ce/papers Proceedings in civil engineering

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ORIGINAL ARTICLE

EUROSTRUCT

Development of corrosion hazard maps for reinforced concrete bridges

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Abstract

Infrastructures in coastal areas are often prone to several hazards, and thus the elaboration of effective risk management plans in such zones are possible if all relevant threats are considered and analyzed. In this context, the assessment of the corrosion hazard attributable to airborne chlorides is of utmost importance since the resulting deterioration phenomena can heavily jeopardize both reliability and resilience of the infrastructures. Therefore, this contribution aims at proposing the preliminary version of a possible framework for the elaboration of corrosion hazard maps at regional scale for coastal areas, with focus on reinforced concrete bridges. The proposed approach encompasses three main steps. First, the relevant stock of infrastructures vulnerable to chloride-induced corrosion is identified and quantified. This requires the collection of relevant features, such as construction type, position, and age. Environmental conditions are examined next, including data about sea waves and salinity, wind, temperature, humidity, rainfall, and chloride deposition rate. Finally, the corrosion hazard is estimated in probabilistic sense. The proposed methodology is presented together with the preliminary results obtained from a relevant case study.

Keywords

Bridge, Chloride, Corrosion, Hazard map, Reinforced concrete

1 Introduction

Coastal areas are one of the most active zones on the planet. To figure out their relevance, it is useful to highlight that coastal shoreline counties in United States occupy less than 10% of the whole land, but 39% of the whole population lived in as per 2010, with a 2020 projected population density almost equal to 200 persons/km^2 (excluding Alaska). As per 2010, the share of population of coastal regions living in Italy within 5 km from the sea was 34%. Because of the large urbanization of the coastal areas (Fig. 1), suitable strategies must be thus implemented to quantify and mitigate the risk at territorial scale for the built environment in such zones.

In fact, coastal areas are prone to many natural hazards such as erosion, big storms, flooding, tsunamis, and sea level rise. Depending on the specific geology of the area, significant volcanic and seismic hazard levels may also take place. Within this framework, the hazard attributable to chloride ingress in concrete deserves careful consideration. This is because the chloride-induced corrosion can result in rapid and severe loss of cross-section area of the steel reinforcement in concrete structures and, ultimately, can significantly reduce their overall performance levels [e.g., 1-7]. Hence, the present work aims at presenting the current efforts towards the development of a probabilistic framework for the assessment of the corrosion hazard for reinforced concrete bridges exposed to marine atmosphere.

2 Sea salt generation, transport, and deposition

The airborne sea salt (i.e., marine aerosol) originates from sea spray formed from breaking surf and ocean whitecaps. It basically consists of microscopic particles able to float in the air. The amount of chloride that can deposit inland thus depends on sea waves characteristic and chloride ion concentration in seawater. On average, the total amount of all non-carbonate salts (also known as sea salinity) dissolved in the world's oceans is about 35 g/l. The chloride ion concentration is about 19 g/l, but it may vary near the coast. These microscopic particles are then transported inland by the winds, where the accumulation rate is basically governed by shoreline distance and weather conditions. A recent study by Alogdianakis et al. [8] has demonstrated that bridges condition may be affected negatively by sea chlorides at coastal distances up to 2–3 km inland. Therefore, the development of chloride-induced corrosion hazard maps for coastal regions would be a useful decision support tool for the management of structures and infrastructures exposed to marine aerosol.

https://doi.org/10.1002/cepa.2130

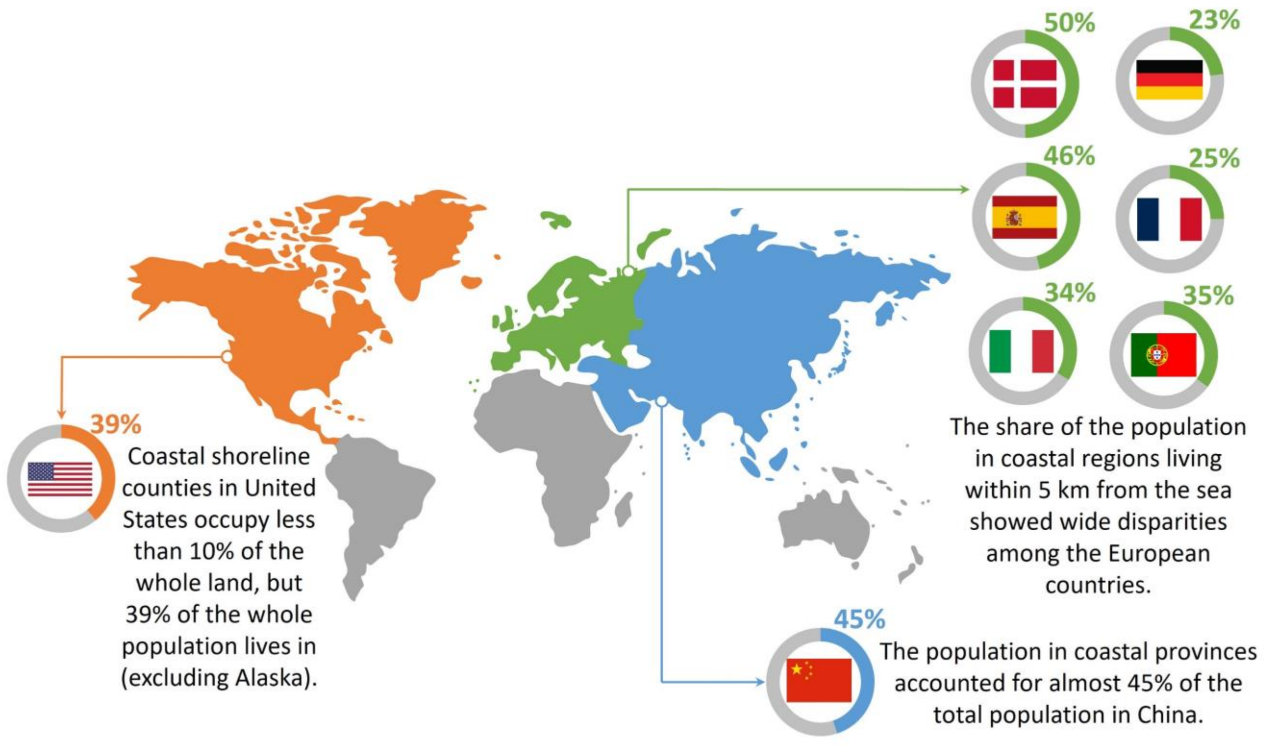

Figure 1 Some statistics about the urbanization of coastal landscapes.

3 A general framework for mapping the chloride-induced corrosion hazard

The general approach proposed for the development of chloride-induced probabilistic corrosion hazard maps for bridges located in coastal regions encompasses three main steps (Fig. 2), namely i) bridge stock analysis, ii) environmental exposure analysis, and iii) hazard analysis.

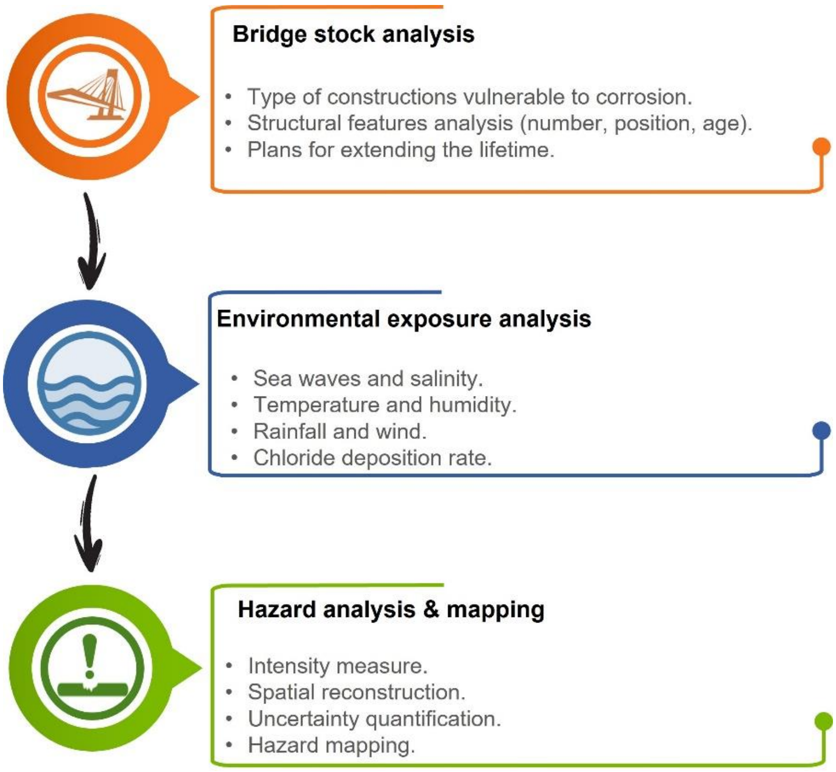

Figure 2 A general framework for the assessment of the chloride-induced corrosion hazard at regional scale in coastal areas.

First, information about number, position with respect to the shoreline and age of the bridges are retrieved. Plans for extending the lifetime of existing infrastructures can be also relevant. The second step deals with the analysis of the exposure conditions. This requires the collection and analysis of relevant environmental data that will be next employed for the development of the corrosion hazard maps. Chloride-induced corrosion hazard maps are then elaborated in the last stage. To this end, the intensity measure that serves at quantifying the hazard must be specified. The selected intensity measure is thus evaluated over the study area considering the involved uncertainties. Therefore, once the technique for estimating the spatial distribution of relevant variables has been defined, corrosion hazard maps are obtained for a given probability of exceedance and an assigned exposure time window, also accounting for the concrete mixture.

4 Case study

The proposed approach has been applied to investigate the corrosion hazard at Oahu Island, which is the third-largest of the Hawaiian Islands, United States. Oahu Island is about 71 km long and 48 km across; its area and shoreline length are about 1,545 km^2 and 365 km, respectively. The following relevant environmental data have been collected and processed.

- Position, age, and actual conditions of concrete bridges and pre-stressed/post-tensioned concrete bridges (sources: State of Hawaii's Open Data, Hawaii Statewide GIS Program, National Bridge Inventory for Hawaii).
- Sea salinity as well as direction and significant sea wave high of the sea waves near the coast (source: Pacific Island Ocean Observing System).
- Wind speed and direction (sources: RAWS USA Climate Archive, National Oceanic and Atmospheric Administration).
- Temperature, relative humidity, and rainfall distribution (source: Climate of Hawaii project).
- Chloride deposition rate (source: State of Hawaii Department of Transportation).

As an example of the collected data, Fig. 3 illustrates some information about bridges position, chloride deposition rate and daily wind maps over the study area.

It can be readily desumed from Fig. 3 that the largest part of the major transportation network basically develops along the island border and several bridges are rather close to the shoreline, which can facilitate the deposition of significant amount of sea chlorides on their surfaces. This fact motivates the elaboration of a chloride-induced corrosion hazard map for the selected study area.

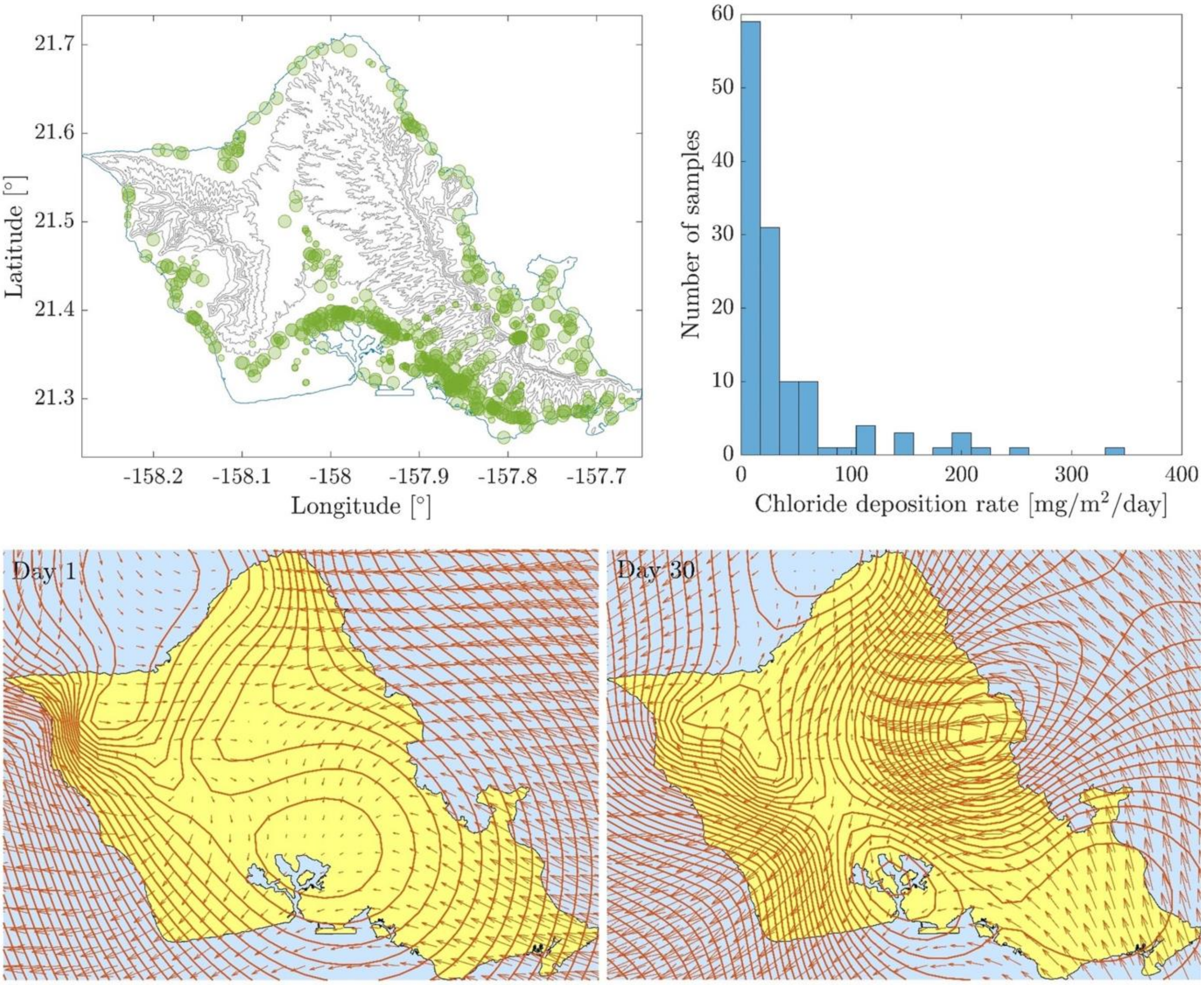

Figure 3 Analysis of some data collected for the study area: position of existing concrete bridges (top row, left), chloride deposition rate (top row, right) and daily wind maps (bottom row).

5 Preliminary results

The definition of the intensity measure plays an important role in hazard assessment. In the field of earthquake engineering, it is common expedient to classify the intensity measures as non-structure-specific and structure-specific. In the present work, the corrosion current density at the reinforcement level is selected as (structure-specific) intensity measure to map the chloride-induced corrosion hazard for reinforced concrete bridges exposed to marine atmosphere. Probabilistic corrosion hazard maps are thus meant at illustrating the spatial distribution of the corrosion intensity measure (i.e., the corrosion current density) for a specific concrete mixture and a given probability of exceedance within an assigned exposure time window. They are elaborated under the assumption that chloride ingress into concrete is a diffusion-like process taking into account the relevant environmental variables and the involved uncertainties. To this end, the study area is first discretizated using an unstructured triangular mesh, and Monte Carlo simulations are then performed at each node. Figure 4 shows the preliminary estimation of the spatial distribution of the corrosion current density for an exposure time window equal to 100 years (the probability of exceedance is 5%). Cement content and water-to-cement ratio are equal to 406 kg/m^3 and 0.50, respectively. Figure 5 show preliminary estimation of the corrosion current density values at concrete bridge sites (see Fig. 1) for different exposure time windows and concrete mixtures, given the probability of exceedance equal to 5%. The curves in Fig. 5 highlight the role of the concrete mixture in ruling the corrosion hazard level, since a low cement content and a large water-to-cement ratio facilitates the corrosion of steel reinforcement.

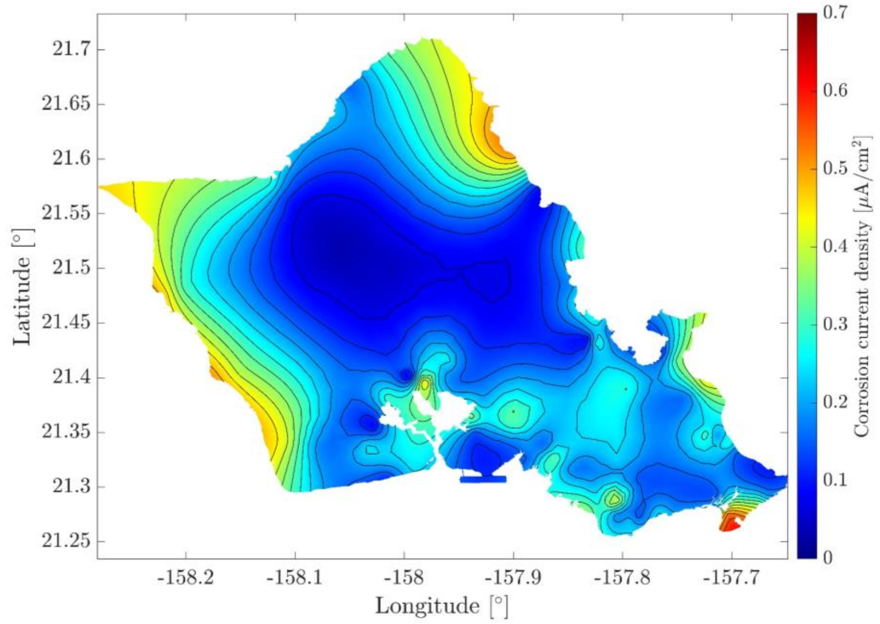

Figure 4 Probabilistic corrosion hazard map in terms of corrosion current density for an exposure time window equal to 100 years and a probability of exceedance equal to 5%. Cement content and water-to-cement ratio are 406 kg/m^3 and 0.50, respectively.

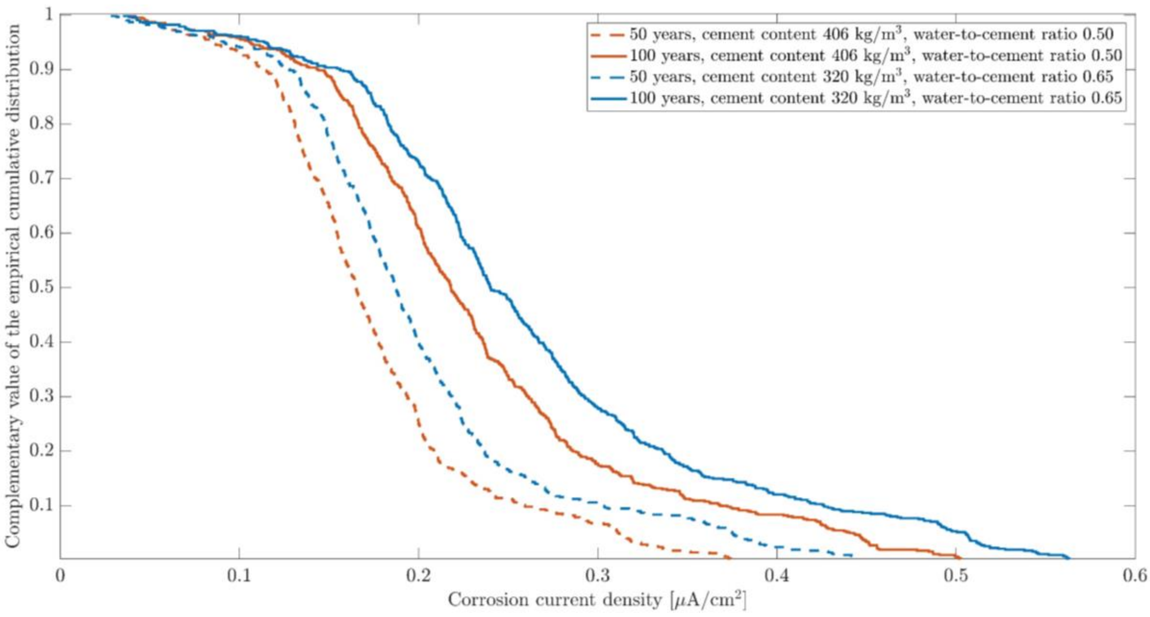

Figure 5 Distribution of the corrosion current density values estimated at the concrete bridge sites for different exposure time windows and concrete mixtures considering a probability of exceedance equal to 5%.

6 Conclusions

The present work illustrated the first version of a possible procedure for mapping the corrosion hazard for reinforced concrete bridges exposed to marine atmosphere at regional scale. Preliminary data elaborations and results have been also reported for a specific case-study, namely Oahu Island (Hawaii, United States).

Although the current efforts towards the development of probabilistic corrosion hazard maps have been illustrated with reference to a specific case-study, the implemented methodology has a broad validity and can be adapted to assess the chloride-induced corrosion hazard for general reinforced concrete structures located in other coastal regions.

Acknowledgements

Giuseppe Quaranta acknowledges the support from Sapienza University of Rome (Grant No. RM120172B37F0628). Bruno Briseghella acknowledges the support from the National Natural Science Foundation of China (Grant No. 51778148). The present study also received partial financial support through MIUR PRIN 2020 (Grant No. 020P5572N_005) and from Reluis (contract protocol n° 53, 23/06/2021).

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