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Disc cutters' layout design of the full-face rock tunnel boring machine (TBM) using a cooperative coevolutionary algorithm †

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Abstract

In rock TBM design the disc cutters' layout design of the full-face rock tunnel boring machine (TBM) is one of the key technologies. However, there are few published papers in literatures for various reasons. In this paper, based on the engineering technical requirements and the corresponding cutter head's structure design requirements, a nonlinear multi-objective disc cutters' layout mathematical model with complex constraints and the corresponding multi-stage solution strategy are presented, in which the whole disc cutters' layout design process is decomposed into the disc cutters' spacing design and the disc cutters' plane layout design. A numerical simulation method based on the FEM theory is adopted to simulate the rock chipping process induced by three TBM disc cutters to determine the optimal cutter spacing. And a cooperative coevolutionary genetic algorithm (CCGA) is adopted to solve the disc cutters' plane layout design problem. Finally, a disc cutters' layout design instance of the TBM is presented to demonstrate the feasibility and effectiveness of the proposed method. The computational results show that the proposed method can be used to solve the disc cutters' layout design problem of the TBM and provide various layout schemes within short running times for the engineers to choose from.

Keywords: Full-face tunnel boring machine; Disc cutters' layout; Coevolutionary algorithm; Spacing

1. Introduction

The full face rock tunnel boring machine (TBM) is a large and special engineering machine for tunnel boring that has been widely applied to subway projects, railway projects, highway projects and water-electricity projects. It is a very high cost machine. Disc cutters' layout design of the TBM is one of the key technologies to improve the global performance of a TBM [1], and it directly affects the boring performance, the service life, the main bearing of the cutter head, the vibration and the noise of the TBM. The main difficulties of disc cutters' layout design of the TBM lie in the combinational explosion of computational complexity, the engineering complexity, and the pragmatic approaches of engineering practices, and belongs to a multi-objective optimization problem with nonlinear constraints.

Disc cutters' layout design of the full face rock TBM is closely related to the theory of cutter's penetration into rocks, the cutting force models and the performance prediction models. The theory of cutter's penetration into rocks is a basis of the cutting force models and the performance prediction models. It is often used to analyze the cutter head's force distribution during the disc cutters' layout design. It is crucial in understanding the stress fields and the resultant fractures that are created beneath the penetrating edge of the disc cutter. In this analysis, three previous theories derived from wedge indentation into rocks are used as a guide: shearing crushing theory, the radial tension cracks crossing theory and the hybrid crushing theory. These theories can be used to study the occurrence of a highly stressed and crushed zone and the radial tension cracks during a cutter's penetration into rocks.

Three cutting forces are exerted on the tip of the disc cutter during excavation: the normal force, the rolling force and the side force. Many investigators have studied the cutting force models that can be used to calculate the the normal force and the rolling force. These models can be divided into two categories: the semi-theoretical model, based on tests and the theoretical analysis of the linear cutting machine (LCM), for example the Colorado School of Mines (CSM) model [1]; and the empirical model, which is based on the historical field

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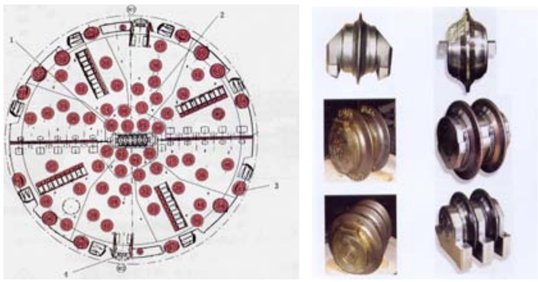
performance of machines, for example the Norwegian Institute of Technology (NTH) model [2]. Gertsch [3] and Song [4] have systematically reviewed the present cutting force models. Rostami [5] adopted the regression analysis method and built the cutting force model based on the experimental data. In the above-mentioned models, the multi-factor cutting force models (e.g. CSM and NTH) are more widely accepted and applied in industry because all the effects of their ground conditions, rock properties, machine parameters, and operational and practical constraints can be accounted for.

The layout of the buckets, the blowholes and the manholes should be considered properly in the layout design of the disc cutters of the cutter head. The layout design of the disc cutters correlates with the forces exerted on the cutter head, the crushed rock mobility and the manufactural process of the cutter head, and it is a technically effective way to improve the boring performance of the TBM [6]. With the increasing complexity of the ground conditions and the practical constraints, the layout design of disc cutters is more difficult and more important, and has become an essential part of the design of a TBM. All successfully designed TBMs, with no exception, have successfully designed the disc cutters' layout. A typical case is the excavation of the Kranji tunnel in Singapore. During the excavation, it was found that the frequency of the ground change between the hard rocks and the residual soil was much higher than what had been expected. The highly abrasive and frequently changing mixed face ground caused high cutter wear, especially flat cutter wear. After reducing the number of disc cutters from 35 to 33 and increasing the cutter spacing of the normal cutter from 90mm to 100mm, it could be seen that the overall progress of the TBM utilization and the abrasion of cutters was clearly better than before [7].

The layout design of the disc cutters includes the disc cutters' spacing design and the disc cutters' plane (circumferential) layout design. Considersing the researches of the disc cutters' spacing design, many investigators adopted the numerical simulation method and the linear cutting machine (LCM) experimental method. Ozdemir [8] and Snowdon [9] used a V-profile disc cutter to do the cutting tests based on the LCM and found that when the cutting spacing was small, the resultant chip size was small too and the specific energy (SE) of the disc cutters was high. When the cutting spacing increased, the resultant chip size became larger and the SE of the disc cutters decreased to the minimum. As the cutting spacing continued to increase, the SE of the disc cutters also increased because the interaction among the disc cutters decreased. Based on the LCM test, CSM [6, 10] systematically analyzed the cutting forces from the LCM testing with intact rock properties, cutting geometry, and cutter geometry and proposed a semi-theoretical computer model that could formulate the cutting forces exerted on tip of the disc cutter. This makes penetration rate prediction possible for a TBM in given rock conditions by using the formulation from the LCM testing. Gertsch [1] conducted a series of full-scale laboratory cutting tests by using a single disc cutter (with 432mm diameter and a constant cross-section profile) and a single rock type (a coarse-grained red granite). Specific energy (SE) considerations indicate that a spacing of 76mm is close to the optimum in this hard, brittle crystalline rock. At this spacing, penetration has very little effect on SE. These results show why spacing near 76mm is commonly found on tunnel boring machines operating in hard rock. Although a great deal of preparation work needs to be done, this kind of physical experiment based on the LCM testing is very practical and can be used to determine the optimal cutting parameters, since it can improve the boring performance and reduce the costs. From 2005 to 2007, Gong Q M [11-13] adopted the discrete element method (DEM) to simulate the rock chipping process induced by two disc cutters and analyzed the influence of the difference of cutters' spacing on the penetration process by setting up a series of two dimensional UDEC models. Many significant conclusions were drawn from analyzing the simulation results. Moon [14] studied the rock cutting parameters by optimizing the ratio of spacing to penetration (S/P) and proposed that the optimal S/P was a linear function of the rock's brittleness and the width of the disc cutters.

After cutting spacing has been determined, the disc cutters are to be placed circumferentially on the plane of the cutter head. There are few published papers on the study of the disc cutters' circumferential layout in the literature. The CSM computing model can be used to design the circumferential layout and calculate the individual loads. Rostami [15] studied the methods of cutter head modeling for the hard rock TBM that had been a successful tool used by the industry at various levels of sophistication relative to the end use. These models are based on the estimation of the cutting forces and can be used for the cutter head design optimization as well as for the performance estimation. Zhang [16] studied the spiral layout rule of the disc cutters and gave out computational equations of the simplified cutter head force distribution. The disc cutters' layout design should meet the geometrical constraints and other performance constraints like the balance constraints and the assembly manufacturing requirements, etc. It is a complex engineering design problem that involves multidisciplinary knowledge. There is a need to establish a practical computational model for the disc cutters' layout, considering factors of the rock properties, the cutting parameters, the performance constraints and the cutting force model. And it is necessary that advanced computational methods should be studied and applied to solve the problem more efficiently.

Theories of the cutters' penetration into rocks, the disc cutters' force models and the cutting spacing have been widely studied, but there are only a few published researches on the disc cutters' layout design. In this study, according to the complex engineering technical requirements and the corresponding cutter head structure design requirements, a nonlinear multi-objective disc cutters' layout mathematical model with complex constraints and the corresponding multi-stage solution strategy is presented, and a numerical simula-



1-Center cutters; 2-Normal cutters;
3-Gauge cutters; 4-Reaming cutters.

Cutting tools

Fig. 1. The disc cutters' layout scheme and the cutting tools [22].

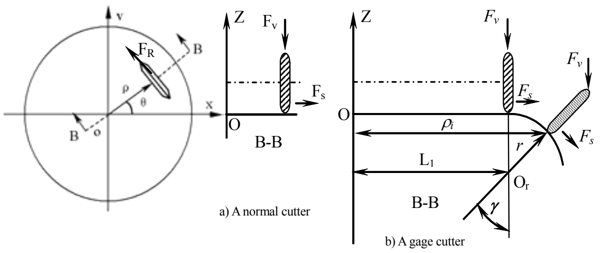


Fig. 2. Individual forces acting on a normal cutter and a gage cutter [23].

tion method and a cooperative coevolutionary algorithm are utilized to solve the disc cutters' layout design problem. Finally, using the above-metioned proposed method, an instance of the disc cutters' layout design of a TBM is presented.

2. Problem statement

As shown in Fig. 1 and Fig. 2, the discs are so arranged that they contact the entire cutting face in the concentric tracks when the cutter head turns. The distance of the cutting tracks and the discs are chosen depending on the rock type and the difficult level of cutting. The sizes of the broken pieces of the rock result from this. The rotating cutter head presses the discs with high pressure against the rock face. The discs therefore make a slicing movement across the rock face. The pressure at the cutting edge of the disc cutters exceeds the compressive strength of the rock and locally grinds it. So the cutting edge of the disc pushes the rolling into the rock, until the advance force and the hardness of the rock are in balance. Through this displacement, described as net penetration, the cutter disc creates a high stress locally, which leads to long flat pieces of rock (chips) breaking off. The cutting forces on a disc cutter mainly contain the normal force, the rolling force and the side force. Fig. 2 illustrates these three cutting forces that are exerted on the tip of the disc cutter during excavation. According to the related literature [12, 15] and the practical engineers' experiences, the technical requirements of disc cutters' layout design can be summarized as follows [23]:

① The amount of the eccentric forces of the whole system is expected to be as small as possible;
② The amount of the eccentric moments of the whole system is expected to be as small as possible;
③ The spacing of the disc cutters needs to be optimized, which means that the specific energy needed to cut off unit volume of rock is expected to be as small as possible;
④ Two adjacent disc cutters should crush the rock successively to maintain high cutting efficiency;
⑤ All the disc cutters should be contained within the cutter head, with no overlapping among the disc cutters;
⑥ The position error of the centroid of the whole system should not exceed an allowable value, and the smaller the better;
⑦ All the disc cutters should not interfere with manholes and buckets, respectively.

3. Mathematical model

Suppose that the set of disc cutters to be located on the cutter head with radius equals to R is ***CUTs*** = $\{Cut_1, Cut_2, \cdots, Cut_n\}$, where n = total number of cutters. As shown in Fig. 1, all the disc cutters are simplified as circles in this study and are regarded as rigid bodies with uniform mass distribution. So the ith cutter can be denoted as $Cut_i\,(p_i, r_i)$, where $p_i = (r_i, \rho_i, \theta_i)^T \in R^3$ is the position of a reference point (the centroid of the object) of Cut_i in the coordinate system *oxyz;* $\rho_i \in (0, R)$ is the radius of the ith cutter from the center of the cutter head; $\theta_i \in [0, 2\pi)$ is the position angle of the ith cutter; $\gamma_i \in [0, \frac{\pi}{2})$ is the tilt angle of the ith cutter; r_i is the radius of the ith cutter. Generally, the tilt angles of the normal cutters are all zero. The masses and dimensions of all the disc cutters are given in advance, so p_i p_i is the variable to be manipulated in the following procedure. Thus, a general disc cutters' layout scheme of a cutter head can be formulated as:

$$\mathrm{X} = \{x_1, x_2, \cdots, x_i, \cdots, x_n\},\ x_i = \{\rho_i, \theta_i, \gamma_i\}\,. \tag{1}$$

Then based on the technical requirements of the disc cutters' layout design, the mathematical model [23] of the whole disc cutters' layout problem can be formulated as follows:

Find a layout scheme $\boldsymbol{X} \in R^{3n}$, such that

$$\min_{\mathrm{X}\in \mathrm{D}}\ \mathrm{y} = \mathrm{f}(\mathrm{X}) = (\mathrm{f}_1(\mathrm{X}), \mathrm{f}_2(\mathrm{X}), \mathrm{f}_3(\mathrm{X}))\,. \tag{2}$$

s.t.

The overlapping constraints：

$$g_1(\mathrm{X}) = \sum_{i=0}^{n-1} \sum_{j=i+1}^{n} \Delta V_{ij} \le 0\,. \tag{3}$$

The two adjacent disc cutters successive rolling cons-traints

$$g_3(X)=\sum_{i=0}^{n-1}(\theta_{i+1}-\theta_i)\geq\Delta\theta\,. \tag{4}$$

The static balance constraints：

$$\begin{aligned}g_4(X)&=\left|x_m-x_e\right|-\delta x_e\leq 0\\ g_5(X)&=\left|y_m-y_e\right|-\delta y_e\leq 0\end{aligned} \tag{5}$$

The manholes and buckets constraints:

$$g_8(X)=\{\forall i\in\{1,\cdots,n\}:cut_i\cap OP\in\varnothing\} \tag{6}$$

where:

D: Feasible region of variable ***X***;

$f_1(X)$: The specific energy needed for cutting off unit volume of rock, which will be described in Section 3.1;

$f_2(X)$: The side force $\boldsymbol{F_s}$ of the cutter head which can be calculated by Eq. (7);

$f_3(X)$: The eccentric moments of the cutter head which can be calculated by Eq. (8);

ΔV_{ij} : The overlapping area between Cut_i and Cut_j;

$\Delta\theta$: The allowable angle difference between two adjacent disc cutters;

(x_m , y_m): The real centroid of the whole system;

(x_e , y_e): The expected position of O_m;

(δx_e , δy_e): The allowable centroid error of the whole system;

$cut_i\cap OP\in\varnothing$ denotes that the *i*th cutter is not overlapped with manholes and buckets, respectively.

$$\begin{aligned}F_S&=\sum_{i=1}^{n}\vec{F}_{si}\\ F_{si}&=\frac{\tau}{2}(r\varphi)\sin r\varphi/2\rho_i\\ \varphi&=\cos^{-1}\frac{r-p}{r}\end{aligned} \tag{7}$$

where:

F_{si} : The side force of the *i*th cutter;

τ : The shear strength of the rock;

φ : The angle of the contact area;

p : The cutter penetration.

$$\begin{aligned}M_v&=\sum_{i=1}^{n}\vec{M}_{vi}\\ M_{vi}&=F_{ti}\rho_i\\ F_{ti}&=CTr\varphi\sqrt[3]{\frac{\sigma_c^2\sigma_t S}{\varphi\sqrt{rT}}}\end{aligned} \tag{8}$$

where:

M_{vi} : The eccentric moments of the *i*th cutter;

F_{ti} : The normal force of the *i*th cutter; in this study, a semi-empirical cutting force model proposed by Rostami [15] is adopted to calculate the normal force. The model is described as Eq. (8).

C : The constant which equals 2.12;

T : The cutter tip width;

σ_c : The uniaxial compressive strength of the rock;

σ_t : The Brazilian indirect tensile strength of the rock;

S : The cutters' spacing.

4. Solution strategies

The disc cutters' layout problem contains several mutually conflicting objectives (e.g., the side force, the eccentric moments etc.) and constraints (e.g., the overlapping constraints, the successive rolling constraints, the manholes and buckets constraints etc.). It belongs to a complex layout problem in mechanics design. Its main difficulties lie in its computing complexity, engineering complexity and practical application complexity. Up till now, strategies for solving the complex layout problems have fallen into two categories, the "divide and conquer" strategy and the all-at-once strategy. The "divide and conquer" strategy is decomposing the whole problem to simplify the searching space. For complex engineering problems, the all-at-once strategy may have difficulties in the following aspects: (1) All variables, objectives and constraints are to be considered together during the layout optimization procedure, which may easily result in a combinational explosion and make the optimization fall into local searching area. (2) For some complex layout problems, it is still necessary to decompose the whole problem to simplify the searching space. So this study presents a "divide and conquer" strategy to solve the disc cutters' layout problem of full face rock TBM.

According to the engineering design process of the disc cutters' layout, a two-stage strategy is presented, which includes the disc cutters' spacing design and the disc cutters' plane layout design. First, the rock chipping process induced by three disc cutters under different spacing is simulated using the finite element method (FEM). The disc cutters' spacing-SE curve is performed to obtain the optimal spacing, then the disc cutters' spacing layout for a cutter head is performed based on the relative rock's properties and the cutter head's configuration. Second, based on the technical requirements of the disc cutters' layout design, a coevolutionary genetic algorithm is adopted to design the disc cutters' plane layout.

4.1 Disc cutters' spacing design

The disc cutters' spacing is to be determined first before the disc cutters' plane layout design. The former is closely related to the rock's properties, the disc cutters' geometry, the cutting parameters and the cutter head's geometry. As was mentioned earlier, many researchers adopted the numerical simulation method and the linear cutting machine (LCM) experimental method to determine the spacing of disc cutters. In their study, the objective used in optimizing the cutters' space was usually to minimize the specific energy (SE) of the disc cutters, which had proven to be one of the most important rules. SE denotes the specific energy needed to cut off a unit volume of rock, and can be calculated by the following equation.

$$SE = \frac{E}{V} = \frac{F_R d}{Spd} = \frac{F_R}{Sp} \tag{9}$$

where d = the cutting distance; S = the cutters' spacing; F_R = the rolling force. Additionally, Gong Q M [11] used maximizing the crashed rock area and thickness as the objectives of the cutters spacing design.

At present, researches on the numerical simulation of the rock fragmentation process induced by disc cutters mainly simulate the process of two normal disc cutters vertically cutting into rocks. The other two types of cutters on the cutter head, the center cutters and the gage cutters, have not been considered. Spacing design of the latter two kinds of disc cutters is a complicated issue which is not only related to the rock properties, the disc cutters' geometry, and the cutting parameters, but also to the cutter head geometry. This is especially for the spacing of the gage disc cutters that decreases along the normal direction of the cutter head. In this study, the numerical simulation method is adopted to perform the spacing design of the normal cutters. Then, based on the spacing of the normal cutters and the geometry of the cutter head, the spacing of the gage disc cutters and the center cutters is determined.

For the center cutters' spacing design, there exist two different design concepts. The first design concept considers the disc cutters' life. To make the center cutters have the same life with the normal disc cutters, spacing of the former should be a little larger than that of the latter. The second design concept considers the cutting conditions of the center cutters. The cutting conditions of the center cutters are very bad and cutters' sideslip movement often takes place, which often results in decreasing of cutting efficiency of the center cutters. Therefore, spacing of the center cutters should be a little smaller than that of the normal cutters. Up till now, which one of the above two concepts should be adopted is still a controversial issue.

Spacing design of the center cutters is also related to the rock's integrity, besides other factors like the disc cutters' life, the cutters' force model, the cutting efficiency, the cutter head's geometry and the cutters' edge angle, When the rock is of good integrity, spacing of the center disc cutters should be a large value to improve the cutting efficiency and to reduce the sideslip phenomena. When the rock is of bad integrity, the rock is mainly crushed instead of being sheared by the disc cutters, so the spacing should be a small value.

The main role of the gage cutters is to keep the tunnel's geometry and reduce the vibration of the cutter head. The practical engineering applications show that the gage cutters are very easy to damage because of their high linear speed and their tilt assemble style, so gage cutters should be set with a little smaller spacing, and their spacing should decrease with the increase of the assemble radius of the gage cutters.

Before the spacing design of the gage cutters, the transition zone in the cutter head should be determined. According to statistical data and human experience, the transition radius in the cutter head is about 300~350mm for the smaller TBMs, where usually 6-8 gage disc cutters are assembled on this zone. For the larger TBMs, the transition radius is about 600~650mm, where usually 6-8 gage disc cutters are assembled on this zone. Radius of the transition zone should be set a reasonable value. If it is too small, the number of gage cutters will decrease and it will result in decreasing of each gage cutter's life. On the contrary, if it is too large, the thickness of the cutter head will increase and the main bearing load will also increase.

After the maximum tilt angle of the gage cutters and the radius of the transition zone have been determined, the next step is to determine the gage cutters' number and each gage cutter's tilt angle. The basic rule is to lay out the gage cutters as many as possible to reduce each gage cutter's load and balance all the gage cutters' abrasion while satisfying all the technical requirements.

The gage cutters' number and each gage cutter's tilt angle can be determined by engineering experience. In this study, we give out a heuristic computational equation for the spacing of the gage cutters as follows:

$$S_i = S_{i-1} * \cos\gamma * \delta$$
$$\delta = \frac{\rho_{i-1}}{\rho_i} \tag{10}$$
$$\rho_i = \rho_{i-1} + S_i \tag{11}$$

where S_i and S_{i-1} denote the spacing of the ith and the (i-1)th gage cutters, respectively; ρ_{i-1} and ρ_i denote the assemble radius of the ith and the (i-1)th gage cutters, respectively.

4.2 Disc cutters' plane layout design

After the disc cutters' spacing design, the assemble radius $\rho \in (0, R)$ and the tilt angles $\gamma \in [0, \frac{\pi}{2})$ of all the disc cutters have been determined, the next stage is to place all the disc cutters in the cutter head circumferentially. Based on the mathematical model of the whole cutters' layout design, the mathematical model of the cutters' plane layout problem can be formulated as follows:

Find a layout scheme $X_\theta = (\theta_1, \theta_2, \cdots, \theta_n) \in R^n$, such that

$$\min_{X \in D} y = f(X_\theta) = (f_2(X_\theta), f_3(X_\theta)). \tag{12}$$

s.t.

The overlapping constraints:

$$g_1(X_\theta) = \sum_{i=0}^{n-1} \sum_{j=i+1}^{n} \Delta V_{ij} \le 0. \tag{13}$$

The two adjacent disc cutters' successive rolling constraints:

$$g_3(X_\theta) = \sum_{i=0}^{n-1}(\theta_{i+1} - \theta_i) \geq \Delta\theta \,. \tag{14}$$

The static balance constraints:

$$\begin{aligned} g_4(X_\theta) &= |x_m - x_e| - \delta x_e \leq 0 \\ g_5(X_\theta) &= |y_m - y_e| - \delta y_e \leq 0 \end{aligned} \,. \tag{15}$$

The manholes and buckets constraints:

$$g_8(X_\theta) = \{\forall i \in \{1, \cdots, n\} : cut_i \cap OP \in \varnothing\} \tag{16}$$

where θ_i is the position angle of the ith cutter, and n is the total number of the cutters.

Please refer to Section 2 for the meanings of the above-mentioned symbols and functions.

4.3 A cooperative coevolutionary method for the disc cutters' plane layout design of the TBM

The disc cutters' plane layout problem belongs to the multi-objective problems with complex nonlinear constraints. Recently, methods for solving these problems have included the traditional optimization algorithms (linear programming methods and gradient-based algorithms), the heuristic rule-based algorithms (octree representation approaches), the stochastic algorithms (genetic algorithms, simulated annealing algorithms and extended pattern search algorithms) and the hybrid algorithms, etc. With the rapid increasing of the size and complexity of the layout problem, a general all-purpose method is not likely and easy to be found in the near future. So it is practical to focus on finding advanced and efficient solving strategies for an in-depth study on complex layout problems, such as coevolutionary methods, human-computer cooperation methods, etc. In this study, the coevolutionary method is adopted to work out the disc cutters' plane layout problem of the TBM.

The coevolutionary method, first proposed by Hillis [17] in 1990, has been a new evolutionary method based on the evolution theory over the last two decades. It simulates the relationships of competition, predation and symbiosis among the natural species and their complementary evolution. It is an evolutionary process from low level to advanced level. According to the biology models, the coevolutionary method can be divided into the competitive coevolutionary algorithm, the predatism-based coevolutionary algorithm and the cooperative coevolutionary algorithm (CCEA). The first two algorithms mainly simulate the competitive mechanism among the populations. The later CCEA mainly simulates the cooperative mechanism among the populations, and it is essentially similar to the solving process of the complex layout problems in that they are both to pursue the global optimal by coordinating the confliction of several subproblems. Therefore, the CCEA is adopted to solve the complex layout problems in this study. In 1994, Potter [18] proposed a CCEA that used multiple cooperating subpopulations to coevolve subcomponents of solution. Based on the CCEA, GA was tested in solving the high-dimensional function optimization problems, and the experimental results showed that CCEA was of a promising framework. In 2004, Bergh [19] proposed a cooperative particle swarm optimization (CPSO) algorithm based on the CCEA. In the same year, Jansen [20] theoretically proved the convergence property and affectivity of the CCEA proposed by Potter.

To utilize the CCEA to solve the complex layout problems more efficiently, four key technologies of the CCEA should be properly solved as follows: (1) decomposition of the original problem; (2) coordination of the subpopulations; (3) selection of the cooperative individuals; (4) evaluation of the individual fitness of each subpopulation.

For the decomposition of the original problem, Potter [18] used a static decomposition strategy that took every variable as a sub-problem to solve the function optimization problem. For the problem of this study, there are two types of TBM cutter head, which are the flat-shaped cutter head and the lightly dome-shaped cutter head. The location of a cutter on the flat-shaped cutter head needs two variables (x, y), while the location of a cutter on the dome-shaped cutter head needs three location variables (x,y,z). In this study, the flat-shaped cutter head is considered. The total number of disc cutters is about 50, the number of variables is about 50*2 = 100. For a dome-shaped cutter head, the number of the variables would be 50*3 = 150. So it can be seen that using Potter's static decomposition strategy, the layout problem of a flat-shaped cutter head will have to be decomposed into about 100 subproblems, which will require too expensive computing time. Since the static decomposition strategy is impractical for this study, we follow the property of the TBM's cutter design, and decompose the original layout problem according to different cutters' types. There are totally three types of cutters: center cutters, normal cutters and gage cutters. In this study, locations of the center cutters have been pre-decided by using human experience. Locations of the normal cutters and the gage cutters are to be solved by a CCEA. So during the optimization process, the normal cutters and the gage cutters are considered the two subproblems, respectively. The interaction methods of the subpopulations of the CCEA are various. The main purpose of the interaction between the subpopulations is to keep all the subpopulations converging on a global consistency objective. The traditional evolutionary algorithms mainly simulate more of the competition among the natural species, and less of the cooperation among them [21]. For the complex engineering layout problem, competition and cooperation usually exist simultaneously. It is important for the evolutionary algorithm to balance the cooperation and competition among the subpopulations, thus to reach a global balance state.

Now that the CCEA mainly adopts the cooperative individual method to exchange the information among the subpopulations, and the individuals of each subpopulation are parts of the whole solution of the problem, the individuals' fitness evaluations of each subpopulation need some cooperative individuals provided by other subpopulations. Suppose that $\boldsymbol{x_{ij}}$ denotes the jth individual of the ith subpopulation. When calculating the fitness value of $\boldsymbol{x_{ij}}$, first a cooperative individual set x_k^{select} (k = 1,2,…, i-1, i+1, …, q) is selected from other subpopulations, where q = the number of subpopulations. The

Begin

Initialize the original cutters' plane layout problem;

Initialize a cooperative co-evolutionary genetic algorithm;

Decompose the original problem into n(n≥2) subproblems SP_i (i=1,2,3…n);

For subproblem SP_i (i=1,2,3…n)

Assign a subpopulation P_i (i=1,2,3…n) for each subproblem;

Select an individual randomly from each subpopulation P_i (i=1,2…N) as the cooperative individuals;

Evaluation;

End For

For each subpopulation P_i (i=1,2,3…n)

Selection, cross and mutation;

Select the best individual from every subpopulation P_i (i=1,2…N) as the cooperative individuals;

Evaluation;

End For

Output s best individuals of every subpopulation;

End

Fig. 3. Flowchart of the cooperative coevolutionary genetic algorithm for the cutters' plane layout problem.

individual $\boldsymbol{x_{ij}}$ and the cooperative individual set x_k^{select} form a whole solution $\boldsymbol{X}$ of the problem, which can be formulated as:

$$X=\{x_1^{select},x_2^{select},\cdots,x_k^{select},\cdots,x_{ij},\cdots,x_q^{select}\}. \quad (17)$$

A whole solution $\boldsymbol{X}$ denotes a complete scheme that can be evaluated to obtain a fitness value. This fitness value is used as the fitness value of the individual $\boldsymbol{x_{ij}}$, and it can be formulated as:

$$f(x_{i,j}) = S(x_1^{select},\cdots\cdots,x_{ij},\cdots,x_q^{select}) \quad (18)$$

where x_1^{select} denotes the cooperative individual provided by the first subpopulation.

According to the above analysis, a cooperative coevolutionary genetic algorithm (CCGA) is used to solve the cutters' plane layout problem. A flowchart of the algorithm is shown in Fig. 3.

Based on the above-mentioned analysis, the solution flowchart of the disc cutters' layout design of TBM is given and illustrated as Fig. 4.

5. Application instance

Taking the disc cutters' layout design of the full face rock TBM of a water tunnel project as a background [23], an application instance is presented. Forty-one disc cutters are needed to be located on the cutter head surface shown in Fig. 1. The relative parameters are as follows: (1) Rock physical properties: the rock is mainly in granite-based geology, the punch shear strength of rock τ = 7-13 (MPa), the uniaxial compressive strength of rock σ_c = 50~93.6 (MPa), and the Brazilian tensile strength σ_t = 2.14~4.0 (MPa). (2) Cutter head geometry: the cutter head radius R = 4.015m, the rotational speed of cutter head ω = 6 (r/min) = 0.6283 rad/s, the mass of each cutter M = 200kg, the diameter of each cutter D = 483mm, the cutter tip width T = 10mm, the cutter penetration P = 7mm, and the cutter edge angle α = 1.5708 rad. The center cutter number n_1 = 8, the gage cutter number n_2 = 10, and the normal cutter number n_3 = 33. As mentioned earlier, locations of the eight center cutters are pre-determined by human experience. So in the optimization process, there are

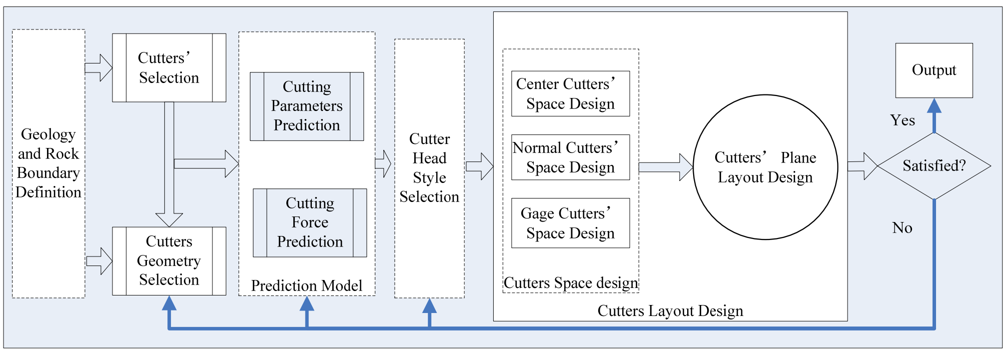


Fig. 4. Flowchart of the disc cutters' layout design.

totally 43 = 33 (the number of normal cutters) + 10 (the number of gage cutters) cutters whose locations need to be decided.

Table 1. Locations of the manholes.

No.	1	2	3	4
ρ /mm	2700.000	2700.000	2700.000	2700.000
θ /rad	1.2217	2.793	4.363	5.934

The technical requirements of the disc cutters' layout design are as follows：the expected centroid position of the cutter head x_e = 0 mm, y_e = 0 mm; the allowable centroid error of the whole system δx_e = 5mm, δy_e = 5mm; and the allowable angle difference $\Delta\theta$ = 45^0. According to the engineering requirements, four manholes are located on the cutter head. The radius of the manholes is 200mm, and the locations of the manholes are listed in Table 1. There are eight buckets located

Table 2. Dimensions and the locations of the buckets.

No.	1	2	3	4	5	6	7	8
ρ /mm	3700.000	3500.000	3700.000	3500.000	3700.000	3500.000	3700.000	3500.000
θ /rad	0.611	1.396	2.182	2.967	3.753	4.538	5.323	6.109
Length/mm	700.000	900.000	700.000	900.000	700.000	900.000	700.000	900.000
Width/mm	300.000	300.000	300.000	300.000	300.000	300.000	300.000	300.000

Table 3. Parameters of rock property.

Name	Density (g/cm^3)	σ (Mpa)	Friction angleφ (°)	Cohesion C (Mpa)	Bulk modulus (10^3MPa)	Poisson's ratio μ
granite	2.75	93.6	33.4	0.9	18	0.19

Table 4. Results of rock fragmentation simulation induced by three disc cutters simultaneously.

Space (mm)	Chip formation steps	Penetration Left (mm)	Penetration Right (mm)	Breaking area A (cm^2)	Energy consumption W (J)	W/A=SE
60	345	15	12	8.1	5.85	0.72
70	395	15	17	11.2	6.87	0.61
80	460	21	20	16.4	8.31	0.51
90	530	22	21	19.4	9.93	0.51

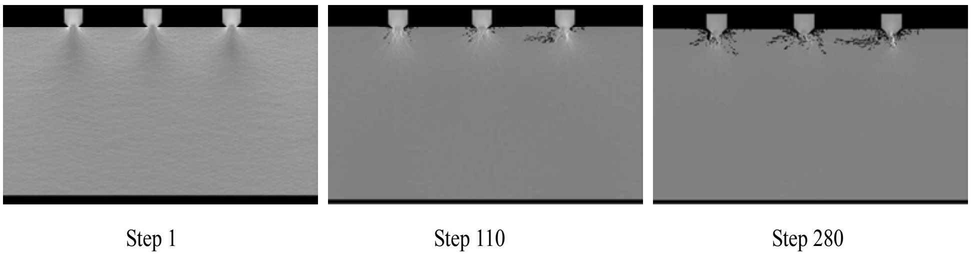


Fig. 5. Numerical simulation of chip formation process induced by three TBM disc cutters.

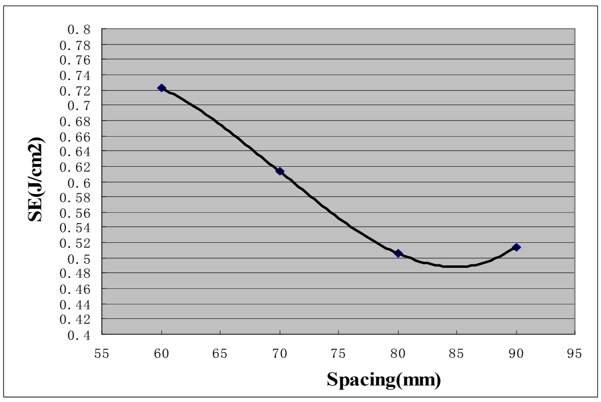


Fig. 6. Variations of SE with different cutter's spacing.

Table 5. Locations of the disc cutters from the center of the cutter head.

No.	1	3	3	4	5	6	7	8	9	10	11	12	13
ρ /mm	70	170	270	370	470	570	670	770	855	940	1025	1110	1195
θ /rad	0.00	3.14	0.00	3.14	1.57	4.71	1.57	4.71	5.59	2.60	3.72	0.79	2.02
γ /rad	0	0	0	0	0	0	0	0	0	0	0	0	0
No.	14	15	16	17	18	19	20	21	22	23	24	25	26
ρ /mm	1280	1365	1450	1535	1620	1705	1790	1875	1960	2045	2130	2215	2300
θ /rad	3.11	0.17	5.11	5.98	2.43	4.23	0.53	3.74	2.03	4.85	0.19	5.55	3.09
γ /rad	0	0	0	0	0	0	0	0	0	0	0	0	0
No.	27	28	29	30	31	32	33	34	35	36	37	38	39
ρ /mm	2385	2470	2555	2640	2725	2810	2895	2980	3065	3150	3235	3320	3405
θ /rad	0.79	2.31	3.91	1.71	0.54	5.09	3.65	5.71	1.96	5.95	0.85	2.37	-0.02
γ /rad	0	0	0	0	0	0	0	0	0	0	0	0	0
No.	40	41	42	43	44	45	46	47	48	49	50	51	
ρ /mm	3490	3575	3646.7	3715.2	3778.6	3835	3882.7	3922.5	3953.9	3978.8	3998.3	4015	
θ /rad	3.35	4.90	2.83	4.39	2.05	0.11	5.45	3.61	1.25	2.66	4.70	0.88	
γ /rad	0	0	0.16	0.31	0.47	0.63	0.78	0.91	1.03	1.13	1.19	1.22	

Table 6. Performance indexes of the optimal layout scheme solved by two methods.

Methods		M_v / KN.m	F_s /KN	x_m /mm	y_m /mm	Overlapping area	Unsuccessive disc cutters' number	Time/*s*
Original human experience scheme		154.840	11.558	-2.135	-0.221	0.000	4	Unknown
CCGA	Best	0.028	0.001	0.080	1.010	0.000	0	1189
	Average	6.623	4.382	-0.532	0.262	0.000	0	1202

Table 7. The maximum stresses and deformations of the cutter head solved the CCGA under different load conditions.

Methods	Von Stress/MPa				Max Deformation/mm			
	Normal load		Full load		Normal load		Full load conditions	
	Max.	aver.	Max.	aver.	Max.	aver.	Max.	aver.
CCGA	111.06	24.30	324.466	70.203	0.438	0.195	1.36	0.905

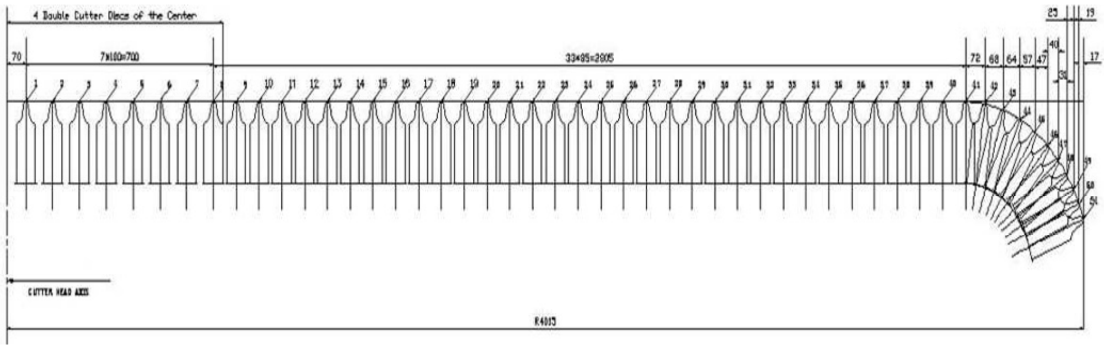
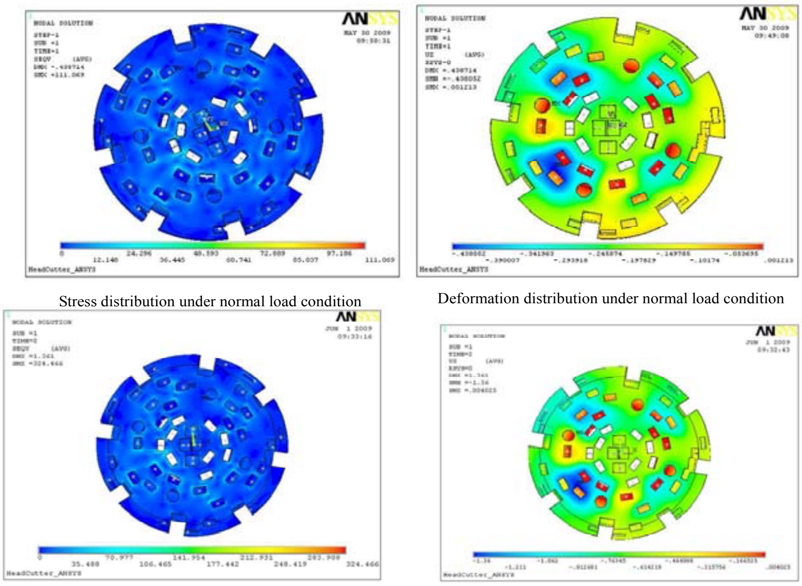


Fig. 7. The disc cutters' spacing layout pattern.

in the cutter head symmetrically, and their locations are listed in Table 2.

Based on the above-mentioned requirements, the first step is to determine the disc cutters' spacing. The disc cutters' spacing layout design includes the spacing design of the center cutters, the normal cutters and the gage cutters. First, the rock's fragmentation simulation software RFPA^{2D} is used and the numerical simulation method of reference [11] is adopted to simulate the rock fragmentation process induced by three disc cutters of TBM under different spacing. Properties of the rock are listed in Table 3. Parameters of the rock's fragmentation simulation are as follows: the penetration of each simulation step is 0.005 mm/step; the model rock size is about 200mm*600mm; and the confining pressure is 20Mpa. The value of the confining pressure is mainly decided by the geological report. The results of the rock's fragmentation simulation induced by three disc cutters simultaneously are listed in Table 4. The numerical simulation process of chip formation induced by the three disc cutters is shown in Fig. 5. The spacing between the three disc cutters is set from 60 mm to 90 mm. The variations curve of SE with different cutter spacing is shown in Fig. 6. From Fig. 6, it can be seen that that the opti-



Stress distribution under normal load condition
Deformation distribution under normal load condition
Stress distribution under full load condition
Deformation distribution under full load condition

Fig. 8. The stress distribution and the deformation distribution of the cutter head of the scheme obtained by the proposed under two load conditions.

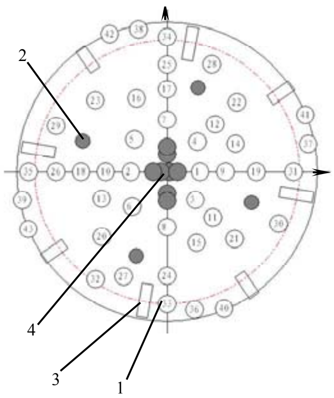
mal spacing is about 83-86mm, so 85mm is selected as the normal cutter's spacing in this study. Second, for the center cutters' spacing, the rolling distance of the center cutters usually is smaller than that of the normal cutters under the same cutter spacing at the same times. Moreover, the rock is of good integrity; it is hard to fully use the shear ability of the cutters to cut the rock if the center cutter spacing is set at a little smaller value, so the center cutter spacing is set 100mm in this study. Last, Eq. (8) is adopted to determine the gage cutters' spacing. The radius ρ measured from the center of the cutter head of all the three types of cutters is listed in Tab. 5. The disc cutters' spacing layout pattern is shown in Fig. 7.

As can be seen from Fig. 7, with the increasing of the radius of the cutters, the cutters' spacing are decreasing. Moreover, the gage cutters' spacing decreases more obviously to balance their lives and abrasions.

After the design of the cutters' spacing, the next step is the cutters' plane layout design. The basic problem of this step is to optimize the objective function formulated by Eq. (9), whilst satisfying all the technological constraints given by Eqs. (10)-(13). A CCGA is designed and programmed to solve this problem.

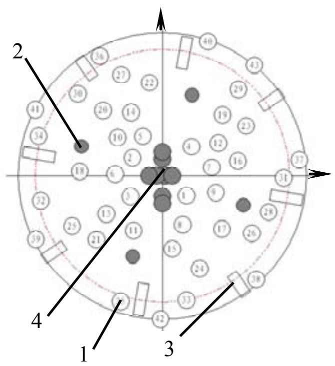
The numerical experiments are run on an AT-compatible PC, with 1700MHz Intel processor with 4 and 512 Mb Memory. The CCGA is run for totally 30 times. The performance indexes of the optimal layout scheme and the original scheme designed by using human experience are listed in Table 6. The original human experience design is illustrated as Fig. 9. The optimal layout scheme obtained by the CCGA is illustrated as Fig. 10.

Then the optimal layout scheme is put into the FEM for analysis. Parameters set in the FEM calculation are: the calculated FEM platform is ANSYS (R) Release 10.0, unit Shell63



1 Normal cutters and gage cutters； 2 Manholes；
3 Buckets；4 Center cutters；

Fig. 9. The original disc cutters' layout scheme obtained by human experience.



1 Normal cutters and gage cutters；
2 Manholes； 3 Buckets；4 Center cutters；

Fig. 10. The optimal disc cutters' layout scheme obtained by the CCGA.

is adopted, the number of units is 63369, the number of nodes is 62193, the density is 7850Kg/m^3, the elastic modulus E = 2.06 × 105MPa, and the Poisson's ratio is 0.3.

Based on the FEM simulation, the maximum stresses and deformations of the cutter head under different load conditions are listed in Table 7. The stress distribution and the deformation distribution of the cutter head of the scheme obtained by the CCGA under two load conditions are shown in Fig. 8.

The data in Table 6 shows that, compared with the original scheme, the scheme obtained by the proposed method is more superior in that:

Values of the side force and the eccentric moments of the cutter head obtained by the later scheme are much smaller than that of the former scheme;

As can be seen in Fig. 8 and Fig. 9, the latter scheme has no unsuccessive cutters and can make all the adjacent disc cutters cut the rock successively with a relatively larger position angle difference, while the former scheme has 4 unsuccessive cutters;

The static balance value of the cutter head of the later scheme is smaller than that of former scheme.

The proposed method is superior to the traditional human experience method in that:

Instead of obtaining only one solution, the proposed method is capable of providing an optimal scheme set for the engineers to choose from, and the difference of the optimal schemes is distinct. Please see Fig. 10.

Using the proposed method, optimal disc cutters' layout schemes can be obtained within shorter running times. It is more efficient and accurate than the human experience method.

The data in Table 7 and Fig. 8 show that:

(1) under the normal load and the full load conditions, the optimal layout scheme obtained by CCGA makes the cutter head have more uniform deformation distribution, and the maximum value of deformation obtained is only less than 1.433mm;

(2) under the normal load condition, the optimal layout scheme makes the cutter head have more uniform stress distribution, and the maximum value of stress is only less than 111Mpa. Under the full load conditions, although the cutter head has a relatively larger local stress and the maximum value of local stress is about 324Mpa, the average value of the stress is only about 70Mpa. All these data show that the obtained optimal scheme satisfies the strength requirements.

6. Conclusions

Based on the complex technical requirements and the cutter head's geometry design requirements, this study formulates a multi-objective disc cutters' layout design model with multiple nonlinear constraints and presents a corresponding two-stage solution strategy that includes the disc cutters' spacing design and the disc cutters' plane layout design. A numerical simulation method based on the FEM theory is adopted to simulate the rock chipping process induced by three TBM disc cutters to determine the optimal cutter spacing. And a CCGA is adopted to solve the disc cutters' plane layout problem. The application instance demonstrates the feasibility and effectiveness of the proposed method. The computational results show that the proposed method is quick in providing Pareto-optimal disc cutters' layout designs for engineers to choose from. The optimal design has been tested to be superior to the human experience design in some aspects.

It should be noted that the proposed design method stays in the numerical experiment level, and has only been compared with the original design in some aspects. It has not been demonstrated in practice. The disc cutters' layout design problem of the TBM belongs to the complex engineering problem, and the proposed disc cutters' layout model is not capable of fully describing all practical aspects of the disc cutters' layout design problems. There are still several questions that need to be solved as follows:

The disc cutters' layout design should consider the difference of the rock boundary conditions synchronously as much as possible and make the cutter head keep higher adaptability and stability;

The multi-disciplinary layout design model and the corresponding solving methods need be further studied;

A great many engineering experiences have been accumulated from the preliminary studies. With the development of the commercial 3D-CAD technologies and the mechanical optimization technologies, the human-computer interaction cutter head design system is to be developed to achieve the cutter head's modeling and the cutter head's optimization design more efficiently.

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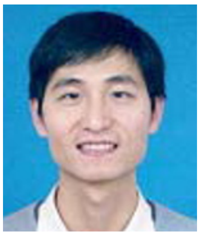

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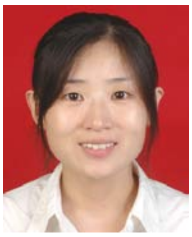

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