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# Probabilistic evaluation method for corrosion risk of steel reinforcement based on concrete resistivity

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## HIGHLIGHTS

- A probabilistic evaluation method for corrosion risk of steel reinforcement was proposed.
- A probabilistic prediction model of concrete resistivity was developed.
- Relationship between concrete resistivity and corrosion rate of steel reinforcement was calibrated.
- Evaluation criterion for corrosion risk of steel reinforcement based on concrete resistivity was proposed.

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## ABSTRACT

In order to overcome the disadvantages of traditional deterministic methods, a probabilistic evaluation method to assess the corrosion risk of steel reinforcement in concrete was proposed based on the probabilistic prediction model of concrete resistivity. The influences of major influential factors including water-to-cement ratio, chloride content, ambient temperature and ambient relative humidity on concrete resistivity were investigated first. Then a probabilistic prediction model of concrete resistivity in terms of the above major influential factors was developed by using the Bayesian theory and the Markov Chain Monte Carlo (MCMC) method. Meanwhile, the evaluation criterion for corrosion risk of steel reinforcement based on concrete resistivity was proposed according to the relationship between concrete resistivity and corrosion rate of steel reinforcement. Finally, a probabilistic evaluation method for corrosion risk of steel reinforcement in concrete was developed by means of the proposed probabilistic prediction model of concrete resistivity. Analysis results show that the proposed probabilistic evaluation method can not only identify the dominant risk of reinforcement corrosion, but also determine the probabilities of steel reinforcement under different corrosion risk levels (e.g. negligible, low, moderate, and high), which could avoid the misjudgment of corrosion risk of steel reinforcement often encountered by the traditional deterministic evaluation methods.



## 1. Introduction

Corrosion of steel reinforcement embedded in concrete has been recognized as one of the major problems on durability deterioration in existing reinforced concrete (RC) structures. It is worthwhile to note that reinforcement corrosion in concrete may not only produce corrosion-induced expansion pressure, which results in cracking and spalling of concrete cover and as a result degrades the service performance of RC structures, but also reduce the cross section of the embedded steel reinforcement bars, which weakens the load-carrying capacity and safety performance of RC structures. Hence, assessment of corrosion risk of steel reinforcement embedded in concrete plays an important role in decision making on maintenance, protection, and repair of existing RC structures [1–3].

Currently, three typical methods including the half-cell potential method, corrosion rate method and concrete resistivity method are often adopted to assess the corrosion risk of steel reinforcement embedded in concrete [4]. Among them, the half-cell potential method evaluates the corrosion risk of steel reinforcement based on the corrosion potential $E_{corr}$ measured by the half-cell potential technique. According to the half-cell potential method [5], the steel reinforcement embedded in concrete is active when $E_{corr} < -0.35$ V vs. CSE, while it is passive when $E_{corr} > -0.2$ V vs.

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CSE. It is clear that the half-cell potential method can only provide a qualitative assessment of corrosion risk of steel reinforcement embedded in concrete, since it does not provide adequate information about the kinetics involved in the corrosion process and therefore it cannot determine the corrosion rate of steel reinforcement. On the other hand, the corrosion rate method divides the corrosion risk of steel reinforcement embedded in concrete into four levels according to the magnitude of corrosion rate $i_{corr}$ [6]: negligible ($i_{corr} < 0.1\ \mu A/cm^2$), low ($0.1\ \mu A/cm^2 \leqslant i_{corr} < 0.5\ \mu A/cm^2$), moderate ($0.5\ \mu A/cm^2 \leqslant i_{corr} < 1.0\ \mu A/cm^2$), and high ($i_{corr} \geqslant 1.0\ \mu A/cm^2$). Comparing with the half-cell potential method, the corrosion rate method provides a quantitative assessment of corrosion risk of steel reinforcement based on corrosion rate. However, the measurement of corrosion rate of steel reinforcement embedded in concrete is a complex work whose precision is easily influenced by many factors such as the compensation of IR drop, the presence of localised corrosion, the interference with other electrical signals, and the determination of the rebar area being tested [7,8]. In order to avoid misleading conclusions, the measurement of corrosion rate of steel reinforcement embedded in concrete usually requires specially designed electrode configurations and careful interpretation [9]. Different from the above two methods, the concrete resistivity method assesses the corrosion risk of steel reinforcement embedded in concrete based on the relationship between concrete resistivity and corrosion rate of steel reinforcement [3,10–13]. According to the results reported by reference [14,15], the concrete resistivity is inversely proportional to the corrosion rate of steel reinforcement embedded in concrete. Gulikers [16] found that the corrosion rate of steel reinforcement embedded in concrete is mainly controlled by the concrete resistivity under dry ambient conditions. Yu, et al. [17] observed that the corrosion process of steel reinforcement in concrete is under the resistance control and the corrosion rate of steel reinforcement usually decreases with the increase of concrete resistivity when the limit current density is high. Huet, et al. [18] investigated the process control of reinforcement corrosion in concrete according to the water saturation degree of concrete ($S_r$), which shows that the reinforcement corrosion is controlled by the concrete resistivity when $S_r < 0.9$. Scott, et al. [19] found that corrosion rate of steel reinforcement in concrete is mainly affected by the oxygen content in the concrete and the thickness of concrete cover when concrete resistivity is low; however, corrosion rate of steel reinforcement in concrete is mainly affected by the concrete resistivity when concrete resistivity is high. According to the above observations, it is obvious that the concrete resistivity not only has a significant influence on the corrosion rate of steel reinforcement, but also may affect the control mode of corrosion process for steel reinforcement embedded in concrete [14–21]. Hence, concrete resistivity can be adopted as one of the most effective parameters to assess the corrosion risk of steel reinforcement embedded in concrete [3,10–13].

Although several typical test methods such as the two-electrode method (TEM) and four-electrode (Wenner) method (WM) have been developed to test the concrete resistivity, field measurements of concrete resistivity are usually affected by many factors such as geometrical constraints, surface contact, concrete non-homogeneity, presence of rebar and ambient conditions [22–24]. These factors may cause significant deviation from the real concrete resistivity, which affects the accuracy of corrosion risk assessment for steel reinforcement embedded in concrete. In order to overcome this disadvantage, various empirical models for concrete resistivity in terms of both environmental and material parameters have been developed based on the non-linear regression analysis of experimental data. Gong, et al. [25] established an empirical model for concrete resistivity in terms of water-to-cement ratio, chloride content and ambient relative humidity. But it ignores the influence of ambient temperature. Yang, et al. [26] proposed an empirical model to describe the relationship between concrete resistivity and water-to-cement ratio, chloride content, ambient temperature, as well as mineral admixtures. However, it neglects the influence of ambient relative humidity. DuraCrete [27] proposed an empirical model of concrete resistivity by taking into account the influences of the ambient relative humidity, ambient temperature, chloride content, as well as the test method. Nevertheless, it is only applicable for the water-to-cement ratio of 0.5. By introducing the correction factor of water-to-cement ratio, Yu, et al. [17] proposed an empirical model of concrete resistivity in terms of the water-to-cement ratio, chloride content, ambient temperature and ambient relative humidity. It should be noted that the above models for concrete resistivity are all deterministic prediction models, which have following disadvantages: Firstly, deterministic prediction models are usually developed based on the non-linear regression analysis of experimental data by using the least square method, which tries to guarantee the global optimization of prediction results, but often with significant deviations comparing with experimental data. Secondly, deterministic prediction models cannot take into account the model errors of empirical models arising from the inaccurate model form or missing variables. Thirdly, the model parameters of deterministic prediction models are all constant, which cannot take into account the influences of uncertainties of material parameters, environmental conditions, test methods and other factors on model parameters [28,29]. Fourthly, deterministic prediction models usually can only identify the dominant risk of reinforcement corrosion, but they cannot determine the probabilities of steel reinforcement under different corrosion risk levels (e.g. negligible, low, moderate, and high). As a result, deterministic prediction models could induce misjudgment for corrosion risk of steel reinforcement, since it ignores the uncertainty of concrete resistivity. Hence, it is desirable to develop a probabilistic evaluation method to assess the corrosion risk of steel reinforcement based on the probabilistic prediction model of concrete resistivity.

In this study, a probabilistic prediction model of concrete resistivity was developed based on the Bayesian theory and the Markov Chain Monte Carlo (MCMC) method first. Then a probabilistic evaluation method to assess corrosion risk of steel reinforcement embedded in concrete was proposed based on the probabilistic prediction model of concrete resistivity. Analysis results show that the proposed method can not only identify the dominant risk of reinforcement corrosion, but also determine the probabilities of steel reinforcement under different corrosion risk levels (e.g. negligible, low, moderate, and high), which could avoid the misjudgment of corrosion risk of steel reinforcement often encountered by the traditional deterministic evaluation methods.

## 2. Evaluation criteria for corrosion risk of steel reinforcement

Currently, three typical evaluation methods including the half-cell potential method, corrosion rate method and concrete resistivity method are usually adopted to assess the corrosion risk of steel reinforcement embedded in concrete [4]. However, the half-cell potential method can only provide a qualitative assessment of corrosion risk of steel reinforcement embedded in concrete. Hence, the evaluation criteria for the corrosion rate method and the concrete resistivity method are investigated in this study.

### 2.1. Evaluation criterion of corrosion risk based on corrosion rate

Corrosion rate is defined as the weight loss of steel reinforcement per unit area and unit time, while corrosion risk is defined as the corrosion activity or corrosion conditions (degree of corro-