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Tunnel Engineering

Comprehensive and Quantitative Evaluation of Subsea Tunnel Route Selection: A Case Study on Bohai Strait

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ABSTRACT

The Bohai Sea is the immense inland sea in China and the Bohai Strait is a sea graben from East China to Northeast China which lies between the Jiaodong Peninsula and the Liaodong Peninsula. Considering the forthcoming Bohai Strait subsea tunnel, the authors selected nine indicators including seabed topography, stratigraphic lithology, geological structure, earthquake, environmental impact, engineering scale, ventilation conditions, residents' satisfaction, and landing position. These indicators are considered as evaluation indexes to evaluate three alternative routes of the Bohai Strait subsea tunnel: line A, line B, and line C. In this paper, the evaluation model of the Bohai Strait subsea tunnel based on analytic hierarchy process (AHP) and extension theory is established. In this regard, the grade of route selection is divided into four categories: excellent, good, average, and bad. Finally, through the model calculations, it is concluded that line B of the Bohai Strait subsea tunnel is the best, and line A is the worst. This method provides a new idea for the evaluation of subsea tunnel site selection and also represents some references for other types of engineering site selection.

1. Introduction

In recent years, the rapid development of infrastructure construction in emerging countries and the upgrading of old facilities in developed countries have led to the appearance of many significant projects (Zhang et al., 2015). These essential projects generally need a long service life and are directly relevant to the people. Hence, the site selection of major projects is becoming more and more critical. A proper site selection can not only reduce the cost of design, construction, and maintenance but also can better ensure the safety of people's lives and property during their service. A poor site selection will not only significantly increase the design difficulty and cost of the project, but also affect the service life of the project, jeopardize the safety of people's lives and property, and even directly lead to the failure of the project construction. There is not much research on this issue in the world. Additionally, there exists even less research on the evaluation of the site selection of subsea tunnels. Based on the site selection of the Bohai Strait subsea tunnel, this paper aims to find an objective and accurate method to evaluate the site selection of the Subsea tunnel project and to provide a new idea for the site selection planning of the Subsea tunnel project in the future.

Since the emergence of subsea tunnels, this type of engineering has appeared more and more all over the world. At the same time, the achievements relevant to subsea tunnels have emerged more broadly (Eisenstein et al., 1994; Nilsen et al., 1994). Although some scholars have studied the method of evaluation of the tunnels site selection, there are few achievements in site selection of subsea tunnels. Russell et al. (1980) used remote sensing data to study the location of tunnels. Wang et al. established a new method of tunnel entrance stability evaluation through the GIS method (Wang et al., 2014). The method has been demonstrated to have good accuracy in locating the tunnel entrance. However, these studies are based on land tunnels rather than subsea tunnels. Moreover, there are significant differences among different types of tunnel site selection methods. For the time being, there are few studies on the route selection of subsea tunnels which largely focus on the study of the minimum rock cover thickness (Xue et al., 2019). In Norway, Dahlø and Nilsen analyzed the minimum rock cover thickness data of 16 Norwegian subsea tunnels and concluded that rock cover thickness is conservative in most

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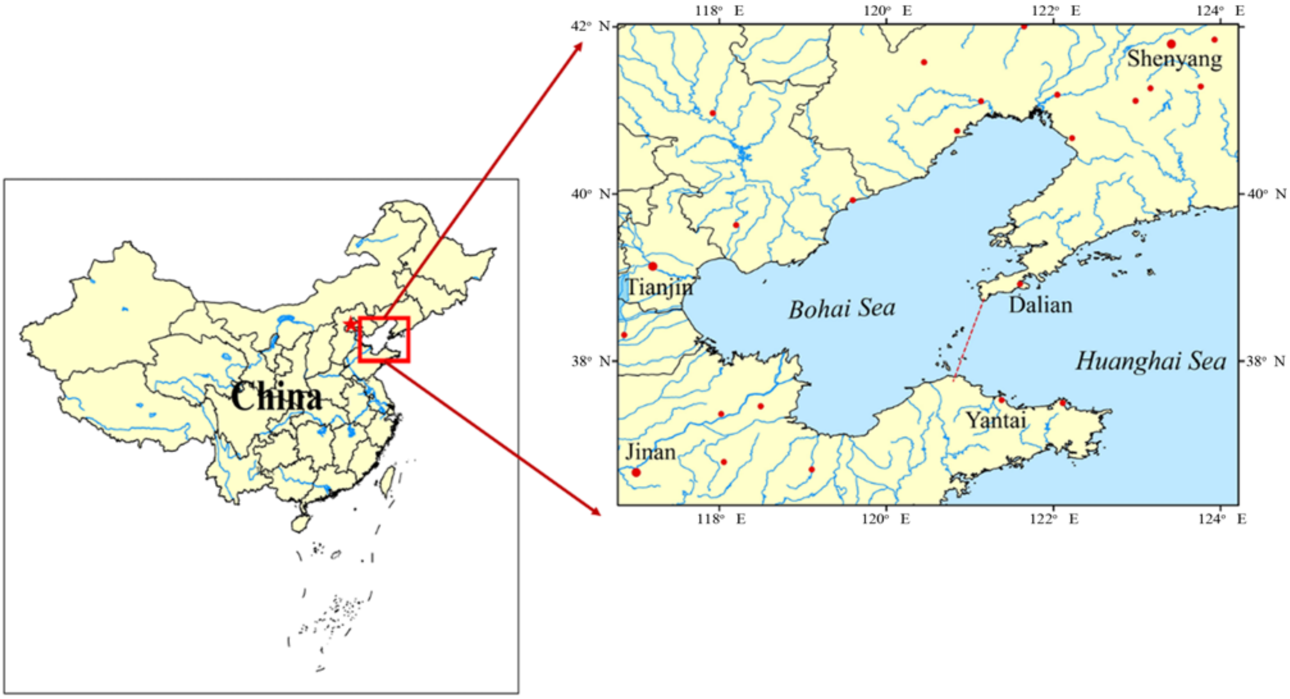

Fig. 1. Location Map of Subsea Tunnel in Bohai Strait

Norwegian subsea tunnel projects (Dahlø et al., 1994). In Japan, Kitamura (1986) analyzed some problems existing in the construction of the Seikan Tunnel and summarized some technical points. Sharifzadeh et al. (2013) calculated the water inflow through numerical fluid dynamics. They also studied the minimum rock cover thickness of undersea tunnels. Xu et al. (2016) used an engineering analogy and numerical method to study the minimum rock cover thickness of subsea tunnels. They also established a set of more suitable ways to determine the minimum rock cover thickness of subsea tunnels. Although the minimum rock cover thickness is influential on the route selection of subsea tunnels, the main indicators that affect the route selection of subsea tunnels are still some basic geological conditions and economic indicators. Many scholars have done a lot of research on route selection of urban rail transit and railway tunnel in mountainous areas (Huang et al., 2013; Kim et al., 2016; Yildirim et al., 2019). Subsea tunnels have existed for more than 80 years, but there are still few studies on site selection evaluation methods. Therefore, it is necessary to fill the existing research gap by establishing an evaluation method for subsea tunnels location with considering the most critical indicators.

The Bohai Sea is China's most immense inland sea, from the Liaodong Peninsula to the Jiaodong Peninsula, surrounded by three continents in the shape of the English letter C, as shown in Fig. 1. The Bohai Strait is 106 km wide. It is a sea graben from East China to Northeast China which lies between the two aforementioned peninsulas. Changshan Islands are distributed in the middle and south of the Bohai Strait, forming navigable navigation channels for ships. The highway and railway transportation network around the Bohai Sea is almost developed, but the "C" type traffic with existing gaps results in an additional 1,500 km railway and 1,600 km expressway from the Liaodong Peninsula to the Jiaodong Peninsula. At the moment, there is only ferry traffic between Yantai and Dalian on both sides of the Bohai Sea. The Bohai Strait belongs to the typhoon area. The gale weather lasts for a long time, and sea fog concentrates from April to July, which often causes the ferry to be delayed or stopped. More importantly, there are substantial risks and uncertainties in shipping. Thus, building a fixed cross-sea passage is a must. Considering the comprehensive discussion on the advantages and disadvantages of the whole tunnel scheme, the whole bridge scheme, and the bridge-tunnel combination scheme in China, the experts in the field of subsea tunnels in China agree with the whole tunnel scheme (Wang et al., 2016). The whole tunnel scheme has the smallest impact on environmentally sensitive areas, marine ecological environment, marine resources utilization, surrounding environment, and shipping. It also has a strong ability to withstand war damage, natural disasters, sudden accidents, and bad weather. The nonlinear comprehensive evaluation methods have been widely studied in many scientific fields and have been made a lot of achievements (Rahmat et al., 2017; Jung et al., 2019). However, these methods are rarely used in subsea tunnel route selection, which leads to the research of subsea tunnel route selection is still in the stage of artificial comparative analysis. Therefore, based on the whole tunnel scheme, this paper employs a multi-indicator comprehensive evaluation method to compare and select tunnel routes and to evaluate various possible landing schemes (Fig. 2). Ultimately, a global, objective, and credible evaluation result of the subsea tunnel site selection scheme for the Bohai Strait is proposed.

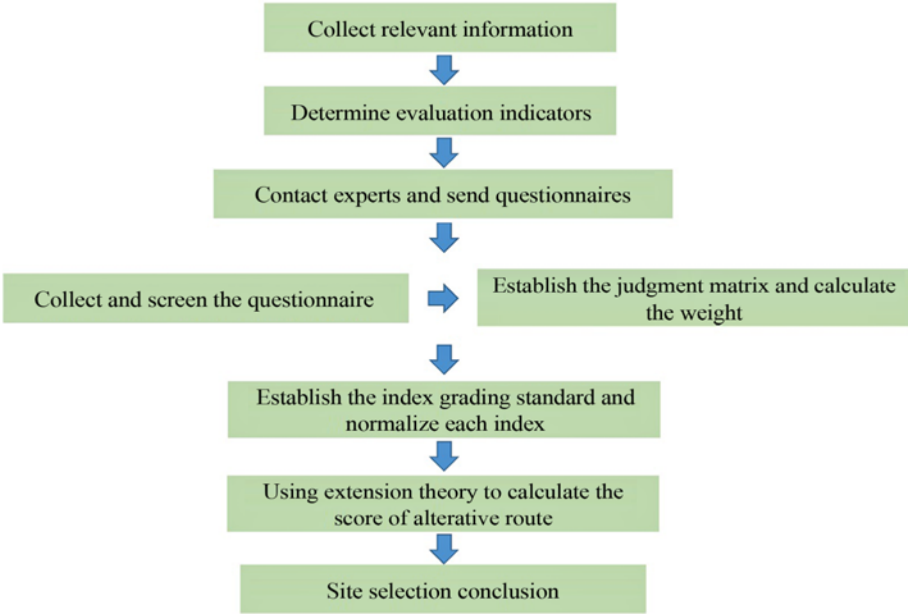

Fig. 2. Quantitative Site Selection Evaluation System for Subsea Tunnels

2. Methodology

An extension method is a combination of qualitative and quantitative methods, which evaluates the research object from the perspective of feasibility and optimization (Cai, 1999). The extensibility of matter element determines the qualitative calculation. Also, the quantitative calculation is carried out by correlation function using extension set theory. This method is a new evaluation method. It can transform each evaluation indicator into a compatible problem (He et al., 2000). By establishing the matter-element model, the conclusion becomes consistent with the actual situation.

The extension theory employs the matter-element theory and extension mathematics as its theoretical framework. Among them, the matter element is the logic cell of extenics. Considering name N for the object, the value of the corresponding characteristic c is v. $R = \{N, c, v\}$ which is called the matter element is used as the fundamental element for describing the object. If the object N has many characteristics, then

$$R = \begin{bmatrix} N & c_1 & v_1 \\ & c_2 & v_2 \\ & \vdots & \vdots \\ & c_n & v_n \end{bmatrix} = \begin{Bmatrix} R_1 \\ R_2 \\ \vdots \\ R_n \end{Bmatrix}, \tag{1}$$

where R is the matter-element with n dimensions, which is denoted as $R = (N, c, v)$.

2.1 Basic Steps of Extenics Evaluation

2.1.1 Determination of the Classical Field

In this paper, the classical field is the range of each grade of the influence indicators, the following formula can be used:

$$R_{0t} = (N_{0t}, c_j, v_{0tj}) = \begin{bmatrix} N_{0t} & c_1 & \langle a_{0t1}, b_{0t1} \rangle \\ & c_2 & \langle a_{0t2}, b_{0t2} \rangle \\ & \vdots & \vdots \\ & c_n & \langle a_{0tn}, b_{0tn} \rangle \end{bmatrix}, \tag{2}$$

$(t = 1, 2, 3, ..., s; j = 1, 2, 3, ..., n)$

where N_{0t} represents the standard object of quality grade t, c_j is the indicator which affects N_{0t} $(j = 1, 2, 3, \ldots, n)$. $< a_{0tj}, b_{0tj} >$ is the range of values (i.e., value range) of the quality grade t, which is the classical field.

2.1.2 Determination of the Controlled Field

In this paper, the controlled field is the total range of influence indicators, the following formula can be used:

$$R_p = (N_p, c_j, v_{pj}) = \begin{bmatrix} N_p & c_1 & \langle a_{p1}, b_{p1} \rangle \\ & c_2 & \langle a_{p2}, b_{p2} \rangle \\ & \vdots & \vdots \\ & c_n & \langle a_{pn}, b_{pn} \rangle \end{bmatrix}, \tag{3}$$

where c_j stands for the No. j indicator of the object N_P, $< a_{Pj}, b_{Pj} >$ is the largest value range of the indicator c_j, which is the controlled field.

2.1.3 Determination of the Matter Element to Be Evaluated

For objects which are needed to be evaluated, the collected indicators information of No. i object is represented by a matter element, which is the matter-element to be evaluated, denoted as R_i:

$$R_i = (N_i, c_j, v_{ij}) = \begin{bmatrix} N_i & c_1 & v_{i1} \\ & c_2 & v_{i2} \\ & \vdots & \vdots \\ & c_n & v_{in} \end{bmatrix}, \tag{4}$$

where N_i is the No. i matter element which is needed to be evaluated, c_j is the indicator determining the quality of the matter-element which is needed to be evaluated (j = 1, 2, 3,…, n), v_{ij} is the value of No. j indicator c_j of No. i object N_i, which is the collected specific data.

2.1.4 Single-Indicator Correlation Degree

The correlation degree of No. j indicator of No. i matter element which has to be evaluated for quality grade t is calculated as follows (Xue et al., 2019):

$$k_{tij} = \begin{cases} \dfrac{-\rho(v_{ij}, v_{0tj})}{|v_{0tj}|} & v_{ij} \in v_{0tj} \\ \dfrac{\rho(v_{ij}, v_{0tj})}{\rho(v_{ij}, v_{pj}) - \rho(v_{ij}, v_{0tj})} & v_{ij} \notin v_{0tj} \end{cases}, \tag{5}$$

where

$$\begin{aligned} \rho(v_{ij}, v_{0tj}) &= \left|v_{ij} - \frac{1}{2}(a_{0tj} + b_{0tj})\right| - \frac{1}{2}(b_{0tj} - a_{0tj}), \\ \rho(v_{ij}, v_{pj}) &= \left|v_{ij} - \frac{1}{2}(a_{0tj} + b_{pj})\right| - \frac{1}{2}(b_{pj} - a_{pj}). \\ &(i = 1, 2, \ldots, m;\ j = 1, 2, \ldots, n; t = 1, 2, 3, \ldots, s) \end{aligned} \tag{6}$$

2.1.5 Comprehensive Correlation Degree

The comprehensive correlation degree refers to the attribution degree of the object which is needed to be evaluated for each evaluation grade. This can be expressed as follows:

$$\begin{aligned} k_{0t}(N_i) &= \sum W_j k_{0t}(v_i) \\ &(i = 1, 2, \ldots, m;\ j = 1, 2, \ldots, n; t = 1, 2, \ldots, s) \end{aligned}, \tag{7}$$

where $k_{0t}(v_i)$ is the correlation degree of the single evaluation indicator of the object to be evaluated, where W_j is the weight coefficient of No. j indicator, which satisfies $\sum_{j=1}^{n} W_j = 1$.

2.1.6 Extension Evaluation Level

For $k_{tmax}(N_i) = max\{k_{0t}(N_i) | i = 1, 2, \ldots, m\}$,

The level of object N_i needed to be evaluated is t. In this regard, the following formula can be used (Xue et al., 2018):

$$\begin{cases} \bar{k}_{0t}(N_i) = \dfrac{k_{0t}(N_i) - \min_t k_{0t}(N_i)}{max_t k_{0t}(N_i) - \min_t k_{0t}(N_i)} \\ t^* = \dfrac{\sum_{t=1}^{s} t\bar{k}_{0t}(N_i)}{\sum_{t=1}^{s} \bar{k}_{0t}(N_i)}, \end{cases} \tag{8}$$

t^* is called the eigenvalue of the level variable of N_i, and the extension evaluation level of the target can be seen from t^*.

2.2 Extension Principle of Site Selection Evaluation

Considering each influencing indicator as the evaluation indicator, according to the calculated weights and corresponding classical field (Eq. 2), Eqs. (5) and (6) are used respectively to calculate the single-indicator correlation degree k_{tij} and the comprehensive correlation degree $k_{0j}(N_i)$ of the matter element needed to be evaluated. Note that $k_{jmax}(N_i) = max\ \{k_{0j}(N_i) | j = 1, 2, \ldots m\}$. That is to say, the site selection grade of the tunnel is j. In combination with Eq. (8), the j^* value of the alternative line is finally obtained as the final evaluation result. According to the above steps, the author compiled the corresponding program *Extension.m* in the MATLAB platform. After inputting relevant data, the program can calculate the grade of the object which is needed to be evaluated.

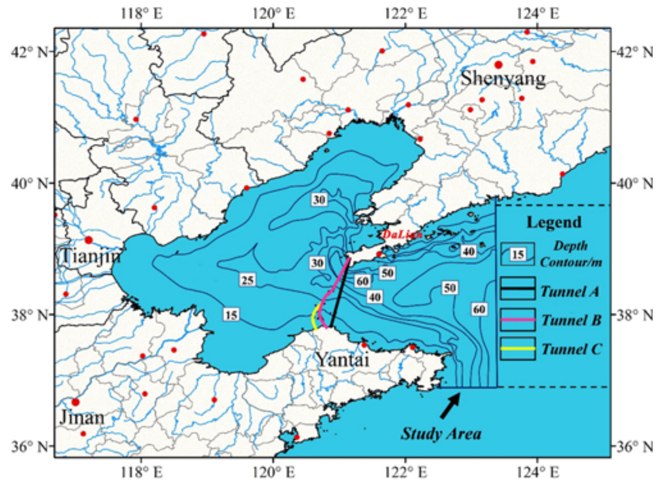

Fig. 3. Seabed Topography and Landform of Bohai Strait

3. Project Overview

3.1 Seabed Topography and Landform

The seabed for the trench ridges across the rugged topography, terrain from west to east and from south to north tilt. The Laotieshan waterway in the south of the Strait forms a V-shaped valley. The fault subsidence on the north side of Northhuangcheng Island is connected with the south slope of the V-shaped valley, forming the deepest and steepest depression in the Strait, as shown in Fig. 3. The average water depth of the Strait is 25 m, and the deepest Laotieshan waterway is 86 m (Wang et al., 2017).

3.2 Formation Lithology

There are many strata with different ages in this area including Quaternary strata, Upper Tertiary strata, Upper Proterozoic phyllite with quartzite strata, and Upper Proterozoic slate quartzite interbedding. The underlying strata are granite. The Quaternary strata are predominantly Alluvium, Dlq-Diluvium, and marine deposit. The Alluvium is composed of 1-3 m thick gravel and brown-red clay. The thickness of Dlq-Diluvium varies greatly, generally 20 – 40 m, and the local thickness is more than 60 M. The Diluvium is mostly composed of gravel, gravel-bearing sub-sandy soil, and sub-clan. They are distributed on both sides of valleys, hillsides, and gentle places. Some are sandwiched with gravel beds and are rich in calcium. The marine deposits consist primarily of gravel, clay, silt, marine remains, and shells, which are distributed in the gentle coastline of major islands. The Upper Tertiary strata are basalts, chiefly distributed in Daheishan

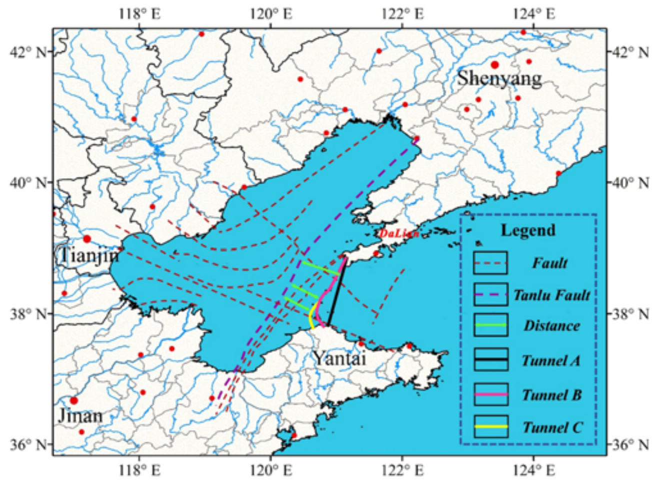

Fig. 4. Fault Distribution in Bohai Strait

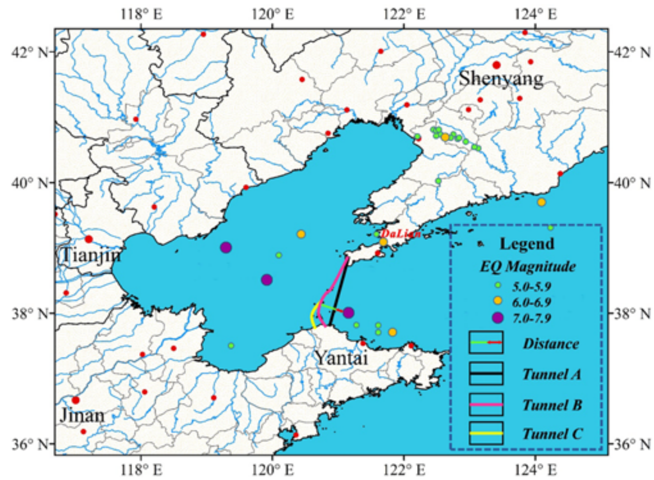

Fig. 5. Seismic Distribution around Bohai Strait

Island with a maximum thickness of 70 m (Wang, 2013).

3.3 Geologic Structure

Three groups of fault zones primarily exist in the geological structure of this area. The first is the Tanlu fault zone, NNE direction, which controls the eastern boundary of the Bohai Bay Basin. The Tanlu fault zone is the central fault zone in a series of NE trending mega-faults on the East Asian continent. It extends more than 2400 kilometers in China and has a magnificent scale and complex structure. It is a mega-active fault zone. The second one is the Zhangjiakou-Penglai fault zone, NWW direction, which controls the secondary structural uplift and depression in the sea area and cuts through the Tanlu fault zone in the central Bohai Sea. The last group is the NEE-EW trending faults, which are distributed in the depressions or uplifts in the western part of the Strait, as shown in Fig. 4 (Wang, 2013).

3.4 The Strait Meteorological Conditions

The annual average temperature in the Bohai Strait is 11.9 C°, the highest is 36.5 C° and the lowest is - 13.3 C°. The annual average gale days are 67.8 days and in winter, gale days are 23.4 days. The maximum wind speed appeared in typhoon No. 9 on August 19, 1985, which was 40 m/s.

3.5 Earthquake

The Bohai Strait belongs to the North China Seismic Region. It can be divided into Hebei Plain Seismic Zone, Tanlu Seismic Zone, Beijing-Bohai Strong Seismic Zone, Liaodong Seismic Zone, Western Liaoning Seismic Zone, and Shijiazhuang-Anqiu Seismic Zone. Ninety percent of the strong earthquakes with a magnitude of 6-6.9 and all large earthquakes with a magnitude greater than 7 occur in these zones, as shown in Fig. 5 (Qi et al., 2013).

4. Site Selection Scheme

After the previous introduction and combined with previous research results, there are currently three alternative routes for the Bohai Strait subsea tunnel, which are Line A, Line B, and Line C (Fig. 6).

Line A: Penglai East Port - Laotieshan. The southern section of the line begins at Penglai East Port, landing on the east side of Lushun Estuary through Dazhushan Island, with a straight line layout. The total length of the line is 113 km. The maximum water depth in the northern part of the Strait is 86 m and in the southern part of the Strait is 30 m. The scheme can use Dazhushan Island to set up a shaft and also to set up an artificial

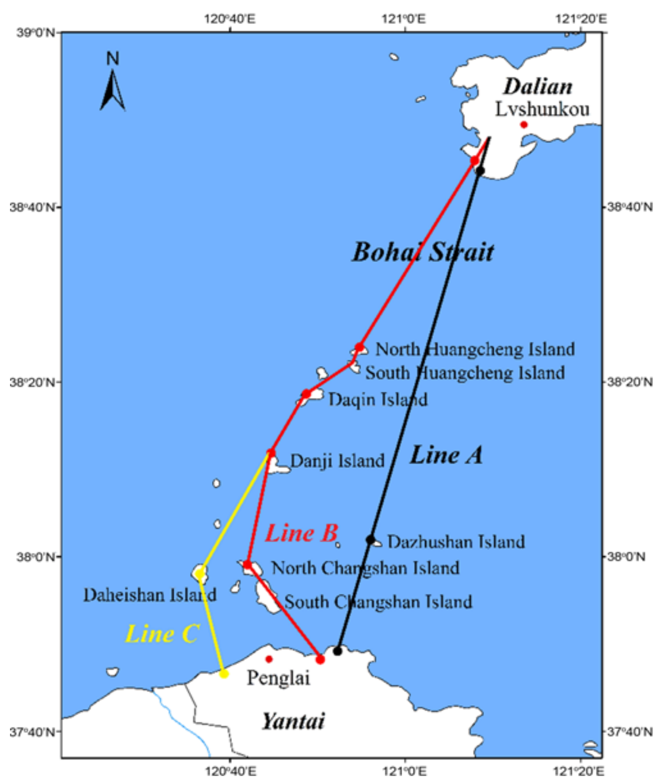

Fig. 6. Optional Route Map of Subsea Tunnel in Bohai Strait

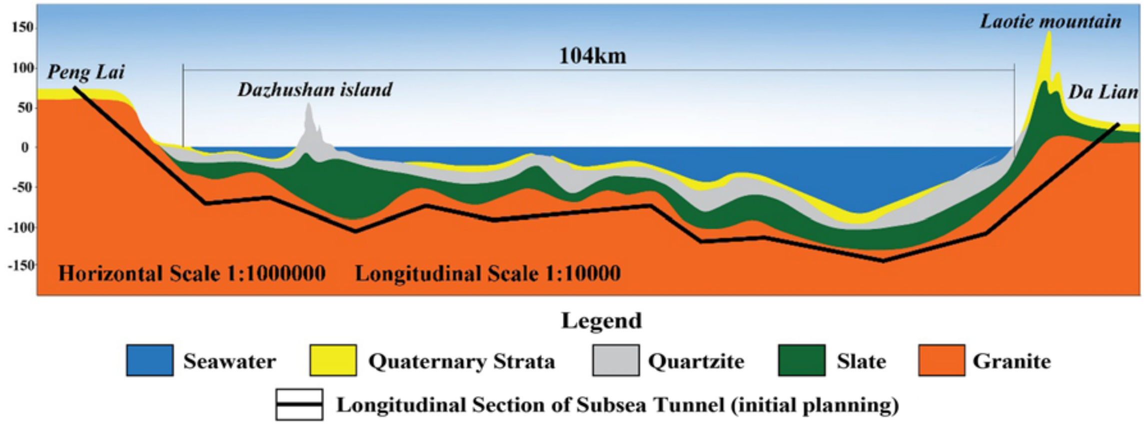

Fig. 7. Geological Profile of Line A

shaft in the northern part of the Strait (Fig. 7).

Line B: Penglai East Port-Nanchangshan Island-Beichangshan Island-Danji Island-Daqin Island-Nanhuangcheng Island-Northhuangcheng Island-Laotieshan. The route starts at Penglai East Port and lands at the northwest corner of Lushun Kou. The total length of the line is 125 km, the maximum water depth in the north is 85 m, and the maximum water depth in the south is 30 m. The scheme can set up vertical shafts on the islands along the route without building new artificial islands (Fig. 8).

Line C: Penglai Beacon Tower -Daheishan Island-Danji Island-Daqin Island-Nanhuangcheng Island-Northhuangcheng Island-Laotieshan. The total length of the line is 124 km, the

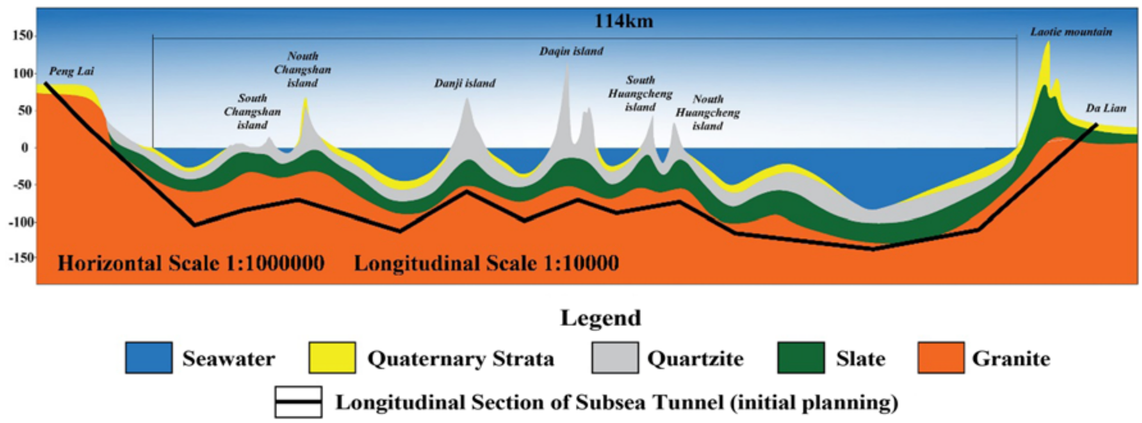

Fig. 8. Geological Profile of Line B

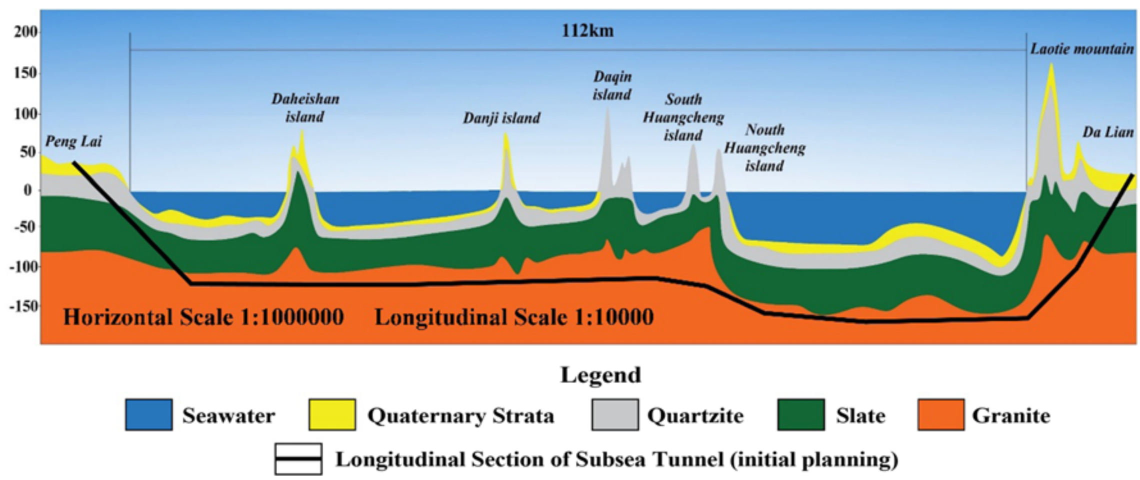

Fig. 9. Geological Profile of Line C

maximum water depth in the northern part of the Strait is 85 m, and the maximum water depth in the southern part of the Strait is 30 m. Shafts can be set up in Northhuangcheng Island and Daheishan Island (Fig. 9).

Due to the consensus on the site selection of the Dalian landing point at the north exit of the subsea tunnel, the Dalian Municipal Government has made reservations for the construction land of the subsea tunnel. Therefore, the divergence of the route selection of the Bohai Strait subsea tunnel is principally concentrated in the southern section. That is the archipelagic section. Through a preliminary analysis, it can be found that the lithology of the three lines is more similar, the rock mass quality is better, and the maximum thickness of the Quaternary strata is about 30 m. The maximum water depth is more similar too, about 80 – 87m. The three lines are located in the middle of the two groups of NNE trending fault zones and are parallel to the direction of the fault zone. They are about 40 km away from the Tanlu fault zone where the main earthquakes take place. The advantages and disadvantages of the three-line schemes are also evident. The length of line A is the shortest, only 113 km. However, in the sea area of 80 km north of Dazhushan Island, it is necessary to build at least one artificial island for construction and tunnel operation ventilation shaft. Line B passes through the main islands between the Straits and has the longest route. It can make full use of the islands to set up the shaft to provide construction sites without artificial islands. It can also set up entrances and exits in the main islands such as Northchangshan Island and Northhuangcheng Island to provide convenient transportation for the islanders. The total length of line C is moderate, and the shaft can be located in Daheishan Island and Northhuangcheng Island, which can meet the requirements of Tunnel Boring Machine (TBM) driving distance, construction, and tunnel operation ventilation. However, the landing point of the beacon platform has a significant impact on the landscape of Penglai, and Daheishan Island as an entrance and exit point is not convenient for residents of Changshan Island to travel.

Generally speaking, any of these three alternative routes can be chosen as a potential route. The main goal of this paper is to propose valuable and objective conclusions for these three alternative routes.

5. Influential indicators

5.1 Seabed Topography

Geomorphology is the basic condition of any engineering construction, which directly determines the construction cost of the above-ground projects and the buried depth of the underground projects. For the subsea tunnel, seabed topography determines the distance between the subsea tunnel and sea level and directly influences the site selection and construction cost of the subsea tunnel. In this paper, the deepest seawater depth H above the subsea tunnel is selected as an influencing indicator for the site selection and evaluation of the subsea tunnel (Fig. 10).

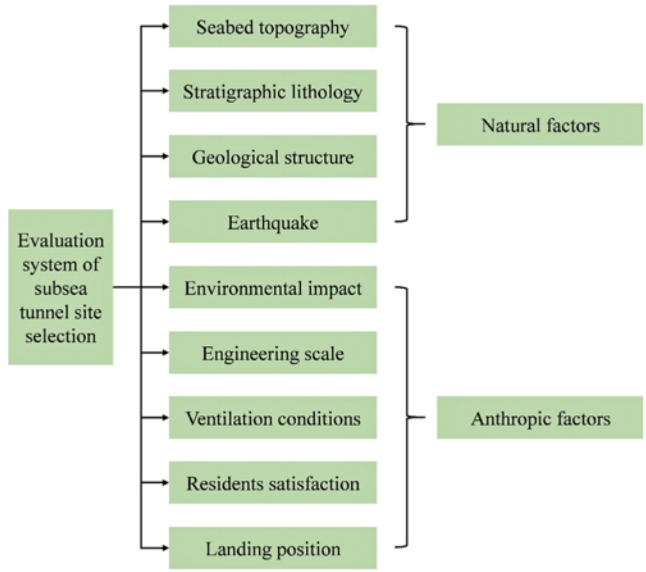

Fig. 10. Site Selection Evaluation Indicators of Bohai Strait Subsea Tunnel

5.2 Stratigraphic Lithology

Subsea tunnel site selection should try to choose rock strata with higher compressive strength lithology (Zhao et al., 2016). Hence, the basic quality index of the rock mass (BQ) is taken as an index in this project (Xue et al., 2020). This indicator is calculated according to the quantitative indicator of the rock uniaxial saturated compressive strength Rc (MPa) and the rock integrity coefficient Kv by the following equation:

$$BQ = 100 + 3Rc + 250Kv. \tag{9}$$

5.3 Geological Structure

It is important to improve the stability of subsea tunnels and to reduce the construction risk by crossing fewer fault zones or by thoroughly avoiding them (Nilsen, 2014). In the Bohai Strait, an NWW-trending fault and a NEE-EW-trending fault control the secondary structural uplift and depression in the sea area and cut through the Tanlu fault zone in the central part of the Bohai Sea. The construction of tunnels in the Bohai Strait will inevitably cross these two faults. Therefore, in this paper, the distance F between the subsea tunnel and Tanlu active fault zone is chosen as the evaluation indicator of the geological structure.

5.4 Earthquake

Earthquakes have a great impact on engineering construction. Although tunnels have a strong resistance to earthquakes, the location of subsea tunnels still should avoid the seismic zones as far as possible (Cheng et al., 2017). In this paper, the closest distance D of the subsea tunnel from the epicenter of an earthquake with a magnitude of 6 or more is selected as the evaluation indicator. The epicenter distribution is selected from the seismic observation records of the past 100 years.

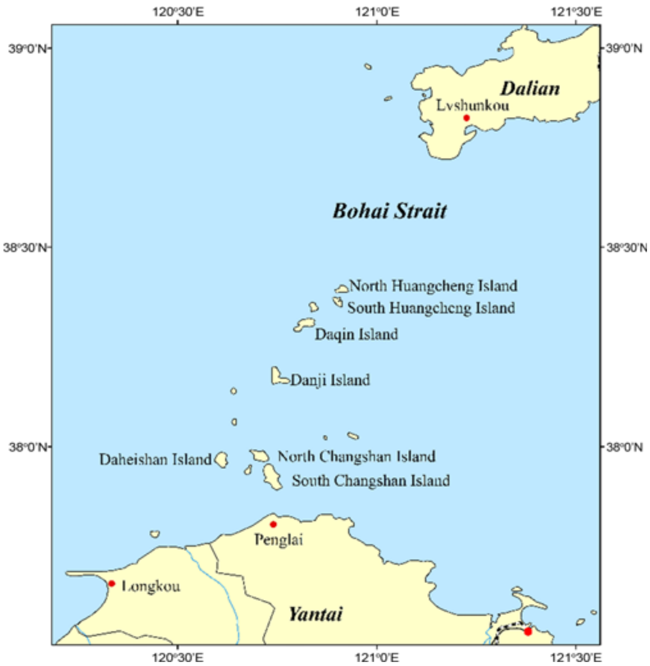

Fig. 11. Schematic Map of Island Location in Bohai Strait

5.5 Environmental Impact

The project site will occupy part of the local land resources which results in changes in the land environment. Therefore, the construction of the project should not only meet the requirements of environmental protection but also reduce the occupied land area as much as possible (Sherman et al., 1994). This project uses S as the evaluation indicator of the land area occupied by the project.

5.6 Engineering Scale

The construction cost and construction cycle of the subsea tunnel determine the feasibility of the construction of the subsea tunnel. The construction of the subsea tunnel should be carried out in such a way that the occurrence of higher engineering costs and longer construction time can be avoided (Anguera R, 2006). In this project, the total length L of the construction of the subsea tunnel is taken as the evaluation indicator.

5.7 Ventilation Conditions

The construction of shafts in Subsea tunnels not only meets the requirements of ventilation, passage, and drainage but also meets the requirements of shaft function and TBM's longest driving distance (Song et al., 2011). There are many natural islands in the Bohai Strait (Fig. 11) suggesting that artificial islands can be avoided in tunnel construction. In this project, the total number of islands is quantified by Q which is considered as the evaluation indicator.

5.8 Residents Satisfaction

A large number of local residents are living on the natural islands between the Bohai Strait tunnels (see Table 1). The tunnels have to be built such that the local residents can travel more conveniently during the operation of the tunnels. In this project, the number of residents R covered by tunnel shaft entrance and exit corridor is taken as the evaluation indicator (Wang et al., 2013).

5.9 Landing Position

The choice of landing position determines the final shape of the subsea tunnel and the land location of the entrance and exit of the subsea tunnel (Wang et al., 2017). This project chooses the reciprocal of the minimum curve radius r of the line and the product of the minimum distance ΔL between the landing point and the railway passenger dedicated line as the evaluation indicator. The minimum curve radius is equal to the radius of the curve in geometry. The reciprocal of this number can reflect the bending degree of the curve and can determine the smoothness of the line. The distance between the landing point and the railway determines the cost of integrating the subsea tunnel into the local railway network.

6. Determination of the Weight of Evaluation Index

To reflect the status and importance of each indicator in the evaluation indicator system, it is necessary to assign different weight coefficients to each indicator after the indicator system is determined (Huang et al., 2018). This paper utilizes the analytic hierarchy process to determine the weight of each indicator in the evaluation indicator system.

The greatest advantage of the analytic hierarchy process is that it allows us to decompose complex problems into several levels and indicators (Dong et al., 2010). It makes simple comparisons and calculations among various indicators and gets the weight of different indicators to provide the basis for the selection of the best scheme (Vaidya et al., 2006). From the perspective of feasibility and optimization of the research object, extenics transforms many evaluation indexes into a compatible problem and concludes the extenics evaluation of the research object. The site selection evaluation of subsea tunnels is a process in which the contradiction problem can be transformed into a compatibility problem by using extension theory. Combining the extension theory and analytic hierarchy process (AHP), this paper applies AHP to determine the weight coefficient of the

Table 1. Distribution of Permanent Residents in Islands

Name	Daheishan island	South changshan island	North changshan island	Danji island	Daqin island	South chenghuang island	North chenghuang island
Population	1,500	21,531	2,961	8,103	4,393	913	2,294

subsea tunnel evaluation indicator. The paper also employs the extension theory to analyze the grade range of the actual evaluation objects.

6.1 Analytic Hierarchy Process Theory

In the evaluation of subsea tunnel site selection, the weight has a significant impact on the final evaluation results such that different weights sometimes lead to different conclusions. There are many methods to determine the weight such as entropy weight method, expert evaluation synthesis method, analytic hierarchy process (AHP), and so on. AHP is a systematic analysis method proposed by Professor Saaty, an American operational researcher in the 1970s. It is an effective method for determining the weight, which divides the indicators in complex problems into interrelated ordered layers and makes them orderly (Ishizaka et al., 2011). It gives a quantitative expression of the relative importance of each layer according to the fuzzy judgment of objective reality. The AHP initially decomposes complex problems into simple constituent indicators step by step and groups these indicators into an ordered hierarchical structure based on dominance relations. Then, by pairwise comparison of these indicators, the relative importance of each indicator at each level can be obtained, and the multi-objective problem can be transformed into a weighted single-objective problem. It is logical, practical, and systematic to use AHP to determine the weight of each evaluation indicator (Li et al., 2017).

6.2 Steps Needed for Weight Determination

In this study, the steps of determining the weights of each evaluation indicator for the site selection of the Bohai Strait subsea tunnel by using AHP were as follows (Saaty, 1990).

6.2.1 Determination of the Evaluation Indicator

Nine evaluation indicators including seabed topography, stratigraphic lithology, geological structure, earthquake, environmental impact, engineering scale, ventilation conditions, residents' satisfaction, and landing position were selected.

6.2.2 Construction of the Judgment Matrix

When AHP is applied to evaluate the relative importance of indicators, the nine-point scale is introduced as shown in Table 2. It compares the values of each element α_{ij} in the judgment matrix as the indicator of row i with that of column j.

By geometrical averaging and normalizing of the row vectors of the comparative judgment matrix, the row vectors represent the weight vectors. Based on the evaluation indicator system of the alternative site selection of the Bohai Strait subsea tunnel and the principle of determining the weight by AHP, a questionnaire survey was designed for the comparative evaluation of line A, line B, and line C of the Subsea Tunnel. A pairwise comparison judgment matrix was constructed based on the expert rating. Out of the fifteen questionnaires distributed to relevant experts, fourteen were recovered and twelve were valid (Appendix). These twelve experts are all senior scholars in the field of subsea tunnel, including eight professors and four associate professors.

Table 3. Judgment Matrix *K*

EI	E1	E2	E3	E4	E5	E6	E7	E8	E9
E1	1	1/3	1/4	1/3	1/2	1/2	1/5	1/3	1/3
E2	3	1	1/3	1/2	2	1	1/4	1	2
E3	4	3	1	2	2	4	1	2	3
E4	3	2	1/2	1	3	2	1/2	1	3
E5	2	1/2	1/2	1/3	1	3	1/4	1/2	1/2
E6	2	1	1/4	1/2	1/3	1	1/4	1/3	1/3
E7	5	4	1	2	4	4	1	2	3
E8	3	1	1/2	1	2	3	1/2	1	2
E9	3	1/2	1/3	1/3	2	3	1/3	1/2	1

Note: E1 — Seabed topography; E2— Stratigraphic lithology; E3 — Geological structure; E4 — Earthquake; E5 — Environmental impact; E6 — Engineering scale; E7— Ventilation conditions; E8—Residents satisfaction; E9—Landing position.

The expert assignment of all questionnaires was processed by the geometric averaging method, namely $\bar{a}_{ij} = \sqrt[6]{\Pi_{n=1}^{6} a_{ij}^{(n)}}$, and the score was rounded to an integer. Ultimately, a comparison judgment matrix K that integrates all the expert opinions was obtained as shown in Table 3.

6.3 Weight Determination

Calculate the row product of judgment matrix K, then geometrically average the row product results, and finally normalize the geometric average results to obtain the weight vector.

$$K = [b_{rj}]_{n \times n} \tag{10}$$

$$\overline{w}_j = \sqrt[n]{\Pi_{j=1}^{n} b_{rj}}, r = 1, 2, 3, \ldots, n \tag{11}$$

Then we normalize the weight vectors and get the indicators weight:

$$w_j = \frac{\overline{w}_j}{\Sigma_{j=1}^{n} w_j}, j = 1, 2, 3, \ldots, n \tag{12}$$

where $\Pi_{j=1}^{n} b_{rj}$ is the product of every line element in the judgment matrix K, and $\overline{w}_j$ is the n-th root of w_j.

Table 2. Ratio Scale of Relative Importance

A index is better than *B* index	Extremely important	Very important	Important	Slightly important	Equal	Slightly minor	Minor	Very minor	Extremely minor
A index evaluation value	9	7	5	3	1	1/3	1/5	1/7	1/9
Remarks	Take 8,6,4,2,1/2,1/4,1/6,1/8 as the median of the above evaluation values								

6.4 Consistency Check

Because of the large number of paired comparisons, it is difficult to achieve complete consistency. In fact, any paired comparison allows for some degree of inconsistency. To solve the consistency problem, it is necessary to test the consistency of the comparative judgment matrix. The steps of consistency checking were as follows:

1. Calculation of the computational consistency indicator *CI* using the following equation:

$$W = (w_1, w_2, \ldots, w_n)^T, \tag{13}$$

$$\lambda_{max} = \Sigma_{j=1}^{n} \frac{(KW)_j}{nw_j}, \tag{14}$$

$$CI = \frac{\lambda_{max} - n}{n-1}, \tag{15}$$

$$CR = \frac{CI}{RI}, \tag{16}$$

where λ_{max} is the characteristic root of the comparative judgment matrix, and n is the number of evaluation indicators, *RI* is the random consistency indicator of judgment matrix *K*, and the numerical value can be found in Table 4, *CI* is the consistency indicator of judgment matrix *K*. When $CR < 0.1$, the consistency of the judgment matrix is acceptable, otherwise, it is necessary to readjust the judgment matrix.

2. Search for the corresponding average random consistency indicator *RI*. For $n = 1, 2, \ldots, 10$, the value of *RI* is shown in Table 4.

It was found through calculations that the maximum eigenvalue λ_{max} of the judgment matrix in this study is 9.4406, and the matrix consistency indicator *CI* is 0.0551. According to the Table 3, when $n = 9$, $RI = 1.46$, $CR = CI / RI = 0.0377 < 0.1$ which satisfies the consistency test.

The weights of each evaluation indicator can be obtained by comparing the judgment matrix in Table 3, as shown in Table 5.

From the weight results of evaluation indexes, it can be seen that ventilation conditions and geological structure are the most critical indicators affecting the site selection of subsea tunnels in the Bohai Strait. Because the development of active faults directly affects the design and construction of tunnels, it has a paramount impact on the construction of subsea tunnels. Ventilation conditions are the most critical auxiliary facilities in the construction of subsea tunnels. They are also considered as the necessary safeguard measures after the completion of subsea tunnels. Thus, ventilation conditions have a significant impact on the site selection of subsea tunnels, especially super-long tunnels such as the Bohai Strait subsea tunnel. Earthquake, residents' satisfaction, and landing position are the main indicators influencing the site selection of the Bohai Strait subsea tunnel. Earthquakes have the most direct impact on the project, however, because the subsea tunnel has stronger seismic resistance than other projects, the earthquake indicators influence is not paramount and has secondary importance. Many indicators impact the landing position including natural indicators and human indicators. Therefore, the landing position is also important for the site selection of subsea tunnels. Residents' satisfaction is also an important indicator. Gaining the support of residents can reduce the resistance in the construction of the subsea tunnel and can improve the management efficiency of the local government as well. The indicators that have little influence on the site selection of the Bohai Strait subsea tunnel are seabed topography, stratigraphic lithology, environmental impact, and engineering scale. The seabed topography and stratigraphic lithology of the Bohai Strait subsea tunnel are basically the same and these two evaluation indexes have a certain one-sided influence on the route selection of the Bohai Strait subsea tunnel. Hence, their weight is small. Environmental impact and engineering scale are the two aspects that must be taken into account in the construction of subsea tunnels. However, these two indicators can be adequately taken into consideration by increasing costs, which are small compared to the overall cost of subsea tunnels.

Table 4. RI Value of Mean Random Consistency Index

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.52	0.89	1.12	1.26	1.36	1.41	1.46	1.49

Note: RI— Average random consistency index.

Table 5. Weight of Evaluation Index

Evaluation index	E1	E2	E3	E4	E5	E6	E7	E8	E9
Weight	0.04	0.09	0.20	0.13	0.06	0.05	0.23	0.12	0.08

Note: E1 — Seabed topography; E2— Stratigraphic lithology; E3 — Geological structure; E4 — Earthquake; E5 — Environmental impact; E6 — Engineering scale; E7— Ventilation conditions; E8—Residents satisfaction; E9—Landing position.

7. Evaluation of Site Selection Scheme for the Bohai Strait Subsea Tunnel

Considering nine evaluation indicators as influencing indicators, the site selection of the Bohai Strait subsea tunnel can be evaluated comprehensively and reasonably by using AHP and extension theory. According to the actual survey work of the Bohai Strait subsea tunnel project and the related literature of the site selection and evaluation of similar subsea projects, the line site selection of the Bohai Strait subsea tunnel is divided into four grades: excellent, good, average, and bad. Through the analysis of a large number of site selection literature, we determined that the evaluation indicator is divided into four levels. Then we study the survey data and route planning of Bohai Strait subsea tunnel, and finally determined the ranges and values of each evaluation indicator. This paper proposes nine evaluation indicators to correspond them to the classification

Table 6. Value Range of Evaluation Index

Evaluation index	Evaluation grade			
	Excellent	Good	Average	Bad
H/m	0 – 30	30 – 50	50 – 100	100 – 120
BQ	640 – 1,000	370 – 640	280 – 370	100 – 280
F/kM	60 – 100	40 – 60	20 – 40	0 – 20
D/kM	80 – 100	50 – 80	20 – 50	0 – 20
S/m^2	0 – 100,000	100,000 – 200,000	200,000 – 300,000	300,000 – 500,000
L/kM	0 – 30	30 – 60	60 – 120	120 – 150
Q/set	6 – 8	4 – 5	2 – 3	<2
R/person	20,000 – 40,000	10,000 – 20,000	5,000 – 10,000	0 – 5,000
ΔL/r	0 – 0.71	0.72 – 3	3 – 10	10 – 12

Note: H—Deepest seawater depth; BQ— Basic quality index of rock mass; F—Distance between subsea tunnel and Tanlu active fault zone; D—Distance between the epicentre of an earthquake; S—Land area occupied by the project; L—Subsea tunnel total length; Q—Number of islands; R—Number of residents; ΔL/r—Landing position index.

Table 7. Normalization of Evaluation Indicators

Evaluation index	Evaluation grade			
	Excellent	Good	Average	Bad
H/m	0-0.25	0.25-0.42	0.42-0.83	0.83-1
BQ	0.6-1	0.3-0.6	0.2-0.3	0-0.2
F/kM	0.6-1	0.4-0.6	0.2-0.4	0-0.2
D/kM	0.8-1	0.5-0.8	0.2-0.5	0-0.2
S/m^2	0-0.2	0.2-0.4	0.4-0.6	0.6-1
L/kM	0-0.2	0.2-0.4	0.4-0.8	0.8-1
Q/set	0.75-1	0.5-0.75	0.25-0.5	0-0.25
R/person	0.5-1	0.25-0.5	0.125-0.25	0-0.125
ΔL/r	0-0.059	0.059-0.25	0.25-0.83	0.83-1

Note: H—Deepest seawater depth; BQ— Basic quality index of rock mass; F—Distance between subsea tunnel and Tanlu active fault zone; D—Distance between the epicentre of an earthquake; S—Land area occupied by the project; L—Subsea tunnel total length; Q—Number of islands; R—Number of residents; ΔL/r—Landing position index.

criteria as shown in Table 6.

Due to the different dimensions of the participating evaluation indexes, the range varies greatly and consequently, it is necessary to normalize each indicator. This is performed using Eq. (17):

$$v'_{ij} = \frac{v_{ij} - v_{ij}^{min}}{v_{ij}^{max} - v_{ij}^{min}}, \tag{17}$$

where v'_{ij} is the standard evaluation value of dimensionless v_{ij}, v_{ij}^{max} is the maximum evaluation value of the ith indicator, and v_{ij}^{min} is the minimum evaluation value of the ith indicator. The results of the dimensionless normalization of each indicator in Table 6 are shown in Table 7.

According to the relevant data of the Bohai Strait subsea tunnel, the corresponding values of nine indices of line A, line B, and line C are obtained as shown in Table 8.

Subsea tunnels are classified as *S1, S2, S3,* and *S4,* respectively. The evaluation indexes are recorded as *C1-C9*. The classical matter elements for each level of subsea tunnel site selection are as follows:

Table 8. Indicator Value of Alternative Line

Alternative line	H	BQ	F	D	S	L	Q	R	ΔL/r
Line A	0.717	0.583	0.35	0.05	0.52	0.753	0.375	0	0
Line B	0.708	0.528	0.20	0.22	0.76	0.833	0.875	0.98	0.23
Line C	0.708	0.511	0.18	0.22	0.72	0.807	0.625	0.40	0.185

Note: H—Deepest seawater depth; BQ— Basic quality index of rock mass; F—Distance between subsea tunnel and Tanlu active fault zone; D—Distance between the epicentre of an earthquake; S—Land area occupied by the project; L—Subsea tunnel total length; Q—Number of islands; R—Number of residents; ΔL/r—Landing position index.

The line grade is excellent:

$$R_{01} = \begin{bmatrix} S_1 & c_1 & \langle 0.00, 0.25 \rangle \\ & c_2 & \langle 0.60, 1.00 \rangle \\ & c_3 & \langle 0.60, 1.00 \rangle \\ & c_4 & \langle 0.80, 1.00 \rangle \\ & c_5 & \langle 0.00, 0.20 \rangle \\ & c_6 & \langle 0.00, 0.20 \rangle \\ & c_7 & \langle 0.75, 1.00 \rangle \\ & c_8 & \langle 0.50, 1.00 \rangle \\ & c_9 & \langle 0.00, 0.059 \rangle \end{bmatrix}.$$

The line grade is good:

$$R_{02} = \begin{bmatrix} S_2 & c_1 & \langle 0.25, 0.42 \rangle \\ & c_2 & \langle 0.30, 0.60 \rangle \\ & c_3 & \langle 0.40, 0.60 \rangle \\ & c_4 & \langle 0.50, 0.80 \rangle \\ & c_5 & \langle 0.20, 0.40 \rangle \\ & c_6 & \langle 0.20, 0.40 \rangle \\ & c_7 & \langle 0.50, 0.74 \rangle \\ & c_8 & \langle 0.25, 0.50 \rangle \\ & c_9 & \langle 0.059, 0.25 \rangle \end{bmatrix}.$$

The line grade is average:

$$R_{03} = \begin{bmatrix} S_3 & c_1 & \langle 0.42, 0.83\rangle \\ & c_2 & \langle 0.20, 0.30\rangle \\ & c_3 & \langle 0.20, 0.40\rangle \\ & c_4 & \langle 0.20, 0.50\rangle \\ & c_5 & \langle 0.40, 0.60\rangle \\ & c_6 & \langle 0.40, 0.80\rangle \\ & c_7 & \langle 0.25, 0.49\rangle \\ & c_8 & \langle 0.125, 0.25\rangle \\ & c_9 & \langle 0.25, 0.83\rangle \end{bmatrix}.$$

The line grade is bad:

$$R_{04} = \begin{bmatrix} S_4 & c_1 & \langle 0.83, 1.00\rangle \\ & c_2 & \langle 0.00, 0.20\rangle \\ & c_3 & \langle 0.00, 0.20\rangle \\ & c_4 & \langle 0.00, 0.20\rangle \\ & c_5 & \langle 0.60, 1.00\rangle \\ & c_6 & \langle 0.80, 1.00\rangle \\ & c_7 & \langle 0.00, 0.24\rangle \\ & c_8 & \langle 0.00, 0.125\rangle \\ & c_9 & \langle 0.83, 1.00\rangle \end{bmatrix}.$$

The controlled field:

$$R_P = \begin{bmatrix} P & c_1 & \langle 0.00, 1.00\rangle \\ & c_2 & \langle 0.00, 1.00\rangle \\ & c_3 & \langle 0.00, 1.00\rangle \\ & c_4 & \langle 0.00, 1.00\rangle \\ & c_5 & \langle 0.00, 1.00\rangle \\ & c_6 & \langle 0.00, 1.00\rangle \\ & c_7 & \langle 0.00, 1.00\rangle \\ & c_8 & \langle 0.00, 1.00\rangle \\ & c_9 & \langle 0.00, 1.00\rangle \end{bmatrix}.$$

The matter elements needed to be evaluated are determined according to Table 7. Line A, Line B, and Line C are represented by R_1 to R_3, respectively.

$$R_1 = \begin{bmatrix} N_1 & c_1 & 0.717 \\ & c_2 & 0.583 \\ & c_3 & 0.35 \\ & c_4 & 0.05 \\ & c_5 & 0.52 \\ & c_6 & 0.753 \\ & c_7 & 0.375 \\ & c_8 & 0.00 \\ & c_9 & 0.00 \end{bmatrix}, R_2 = \begin{bmatrix} N_2 & c_1 & 0.708 \\ & c_2 & 0.528 \\ & c_3 & 0.20 \\ & c_4 & 0.20 \\ & c_5 & 0.76 \\ & c_6 & 0.833 \\ & c_7 & 0.75 \\ & c_8 & 0.98 \\ & c_9 & 0.457 \end{bmatrix}, R_3 = \begin{bmatrix} N_3 & c_1 & 0.708 \\ & c_2 & 0.511 \\ & c_3 & 0.19 \\ & c_4 & 0.21 \\ & c_5 & 0.72 \\ & c_6 & 0.807 \\ & c_7 & 0.625 \\ & c_8 & 0.415 \\ & c_9 & 0.137 \end{bmatrix}$$

After constructing the classical matter-elements, the controlled matter-elements, and matter-elements needed to be evaluated for each grade, and also after combining the weight of each evaluation indicator and using the program *Extension.m*, the comprehensive correlation degree and extension evaluation grade of alternative lines can be calculated. The calculation results are shown in Table 9.

Table 9. Comprehensive Relevance Degree of Three Lines

Alternative lines	Excellent	Good	Average	Bad
Line A	-0.51653	-0.45758	-0.05522	-0.23605
Line B	-0.25324	-0.46873	-0.32848	-0.40497
Line C	-0.45146	-0.04352	-0.15981	-0.28328

According to Eq. (7), the grade of line A is level three, the grade of line B is level one, and the grade of line C is level two.

Based on Eq. (8), the t^* value of the alternative lines can be obtained. As the final evaluation result, the result of the program output is as follows:

{Line A = 3.2767, Line B = 2.1033, Line C = 2.7525}

From the above result, it can be concluded that the optimal line for the Bohai Strait subsea tunnel is line B. Line C takes second place and line A is the worst. From the result of Eq. (7), we can know the grade of each alternative line. From the result of Eq. (8), we can know the specific score of each alternative line, and the smaller the score, the better the line. These two results can be mutually verified. Different from the result $k_{tmax}(N_i)$, t^* is more specific. If there are two alternative lines with the same grade, we can not know the difference between the two lines only through $k_{tmax}(N_i)$, but we can see the difference by t^*. The result t^* obtained from Eq. (8) is more intuitive, and the specific score and ranking of each line are very clear. Through the result $k_{tmax}(N_i)$, we can't distinguish the difference of the same grade alternative lines, which is the inherent drawback of the extension theory. By improving the extension theory, we creatively put forward the parameter t^* to further deepen it. The problem that the extension theory can only be classified but can't be sorted at the same grade is solved by this parameter. In this paper, we apply the theory to the field of subsea tunnel site selection, and the results show that the method is effective in this field. This case study has made some contribution for the innovation of the subsea tunnel siting model quantification and the application field expansion of extension theory.

8. Discussion

1. This paper evaluated the alternative lines of the Bohai Strait subsea tunnel by quantitative evaluation method. The data were based on the preliminary investigation results of the Bohai Strait subsea tunnel project. Because the data were more general and macro, there are still many uncertainties. For example, the geological structure of the three alternative lines suggested that only two faults are crossed, however, specific data did not support the lithology, distribution, and activity of the two faults. It is also uncertain whether there are other faults or other undesirable geological structures in the Strait. As a result, to procure a more reliable basis for evaluation, it is urgent to carry out a comprehensive and

detailed survey of the Bohai Strait and to further study the site selection based on the detailed survey results.

2. Bohai Strait subsea tunnel is a rare subsea tunnel in the world because of its long-distance, large burial depth, significant engineering details, and tremendous investment. The construction of such a landmark project needs to be treated more carefully and scientifically especially concerning the subsea tunnel site selection. To do this, the various influencing indicators need to be balanced to make an accurate judgment. The subsea tunnel has to win the support of the public and the favor of the investors. Thus, it is necessary to conduct more extensive and in-depth research on the Bohai Strait subsea tunnel to gain beneficial experience in the construction of the super-long subsea tunnel. Such research is also needed to provide a rich and comprehensive reference for the construction of the long subsea tunnel in the future.

9. Conclusions

The following striking conclusions were achieved during this research:

Based on the Bohai Strait subsea tunnel project, this paper employed a new method to evaluate the site selection of the subsea tunnel and to assess three alternative lines of the subsea tunnel comprehensively. In this respect, nine evaluation indicators were selected to establish an evaluation indicator system. By combining the analytic hierarchy process and extension theory, an evaluation model for site selection of the subsea tunnel in the Bohai Strait was established. This model not only provides a reference for the construction of the Bohai Strait subsea tunnel but also offers some references for the site selection of the subsea tunnels in other parts of the world as well.

The Bohai Strait subsea tunnel has three alternative lines; each of them has obvious advantages and disadvantages. This study established an evaluation model for the subsea tunnel site selection of the Bohai Strait and evaluated each line by a quantitative method comprehensively and objectively. Finally, the result indicated that line B is the best option, line C is the second option, and line A is the worst choice.

At present, the research on the location evaluation of the subsea tunnel is still at a primary level and most of the route schemes still rely on the subjective experience of experts. Although these schemes can take full advantage of the experience of the experts, they can not avoid the shortcomings of subjective one-sidedness and so on. In this research, by giving full play to the experience of experts, the comprehensive quantitative evaluation method was introduced into the location evaluation of the subsea tunnel. Through this method, a contribution was made regarding the location evaluation of the subsea tunnel and an ultimate result was proposed.

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Appendix: Sample of Questionnaires

Table 10. Questionnaire for Expert 1

EI	E1	E2	E3	E4	E5	E6	E7	E8	E9
E1	1	1/2	1/3	1/3	1/3	1/2	1/4	1/3	1/2
E2	2	1	1/3	1/2	1	1	1/3	1/2	2
E3	3	3	1	2	1	3	1	3	4
E4	3	2	1/2	1	2	3	1/2	1	3
E5	3	1	1	1/2	1	2	1/4	1	1/2
E6	2	1	1/3	1/3	1/2	1	1/3	1/4	1/2
E7	4	3	1	2	4	3	1	3	3
E8	3	2	1/3	1	1	4	1/3	1	2
E9	2	1/2	1/4	1/3	2	2	1/3	1/2	1

Table 11. Questionnaire for Expert 2

EI	E1	E2	E3	E4	E5	E6	E7	E8	E9
E1	1	1/3	1/3	1/2	1/2	1/2	1/4	1/3	1/3
E2	3	1	1/3	1	2	1/2	1/3	1/2	2
E3	3	3	1	1	1	3	2	1	2
E4	2	1	1	1	3	3	1	2	3
E5	2	1/2	1	1/3	1	3	1/4	1/2	1
E6	2	2	1/3	1/3	1/3	1	1/4	1/3	1/4
E7	4	3	1/2	1	4	4	1	2	3
E8	3	2	1	1/2	2	3	1/2	1	2
E9	3	1/2	1/2	1/3	1	4	1/3	1/2	1

Table 12. Questionnaire for Expert 3

EI	E1	E2	E3	E4	E5	E6	E7	E8	E9
E1	1	1/3	1/4	1/4	1/2	1/2	1/5	1/3	1/3
E2	3	1	1/4	1/2	2	1/2	1/4	1	1
E3	4	4	1	2	2	4	2	2	3
E4	4	2	1/2	1	3	2	1/2	1	3
E5	2	1/2	1/2	1/3	1	3	1/3	1/2	1/2
E6	2	2	1/4	1/2	1/3	1	1/3	1/4	1/4
E7	5	4	1/2	2	3	3	1	2	3
E8	3	1	1/2	1	2	4	1/2	1	2
E9	3	1	1/3	1/3	2	4	1/3	1/2	1

Table 13. Questionnaire for Expert 4

EI	E1	E2	E3	E4	E5	E6	E7	E8	E9
E1	1	1/2	1/4	1/3	1/2	1/3	1/4	1/4	1/4
E2	2	1	1/2	1/3	3	1/2	1/4	2	3
E3	4	2	1	2	2	3	1	3	3
E4	3	3	1/2	1	4	2	1/2	1	4
E5	2	1/3	1/2	1/4	1	4	1/3	1	1
E6	3	2	1/3	1/2	1/4	1	1/5	1/4	1/3
E7	4	4	1	2	3	5	1	2	4
E8	4	1/2	1/3	1	1	4	1/2	1	3
E9	4	1/3	1/3	1/4	1	3	1/4	1/3	1

Table 14. Questionnaire for Expert 5

EI	E1	E2	E3	E4	E5	E6	E7	E8	E9
E1	1	1/4	1/4	1/3	1/2	1/2	1/5	1/3	1/3
E2	4	1	1/4	1/2	2	1	1/5	1/2	2
E3	4	4	1	3	3	3	1	1	3
E4	3	2	1/3	1	2	1	1/3	1/2	2
E5	2	1/2	1/3	1/2	1	4	1/3	1	1/2
E6	2	1	1/3	1	1/4	1	1/4	1/3	1/2
E7	5	5	1	3	3	4	1	2	3
E8	3	2	1	2	1	3	1/2	1	2
E9	3	1/2	1/3	1/2	2	2	1/3	1/2	1

Table 15. Questionnaire for Expert 6

EI	E1	E2	E3	E4	E5	E6	E7	E8	E9
E1	1	1/3	1/3	1/3	1/3	1/3	1/5	1/2	1/2
E2	3	1	1/2	1	2	2	1/5	1/2	2
E3	3	2	1	2	2	4	2	2	4
E4	3	1	1/2	1	3	3	1	2	2
E5	3	1/2	1/2	1/3	1	2	1/4	1/2	1/3
E6	3	1/2	1/4	1/3	1/2	1	1/3	1/3	1/2
E7	5	5	1/2	1	4	3	1	2	2
E8	2	2	1/2	1/2	2	3	1/2	1	1
E9	2	1/2	1/4	1/2	3	2	1/2	1	1

Table 16. Questionnaire for Expert 7

EI	E1	E2	E3	E4	E5	E6	E7	E8	E9
E1	1	1/3	1/5	1/2	1/2	1/2	1/5	1/4	1/4
E2	3	1	1/3	1/3	1	1	1/4	1/2	3
E3	5	3	1	1	3	4	1/2	2	2
E4	2	3	1	1	4	2	1	2	3
E5	2	1	1/3	1/4	1	3	1/3	1/3	1/3
E6	2	1	1/4	1/2	1/3	1	1/3	1/3	1/3
E7	5	4	2	1	3	3	1	3	4
E8	4	2	1/2	2	3	3	1/3	1	3
E9	4	1/3	1/2	1/3	3	3	1/4	1/3	1

Table 17. Questionnaire for Expert 8

EI	E1	E2	E3	E4	E5	E6	E7	E8	E9
E1	1	1/2	1/4	1/4	1/2	1/2	1/5	1/3	1/4
E2	2	1	1/3	1/2	2	2	1/4	1	2
E3	4	3	1	3	1	5	2	3	2
E4	4	2	1/3	1	4	2	1/2	1	3
E5	2	1/2	1	1/4	1	3	1/4	1/3	1/3
E6	2	1/2	1/5	1/2	1/3	1	1/4	1/3	1/3
E7	5	4	1/2	2	4	4	1	2	2
E8	3	1	1/3	1	3	3	1/2	1	2
E9	4	1/2	1/2	1/3	3	3	1/2	1/2	1

Table 18. Questionnaire for Expert 9

EI	E1	E2	E3	E4	E5	E6	E7	E8	E9
E2	3	1	1/2	1/3	3	1	1/3	1/2	1
E3	5	2	1	2	3	4	1	3	5
E4	2	3	1/2	1	3	3	1/2	1/2	3
E5	2	1/3	1/3	1/3	1	4	1/2	1/2	1/2
E6	1	1	1/4	1/3	1/4	1	1/4	1/2	1/3
E7	4	3	1	2	2	4	1	2	2
E8	3	2	1/3	2	2	2	1/2	1	1
E9	3	1	1/5	1/3	2	3	1/2	1	1

Table 19. Questionnaire for Expert 10

EI	E1	E2	E3	E4	E5	E6	E7	E8	E9
E1	1	1/2	1/5	1/3	1/3	1/3	1/5	1/4	1/3
E2	2	1	1/3	1/2	2	1	1/4	1	3
E3	5	3	1	2	2	5	1	2	3
E4	3	2	1/2	1	3	2	1/2	1/2	2
E5	3	1/2	1/2	1/3	1	2	1/5	1/3	1/2
E6	3	1	1/5	1/2	1/2	1	1/3	1/3	1/3
E7	5	4	1	2	5	3	1	2	3
E8	4	1	1/2	2	3	3	1/2	1	2
E9	3	1/3	1/3	1/2	2	3	1/3	1/2	1

Table 20. Questionnaire for Expert 11

EI	E1	E2	E3	E4	E5	E6	E7	E8	E9
E1	1	1/4	1/4	1/3	1/3	1/2	1/5	1/3	1/3
E2	4	1	1/2	1/3	1	1/2	1/3	1/2	1
E3	4	2	1	2	2	3	1/2	3	2
E4	3	3	1/2	1	2	1	1/3	1/2	2
E5	3	1	1/2	1/2	1	3	1/5	1/2	1/3
E6	2	2	1/3	1	1/3	1	1/5	1/3	1/4
E7	5	3	2	3	5	5	1	3	3
E8	3	2	1/3	2	2	3	1/3	1	2
E9	3	1	1/2	1/2	3	4	1/3	1/2	1

Table 21. Questionnaire for Expert 12

EI	E1	E2	E3	E4	E5	E6	E7	E8	E9
E1	1	1/3	1/3	1/2	1/2	1/2	1/5	1/2	1/4
E2	3	1	1/4	1	2	1	1/5	1	2
E3	3	4	1	3	2	3	1	2	3
E4	2	1	1/3	1	4	3	1/2	2	4
E5	2	1/2	1/2	1/4	1	3	1/5	1/2	1/2
E6	2	1	1/3	1/3	1/3	1	1/4	1/2	1/3
E7	5	5	1	2	5	4	1	2	3
E8	2	1	1/2	1/2	2	2	1/2	1	1
E9	4	1/2	1/3	1/4	2	3	1/3	1	1