The Determination of Optimal Time for Bridge Preventive Maintenance Based on Particle Swarm Optimization Algorithm

Wei Wang
Research Institute of Highway Ministry of Transport, Beijing, 100088, China
*Corresponding author’s e-mail: 20217161@qq.com

Abstract. This paper constructs the full life cycle cost model, durable life extension and maintenance period mathematical model for preventive maintenance of bridges, and introduces software to calculate the multiple regression equation of maintenance effects to durable life extension years and maintenance costs. Particle swarm optimization algorithm is used to select the best time selection model for comprehensive and integrative control of three targets including preventive maintenance effects, maintenance costs and durable life extension of bridges.

1. Background
In recent years, with the development of the transportation industry, the bridge structure plays a more and more important role. With increase of traffic loads of the road network and the operation time, there are some problems such as poor operational performance, low durability, short service life and poor full life cycle economic indicator in all highway bridges. The bridge problems have severely affected its normal service functions, and there are many factors affecting degradation of the bridge structure.

In addition to relatively severe impacts on overloading vehicles, the defects in the existing maintenance system and methods also shouldn’t be neglected. In the implementation of the bridge maintenance and reconstruction, much attention has been paid to reinforcement and reconstruction but less attention has been paid to maintenance, and especially there is no systematic study carried out so far in terms of the preventive maintenance affecting the durability of bridges in China.

This paper mainly focuses on the solving countermeasures of implementing preventive maintenance with the minimum costs at the most appropriate time, so as to keep the bridges in good working conditions and longer design service life, and avoid huge costs incurred by repair or replacement of major bridges and significant impacts on the society caused by traffic interruption.

2. Establishment of Preventive Maintenance Cost and Durable Life Extension Model of Bridges
2.1. Preventive maintenance, durable life extension and maintenance period mathematical model of bridges[1-3]
Environmental ratings, durability analysis and estimation are carried out against bridge construction conditions and features of usage environment. This paper focuses on studying degradation of concrete protective cover under carbonation environment factors. Preventive measures are taken in time and factors that may cause degradation of concrete materials are isolated when surface degradation of the components doesn’t occur, so as to guarantee the component free from degradation.
Preventive maintenance measures A are taken under effects of carbonization factors, and period of validity of the protective effects is T. Fig 1 shows the degradation curve of main components to a concrete bridge. According to existing degradation law of the part, its life ends at \( t_F \), and the degradation time extended is T when implementing preventive maintenance measures A at such bridge at \( t_1 \), then actual life of such part is extended to \( t_F' \), \( t_F' = t_F + T \).

In actual engineering projects, the effects of preventive maintenance measures may be affected by many factors, thus, partial safety factor \( \beta \) is introduced for valid period T of the preventive maintenance measures. Two influencing factors shall be considered here, then:

\[
\beta_i = \beta_a \cdot \beta_b \quad (1)
\]

In the formula:
- \( \beta_a \) - Partial safety factor of the \( i \) time preventive maintenance effects;
- \( \beta_a \) - Concrete age influence coefficient; the ratio of remaining degradation life in total normal degradation life in primary preventive maintenance effect. i.e. \( (t_F - t_1) / t_F \) in Fig1;
- \( \beta_b \) - Multi-factor combined effect coefficient; for environmental factor effects, main factors are generally selected for computation of preventive maintenance with the coefficient taking 1.0, and the coefficient takes 0.9 if there are other strong environmental factor effects at the same time (when the effect grade is above 2).

The actual durable life extension years are \( t_{ext} \) under multiple preventive maintenance measures, i.e. the difference between target service life \( t_{F'} \) and service life \( t_F \) without preventive maintenance conditions is:

\[
t_{ext} = \sum_{i=1}^{n} \beta_i T \quad (2)
\]

In the formula:
- \( t_{ext} \) - Durable life extension years;
- \( n \) - Times of preventive maintenance;
- \( \beta_i \) - Partial safety factor of the \( i \) time preventive maintenance effects;
- \( T \) - Valid period of preventive maintenance measures.

When there are no obvious changes in environmental conditions, \( \beta_i = \beta_{i0} \), i.e.:

\[
t_{ext} = n\beta T \quad (3)
\]

2.2. Deterioration model of concrete parts under preventive maintenance effects
The rebars begin to be corroded when concrete of the bridge structure degrades to the time of normal operation and daily maintenance, and the elements reach to their limit states of durability. There is still away from existing service life of the bridge at the moment, and preventive maintenance measures shall be taken in the operation process to ensure that features of durable limit state doesn’t occur before service life of the bridge is reached.

The degradation model at final stage of the concrete elements, under the effects of preventive maintenance measures, can be summarized as:

$$x = g(t - \sum_{i=1}^{n} \tau_i + \sum_{i=1}^{n} \mu_i \gamma_i)$$

(4)

In the formula:

- **n** - Times of preventive maintenance;
- **\tau_i** - Valid period of the *i* time preventive maintenance measures;
- **\mu_i** - Actual degradation rate of concrete under the condition of preventive maintenance measures, which shall be determined through tests;
- **t\_ni** - Implementation time of applying preventive maintenance operation for the *i* time; **t\_ni** is the primary preventive maintenance time, **t\_ni = t\_ni + (i - 1)\Delta t**.

2.3. Full life cycle cost model for bridge preventive maintenance

The preventive maintenance project of bridges is featured by simple engineering contents, short operation period and complex process. According to the engineering characteristics of preventive maintenance, costs closely related to the preventive maintenance project are selected from the cost constitution elements of construction projects to establish cost structure of the preventive maintenance project. According to the effect model of multiple preventive maintenance, when preventive maintenance activity is used to the degraded bridges, durability status of the original bridge member is **d_0**, and the degradation rate is **\alpha**; the durability index increases by **\gamma_1** after implementing the first time of preventive maintenance at **t\_p1**, and corresponding cost is **C\_1**. Then, the durability index continues to degrade at **\theta**, the maintenance effect disappears at **t\_p1 + t\_PD** and the degradation rate is restored to **\alpha**; the second time of preventive maintenance is applied at **t\_p1 + t\_p**, the structure durability index increases by **\gamma_2**, and corresponding cost is **C\_2**, and so on. The number of total times that preventive maintenance has been carried out when the bridge reaches its service life is **n**, and the calculation model for costs of preventive maintenance in life cycle of the bridge member under the condition of considering time value of funds is:

$$C(t\_p1, t\_p) = \sum_{i=1}^{n(t\_p1, t\_p)} C_i(t\_p1, t\_p) \frac{1}{(1 + r)^{t\_p1 + (i - 1)t\_p}}$$

(5)

In the formula:

- **C\_p(t\_1, t\_n)** - Total costs of preventive maintenance of bridges;
- **n(t\_p1, t\_p)** - The number of times that preventive maintenance is carried out in life cycle of bridges; all these parameters are related to starting time and time interval of preventive maintenance.
- **r** - Social discount rate (%), the expenditure of preventive maintenance projects comes from the maintenance costs. Different from investment of the construction project, the value of social discount rate shall be lower than the construction project.

3. Selection of optimal time for preventive maintenance based on particle swarm optimization
3.1. Basis for establishment of optimization model of particle swarm optimization

In order to study the quantification equation of maintenance effects, this paper establishes a multivariate function relation \( Q = f(C, t_{ext}) \) between the maintenance effects, durable life extension years and the maintenance costs and uses SPSS software to analyze the multiple regressions of maintenance effect on durable life extension years and maintenance costs. SPSS is used to carry out linear or nonlinear regression analysis through fitting a group of observation values with the “least square method”. This tool can be used to analyze how a single dependent variable is affected by one or more independent variable(s). By analyzing data, multiple regression equations of maintenance effect on durability life extension and maintenance cost are established as follows:

\[
Q = \alpha C + \beta_{ext} + \gamma C_{ext} + \phi C^2 + \varphi_{ext}^2 + \lambda 
(6)
\]

3.2. Optimized selection model of particle swarm optimization

Particle swarm optimization can give the best solution to the multi-objective problem of the comprehensive optimization of the maintenance effect, durability life extension term and maintenance cost. In fact, establishing the optimal timing selection model based on the expected degree of maintenance effect is to convert the multi-objective problem into a single-objective problem by applying the idea of objective programming.

The multi-objective optimization model of bridge preventive maintenance is established as follows:

Objective function: \( \max \{ p_1 d_1^+, p_2 (d_2^* + d_2^-) \} \min \{ p_3 d_3^+ \} \)  

Constraint condition: \( t_{cot} + d_1^- - d_1^+ = t_{plan} \)

\( Q_{cot} = f(C, t_{ext}) + d_2^- - d_2^+ = Q_{plan} \)

\( C_{cot} = \sum_{i=1}^{n(t_{p1}, t_{p2})} C_i(t_{p1}, t_{p2}) \frac{1}{(1 + r)^{(t_{plan} - t_{cot})}} + \alpha_1 t_{plan} - t_{cot} + \alpha_2 t_{cot} + d_3^- - d_3^+ = C_{plan} \)

In the formula: \( Q_{cot}, t_{cot} \) and \( C_{cot} \) respectively represent the calculated maintenance effect, durability life extension term, maintenance cost obtained from the network optimization;

\( p_1, p_2, p_3 \)-Priority label;

\( d_1^-, d_1^+, d_2^-, d_2^+, d_3^-, d_3^+ \)-Positive and negative difference variable.

In the MATLAB environment, we use real number encoding for particles and their velocity in the particle swarm. The inertia weight is introduced to control development and exploration, thereby reducing the need for determining \( v_{max} \).

The iterative formula for PSO algorithm is to introduce inertia weight:

\[
v_{i+1, id} = w v_{id} + c_1 rand( ) (p_{id} - x_{id}) + c_2 Rand( ) (p_{gd} - x_{id}) 
(8)
\]

\[
x_{i+1, id} = x_{id} + v_{id} 
(9)
\]

In the formula: \( c_1 \) and \( c_2 \) are acceleration constants, usually \( c_1 = c_2 = 2 \); \( rand() \) and \( Rand() \) is a random function value field \( [0,1] \); \( V_{id} \) is \( d \) dimension particle search, speed \( v_{id} \leq v_{max,d} \) and \( v_i = v_{max} \), limit \( v_{id} = v_{max,d} \), \( w \) can be set to decrease linearly with the decrease of time and progressively decrease from 0.9 to 0.4. In addition, there are not many parameters that need to be adjusted in the PSO. The following lists the parameters and experience settings: the number of particles generally takes 20-40. In fact, for most of the problems, 10 particles are enough to get good results. However, for the more difficult problems or specific types of problems, the number of particles can take 100 or 200. The optimal solution is found through the particle swarm optimization and achieves the comprehensive optimization of maintenance effect, durability life extension term and maintenance cost to ensure that the set goals of...
bridge preventive maintenance measures are successfully completed and the optimum efficiency is achieved.

4. Conclusions
This paper introduces Particle Swarm Optimization into three major objectives of optimization model of integrated control including preventive maintenance effect, maintenance cost and durability life extension of bridges. SPSS software is applied to calculate the multiple regression equation of maintenance effect on durability life extension term and maintenance costs, which provides a strongly practical and reliable method for the decision-making of timing and cost of preventive maintenance and also has a great significance in improving China’s theoretical system of bridge preventive maintenance.

References
[1] Zhang Jinquan, Su Jian, Cheng Shoushan et al. The Concrete Bridge Material Condition and Durability Detection and Evaluation Guidelines and Project[M]. Beijing: China Communications
[2] Zhang Xia. Research on Preventive Maintenance System of Concrete Bridge [D]. Shan xi: Chang’an University 2012. Press, 2007.
[3] Wang Chunsheng, Zhou Jiang, Wang Yujiao, Dong Xiaohong. Fatigue Life and Service Safety Assessment for Existing Concrete Bridges[J]. China Journal of Highway and Transport, 2012(11):101-107.
[4] Bian Jingmei, Liang Jinguo, Yao Weijing. The application of reliability degradation model in bridge repair in decision making[J]. Journal of China & Foreign Highway, 2010(6):164-168.
[5] Guo Yan, Li Nan, Li Xingsen. Multi-mode multiple resources leveling and multi-objective particle swarm optimization with dynamic population [J]. Control and Decision, 2013 (1):131-135.
[6] Hou Zhirong, Lu Zhensu. Particle Swarm Optimization with Application Based on MATLAB[J]. Computer Simulation, 2003 (10):68-70.