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DURABILITY ASSESSMENT AND RE-DESIGN OF COASTAL CONCRETE BRIDGE THROUGH A NON-DESTRUCTIVE DAMAGE DETECTION METHOD

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Experts and governments have long focused on reducing the costs of repairing and maintaining crucial structures such as bridges through continuous maintenance and repair. In the meantime, using appropriate methods for identifying possible damage and researching how much a partial re-design will lower the costs of repairing and maintaining a structure over its lifetime, considering the structure's environment and damage causes. This study explores the cost-effectiveness of two damage prediction methods using the power spectral density (PSD) method compared to the conventional method of detecting damage by re-designing different concrete cover thicknesses for a coastal reinforced concrete bridge. The study evaluates the impact of chloride ions on the location and extent of damage over the bridge's lifetime and compares the total maintenance and repair costs. The results show that while the PSD method is effective for concrete structures with low concrete covers, increasing the concrete cover thickness may result in higher repair costs.

Keywords: life cycle cost assessment; non-destructive damage detection methods; coastal concrete bridge; steel corrosion; chloride corrosion; maintenance and repair techniques

DURABILIDAD Y REDISEÑO DE UN PUENTE DE HORMIGÓN EN AMBIENTE COSTERO MEDIANTE UN MÉTODO NO DESTRUCTIVO DE DETECCIÓN DE DAÑOS

Los expertos y los gobiernos llevan tiempo centrándose en reducir los costes de reparación y mantenimiento de estructuras cruciales como los puentes mediante un mantenimiento y una reparación continuos. Este estudio explora la rentabilidad de dos métodos de predicción de daños mediante el método de densidad espectral de potencia (PSD) en comparación con el método convencional de detección de daños mediante el rediseño de diferentes espesores de recubrimiento de hormigón para un puente costero de hormigón armado. El estudio evalúa el impacto de los iones cloruro en la localización y extensión de los daños a lo largo de la vida útil del puente y compara los costes totales de mantenimiento y reparación. Los resultados muestran que, si bien el método PSD es eficaz para estructuras de hormigón con recubrimientos de hormigón bajos, el aumento del espesor del recubrimiento de hormigón puede dar lugar a mayores costes de reparación.

Palabras clave: evaluación del coste del ciclo de vida; métodos no destructivos de detección de daños; puente costero de hormigón; corrosión del acero; corrosión por cloruros; técnicas de mantenimiento y reparación

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1. Introduction

Engineers and scholars have debated structural lifetime costs for decades. Design, building, repair, maintenance, and demolition are necessary expenses of civil structure activities. Bridges' life cycle costs include maintenance and repair expenditures. Many variables lower building maintenance expenses over time. Accurate health monitoring and damage detection technologies to forecast structural element deterioration throughout a structure's life cycle may save repair and maintenance expenses. Destructive and non-destructive technologies are employed to identify structural deterioration (Su, Dong, & Pei, 2022). Tests sometimes include removing structural samples to measure damage in destructive techniques. However, non-destructive methods may detect cracks or damages without harming the structure (Momeni & Ebrahimkhanlou, 2022). Several signal-based approaches as non-destructive methods include the time, frequency, and time-frequency domains (Liu et al., 2023). Some usable frequency domain techniques as variations in dynamic features, including natural frequency (Khodadadi & Mirjalili, 2022; Loya, Aranda-Ruiz & Zaera, 2022), modal Curvatures (Yang et al., 2022; Nguyen et al., 2020), mode shape (Hassani, Mousavi, & Gandomi 2022; Zhang et al., 2022), modal strain energy (MSE) (Shirazi et al., 2023; Daneshvar, 2022; Nguyen, & Livaoğlu 2022), frequency response functions (FRF), and power spectral density (PSD) (Fang et al. 2023; Hadizadeh-Bazaz, Navarro, & Yepes 2022) are employed in vibration-based damage detection, some popular non-destructive testing methods.

On the other hand, it is necessary to investigate the performance of some non-destructive damage detection methods in different situations and conditions in order to the life cycle assessment (LCA) that includes environmental impact (Navarro, Yepes, Martí & González-vidosa, 2018) and social impact (Navarro, Yepes, & Martí, 2018) and in addition, life-cycle cost analysis (LCCA) of these techniques to decrease total costs in different stages of a structure from design and construction to end the life of the civil structure. Various research looked at the LCCA in some buildings and with other methods and conditions in the lifetime of some civil structures. Mirzaeefard, Mirtaheri, & Hariri-Ardebili, (2023) assessed the damage cost in several limit states of a pile-supported wharf damaged by corrosion. Then the LCC analysis considers crane damage and inspection and maintenance expenses. Vasishta, Mehany, & Killingsworth, (2023) compared the environmental and life-cycle costs of precast and cast-in-place (CIP) construction technologies. Thus, using Open LCA software and the NIST guidelines for LCCA, a cradle-to-grave methodology was applied to examine these consequences for precast and cast-in-place building systems. Heidari, Heravi, & Esmaeeli, (2020) developed a probabilistic and uncertain approach to estimate the life-cycle costs and environmental impacts of pavements.

The performance of each non-destructive damage identification method and the life cycle and life cycle cost assessment of each technique in any type of structure and according to different conditions and situations requires a detailed investigation. Although in this regard, Hadizadeh-Bazaz, Navarro, & Yepes (2023) examined the efficacy of the non-destructive damage-prediction PSD technique for a coastal concrete structure and its relevance in LCCA to decrease maintenance and repair costs due to chloride ions in marine and coastal environment.

This study employs the PSD method to identify damages for a coastal concrete bridge designed by changing the concrete cover for various parts and elements exposed to chloride ion corrosion in order to evaluate the performance of this damage detection method on LCC by changing the thickness of the cover as one of the influential factors in chloride corrosion damage. For this purpose, the effect of increasing the concrete cover of the structure on the performance of the PSD method was analyzed and compared with the conventional method in predicting the chloride corrosion damage prediction method during the lifetime of this marine concrete bridge. Then LCCA and total costs related to differentiation and maintenance were compared and analyzed using these methods for different concrete covers. During this bridge's lifetime (100 years), PSD, as a frequency-domain approach, was tracked utilizing sensitivity equations and the linear least squares method. This structure's health was monitored yearly using these techniques and under changes in dynamic components, such as the stiffness and mass of rebars and bridge construction parts. The result of this study can help engineers and specialists in this field for more information about the performance and drawbacks of this dynamic and non-destructive damage detection method in coastal and marine environments.

2. Objectives

The following are some of the main goals of this research:

- Analyze the ability of the PSD method to detect damage and corrosion in the case of changes in the thickness of the concrete cover of the structure.
- Determining the amount of effects of damage detection through a non-destructive method effectively reduces the total costs of repairing and maintaining the structure.

3. Methodology

To analyze the effect of increasing the concrete cover of the structure and to evaluate non-destructive damage detection methods for detecting corrosion damage in the case of minor changes in the design and implementation of a coastal concrete bridge was done in stages. The first stage utilized Fick's second chloride diffusion equation to estimate steel component service life for different concrete cover thicknesses. Then, using the PSD approach, the presence, amount, and location of chloride damage were determined for the various concrete cover scenarios for the RC bridge. Finally, according to damages predicted for each area and element of the structure, determine the total life cycle cost for each section of the structure for repair activities in the lifetime of a structure by considering the discount rate for LCCA.

3.1 Prediction strategies for corrosion deterioration in steel rebars

Most steel is fragile and easily broken by both natural and manufactured things. These corrosions are common in coastal areas, where large amounts of corrosion-causing chloride ions are present. In marine and coastal regions, structures like bridges and buildings made of reinforced concrete often cause corrosion in steel rebars.

The total time until chloride corrosion (t_l) according to the damages and chloride corrosion by Tuutti (1982) is the service life of the reinforcements of the bridge structure when the initiation and propagation phases are assumed together, as shown in the following equations (Spanish Ministry of Public Works, 2008).

$$t_l = t_i + t_p \tag{1}$$

The corrosion initiation period (t_i) is the time it takes chlorides to reach a concentration that starts rebar corrosion (chloride threshold, dependent on the steel properties and, to some extent, on the concrete properties). The t_p is also the time it takes corrosion to spread across a structural section before it fails (Spanish Ministry of Public Works, 2008).

A physical model tracks chloride ions in concrete cover to determine initiation time using Fickian models, assuming a uniform porous cover that diffuses ions in suitable humidity. Chloride drives diffusive action between the surface and cover, and Fick's equation is used to determine chloride diffusion in the cover. The equation from Fib Bulletin 34 (2006) assumes a constant, time-independent surface chloride concentration. The predicted chloride level in the concrete cover at depth *x* and time *t* is:

$$C(x.t) = C_s.\left(1 - erf\left(\frac{x}{2\sqrt{D_{0.x}.(\frac{t_0}{t})^{\alpha}.t}}\right)\right) \tag{2}$$

where *C(x,t)* is the chloride concentration at depth *x* and time t and C_s is the concentration of chloride ions at the concrete's outside surface. The chloride transport time *t* into the concrete element is given by the inverse action on equation 2 that in this equation considered $C(x,t)=C_t$.

$$t_i = \frac{x^2}{4D}\left[erf^{-1}\left(\frac{C_s - C_t}{C_s}\right)\right]^{-2} \tag{3}$$

In this instance, *D* refers to the chloride diffusion coefficient, which shifts over time as the concrete ages according to the formula $D = D_0(t_0)(t_0/t)^n$. After the initiation stage of chloride diffusion, the propagation chloride corrosion phase (t_p) begins when chloride ions on the surface of the inner rebars begin to corrode steel reinforcements. The stiffness and cross-sectional area of the steel bars are gradually decreased by chloride corrosion. The Spanish Concrete Design Code (2008) offers the formula below to determine the propagation time:

$$t_p = \frac{80}{\phi}\frac{d}{V_{corr}} \tag{4}$$

Where *d* is the concrete cover's thickness, ϕ is the diameter of the rebar, and V_{corr} is the corrosion rate.

In this study, according to the Spanish concrete design code (2008), the durability parameters for the Arosa bridge were considered as follows for calculating conventional chloride corrosion in steel rebars. The C_s (% of concrete weight) for the aerial, submerged, and tidal zone are respectively equal to 0.14, 0.72, and 0.5. And also, V_{corr} values for the aerial, submerged, and tidal areas are equal to 20, 4, and 50 (μm/year), respectively. In addition, D_0 is equal to 10 (×10−12m2/s).

According to the Spanish concrete design code (2008), as shown in this study and other research (Navarro, Martí, & Yepes, 2019; Bruet et al., 2018; Frontera, & Cladera, 2022), the critical chloride concentration (C_{th}) must be determined by the designer in accordance with the specific concerns related to the structure, whereas under normal conditions, a value of 0.6% of the cement weight can be used to evaluate the limit state in terms of passive reinforcement corrosion. In addition to this analysis, in this study, the thickness of the concrete cover of the structure in the deck part was performed for the thicknesses of 3 (Refrense), 3.5, 4, 5, and 6 cm and for the columns with the thickness of the concrete cover of 4 (Refrense), 4.5, 5, 6, and 7 cm.

The following formula, which considers the initiation and propagation levels for chloride corrosion of reinforcements of an RC maritime or coastal structure, may be used to forecast, as a percentage, the damages throughout the period produced by chloride corrosion.

$$Dam_{steel}(t) = \frac{t - t_i}{t_p} \times 100 \tag{5}$$

Where the Dam_{steel} is the percentage of reinforcement damaged by chloride corrosion for each year (t) since the start of the propagation t_p.

The damage to the RC bridge's deck and columns were based on scenarios and marine exposure classifications, such as Aerial, Sub-merged, and Tide zone. Also, the percentage of chloride corrosion damage to the concrete of the RC structure was found, along with the results of changes in stiffness and loss of cross-section rebar area for damage identification.

3.2 Damage detection through non-destructive damage detection methods

A structure's integrity can be assessed using non-destructive damage detection methods. Preserving structures requires these methods. They can spot damage before it worsens. The power spectral density methods(PSD) are used in modal analysis, a non-destructive damage detection method. A structure's natural frequencies, vibration modes, and damping ratios are measured using modal analysis. PSD can detect modal parameter changes that indicate damage. The PSD of vibration signals determines the response's spectral content, which can mean damage if the modal parameters change. Due to its reliance on vibration and signals, the PSD was calculated using the frequency response function with the help of the following equations (Zheng et al., 2015; Pedram, Esfandiari & Khedmati, 2017; Hadizadeh-Bazaz, Navarro, & Yepes, 2023). The structural response PSD equation is simplified as follows:

$$S_{XX}(\omega) = H^*(\omega) S_{FF}(\omega) H^T(\omega) \tag{6}$$

Where S_{FF} is the PSD inputs matrix for every active degree of freedom (DOF) and $H^*(\omega)$ is the complex conjugate of a transfer function according to the following equation:

$$H(\omega) = (K - \omega^2 M + i\omega C)^{-1} \tag{7}$$

K, M, and C represent the matrices of stiffness, mass, and damping, respectively; denotes the frequency, and I equals -1 times the frequency. Model updating based on the sensitivity equation for the power spectral density equation can be expanded as follows by considering (K-$\omega^2 M$+$i\omega C$=$Z(\omega)$) in the below equation:

$$Z^*(\omega) S_{XX}(\omega) = S_{FF}(\omega) H^T(\omega) \tag{8}$$

Where in this equation, $Z(\omega)$ is the impedance matrix, and the transfer function inverse that this equation for corrosion damages caused for structure is as follows:

$$[Z^*(\omega) + \Delta Z^*(\omega)][S_{XX}(\omega) + \Delta S_{XX}] = S_{FF}(\omega)[H^T(\omega) + \Delta H^T(\omega)] \tag{9}$$

The power spectral density function equation is modified by taking into account ($\Delta Z(\omega)$=ΔK-$\omega^2 \Delta M$+$i\omega \Delta C$) and ($H_D(\omega)$=$[Z(\omega)+\Delta Z(\omega)]^{-1}$) was modified. Where $H_D(w)$ was the frequency response function of damaged structural elements in each year of structure life. There for, the up equation can be simplified as follow:

$$\Delta S_{XX}(\omega) = H_D^*(\omega) S_{FF}(\omega) \Delta H^T(\omega) - H_D^*(\omega) \Delta Z^*(\omega) S_{XX}(\omega) \tag{10}$$

H^*_D is the complex conjugate of the damaged structure elements transfer function during reinforcement chloride corrosion from conventional chloride corrosion deterioration proses in coastal structures. As the expression of the exact ΔH presented by Hadizadeh-Bazaz, Navarro, & Yepes (2022); Esfandiari et al. (2009) in the following equation:

$$H(\omega) = -H_D(\omega)(\Delta K - \omega^2 \Delta M + i\omega C) H^T(\omega) \tag{11}$$

Therefore PSD, according to the mentioned equations, can rewrite as follows:

$$\Delta S_{XX}(\omega) = -H_D^*(\omega)S_{FF}(\omega)H_D(\omega)(\Delta Z(\omega))H^T(\omega) - H_D^*(\omega)(\Delta Z^*(\omega))H^*(\omega)S_{FF}(\omega)H^T(\omega) \quad (12)$$

To determine the effects of corrosion on reinforcement bars and the system's structural behavior, each reinforced concrete element's stiffness and other dynamic properties in proportion to the corrosion damage computed for the rebars at each time. The stiffness, mass, and damping matrices modify due to dimensionless structural parameter changes:

$$\begin{cases} \Delta K = \sum_{n=1}^{ne} K_n \Delta P_n^K \\ \Delta M = \sum_{n=1}^{ne} M_n \Delta P_n^M \\ \Delta C = \sum_{n=1}^{ne} C_n \Delta P_n^C \end{cases} \quad (13)$$

The stage of stiffness, mass, and damping matrices of a structure's structural components are K_n, M_n, and C_n. where structural parameter variations are between -1 and 1.

The monitoring of changes in stiffness, mass, and damping of a structure owing to probable damage to a structure using the PSD damage detection technique has been estimated by considering ($\Delta Z(\omega)=\Delta K-\omega^2\Delta M+i\omega\Delta C$). The sensitivity matrices allocated to the n^{th} parameter of structure for getting the unknown stiffness, mass, and damping ratios are as follows, based on changes in dynamic characteristics caused by damage causes such as chloride corrosion damages.

$$\begin{cases} S^K = -H_D^*(\omega)S_{FF}(\omega)H_D(\omega)K_nH^T(\omega) - H_D^*(\omega)K_nH(w)S_{FF}(\omega)H^T(\omega) \\ S^M = \omega^2(H_D^*(\omega)S_{FF}(\omega)H_D(\omega)M_nH^T(\omega) + H_D^*(\omega)M_nH(w)S_{FF}(\omega)H^T(\omega) \\ S^C = i\omega(-H_D^*(\omega)S_{FF}(\omega)H_D(\omega)C_nH^T(\omega) + H_D^*(\omega)C_nH(w)S_{FF}(\omega)H^T(\omega) \end{cases} \quad (14)$$

The final equation of PSD for estimating changes in dynamic characteristics parameter during damage repetition for each year is given by the following equation:

$$\Delta S_{xx} = S^K\Delta p_K + S^M\Delta p_M + S^C\Delta p_C \quad (15)$$

Where Δp_K, Δp_M, and Δp_C use chloride corrosion deterioration of reinforcement equations and the power spectral density method to monitor the changes in stiffness and reinforcement loss cross-section areas in the RC marine bridge elements over time.

3.3 LCCA through the damage detection methods

One of the essential things to consider when evaluating a bridge's performance is its life-cycle cost. The LCCA for the bridge was calculated using the location and percentage of damages expected annually by damage-detecting methods. Each stage of a structure's life cycle and life cycle cost typically includes production, construction, usage and maintenance, and eventually, the end of the structure's existence. As a result, the following formulas may be used to estimate the bridge's projected cost during its life cycle (Hadizadeh-Bazaz, Navarro, & Yepes, 2023; Frangopol, Dong, Sabatino, 2017).

$$C_T = C_I + C_M + C_{INS} + C_R + C_{Dam} \tag{16}$$

Where the C_I represents the initiation cost, C_M represents the maintenance cost, C_{INS} represents the inspection cost, C_R represents the total repair cost, and C_{Dam} represents the anticipated damage cost in the calculation. The entire cost of the concrete bridge repair operation may be determined using the following items:

$$C_R(t_V) = C_{DNRC}(t_V) + C_{DRC}(t_V) + C_{SM}(t_V) + C_{PE}(t_V) + C_S(t_V) + C_C(t_V) \tag{17}$$

Where t_v is the interval time period studied; C_{DNRC}, is the cost of demolishing non-reinforced concrete parts like the structure's cover; C_{DRC}, is the cost of demolishing reinforced concrete parts like the bridge's structural parts; C_{SM}, is the cost of sorting and recycling demolition debris; C_{PE}, the cost of preparing equipment for repairing the bridge's concrete and rebars; and C_S, is the overall cost of buying and replacing damaged steel reinforcements, and also C_C is the total cost of the concrete parts include material and activities of the bridge damaged over the time. Corrosion and damages caused by the presence of chloride ions in coastal structures, as well as other factors, such as floods and earthquakes following a Poisson process, can all be factored into the total life-cycle damages in each structural part and element of a bridge within the time interval (Hadizadeh-Bazaz, Navarro, & Yepes, 2023; Frangopol, Dong, Sabatino, 2017; Dong, & Frangopol, 2016).

$$C_D(t_v) = \sum_K^{N(t_v)} D(t_k).\, e^{-rt_k} \tag{18}$$

N(tv) is the number and amount of damage factors on a structure during the interval. As anticipated by the PSD approach, annual damages due to chloride corrosion are denoted by *D*, where *D* is expressed as a percentage of the yearly damages at time t_v. The discount rate used here is represented by (r = 5%). According to the Poisson model, t_k follows the uniform interval distribution $[0,\ t_v]$ with a mean rate λ_f. The projected yearly proportion of bridge element damage owing to hazard effects may be stated as ($N(t_v) = \lambda_f \times t_v$). Therefore, the corrosion damages bridge element's value can be obtained from the following equation (Hadizadeh-Bazaz, Navarro, & Yepes, 2023; Frangopol, Dong, Sabatino, 2017; Yeo, 2005).

$$E[C_D(t_v)] = \frac{\lambda_f \,.\, E(D)}{r} \,.\, (1 - e^{-rt_k}) \tag{19}$$

At the last step of the LCCA process, the equation calculates the overall expenses of bridge repair and maintenance in proportion to the percentage of damage projected for the whole bridge by the following equation (Lee, Cho, & Cha, 2006):

$$E[C_T(\bar{x}.t_v)] = C_I + C_M + \sum_{t=1}^{t_v}\left[\frac{\left(\sum_{t=1}^{N(t_v)} E[C_{DNRC}(\bar{x}.t)] + \sum_{t=1}^{N(t_v)} E[C_{DRC}(\bar{x}.t)] + \sum_{t=1}^{N(t_v)} E[C_{SM}(\bar{x}.t)] + \sum_{t=1}^{N(t_v)} E[C_{PE}(\bar{x}.t)] + \sum_{t=1}^{N(t_v)} E[C_S(\bar{x}.t)] + \sum_{t=1}^{N(t_v)} E[C_C(\bar{x}.t)]\right)}{(1+r)^t}\right] + C_D \quad (20)$$

Where in this equation, $\sum_{t=1}^{N(t_v)} E[C_{DNRC}(\bar{x}.t)]$, $\sum_{t=1}^{N(t_v)} E[C_{DRC}(\bar{x}.t)]$, $\sum_{t=1}^{N(t_v)} E[C_{SM}(\bar{x}.t)]$, $\sum_{t=1}^{N(t_v)} E[C_{PE}(\bar{x}.t)]$, $\sum_{t=1}^{N(t_v)} E[C_S(\bar{x}.t)]$, and also $\sum_{t=1}^{N(t_v)} E[C_C(\bar{x}.t)]$ are respectively the total costs of demolishing the unreinforced concrete parts, the reinforced concrete parts demolition, management, separation, and categorization of debris resulting from destruction, installation, and subsequent removal formwork for repair concrete activity, repair and replacement damaged bar steel with corrugated bar steel with improved ductility characteristics and also prepare and pour concrete costs during and until end of coastal structure life. In this analysis, the LCC of the whole structure is determined and assessed based on the damage sustained by the structure each year, the quantity of corrosion of metal components during the structure's life, and the structure's service life.

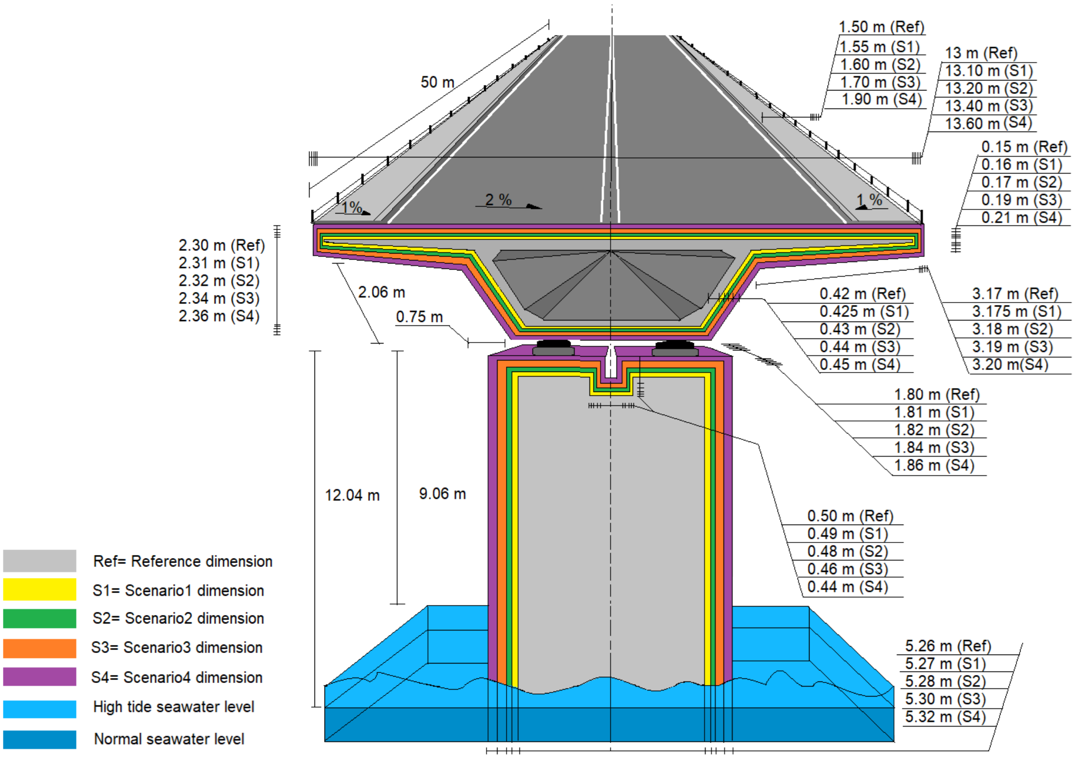
Overall the methodology of this study this investigation encompasses a comprehensive analysis and calculation methodology, which includes the following steps:

First, according to the Spanish Ministry of Public Works (2008), the service life and damages caused by chloride corrosion on the inner rebars of reinforced concrete structures in marine or coastal environments involved chloride corrosion predicted through a conventional technique. Then, according to the change in diameter and changes in dynamic properties such as stiffness and mass of reinforcement for every element for every year of the bridge life (100 years), the amount of corrosion damage depending on the situation of each element of the bridge structure to seawater calculated as Dam_{steel} in equation (5). In the second step, according to the rebars, damages for every bridge section through the PSD method as a non-destructive and dynamic damage detection method monitored damage percentage in every concrete bridge section of the deck and columns yearly. For this purpose, sensitive equations and considering different dynamics that characterize the structures every year after building the bridge were analyzed and calculated as equations (15). Finally, the total cost and LCC for maintenance and also whole repairs activities and materials (concrete, rebars) needed according to damages predicted *D(t)* in the first and second step for every element were obtained and then calculated by using equation (20), updating for every year and every element and section of the bridge by considering discount rate 5% calculated and then annalizes compared.

4. Model description

The Arosa Bridge is a coastal concrete bridge in Galicia, Spain. Its name comes from its location. This bridge measures a total of 1980 meters in length and consists of 40 spans (the first and end spans are 40 m, and the other 38 intermediate spans are 50 m). The geometry and durability characteristics of this design were derived from research that was published in the past (González, Aguilera, & García, 2013; Pérez-Fadón, 1985; and Pérez-Fadón, 1986). As seen in Figure 1, a single box girder supports the concrete bridge deck by 13 meters wide (including two 1.5-meter-wide walkways) and 2.30 meters high. The column is 5.26 m broad and 1.80 m thick. During high tide, the bridge deck is 9.6 m above the seawater.

Figure 1: The cross-section dimension of the coastal and concrete Arosa bridge

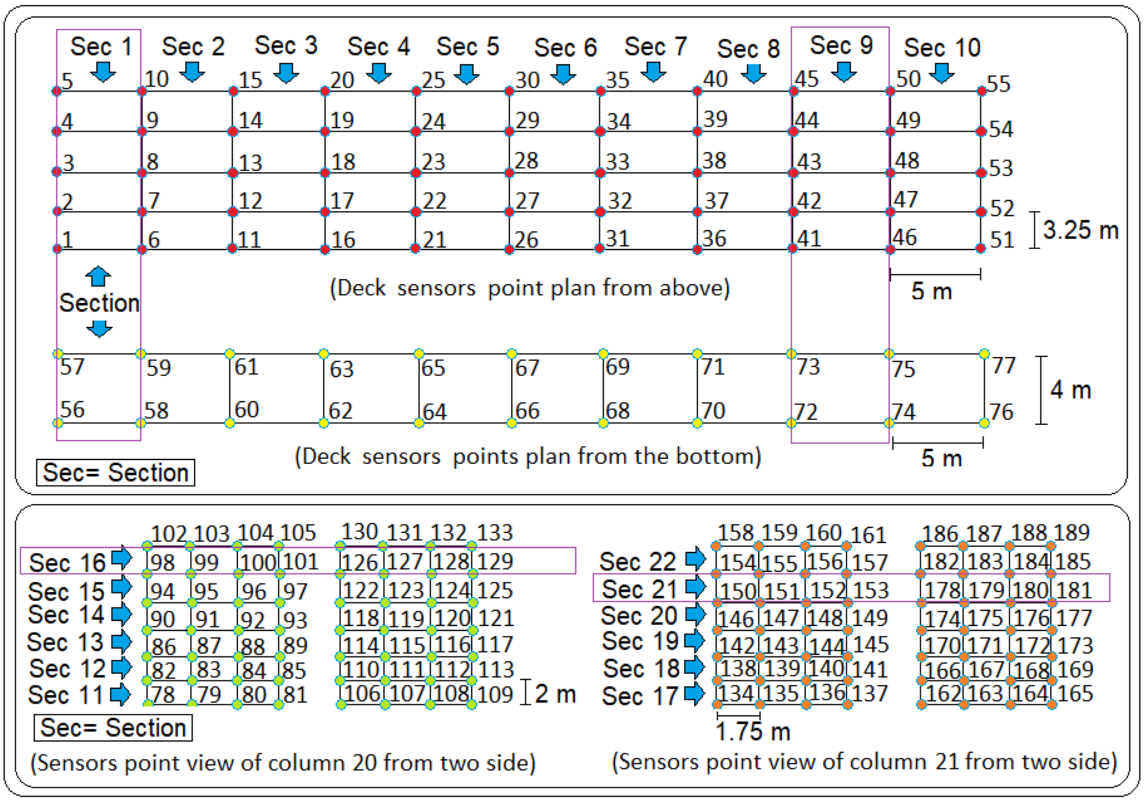


According to Figure 1, the dimensions and sizes for the actual and original dimensions of the bridge (reference dimensions), as well as the different design scenarios of different thicknesses of the bridge in the case of increasing the thickness of the concrete cover in the deck and columns of the bridge in order to the performance of a damage detection method in the thickness of the concrete cover scenarios for each thickness increase, including 0.5 cm, then 1 cm, then 2 cm, and finally 3 cm.

4.1 Analysis in the numerical model description

As computers and sensors become faster and more capable, the use of non-destructive, independent models based on numerical models of buildings to identify damage is tempting to engineers and academics. Using the PSD vibration and signal-based technique, chloride ions damaged a coastal concrete bridge numerical model. The bridge's numerical model evaluated specified places and sensors at certain distances for health monitoring each year from the start to the conclusion of the concrete bridge reinforcement's corrosion period. Figure 2 shows a span with a deck and two piers numbered 1 to 167. The bridge's deepest stretch is the most susceptible to chloride assault.

Figure 2: Sensor point numbering and division in each section of a span of the Arosa bridge



In Figure 2, sensor points numbered from 1 to 77 for the bridge deck are 5 m apart in length and 3 m apart in breadth. One pier numbered 78 to 189, is 1.75 m wide and 2 m high, with 1.80 m separating the pier width locations. Some points were determined as simulation points, and others were measuring points to track chloride attack damage at each bridge position. These simulation and measurement points were believed to be fixed for yearly test monitoring and analysis. In addition, depending on each scenario of concrete cover, the situation and distance were a little bit changed according to increasing concrete cover in different analyses for each scenario of the deck and column of the bridge. So, on the bridge deck span, simulation points 3, 18, 33, 48, 58, 59, 64, 65, 70, 71, 76, and 77 were chosen, and between piers, points 86, 89, 98, 101, 115, 116, 127, 128, 135, 136, 147, 148, 159, 160, 162, 165, 174, 177, 186, 189, and 189 were evaluated. These points were assessed for each year of the bridge's existence in the same position.

In general, numerical analysis of LCC using a non-destructive method to find damage in concrete and coastal bridge structures in order to repair and maintain damage caused by corrosion by chloride ions for different scenarios of cover thickness design has some stages. In the first stage, damage detection in reinforced concrete was analyzed using various methods, including the PSD and conventional methods. Following that, the operation and repair activities were considered to determine the repair and maintenance costs during the structure's lifetime for the damages to each area and part of the bridge that was greater than 20%. In the last stage, according to the determination repair time of each element and the percentage of base damage, the total costs for repairing the structure during the structure's life are calculated by 10% noise and error. These analyses and monitoring were done for every concrete cover scenario to compare the performance of increasing thickness of concrete cover in the same structure in performance to damage detection methods and LCCA through corrosion. Analyses were done via MATLAB, and Open Sees software to examine the PSD and conventional methods.

According to the Spain Ministry of Transport, Mobility and Urban Agenda cod and costs (2022), the repair activity cost (EUR) for the concrete and coastal Arosa bridge includes in Table 1.

Table 1: Total repair activity cost (EUR) for the service life of the coastal Arosa bridge.

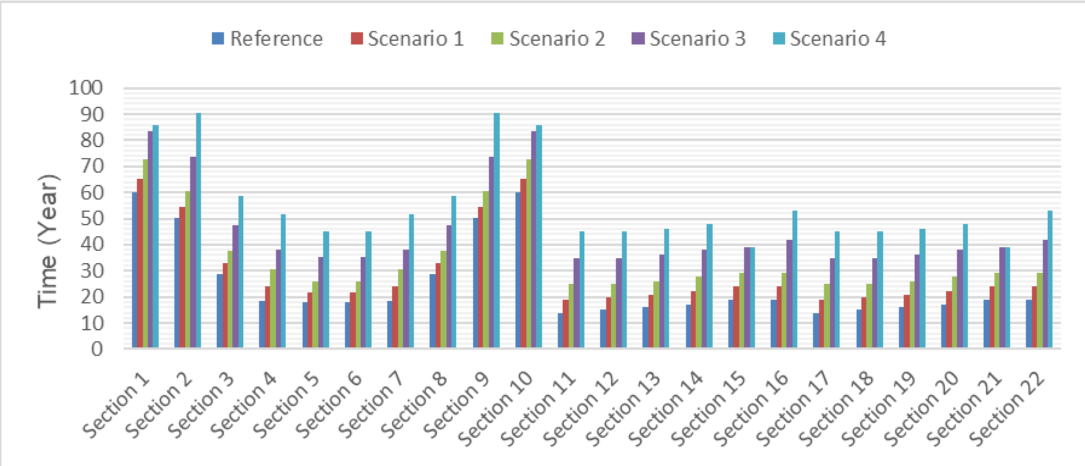
No	Maintenance and repair activities	Description / Includes	Price per unit (€)	Unit
1	Unreinforced concrete demolition	Debris removal, loading, and transfer to approved management within 60 km	30.20	m^3
2	Reinforced concrete demolition	Debris removal, loading, and transfer to approved management within 60 km	33.07	m3
3	Dismantling, sorting, and categorizing waste	Loading and transporting bricks, tiles, ceramics, or a combination of these non-hazardous building materials (excluding dirt and stones)	7.78	ton
4	Repair concrete formwork and remove them	Double-folded, wood cleaning, wetting, release agent, and complimentary materials for stability and proper execution	33.91	m^2
5	Replace and replace damaged bar steel with corrugated bar steel with enhanced ductility	Including cutting and bending, placement of overlaps, breakout, and binding annealed wire and separators	1.81	kg
6	Total new concrete activities	Prepare and pour concrete piles, stirrups, headboards, beams, deck boards, slabs, walls, and frames	147.01	m^3

The total costs of repairing this bridge using the materials and activities mentioned in Table 1 can be estimated using the number of breakdowns and damage incidents each year as the basis for the cost estimate. It was compared to both the PSD and the conventional approaches.

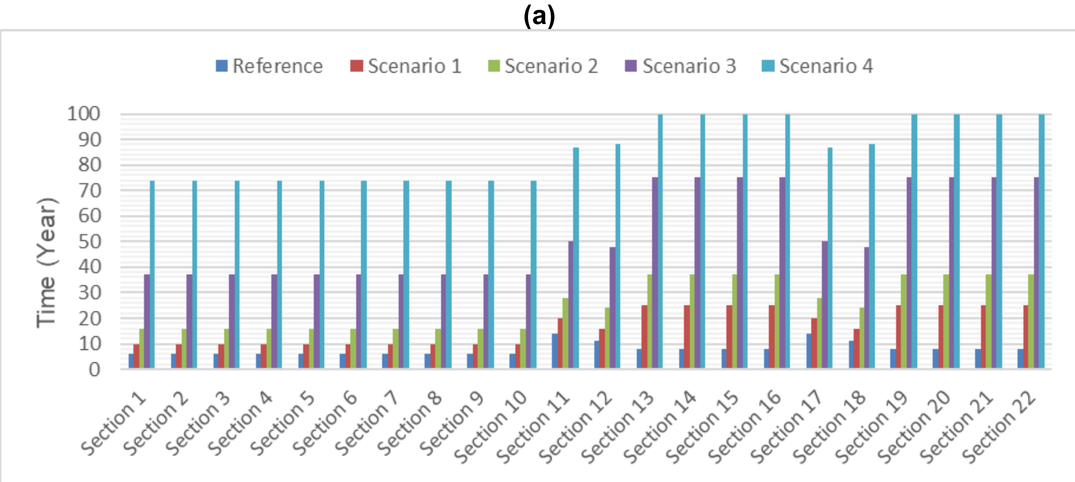
5. Results

The results of examining the PSD method with a different approach in detecting the location and extent of damage to a coastal reinforced concrete bridge exposed to corrosion and damage by chloride ions for each year of the life of this bridge for different design scenarios increased the thickness of the concrete cover of the structure was compared with the results of the conventional method in diagnosing service life and predicting damage caused by chloride for different scenarios. Figure 3 depicts the average time and period of repair and maintenance for each section of the bridge using two methods and for different scenarios, based on the bridge's life span of 100 years and 20% damage as a percentage of the base damage in each element and part of the bridge.

Figure 3: Compare service life and repair time in the bridge by (a) PSD method and (b) Conventional method



(a)

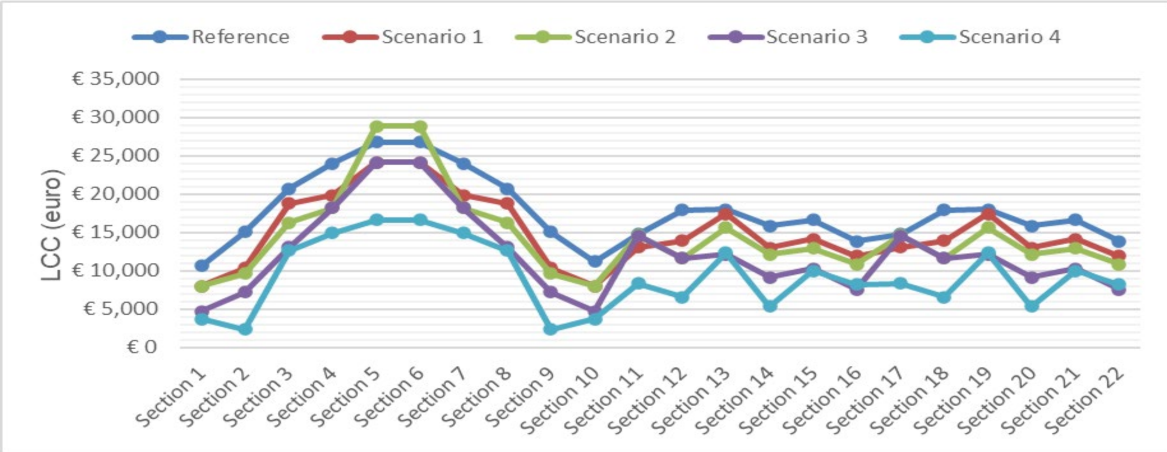


(b)

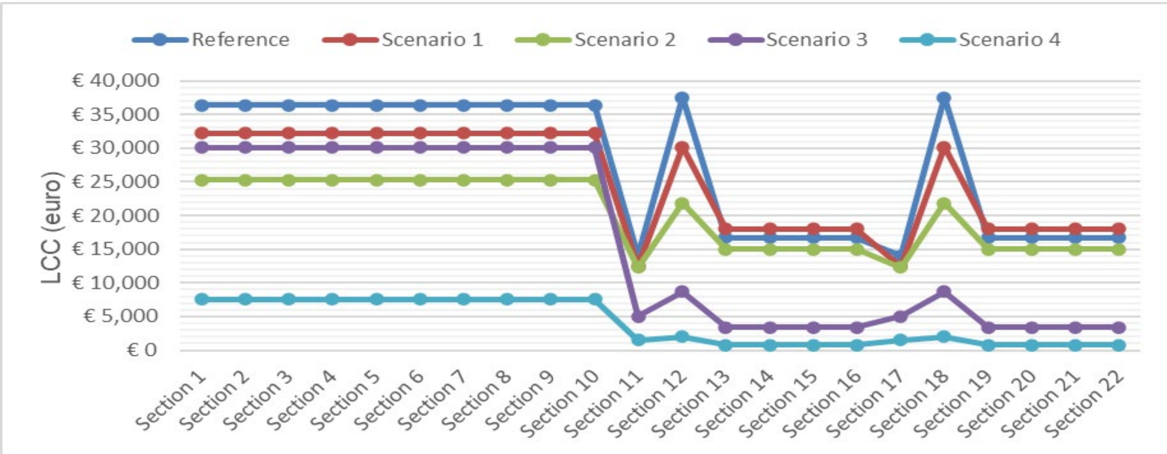
Figure 3 for different scenarios of concrete cover thickness includes reference dimensions 3 cm thick cover for the deck and 4 cm thick concrete cover for columns in a span of the bridge. As reference dimensions according to the different concrete cover of the bridge in scenarios 1 to 4, it increases respectively by 0.5, 1, 2, and 3 cm. The service life period for repairing the bridge in the bridge lifetime (100 years) by considering damage elements 20% and more than through to the PSD method for scenarios 1 to 4 for the deck sections are respectively average about 3, 12, 17 and 27 years for the period repair time. And, for the columns, this time for service life, the columns for scenarios 1 to 4 are respectively about 3, 10, 20, and 28 years. On the other hand, this analysis using the conventional method according to four different scenarios increases for the deck, for scenarios 1, 2, 3, and 4, about 2, 10, 30, and 70 years, respectively, and also, by this method, average service life period for the columns sections for scenarios 1 to 4, respectively 10, 20, 60 and 80 years.

The results of the final LCD according to the different scenarios in the design of the concrete cover thickness of the structure in order to repair the structure according to the method of detecting and predicting PSD damage in comparison with the conventional method for different sections of the deck and columns of a span of the bridge are shown in Figure 4.

Figure 4: Life cycle cost assessment in the bridge by (a) PSD method and (b) Conventional method



(a)



(b)

According to the results of Figure 4, it is shown that the difference in the total price for the repair and maintenance of a bridge span for the reference dimensions of the bridge using the PSD method is about 261445 euros, according to the discount rate of 5% during the life of the structure. Meanwhile, according to the different scenarios of the thickness of the concrete cover of the structure, for the first to third scenarios, the difference in the cost of using the PSD method compared to the conventional method is about 246,675 euros, 128,253 euros, and 90,902 euros for a bridge span. But, the fourth scenario shows that the conventional method has a lower cost difference of 112,570 euros.

6. Conclusions

In conclusion, the performance of the PSD method in the case of a change in the thickness of the concrete cover of the bridge and the performance and accuracy of this method in detecting the location and the amount of damage caused by corrosion in each year of the structure's life showed that the PSD method has a more suitable performance. It is better than the conventional method of detecting damage caused by corrosion. Also, the PSD method detected the amount and location of damage in each year of the structure's life in each part and element of the bridge separately. In contrast, the conventional method predicts damages in an integrated manner in the deck part, which shows its superiority. The PSD method effectively detects the damage's location in different bridge elements.

Moreover, the total LCC for total repair and maintenance activities costs can be saved by the PSD methods for damage detection by about 59.7%, 57.7%, 71.2%, and 74.45% through the reference and scenarios 1–3. On the other hand, through the concrete cover design dimensions of scenario number 4, the conventional method can save about 44.1% of the total cost of repair and maintenance activities.

Overall, this research showed that the PSD method could determine where and how badly chloride ions have damaged a reinforced concrete structure near the coast. It was also found that increasing the thickness of the concrete cover and the distance of the rebars from the surface and sensor points can negatively affect the performance of this method. To minimize the effects of concrete cover on PSD damage detection, choosing appropriate sensor locations and using high-sensitivity sensors to detect signal changes is vital. In addition, using advanced signal processing techniques, such as wavelet analysis or Fourier transform, can help extract damage-related features from the signals even in the presence of a thick concrete cover.

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