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Intelligent Optimization of the Structure of the Large Section Highway Tunnel Based on Improved Immune Genetic Algorithm

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As in the building of deep buried long tunnels, there are complicated conditions such as great deformation, high stress, multi-variables, high non-linearity and so on, the algorithm for structure optimization and its application in tunnel engineering are still in the starting stage. Along with the rapid development of highways across the country, it has become a very urgent task to be tackled to carry out the optimization design of the structure of the section of the tunnel to lessen excavation workload and to reinforce the support. Artificial intelligence demonstrates an extremely strong capability of identifying, expressing and disposing such kind of multiple variables and complicated non-linear relations. In this paper, a comprehensive consideration of the strategy of the selection and updating of the concentration and adaptability of the immune algorithm is made to replace the selection mode in the original genetic algorithm which depending simply on the adaptability value. Such an algorithm has the advantages of both the immune algorithm and the genetic algorithm, thus serving the purpose of not only enhancing the individual adaptability but maintaining the individual diversity as well. By use of the identifying function of the antigen memory, the global search capability of the immune genetic algorithm is raised, thereby avoiding the occurrence of the premature phenomenon. By optimizing the structure of the section of the Huayuan tunnel, the current excavation area and support design are adjusted. A conclusion with applicable value is arrived at. At a higher computational speed and a higher efficiency, the current method is verified to have advantages in the optimization computation of the tunnel project. This also suggests that the application of the immune genetic algorithm has a practical significance to the stability assessment and informationization design of the wall rock of the tunnel.

1. Introduction

The structure optimization theory has been put into practice over a century since the introduction of the Maxwell theory (Maxwell, 1890) and Michell truss (Michell, 1905). In particular, in the past 30 years, the optimization theory has achieved an substantial development regarding algorithm and application, and the application field has been involved with many aspects such as aviation and aerospace, mechanical and civil construction area, etc (Schimit et al., 1960). However, in the field of tunnel and underground structure optimization, due to the complexity of the tunnel underground structure, there are so many parameters to be optimized (e.g. the support and protection structure, surrounding rock load, construction decision, etc.), and problems involved with the optimization of multi-variables and high non-linearity that its research and application is just at the starting beginning stage and the references and examples that can be taken for reference are not much reported. The limited examples are as follows: Japanese Hiroshi Yoshi and Shiro Sakurai applied the strain control to make the optimization of the tunnel structure; Indian scholar T. Amirsoleymani discussed about the optimization method of the oval section of a water diversion tunnel based on the assumption of the linear elasticity of rock mass and proposed a best geometric shape method to eliminate the tensile stress around the tunnel while keeping the minimum compressive stress; With the

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optimization selection of the shape of the tunnel structure and the stability of the structural design of the support in the big tunnel of the long and large high-grade highways as the core problem, Liu Xiaobing et al proposed three kinds of optimization selection methods (the single-center circle, three-center tabular circle , and three-center sharp circle) for the shape of the lining section (Liu et al., 1995; Wei, 2016).

2. Improved immune genetic algorithm

2.1 Features of the immune genetic algorithm

It has been discovered in the application practice that in the genetic algorithm there are some unsatisfactory problems. For instance, the premature phenomenon is easy to occur; the local optimization capability is limited; at present, there is no rational basis on which to select the operating parameters of the algorithm; in the basic genetic algorithm, there are still such problems that it is impossible to converge to the globally optimal solution with the probability 1 (Chang et al., 2002). Aiming at the deficiency in the genetic algorithm, different immune information processing mechanisms are introduced to improve the genetic algorithm to the immune genetic algorithm (IGA) by combining the immune mechanism with the genetic algorithm (Zheng et al., 2005). The immune genetic algorithm means that on the basis of the basic genetic algorithm are increased the modules for determining the concentration probability, improvement, inhibition and dispersion of the antibody to enhance the diversity in its involution process (Donald et al., 1997).

2.2 Improved immune genetic algorithm

The updated selection strategy, which is formed by making a comprehensive consideration of the concentration and adaptability, is used to replace the selection mode of the original genetic algorithm that depends simply on the adaptability value. The adaptability, which is determined by the similarity vector distance of the antibody, serves as the mechanism to select the final antibody. Certain antibodies that have higher concentration and whose concentration is relatively low enter into the next generation to eliminate the individual copying operation of the basic genetic algorithm carried out after its selection, and to avoid the massive occurrence of the diversity affecting the species of identical individuals. As a result, this only give the good individuals more opportunities to take part in the cross operation, thereby achieving the goal not only to enhance the adaptability but maintain the diversity of the individual as well (Yu et al., 1998).

1) Antibody and antigen affinity calculation

The diversity of antibody is a feature of biological immune system. According to the characteristics of the genetic algorithm, in the immune system is introduced the information entropy 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, the information entropy of the j-th gene locus of all N antibodies in the immune system is written as:

$$E_j(N) = \sum_{i=1}^{n_i} P_{ij} \log(\frac{1}{P_{ij}}) \tag{1}$$

in which Pij - probability to take the i-th allele at j-th gene locus; N - total number of the allele at the gene locus. The adaptability assessment is to find out the best antibody in the antibody group and generate new species. The assessment method is to compare the affinity between the antibodies and that between the antibodies and antigens. The equation for determining the infinity between the antibodies is expressed as:

$$(A_{tt})_{ij} = \frac{1}{1+E(2)} \tag{2}$$

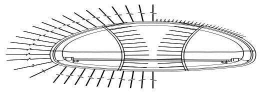
$$E(2) = \frac{1}{M}\sum_{k=1}^{M} E_k \tag{3}$$

The equation for determining the infinity between the antibodies and antigens is expressed as:

$$(A_{yt})_i = g_j(X) \tag{4}$$

Where - infinity function of the antibody i; y – antigen.

2) In order to maintain antibody diversity, it requires concentration to adjust the fitness. According to Jerne's proposed immune network theory, the dynamic equation for calculating antibody excitation levels and concentrations is shown as：



(5)

$$\alpha_i(n) = \frac{1}{1+\exp(0.5 - A_i(n))} \tag{6}$$

α - the interaction rate of antibody i for other antibodies; β - the interaction rate of antibody i on the antigen
Ai(n) - the level of excitement of the i-th individual at time n; ai(n) - the concentration of the i-th individual at time n
mij - the affinity coefficient between antibody i and j; mik - the rejection coefficient between antibody i and k
ki - natural mortality rate of antibody i; gi - the matching rate between antibody i and antigen
N - number of antibodies; r - the integrated excitation coefficient between antibody i and j

The concentration of the antibody was calculated according to the above formula. Then the simple genetic algorithm is used to calculate the ratio of the fitness value and the average value of a single individual, Concentration control is achieved by taking into account the effects of concentration. To overcome this problem, the selection probability based on the similarity vector distance is proposed by considering the similarity between coding of each antibody
Introduce Euclidean distance, the distance among antibodies a_1, a_1, ..., an is:

$$d = \sqrt{\sum_{1\le i\le n}(a_i - b_i)^2} \tag{7}$$

The probability of antibody selection based on similarity vector can be expressed by the following equation:

$$P(x_i) = \varepsilon\frac{\rho(x_i)}{\sum_{i=1}^{N}\rho(x_i)} + (1-\alpha)\frac{1}{N}e^{-\frac{\alpha_i(n)}{\kappa}} \tag{8}$$

$$\rho(x_i) = \sum_{j=1}^{N}\left|f(x_i) - f(x_j)\right| \tag{9}$$

Where ε, κ - adjustment factor, interval [0, 1]
(xi) - optimization solution; f (xi) - fitness function
From the above formula, when the concentration is determined, the antibody vector distance is proportional to the selection probability; when the antibody vector distance is determined, the concentration is inversely proportional to the selection probability

3. Optimization of the tunnel structural model

3.1 Optimization example

The Huayuan tunnel of the Shiyan-Manchuan highway is located in the Huangyunpu Village, Xiangkou Township, Xunxi County, Hubei Province. It is a small spacing four-driveway highway tunnel with the downlink and uplink separated. The number of the starting and ending piles on the left line of the tunnel is ZK91+705~ZK92+130, the total length being 425m. The number of the starting and ending piles on the right line is YK91+705.227~YK92+133.426, the total length being 428.199m. The maximum burying depth of the tunnel is about 85m. The excavation height is 13.60m. The net width of the tunnel is 18m. The height-span ratio of the section is 0.654. It is a super-large tabular tunnel.

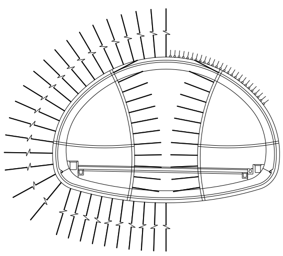


Figure 1: Existing design section

3.2 Overview of existing designs

According to the design data, the tunnel cross section shape as shown in Figure 1: V level of the surrounding rock deep geological survey and engineering material price as follows:

Table 1: Material price

Excavation price	Initial lining concrete price	Two lining concrete price	Backfill concrete unit price	Steel price
0.052	0.7	0.399	0.213	5

Note: (1) the unit price of steel is 1000 yuan / ton, the other unit price is 1000 yuan / cubic meter. (2) the price of all materials provided by the Design Institute (the initial support price is 130 thousand per meter, excluding the remaining four after calculation)

3.3 Optimization constraint conditions

1. The basic judgment conditions for the tunnel optimization model are:
1) if the stress of the tunnel section structure satisfies the requirements;
2) if the monitored deformation of the tunnel wall rock satisfies the requirements of the specifications;
3) if it is able to obtain the total construction cost of the section by determining the construction cost of the longitudinal reinforcement, and the construction cost of the excavation and concrete used for the tunnel
2. Analyzing the optimization strategy of various constraint conditions
1) In terms of the computational mode and the size of the reperformance ratio of the tunnel, determining if the stress of the tunnel satisfies the requirements. In the model, the most dangerous section of the tunnel is taken as the reference section for reinforcement to select and distribute steel bars. The process for distributing steel bars is as follows (Peng et al., 2001):
(1) Make the reinforcement for all beam units by determining the stress of the tunnel. If any beam unit is found to be over-reinforced, then, due to irrational stress of the tunnel, it is possible to determine that the tunnel model does not meet the requirements so that it is needed to make optimization adjustment. If the reinforcement for all beam units lies in the rational range, the unit with the largest reinforcement rate will be taken as a benchmark. This value will be taken as the reinforcement rate for the entire circumference of the tunnel and used to determine the amount of reinforcement bars for the section of the tunnel.
(2) Get the displacement of each finite element node through the finite element computation. An point-to-point analysis is made on each node of the computational mode. If the displacement of any node exceeds the indicated value, the tunnel mode is judged to be irrational and relevant adjustment is to be made during the optimization search.
(3) The construction cost of the tunnel mainly covers the cost for excavation, concrete, invert backfill and reinforcement.
2) Excavation cost:

$$f_1(X) = p_e S_e(X) \tag{10}$$

$S_\varepsilon(X)$- The volume of excavation section per unit length (Figure 2); P_ε- Excavation price per unit volume (including general unit price of temporary support)

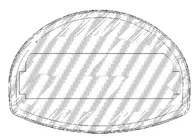


Figure 2: Excavation area

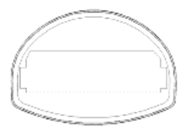


Figure 3: Initial lining concrete area

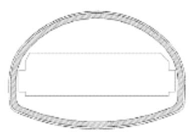


Figure 4: The area of two lining concrete

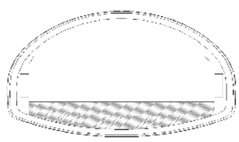


Figure 5: Backfill area of inverted arch

3) Concrete cost

$$f_2(X) = p_{c1}S_{c1}(X) + p_{c2}S_{c2}(X) \quad (11)$$

$S_{c1}(X)$, $S_{c2}(X)$- The area of initial lining concrete and two lining concrete in the section; P_{c1}, P_{c2}- Unit volume of initial lining concrete (including the initial support of the integrated unit price) and two lining concrete unit price

4) The cost of invert backfills

$$f_3(X) = p_h S_h(X) \quad (12)$$

$S_k(X)$ - Volume of concrete filled in section; P_h- Price per unit volume of backfill concrete
5) Reinforcement cost in second lining concrete

$$f_4(X) = p_s S_s(X) \quad (13)$$

$S_s(X)$ - The weight of the steel bar in the two-lining concrete in the section, according to the results of post treatment of tunnel structure; P_s - The price of steel bar per unit weight
6) The total cost function is:

$$f(X) = f_1(X) + f_2(X) + f_3(X) + f_4(X) \quad (14)$$

3.4 Concrete realization of optimization model

The optimization model of tunnel is established by considering the stress, deformation and cost of the tunnel, the specific optimization process is as follows:
1. Optimization variables
It is necessary to consider the influence of various factors on the stress, deformation and cost of the tunnel when calculation model of tunnel section is established. Three variables with the greatest impact on these factors were selected as the optimized design variables: the top arch height, the two lining thickness and the arch length.
2. Objective function
The objective of the cross-section optimization is economical and practical, so the objective function of the optimization model is based on the safe and practical tunnel cost. The objective for the section optimization is:

$$f(X) = f_1(X) + f_2(X) + f_3(X) + f_4(X) \quad (15)$$

The rationality of the use, stress and deformation of the tunnel is embodied in the optimization constraint conditions the objective function covers.

3.5 Section optimization for V-grade rock buried under 200m

After the optimization, various geometric parameters of the tunnel structure are compared with those in the original design as shown in Table 1.

Table 1: Geometric parameter

Optimization analysis	Top arch Net height (m)	Invert depth (m)	Thickness of secondary lining (m)	Height-span ratio	Excavation Area (m^2)
Optimization result	3.5	1.9	0.68	0.586	201.7
Existing design	4	2.2	0.65	0.633	229.4

Various cost parameters for the section of the tunnel structure and comparison of optimized results with the original design are as shown in Table 2.

Table 2: Construction cost comparison (Unit: 1000 yuan)

	Reinforce-cement	Preliminary lining concrete	Secondary lining concrete	Invert backfill	Excavation	Total
Optimization result	12.7	15.0	17.0	2.1	19.6	66.4
Existing design	11.3	17.1	16.4	2.6	20.1	67.5

Note: The unit for the construction cost is 1000 yuan/prolonged meter.

Through the optimization analysis of the deep section of the V-level surrounding rock, the thickness of the lining is larger than that of the existing design, and the reinforcement is larger than the existing design. But the final cost is still lower than the original design of 1.1 thousand yuan, the total cost reduction of 1.6% due to the other cost reductions. As the optimization model used in the optimization of conservative, so the results are better than the original design more reliable and safe.

4. Conclusion

1. Selecting the updated strategy by making a comprehensive consideration of the concentration and adaptability using the improved immune algorithm, the similarity vector distance of the antibody is used to determine the adaptability and serves as the selection mechanism for the final antibody. The individual copying operation of the basic genetic algorithm conducted after the selection is eliminated so that the massive occurrence of the identical individuals affecting of the diversity of the species is avoided. When certain antibodies with higher adaptability and relatively low concentration enter into the next generation, it is possible to achieve the objective of not only enhancing the individual adaptability but maintaining the individual diversity as well. It is able to determine the operating parameters of the algorithm in a simpler way, ensure the global and local optimization searching capability, and avoid as much as possible the occurrence of the premature phenomenon.
2. After optimizing the section structure of the Huayuan tunnel and making a comprehensive consideration of the stress, deformation and construction cost, etc. of the tunnel, with the minimization of the construction cost of the tunnel as the objective, a conclusion with applicable value has been arrived at. The priority of the current method in the optimization computation of the tunnel engineering has been verified at a higher computational speed and with a higher efficiency. This also shows that the improved immune genetic algorithm has a practical significance to the wall rock stability assessment and Informaionization design of the tunnel.

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