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# AHP-Ideal Point Model for Large Underground Petroleum Storage Site Selection: An Engineering Application

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**Abstract:** Scientific site selection can significantly reduce construction risk and cost during construction of underground petroleum storage. Based on the analytic hierarchy process (AHP) theory and ideal point theory, a new site selection model for large underground petroleum storage is established in this paper. Nine indicators are selected as evaluation indices, including joint development, natural water-sealed condition, rock mass strength, in situ stress, environmental ecological vulnerability, regional stability, technical and economic conditions, topography, and meteorological conditions. Based on AHP theory, the weight of each evaluation index is determined. Secondly, the positive and negative ideal solutions of these evaluation indices are determined using ideal point theory. The ideal point evaluation function of each evaluation index is built to calculate the degree of closeness for the evaluation samples. Finally, the accuracy of the model is verified by using the model to evaluate the first underground petroleum storage project in China. The results show that the first six indicators are main controlling factors, and the sum of their weight is 88.3%. The result of the evaluation site level is good (II), which is suitable for construction. Moreover, the feasibility and accuracy of the evaluation criteria, and evaluation method is verified after cooperation with the power coefficient method and expert evaluation method. The research results can provide some references to the site selection of similar key projects.

**Keywords:** underground petroleum storage; site selection evaluation; analytic hierarchy process theory; ideal point theory

## 1. Introduction

Underground water-sealed petroleum storage is an important method for storing national strategic reserves of oil (gas). The petroleum reservoir principle of water-sealed rock caverns states that petroleum may be safely stored in an underground cavern below the stable groundwater level [1]. After World War II, the Scandinavian Peninsula, South Korea, Japan, the United States, Germany, France, Saudi Arabia, and other countries and regions established groundwater-sealed petroleum reservoirs [2–5]. In some countries, the total oil reserves in contained groundwater caverns are in excess of tens of millions of cubic meters. China began to carry out research and construction on underground petroleum storage in the 1970s. At present, only a few relatively small underground petroleum storage reservoirs were built, which do not meet the needs of the current national strategic oil reserves. It is imperative to construct a large number of underground water-sealed petroleum storages units in the future [6].

Site selection has significant implications for construction risk, cost, and maintenance. Underground water-sealed petroleum storage units have stringent requirements on the storage environment. Once oil (gas) begins to leak, the cave is damaged, which may cause significant losses. Therefore, scientific and rational site selection is of great significance to the long-term stability of groundwater caverns.

At present, the study of underground water-sealed petroleum storage mainly focuses on three aspects [7–9]: regional stability, rock mass stability, and groundwater conditions. Regional stability is an important prerequisite for ensuring project safety. Regional stability research in the planning and site selection stage has important strategic significance so that site selection can avoid potential stability risks as much as possible. Regional stability studies that were carried out for relevant key projects, such as the Three Gorges Project [10], the South-North Water Diversion Project [11], and a nuclear power stations selections [12], can provide references and support for the site selection of underground water-sealed petroleum storage. Rock mass stability and groundwater conditions are studied based on either the theory of continuous medium or discontinuous medium. Considering the anisotropy of the rock mass, the stability of the surrounding rock of the underground oil reservoir during excavation, support, pressurization, and commissioning were analyzed [5,13–15]. Furthermore, the stability of underground water-sealed petroleum storage under two-dimensional and three-dimensional fluid-solid coupling was studied using numerical simulation [16,17]. The discrete model is more reasonable than the continuous model for reflecting groundwater seepage into the fractured rock mass.

There are many factors influencing site selection evaluation of water-sealed oil storage, including factors such as regional stability, geological conditions, hydrogeology, water-sealed condition, safety, environmental protection type, technical and economic feasibility, and field construction conditions. The general principles to be followed when establishing a strategic oil reserve are to locate: (1) the lowest reserve costs; (2) the highest degree of safety and reliability; (3) the most suitable geological conditions; and (4) the most convenient storage and distribution of the oil [18]. At present, there is no uniform standard for site selection in different countries around the world. Similar research work is commonly held as national secrets and is not publically available [1,19].

Therefore, how to evaluate the location of an oil depot scientifically, reasonably, and economically is an urgent problem. This paper set up a site selection evaluation system of underground petroleum storage from aspects of engineering geological conditions, rock stability, and groundwater conditions. In the meanwhile, a new site selection evaluation model based on the analytic hierarchy process (AHP) theory and ideal point theory is established for high accuracy and maneuverability to solve urgent engineering problems.

## 2. Materials and Methods

### *2.1. Study Area*

#### 2.1.1. Project Situation

The underground project is the first large-scale underground petroleum storage construction project in Qingdao, China. The main body of the structure is located on the south side of Longque Mountain. The average ground elevation is 220 m, the maximum elevation is 350.9 m, the lowest elevation is 97.50 m, and the relative height difference is 253.40 m. The underground petroleum storage is oriented in the north–west direction, with an east–west width of 600 m and a north–south width of 838 m. The underground reservoir is composed of nine caverns. The storage cavern spans 20 m. The height is 30 m and the cross-section shape is a straight wall with a round arch. The space between the cavern wall and the wall of the adjacent construction tunnel is 25 m, and the interval between the two caverns is 30 m (Figure 1) [1].

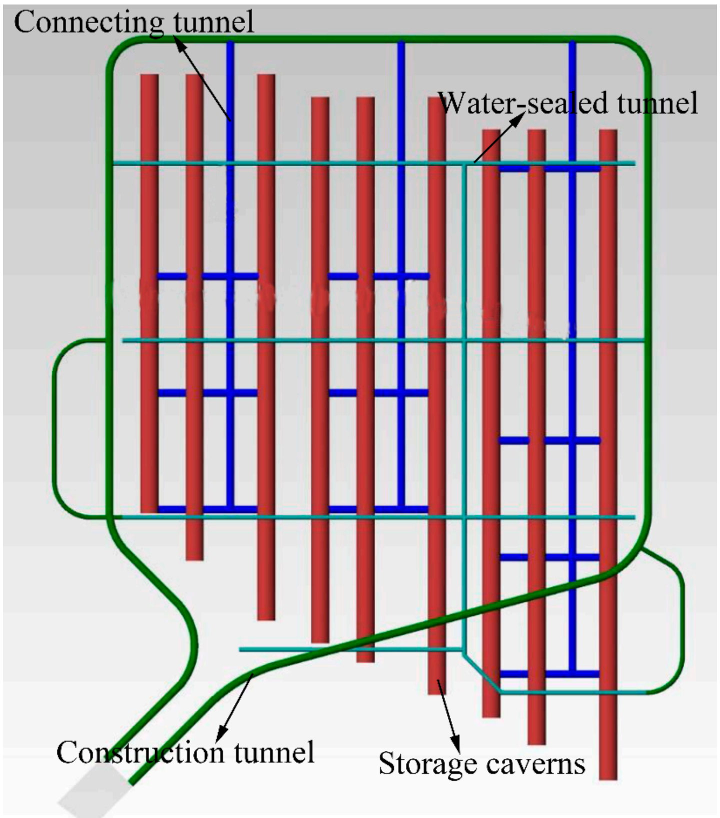


**Figure 1.** Layout plan of underground water-sealed petroleum storage depot.

#### 2.1.2. Hydrogeology

The main groundwater source in this area is fractured rock mass pore water and bedrock fissure water. Water depth is between 0.18 and 143.00 m, and the average precipitation is between 711.2 and 798.6 mm, mainly in the period from June to September. Groundwater is supplied by rainfall.

#### 2.1.3. In Situ Stress

The stress in the reservoir area is dominated by horizontal tectonic stresses defined by a: (1) maximum principal stress of 13–16 MPa, the minimum horizontal principal stress of 6–9 MPa, and vertical stress of 3–10 MPa. The relationship between the three principal stresses is $\sigma_H > \sigma_h > \sigma_v$, and the maximum principal stress is the horizontal principal stress; and (2) The maximum principal stress is in the W–NW direction. The basic seismic intensity of the site is six degrees, and the basic acceleration of the designed earthquake is 0.05 $g$.

#### 2.1.4. Formation Lithology

The primary rock formations in the cavern include: (1) an Early Cretaceous Monzogranite with a fine-grained granitic texture, blocky structure, complete rock mass, and high strength; and (2) a Late Proterozoic granite with a fine-grained granitic gneiss texture, blocky structure, and its rock mass ranging from broken to complete, which accounts for more than 80% of the rock mass in the storage cavern.

#### 2.1.5. Geological Structure

There are many fractures in and around the reservoir area, and the surface rock masses above the fault area are broken, the width of the crushing zone is no more than 1 m and the influence zone of fault is no more than 10 m. The development of fissures in the reservoir area is affected by several major faults. There are four main structural planes present (Table 1, Figure 2).

**Table 1.** Main structure fissures statistics in the reservoir area.

| No. | Occurrence | Dip | Type |
|---|---|---|---|
| L1 | 60~75° | ∠70~80° | Structure fissure |
| L2 | 83~88° | ∠75~82° | Structure fissure |
| L3 | 112° | ∠56° | Structure fissure |
| L4 | 136~143° | ∠74~85° | Structure fissure |

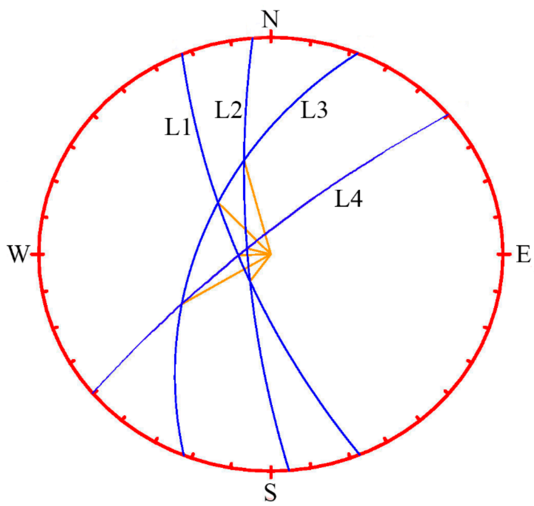


**Figure 2.** Main structure fissures stereographic projection.

## 2.2. Method

### 2.2.1. AHP Principle of Site Selection Evaluation Indices

The analytic hierarchy process (AHP) is a structured technique for organizing and analyzing complex decisions, based on mathematics and psychology. It was developed by Thomas L. Saaty in the 1970s [20] and has been extensively studied and refined since then. It has particular application in group decision-making, and is used around the world in a wide variety of decision situations.

The weight of each evaluation index is analyzed by using the AHP. A hierarchical model is built, and a judgment matrix is constructed. $P = (a_{ij})_{n\times n}$ for each level by using the 1~9 scale method proposed by professor Saaty [21]. $a_{ij}$ represents the relative importance of $i$th indicator to the $j$th indicator. Equations (1)–(4) are used to calculate the factor weight vector $\omega$, the maximum eigenvalue $\lambda_{max}$, and the random consistency ratio $CR$, When $CR < 0.1$, it is considered that the consistency of the judgment matrix is acceptable, and if it is not satisfied, the judgment matrix $P = (a_{ij})_{n\times n}$ must be modified again [22]. When $n$ is 3 to 10, the random consistency ratio $RI$ values are, respectively, 0.58, 0.90, 1.12, 1.24, 1.32, 1.41, 1.45, and 1.49.

$$W_i = \frac{\left(\prod_{j=1}^{n} a_{ij}\right)^{\frac{1}{n}}}{\sum_{i=1}^{n}\left(\prod_{j=1}^{n} a_{ij}\right)^{\frac{1}{n}}} \tag{1}$$

$$\lambda_{max} = \frac{\sum_{i=1}^{n}((P\omega)_i/\omega_i)}{n} \tag{2}$$

$$CI = \frac{\lambda_{max} - n}{n-1} \tag{3}$$

$$CR = \frac{CI}{RI} \tag{4}$$

In order to keep the judgment matrix objective, this paper examines relevant engineering examples by means of statistical and literature studies [1,10–12]. The main factors that need to be considered in the selection of underground water-sealed petroleum storage depots are analyzed from the aspects of construction difficulty, geological conditions, and construction conditions. In the AHP theory, site selection suitability evaluation of large underground petroleum storage is the target (upper) level, remarked as the A layer, and then the nine indicators are the guidelines (lower) layer, remarked as B1 to B9. The hierarchical model of the main influencing factors is shown in Table 2. In addition, the relationship between the various factors and the impact degree of the various factors on site selection are examined by analysis of the weight of the factors.

**Table 2.** Site selection evaluation hierarchical model of main influencing factors.

| Target A Layer | Single Evaluation Index of B Layer |
|---|---|
| Large Underground Petroleum Storage Site Selection Evaluation (A) | Joint development B1<br>Natural Water-Sealed Condition B2<br>Rock Mass Strength B3<br>In situ Stress B4<br>Environmental Vulnerability B5<br>Regional Stability B6<br>Technical and Economic Condition B7<br>Topography B8<br>Meteorological conditions B9 |

### 2.2.2. Evaluation Principle Based on the Ideal Point Method

The ideal point method [23] is a multi-objective planning method. It constructs positive and negative ideal points about these indices of large underground petroleum storage site selection by considering a variety of factors and determines whether the target attribute of the evaluated object is close to the ideal point or not. This paper initially confirms weight values of all site selection indicators by using the AHP method, and then evaluates the site selection of an underground petroleum storage by using the ideal point method [23,24]. The evaluation procedure is discussed in detail in the Figure 3.

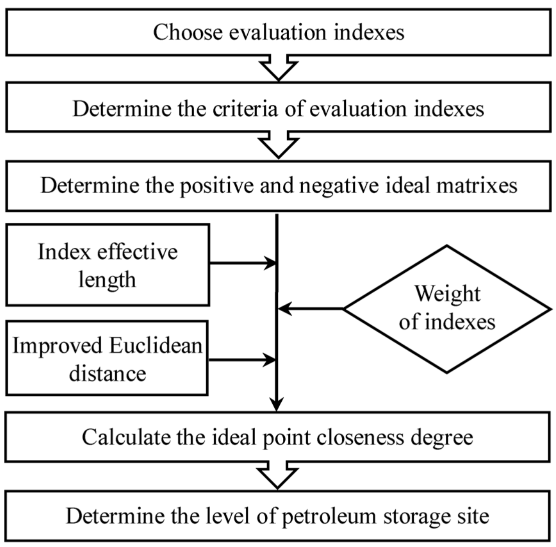


**Figure 3.** Ideal point method evaluation process.

Establishment of Evaluation Indicators Function

Assuming there are $n$ evaluation indices of site selection model, and these $n$ evaluation indices are regarded as $n$ objective function to evaluate the site selection, the evaluation system can be expressed as a vector function as $F(x) = [f_1(x), f_2(x), \ldots, f_n(x)]$.

Confirm Positive and Negative Ideal Points

The evaluation indicators of site selection of underground petroleum storage can be divided into positive indicators and reverse indicators. The site selection suitability increases with an increase in any of the positive indicators, whereas the site selection suitability increases with a decrease in the reverse indicators, or vice versa. Suppose the site selection evaluation indicators of underground petroleum storage show a monotonous trend, the positive and negative ideal points can be confirmed.

If the site selection evaluation indicators are positive, the corresponding vectors of the positive and negative ideal points are as follows:

$$\begin{cases} f_i^*(+) = max f_i(x),\ i = 1, 2, \cdots, n \\ f_i^*(-) = min f_i(x),\ i = 1, 2, \cdots, n \end{cases} \tag{5}$$

If the site selection evaluation indicators are negative, the corresponding vectors of the positive and negative ideal points are as follows:

$$\begin{cases} f_i^*(+) = min f_i(x),\ i = 1, 2, \cdots, n \\ f_i^*(-) = max f_i(x),\ i = 1, 2, \cdots, n \end{cases} \tag{6}$$

where $f_i^*(+)$ and $f_i^*(-)$ refer to the positive ideal point and negative ideal point vectors of the $i$th indicator of the site selection evaluation indicators.

Ideal Point Evaluation Function

The ideal point evaluation function refers to the distance from the indicator to the ideal point and from the indicator to the negative ideal point. Here, considering the different units and the value of each index, the improved Euclidean distance is used to define the relative distances to the positive ideal point and to the negative ideal point. The parameter $L_i$ refers to the effective length of the index and is shown as Equation (7):

$$L_i = |f_i(x)_{max} - f_i(x)_{min}| \tag{7}$$

The distance to the positive ideal point is shown as Equation (8):

$$D_1 = \left\{ \sum_{i=1}^{n} W_i \left[ \frac{f_i(x) - f_i^*(+)}{L_i} \right]^2 \right\}^{1/2} \tag{8}$$

The distance to the negative ideal point is shown as Equation (9):

$$D_2 = \left\{ \sum_{i=1}^{n} W_i \left[ \frac{f_i(x) - f_i^*(-)}{L_i} \right]^2 \right\}^{1/2} \tag{9}$$

Calculate the Ideal Point Closeness Degree

The calculation equation for the ideal point closeness degree is:

$$T = D_2/(D_1 + D_2) \tag{10}$$

Apparently, $T$ is in the interval station of [0, 1]. If $T$ is large, then the distance to the positive ideal point is close and the distance to the negative ideal point is far.

### *2.3. Site Selection Evaluation System of Underground Petroleum Storage*

#### 2.3.1. Site Selection-Influencing Factors

##### Joint Development

An underground petroleum storage depot requires a rock mass with relatively high structural integrity. The fewer the joints, the greater the stability of the caverns, and the better the water sealability of the caverns. The rock mass integrity index ($K_V$) can be used as the quantitative evaluation index for the numbers of joints. The rock mass integrity index ($K_V$) is chosen as the quantitative evaluation index for the joint development.

##### Natural Water-Sealed Condition

The site must maintain a stable groundwater level so that the water pressure can seal the joints in the rock mass. Water seal conditions require the vertical hydraulic gradient above the cave to be greater than 1. The higher the groundwater level is, the shallower the cave, which reduces construction time and cost. We select the maximum depth of the underground buried depth ($Dw$) as a quantitative evaluation index, and its maximum value is set as 100 m [19,25]. If the depth is greater than 100 m, the area is deemed unsuitable.

##### Rock Mass Strength

The site for an underground water-sealed petroleum storage depot requires a rock mass with high completeness and relatively high strength. Therefore, the uniaxial compressive strength of the saturated rock ($R_b$) can be used as a quantitative evaluation index.

##### In Situ Stress

Generally, storage depots require construction in low and medium in situ stress zones. Extremely high in situ stress will affect the stability of the surrounding rock and cause deformation or failure of the cavern wall [26]. The ratio ($M$) of maximum uniaxial compressive strength to the maximum principal stress is chosen as a quantitative evaluation index.

##### Environmental Ecological Vulnerability

The environmental/ecological vulnerability in the depot site is classified into four grades according to environmental/ecological vulnerability indices ($EVI$) [27]: slight vulnerability (<2), mild vulnerability (2–3), medium vulnerability (3–4), and high vulnerability (4–5). The indices are used to evaluate the influence of the petroleum storage depot on the local ecological environment.

##### Regional Stability

High regional stability is needed to ensure the safety of an underground water-sealed petroleum storage depot. Regional fractures near the underground water-sealed petroleum storage depot must be avoided. The basic seismic intensity ($I$) can be selected as a quantitative evaluation index.

##### Technical and Economic Conditions

An underground water-sealed petroleum storage depot requires relatively less workload for operation and maintenance as opposed to construction. The influences of technical and economic conditions on the depot site are reflected mainly by the storage and distribution of oil transport conditions ($LT$). Therefore, the distance between the depot site and the petroleum jetty or oil refinery should be selected as a quantitative evaluation index, with the maximum value equivalent to 100 km. If the shortest distance is longer than 100 km, the area is deemed unsuitable.

Topography

For an underground storage depot, it is best to choose a relatively flat terrain mountain area that is easy to conduct geological exploration and construction; therefore, it can save costs for investment. As for the topography, the relative topographical height difference in the depot site ($H_R$) is selected as the quantitative evaluation index, with the maximum value equivalent to 1 km. If the relative height is higher than 1 km, the area is deemed unsuitable.

Meteorological Conditions

Meteorology conditions determine the amount of rainfall in the storage depot area. To some degree, precipitation increases the supply of groundwater, but if the amount of rainfall is too large, leaks and flooding may occur during construction making it difficult to construct the reservoir. The indicator is expressed in terms of rainfall ($R$).

#### 2.3.2. Site Selection Evaluation Criteria

The above nine influencing factors are selected as discriminant factors, and the suitability of underground petroleum storage site selection is evaluated by the analytic hierarchy process (AHP) and the ideal point method, which can provide a reasonable basis for the site selection. According to the relevant norms in China, the relevant underground engineering projects, and related literatures [1,18,19], the quality of the underground petroleum storage is divided into four levels: excellent (I), good (II), medium (III), and poor (IV). We put forward the corresponding criterion for the nine evaluation factors (Table 3).

**Table 3.** Classification standard for selected site grades of storage depots.

| No. | Evaluation Index | Site Level | | | |
|---|---|---|---|---|---|
| | | Honor (I) | Good (II) | Average (III) | Poor (IV) |
| B1 | $K_V$ | 0.75~1 | 0.5~0.75 | 0.35~0.55 | 0~0.35 |
| B2 | $D_W$/m | 0~20 | 20~45 | 45~70 | 70~100 |
| B3 | $R_b$/MPa | 60~100 | 30~60 | 15~30 | 0~15 |
| B4 | $M$ | 7~10 | 5~7 | 2.5~5 | 0~2.5 |
| B5 | $EVI$ | 0~2 | 2~3 | 3~4 | 4~5 |
| B6 | $I$ | 0~4 | 4~7 | 7~8.5 | 8.5~10 |
| B7 | $L_T$/km | 0~25 | 25~50 | 50~75 | 75~100 |
| B8 | $H_R$/m | 0~200 | 200~450 | 450~700 | 700~1000 |
| B9 | $R$/mm | 0~80 | 80~180 | 180~240 | 240~400 |

## 3. Results

The AHP-ideal point model is tested by applying the site selection evaluation to an underground petroleum storage in China. The indicators of the study are shown in Table 4.

**Table 4.** Index value of each influencing factor of depot site.

| No. | $H_R$ | $M$ | $R_b$ | $K_V$ | $D_W$ | $EVI$ | $I$ | $L_T$ | $R$ |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 169 | 8.6 | 78 | 0.68 | 14 | 1.5 | 3 | 26 | 65 |

The steps of the site selection AHP-Ideal point model are as follows:

(1) Based on the geological conditions, construction difficulties, and economic costs, we construct the judgment matrix by using the 1~9 scale method proposed by professor Saaty [20,21].

$$P_{A-B} = \left|\begin{array}{cccccccccc} & B1 & B2 & B3 & B4 & B5 & B6 & B7 & B8 & B9 \\ B1 & 1 & 1 & 2 & 3 & 4 & 4 & 5 & 6 & 7 \\ B2 & 1 & 1 & 2 & 3 & 4 & 4 & 5 & 6 & 7 \\ B3 & 1/2 & 1/2 & 1 & 2 & 2 & 2 & 3 & 3 & 4 \\ B4 & 1/3 & 1/3 & 1/2 & 1 & 1 & 1 & 2 & 3 & 3 \\ B5 & 1/4 & 1/4 & 1/2 & 1 & 1 & 2 & 2 & 3 & 3 \\ B6 & 1/4 & 1/4 & 1/2 & 1 & 1/2 & 1 & 1 & 2 & 2 \\ B7 & 1/5 & 1/5 & 1/3 & 1/2 & 1/2 & 1 & 1 & 2 & 2 \\ B8 & 1/6 & 1/6 & 1/3 & 1/3 & 1/3 & 1/2 & 1/2 & 1 & 1 \\ B9 & 1/7 & 1/7 & 1/4 & 1/3 & 1/3 & 1/2 & 1/2 & 1 & 1 \end{array}\right| \quad (11)$$

(2) Use Equations (1)–(4) to determine the weight of each evaluation index, we obtain weight vector $\omega$ = [0.256, 0.256, 0.137, 0.082, 0.076, 0.076, 0.049, 0.040, 0.028], the maximum eigenvalue $\lambda_{max}$ = 9.108, $CI$ = 0.0135, the random consistency ratio $CR$ = 0.0093 < 1, and this satisfies the consistency condition.

(3) Based on ideal point mathematical theory, we determine the positive ideal and negative ideal solution for these evaluation indices. Using Equations (5) and (6), the positive ideal point matrix $F^*(+)$ and the negative ideal point matrix $F^*(-)$ of grades I to IV of the site selection can be obtained as follows:

$$F^*(+) = \left|\begin{array}{ccccccccc} B1 & B2 & B3 & B4 & B5 & B6 & B7 & B8 & B9 \\ 1 & 0 & 100 & 10 & 0 & 0 & 0 & 0 & 0 \\ 0.75 & 10 & 60 & 7 & 2 & 4 & 25 & 200 & 80 \\ 0.55 & 22.5 & 30 & 5 & 3 & 7 & 50 & 450 & 180 \\ 0.35 & 35 & 15 & 2.5 & 4 & 8.5 & 75 & 700 & 240 \end{array}\right| \quad (12)$$

$$F^*(-) = \left|\begin{array}{ccccccccc} B1 & B2 & B3 & B4 & B5 & B6 & B7 & B8 & B9 \\ 0.75 & 10 & 60 & 7 & 2 & 4 & 25 & 200 & 80 \\ 0.55 & 22.5 & 30 & 5 & 3 & 7 & 50 & 450 & 180 \\ 0.35 & 35 & 15 & 2.5 & 4 & 8.5 & 75 & 700 & 240 \\ 0 & 50 & 0 & 0 & 5 & 10 & 100 & 1000 & 400 \end{array}\right| \quad (13)$$

(4) We add the index effective length to the ideal point evaluation function of each evaluation index, then use Equations (7)–(10) to calculate the ideal point closeness (Table 5). This site is rated as level II, which is suitable for construction.

**Table 5.** Comparison of the results of different evaluation methods.

| No. | Closeness of the Ideal Point | | | | Proposed Method | Power Coefficient Method | Expert Evaluate Grade |
|---|---|---|---|---|---|---|---|
| | $T_{\mathrm{I}}$ | $T_{\mathrm{II}}$ | $T_{\mathrm{III}}$ | $T_{\mathrm{IV}}$ | | | |
| 1 | 0.300 | 0.785 | 0.631 | 0.604 | II | I | I~II |

## 4. Discussion

Among the nine indicators, joint development, natural water-sealed condition, and rock mass strength have the greatest influence on the AHP-ideal point model, and the sum of these weights is 64.9%. Joint development and rock mass strength directly reflect the stability of the caverns. The better the two indicators, the more stable the caverns. In addition, the natural water-sealed condition reflects the level of groundwater. In the case of good rock integrity, the underground petroleum storage must also have a stable groundwater level to keep a certain water head to form a water seal to seal the oil and, therefore, it also occupies a larger weight. In situ stress, environmental ecological vulnerability, and regional stability rank in second place with a total weight of 23.4%. The magnitude of the in situ stress also directly determines the stability of the caverns and the selection of support parameters so that it occupies a larger weight. Although the environmental ecological vulnerability does not directly determine the location of the depot, it reflects the construction influence of the oil depot on the ecological environment. Regional stability determines the risk of safe operation of the depot, so the two also have a greater weight. Finally, the sum of the weights of the technical and economic conditions, topography and meteorological conditions, is 11.7%. Topography and technical and economic conditions determine the cost and technical difficulty of construction, operation, and maintenance, but they are not direct determinants of the site selection. Meteorological conditions reflect the amount of rainfall in this area, neither too much nor too little, are suitable; therefore, it is not a direct determinant.

In the ideal point method, the authors consider the different units and the value of each index, such as the $K_v$ and $R_b$, and use the improved Euclidean distance to define the relative distances to the positive ideal point and to the negative ideal point.

In the proposed AHP-ideal point model, from a single indicator point of view these six indices B3, B4, B5, B6, B8, and B9, belong to level I, and these three indices B1, B2, B7, belong to level II, it seems that the evaluation result of this site should be level I. On the other hand, B1 and B2 are the main indices of significance for the sum of their weight is 51.6% in the AHP point model. Thus, how to determine the site level is a confusing problem. In order to solve it, the ideal point theory is applied to make a comprehensive evaluation, finally the evaluation result of this site is level II, which is suitable for construction. The results of the proposed AHP-ideal point method were compared with that of the power coefficient method [1] and the expert evaluation method. Both methods determine the site is suitable for construction, but each evaluation is slightly different. The power coefficient method establishes the weight value of each factor though the weight back analysis method and the weight of the selection by the number of samples, and the accuracy of the weight is limited by the number of samples. In addition, the expert evaluation method relies on the expert's engineering experience, which is a kind of macro-site evaluation and cannot quantitatively consider the correlation between factors in the site evaluation, producing a qualitative solution. When samples are relatively few, the expert's engineering experience is very helpful in evaluating the site selection. Therefore, we believe that the use of the analytic hierarchy process based on expert evaluation to quantitatively analyze the correlation between the factors is an effective way to evaluate a site. Lastly, there is only one sample in this paper. However, given the successful application of the analytic hierarchy process and the ideal point method in the related literature [23,28–30], the analytic hierarchy process and the ideal point method can provide a reference for the correctness of this site evaluation model.

## 5. Conclusions

The site selection of the large underground petroleum storage is affected by a variety of factors, with uncertainty and non-linear characteristics. Considering the geological conditions, rock stability, and groundwater conditions, the following nine indicators are selected as evaluation indices: joint development, natural water-sealed condition, rock mass strength, in situ stress, environmental ecological vulnerability, regional stability, technical and economic condition, topography, and meteorological conditions, and the selection evaluation system of underground petroleum storage sites is established.

Based on the statistical and analytic hierarchy process, the evaluation factors of site selection and its weights are studied. Results show that the primary controlling factors are joint development, natural water-sealed condition, rock mass strength, in situ stress, environmental ecological vulnerability, and regional stability. The non-controlling factors are technical and economic conditions, topography, and meteorological conditions.

Based on the analytic hierarchy process (AHP) theory and ideal point theory, a new site selection model for large underground petroleum storage is built. The accuracy of the model is verified by using the model to evaluate the site selection of the first underground petroleum storage project in China. The site level is good and the site is suitable for construction. These results can provide references for future site selection of underground petroleum storage.

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**Conflicts of Interest:** The authors declare no conflict of interest.

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