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Monitoring of the Corrosion on a Steel Sheet-pile Marine Breakwater by Systematic Thickness Measurements

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Abstract: In Quepos, Pacific of Costa Rica, it was finished on 2010 the first phase of a marina, including two mix breakwaters, with rubble mound (rocks and concrete units), and 25 circular steel sheet piles cofferdam cells, filled with sand and gravel. The maintenance plan, considers tracking sheet pile corrosion, comparing 'actual' against expected rates, checking structural limits, and programming countermeasures if accelerated corrosion is identified. Specific control sections, along the breakwaters, both inside and outside the basin, were established. In each section, thicknesses were measured every meter from the top of the steel cell to seabed using an ultrasonic equipment, and an underwater transducer. Both land crew, and divers for submerged portions, were used. The measurements campaigns are for several years from 2011 to 2016. Sectors of the breakwater with varied corrosion attack levels could be differentiated. Also, corrosion rates and lifespans were estimated, both general for the structures, and specific for each section and level. In turn, this allowed to identify maintenance priorities, defining sites where measures of corrosion protection should initiate, as well, to have confidence in the structural capacity and safety of the breakwaters.

Key words: Monitoring of structures, maritime works, sheet piling, corrosion, ultrasonic thickness measurements.

1. Introduction

1.1 Objective

The maintenance monitoring follows the corrosion experienced by cellular steel cofferdam breakwaters of a marina, tracking the corrosion experienced by the cells, and comparing the 'actual' against the expected corrosion rates, checking that the structural limits for thickness are not exceeded, and programming countermeasures in case that are identified potential areas of accelerated corrosion.

1.2 Descriptions

The marina breakwaters defining the basin (inside), are mixed, with combinations of rubble mound slope breakwaters (rocks and precast concrete units), and steel plain sheet pile cells in circular arrangements, known as cellular cofferdams (Figs. 1 and 2).

Some of the cells were covered with rubble mound (concrete dolos and rock), or have 1-3 m high concrete parapets on top, to complete the required height for swell. The locations of these breakwaters are:

- 737 m breakwater at north (North Breakwater) with a 353 m rubble mound section, and 16 circular cells of 18.6 m in diameter.
- 219 m at south-east (South Breakwater) with a 60 m rubble mound section, and 9 circular cells, 1 of 18.6 m in diameter and 8 of 12.2 m.

The sheet piles are Arcelor AS-500 type, 500 mm width. The thicknesses vary per the diameter of the cells, being 11.0 mm in the cells of 12.2 m, and 12.7 mm in the 18.6 m cells.

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Fig. 1 Aerial view from 2010 of the Marina in Quepos.

The steel of these sheet piles is ASTM A690, which is ‘marine’ steel, with a yield strength of 345 MPa. It is recognized in the literature that, this type of steel has a corrosion resistance of 2-3 times more than normal steel on the splash zone (wave and tidal exchange), but not in the submerged part where normal and marine steel have similar corrosion rates.

The sheet piles were not protected by barrier i.e. with no paint or coatings prior to their installation, nor with concrete or other material once installed. Also, no anodes were placed for cathodic protection of the submerged part. As result, of these design decisions, corrosion is expected to occur without restrictions.

The designer, considered for the tidal and splash zone, as well for the submerged part, an over-thickness that could corrode during the lifespan of the structure, without affecting the capacity of the cells. This leads to the need to follow up the corrosion of the sheet piles, verifying if the thicknesses are within secure limits.

2. Method Statement

2.1 Measurement Sections definitions

Several control sections were chosen around the breakwater cells, a one section per cell or arch inside and two sections per cell or arch outside, to be controlled annually.

These was done in this way to have a general distribution of measurements around the breakwaters, and to consider different exposition conditions, for the cells inside and outside the basin.

Also, other few measurements were performed behind rock revetments, provisionally withdrawing rubble mound, and in diaphragm sheet piles- or cell elements within the fill-, by previously excavating the gravel and sand. This was made to understand the behavior of these sections compared to exposed cells.

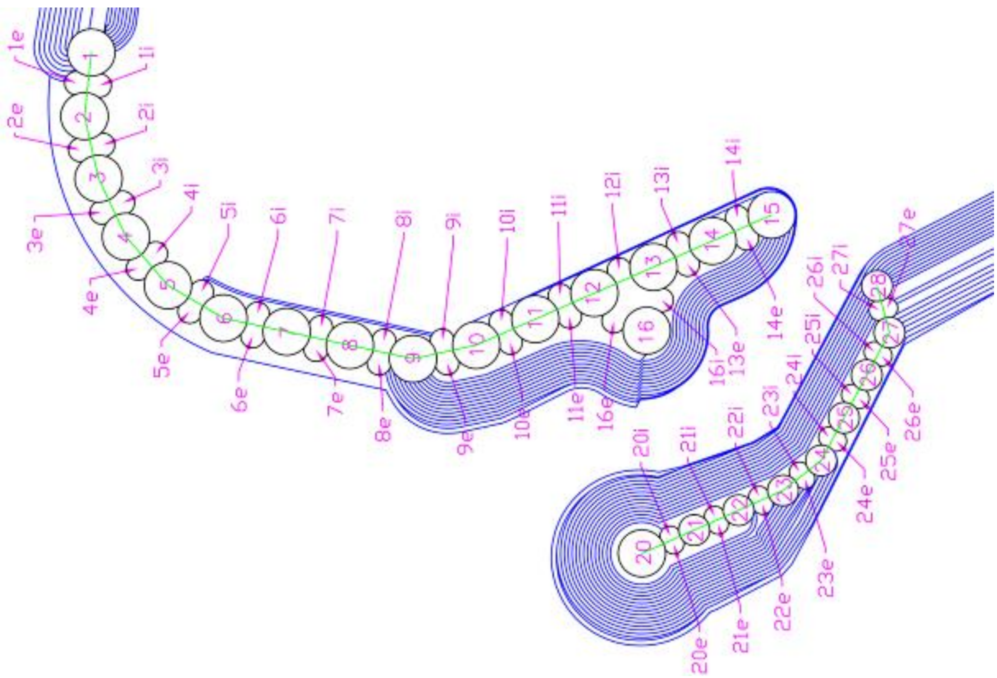


Fig. 2 Arrangements and numbering for the cells and arcs.

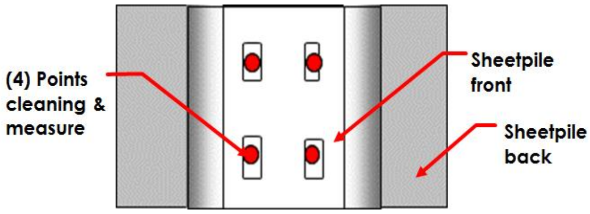


Fig. 3 Measurement scheme of points at each elevation.

A nomenclature was adopted to define every measurement elevation, including the cell number, the specific sheet-pile (numbered from the joint), and measuring the height from the top of the cell. At each elevation 4 points were measured as shown on Fig. 3, so that minimum and average values could be considered for statistical purposes.

Defining the measurements in such way, allows re-staking the section and points in a simple way, tp repeat them during annual campaigns.

When the measurements were above the water, access to the measuring points was done with stairs and platforms. Meanwhile, measurements below the water were made with the help of divers.

2.2 Cleaning of measurement points

An air needle powered by a compressor, was used to clean the sheetpile surface from marine life and corrosion, at each measurement point. The cleaning was done in a circle no more than 10 cm in diameter.

Fig. 4 shows this activity for underwater measurement points. This cleaning was executed also above water, in a similar way (i.e. with the same equipment).

2.3 Measurements

The thickness measurements themselves, were made with an ultrasonic equipment (UT), nominal frequency 5 MHz, and a straight ½ in. diameter underwater transducer transducer, with a 15 m in cable, so that the measuring device was at the upper part of the cell all time.

Fig. 5 shows a measurement with the underwater equipment. For comparison reasons and easiness, the same underwater transducer was used for the above water measurements.

2.4 Measurement Campaigns

The last measurement campaign, finished on April 2016, when the sheet piles had from 7-8 years of being constructed. Other measurement campaigns were executed before, as indicated:

- June to August of 2011.
- September of 2011.
- January of 2012, measurements of arches and internal and external cells.
- March 2012, measurements on a section outside the breakwaters, behind the rubblemound.
- June 2012 thicknesses measurements in the diaphragm wall, or inside the fill of the cells.
- February 2013.
- January 2015.

Fig. 4 Underwater cleaning of measurement points.

Fig. 5 Underwater thicknesses measurement UT sensor.

3. Results

3.1 Minimum structural thicknesses

To calculate the minimum admissible thicknesses design loads are used to estimate the sheet pile hoop tensions, using the procedure from the Corp of Engineers and Pile Buck Manuals [2] [3]:

$$F_{t,Rd} = min\left(\frac{0,8 \cdot R_{k,s}}{S.F.}, \frac{t_w \cdot f_y}{S.F.}\right)$$

$$F_{t,Ed} = p_{m,Ed} \cdot r_m$$

$$F_{t,Ed} \leq F_{t,Rd}$$

where,

- $P_{t,Rd}$ *is the admissible tension*
- r_m *is the cell radius*
- t_w *is the sheet-pile thickness*
- f_y *is the sheet-pile material yield stress*
- $p_{m,Ed}$ *is the maximum tension, which can be calculated with several formulas*
- $P_{t,Ed}$ *the maximum cell tension force /length*
- $R_{k,s}$ *interlock tension force*
- ***S.F.*** *is a safety factor*

For simplicity, the pressure in the splash zone was considered half of the pressure in the immersed zone, the last calculated per the analytical formulation.

The critical could varies from cell to cell and could be either above or underwater. Corrosion levels are higher at tidal zone, but tension forces diminish. Below water, the highest tension of the sheet-pile occurs around the seabed level or just above, but corrosion is lower.

On other side, joint interlock tension loss due to corrosion is difficult to measure, so an alternative approach was considered.

It was assumed a relationship between the measured thickness and the maximum tension that theoretically can support the connection. This is based on ARCELOR design manual as per reference [4].

Then, it is extrapolated the thickness of the sheet pile corresponding to the tension calculated for the joint. The safety factor used on the formulas was 1.5.

On Chart 1, are summarized minimum thicknesses in the inner and outer exposed cells of main and connecting arches, as for the connecting joints.

In addition to of a circular steel cell filling, other interactions, such as the presence of concrete parapets, or the effect of external waves, may be neglected, since they do not affect the internal pressure of the cell and hoop tension of the sheet piles.

It is observed that the thicknesses for having failure, are in fact low, compared with the theoretical thicknesses of the piles, which are 3-4 times higher.

Thicknesses are greater for the joints compared to other sheet-piles. On the 18.6 m cells sheet-piles above water require higher thicknesses compared to those below water, and the opposite for the 12.2 m cells.

3.2 Thicknesses Measurements

The measurements from 2016, for the inside of the north breakwater, could be seen graphically in Fig. 6. On this graph, one section is considered per cell, so in cases with 2 sections measured per cell, conservatively

Table 1 Minimum thickness (mm) to comply with the cell design hoop tension and a 1.5 safety factor.

Location			12.2 m cell	18.6 m cell
OUTSIDE	Above water	Sheetpile	1.8	1.4
		Joint	2.5	1.9
	Below water	Sheetpile	1.4	2.4
		Joint	2.2	3.4
INSIDE	Above water	Sheetpile	1.3	1.6
		Joint	2.0	1.9
	Below water	Sheetpile	1.2	2.5
		Joint	1.9	3.5

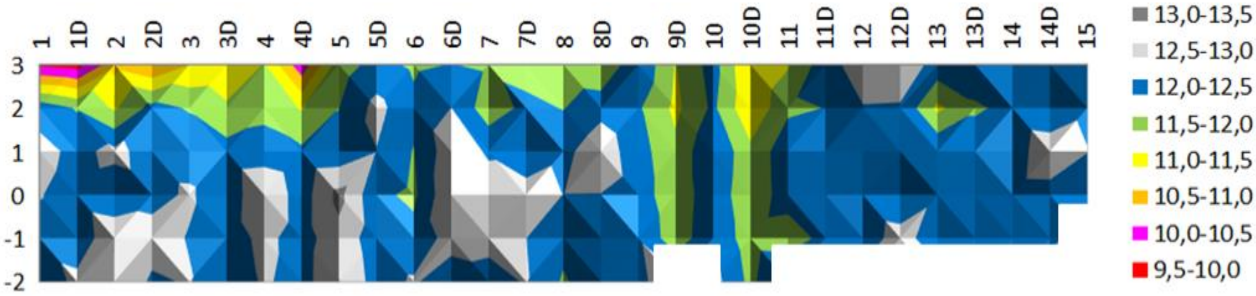
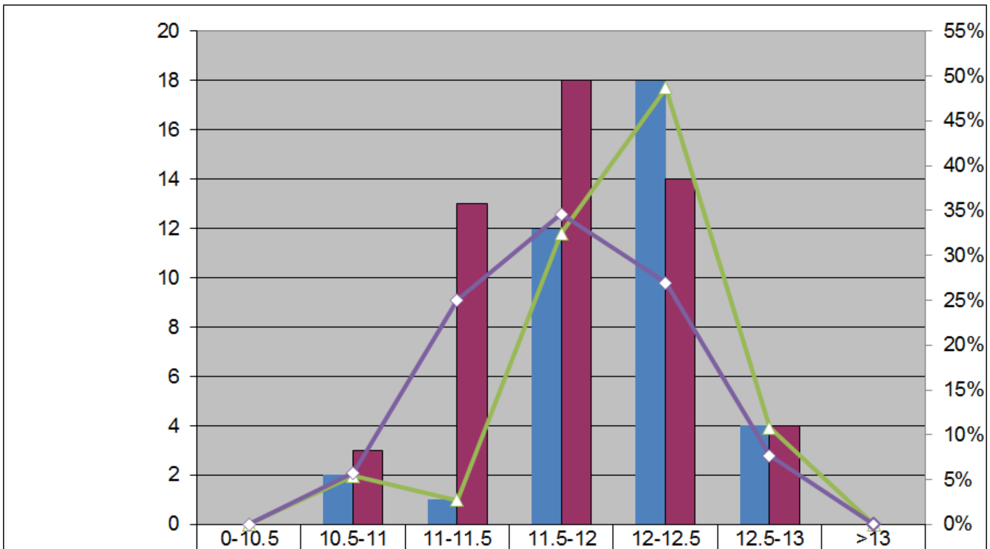


Fig. 6 Thicknesses(mm) at different elevations (from LLWL) and sections (one per cell) north breakwater inside.



	0-10.5	10.5-11	11-11.5	11.5-12	12-12.5	12.5-13	>13
Below water	0	2	1	12	18	4	0
Above water	0	3	13	18	14	4	0
% Below water	0.00%	5.41%	2.70%	32.43%	48.65%	10.81%	0.00%
% Above water	0.00%	5.77%	25.00%	34.62%	26.92%	7.69%	0.00%

Fig. 7 Thicknesses measurements distribution for the north breakwater outside.

the one with lower thicknesses is included. Levels are in meters from the Lowest Water Level Spring (LLWS) so that effects of tides are recognized.

From this graphs, specific cells with lower thicknesses i.e. higher corrosion could be identified. For example, above +1 m LLWS inside cells 1-5 and above +1 LLWS outside cells 1-8 with more corrosion on cell 6 around 0 LLWS.

On the other hand, statistically, the distribution of quantity of measurements for given ranges are also considered, as shown in Fig. 7. In this case, applies for the outside part of the breakwater.

Inside the north breakwater, 49% of measurements above LLWS and 60% below LLWS are between 12,0-12,5 mm, and the minimum measured thickness was 9,8 mm.

Meanwhile, outside the north breakwater, 35% of measurements above LLWS are from 11,5-12 mm, and 49% below LLWS are from 12-12,5 mm, with a minimum measured thickness of 10,6 mm.

From previous and as expected, corrosion attack is higher above LLWS, and lower below it.

3.3 Thicknesses versus time

The measurements of the four campaigns carried out, were plotted against the years between measurement and sheetpiles construction. This comparison considers the generalized behavior of sheet piles over time.

Fig. 8 shows the case corresponding to the inside part of the North Breakwater. Similar cases were addressed for the other conditions North-South, inside-outside.

Fig. 8 Set of all thicknesses measurements inside the north breakwater vs construction time.

Because the construction of the breakwater cells, was done over a period of several months, the figure ends up having a distribution of points that allows to validate the observations and the calculations made in this manner.

As expected, it is concluded that the general behavior no matter the condition (North-South, inside-outside) is loss of thickness (or corrosion).

In general, in the North and South Breakwaters, the lower thicknesses are in the sheet piles above +0 m of the lowest spring tide (LWWS). The trend seems to be that higher up on the sheetpile corrosion is greater.

In the North Breakwater, the losses outside and inside the basin are in the same magnitude order. In the South Breakwater, this cannot be concluded because there is only one section in the inner part due to the rubblemound laying in almost all internal cells.

Inside the basin, there is more corrosion of the curved part in the North Breakwater, compared to the rest of the sheet piling. On the other hand, outside, the greater corrosion is on the most exposed cells to waves. Outside the South Breakwater, and depending on height, corrosion is concentrated on central cells.

3.4 Thicknesses differences

Additional to the general comparison, also were calculated the differences from 2012 to 2016 between data of the same measurement points.

For the same section the average differences are from 0,46 to 1,10 mm and maximum from 1,22 to 2,61 mm. Those differences are summarized in Fig. 9.

As shown, few measurements were higher on 2016 compared with the ones from 2012. That may be due to differences in equipment or cleaning, and because, by procedure, the measurement is directly on site (no coupons), which never happens in the same exact spot.

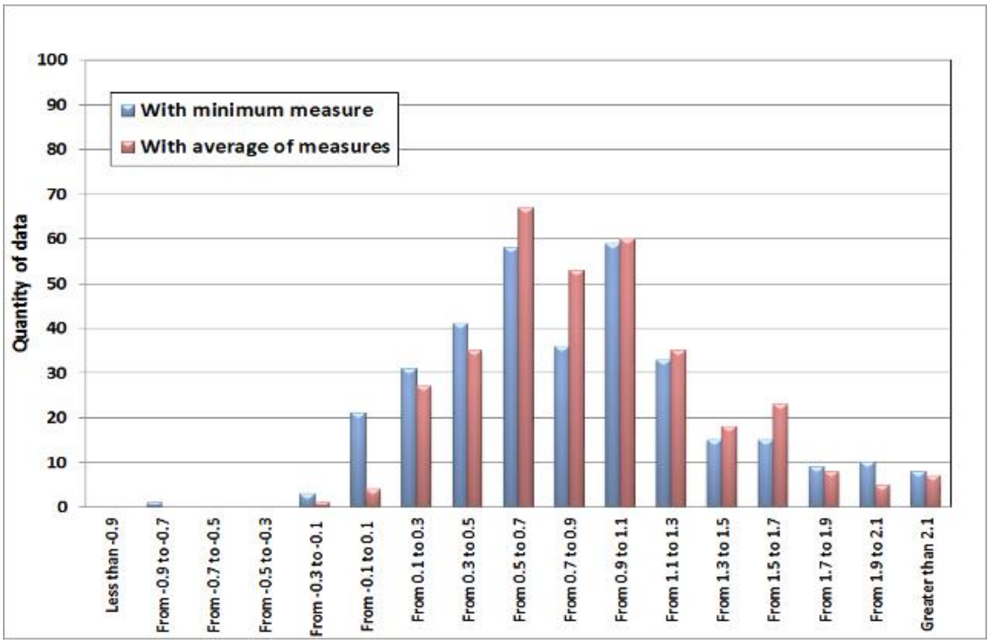


Fig. 9 Thicknesses differences for all the measurements.

This is, in each measurement, a section of about 10 cm diameter is cleaned for each point, and the transducer is placed within this area, on the sheet pile surface so that the equipment could read. As the surface is irregular, some differences between measurements from different years are expected.

3.5 Corrosion Rates

Linear best fit lines were determined, with the measurements from 2012 to 2016 as part of the same set of data. For considering lower limits for the best fits, two other parallel lines to the fit line with a separation between them of 0.5 mm, were included.

Fig. 10 shows the data and adjustment lines for the intern section of the North Breakwater. The same was done for other combinations north-south breakwater, inside-outside sections and over-under water.

These comparisons are intended to consider the general behavior of the breakwater. Low correlations in settings are expected, as they include different levels and locations along breakwaters, where individual corrosion rates are not the same.

The slope of the adjustment lines can be considered as an average corrosion rate of the structure section. In the case, for the external north breakwater above the water, is 0.23 mm/year, which is high, but expected for Tropics and no barrier or cathodic protection.

On the other hand, the estimates of the corrosion rates for each of the measured points are made based on the average of the measurements in each of the elevations or the minimum in the same section and elevation.

The rates averaged from 0.11 to 0.26 mm/year, which are high. It should be clarified that these rates have been calculated with a four-year term (2012 to 2016), and it is expected that the estimates will improve over the years, and more data.

3.5 Estimated Lifespan

Considering that the best fit lines and their parallel lines, and their intersection with the minimum thicknesses, is possible to establish general lifespans (useful lifes) for the steel breakwaters, for each of the conditions analyzed (combinations of north-south breakwaters, inside-outside the marina, or above-below sea level), which are summarized in *Chart 2*.

Lifespans can also be calculated based on the differences between the average measurements of 2012 and 2016 for each point. For each cell, the difference

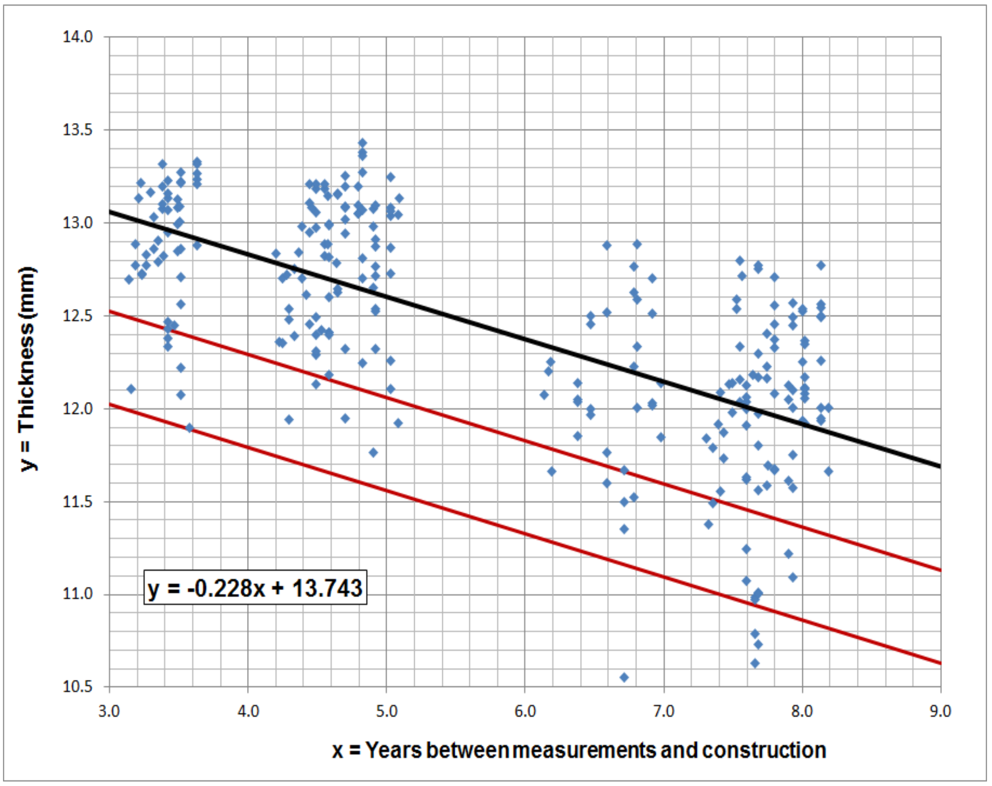


Fig. 10 Adjustment lines for the north breakwater outside and above waterline.

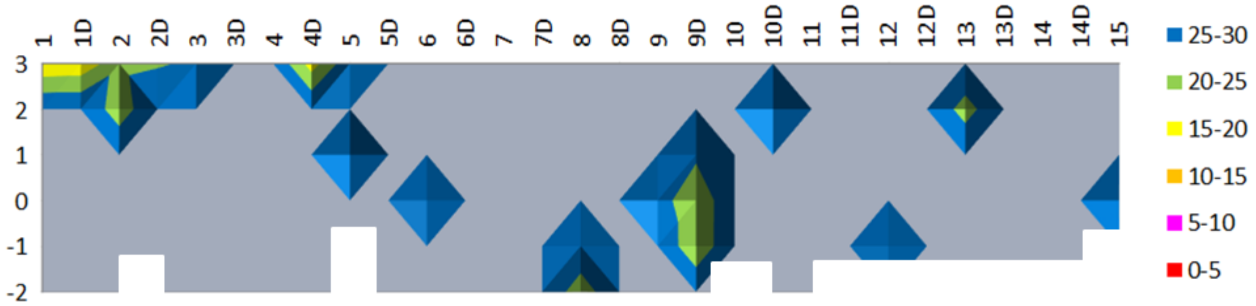


Fig. 11 Calculated lifespans (years) at different elevations (from LLWL) and sections (one per cell) north breakwater inside.

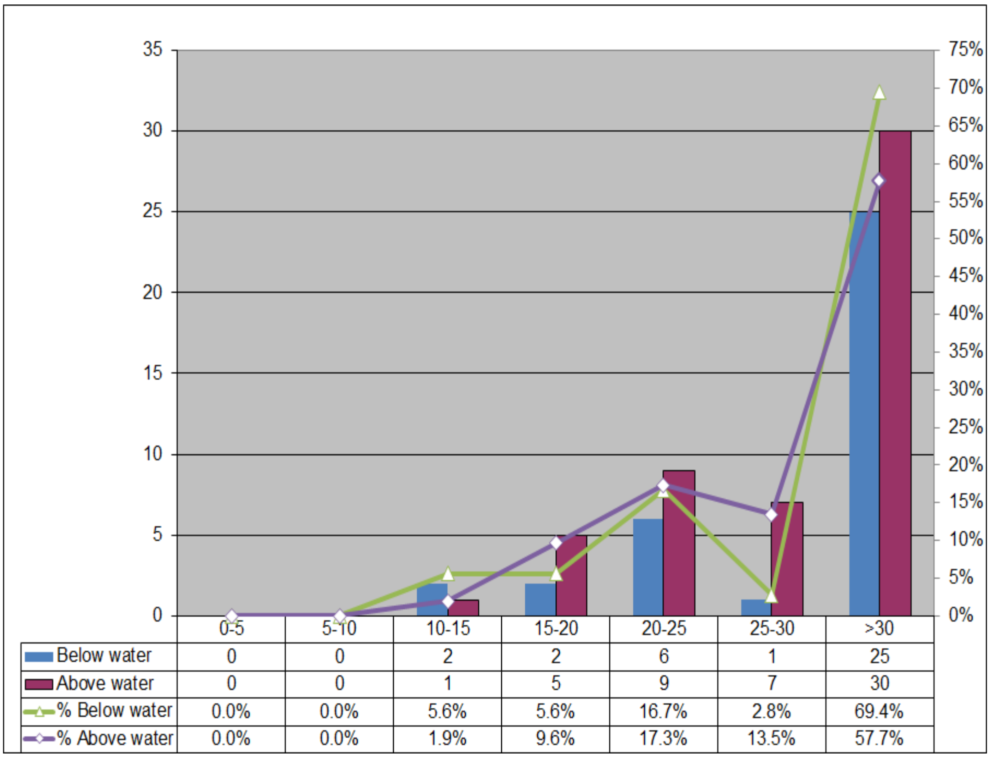
between the current measurement of the point, and the minimum safe thickness according the structural calculation, is a remnant of corrosion (available corrosion thickness).

The time in years required for the estimated measurement rate to corrode the remaining material up to the minimum thickness, is related to the lifespan for the sheet pile at that specific point.

The previous is summarized on Figs. 11 and 12, respectively for the north breakwater inside and outside, from which it could be inferred that most of the points would have lifespans over 30 years.

However, there are critical cases with lifespans between 10-20 years. Among the conditions under-over water and inside-outside the marina, the conditions over water and outside the marina has lower lifespans.

For example, in the north breakwater, 86-89% of inside cells have lifespans of more than 30 years, with minimum individual lifespans form 15-20 years. Meanwhile, outside 58-69% of cells have more than 30 years with minimum individual lifespans 10-15 years.



	0-5	5-10	10-15	15-20	20-25	25-30	>30
Below water	0	0	2	2	6	1	25
Above water	0	0	1	5	9	7	30
% Below water	0.0%	0.0%	5.6%	5.6%	16.7%	2.8%	69.4%
% Above water	0.0%	0.0%	1.9%	9.6%	17.3%	13.5%	57.7%

Fig. 12 Lifespans for individual measurements at the north breakwater outside.

6. Future Activities

6.1 Measurements Follow-up

Sheet piles should be monitored in accordance with the guidelines explained herein. Compared with current measurements, every new annually campaign of measurements, that will have more time from the baseline (year 2012), will help determining a more exact corrosion rate for the sheet piles.

In addition, as sheet piles are losing thickness, more attention should be paid to subsequent thickness measurement campaigns to detect problems.

6.2 Sheet Pile Protections

Quantifying the conditions of the cell piles, by sections and points, including the general and specific lifespans, makes possible to establish the maintenance priorities for the steel cofferdams.

The protection procedures vary per area and position of the sheet piles. For example, if they are in the splash zone, tidal interchange zone, or submerged zone, or if they are sheet piles of the main, arch or diaphragm cells.

At this moment, only the application of a barrier protection in the areas above water with higher overall corrosion, is being recommended. This could vary if there are important changes on corrosion rates or behavior.

6.3 Tidal and Splash Coatings

Prior to the application of coatings and related products, a surface preparation is required. All sheet piles must be clean of oil, grease, any foreign material or loose material, as well as any other contamination that could affect adhesion of the coating to be applied.

For preparation of substrates, standards based on The Society for Protective Coatings (SSPC) or the National Association of Corrosion Engineers (NACE) should be followed. Performance testing of products are per the American Society for Testing and Materials (ASTM).

It is recommended that the surface is prepared to standard SSPC-SP-10 (SA 2.5; NACE 2) "Surface near white metal" using abrasive cleaning or flushing.

Mechanical means such as abrasive discs, scalers or other devices may be used, provided that they are able to produce deep cleaning of the surface, as required.

Wire brush cleaning should be avoided as it usually spread the contamination, and not remove it. It must be tried to remove even the contamination of surfaces with oil, applying if it is the case powder soap or liquid, since this affects the adhesion of the coatings.

Regarding the coatings themselves, suitable and resistant products must be used for the application, whether they can be applied and cured on and under water. Cofferdams which allow the insulation and extraction of water from a section of the wall could be used for “dry” applications of the coatings.

In all cases, the recommendations is to follow the manufacturers' technical sheets regarding safety standards, surface preparation, product mixtures, application and curing conditions of such coatings.

Once installed, the coatings should be inspected visually, and with instruments for detecting possible defects. Mainly thicknesses measures of dry film, to compare with the minimum and maximum recommended by the manufacturer, as well as of continuity of the coatings on the applied surface.

6.4 Tidal and Splash Concreter Covers

In the case of concrete covers, to warranty the complete adhesion of the concrete to the surface, it is required, in addition to the cleaning (which does not need to be made to white metal), the placement of shear connectors, which are welded steel elements to sheet piles, for anchorage, and a internal reinforcing steel mesh. Thicknesses of covers varies from 10 cm and up.

The dimensions, thicknesses of the coatings as well as the shear and reinforcing mesh connectors must be designed. Surface cleaning can be pre-cast prior to formwork and final coating casting, as required.

It is recommended to use concrete with a minimum resistance of 350 kg/cm^2, due to the direct exposure condition due to the waves and sea currents. The usual controls must be carried in the manufacture, placement and curing of these covers.

Primarily, the segregations and washes of the concrete should be avoided, proceeding if necessary, to the use of impermeable forms and in which the water is withdrawn from them. Attention should be paid to the construction joints, which should be conveniently waterproofed by means of water-stops, tapes, paints and in other ways.

6.3 Underwater Cathodic Protection

The area and location of the surface to be protected, water resistivity, and time of protection, drives the size and quantity of sacrificial anodes required per design. The anodes are placed on the surface, which, when in contact with the sea water, produces an electric current between the anode and the surface. Anodes are the elements that corrode and wear, instead of the steel surface to which they protect. Accordingly, they are usually referred to as sacrificial anodes.

The usual installation procedure, discussed in this section, is by means of hot underwater welding, although other methodologies could be used, if they warranty the electrical continuity between the surface of the sheet piling and the installed anode.

The surfaces of the existing sheet pile where it is to be welded the anode, must be cleaned either by manual means (rackets and wire brushes), and / or pneumatic and hydraulic (compressor and grinders or escalators).

The area must be clean of marine life, and corrosion products. The cleaning must be such that a free minimum area around of anodes legs is appropriate for welding of them.

The anodes must be lowered to the water by mechanical and safe methods, so that neither personnel on the ground nor divers take risks or lift unnecessary weights. Each anode to be installed, must be placed at the location where it will be welded.

If necessary, temporary structures may be used, which should not damage the sheet pile. Care should be taken not to leave a gap between the anode holding leg and the surface of the sheet pile.

With the anode secured in the position, it is welded. Safety standards should be applied, mainly the use of a switch to discontinue the current when the welding electrode is not in use, and direct reverse current in the polarity of the welding machine.

On the surface, is advisable to make a record of several aspects of welding as location, polarity, amperage, voltage, electrode characteristics, and so on. Welds must also be inspected after for defects.

Finally, it should be checked if the anodes give the minimum required protection to the sheet-piles, by measuring the electrical potentials generated by the system. The measurement of these potentials must be done by means of a multimeter and reference electrode. The negative phase is connected to the reference electrode in the water, and the positive part to an attachment connecting the sheet pile. A maximum negative potential must be met at different heights in the water to be protected.

7. Conclusions

For the maintenance follow-up of a steel sheet piles cells of a mixed breakwater, at a marina in Quepos, Puntarenas, Costa Rica, several thickness yearly measurements with ultrasonic equipment were executed, in several campaigns from 2011 to 2016.

The purpose of the control is to verify the condition of the cells, at north and south breakwaters, both inside and outside the marina, and below and above waterline.

From the comparison, of 2016 measurements with those of the previous campaigns, it is possible to determine the phenomenon of corrosion is being presented in the steel sheet piles.

However, this corrosion is not homogeneous and there are different conditions for the outside and inside cells of the marina, above and below the water, as well along the breakwaters.

At first, external sheet pilings tend to have more corrosion than internal ones, probably because they are being more attacked by waves. Also, more degree of corrosion is given on the sheet piles in the splash zone, and within this zone, the corrosion is greater and has more dispersion in the upper part of the cell.

General corrosion rates are estimated based on the regression of the absolute measurements of the years 2012-2016, to estimate the overall trend.

Also, specific rates for each elevation were obtained from the averages and minimum values of the measurements points, taken as the initial thickness of the sheet pile, the measurement of year 2012.

Thus, the difference is obtained with the measurement of 2016, which represents the thickness lost by corrosion between those years.

The remaining lifespan is calculated, from the date of the last campaign (April 2016). The corrosion limit is the calculated minimum thicknesses, by tension of the sheet piles or joints.

The calculation of useful life from general trend data, is compatible with the required for the structure, of at least 30 years. On the other hand, considering each section and specific level, there are cases with smaller lifespans, including isolated cases with 10-20 years, mainly on sectors identified as critic.

By quantifying the sheet pile thicknesses on different sections and levels, it is possible to identify critical sections and apply specific and directed solutions, and protect those specific sections of sheet piles, rather than apply general solutions.

This in turn, allows in the maintenance, to make a more efficient, economic and safe use of the resources, to apply when they are required.

At this moment, the protection from corrosion, of the steel surfaces is what is recommend, since structurally thicknesses are above for what is required, as minimum by design. This protection could be done, above water in the intertidal and splash zones by barriers (coatings or concrete cover), and below water using cathodic protection.

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