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Grey correlation analysis of sensitive factors of concrete structures durability*

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Abstract. Concrete structures durability is affected by a number of factors which have different sensitivity. According to level of sensitivity classified the influence factors could promote concrete structures durability design. The disadvantage of traditional methods of sensitivity analysis in concrete structures durability is the larger number of samples. The grey correlation theory was used to analyze the degree of the sensitivity of the influence factors and comparison with traditional methods of calculation. The results show that the grey correlation analysis method could quantify the levels of the sensitive factors and with higher reliability. A new way to study the durability of concrete structures was provided.

1 Introduction

Service life prediction is an important reference index to judge whether the concrete structures reach the design standards. According to the available theories to predict the service life of concrete structure, durability of the structural members is closely related to humidity, the temperature, structure type, concrete material mix ratio, and the concrete diffusion coefficient. When carrying out service life prediction, the specifically quantified values for every parameter were used by the prediction model to get the forecasting result [1].

Amey [2] (1998) had studied the prediction method of service life of marine concrete structure, considering the parameters changes such as the temperature change , the concrete structure environment change ,and the chlorine ion diffusion coefficient change. The tradition Fick second law was used by Weyers [3] (1998), regarding the diffusion coefficient as a constant, to establish the concrete structure service life time prediction model under the chlorine ion environment. Wang Shengnian [4] (2001) also used the chlorine ion diffusion experiment data of Zhanjiang harbor to forecast the service life of marine concrete structures of the present stage of China, adopting the tradition Fick second law.Tian Junfeng [5] (2002) analyzed some factors which can affected the service life of concrete structure durability, on the basis of the Fick second law. Computer and artificial intelligence technologies have been used to forecast concrete durability. Yang Zeying [6] evaluated the concrete bridge durability by artificial neural networks and Genetic Algorithm (GA).

However, the practices have proved that the affecting parameters to concrete durability/service life have an uncertainty and highly sensitive to subjective factors, It's necessary to analyze the sensitivity of each affected parameters for service life prediction of concrete structure and find out the sensitive factors [7]. The affected degree of the service life prediction result because of the sensitive factors can be determined, so as to ensure the reliability and accuracy of service life prediction on the basis of the certain prediction model.Lu Mu[8] considered the durability of concrete was an "grey system", including objective and subjective index. It's scientific and objective to evaluate the durability of concrete by grey theory. The grey correlation theory was used to analyze the sensitive of the affected factors and the research result was given in this paper.

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2 Durability theories

There are three endurance life criterions in the evaluation and prediction for the durability of concrete structures: carbonization or chloride ion erosion criterion, rebars corrosion crack criterion, and the crack limit criterion.Fig.1 shows the relationship between the service life criterions.

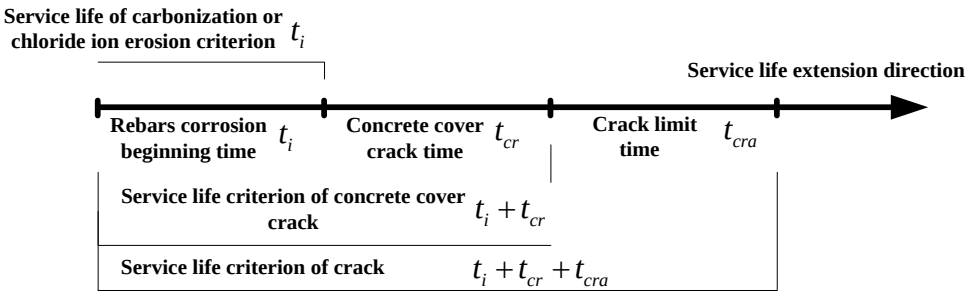

Fig.1 Relationship between service life criterions

3 Grey correlation analysis

The traditional sensitivity analysis is a "change-one-factor-at-a-time method'': one factor is varied while all others are fixed. However, the simplicity of the method may yield unreliable results and an inadequate conclusion because factors have an uncertainty][9]. Deng [7] presented a method of grey correlation analysis, which addresses some of the shortcomings of the traditional method. The basic concept of grey correlation analysis is to determine whether a relationship among a series of data is close, based on the degree of similarity among the geometric shapes of the data series' curves. Closer curves indicate a greater the correlation among the relative data series. The grey correlation grades are determined from the grey correlation coefficients, which measure the degree of similarity among sequences. The order of sensitivity of the affected factors to durability of concrete structure can then be determined based on the calculated grey correlation grades. The method has been extensively applied across many areas, such as auto control design, water resource development, and hydroelectric generation scheduling and environmental management.

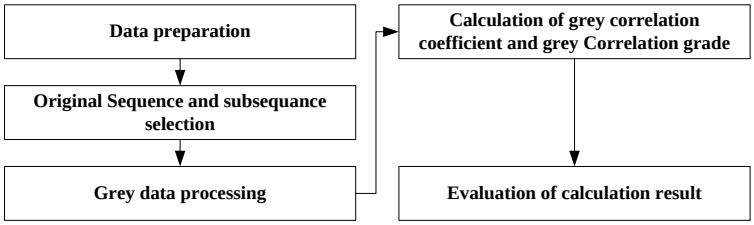

Fig. 2 Flow chart of grey correlation model

3.1 Grey data preparation. To calculate grey correlation coefficients, grey data processing must be performed. A series of various units must be transformed to be dimensionless. Usually, each series is normalized by dividing the data in the original series by their average. Let the original reference sequence and sequence for comparison be represented as $x_o(k)$ and $x_i(k)$, $i = 1, 2, \cdots, m, k = 1, 2, \cdots, n$ respectively, where m is the total number of factors to be considered and n is the total number of observation data. Data preprocessing converts the original sequence to a comparable sequence. Several methodologies of preprocessing data can be used in grey relation analysis, depending on the characteristics of the original sequence [9] If the target value of the original sequence is ''the-larger-the-better''(the case that larger value means the better performance), then the original sequence is normalized as follows:

$$x_i^*(k) = \frac{x_i(k) - \min x_i(k)}{\max x_i(k) - \min x_i(k)} \qquad (1)$$

If it is "the-smaller-the-better", then the original sequence is normalized as follows:

$$x_i^*(k) = \frac{\max x_i(k) - x_i(k)}{\max x_i(k) - \min x_i(k)} \quad (2)$$

3.2 Grey correlation coefficient and grey correlation grade. After grey data processing, a grey correlation coefficient is determined using the preprocessed sequence. The grey correlation coefficient is defined as [8],

$$\gamma(x_o(k), x_i(k)) = \frac{\Delta_{\min} + \xi\Delta_{\max}}{\Delta_{oi}(k) + \xi\Delta_{\max}} \quad (3)$$

Where $\xi \in (0,1)$ is the distinguishing coefficient, generally ξ is taken as 0.5 [7]. $\Delta_{oi}(k)$ is the sequence of deviation of the reference sequence $x_0^*(k)$ from the sequence $x_i^*(k)$ for comparison;

$$\Delta_{oi}(k) = | x_o^*(k) - x_i^*(k) | \quad (4)$$

$$\Delta_{\max} = \max_{\forall j \in i} \max_{\forall k} | x_o^*(k) - x_j^*(k) | \quad (5)$$

$$\Delta_{\min} = \min_{\forall j \in i} \min_{\forall k} | x_o^*(k) - x_j^*(k) | \quad (6)$$

The grey correlation grade is an average of the grey correlation coefficients and is defined as equation (7).

$$\Gamma_i(x_o^*, x_i^*) = \frac{1}{n}\sum_{k=1}^{n} \gamma(x_o^*(k), x_i^*(k)) \quad (7)$$

Herein, the grey correlation grade represents the degree of correlation between the reference sequence and the sequence for comparison. If a particular sequence for comparison is more important to the reference sequence than other comparable sequences, then the grey correlation grade between that comparable sequence and reference sequence exceed the other grey correlation grades. If the comparable sequence is consistent with the reference sequence, then the grey correlation grade is close to unity. Grey relational analysis measures the absolute differences between sequences, and so can be used to measure the approximate correlation of sequences [9].

4 Experiment analysis

4.1 Determine the sequence. According to the discussion of above different service life models, carbonization service life, chloride ion erosion service life, concrete cover crack service life and crack limit service life can be regarded as the affected factors of the durability prediction for concrete structure. Herein, carbonization service life, chloride ion erosion service life, concrete cover crack service life and crack limit service life were selected as the sequence A， and the durability service life correspondence to the affected factors were original sequence B.

Sequence A：

$$A = \begin{bmatrix} A_1 \\ A_2 \\ \vdots \\ A_m \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{bmatrix}$$

Original sequence B：

$$B = \begin{bmatrix} B_1 \\ B_2 \\ \vdots \\ B_m \end{bmatrix} = \begin{bmatrix} b_{11} & b_{12} & \cdots & b_{1n} \\ b_{21} & b_{22} & \cdots & b_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ b_{m1} & b_{m2} & \cdots & b_{mn} \end{bmatrix}$$

4.2 Analysis of calculation result. On the basis of the data selected from reference [1], took the chloride ion erosion service life as one example to carry out the grey correlation analysis. According to the chloride ion erosion service life prediction model， chloride ion density, water cement ratio, environment humidity and chloride ion density of member surface were used to established sequence A and chloride ion erosion service life were used to established original sequence B.The detailed information is shown in table1-4.

Table 1 Service life with *[Cl⁻]* density changed

[Cl⁻] critical density	0.48	0.504	0.528	0.552	0.576	0.6	0.624
chloride ion erosion service life	12.618	12.7871	12.9596	13.1356	13.3152	13.4985	13.6856
[Cl⁻] critical density	0.648	0.672	0.696	0.72			
chloride ion erosion service life	13.8767	14.0718	14.271	14.4745			

Table 2 Service life with *w/c* changed

Water cement ratio	0.28	0.294	0.308	0.322	0.336	0.35	0.364
chloride ion erosion service life	17.3186	16.4766	15.6755	14.9134	14.1883	13.4985	12.8422
Water cement ratio	0.378	0.392	0.406	0.42			
chloride ion erosion service life	12.2179	11.6238	11.0587	10.5211			

Table 3 Service life with *RH* w/c changed

environment humidity	0.702	0.7176	0.7332	0.7488	0.7644	0.78	0.7956
chloride ion erosion service life	18.2408	17.1748	16.1711	15.2261	14.3363	13.4985	12.7097
environment humidity	0.8112	0.8268	0.8424	0.858			
chloride ion erosion service life	11.9669	11.2676	10.6091	9.8892			

Table 4 Service life with *[Cl⁻]* density changed in surface of concrete members

[Cl⁻] of member surface	17.1	17.48	17.86	18.24	18.62	19	19.38
chloride ion erosion service life	14.0281	13.9103	13.799	13.6935	13.5935	13.4985	13.4082
[Cl⁻] of member surface	19.76	20.14	20.52	20.9			
chloride ion erosion service life	13.3222	13.2402	13.1619	13.0872			

Before calculated grey correlation coefficient, the grey data processing must be performed in term of equation (1).The processed matrix A (sequence) and B (reference sequence) are as follows:

$$A=\begin{bmatrix} 1.0000 & 1.0500 & 1.1000 & 1.1500 & 1.2000 & 1.2500 & 1.3000 & 1.3500 & 1.4000 & 1.4500 & 1.5000 \\ 1.0000 & 1.0500 & 1.1000 & 1.1500 & 1.2000 & 1.2500 & 1.3000 & 1.3500 & 1.4000 & 1.4500 & 1.5000 \\ 1.0000 & 1.0222 & 1.0444 & 1.0667 & 1.0889 & 1.1111 & 1.1333 & 1.1556 & 1.1778 & 1.2000 & 1.2222 \\ 1.0000 & 1.0222 & 1.0444 & 1.0667 & 1.0889 & 1.1111 & 1.1333 & 1.1556 & 1.1778 & 1.2000 & 1.2222 \end{bmatrix}$$

$$B=\begin{bmatrix} 1.0000 & 1.0134 & 1.0271 & 1.0410 & 1.0553 & 1.0698 & 1.0846 & 1.0998 & 1.1152 & 1.1310 & 1.1471 \\ 1.0000 & 0.9514 & 0.9051 & 0.8611 & 0.8193 & 0.7794 & 0.7415 & 0.7055 & 0.6712 & 0.6385 & 0.6075 \\ 1.0000 & 0.9416 & 0.8865 & 0.8347 & 0.7859 & 0.7400 & 0.6968 & 0.6561 & 0.6177 & 0.5816 & 0.5421 \\ 1.0000 & 0.9916 & 0.9837 & 0.9761 & 0.9690 & 0.9622 & 0.9558 & 0.9497 & 0.9438 & 0.9383 & 0.9329 \end{bmatrix}$$

Where the [Cl⁻]([Cl⁻] density), w/c(water cement ratio), RH(humidity)and Cs([Cl⁻] density of concrete member surface) were took as sequence number: x_1， x_2， x_3 and x_4, and the chloride ion erosion service life were taken as reference sequence x_{o1}， x_{o2}， x_{o3} and x_{o4}. $\Delta_{oi}(k)$ and $\gamma(x_o(k), x_i(k))$ can be calculate according to the equation equation (3) and equation (4).

$$\Delta_{oi}=\begin{bmatrix} 0 & 0.0366 & 0.0729 & 0.1090 & 0.1447 & 0.1802 & 0.2154 & 0.2502 & 0.2848 & 0.3190 & 0.3529 \\ 0 & 0.0986 & 0.1949 & 0.2889 & 0.3807 & 0.4706 & 0.5585 & 0.6445 & 0.7288 & 0.8115 & 0.8925 \\ 0 & 0.0806 & 0.1579 & 0.2320 & 0.3030 & 0.3711 & 0.4365 & 0.4995 & 0.5601 & 0.6184 & 0.6801 \\ 0 & 0.0306 & 0.0607 & 0.0906 & 0.1199 & 0.1489 & 0.1775 & 0.2059 & 0.2340 & 0.2617 & 0.2893 \end{bmatrix}$$

$$\gamma(x_o(k), x_i(k)) = \begin{bmatrix} 1.0000 & 0.9606 & 0.9245 & 0.8912 & 0.8605 & 0.8320 & 0.8056 & 0.7810 & 0.7581 & 0.7367 & 0.7166 \\ 1.0000 & 0.9005 & 0.8208 & 0.7555 & 0.7010 & 0.6548 & 0.6151 & 0.5807 & 0.5505 & 0.5238 & 0.5000 \\ 1.0000 & 0.9172 & 0.8497 & 0.7937 & 0.7465 & 0.7063 & 0.6716 & 0.6412 & 0.6144 & 0.5907 & 0.5675 \\ 1.0000 & 0.9669 & 0.9363 & 0.9078 & 0.8816 & 0.8570 & 0.8341 & 0.8125 & 0.7923 & 0.7733 & 0.7552 \end{bmatrix}$$

The grey correlation grade can be got by the equation (7), and the result was as follows:

$$\Gamma = \begin{bmatrix} 0.8424 & 0.6911 & 0.7363 & 0.8652 \end{bmatrix}^T$$

Grey correlation grade is a changeable value from 0 to 1. If the correlation grade is closer to 1, then the affected factors is more sensitive. The calculation result showed that among the affected factor s of chloride ion erosion service life, the sensitive of [Cl^-] density of member surface is the highest and water cement is the lowest. The other affected factors can be got by the same method based on the information in table 5.

This paper took the [Cl^-] density ,w/c,RH and Cs as the affected factors to analyze the senstivity of them. The conclusion showed in fig.4 indicates that the Cs must be considered firstly ,also the grey correlation analysis is a new method to analyze durability of concrete structure.

Table 5 Affected factors and the possible variation range

Carbonization service life	parameters	C	T	RH	f_{cuk}	k_{ce}	k_{co2}	K_{kl}	K_{kt}	K_{ks}
	Reference Value	50.0	20.8	0.78	20.1	6.0	1.3	1.0	1.2	1.0
	Change feild	45.0～55.0	19.76～21.84	0.702～0.858	19.095～21.105	4.8～7.2	1.04～1.56	0.9～1.1	1.08～1.32	0.9～1.1
chloride ion erosion service life	parameters	[Cl^-]		w/c		RH		C_s		
	Reference Value	0.6		0.35		0.78		19.0		
	Change feild	0.48～0.72		0.28～0.42		0.702～0.858		17.1～20.9		
Cover crack service life	parameters	C	T	RH	f_{cuk}	k_{ce}	d	k_{cl}	k_{crl}	
	Reference Value	50	20.8	0.78	20.1	6.0	22.0	1.0	1.35	
	Change feild	45.0～55.0	19.76～21.84	0.702～0.858	19.095～21.105	4.8～7.2	19.8～24.2	0.9～1.1	1.08～1.62	
Crack limit service life	parameters	k_c		K_f	K_d		K_t		K_{RH}	
	Reference Value	0.59		0.996	1.132		1.118		1.17	
	Change feild	0.531～0.649		0.8964～1.0956	1.019～1.245		1.006～1.230		1.053～1.287	

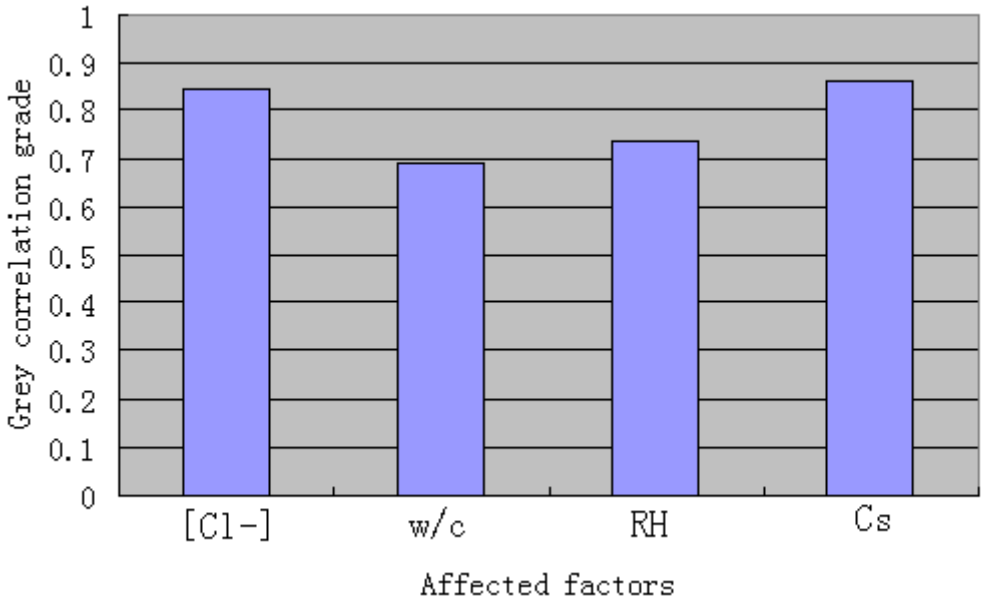

Fig.3 Sensitivity curve of [Cl⁻] erosion

5 Conclusions

It's a meaningful trial that using the grey correlation theory to analyze the sensitivity of the factors which can affect the concrete structure durability. The result indicated that grey correlation model can carries out sensitivity analysis well for the affected factors of concrete structure durability, is able to determine the quantity of the affect degree. And a new method to study the correlation of factors affecting concrete structure durability has been provided.

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