evaluation dimensions and criteria are described below.

4.1 Analysis results of evaluation dimensions and criteria

By consulting engineering construction safety manuals and literature on practical construction disasters, we designed a questionnaire regarding evaluation dimensions and criteria for the procurement of environment monitoring equipment for tunnel construction through interviews with a total of 11 experts. The 11 experts consisted of four senior engineers, three people employed by the government to formulate safety regulation, and four academics specializing in construction environment operating safety. After pairwise comparison of four evaluation dimensions and 13 evaluation criteria, the values of *C.I.* and *C.R.* of different scales were calculated, and the results are shown in Table 5. These values are all below 0.1, suggesting that all dimensions can satisfy the consistency requirements.

Table 5
Analysis results of different evaluation dimensions and criteria.

Dimension	Weight	Ranking	Evaluation criterion	Weight	Ranking	Overall weight	Overall ranking
D_1 Quality evaluation	0.43	1	C_1 Product yield rate	0.21	3	0.090	3
			C_2 Sensor precision	0.31	1	0.131	1
			C_3 Safety and stability	0.29	2	0.125	2
			C_4 Sensing speed	0.19	4	0.082	5
D_2 Delivery time evaluation	0.19	3	C_5 Emergency delivery capability	0.24	3	0.046	12
			C_6 Contractual capability	0.41	1	0.078	6
			C_7 Reaction capability to order change	0.35	2	0.067	8
D_3 Cost evaluation	0.17	4	C_8 Payment method of purchaser	0.35	2	0.060	10
			C_9 Negotiation space for purchase quantity	0.21	3	0.036	13
			C_{10} Quotation competitiveness	0.44	1	0.075	7
D_4 Management control evaluation	0.21	2	C_{11} Crisis management capability	0.42	1	0.088	4
			C_{12} Capability of dealing with defective products	0.31	2	0.065	9
			C_{13} Customer complaint handling capability	0.27	3	0.057	11

In general, calculating the cost of environment monitoring equipment for tunnel construction involves many factors, including the required materials, devices, and labor. Although the designers are familiar with structural mechanics, building design, and price evaluation methods, they do not sufficiently consider the safety design during construction. Most projector organizers still adopt the principle of lowest-quotation competitive bidding. Accordingly, expenditure on health and safety is usually cut. In other words, bidders can reduce construction costs and win bids by offering a low price, which reduces the construction health and safety budget compiled by the original project sponsor. Expenditure on health and safety may even be misappropriated for other purposes during the construction.

This study focuses on the evaluation of the procurement of environment monitoring equipment for tunnel construction. The analysis results showed that the quality evaluation (D_1), with a weight of 0.43, was the most important evaluation dimension, followed by the management control evaluation (D_4) with a weight of 0.21, the delivery time evaluation (D_2) with a weight of 0.19, and finally, the cost evaluation (D_3) with a weight of 0.17. From the dimension weight analysis, it was concluded that quality has the greatest importance when purchasing environment monitoring equipment for tunnel construction.

According to our research results, the evaluation and selection of suppliers of environment monitoring equipment for tunnel construction should be based on the quality and management of sensing systems as priority factors, rather than cost. In terms of evaluation criteria, sensor precision (C_2) is the most important with a weight of 0.131, followed by safety and stability (C_3) with a weight of 0.125 and the product yield rate (C_1) with a weight of 0.09. Sensing equipment with high precision and high safety and stability should be given top priority.

4.2 Empirical evaluation of suppliers of environment monitoring equipment for tunnel construction

To verify the applicability of the proposed evaluation indicator mode, we adopted the contracting approach in tunnel engineering and selected three suppliers of environment monitoring equipment for tunnel construction based on the established evaluation model and the weights of various evaluation criteria. The evaluation scales of priorities were calculated using the overall weights of the hierarchical evaluation criteria and validated by the decisions of the expert group. Table 6 lists the priority ranking of the suppliers of environment monitoring equipment for tunnel construction.

According to overall empirical ranking results, we found that supplier B has the highest ranking, followed by supplier C and supplier A. The expert group made an objective and fair selection based on the overall weights of various criteria, and the ranking results were not influenced by the price. Based on the feedback from the 11 experts, it is recommended that the suppliers of environment monitoring equipment that can best satisfy the requirements within the construction budget are selected. Under the premise of ensuring the functions and quality of environment monitoring equipment, the procurement should meet the safety and quality specifications of the construction operation. With the help of a group of experts, the most suitable supplier for organizers of engineering projects can be determined after an evaluation meeting and procedure based on the evaluation criteria established in this study.

Table 6
Empirical evaluation results of suppliers.

Dimension	Evaluation criterion	Weight	Supplier A	Supplier B	Supplier C
D_1 Quality evaluation	C_1 Product yield rate	0.090	0.025	0.037	0.028
	C_2 Sensor precision	0.131	0.036	0.051	0.044
	C_3 Safety and stability	0.125	0.024	0.055	0.046
	C_4 Sensing speed	0.082	0.024	0.032	0.025
D_2 Delivery time evaluation	C_5 Emergency delivery capability	0.046	0.014	0.016	0.016
	C_6 Contractual capability	0.078	0.025	0.023	0.030
	C_7 Reaction capability to order change	0.067	0.022	0.021	0.024
D_3 Cost evaluation	C_8 Payment method of purchaser	0.060	0.025	0.013	0.023
	C_9 Negotiation space for purchase quantity	0.036	0.015	0.010	0.010
	C_{10} Quotation competitiveness	0.075	0.034	0.027	0.014
D_4 Management control evaluation	C_{11} Crisis management capability	0.088	0.017	0.037	0.034
	C_{12} Capability of dealing with defective products	0.065	0.014	0.025	0.026
	C_{13} Customer complaint handling capability	0.057	0.013	0.018	0.026
	P.I.		0.288	0.365	0.347

5. Conclusions

In this study, to evaluate the procurement of environment monitoring equipment for tunnel construction, we established an objective and fair hierarchical evaluation structure based on the properties of sensing equipment, in which four evaluation dimensions and 13 evaluation criteria were defined. The established hierarchical structure also includes evaluation contents in the procurement of public construction that are systematic and complete and can assist in the practical evaluation and selection of suppliers. Three suppliers on the market were evaluated on various criteria by pairwise comparison. Then, the scores of various criteria for the three suppliers were calculated, avoiding the difficulties in judgment based on the direct scoring of various criteria during procurement. The established hierarchical structure can be used to evaluate and select suppliers of environment monitoring equipment for tunnel construction. The weights of various dimensions and criteria can be adjusted in different cases according to the different opinions of the group of experts. The findings and contributions of the study are as follows:

A. AHP has a wide range of applications in the selection of suppliers but has rarely been used to select suppliers of environment monitoring equipment for tunnel construction in governmental units. Therefore, the results of this study can serve as important guidelines for purchasers in public engineering units regarding the selection of suppliers.
B. The hierarchy in this study is not completely in accordance with the criteria defined in the literature. It added novel sensor technologies and improvements to previous construction disaster cases. The attributes in this study have different reference values. The weights of

each dimension and the whole hierarchy were calculated to determine the priority of different supplier schemes appropriate for governmental units.

C. The established supplier evaluation table and the weighted scoring table were empirically validated and can be used as references in future procurement to avoid unfairness in selection.

D. Environment monitoring equipment for tunnel construction is important for worker safety. Suppliers who can provide precise, safe, and stable sensing equipment should be preferred for procurement. Field construction can be improved on the basis of detection results, thereby ensuring a healthy and safe operating environment for workers and improving the competitiveness of companies.

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