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An innovative approach for corrosion control to enable asset management of steel elements in coastal infrastructure

Un enfoque innovador de control de la corrosión para habilitar la gestión de activos de los elementos de acero en infraestructura costera

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Felipe Repetto[1,2], Gustavo Boré[1,3], Martín Eliceiry[1], Samuel Sabaini[1] and Matías Covarrubias[1]

[1] BMEC Ingeniería, Edmundo Eluchans 2525, Viña del Mar, Chile, felipe.repetto@naucrat.es, gustavo.bore@bmec.cl, martin.eliceiry@naucrat.es, samuel.sabaini@naucrat.es, matias.covarrubias@naucrat.es

[2] Department of Management, Economics and Industrial Engineering, Politecnico di Milano, via Lambruschini 4/b, Milan, Italia, felipejavier.repetto@polimi.it

[3] Departamento de Ingeniería Mecánica, Universidad Técnica Federico Santa María, Avenida España 1680, Casilla 110-V, Valparaíso, Chile, gustavo.bore@usm.cl

Corrosion is an important issue of coastal infrastructure design, operation and maintenance. In this paper, the current approaches for its control in steel bridge and sheet piles are identified and characterised. The barriers identified for these approaches are: occupational health and safety, manual-artisanal solutions in place, and uncertainty of maintenance results. Being asset management the main driver for an innovative approach, the following characteristic are identified to advance in corrosion control approaches: automation, remotely controlled operations, certification process and data collection. Finally, the need for new approaches is identified where the interest for infrastructure requalification as part of an Asset Management Plan can simultaneously deliver economic and social outcomes.

Keywords: corrosion control, coastal infrastructure, steelpile, sheet pile, asset management, protective coating, tape wrapping, jacketing

La corrosión es un tema importante del diseño, operación y mantenimiento de la infraestructura costera. En este artículo, se identifican y caracterizan los enfoques actuales para su control en pilotes y tablestacas de acero. Las barreras identificadas para estos enfoques son: salud ocupacional y seguridad en el trabajo, soluciones manuales artesanales e incertidumbre en los resultados de mantenimiento. Siendo la gestión de activos el principal impulsor de un enfoque innovador, se identifican las siguientes características para avanzar en los enfoques de control de la corrosión: automatización, operaciones controladas de forma remota, capacidad de certificación de procesos, y recopilación de datos. Finalmente, se identifica la necesidad de nuevos enfoques de interés para la renovación o extensión de la vida útil de la infraestructura que, como parte de un plan de gestión de activos, puede generar simultáneamente beneficios económicos y sociales.

Palabras clave: control de la corrosión, infraestructura costera, pilote de acero, tablestaca, gestión de activos, recubrimiento, encintado, encamisado

Introduction

The importance of controlling corrosion of infrastructure relies mainly in the loss of metal thickness it produces, which reduces the structural capacity and puts at risk workers, the environment and operations and hence, potentially compromising socio-economic sustainability. Therefore, corrosion needs to be approached as an inevitable issue for steel and reinforced concrete infrastructure (Valdez *et al*., 2016).

When infrastructure is placed in a coastal area, particularly under and above the water, it is exposed not only to a marine and corrosive environment, but also to the action of the wave climate. The permanent wetting produced by the natural sway of the sea level due to tides and waves, makes the area between the minimum and maximum sea water level to be exposed to very high levels of corrosion. Therefore, corrosion rates in the low waters, tidal and splash zones are higher than those in the continuously submerged zone (Jeffrey and Melchers, 2009). Accelerated low water corrosion (ALWC) typical rates can be of 0.5 mm/side/year and even rates of more than 1 mm/side/year have been recorded in steel piles (Kumar and Stephenson, 2005; Valdez *et al*., 2016).

Corrosion is a primary reason for steel piles failure (Maharaj, 1998) together with structure overloading and extreme events. Corrosion is commonly accounted for in the design and construction stages. Five control mechanisms can be adopted during design and construction to minimize corrosion, namely design, material selection, protective coating, cathodic protection and chemical treatment (Ameh and Ikpeseni, 2018). For instance, it can be considered by allowing a thickness reduction for the design lifetime of the structure. To do so, a rate of corrosion needs to be defined. Corrosion rates that structural engineers generally can count on are rather generic (Jeffrey and Melchers, 2009) which may not be representative to the specific site conditions. The corrosion rate depends on the seawater local conditions, the presence of contaminants and oxygen, and the type of soil. Furthermore, it can be slowed down by applying protective coating and by installing a cathodic protection (Jeffrey and Melchers, 2009). However, cathodic protection does not work above the water (Chernov and Buslov, 2004). From a structural point of view, the design can also be adapted so that the zone with higher corrosion rate is not the one where the maximum bending moment takes place (Sexton *et al*., 2017). Nevertheless, changes of design specifications for constructability reasons may still reduce the effectiveness of structures in terms of their corrosion, i.e. structural connections.

Corrosion happens to be a problem that for almost all coastal infrastructure, sooner or later, must be approached to prevent structural failure (Kitane *et al*., 2008) and to extend the lifetime of structures. So, first, it is of high importance that corrosion is faced when maintenance is required and planned. Second, corrosion needs to be approached taking into consideration and being compliant with existing national and international standards as infrastructure lifetime is usually extended above the initial design assumptions. Finally, if proper management of physical assets is to be conducted, thickness reduction and corrosion rate become the key indicators to estimate the loss of structural capacity and hence, the risk level that increases the probability of failure and unavailability.

The aim of this paper is to study the existing approaches of corrosion control for coastal infrastructure, particularly steel piles, to identify the main barriers. Consequently, drivers for an innovative approach are identified to conclude listing the key characteristics of a new approach.

Existing approaches for corrosion control in coastal infrastructure

Corrosion in the seawater environment has two phases: aerobic corrosion when oxidation controls, and anaerobic corrosion under microbial conditions (Melchers, 2006). Cathodic protection is a well-known best-practice strategy to avoid corrosion and it is widely used in coastal and marine environments. Therefore, it is not further included. For the aim of this paper, steel structural elements are studied as these correspond to the enabling elements over which the key port operations take place. The main steel elements are bridge piles and sheet piles.

Bridge piles

When it comes to controlling corrosion in bridge piles the following approaches are identified: tape wrapping; protective coatings, and pile jacketing (Table 1). Figure 1 shows regular bridge piles under corrosion control and maintenance.

Figure 1: Bridge piles under corrosion control and maintenance.

Tape wrapping consists of the application of a tape around the perimeter of a bridge pile covering the area of interest, avoiding oxygen to contact the pile.

Protective coatings consist of the application of different coatings, single or multilayer to protect a specific area of the surface of the bridge pile.

Table 1: Corrosion control approaches for bridge piles in marine environments

Approach	Advantage	Disadvantage
Tape wrapping (petrolatum or wax)	Can be applied to tubular and H-section piles (Green *et al.*, 2012). Seals out air and moisture to stop corrosion (Husain *et al.*, 2004). Possibility of warranty issue under specific installation conditions (Aziz *et al.*, 2011).	Does not provide structural integrity. Difficulty of steel thickness and corrosion inspection. Needs installation by humans under dangerous conditions.
Protective coatings	Diverse coatings available, e.g. coal tar enamel, fusion bonded epoxy, two-layer coating that usually consist of fusion bonded epoxy bonded to polypropylene and three-layer coating which consist of fusion bonded epoxy (Ameh and Ikpeseni, 2018). Compatible with cathodic protection (James and Hattingh, 2015).	Requires previous strict pre-treatment and sealing of the metallic surface from the corrosive environment, and time for coatings to dry after application (Zhongdao *et al.*, 1989). Inadequate and difficult operational or maintenance conditions (Husain *et al.*, 2004; Melchers, 2006).
Pile jacketing	Installation time can be more than 50% less compared to petrolatum or wax tape wrapping (Husain *et al.*, 2004).	Inadequate jacket installation and concrete grout cracking by installation or by seismic activity may allow steel to corrode. Difficulty of steel thickness and corrosion inspection. Requires installation by humans and crane under dangerous conditions.

Pile jacketing consists of the installation of a jacket around the bridge pile, available in different materials. After being sealed, the space in between is filled which again can be done with different materials for instance, concrete grout.

Sheet piles

The approaches to control corrosion of sheet piles include: protective coating; protective steel patches; extension of concrete cap pile across the exposed steel zone below the mean low water level or MLW level (Chernov and Buslov, 2004). Also, these approaches can be adopted in combination, for instance, with epoxy resins.

Protective coatings consist of the application of different coatings, single or multilayer to protect a specific area of the surface of the bridge pile. For sheet piles, in some cases these are applied with the help of a caisson to create a dry environment.

Protective steel patches consist of welded pieces of steel that replace and reinforce the area of interest.

Extension of concrete cap pile consist of covering the area of steel exposed to continuous wetting by extending the concrete cap pile of the quay apron.

As reported by Chernov and Buslov (2004), these approaches present the advantages and disadvantages as summarized in Table 2.

Table 2: Corrosion control approaches for sheet piles in marine environments

Approach	Advantage	Disadvantage
Protective coatings	May be efficient within a certain range of conditions. Compatible with cathodic protection (James and Hattingh, 2015).	Coatings have limited durability above the water (Chernov and Buslov, 2004) Requires proper cleaning preparation of the steel surface (achievable by isolating the area from seawater with the help of a caisson).
Protective welded steel patches	Provides structural integrity.	Mostly a temporary solution (Chernov and Buslov, 2004) to be complemented with another one.
Extension of concrete cap pile across the exposed steel zone	Durable and reliable alternative for sheet piles	Relatively expensive. If done using precast front panels as formwork corrosion of reinforcement of the precast panel and the addition of the front panel generates a bulge in the bulkhead line which may require re-fendering

Barriers of the existing approaches

The descriptions provided in Tables 1 and 2 give evidences that there are several approaches for corrosion control in bridge piles and sheet piles. Each approach has their advantages and drawbacks. The following barriers of the existing approaches can be identified:

• Occupational health and safety: all approaches entail dangerous work conditions for personnel in the field.

• Manual-artisanal solutions: all approaches require workers and/or divers to apply the selected solution. This may cause, for instance, to stop operations around the area under maintenance and hence, many times, without being able to control and register the conditions of application and results.

• Uncertainty of maintenance: for approaches that cover the steel pile, *e.g.* pile jacketing and tape wrapping, it is difficult to verify if the maintenance is producing the expected results. These approaches may even hide the corrosion beneath them, without showing evidence of the pile status until a failure occurs.

Drivers for an innovative approach

The main driver to an innovative approach that overcomes the aforementioned barriers is to have the possibility to do proper asset management. This is, to be able to establish, implement, maintain and improve an asset management system, for example, according to the ISO 55000 (International Standard covering management of assets of any kind). Rephrasing the barriers mentioned above, an innovative approach to control corrosion in steel coastal infrastructure should ensure safer conditions for workers involved in the maintenance, be standardised meaning the results of its implementation being verifiable and compared to a standard, and finally, it should grant its efficacy, a process that, again, should be verifiable to give adequate time to react to avoid a structural failure.

Characteristics of an innovative approach

A set of key characteristics identified for an innovative approach for corrosion control is proposed to overcome the barriers:

• Automatized: the automation of part or all corrosion control maintenance processes to significantly reduce the occupational health and safety risks. An automated process should consider the control over several parameters such as material thickness, position, distance, pressure, motion, humidity, temperature, flow and others, while delivering appropriate data to ensure an adequate quality control of the process.

• Remotely controlled: the ability to prepare and/or interfere the processes from local-remote to control and monitoring of the maintenance. An innovative approach should consider human-machine-interfaces near the machine to properly operate the process without intervening directly with the machine. Accordingly, appropriate sensors and actuators suited for environment should be used to perform correctly, emulating on-shop-style procedures.

• Certifiable process: to be able to measure and control the corrosion maintenance outcomes after its application and on a regular basis to minimise and plan the interventions of assets. By doing so, it avoids the need to be certified by a qualified surveyor, exposing the person to high risk working conditions which make very difficult to do proper measurements and reliable inspections. The instruments on board an automated approach can lead to accurate data and with it, to an adequate certified process.

• Data collection: the capability of the process to collect appropriate data to feed an asset management program according to actual status of the structure. The automated process should register the pile steel thickness, application parameters and date of maintenance, to properly program the next maintenance operation, recalculate the corrosion rate of the site and compare the actual corrosion rate with the design corrosion rate.

These characteristics enable defining and implementing a proper asset management plan to deliver not only economical, but also better environmental and social outcomes. The infrastructure can be monitored and hence, supporting relevant processes of decision making.

Conclusions

The effects of infrastructure corrosion must be managed from several perspectives including design and construction, operations and maintenance. The current approaches propose wrapping or patching infrastructure, the manual application of one or more coatings under water (or inside a caisson for sheetpiles), and the cover of infrastructure with new materials. The design and construction phases are where the most relevant measures are currently considered. However, from an operational and maintenance point of view, the current approaches do not deliver long-lasting results, compromising the functionality of structural components which may reduce their performance and put the infrastructure at high risk, and create production time losses for terminals.

From a safety point of view, the current approaches can be bettered to reduce the risk not only of personnel but also of equipment. The current study highlights:

- The relevance of measuring and controlling corrosion in coastal infrastructure to ensure adequate asset management.
- The opportunity to produce specific and updated corrosion maps of corrosion rates to be used on future designs and constructions based on the data obtained during the maintenance service.
- That corrosion maintenance projects should be coordinated with other shut downs that restrict operations to minimise the loss of availability.
- That if severe corrosion is already present, a remediation strategy must be put in place, ideally as part of the Asset Management Plan

The characteristics of an innovative approach are proposed in order to foster further research and studies to better understand corrosion control practices, as well as to promote the realization of pilot projects that develop new corrosion control techniques over coastal infrastructure. New techniques are identified to be of great interest for infrastructure requalification that simultaneously delivers economic and social outcomes.

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