Intelligent Optimization of Highway Tunnel Space Structure Based on Improved Immune Genetic Algorithm

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ABSTRACT

Because of the complicated conditions, great deformation, high stress, multi-variables, high non-linearity, the algorithm for structure optimization and its application in tunnel engineering has just been at the right beginning. However, how to make optimized design of structure for tunnel section, reduce excavation and increase support is a very urgent task now. Artificial intelligence shows extremely strong capability in identifying, expressing and disposing such kind of multiple variables and complicated non-linear relation. In this paper, the pure selection mode depend on the fitness value in the original genetic algorithm replaced by the selection of update method of concentration and fitness of immune algorithm generally, and the fitness is determined through similarity vector-distance of antibody ,so adjusting the algorithm in balance between the similarity and concentration by changing some parameters. The method incorporated with advantages of immune algorithm and good qualities of genetic algorithm. Through the function of antigen recognition memory, the overall search capability of immune genetic algorithm can be enhanced avoiding premature phenomenon. It is able to adjust the excavation area and support and protection design in the current design to get the conclusion with practical value by means of optimization of structure surface of the garden tunnel, verifying the advantages of this method in optimization calculation of tunnel engineering at faster calculation speed and higher efficiency and also indicating the improved immune genetic algorithm has practical significance in the stability evaluation of tunnel rock and information design.

KEYWORDS: immune genetic algorithm, tunnel, super-large section, optimization
INTRODUCTION

In such a country with many mountains, the construction scale of highway tunnel becomes bigger and bigger while the tunnel plays positive part in overcoming mountains and other terrain obstacles, safeguarding the best road alignment, cutting travel distance, increasing vehicle speed, lowering oil consumption, guaranteeing travel conformity, reducing the incidence rate of traffic accident, protecting the environment and saving land as well as providing good economic and social benefits, etc. as an important composition of highway in mountain areas. With the increase of investment in highway construction by the country, highway construction develops drastically and highway tunnel are in bigger and bigger scale. Therefore, large section and great depth will be the general trend for the development of tunnel engineering in the 21st century in our country, in which the engineering cost will take up more and more proportion in the overall highway engineering construction. Sometimes, if a highway project can proceed depends on the construction investment in tunnel in such project. Under current circumstances, it costs quite a lot to construct the tunnel resulting in slow and delayed highway construction. In this case, to lower the general cost of highway tunnel, save investment and make careful design, namely to construct highway tunnel in the most economic approach is an urgent task at present [1]. The structure optimization design of tunnel section dose not only includes optimizing the shape of tunnel section and lowering excavation area for tunnel, but also making optimization on the general cost of tunnel so as to lower the total cost of tunnel [2]. Under the current state in our country, it is obviously an approach with very obvious economic benefits to make optimization design of the tunnel, especially suitable to solve the conflict between urgency of high level road and capital scarcity.

The structure optimization theory has existed for over a century since the appearance of Maxwell theory (Maxwell,1890) and Michell truss (Michell,1905). In particular, the optimization theory, algorithm and application developed quite a lot in the past 30 years as it has been applied in many aspects regarding aviation and aerospace, mechanical and civil construction area, etc [3]. However, in the field of tunnel and underground structure optimization, due to the complexity of tunnel and underground structure, there’s so many parameters needed to be optimized (e.g. support and protection structure, rock load, construction decision, etc.) and optimization of multi-variables and high non-linearity involved so that its research and application is just at the right beginning and quite few documentations and examples can be taken for reference. For example, Japanese Hiroshi Yoshi and Shiro Sakurai uses strain control to make optimization of tunnel structure; Indian T. Amirsoleymani discussed about the optimization method of oval section of water diversion tunnel according to the assumption of linear elasticity of rock mass and proposed a best geometric shape method to eliminate the tensile stress around the tunnel while keep the minimum compressive stress; Liu Yihu from Hunan University proposed optimization selection methods [3] for three kinds of shape of lining section (single-center circle, three-center sharp circle, three-center tabular circle) by taking the optimization selection of section for tunnel structure in long and
large highway tunnel and stability for the structure design of support and protection for the tunnel as the core issue\(^4\)\(^7\).

**IMPROVED IMMUNE GENETIC ALGORITHM**

**Features of immune genetic algorithm**

As a random search algorithm for overall optimization with the feature of self adaptability and parallel process, genetic algorithm is able to lead the following search process according to individual fitness with clear direction, finishing the adjustment process in the way of self adaptation. The parallel process feature of genetic algorithm represents that there’s certain independence of all genetic operation from some colony in certain scale to the individuals in the colony. Such kind of parallelism enables the genetic algorithm to take advantage of colony information effectively and master the condition of overall search space so that it is easy to access the most promising area for the search process avoiding search of some points not required and improving the search efficiency of the algorithm. The genetic algorithm has another feature making the algorithm with overall optimized search performance by means of cross operation among individuals in colony and mutation operation of individuals to generate new individuals and keep diversity of species. However, it is founded that there’re some unsatisfactory problems in genetic algorithm through application and practice, e.g. easily happened premature phenomenon, poor local optimization capability and no existing reasonable basis for the operation parameters of the algorithm as well as failure of convergence at probability 1 to the best overall optimized solution for basic genetic algorithm\(^8\). In allusion to those deficiencies existing in genetic algorithm, I hereby combine the immune system and genetic algorithm into the immune genetic algorithm (IGA)\(^9\) starting from the improvement of optimization performance and introducing different processing systems of immune information. Immune genetic algorithm is to add calculation of concentration probability, advancement and control of antibody, calculation of spread of antibody and other modules to improve the diversity of antibody in the evolution process on the basis of basic genetic algorithm.

**Improved immune genetic algorithm**

In the improved algorithm proposed in this paper, it replaces the selection method purely based on the adaptability value in the original genetic algorithm by the selection and update strategy in general consideration of concentration and adaptability which is determined by the similarity vector-distance of antibody, and take it as the final selection system for antibody while pass some antibodies with high adaptability and relatively low concentration to the generation. The individual copy operation in genetic algorithm is canceled after the selection avoiding large quantity of same individuals appearing
to influence the diversity of species. Good individuals are only entitled to more chance for cross operation so as to improve individual adaptability and maintain individual diversity\cite{11}\cite{12}.

The probability of selection in similarity vector-distance is used as the selection system for antibody. It is able to achieve balanced adjustment between similarity and concentration of the overall algorithm by changing the selection system for antibody so as to make the whole algorithm with advantages of immune algorithm together with good quality of genetic algorithm.

**Calculation of antibody and antigen affinity**

The diversity of antibody is a feature of biological immune system. According to the characteristics of genetic algorithm, introduce the information entropy in the immune system to estimate the change process of diversity and allele probability in the antibody. Suppose the immune system consists of $N$ antibodies and one single antibody contains $M$ genes, in line with the information entropy theory, then the entropy of $j$ gene locus for all $N$ antibodies in the immune system is shown in equation (1).

$$E_j(N) = \sum_{i=1}^{N} P_{ij} \log\left(\frac{1}{P_{ij}}\right)$$  \hspace{1cm} (1)

Where $P_{ij}$ is the probability to take the $i$ allele at $j$ gene locus; $N$ refers to the total number of allele on gene locus.

Adaptability estimation is to find out the best antibody in the antibody group and generate new species in the method of making comparison of affinity of antibodies, antibody and antigen, in which the calculation of affinity of antibodies can be expressed shown in equation (2) and equation (3).

$$A_y)_{ij} = \frac{1}{1 + E(2)}$$  \hspace{1cm} (2)

$$E(2) = \frac{1}{M} \sum_{k=1}^{M} E_k$$  \hspace{1cm} (3)

The calculation formula of affinity of antibody and antigen is shown in equation (4).

$$(A_i y) = g_y(X)$$  \hspace{1cm} (4)

Where, $g_y(X)$ refers to the affinity function of antibody $I$ while $y$ represents the antigen.

In order to keep the diversity of antibody, it is required to adjust the adaptability with concentration. In accordance with the immune network theory by Jerne, the dynamic equation to calculate the incentive level and concentration of antibody is show in equation (5) and equation (6).

$$A_i(n+1) = A_i(n) + \frac{\sum_{j=1}^{N} \gamma_j A_j(n)}{N} + \beta g_i - k_i) A_i(n)$$  \hspace{1cm} (5)
\[ \alpha_i(n) = \frac{1}{1 + \exp(0.5 - A_i(n))} \]  

(6)

where \( \alpha \) is the interaction rate of antibody \( i \) against other antibody; \( \beta \) is the interaction rate of antibody \( i \) against antigen; \( A_i(t) \) is the incentive of individual \( i \) at \( t \) time; \( a_i(t) \) is concentration of individual \( i \) at \( t \) time; \( m_{ij} \) is affinity coefficient between antibody \( i \) and \( j \); \( m-i-k \) is exclusion factor between antibody \( i \) and \( k \); \( k_i \) is natural mortality of antibody \( i \); \( g_i \) is matching rate of antibody \( i \) and antigen; \( N \) is amount of antibody; \( r \) is integrated incentive factor between antibody \( i \) and \( j \).

From the formula above, work out the concentration of antibody \( \alpha_i(n) \), then figure out the ration of adaptability and average value of single individual and move to consider the influence of concentration and take concentration control. In conventional algorithm, the higher the individual adaptability is, the more possible to be selected and individual of similar adaptability in the group will increase sharply so that the algorithm will not mature and converge. To overcome this problem, here is the probability of selection based on similarity vector-distance considering the similarity of all antibodies on code.

Introduce Euclidean Distance, the distance between antibody \( a_1, a_2, \ldots, a_n \) are as shown in equation (7).

\[ d = \sqrt{\sum_{i \leq j} (a_i - b_j)^2} \]  

(7)

The value of \( d \) is inversely proportional to the imilarity. If \( d=0 \), the two antibodies are same.

Therefore, the selection probability of antibody based on similarity vector-distance can be expressed in equation (8) and equation (9).

\[ P(x_i) = \frac{\rho(x_i)}{\sum_{i=1}^{N} \rho(x_i)} + (1 - \alpha) \frac{1}{N} e^{-\frac{\alpha_i(n)}{x}} \]  

(8)

\[ \rho(x_i) = \sum_{j=1}^{N} |f(x_i) - f(x_j)| \]  

(9)

Where, \( \varepsilon \) & \( k \) are the regulatory factor \([0, 1]\); \( (x_i) \) is optimal solution; \( f(x_i) \) is adaptability function.

From the formula above, when determining the concentration, the vector distance of antibody is directly proportional to the probability of selection; while determining the vector distance of antibody, the concentration is inversely proportional to the probability of selection.

In simulation of the secondary response feature of immune system, a cell memory bank is designed including the design of characteristic code of the problem category, parameter of problem characteristic and memory bank of antibody in memory area filed taking advantage of the mechanism of immune memory. It will help boost the diversity of application range for algorithm and enable the memory bank to reserve optimal solution for generations in evolution as well as used as the basis for similar problem in conformation of initial species. It is able to increase search speed and enhance
general search capability of the algorithm to use such antigen memory function; it will overcome the
defect of basic genetic algorithm as easy to run into local optimal solution by extracting effective
information from the optimal individual and creating new approach for production of immune vaccine
to make the algorithm with good performance of overall convergence during the evolution of species.

**Design of immune genetic algorithm**

Through analysis of some limitation of genetic algorithm and causes, on the basis of vaccine
extraction of artificial immune system, vaccination, immune memory, gene affinity and mutation as
well as other principles and in combination of basic framework of genetic algorithm, an improved
immune genetic algorithm is proposed. The process of the algorithm is as shown in Figure.1.

![Diagram](image)

**Figure 1:** Process of improved immune genetic algorithm
CONSTRUCTION OF TUNNEL CALCULATION MODEL AND CONSTRAINTS

Given a series of factors including the application requirements, force bearing, deformation and cost of the tunnel, set up the calculation model for the tunnel and make calculation, then make post-processing analysis of calculation results.

Setup of geometric model

The geometric model for tunnel includes: (1) tunnel bound; (2) internal profile shape of tunnel; (3) shape of external profile for the secondary lining of the tunnel; (4) shape of external profile for the preliminary lining of the tunnel; for the tunnel section in symmetric structure, it can be analyzed only with half of the tunnel structure. Take the left side of the tunnel which is made up of five arcs tangent with adjacent ones. Every arc shall be determined by five parameters. Since there’re certain constraints between arcs, only eight independent parameters are enough. The program may enter 8 parameters (see figure 2), tabular tunnel in large section of IV and V grade rock is generally five-center circle section (the same way for other section forms), the section form is as shown in Figure 3.

![Figure 2: Geometric model for the tunnel](image-url)
Setup of calculation model

Set up tunnel calculation model from geometric model, in compliance with the rock category condition, tunnel burying condition, etc., work out the rock pressure on the tunnel in different calculation theories for rock pressure and finally apply the load and rock elasticity constraint on the tunnel margin as the boundary condition to get the tunnel calculation model finally (figure 3) including:

1) Closed framework based on the secondary lining structure of the tunnel;
2) Load functioning at the framework;
3) Elastic support attached to the closed framework;
According to the calculation model and reinforcement rate of the tunnel, indirectly estimate if the force born by the tunnel meets requirements. In the model, select the most dangerous section in the tunnel as the benchmark section for reinforcement. Reinforcement process is as follows.

1. Calculate the force bearing condition of the tunnel, match steel bars to all beam units, in case of any excess in the beam unit, the tunnel force bearing is not reasonable and it shall be adjusted and optimized; if the reinforcement for all beam units are within reasonable scope, take the unit with maximum reinforcement rate as the benchmark and such value for all whole circumference lining reinforcement rate of the tunnel, then work out the consumption of steel bars for the tunnel section.

2. Get the displacement condition of every finite element node through finite element calculation. Make analysis of every node of calculation model one by one, in the event that the displacement of node exceeds the designated value, such tunnel model is inconsequent and shall be adjusted in optimization search.

3. Tunnel cost mainly including excavation, concrete cost, invert backfill and reinforcement cost. Excavation cost is shown in equation (10)

\[
f_t(X) = p_e S_e(X)
\]  

where, \( S_e(X) \) is excavation volume at unit length of the section (Figure 5); \( p_e \) is excavation price of unit volume (including general unit price of temporary support)
Concrete cost is shown in equation (11).

\[ f_2(X) = p_{c1}S_{c1}(X) + p_{c2}S_{c2}(X) \] \hspace{1cm} (11)

Where, \( S_{c1}(X) \) and \( S_{c2}(X) \) are area of preliminary and secondary lining concrete for the section; \( p_{c1} \) and \( p_{c2} \) are unit price of preliminary and secondary lining concrete at unit volume (including the general unit price of initial support).

Cost of invert backfill is shown in equation (12).

\[ f_3(X) = p_hS_h(X) \] \hspace{1cm} (12)
where, $S(X)$ is volume of backfill concrete for the section; $p_h$ is price of backfill concrete at unit volume.

Cost of reinforcement in the secondary lining concrete is shown in equation (13).

$$f_3(X) = p_s S(X)$$  \hspace{1cm} (13)

where, $S(X)$ is weight of reinforcement in the secondary lining concrete for the section, obtained from the result processed in line with the tunnel structure; $p_s$ is price of reinforced steel bar at unit weight.

Integrating the cost of said items, the total cost function is shown in equation (14).

$$f(X) = f_1(X) + f_2(X) + f_3(X) + f_4(X)$$ \hspace{1cm} (14)

**OPTIMIZATION OF TUNNEL STRUCTURE MODEL**

**Concrete achievement of optimized model**

Build the optimization model for tunnel by taking the force, deformation and cost condition of the tunnel into consideration, detailed optimization process is shown in Figure 7.

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**Figure 7: Optimization process**
The calculation model for tunnel section takes the influence of various factors on the force, deformation and cost of tunnel into account and selects three variables which have most significant influence on those factors as the design variable for optimization: net height of top arch, thickness of secondary lining and invert depth. Section optimization is targeted at economy and utility, therefore, the objective function of this optimization model takes the cost of tunnel for economy and utility as the basis in the equation (14).

\[ f(X) = f_1(X) + f_2(X) + f_3(X) + f_4(X) \]  

(14)

The reasonability for application, force and deformation of tunnel is embodied in the optimized constraints included in the objective function.

**OPTIMIZATION EXAMPLE**

The garden tunnel locates at yellow cloud booth village, fragrant mouth town, Yunxi County, in design of small spacing tunnel for four-driveway highway downlink and uplink separately. The starting and ending pile on the left line of the tunnel is ZK91+705~ZK92+130, at the total length of 425m; while the pile on the right line is YK91+705.227~YK92+133.426, at the full length of 428.199m and maximum burying depth about 85m. The entrance of the tunnel is constructed in bamboo-cut portal. With the excavation height at 13.60 m and net width of the tunnel at 18.0 m and high-span ratio of the section at 0.654, it is a super-large tabular tunnel.

In the tunnel design, the fifth grade deep burying segment has most significant influence on the whole tunnel, being taking as the typical control face of the tunnel, on which the internal profile of the tunnel is determined. This case will give analysis on the section of this tunnel (the unit price used in the analysis is the unit price used by the owner for tender). In order to give comparison of the optimization results, here comes the general review of existing design.

**General review of existing design**

According to the design data, the section shape of tunnel is shown in Figure8. Geological condition of deep burying segment for V grade rock and price of engineering materials are shown in Table 1 and Table 2.

**Table 1:** The value for physical parameters of rock

<table>
<thead>
<tr>
<th>Bulk density $\gamma$ kN.m$^{-2}$</th>
<th>Elastic modulus $E$ (MPa)</th>
<th>Poisson's ratio $\mu$</th>
<th>Cohesion $c$ (MPa)</th>
<th>Friction angle $\varphi$ (°)</th>
<th>Density $\rho$ (kg/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>28</td>
<td>370.47</td>
<td>0.19</td>
<td>0.18</td>
<td>33.82</td>
<td>2700</td>
</tr>
</tbody>
</table>
Table 2: Material price

<table>
<thead>
<tr>
<th>Material</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excavation price</td>
<td>0.052</td>
</tr>
<tr>
<td>Preliminary concrete price</td>
<td>0.7</td>
</tr>
<tr>
<td>Secondary lining concrete price</td>
<td>0.399</td>
</tr>
<tr>
<td>Backfill concrete price</td>
<td>0.213</td>
</tr>
<tr>
<td>Steel price</td>
<td>5</td>
</tr>
</tbody>
</table>

Figure 8: Section of current design

As this rock segment is at shallow burring segment, the rock pressure can be calculated in the method specified in the highway tunnel regulation. During the optimization, the geological conditions of the tunnel and cost of engineering materials are the same with the original design, so parameters for the structure reinforcement of the tunnel and analysis of rock deformation is shown in Table 3.

Table 3: Basic parameters

<table>
<thead>
<tr>
<th>concrete grade</th>
<th>Grade of steel</th>
<th>Safety factor</th>
<th>Thickness of protective layer</th>
<th>Maximum deformation</th>
</tr>
</thead>
<tbody>
<tr>
<td>c30</td>
<td>2</td>
<td>2</td>
<td>50mm</td>
<td>50mm</td>
</tr>
</tbody>
</table>

After the optimization, various geometric parameters of the tunnel structure are compared with those in the original design as shown in Table 4.

Table 4: geometric parameter

<table>
<thead>
<tr>
<th>Optimization analysis</th>
<th>arch top height /m</th>
<th>Invert depth /m</th>
<th>Thickness of secondary lining /m</th>
<th>Height-span ratio</th>
<th>Excavation area /m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimization result</td>
<td>3.5</td>
<td>1.9</td>
<td>0.68</td>
<td>0.586</td>
<td>201.7</td>
</tr>
<tr>
<td>Existing design</td>
<td>4</td>
<td>2.2</td>
<td>0.65</td>
<td>0.633</td>
<td>229.4</td>
</tr>
</tbody>
</table>

Various cost parameters for the section of tunnel structure and comparison with the original design is shown in Table 5.
Table 5: Cost list (Unit: a thousand Yuan )

<table>
<thead>
<tr>
<th></th>
<th>Reinforcement</th>
<th>preliminary lining concrete</th>
<th>secondary lining concrete</th>
<th>Invert backfill</th>
<th>Excavation</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimization result</td>
<td>12.7</td>
<td>15.0</td>
<td>17.0</td>
<td>2.1</td>
<td>19.6</td>
<td>66.4</td>
</tr>
<tr>
<td>Existing design</td>
<td>11.3</td>
<td>17.1</td>
<td>16.4</td>
<td>2.6</td>
<td>20.1</td>
<td>67.5</td>
</tr>
</tbody>
</table>

As shown in Table 5, it adopts whole circumference stratigraphic spring model as the calculation model in this optimization while the spring vertical or parallel with the coordinate axis is used in the original design, according to analysis and comparison of test calculation results, the calculation result of this optimization is more conservative than the original design. After the optimization analysis of shallow burring segment for V grade rock, the lining thickness is higher than the current design and so is the quantity of reinforcement. However, the cost of all other items is reduced to make the final cost 1100 Yuan lower than the original design, at 1.6% decrease rate for the total cost. Due to the conservative calculation model used in this optimization, so the optimized result is more safe and reliable than the original design.

CONCLUSION

The main conclusions are as follows.

(1) The genetic algorithm is improved considering the concentration and fitness, and the fitness is determined by similarity vector distance of antibody. The fitness is used selection mechanism of antibody, and canceled individual copy operation after the selection of basic genetic algorithm, which could avoid the appearing of a large number of individuals to affect the population diversity.

(2) Some low antibody and higher fitness antibody which are put into the next generation could improve the fitness of individual and maintained the individual diversity. It could determine running parameters of algorithm simply and ensure global and local optimization ability of the algorithm, which could avoid premature phenomenon.

(3) The force, deformation and construction cost of the tunnel are considered, and the tunnel discontinuity is optimized aiming at the minimum cost of the tunnel. The advantages of optimization calculation in tunnel engineering which is faster calculation speed and high efficiency are verified, which shows that the improved immune genetic algorithm has the practical significance in stability evaluation and information design of tunnel surrounding rock.
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