Evaluation on the adaptability of shield cutter head system design

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Abstract. The difference between the design adaptabilities of shield cutter head system has a strong impact on the tunnelling efficiency. How to study and evaluate its design adaptability is an urgent problem to be solved. In this paper, based on the membership matching degree of adaptability quality of shield cutter head system between the existing design and ideal design, and taking the matching degree as the initial data of the evaluation model, a design adaptability analysis model and evaluation method based on entropy weight improved TOPSIS are proposed. Taking the existing design of shield cutter head system as an example, the adaptability in subway construction are analysed and evaluated. The 9 adaptability indexes are ranked, and the conclusion is drawn that the adaptability of 17 design tasks of the cutter head system are general, which verifies the practicability and credibility of the method.

1. Introduction

Shield tunneling machine is an individualized product with customization and specificity, and its design focuses on the engineering and hydrogeological characteristics of a certain region, so as to achieve better matching and coordination between machinery and rock and soil. If the cutter head system does not adapt to the rock and soil types, mechanical properties and hydrogeological conditions, it will lead to engineering problems in tunnel construction, such as tunneling difficulties, rapid wear of cutters, structural damage and seizure of cutter head, mud cake on cutter head and instability of excavation face, which will seriously affect tunneling efficiency, construction safety and service life. The adaptability of design refers to the accessibility of new design by adjusting and modifying the existing design to meet the new demand change. At present, the adaptability study of shield cutter head system mainly involves the selection of cutter head structure, setting of tunneling parameters, adaptability analysis and evaluation, etc. Bilgin [1] studied the adaptability selection of shield machine cutter head and its structure of Istanbul Della goss sewage tunnel. Zhang [2] took the shield construction of Xi 'an metro line 4 as an example, and studied the setting and control of driving parameters. Duan [3] studied the adaptive setting of the parameters such as propulsion unloading control and propulsion speed in the context of tunneling project from the Sungang station to Honghu station section of Shenzhen Metro Line 7. Lin [4] studied the selection of shield cutter head structure and the setting of driving parameters for the construction of pile foundation of bridge. Zhao [5] aimed at the serious deformation and damage of the tool during the construction of the shield. The dynamic characteristics of the cutter were studied, and the structure was optimized and improved. Deng [6] studied the formation adaptability of thrust device of the cutter head system. Zhan [7] took the tunnel construction of Chegongmiao - Hongshuwan of Shenzhen Metro Line 11 as the background and carried out the geological adaptability of the first Chinese Φ7m composite earth pressure balance shield machine . The poor adaptability of the cutter head system design is the main cause of tunneling accident. However, the foreign related technology is tightly sealed, and the design adaptability evaluation of cutter head system has become an urgent problem to be solved. In this paper, the adaptability of cutter head system design is systematically and comprehensively studied and evaluated from 9 aspects of matching, which provides an operable idea for improving the design.

2. Indexes and model data of cutter head system design adaptability

The extension of cutter head system design in life and application ability is called adaptation process. Through the investigation of both the manufacturer and the product user, a comprehensive analysis is made on the adaptability of 9 aspects including geological conditions, tunneling parameters, excavation surface stability, engineering construction, construction safety, technology, economy and environmental protection and durability. Taking the degree of membership matching of the quality in the 9 aspects between current design and ideal design as the initial data of model.

It is assumed that the design P of shield cutter head system can be decomposed into n adaptive design tasks. (Adaptive design task set $TP = \{TP_1, TP_2, \cdots, TP_n\}$), The i th design task is TP_i $(i = 1, 2, \cdots, n)$, The current design of cutter head system is O (source), and the ideal new design is D (target). $S(D, O)$ represents the membership matching degree of the adaptability quality of the existing design O relative to the ideal new design D, which is evaluated in the range [0, 1]. 1 indicates perfect match, and 0 indicates no match. $S(D_{ij}, O_{ij})$ represents the membership matching value on the j th adaptability index of the i th design task. The formula below can be obtained:

$$S(D,O) = \sum_{i=1}^{n}\sum_{j=1}^{m}\alpha_{ij} \times S(D_{ij}, O_{ij}) / \sum_{i=1}^{n}\sum_{j=1}^{m}\alpha_{ij} \tag{1}$$

In formula (1), α_{ij} indicates that the matching degree of item i design task on the adaptability of item j accounted for the weight of the overall matching degree.

It is necessary to carry out the adaptability analysis of m index for each design task. Suppose the design eigenvectors of O and D are $R_{O_{ij}} = (r_{O_{ij}1}, r_{O_{ij}2}, \cdots, r_{O_{ij}T})$ and $R_{D_j} = (r_{D_j1}, r_{D_j2}, \cdots, r_{D_jT})$. x_{ij} is defined as the matching degree on the adaptability requirement of item j when the cutter head system design P executes its item i design task TP_i. The original data matrix formed by x_{ij} is $X = (x_{ij})_{n\times m}$.

$$x_{ij} = S(D_{ij}, O_{ij}) = S(R_{D_{ij}}, R_{O_{ij}}) = S([r_{D_{ij}1}, r_{D_{ij}2}, \cdots, r_{D_{ij}T}], [r_{O_{ij}1}, r_{O_{ij}2}, \cdots, r_{O_{ij}T}]) = \sum_{k=1}^{T}\lambda_{ijk} \times S(r_{D_{ij}k}, r_{O_{ij}k}) / \sum_{k=1}^{T}\lambda_{ijk} \tag{2}$$

In formula (2), λ_{ijk} represents the weight of the k element of the design feature vector of the j index of the i design task. $S(r_{D_{ij}k}, r_{O_{ij}k})$ is the matching degree between the corresponding design characteristic elements.

To calculate the matching degree $S(r_{D_{ij}k}, r_{O_{ij}k})$ between $r_{D_{ij}k}$ and $r_{O_{ij}k}$, an appropriate membership function should be selected first, and the commonly used ones include trigonometric function, trapezoid function and gaussian function [8]. Considering that $r_{D_{ij}k}$ and $r_{O_{ij}k}$ in practical engineering are mostly subject to normal distribution, gaussian function can be used to obtain more effective results. Therefore, typical gaussian function is selected in this paper. If the smaller $r_{D_{ij}k}$ is, the higher matching degree is relative to $r_{O_{ij}k}$, the partial small function is constructed. In the same way, the partial large function or the intermediate function is constructed. In addition, if $r_{D_{ij}k}$ and $r_{O_{ij}k}$ are qualitative attributes, the qualitative attribute type function should be constructed.

3. Evaluation method for shield cutter head system design adaptability

As an effective method of multi-objective decision analysis, TOPSIS has the advantages of intuitive principle and low requirement on samples. However, the determination of weight is subjective and arbitrary, and it is difficult to find positive and negative ideal solutions [9]. On the bases of the original matrix of the adaptability evaluation model for the design of the cutter head system of shield machine, this paper uses information entropy to assign weight objectively, and normalizes the data matrix in the specific operation of TOPSIS method, limits the range of positive and negative ideal solutions, simplifies the solution, improves the model and method, and evaluates the shield machine to evaluate the adaptability of shield machine tool system design. The specific process is as follows:

Step 1: Normalize the data of the original matrix X, and get the matrix $Y=(y_{ij})_{n\times m}$

$$y_{ij}=\frac{x_{ij}}{\left(\sum_{j=1}^{m}x_{ij}^{2}\right)^{\frac{1}{2}}} \tag{3}$$

In formula (3), $y_{ij}\in[0,1]$. $i=1,2,\cdots,n; j=1,2,\cdots,m$.

Step 2: Calculate the adaptability proportion of the i th design task in the j th evaluation index

$$p_{ij}=\frac{y_{ij}}{\sum_{j=1}^{m}y_{ij}} \tag{4}$$

Step 3: Calculate the entropy value e_i of the i th design task

$$e_i=-\frac{1}{\ln n}\sum_{j=1}^{m}p_{ij}\ln p_{ij} \tag{5}$$

In the formula (5), the scope of entropy is $e_i\in[0,1]$.

Step 4: Calculate the dominance g_i of the i th design task

$$g_i=1-e_i \tag{6}$$

For a given i, the smaller the difference of x_{ij} is, the larger the e_i is, and the smaller the g_i is, which reflects that the smaller the influence of this design task Tp_i on the adaptability of various aspects. Table 1 lists the grade division of the adaptive dominance evaluation [10].

Table 1. Classification of adaptive dominance evaluation.

Value range of dominance	$g_i<0.15$	$0.15\le g_i<0.3$	$0.3\le g_i<0.5$	$0.5\le g_i\le 1$
Evaluation grade	poor	commonly	good	excellent

Step 5: Calculate the entropy weight ω_i of the i th design task

$$\omega_{i=}\frac{g_i}{m-\sum_{i=1}^{n}e_i} \tag{7}$$

Step 6: Construct the weighted canonical matrix $R=(r_{ij})_{n\times m}$

$$r_{ij} = \omega_i y_{ij} \tag{8}$$

Step 7: Determine the positive ideal solution A^+ and the negative ideal solution A^-.

The solving process for elements of positive and negative ideal solutions in the traditional TOPSIS method is complicated because of the wide range of values. The TOPSIS method is now being improved. In formula (3), normalize any element of matrix $Y: y_{ij} \in [0,1]$, limit the lowest and highest target attribute value between 0 and 1. According to the 9 adaptability indices of the cutter head system design, the positive ideal solution expects the existing design to have the highest membership matching degree of adaptability with respect to the qualities of the ideal new design, therefore, all have $a_j^+ = 1, a_j^- = 0$. The positive and negative ideal solutions are respectively:

$$A^+ = (a_1^+, a_2^+, \cdots, a_m^+) = (1,1,\cdots,1), \quad A^- = (a_1^-, a_2^-, \cdots, a_m^-) = (0,0,\cdots,0) \tag{9}$$

Step 8: Calculating the Euclidean distance between each index and the positive (negative) ideal solution

$$d_j^+ = \left[\sum_{i=1}^{m} \omega_i^2 (y_{ij} - 1)^2\right]^{\frac{1}{2}}, \quad d_j^- = \left[\sum_{i=1}^{m} \omega_i^2 (y_{ij} - 0)^2\right]^{\frac{1}{2}} \tag{10}$$

Step 9: Calculate the relative degree c_j between each adaptability index and the ideal solution

$$c_j = \begin{cases} \dfrac{d_j^-}{d_j^+}, & d_j^+ \neq 0 \\ +\infty, & d_j^+ = 0 \end{cases} \tag{11}$$

Step 10: The adaptability of each adaptability index is ranked according to the relative proximity. The higher the c_j is, the stronger the adaptability of the corresponding index is.

4. Examples of application

Taking the existing design of shield cutter head system as an example, its adaptability was is analyzed and evaluated when it was applied to subway construction in a city. The project has a left length of 2321.216m and a right length of 2362.817m. The maximum longitudinal slope is 22‰, the roof is buried 10-15m deep, and the overburden thickness of the reach across the river is about 7 meters. In the survey site, there are drift rocks with particle size greater than 300mm, and the foundation pit near the tunnel contains particles with particle size greater than 650mm. The silty clay layer accounts for 6%, conglomerate accounts for 16% and pebbles account for 78%. The maximum natural compressive strength of pebbles can reach more than 100MPa.

4.1. main parameters of current design of cutter head system.

Shield machine total quality: 520 t, the total installed power: 1744.6 kw, the overall shape dimension: Φ6280 x75000mm. The main parameters are shown in table 2.

Table 2. Main parameters of cutter head system design of shield machine.

Cutter head and cutter parameters		Driving parameters	Other parameters
Cutter head form: radials	Hob diameter: 17in	Total installed power: 1744.6kW	Working pressure: 0.3Mpa
Φ6130mm (cutter ring outside diameter)	One set of tower hob, travel: 50mm, oil pipes: 2	Maximum torque of cutter head: I-4500 kN.mm, II-1970kN.mm	Screw conveyor gate: 2 at either end
Outline diameter: Φ6280mm	Double blade hob: 4	Propulsion: 34210KN	Maximum excavating capacity: 300m^3/h
Head aperture: 8 long holes	Single blade hob: 31	Torque of cutter off-the-hook: 5300kN.mm	Helical belt extension stroke: 1000mm
Head aperture ratio: 28%	Front teeth cutter: 64	Hob starting torque: 20-50 kN.mm	Stir bar: 2
Head and driving device are connected by flanges	Edge teeth cutter: 16	Propeller hydraulic cylinder size: Φ220mmXΦ180mmX2000mm	Synchronous grouting pipes: 4
Flange and head are connected by 4 spokes	Height of center hob: 175 mm	Propeller hydraulic cylinders: 30	Foam pipe: 4
Panel is welded by latticed Hardox wear-resistant material	Height of front hob: 175 mm	Articulated cylinder size: Φ180mmXΦ80mmX150mm	Ballast-soil improvement system: 2 sets (foam system and bentonite system)
Head rim is welded wear rib	Height of edge hob: 15-20 mm	Working pressure of hydraulic system: 30Mpa	Shield tail grease injection tube: 8
Distance between the front cutters: usually 100mm, sometimes 115-120mm	Blade height: 140mm	Cutterhead speed:0-6.1r/min	Shield tail seal pressure: 0.5MPa
Distance between edge cutter is <90 mm	Height of cutter: 140mm	Maximum excavating velocity: 80mm/min	Tool change: carry out cabin with pressure

4.2. adaptive task evaluation of cutter head system design.

Establish the adaptive task set Tp={Cutterhead form, Cutterhead diameter, ……, Stir bar}. They are represented by Tp_1 to Tp_{17}. And the initial data for design adaptability of Tp_1-Tp_{17} is shown in table 3.

Table 3. Initial data.

Adaptive task	Adaptability to geological conditions	Adaptability of tunnelling parameters	Adaptability to excavation surface stabilization	Adaptability to engineering construction	Adaptability to durability	Adaptability to construction safety	technical adaptability	Economic adaptability	Adaptability to environmental protection
Cutterhead form	0.545	0.522	0.451	0.595	0.448	0.558	0.687	0.553	0.772
Cutterhead diameter	0.781	0.723	0.741	0.733	0.723	0.763	0.805	0.687	0.617
Aperture ratio	0.538	0.676	0.658	0.818	0.556	0.602	0.732	0.705	0.725
Cutter wear resistant setting	0.523	0.727	0.723	0.823	0.707	0.755	0.685	0.594	0.737
Cutter seat setting	0.629	0.752	0.709	0.749	0.672	0.738	0.706	0.612	0.712
Hob size and quantity	0.598	0.672	0.798	0.798	0.472	0.524	0.695	0.478	0.578
Teeth-cutter size and quantity	0.586	0.678	0.806	0.806	0.478	0.572	0.665	0.495	0.595
Scraper size and quantity	0.542	0.639	0.842	0.842	0.439	0.523	0.631	0.463	0.663
Cutter spacing	0.472	0.789	0.772	0.752	0.689	0.612	0.717	0.691	0.601
Over cutter stroke	0.719	0.816	0.669	0.789	0.606	0.715	0.755	0.572	0.672
Hob height	0.587	0.672	0.707	0.747	0.472	0.629	0.707	0.765	0.638
Scraper height	0.840	0.838	0.734	0.840	0.838	0.523	0.715	0.787	0.647
Cutting tool height	0.84	0.823	0.774	0.84	0.523	0.797	0.798	0.771	0.771
Tool wear setting	0.523	0.725	0.723	0.823	0.775	0.658	0.772	0.562	0.822
Foam system	0.637	0.806	0.737	0.737	0.606	0.771	0.644	0.604	0.504
Bentonite system	0.537	0.706	0.757	0.717	0.616	0.781	0.654	0.594	0.494
Stir bar	0.687	0.776	0.667	0.737	0.556	0.701	0.744	0.704	0.754

According to formula (3)-(6), the dominance g_i of each adaptive task can be obtained, as shown in table 4.

Table 4. Dominance of each adaptive task.

Adaptive tasks	1	2	3	4	5	6	7	8	9
g_i	0.2296	0.2254	0.2274	0.2271	0.2253	0.2308	0.2300	0.2332	0.2281
Adaptive tasks	10	11	12	13	14	15	16	17	
g_i	0.2266	0.2276	0.2280	0.2272	0.2283	0.2278	0.2281	0.2259	

The g_1 to g_{17} of all the adaptive tasks in Table 4 is between [0.2253 and 0.2332]. According to table 1, the evaluation grade of adaptability superiority for 17 design tasks is general.

4.3. Sequencing of adaptive evaluation index.

According to formula (7) - (13), the relative proximity c_j of 9 adaptability indexes and their ranking can be calculated, as shown in table 5.

Table 5. Relative proximity and sorting results.

Adaptability index	Adaptability to geological conditions	Adaptability of tunnelling parameters	Adaptability to excavation surface stabilization	Adaptability to engineering construction	Adaptability to durability	Adaptability to construction safety	technical adaptability	Economic adaptability	Adaptability to environmental protection
c_j	0.4355	0.5455	0.4961	0.5924	0.4101	0.4717	0.5263	0.4364	0.4847
Sorting result	8	2	4	1	9	6	3	7	5

From table 5, it is shown that the cutter head system design focus on the matching of the excavated section and external dimension, supporting method and supporting strength, the construction period and schedule; focus on the matching between the design parameters of the cutter head system and the construction driving parameters, such as driving thrust, rotary speed, torque, driving speed, cutting quantity; focus on the matching among technical integration, selection and refining. At the same time, it is found that the design of the cutter head system has relatively lower adaptability to construction safety, economy, geological conditions and durability. The main reasons are as follows: manufacturers must design and manufacture shield machine according to specific construction geological conditions, resulting in high price and serious impact on economic adaptability. Shield tunneling often encounters various geological and hydrological conditions, and the construction environment is complex and changeful, which makes the tunneling difficult to perfectly solve various problems in the construction of complex strata, resulting in poor adaptability of geological conditions. During tunneling, due to the effect of cutters on conglomerate and pebbles in silty clay layer, it is easy to cause large wear, poor durability and poor adaptability. The adaptability sequencing results of 9 indexes designed by this method are consistent with the actual. It has better practicability and credibility.

5. Conclusion

In this paper, the whole design task of shield cutter head system was decomposed, and the adaptability design task set was established. Based on entropy weight improved TOPSIS method, the adaptability of design was analyzed and evaluated, and the following conclusions were drawn:

(1) An analysis model and method based on entropy theory and improved TOPSIS method was proposed, which was successfully applied to the adaptability evaluation of cutter head system design.

(2) The adaptive advantage value of 17 design tasks of cutter head system design is between [0.2253, 0.2332], and the evaluation grade is all general, indicating that the overall adaptability of this cutter head system design needs to be further improved.

(3) The 9 adaptability indexes are ranked. It can be seen that to further improve the overall adaptability level of the shield machine cutter system design, the economic adaptability, geological adaptability and durability adaptability should be emphasized. This provides a good idea for improving the design level and market competitiveness of domestic shield machine in the future.

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