Hindawi
Advances in Civil Engineering
Volume 2022, Article ID 6557898, 12 pages
https://doi.org/10.1155/2022/6557898

Research Article

Potential Structural Damage Characterization through Remote Sensing Data: A Nondestructive Experimental Case Study

Marta Terrados-Cristos, Francisco Ortega-Fernández, Marina Díaz-Piloneta, Vicente Rodríguez Montequín, and Javier García González

Project Engineering Department, University of Oviedo, Oviedo 33004, Spain

Correspondence should be addressed to Marta Terrados-Cristos; marta.terrados@api.uniovi.es

Received 25 February 2022; Revised 13 May 2022; Accepted 17 May 2022; Published 2 June 2022

Academic Editor: Meisam Gordan

Atmospheric corrosion, especially in coastal environments, is a major structural problem affecting metallic structures in various sectors. Structural health monitoring systems based on satellite information can help to ensure the proper behavior of civil structures and are an interesting alternative for remote locations. The aim of this case study is to relate remote sensing information to the results of experimental studies for potential structural damage characterization. The ultimate idea is to characterize any environment without long testing periods or sampling costs. Comparative nondestructive experimental tests involving different locations, sampling techniques, and study periods are performed. The results obtained are analyzed and compared with meteorological satellite data characterization at each site. The experimental test results show sufficient statistical significance ($p < 0.05$), confirming that the areas potentially most susceptible to corrosion can be identified using information from remote sensing satellites based on orientation, wind conditions, and wind origin. This can be used to facilitate the remote design and monitoring of structures more accurately with a stability guarantee.

1. Introduction

Civil structures deteriorate in various ways [1]. The principal causes of damage, failure, or even collapse of a civil structure are aging, climate conditions, deterioration of some components, deficient designs, and natural disasters [2, 3]. Although some of these issues can cause rapid failure [4], damage due to corrosion or fatigue tends to occur over extended periods of time. Nevertheless, these damages can be prevented if corrective actions are taken timely [5]. Therefore, it is of the utmost importance to monitor civil structures continuously to assess their structural conditions and provide early warning against structural damage [6].

Corrosion is one of the major structural defects in metallic structures [7], particularly in coastal environments [8]. Moreover, the fact that this problem can occur in any area [9] complicates its visual assessment, which is already an expensive, imprecise, and time-consuming task [10]. Traditional approaches for damage diagnosis of civil structures are mainly based on visual inspection. However, the size and conditions of the structures make this process increasingly difficult. Globalization has led to the design and development of many remote projects, which complicates routine monitoring and highlights the importance of using satellite remote sensing data to study environmental problems on a global scale [11].

Structural health monitoring (SHM) is an important process for assessing the health and integrity of civil structures to prevent structural damage [12]. SHM systems are widely used to achieve adequate performance in civil structures [13] and proper maintenance management [14]. Progress in technology and sensors has led to the transformation of SHM into a new form of monitoring [4, 15]. SHM systems generally include damage detection, location, and quantification [16], and damage detection is precisely the most critical one [1].

SHM is a broad and highly interdisciplinary field of research involving experimental testing, system identification, data acquisition and management, and long-term measurement of the environmental and specific operational conditions [17, 18]. Numerous damage detection applications can be found in almost every field.

Owing to recent advances in sensing and data acquisition systems, the use of these techniques in engineering applications has become an interesting development. There are multiple examples of different applications, such as modeling structural resistance and response [19, 20], studies based on vibration control [1, 12, 21], using machine learning techniques in SHM [16, 17, 22–24], and new approaches, such as smartphone-centric multisensory solutions [4].

All of them are trying to monitor, predict, or prevent damage from occurring, as early damage detection is an important concern for the scientific civil community [25]. However, a more efficient approach is to design or redesign structures based on these potential problems.

Most civil engineering projects involve metallic structures, generally made of bare or coated steel [26], which suffer from atmospheric corrosion [27]. Structural degradation in coastal areas is a particularly important problem because of its significance to society [28]. Approximately 40% of the world's population lives within 100 km of the coast [29] and it is precisely in these areas where industries are often located. Many studies have corroborated that the deposition rate of chloride is a critical factor that affects the atmospheric corrosion of metals [30] and the influence of chloride-contaminated environments on durability [31].

Thus, experimentally studying the deposition mechanisms of this atmospheric pollutant and relating the results to remote satellite data can help to predict and prevent potential structural damage. Hence, with prior knowledge of the most susceptible locations, it may not be necessary to allocate resources to monitor large, complex civil structures and the problem of SHM monitoring may be limited to certain areas.

Therefore, the main objective of this study was to propose a novel method for preliminary analysis of potential structural damage. The aim of this case study was to relate remote sensing information to the results of nondestructive experimental studies for potential structural damage characterization. This approach provides valuable information in a simple manner. Consequently, it makes it possible to design and monitor structures remotely and more accurately.

2. Materials and Methods

An outline of the methodology used in this study is shown in Figure 1. The first stage consisted of characterizing each site and studying its meteorological variables (temperature, relative humidity, wind speed, wind direction, and precipitation). Climatic information was obtained from remote-sensing satellites. This information was downloaded and processed to create a global database using Web servers. The next step in structuring and homogenizing the study data began by identifying and cleaning anomalous values. In addition, basic statistical analyses (means, deviations, maxima, minima, etc.) were performed. To ensure representativeness, these variables and their relationships were analyzed both during the study period and in the previous year. The possible relationships between the variables were studied, and the results were represented graphically for their correct interpretation.

The second stage included experimental studies. Sample preparation, using one of the three techniques further explained in Section 3.1, was performed according to what is indicated in the ISO 9225 : 2012 standard "Corrosion of metals and alloys. Corrosivity of atmospheres. Measurement of environmental parameters affecting the corrosivity of atmospheres" [32]. The samples were then exposed. Control samples were added in all cases. Subsequently, once the test period was completed, the samples were removed, processed as indicated in the standards, and analyzed by ion chromatography (METROHM 883 Basic IC plus).

In the third and last stage, the results of the tests were analyzed together with the results of the meteorological characterization of satellite data, which allowed drawing joint conclusions.

2.1. Sample Preparation. Three techniques were used to determine the chloride deposition. The ISO 9225 : 2012 standard sets the procedures for sample preparation using the wet candle and dry plate methods. As the previous methods were found to have limitations, it was necessary to develop a more accurate method to differentiate the impact of wind and rain, so the third option used in this experimental study was a new method based on the wet candle method (hereinafter referred to as "Covered candle").

2.1.1. Dry Plate. This technique is based on exposing a known area of double-layered gauze protected from rain and measuring by chemical analysis the amount of captured chlorides coming from one direction and deposited on the surface of the gauze. Chloride deposition is expressed in milligrams per square meter per day [$mg{\cdot}m^{-2}\,day^{-1}$]. Sample preparation, test duration, management of the final solution, and calculation of results are defined in Annex E of ISO 9225 : 2012 [32].

2.1.2. Wet Candle. The technique consists of a wet textile surface wrapped in the form of a cylinder and a water reservoir to maintain the wet condition of the gauze. This method allows the collection of aerosols from all directions. The amount of chloride deposited is determined by chemical analysis, and subsequently, the chloride deposition rate [$mg{\cdot}m^{-2}\,day^{-1}$] is calculated.

The sampling devices and solution used and the collection of the samples and the final calculation of the deposition are described in Annex D of ISO 9225 : 2012 [32].

2.1.3. Covered Candle. This is an altered version of the wet candle method, which provides an option for monitoring the effect of precipitation on the final chloride ion deposition. The main limitation of the wet candle method is that it does

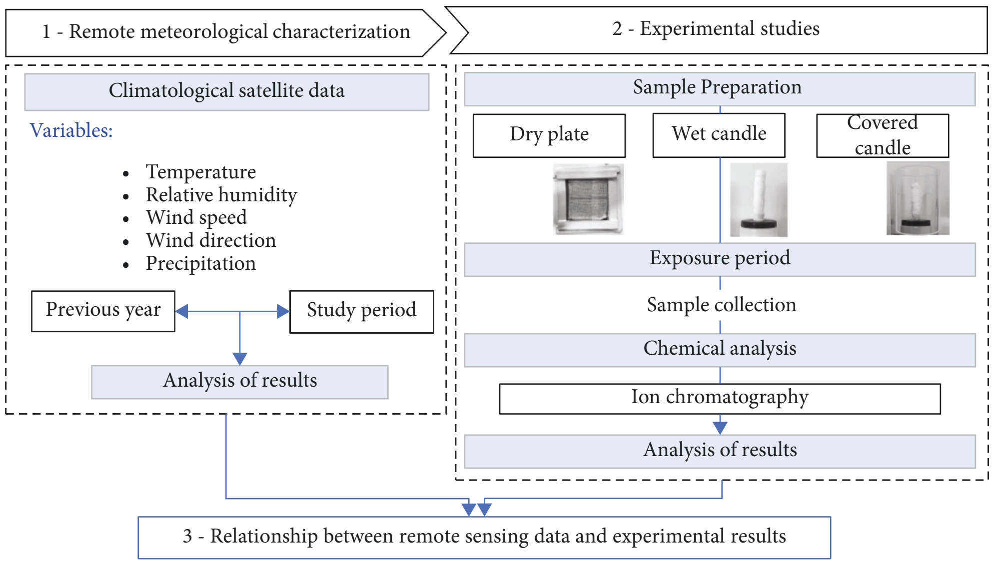


Figure 1: Outline of the common methodology for all tests.

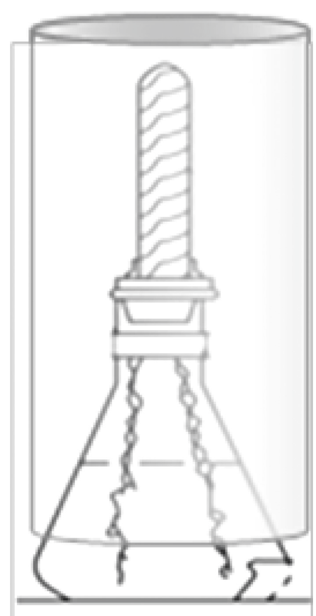


Figure 2: Proposed scheme for sample's collection in the covered candle method.

not allow differentiation between pollutant deposition by wind and pollutants deposited by rain. Cases where structures are located protected from wind but perfectly exposed to rain (e.g., in squares surrounded by skyscrapers) are suitable for this approach. This method includes a cover of plastic or similar material to isolate the sample from wind action (see the scheme in Figure 2).

2.2. Test Description. Three different experimental tests were conducted throughout the investigation. Each of them attempts to analyze and clarify a different hypothesis and study the influence of one or multiple climatic variables on the final pollutant deposition.

2.2.1. Test I: Influence of Wind Direction and Wind Origin on Chloride Deposition. Previous chloride deposition models only consider the distance to the sea, but this generates errors. The aim of this test was to analyze the influence of the relative wind position, together with the importance of the origin of the wind (wind from the sea or from land), in an

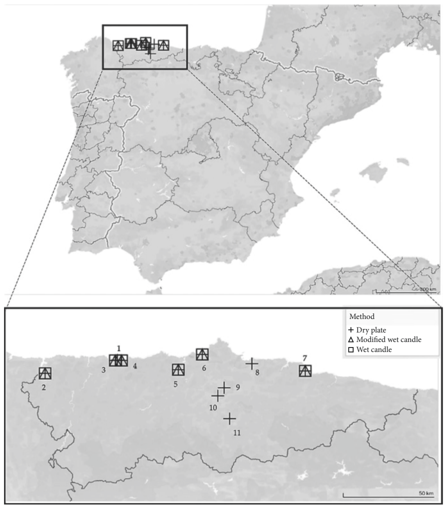


Figure 3: Location of samples in northern Spain distributed for all three different tests.

attempt to clarify why there are differences between deposition for the same distance and atmospheric conditions.

Samples in the same location were set in four different positions: upwind + wind coming and not coming from the sea, and downwind + wind coming and not coming from the sea. To achieve the objective described for Test I, tests were carried out at two successive time intervals. Thus, given the characteristics of the local wind and the possible positions of the samples in the four cardinal orientations, it was possible to obtain the range of events to be studied using the above-described dry plate technique.

2.2.2. Test II: Influence of Location, Orientation, and Atmospheric Conditions on Chloride Deposition. The aim of this test was to analyze the influence of the distance from the sample to the pollutant emitting source together with some other atmospheric variables (temperature, precipitation, wind, and relative humidity) and to consider the relative position between the structure and prevailing wind direction at each site.

The aim was to determine which wind speed thresholds appear in chloride deposition and transportation under such circumstances. In addition, the role of wind direction with respect to precipitation was studied. All samples were distributed at different distances from the sea at the locations shown in Figure 3, and the dry plate technique was employed.

2.2.3. Test III: Influence of Precipitations and Wind on Chloride Deposition. This third test studied the influence of precipitation on pollutant deposition and the role of precipitation in the presence and absence of wind.

The results obtained by the two different techniques were compared: the wet candle technique and its new version. Thus, one method involved total exposure to atmospheric variables and the other was isolated from the wind. The samples were collected at different points in the region. The final sample distributions at different test points are shown in Figure 3. The experimental sites include one-, two-, or three-sample techniques.

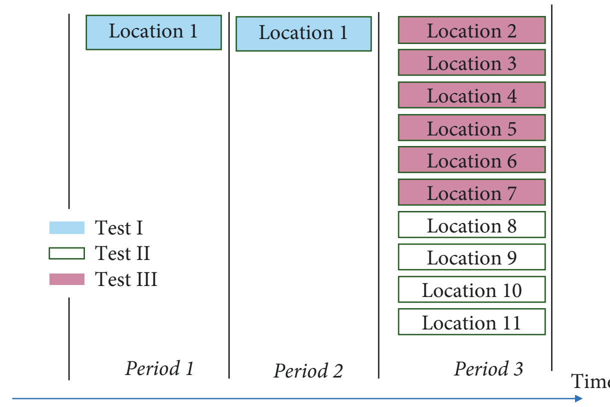


Figure 4: Distribution of all three tests and their locations over time.

The time planning for the three tests is presented in Figure 4. The combinations of the different tests and locations are indicated by the colors of the bar and outline. It can be observed how some locations participated in Tests I and II, others only in Test II, and the third selection of locations in Tests II and III, based on climatological conditions and availability.

Table 1 summarizes the methods, locations, and study periods for each of the three tests.

2.3. Statistical Analysis. Data obtained from the experimental tests were statistically analyzed using SPSS 22.0 software. Student's t-test for independent samples was used to assess whether there were significant statistical differences between the means at a confidence level of $p < 0.05$.

3. Results and Discussion

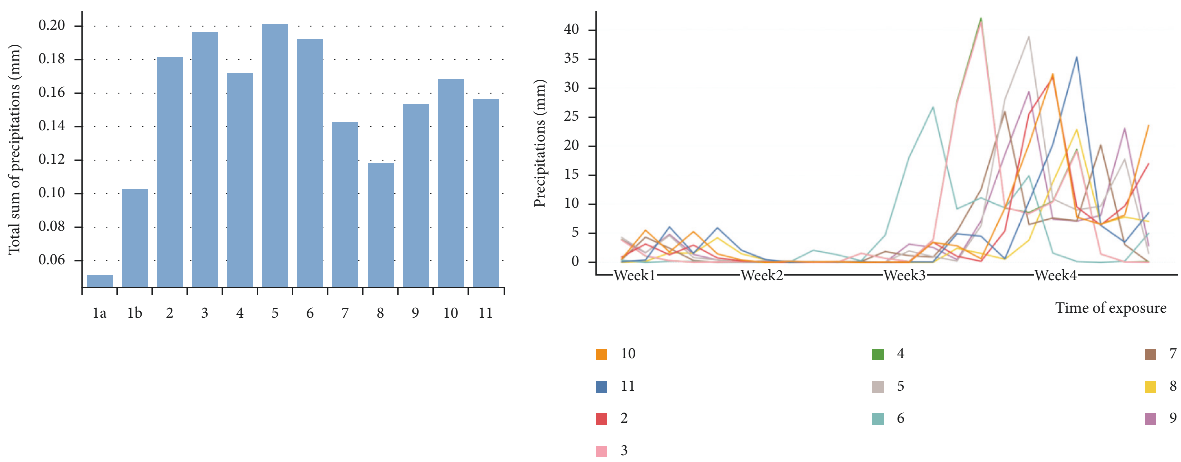
3.1. Results of Meteorological Characterization

3.1.1. Precipitations. Figure 5(a) shows the accumulated precipitation for each location during the study period, represented by vertical bars. As test I was performed over two different periods. In Figure 5, location 1 was divided into 1a and 1b, referring to these two study periods. At location 1, hardly any rainfall occurred during the first test interval (1a). In the second test interval (1b) at the same location, the rainfall increased considerably. For the rest of the locations, similar results were observed, with abundant precipitation, except for one specific location (number 8).

Figure 5(b) presents the distribution of precipitation data over time. Each line represents the location. Although the number of lines is large and visualization may be difficult, it is clearly observed that the weather was rather dry at the beginning, with a large amount of rainfall at the end for all sites.

Table 1: Summary of the different techniques, locations, and study periods involved in the three tests.

	Technique			Location		Study period	
	Dry plate	Wet candle	Covered candle	One location	Multiple locations	One period	Two periods
Test I	x			X			x
Test II	x				x	x	
Test III		x	x		x	x	



(a)
(b)

Figure 5: (a) Cumulative rainfall during the study periods at each location. (b) Distribution of rainfall by location over time.

3.1.2. Relative Humidity and Temperature. As stated in the literature, both relative humidity [33, 34] and temperature [35] may be parameters influencing atmospheric corrosion. Nevertheless, the average relative humidity during the sampling period and the average temperature at each location did not vary sufficiently during that period to be considered influential.

3.1.3. Wind Speed. Wind analysis is more complex because, in addition to wind speed, wind gusts and direction are also important [36–38]. Some authors agree that the influence of wind speed becomes clearer above a certain threshold; however, there is no single reference value [39, 40]. At none of the locations were very high wind speeds recorded; however, it is true that the closer to the sea, the higher the average wind speeds.

However, the maximum wind gusts measured during the study period showed winds of up to 12 m/s at some points along the coast. In the central areas and farther away from the coast, the highest measured speeds did not exceed 6 m/s.

3.1.4. Wind Direction. Finally, in addition to wind speed, wind direction plays a relevant role. Analyzing the prevailing winds at a given location can help identify the most dangerous areas [41]. To study the possibility of relating monthly wind directions to annual wind directions, predominant wind directions over the study period were compared to wind directions considering annual data (year 2020). After analyzing this parameter, the results provided relevant conclusions from several perspectives (Figure 6). First, when comparing the prevailing winds of the study period in the year 2021 (green arrow), it was observed that they remained perfectly consistent with the prevailing directions obtained during the same period in the previous year (yellow arrow), as no yellow arrows could be seen. However, the prevailing directions for a specific period do not necessarily correspond with the annual directions (blue arrow).

Another important factor was the sensitivity of the prevailing wind direction at each point. As stated above and as many authors agree [39, 40, 42], there are minimum wind speeds (threshold speeds) for the transport of pollutants over long distances. Below this threshold, the wind is not sufficiently strong. However, determining this threshold is complex. For the same study period, considering a certain minimum wind speed condition, the results of the predominant wind direction may also change. Prior to these calculations of the predominant directions, the results are filtered so that only values greater than a certain threshold speed (3 m/s (red arrow) and 2 m/s (orange arrow)) are considered, and the directions may vary. The values of the predominant directions could be changed only by varying the threshold velocity by 1 m/s, which shows the complexity of this parameter.

3.2. Results of Experimental Studies

3.2.1. Test I. The results of the localized test are presented in Figure 7. The upper part of the figure shows the chloride deposition results during the first time interval (left) and the second time interval (right). Below, the wind rose during each study period is included. The blue dots represent the

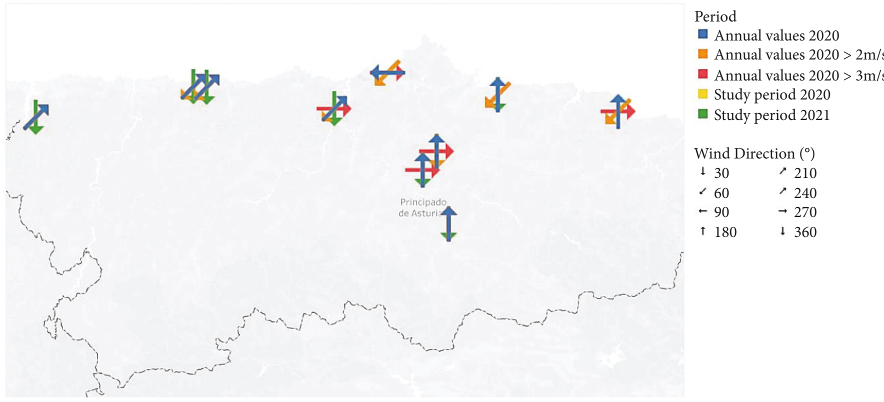


Figure 6: Prevailing wind directions at different sampling sites and periods.

north-facing samples (facing the sea) and the orange dots represent the south-facing samples (not facing the sea). In addition, the triangular shape represents the height of the samples; where the triangles with the tip upward, the samples are at the highest altitude.

Analyzing all this together, we observe the first period with a predominantly north-easterly wind of marine origin. The windward samples showed higher depositions at both heights, and the difference from the south-facing samples was very clear. In contrast, during the second study period, the prevailing winds were from the SW, and although the capacity of the wind to transport particles was approximately the same in both periods (similar wind speeds and frequencies), the final result was not similar. Therefore, the origin of the wind (marine or nonmarine) was the most important and relevant difference between the two studies.

Other studies have analyzed the importance of the orientation of the structure for pollutant deposition [41] but not whether the wind comes from an emitting source or from another direction.

Comparing the differences in pollutant deposition between the north and south faces during the first study period, a highly significant difference was observed ($p < 0.00028$). In contrast, if the same comparison was made during the second study period, no significant difference ($p > 0.16$) in the deposition of marine pollutants was observed between the samples that received more wind but had a nonmarine origin and those with little exposure to the wind but whose wind came from the sea.

The clearest differences were observed when comparisons were made between the two study periods. In the samples exposed to the north and, therefore, directly exposed to the sea, there was a large difference ($p < 4.11\ \mathrm{E}^{-05}$) between the two periods.

If the wind energies were compared as proposed by Meira et al. [39] to detect if they were equivalent, it was observed that the energy of pollutant transport was practically the same, as the difference was not very significant ($p > 0.1$), but the deposition results again showed clear differences ($p < 0.03$).

However, this is undoubtedly not the only influential factor. In the analysis of the precipitation results mentioned above (Figure 6), during the first study period, the accumulated precipitation was up to four times lower than that in the second period, where, although it did not rain excessively, it did rain much more than in the previous period. Thus, the chloride ions were not in the air ready to be transported but on the surface.

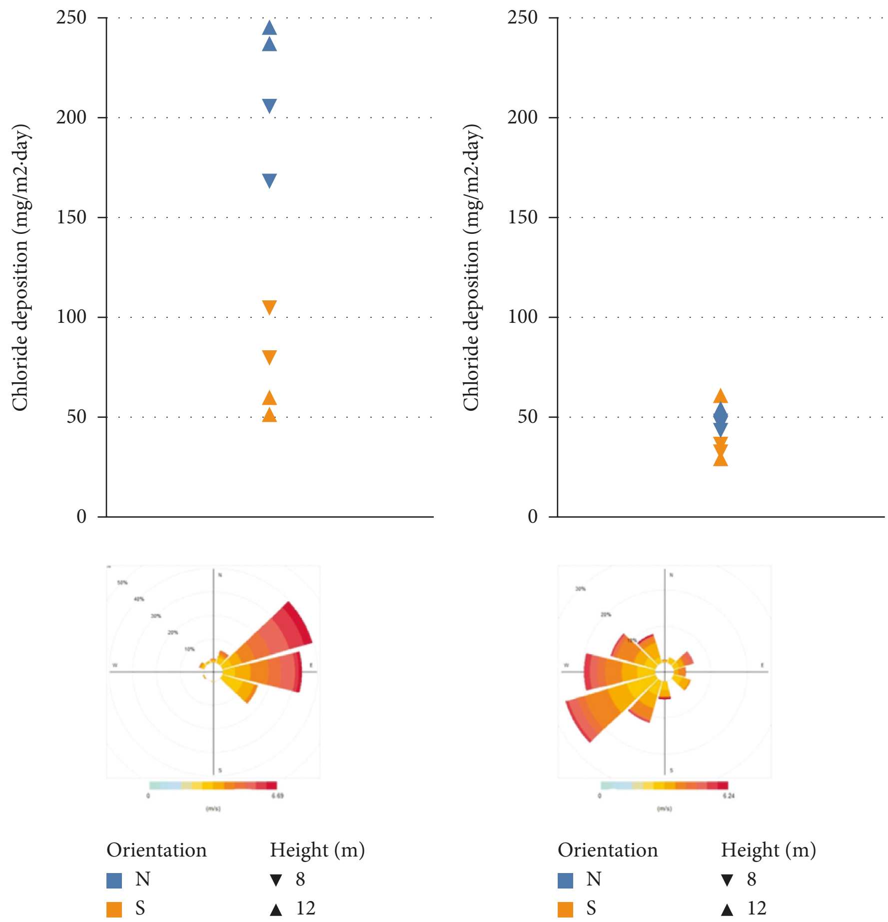
Comparing the results, even if there was a difference in precipitation between periods, which decreased the pollutant content of the atmosphere [35], there was no difference in deposition ($p < 0.03$); therefore, the relationship between wind orientation and origin was the most relevant factor.

This could confirm two points:

(i) In addition to the importance of the relative position between the orientation of the prevailing wind and the structure, the origin of these wind gusts is also important because if the wind is very strong but does not come from the sea but from inland, it may bring fewer chloride ions.

(ii) The role of the wind cannot be understood as an isolated variable, and precipitation (periodicity, quantity, etc.) seems to be important too, not so much for its action as a transport mechanism but for its interaction with the environment, cleaning the structures or reducing the chloride content in the atmosphere, Wash-out effect [43].

Finally, regarding this first test, when comparing the results of the deposition differences relative to elevation, as proposed in [44, 45], we agreed that for this case study, at a distance of only 4 m as in the present situation, no clear differences ($p > 0.31$) were observed between the two scenarios.



(a) (b)

Figure 7: Results of the localized tests: first study period (a). Second study period (b).

Figure 8: Results of test II, representation of deposition at each study location.

3.2.2. Test II. Figure 8 presents a summary of the results from Test II. The size of the circle indicates the amount of sea salt deposited. The values obtained as a function of geographical location were logical. The closer to the coast, the higher the deposition [44, 46, 47]. In agreement with other studies, the deposited salt concentration decreased as it moved away from the ocean [48, 49] when there were no additional sources to replace these losses. However, there was a southern point that stood out owing to its value in addition to its remoteness from the sea. It should be noted that other less influential sources can generate chloride, e.g., biomass combustion [50], coal burning [35], or industrial fumes [51].

It would be interesting to analyze these data by considering the orientation of each sample at each site

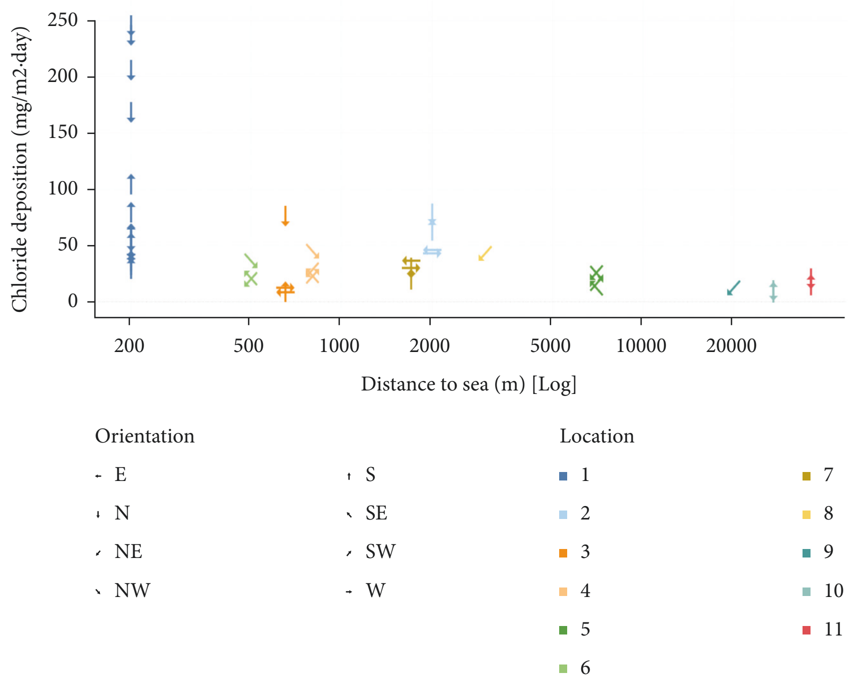


Figure 9: Chloride deposition as a function of distance from the sea in meters (logarithmic scale).

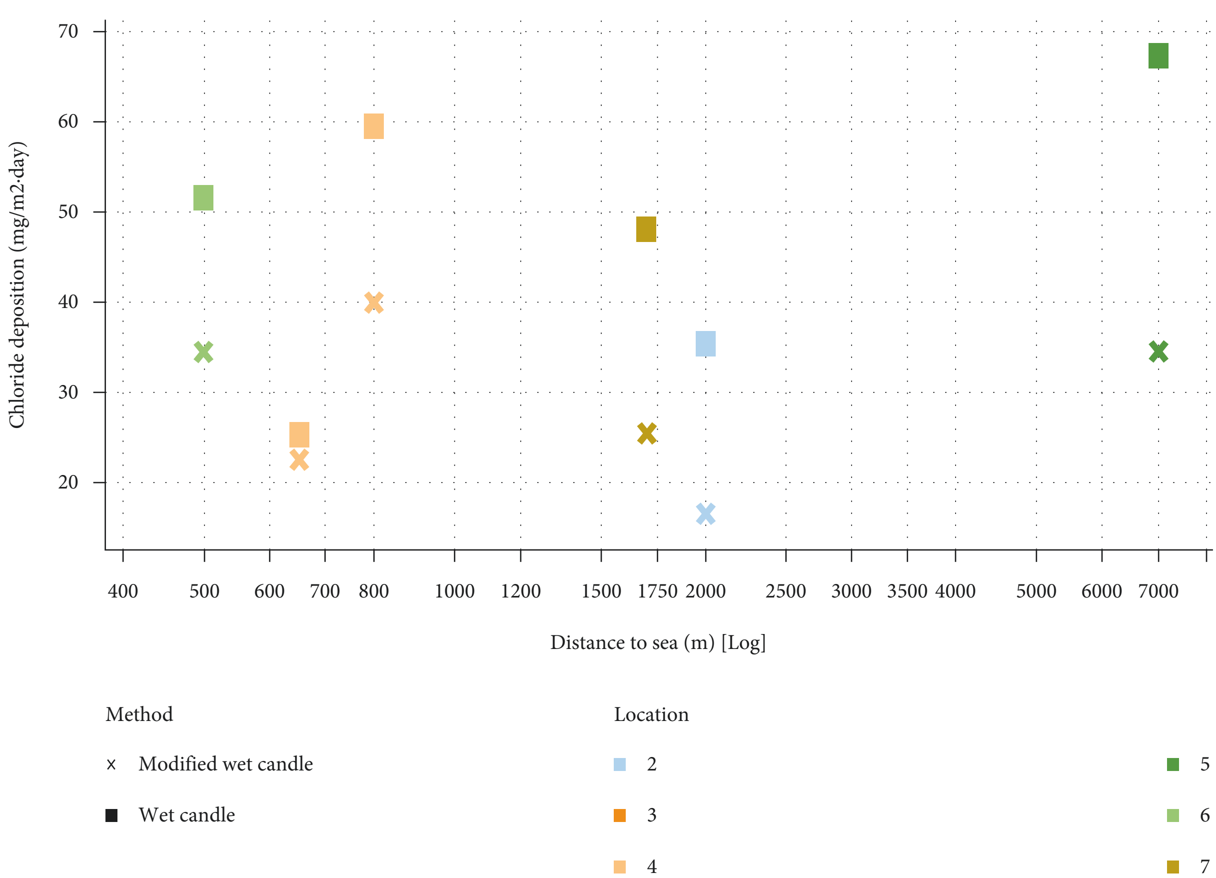


Figure 10: Representation of chloride deposition versus distance to coast in test III.

(Figure 9). All 11 locations were identified by both their color and equal distance to the sea. The results from test I (location 1) are also included in the graphic to gain a perspective. Thus, it is clear that the chloride content generally decreases as the distance increases. However, as each arrow indicates, there were significant differences between the orientations.

Relevant results were obtained when the values obtained during the second test were analyzed. First, it can be observed that chloride depositions are generally lower than those in test I, even considering the distance, probably because it was a period of much more rainfall than the previous one. This is in agreement with what Binyehmed et al. [35] found after analyzing the results of their experimental studies, which corroborated the increased chloride deposition rate in dry seasons compared to that in wet seasons. Besides, it can be observed that results can differ significantly depending on the orientation and origin of the wind, as demonstrated in test I. These differences in deposition became more remarkable with increasing proximity to the coast. More specifically, all the samples exposed to sea wind (coming from the north) had higher depositions than those from the other directions ($p < 0.01$), although these depositions progressively decreased in all cases as they moved away from the coast. Certainly, as the distance to the sea increased, the sensitivity of the orientation decreased.

3.2.3. Test III. The results of the final experiment are presented in Figure 10. This figure shows the deposition values versus distance from the shore. Each location is represented by a color; therefore, samples of the same color were subjected to the same meteorological conditions during the study period. However, the shape of the figure indicates the sampling techniques it represents.

The values obtained using the standard wet candle method were significantly higher than those of the modified counterpart ($p < 0.01$). These are the same study and meteorological conditions, except for the fact that the wet candle method is exposed to the wind and the covered candle method is not. Thus, the important role played by this variable is once again reflected, as stated in [36, 38], among other reports. It is risky to simplify the relationship between pollutant deposition and distance to the sea because the effectiveness of transportation or the existence of alternative sources may be important, as the results of location 5 demonstrated. The effect of blocking conditions on the final deposition result was studied in [41, 52, 53] but referred to as land cover.

The main source of these chloride ions is the ocean [41]. However, the distance to the ocean does not reflect exclusively the efficiency of chloride transport or the rate at which it falls or precipitates, among other effects; therefore, its parameterization varies from place to place [54]. Thus, this alternative technique may be used in cases such as those here studied, in which precipitation but no wind is present.

Atmospheric corrosion is a complex electrochemical process that involves many factors and variables [55]. The degradation suffered by the structures due to the action of chloride ions is clear [43, 56, 57] and it could be directly related to the protectiveness of the rust layers [58].

Therefore, to ensure sufficiently safe and useful life conditions, studying climatic variables, such as those proposed herein, can help identify potential damages [59]. The efficiency and complexity of airborne transportation are crucial for such processes [60]. In addition, it may be applicable and relevant to other important contaminants [61, 62].

4. Conclusions

Atmospheric corrosion in coastal environments has serious economic and environmental consequences owing to the degradation of structures, which forces the implementation of measures that have an impact on solution sustainability. SHM systems based on satellite information are an interesting alternative for monitoring remote locations. Studying and analyzing the most vulnerable zones of a structure prior to applying an SHM method may reduce the monitoring and modeling time and cost. This investigation focused on studying the deposition process of chloride contaminants as the most relevant factor for corrosion in coastal environments. Traditional approaches estimate chloride content only after direct measurement or by distance to the sea. Direct measurement is affected by the limitations of the current methods, which do not consider the effect of rainfall and relating it exclusively to distance to the sea involves serious errors. The results of the performed experimental tests based on meteorological sensor data, both localized and distributed, supported these ideas and allowed drawing the following main conclusions:

(i) The relative position between the orientation of the structure and the prevailing wind direction is a very important factor.

(ii) In addition to prevailing winds, it is of the utmost importance to consider the origin of that wind because when it comes from nonmarine areas, the transport and, therefore, the deposition of marine pollutants will be much lower.

(iii) Neither temperature nor relative humidity shows sufficiently large variations in the period and place of study to clarify its role in this phenomenon, although it is not possible to rule out their involvement.

(iv) The role of precipitation is also important, not only because it produces a washing effect and cleans the surfaces of contaminants, but also because, even when it does not act directly on the surface, it can reduce the chloride content in the environment, thus avoiding its transport and deposition by the wind. Precipitation periodicity is an important variable. However, one of the main limitations observed during the tests was the difficulty in forecasting precipitation.

(v) The new covered candle deposition measurement method can separate the contributions made by the wind from those made by rain, which allows modeling the phenomenon in a much deeper way. Even with the new method, there are many limitations in the use of real data, as it lacks representativeness for having been collected over short periods of time.

(vi) The experimental test results show with sufficient statistical significance that the areas potentially most susceptible to corrosion can be identified using information from remote sensing satellites based on orientation, wind conditions, and wind origin.

In future research, it is proposed to quantify numerically the values of wind power or energy for each orientation and location studied. Thus, it will be possible to obtain the minimum wind threshold for the case study.

It is necessary to develop models that consider the orientation, velocity, and percentage distribution of the wind source to make a deposition model. With all these conditions, a model can be built that provides, without needing sensors, an accurate estimation of the corrosion at a given location. This can be used both for the diagnosis of existing structures and for the optimized design of new structures. This better prediction will improve the estimation of corrosion of structures exposed to weathering and, eventually, enable an optimization of structural design from the economic and environmental sustainability point of view.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

Acknowledgments

This study was funded by the Regional Ministry of Science and Innovation and the University of the Principality of Asturias (grant number AYUD/2021/50953).

References

[1] O. Avci, O. Abdeljaber, S. Kiranyaz, M. Hussein, M. Gabbouj, and D. J. Inman, "A review of vibration-based damage detection in civil structures: from traditional methods to Machine Learning and Deep Learning applications," *Mechanical Systems and Signal Processing*, vol. 147, Article ID 107077, 2021.

[2] F. Seguel and V. Meruane, "Damage assessment in a sandwich panel based on full-field vibration measurements," *Journal of Sound and Vibration*, vol. 417, pp. 1–18, 2018.

[3] "Deep learning and its applications to machine health monitoring," *Mechanical Systems and Signal Processing*, vol. 115, pp. 213–237, 2019.

[4] E. Ozer and M. Q. Feng, "Structural health monitoring," in *Start-Up Creation*, F. Pacheco-Torgal, E. Rasmussen, C.-G. Granqvist, V. Ivanov, A. Kaklauskas, and S. Makonin, Eds., pp. 345–367, Woodhead Publishing, Second Edition, 2020.

[5] R.-T. Wu and M. R. Jahanshahi, "Data fusion approaches for structural health monitoring and system identification: past, present, and future," *Structural Health Monitoring*, vol. 19, no. 2, pp. 552–586, 2020.

[6] M. Mishra, P. B. Lourenço, and G. V. Ramana, "Structural health monitoring of civil engineering structures by using the internet of things: a review," *Journal of Building Engineering*, vol. 48, Article ID 103954, 2022.

[7] C. H. Tan, F. R. Mahamd Adikan, Y. G. Shee, and B. K. Yap, "Nondestructive fiber Bragg grating based sensing system: early corrosion detection for structural health monitoring," *Sensors and Actuators A: Physical*, vol. 268, pp. 61–67, 2017.

[8] M. Abbas and M. Shafiee, "An overview of maintenance management strategies for corroded steel structures in extreme marine environments," *Marine Structures*, vol. 71, Article ID 102718, 2020.

[9] M. Wasim and M. B. Djukic, "External corrosion of oil and gas pipelines: a review of failure mechanisms and predictive preventions," *Journal of Natural Gas Science and Engineering*, vol. 100, Article ID 104467, 2022.

[10] D. Ziaja and P. Nazarko, "SHM system for anomaly detection of bolted joints in engineering structures," *Structures*, vol. 33, pp. 3877–3884, 2021.

[11] M. Gong, D. Ruth, M. Claire et al., "Adaptive smoothing to identify spatial structure in global lake ecological processes using satellite remote sensing data," *Spat. Stat.*, Article ID 100615, 2022.

[12] S. Das, P. Saha, and S. K. Patro, "Vibration-based damage detection techniques used for health monitoring of structures: a review," *Journal of Civil Structural Health Monitoring*, vol. 6, no. 3, pp. 477–507, 2016.

[13] M. Gordan, S. R. Sabbagh-Yazdi, Z. Ismail et al., "State-of-the-art review on advancements of data mining in structural health monitoring," *Measurement*, vol. 193, Article ID 110939, 2022.

[14] M. Meribout, S. Mekid, N. Kharoua, and L. Khezzar, "Online monitoring of structural materials integrity in process industry for I4.0: a focus on material loss through erosion and corrosion sensing," *Measurement*, vol. 176, Article ID 109110, 2021.

[15] F. J. Pallarés, M. Betti, G. Bartoli, and L. Pallarés, "Structural health monitoring (SHM) and Nondestructive testing (NDT) of slender masonry structures: a practical review," *Construction and Building Materials*, vol. 297, Article ID 123768, 2021.

[16] M. Hassan Daneshvar and H. Sarmadi, "Unsupervised learning-based damage assessment of full-scale civil structures under long-term and short-term monitoring," *Engineering Structures*, vol. 256, Article ID 114059, 2022.

[17] O. Avci, O. Abdeljaber, S. Kiranyaz, M. Hussein, and D. J. Inman, "Wireless and real-time structural damage detection: a novel decentralized method for wireless sensor networks," *Journal of Sound and Vibration*, vol. 424, pp. 158–172, 2018.

[18] F. N. Catbas, O. Celik, O. Avci, O. Abdeljaber, M. Gul, and N. T. Do, "Sensing and monitoring for stadium structures: a

review of recent advances and a forward look," *Front. Built Environ.*vol. 3, 2017.
[19] S. Lee and C. Lee, "Prediction of shear strength of FRP-reinforced concrete flexural members without stirrups using artificial neural networks," *Engineering Structures*, vol. 61, pp. 99–112, 2014.
[20] H. Salehi and R. Burgueño, "Emerging artificial intelligence methods in structural engineering," *Engineering Structures*, vol. 171, pp. 170–189, 2018.
[21] F. Shadan, F. Khoshnoudian, and A. Esfandiari, "A frequency response-based structural damage identification using model updating method," *Structural Control and Health Monitoring*, vol. 23, no. 2, pp. 286–302, 2016.
[22] M. H. Daneshvar, A. Gharighoran, S. A. Zareei, and A. Karamodin, "Early damage detection under massive data via innovative hybrid methods: application to a large-scale cable-stayed bridge," *Structure and Infrastructure Engineering*, vol. 17, no. 7, pp. 902–920, 2021.
[23] H. Sarmadi, A. Entezami, B. Saeedi Razavi, and K.-V. Yuen, "Ensemble learning-based structural health monitoring by Mahalanobis distance metrics," *Structural Control and Health Monitoring*, vol. 28, no. 2, Article ID e2663, 2021.
[24] A. Entezami, H. Shariatmadar, and S. Mariani, "Early damage assessment in large-scale structures by innovative statistical pattern recognition methods based on time series modeling and novelty detection," *Advances in Engineering Software*, vol. 150, Article ID 102923, 2020.
[25] M. H. Rafiei and H. Adeli, "A novel machine learning-based algorithm to detect damage in high-rise building structures," *The Structural Design of Tall and Special Buildings*, vol. 26, no. 18, Article ID e1400, 2017.
[26] L. Yan, Y. Diao, Z. Lang, and K. Gao, "Corrosion rate prediction and influencing factors evaluation of low-alloy steels in marine atmosphere using machine learning approach," *Science and Technology of Advanced Materials*, vol. 21, no. 1, pp. 359–370, 2020.
[27] E. Diler, F. Peltier, J. Becker, and D. Thierry, "Real-time corrosion monitoring of aluminium alloys under chloride-contaminated atmospheric conditions," *Materials and Corrosion*, vol. 72, no. 8, pp. 1377–1387, 2021.
[28] B. Santosh Kumar, S. A. Sannasiraj, and K. Murali, "Effect of climate change in the deterioration of a berthing structure in a tropical environment," *J. Inst. Eng. India Ser. A*, vol. 102, no. 3, pp. 697–703, 2021.
[29] N. Brett, "Why we should care about vulnerable coastal communities," 2019, https://ani.seafdec.org.ph/handle/20.500.12174/5473.
[30] W. Choi, D. Lee, and C. B. Bahn, "Quantitative analysis methods of chloride deposition on silver for atmospheric corrosion monitoring in South Korea," *Corrosion*, vol. 77, no. 1, pp. 53–61, 2021.
[31] N. Russo, M. Gastaldi, L. Schiavi, A. Strini, R. Zanoni, and F. Lollini, "78_Effect of cracks on the service life of RC structures exposed to chlorides," *Acta Polytech. CTU Proc.*vol. 33, pp. 511–517, 2022.
[32] ISO, "ISO/TC 156 Corrosion of metals and alloys, 'ISO 9225:2012 Corrosion of metals and alloys — corrosivity of atmospheres — measurement of environmental parameters affecting corrosivity of atmospheres," 2012, https://www.iso.org/.
[33] P. Haberecht, "Pollution Deposition Rates on Insulator (HV) Surfaces for Use in Atmospheric Corrosivity Estimation," University of Newcastle, Callaghan, Australia, Doctor of Philosophy, 2008.
[34] G. R. Meira, M. C. Andrade, I. J. Padaratz, M. C. Alonso, and J. C. Borba, "Measurements and modelling of marine salt transportation and deposition in a tropical region in Brazil," *Atmospheric Environment*, vol. 40, no. 29, pp. 5596–5607, 2006.
[35] F. M. Binyehmed, A. M. Abdullah, R. M. Zawawi, R. E. Elawad, and K. Youssef, "Deposition Rate of Chloride DRC as a Corrosive Agent in Several Locations in the Klang Valley, Malaysia," *Sci.Int.*vol. 29, no. 2, 2017.
[36] I. Díaz, H. Cano, P. Lopesino et al., "Five-year atmospheric corrosion of Cu, Cr and Ni weathering steels in a wide range of environments," *Corrosion Science*, vol. 141, pp. 146–157, 2018.
[37] A. W. Momber, S. Buchbach, P. Plagemann, and T. Marquardt, "Edge coverage of organic coatings and corrosion protection over edges under simulated ballast water tank conditions," *Progress in Organic Coatings*, vol. 108, pp. 90–92, 2017.
[38] T. Duan, W. Peng, K. Ding et al., "Long-term field exposure corrosion behavior investigation of 316L stainless steel in the deep sea environment," *Ocean Engineering*, vol. 189, Article ID 106405, 2019.
[39] G. R. Meira, W. T. A. Pinto, E. E. P. Lima, and C. Andrade, "Vertical distribution of marine aerosol salinity in a Brazilian coastal area – the influence of wind speed and the impact on chloride accumulation into concrete," *Construction and Building Materials*, vol. 135, pp. 287–296, 2017.
[40] J. Piazzola and S. Despiau, "Contribution of marine aerosols in the particle size distributions observed in Mediterranean coastal zone," *Atmospheric Environment*, vol. 31, no. 18, pp. 2991–3009, 1997.
[41] J. Liu, G. Ou, Q. Qiu, F. Xing, K. Tang, and J. Zeng, "Atmospheric chloride deposition in field concrete at coastal region," *Construction and Building Materials*, vol. 190, pp. 1015–1022, 2018.
[42] J. C. Guerra, A. Castañeda, F. Corvo, J. J. Howland, and J. Rodríguez, "Atmospheric corrosion of low carbon steel in a coastal zone of Ecuador: anomalous behavior of chloride deposition versus distance from the sea," *Materials and Corrosion*, vol. 70, no. 3, pp. 444–460, 2019.
[43] R. Wattanapornprom and T. Ishida, "Modeling of chloride penetration into concrete under airborne chloride environmental conditions combined with washout effects," *Journal of Advanced Concrete Technology*, vol. 15, no. 3, pp. 126–142, 2017.
[44] B. Liu, X. Mu, Y. Yang et al., "Effect of tin addition on corrosion behavior of a low-alloy steel in simulated costal-industrial atmosphere," *Journal of Materials Science & Technology*, vol. 35, no. 7, pp. 1228–1239, 2019.
[45] G. R. Meira, C. Andrade, I. J. Padaratz, C. Alonso, and J. C. Borba Jr., "Chloride penetration into concrete structures in the marine atmosphere zone - relationship between deposition of chlorides on the wet candle and chlorides accumulated into concrete," *Cement and Concrete Composites*, vol. 29, no. 9, pp. 667–676, 2007.
[46] D. de la Fuente, I. Díaz, J. Simancas, B. Chico, and M. Morcillo, "Long-term atmospheric corrosion of mild steel," *Corrosion Science*, vol. 53, no. 2, pp. 604–617, 2011.
[47] J. Alcántara, B. Chico, J. Simancas, I. Díaz, D. de la Fuente, and M. Morcillo, "An attempt to classify the morphologies presented by different rust phases formed during the exposure of carbon steel to marine atmospheres," *Materials Characterization*, vol. 118, pp. 65–78, 2016.

[48] M. E. R. Gustafsson and L. G. Franzén, "Dry deposition and concentration of marine aerosols in a coastal area, SW Sweden," *Atmospheric Environment*, vol. 30, no. 6, pp. 977–989, 1996.
[49] P. J. Davies and R. S. Crosbie, "Mapping the spatial distribution of chloride deposition across Australia," *Journal of Hydrology*, vol. 561, pp. 76–88, 2018.
[50] K. A. Pratt, S. M. Murphy, R. Subramanian et al., "Flight-based chemical characterization of biomass burning aerosols within two prescribed burn smoke plumes," *Atmospheric Chemistry and Physics*, vol. 11, no. 24, Article ID 12549, 2011.
[51] R. C. Moffet, B. de Foy, L. T. Molina, M. J. Molina, and K. A. Prather, "Measurement of ambient aerosols in northern Mexico City by single particle mass spectrometry," *Atmospheric Chemistry and Physics*, vol. 8, no. 16, pp. 4499–4516, 2008.
[52] K. Slamova, "Mapping Atmospheric Corrosion in Coastal Regions: Methods and Results," *Journal of Photonics for Energy*, vol. 2, no. 1, Article ID 022003, 2012.
[53] A. Castañeda, F. Corvo, J. J. Howland, and R. Marrero, "Penetration of marine aerosol in a tropical coastal city: Havana," *Atmósfera*, vol. 31, no. 1, pp. 87–104, 2018.
[54] H. Guan, A. J. Love, C. T. Simmons, O. Makhnin, and A. S. Kayaalp, "Factors influencing chloride deposition in a coastal hilly area and application to chloride deposition mapping," *Hydrology and Earth System Sciences*, vol. 14, no. 5, pp. 801–813, 2010.
[55] M. Kubzova, V. Krivy, and K. Kreislova, "Influence of chloride deposition on corrosion products," *Procedia Engineering*, vol. 192, pp. 504–509, 2017.
[56] S. Hu, Z. Wang, Y. Guo, and G. Xiao, "Life-cycle seismic fragility assessment of existing RC bridges subject to chloride-induced corrosion in marine environment," *Advances in Civil Engineering*, vol. 2021, Article ID e9640521, 18 pages, 2021.
[57] Y. Gu, A. Yu, and X. Zhang, "Seismic performance of offshore piers under wave impact and chloride ion corrosion environment," *Shock and Vibration*, vol. 2021, pp. 1–19, 2021.
[58] H. Chen, H. Cui, Z. He, L. Lu, and Y. Huang, "Influence of chloride deposition rate on rust layer protectiveness and corrosion severity of mild steel in tropical coastal atmosphere," *Materials Chemistry and Physics*, vol. 259, Article ID 123971, 2021.
[59] M. Ormellese, S. Beretta, T. Bellezze, and F. Bolzoni, "Atmospheric Corrosion Behavior of Zinc and Zinc Alloys: Comparison between Natural and Accelerated Exposure," 2021, https://onepetro.org/NACECORR/proceedings/CORR21/8-CORR21/D081S029R008/464011.
[60] R. Wattanapornprom, P. Limtong, T. Ishida, P. Pheinsusom, and W. Pansuk, "Airborne chloride intensity and chloride ion penetration into mortar specimen in Thailand," *Engineering Journal*, vol. 24, no. 2, pp. 87–100, 2020.
[61] M. H. Nazir, A. Saeed, and Z. Khan, "A comprehensive predictive corrosion model incorporating varying environmental gas pollutants applied to wider steel applications," *Materials Chemistry and Physics*, vol. 193, pp. 19–34, 2017.
[62] G. Battista, "Analysis of the air pollution sources in the city of rome (Italy)," *Energy Procedia*, vol. 126, pp. 392–397, 2017.