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A data heterogeneity modeling and quantification approach for field pre-assessment of chloride-induced corrosion in aging infrastructures

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ABSTRACT

Aging infrastructures (e.g. roads, bridges and water mains) in America are deteriorating and becoming structurally deficient and their reliability and safety issues become matters of great concern. For the reinforced concrete infrastructures in marine environments, one of the leading failure causes is chloride-induced corrosion, which consists of a complex electrochemical process of chloride ingress. Inspecting chloride ingress conditions involves the costly and time-consuming procedures of extracting cores and performing laboratory analysis. Based on the limited resources, it will be desirable to develop pre-assessment approaches in evaluating chloride-induced corrosion conditions before extracting cores. Existing approaches mainly rely on engineering experience and/or visual inspection, which may be subjective or subject to visual inspection error. Existing approaches in analyzing trajectory profiles are often restricted by the oversimplification of homogeneity assumption and failed to address the potential heterogeneity among profiles data. This paper proposes an evidence-based analytical approach for chloride ingress pre-assessment by comprehensively exploring, quantifying and analyzing the historical heterogeneous chloride ingress profiles data and associating them with inexpensive external factors information, which are often readily available from concrete suppliers and bridge inventory databases. Given inexpensive information of a location to be inspected, the propose work can provide rich pre-assessment results, which will facilitate engineers to prioritize their resources and schedules and first inspect those most at-risk locations. A real-world case study is provided to illustrate the proposed work and demonstrate its validity and performance.

1. Introduction

Having been serving as the backbone of America's development in the past decades, the critical infrastructure systems (e.g. roads, bridges and water mains) are aging, deteriorating and becoming structurally deficient. According to the 2013 Report Card of Americas Infrastructure [1], categories of bridges got C+ grades (indicating the mediocre condition) while the category of roads only received a D grade (indicating the poor condition) under the evaluations of capacity, maintenance and public safety. As a critical element in the transportation system, marine bridges with reinforced concrete (RC) have been brought into focus because of the more frequent occurrence of collapses throughout the nation [2,3]. A major failure mechanism for bridges in marine environments is the chloride-induced corrosion of RC [4]. For instance, two thirds of Florida's 5500 bridges are exposed to chloride-rich salt water, making themselves vulnerable to chloride-induced corrosion. Maintaining reliability and service life of such bridges has become matters of great concern.

Chloride-induced corrosion mainly consists of two periods, namely the initiation period and the propagation period [4,5]. In the initiation period of chloride ingress, chloride ions from marine environments gradually diffuse through RC towards the reinforcing bars and eventually cause the depassivation of steel. In the propagation period of corrosion, the chemical products from corroded steel become expansive and tend to occupy more volume than the original steel. Thus, more tensile stresses are generated in the surrounding concrete substructures, resulting in longitudinal cracking of the concrete covers, reduction in the cross section of steel and the loss of concrete-steel bond [4]. Since the detrimental process of steel corrosion is initiated at the end of initiation period when the chloride concentration reaches a threshold level, studying the chloride ingress profiles through RC during the initiation period becomes particularly important and therefore is within the scope

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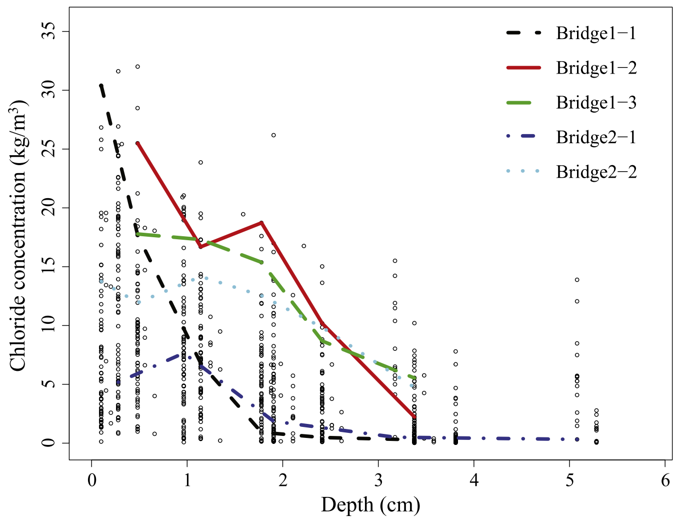

Fig. 1. Real data of heterogeneous chloride ingress profiles.

of this paper. For studies of steel corrosion in propagation period, please refer to [6] and references therein.

Chloride ingress process through RC is a complex electrochemical process and the resulting chloride concentration in RC cannot be directly measured. In practice, the typical approach adopted by engineers is to extract core samples from the concrete structure and perform chemical analysis in laboratory to measure chloride concentration profiles of extracted cores [7]. Based on the measured chloride concentration profiles, different physical models, such as diffusion models based on Fick's second law [8–11] and spatial modeling [12–14] can be employed to evaluate the corrosion initiation time or the probability of chloride-induced corrosion initiation. Although accurate and reliable, the process of extracting cores and performing laboratory analysis is costly [15], time-consuming and requires extensive resources of labor and equipments [16]. In addition, due to the destructive nature of extracting cores, extraction of a large number of cores should be avoided. Facing with the limited budget, physical constraints and a large number of possible locations to be inspected, it will be desirable to develop some analytical tools that will help pre-assess the chloride-induced corrosion conditions before extracting cores. It will facilitate engineers to prioritize their available resources and first inspect those most at-risk locations. Existing pre-assessment approaches mainly rely on engineering experience and/or visual inspection [7,17,18], which may be subjective, varying from engineer to engineer and subject to visual inspection error. It will be desirable to develop more evidence-based analytical approaches for pre-assessment. To fill the research gaps, this paper aims to develop analytical pre-assessment tools by taking advantage of available historical chloride ingress profiles data and associating them with inexpensive external factors information, which are often readily available from concrete suppliers and bridge inventory databases. Fig. 1 displays the historical chloride ingress profiles data of core samples extracted from multiple marine bridges in Florida. Laboratory chemical analysis [19] was conducted for the extracted concrete cores to evaluate their chloride concentration profiles.

Existing data modeling approaches in studying trajectory profiles, e.g., light intensity trajectories of laser devices [20,21], vibration signals of bearings [22] and degradation profiles of batteries [23,24], mainly assumed that all the investigated units (e.g., laser devices, bearings or batteries) were similar and exhibited the same or similar profile patterns. Therefore, the overall population of units was assumed as homogeneous. However, in the chloride ingress profiles, the investigated units of concrete cores may be extracted from different bridges at different ages, from the same bridge but different locations or from the same bridge and location but with different pre-existing conditions and environmental factors' influence. As shown in Fig. 1, concrete cores are sliced at different depths with chloride concentrations of core slices (represented in open dots) directly measured in the unit of "kg/m^3" (i.e., kilogram per cubic meter). Such chloride ingress trajectory profiles exhibit heterogeneous profile patterns. For instance, different cores from different bridges (e.g., "Bridge1-3" and "Bridge2-2") may exhibit similar profile patterns, where "Bridge1-3" is an abbreviation identifier that represents the first bridge and its third extracted concrete core sample. In addition, different cores from the same bridges may also exhibit similar (e.g., "Bridge1-2" and "Bridge1-3") or different (e.g., "Bridge1-1" and "Bridge1-3") profile patterns. It will be desirable to quantify such heterogeneity in chloride ingress profiles since homogeneity assumption becomes inappropriate. However, bridge itself is not an appropriate identifier to differentiate heterogeneous profile patterns and trajectory profiles with similar patterns are formed into virtual groups with latent heterogeneity.

To take into account data heterogeneity, mixture model is one of the popular modeling framework due to its intuitive construction and great modeling flexibility. It has been successfully investigated in some of existing works to model and quantify heterogeneity of reliability data and/or trajectory profiles. For instance, Buar et al. [25] proposed a mixture model for Weibull distribution in reliability estimation of lifetime data. Li and Liu [26] considered the mixture hazard regression to model lifetime data with latent heterogeneity. Yuan and Ji [27] developed a mixture of Gaussian distribution to account for the unit-to-unit variability of heterogeneous degradation data. Park [28] proposed a mixture of nonparametric regression model to characterize heterogeneous nanocrystal growth profiles. Mixture models characterize the heterogeneous population using multiple homogeneous sub-populations [29–31] and most of the existing mixture modeling approaches stopped at identification of the sub-populations. There is a lack of post analysis regarding each sub-population. For instance, how each sub-population is formed and what external contributing factors, e.g., concrete structure properties and environmental conditions, will affect those sub-populations?

To answer the aforementioned research questions and fill the gap in existing literature, this paper proposes an evidence-based analytical approach for pre-assessment of chloride-induced corrosion conditions by comprehensively exploring, quantifying and analyzing of the heterogeneous chloride ingress profiles obtained from multiple marine bridges. Specifically, a mixture of basis function model is proposed to characterize the chloride concentration trajectories, identify the number of heterogeneous sub-populations and quantify the heterogeneity in the chloride ingress profiles. Model estimation and selection strategies are further developed with the closed-form iterative updating procedures obtained to facilitate estimation convenience in practice. Based on the heterogeneity quantification results, a multi-class classification problem is formulated to investigate, visualize and explain how different inexpensive external factors will contribute to such heterogeneity in chloride ingress process. Given external factors information of a location to be inspected, the proposed model can predict its corresponding chloride concentration trajectory with variability bounds. The proposed works realize the evidence-based pre-assessment before performing in-depth inspection studies of core extraction and laboratory analysis. It will better inform the engineers in allocating and prioritizing their limited inspection resources.

The rest of this paper is organized as follow: Section 2 introduces the proposed heterogeneity exploration and qualification methodology for chloride ingress profiles. Section 3 gives a real-world case study of analyzing chloride ingress profiles extracted from a field survey and illustrates the validity of the proposed approach. Section 4 draws the conclusion.