Maintenance Timing and Countermeasures of Concrete Bridges under Environmental Impact

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Abstract. In order to guarantee the expected service life of the bridge and reasonably allocate limited maintenance fund, this paper focuses on the timing of the bridge maintenance. By studying the degradation mechanism of bridge structure, we establish the degradation model of concrete bridge structure and the multi-objective optimization model. Through minimizing the maintenance cost, the bridge maintenance time can be determined. Furthermore, according to the environmental impact and the effect of various maintenance methods, we develop the maintenance countermeasures list, which builds up a good basis for the scientific quantitative analysis of preventive maintenance.

1. Introduction
With the development of China’s highway transportation industry, the bridge construction has achieved leap-forward development. According to government department’s statistic, till the end of 2016, there were more than 800,000 highway bridges in China, of which concrete bridges accounted for more than 95%. However, the combination of complex environment and vehicle load has caused damage to the bridge structure and affected its normal function. In order to achieve the goal availability, safety and efficient of road network traffic, besides implementing strict quality and safety control in bridge construction, choosing appropriate maintenance time and countermeasures is an important issue, which can rationally allocate the limited maintenance funds and ensure the bridge safety.

The maintenance and repair of bridges can effectively alleviate the degradation of bridge performance. According to the maintenance timing, it can be divided into four situations, as shown in Fig. 1 [1]. The degenerative and corrective maintenances are taken after deterioration of bridge. The preventive maintenance is a pre-set maintenance measure that is taken designedly to ensure that the bridge reaches the expected service life. In this paper, the degradation mechanism of bridge structure under the environment impact is studied. We establish the degradation model of concrete bridge structure and propose one multi-objective optimization model to determine the timing of bridge maintenance. According to the degree of environmental impact and the effect of various maintenance methods, the corresponding countermeasure list is formulated.
Figure 1. Classification of the bridge maintenance.

2. Degradation and cost models of concrete bridge under the environmental impact

Bridge performance is directly related to the operation of the road. Proper maintenance of the bridge can ensure normal use during its life cycle. Due to the great uncertainty of bridge degradation, establishing a scientific and accurate degradation and cost model is the basis for determining the timing of bridge maintenance.

2.1. Degradation model of concrete bridge under the environmental impact

The performance of the bridge can be represented by reliability indicators that characterize safety and state indicators that characterize durability. Due to the discrete nature of the concrete structure, local degradation may have occurred seriously while the concrete in most areas is still in good condition. In order to ensure the safety of the concrete bridge structure, we take the start of rusting of steel bar caused by the degradation of the concrete protective layer as the limit state. Table 1 lists the degradation model of concrete bridges under the environmental effects including carbonization, chloride attack and sulfate attack [2]. When the bridge evaluation believes that the component can not meet the requirements, that is, when the rusting time of the steel bar is less than the target life TF0, it is necessary to take maintenance measures. The problem how to ensure the best maintenance cost during the life span need to be solved by determining the maintenance timing.
Table 1. Degradation model of in-service concrete bridge under different environmental effects.

| Environmental effect | Deterioration model | index | Description |
|----------------------|---------------------|-------|-------------|
| Carbonization        |                     | $x_c$ | The measured depth of carbonization (mm) |
|                      |                     | $t_0$ | The measured time (a) |
|                      |                     |       | The carbonization remain is $x_0 = \left(1.2 - 0.35k^{0.5}\right) \cdot 6.0 \div \left(m+1.6\right) \cdot (1.5 + 0.84k)$ where $D_c$ is the parameter related to the thickness of the concrete protective layer and the carbonization coefficient. |
|                      |                     | $k$   | $x_0 = \left(1.2 - 0.35k^{0.5}\right) \cdot 6.0 \div \left(m+1.6\right) \cdot (1.5 + 0.84k)$ |
|                      |                     | $t_r = \left(c - x_0 \right)^2 \div k$ | In the case of $c \leq 28mm$, when $k \geq 0.8$, $D_c = c$; when $k < 0.8$, $D_c = c - 0.16 / k$. In the case of $c > 28mm$, when $k \geq 1.0$, (if $k > 3.3$, we take $k = 3.3$), $D_c = c + 0.066(c - 28)^{0.74k}$; when $k < 1.0$, $D_c = c - 0.389(c - 28)(0.16 / k)^{1.5}$. When the bridge is in the area where humidity $\leq 75\%$, $m$ is 3.5 to 4.0; when $\geq 75\%$, $m$ is 4.0 to 4.5; if the area has special weather condition, such as acid rain, the value of $m$ should be evaluated by the measured results. |
|                      |                     | $x_0$ | The measured time (a) |
|                       |                     |       | $D_c = c - 0.16 / k$. |
| Chloride attack       |                     | $c$   | Measured protective layer thickness (mm) |
|                      |                     | $M_{cr}$ | Critical chloride ion concentration of steel corrosion (kg/m$^3$) |
|                      |                     | $M_s$  | Chloride ion concentration on concrete surface (kg/m$^3$) |
|                      |                     | $erf$ | Error function |
|                      |                     | $D$   | Chloride ion diffusion coefficient (m$^2$/a) |
| Sulfate attack        |                     | $c$   | Measured protective layer thickness (mm) |
|                      |                     | $C_0$ | Sulfate surface volume concentration (moles/cm$^3$) |
|                      |                     | $C_s$ | Volume concentration of tricalcium sulfate (moles/cm$^3$) |
|                      |                     | $D_{s}$ | Diffusion coefficient (m$^2$/a) |

2.2. Degradation model after taking maintenance measures

According to the degradation model of concrete materials under different environmental effects, it can be seen that when there is no degradation on the surface of bridge member, timely maintenance can isolate the deleterious effects and protect bridge from degradation. In this paper, by analyzing the characteristics of existing models, combined with the degradation situations of the actual bridge structure after maintenance, we propose one nonlinear degradation—degradation delay—nonlinear improvement degradation model, as shown in Fig. 2 [3, 4]. After a certain conservation measure, the
delay time of deterioration $D$ is introduced as an approximate estimation of the actual effect of the maintenance. We set $TF_0$ as the life of the bridge without maintenance according to the established degradation model. When the maintenance measure is applied to the bridge at time $T_1$, the actual life of the bridge is extended to $TF_1$. Since the delay time $D$ is related to many factors, such as the type and scale of the bridge, and environment, the value should be set with reference to the actual situation of the specific project combined with the comprehensive analysis of the expert opinions.

Figure 2. Degradation model after taking maintenance measures.

2.3. Maintenance cost model
Considering the time value of funds, the calculation model of maintenance costs during the whole life of bridge members is

$$C_p(T_1, T_n) = \sum_{i=1}^{n} C_i(T_i) \frac{1}{(1+r)^i}$$

where $C_p(T_1, T_n)$ is the total cost of bridge maintenance, which is a function of maintenance start time $T_1$ and interval, $n$ is the maintenance number, and $r$ is the social discount rate (%).

3. Multi-objective optimization model
The optimization process is to search for the optimal solution in all possible choices for the problem. If only one goal is considered, it becomes a single-objective optimization problem. If more than one targets need to be considered at the same time, it becomes a multi-objective optimization problem. In this paper, we consider that when the condition and service life of the bridge is not lower than its respective target value, the minimum cost of maintenance is searching, that is,

Objective function: MAX (bridge condition)
Constraint: $C_p (T_1, T_n) \rightarrow$min
$TF_i (i = 1, 2, 3 \ldots ) \geq$ design life,

Since the time value of funds, choosing different values of maintenance time will result in a large difference in the final cumulative maintenance costs. Therefore, we take the maintenance start time $T_1$ and the interval $T$ as the optimized variables.

4. Maintenance measures for concrete bridges under environmental impact
The common diseases of concrete bridges are caused by environmental impact. Some diseases are the results of a combination of various environmental effects, which will affect and promote each other and become complex and changeable. Here we mainly consider three environmental effects and list the common conservation measures in Table 2 [5]. The protection effects of the seven types of
conservation measures have their own advantages, and the corresponding countermeasures should be taken according to the environmental effects.

Table 2. Various maintenance countermeasures and environmental effects.

| Maintenance countermeasures       | Environmental effects | Carbonization | Chloride attack | Sulfate attack |
|-----------------------------------|-----------------------|---------------|-----------------|----------------|
| Modified resin emulsion           | ☆☆                    | ☆☆☆☆☆         | ☆               |
| New modified epoxy resin coating  | ☆☆☆                   | ☆☆☆☆☆☆        | ☆               |
| Organosilane penetrant            | ☆                     | ☆☆☆☆☆☆        | ☆               |
| Spray polyurea elastomer          | ☆☆                    | ☆☆☆☆☆         | ☆               |
| Flexible fluorocarbon surface coating | ☆☆                | ☆☆☆☆☆        | ☆               |
| Concrete re-alkalinization        | ☆☆☆                   | ☆☆☆☆☆☆        | ☆               |
| Cathodic protection               | ☆                     | ☆☆☆☆☆☆        | ☆               |

Note: ☆ represents the effect of use.

5. Case analysis

We take Houniufang bridge as an example. The total length of the bridge is 38.3m, the bridge span is 1-7.7+2-10.5+1-7.7m, the full width of the bridge is 8.0m, and the bridge width is 1.0m (sidewalk) +6.0m (lane) + 1.0m (sidewalk). The upper structure is a reinforced concrete continuous π-beam, four beams are arranged laterally, four transverse partitions are arranged longitudinally, and the support is a plate rubber bearing. The lower structure is a reinforced concrete embedded abutment and a frame-type pier, and the abutment foundation is a pile foundation.

![Bridge overview](image)

Figure 3. Bridge overview.

According to the bridge construction conditions and the environment, the bridge is determined to be in the general atmospheric environment, and the degradation model about carbonization is chosen.

5.1. Parameters of degradation model

By measuring, we know that for this bridge, $c_x=15\text{mm}$ and $t_0=10$. Based on Table1, we have

$$t_r = \left(\frac{c_x}{k} - \frac{15}{\sqrt{10}}\right)^2 = \left(\frac{22.74}{4.74}\right)^2 = 22.68;$$

where $k = \frac{x}{t_0} = \frac{15}{10} = 4.74$ and $x_0 = (1.2 - 0.35k^{0.5})\cdot D_c - \frac{6.0}{m+1.5} (1.5 + 0.84k) = 7.41$.

The calculation results show that the rusting time of the steel bars is 23 years. So the maintenance measures should be taken before this time. In this paper, the most commonly used (yearly) regular maintenance model is adopted, and the maintenance start time $T_1$ and the interval $T$ are the main control variables for maintenance optimization.
5.2. Cost model and analysis

In this paper, the cost $C$ of a single maintenance is decomposed into a fixed cost $C_0$ and a cost $C(x_t)$ related to the degree of degradation. In the model herein, the degree of degradation is represented by the carbonization depth $x_t$. The relationship between $C_0$ and $C(x_t)$ is very important for the choice of maintenance timing. When $C_0$ is the main cost, the maintenance start time will be postponed as much as possible, and the maintenance interval will be more prolonged to reduce the number of maintenance and reduce the total cost. Conversely, when $C(x_t)$ is the main cost, the maintenance start time will be as early as possible, and the maintenance interval will be as long as possible, because this will reduce the degree of degradation for each maintenance, thus reducing the total cost. The relationship between $C_0$ and $C(x_t)$ varies with the maintenance conditions and the external environment. Here we only consider the case that $C_0$ and $C(x_t)$ are comparable.

In addition, the relationship between maintenance cost $C(x_t)$ and $x_t$ will affect the maintenance timing. For the sake of simplicity, this paper only considers the carbonization model, which is to characterize the degradation of the bridge with the depth of carbonization $x_t$. In fact, there are many kinds of degradation effects, such as chloride ion erosion and sulfate attack. Therefore, it is necessary to theoretically analyze $C$ according to the actual situation and determine the relationship between $C(x_t)$ and $x_t$, which may be linear $C(x_t) - x_t$, nonlinear $C(x_t) - x_t^n$ or $C(x_t) - \exp(k_x \cdot x_t)$, etc. In this example, the depth of carbonation has a decisive influence on the choice of maintenance measures, which in turn affects maintenance costs. When the carbonization depth is smaller than the thickness of the protective layer, since the carbonized layer is relatively hard, we can choose high-quality paint to seal the surface. If the carbonized layer is loose and peeled off, the carbonized layer should be removed firstly, and the high-strength mortar should be painted or the high-strength concrete should be poured. When the carbonization depth is large and the steel corrosion is obvious, we also need to remove the rust, and carry out the steel reinforcement and even the reconstruction. Therefore, this paper uses the $C(x_t) - \exp(k_x \cdot x_t)$ model.

5.3. Maintenance timing optimization

According to the relevant indicator parameters of the degradation model, the maintenance start time should be less than 23 years. When the carbonization depth is small, the new modified epoxy resin coating method can be used. The new modified epoxy resin coating has the effects including anti-aging, acid rain resistance, carbonization prevention, and so on. The coating can significantly reduce the number of concrete repairs, prevent environmental pollution, and reduce maintenance costs. The durability of the new modified epoxy resin coating is 10 to 20 years. In this case, the degradation delay time $D$ is selected to be 10 years. At the same time, the social discount rate is 2%. The maintenance effect of bridge is shown in Fig. 4. The orange curve shows the carbonization depth as a function of time, and the blue curve shows the carbonization depth degradation curve after the maintenance.

According to the maintenance cost model, the multi-objective planning problem of the bivariate (maintenance start time $T_1$ and interval $T$) is solved here. That is, the maintenance cost is minimized during the analysis period, and at the same time the durability of the component is maximized and the service life is maximized. During the life cycle, the guidelines for bridge maintenance arrangements are to meet structural durability requirements while ensuring minimal maintenance costs. Here we use the numerical calculation directly to solve this problem. For more complex multivariable problems, optimization algorithms such as genetic algorithm can be used. The calculation can determine that the start time for maintenance is 16 years and the maintenance interval is 28 years (Fig. 4). The maintenance costs vary with the maintenance interval as shown in Fig. 5.
Figure 4. The maintenance effect of bridge.

Figure 5. The maintenance costs vs the interval.

The discontinuity of the curve in Fig. 5 is caused by the jump of the maintenance number n. The initial cost is high because the time interval is short and the number of maintenance is high. On the contrary, when the interval becomes long and the number of maintenance is small, the single maintenance cost is high, resulting in an increase in the total cost. Therefore, choosing the appropriate maintenance start time and interval can provide the most cost-effective maintenance opportunity.

6. Conclusion
In this paper, the basic theory of bridge maintenance timing and countermeasures is researched, and the models of bridge degradation and cost are established, which are verified by numerical examples.

The bridge degradation model is the basis for determining the maintenance timing. This paper proposes the nonlinear degradation—degradation delay—nonlinear improvement degradation model by analyzing the characteristics of the concrete bridge degradation model under environmental impact, such as carbonization, chloride attack and sulfate attack.

According to the principle of economics, we propose the bridge maintenance cost model and use the multi-objective optimization to determine the maintenance timing. When the bridge condition and
the service life are not lower than the target value, we can get the minimum total cost of maintenance
cost.

Based on the actual bridge maintenance countermeasures, the determination and optimization of
the bridge maintenance timing are carried out, and the application value of the model framework is
preliminarily demonstrated. This is helpful to change the traditional concept of neglecting preventive
maintenance.

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