CORROSION EVALUATION WITH MEASUREMENTS OF MARITIME STEEL STRUCTURES IN COSTA RICA

by

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1. INTRODUCTION

Due to the easiness of construction, many maritime structures, principally, foundation piles and earth retaining walls are made of steel. Consequently, these structures are subject to corrosion that could be severe because of the direct contact with seawater and/or spray.

For such structures, some inspection and measurements, are accomplished as quality control during construction. However, in most cases, corrosion assessment, during service life, is negligible. Afterwards remediation countermeasures, are often costly and done with poor knowledge of which areas are critical.

Nevertheless, there are some advantages in doing measurements for maintenance evaluations. Maybe the most important is to detect differences in the behavior of similar-type elements, and establish the priorities for maintenance.

This paper considers three study cases, located in the Pacific of Costa Rica, with after construction evaluation or follow up of maritime structures, including thicknesses of steel elements and electrical potential measures of cathodic protection systems. These cases are a) A Cellular Cofferdam Breakwater at Quepos, b) A Sheet-pile wall at Caldera Port and c) A Trestle at Punta Morales Pier.

Key words: Monitoring of structures, steel maritime structures, corrosion, ultrasonic thickness measurements, cathodic protection.

2. CELLULAR COFFERDAM BREAKWATER AT QUEPOS

2.1 Descriptions

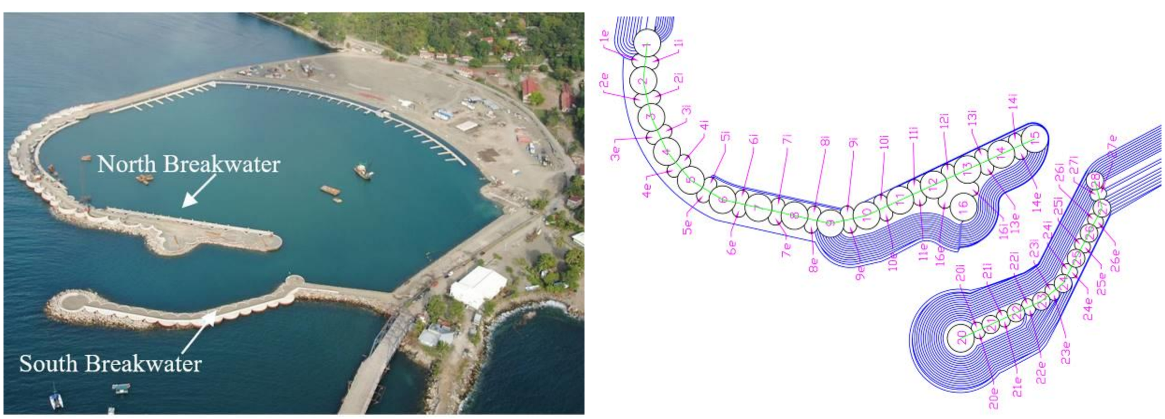

Fig. 1 (Left) Aerial view of the Marina from 2010 (Right) Arrangement and numbering of cells

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The first phase of a marina in Quepos, Costa Rica, finished construction in 2010. This phase included two mix breakwaters, both with rubblemound and circular cells of sheet piles, on marine steel and filled with sand and gravel. These breakwaters are 956 meters long and have 25 circular cells from 12 to 18 meters in diameter, with interconnection arches, in water depths from 1-6 m below low water level or LWL (*Fig. 1*).

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

Therefore, 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, keeping the real capacity of the cells unaffected. The maintenance plan for the marina, considers tracking the corrosion experienced by the steel sheet-piles, and comparing 'actual' against expected corrosion rates. An analysis is then required to check that the structural limits for the corrosion additional thickness are not exceeded.

2.2. Method Statement

Specific control sections, distributed along the breakwater, were considered both inside and outside the marina basin, being one section per cell or arch inside, and two sections per cell or arch outside. In this way, a general distribution of the corrosion condition around the breakwaters, with different exposition for the cells, could be surveyed. The sections are to be controlled annually, although not all the sections were taken in each campaign.

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

In each section, thicknesses were measured, using ultrasonic equipment and a special underwater transducer, every meter from the top of the cell, about +4 m LWL to the seabed. When the measurements were above the water, access to the points was done with stairs and platforms. On the other hand, measurements below the water required divers.

A nomenclature was adopted to define every measurement location, including the cell number, the specific sheet-pile (starting from the joint), and measuring the height from top of the cell down. At each elevation, 4 points were measured as shown in *Fig. 2*, so that minimum and average values could be considered for statistical purposes. Relating the measurements to a specific location, allows re-staking each section and points in a simple way, so that they could be repeated during annual measurements.

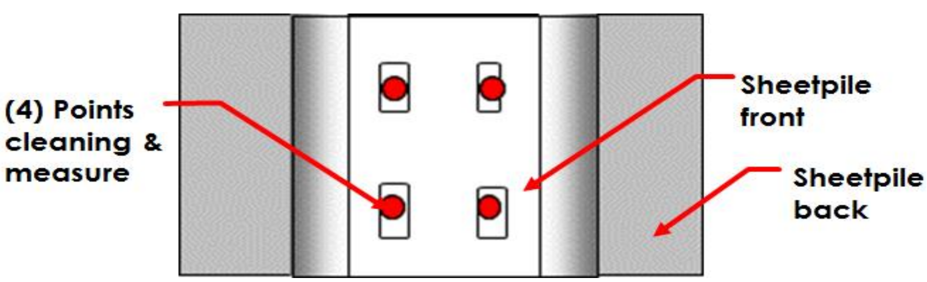


Fig. 2 Scheme of points measurements at each elevation.

Update annual campaigns measurements, are from 2011 to 2013, and 2015 to 2017. The campaign, included in this paper, was the one from April 2016, when the sheet piles had from 7-8 years of being installed. This year was chosen over 2017, since in 2016 all the sections were measured, which did not happen in 2017, when the measures were partial.

An air needle powered by a compressor was used at each measurement point to clean the sheet-pile surface from marine life and corrosion. The cleaning was done in a circle with no more than 10 cm in diameter. This cleaning was executed also above water, likewise with the same equipment.

The thickness measurements were made with a UT (ultrasonic equipment), having a nominal frequency of 5 MHz, and a straight ½ in. diameter underwater transducer, with a 15 m in cable, so that the measuring device was at the upper part of the cell all time. *Fig. 3* shows the cleaning and the installation of the underwater transducer at the surface during the measurement of one of the points.

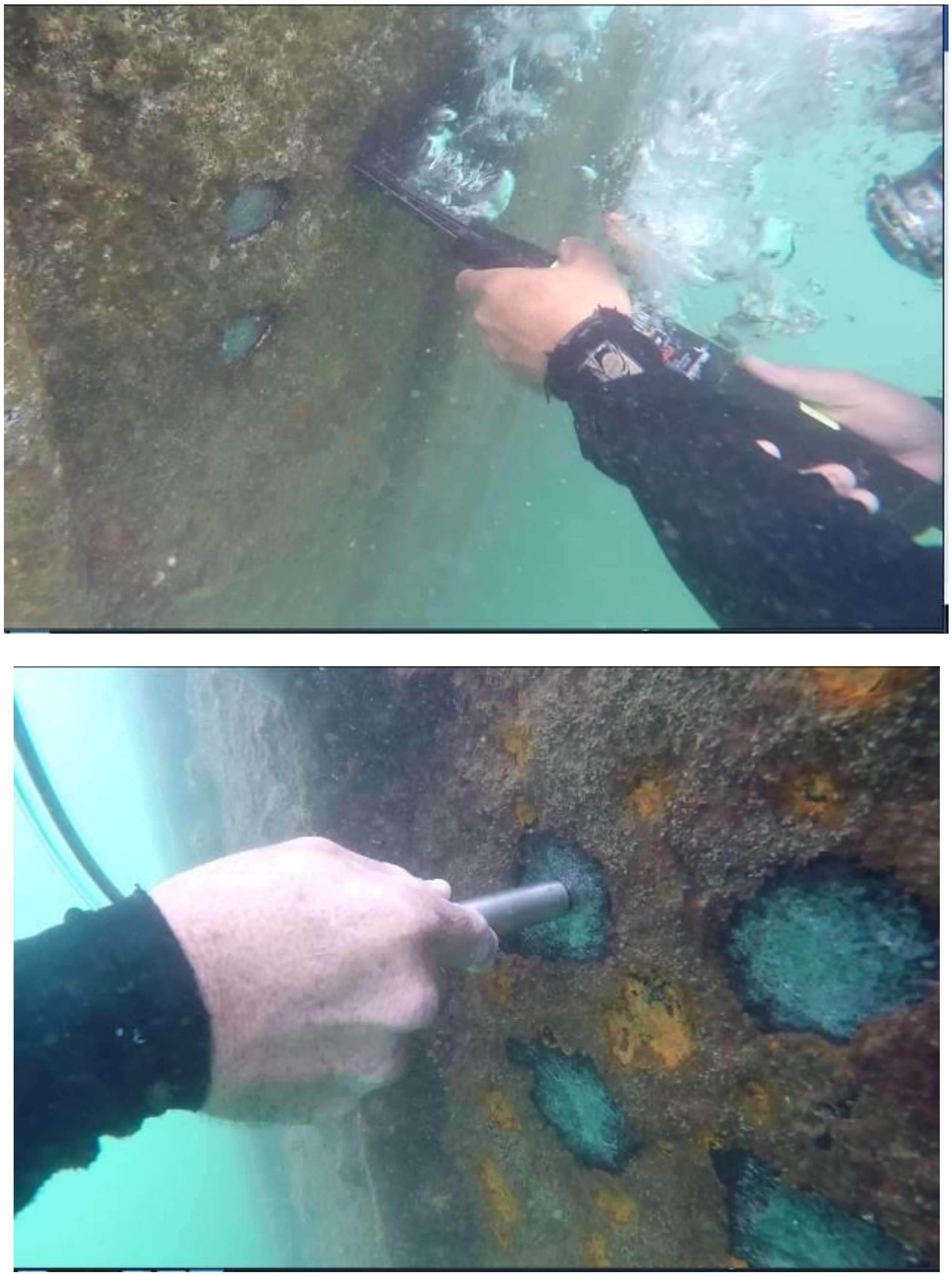


Fig. 3 Underwater Procedures at the Marina in Quepos (Above) Cleaning of measurement points (Below) Thicknesses measurement with ultrasonic sensor.

2.3 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]:

$$F_{t,Rd} = \min\left(\frac{0.8 \cdot R_{k,s}}{S.F.}, \frac{t_w \cdot f_y}{S.F.}\right) \qquad F_{t,Ed} = p_{m,Ed} \cdot r_M \qquad F_{t,Ed} \leq F_{t,Rd} \qquad (1)\ (2)\ (3)$$

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 as per the analytical formulation. About this must be considered that critical elevations vary from cell to cell and could be either above or underwater. To explain, corrosion levels are higher at tidal zone, but tension forces diminish. Opposed to this, below water, the highest tension of the sheet-pile occurs around or just above the seabed level, but corrosion rates are smaller.

It must be recognized that, joint interlock tension loss due to corrosion is difficult to measure, so an alternative approach was considered. It was assumed a linear relationship between the measured thickness and the maximum tension that theoretically can support the connection. This is based on ARCELOR design manual [4]. Then, the thickness of the sheet pile corresponding to the tension calculated for the joint is extrapolated. The safety factor used in the formulas was 1.5.

In *Table 1*, summarizes the minimum calculated thicknesses for the combination of inner and outer exposed cells, main and connecting arches, as well for the connecting yees (or joints). In this calculus, besides 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 toward the outside of the cell which drives the hoop tension of the sheet-piles.

Table 1 Minimum thickness (mm) to comply with cell hoop tension and a 1.5 safety factor [5].

Location			12.2 m cells	18.6 m cells
Outside the basin	Above LWL	Sheetpile	1.8	1.4
		Joint	2.5	1.9
	Below LWL	Sheetpile	1.4	2.4
		Joint	2.2	3.4
Inside the basin	Above LWL	Sheetpile	1.3	1.6
		Joint	2.0	1.9
	Below LWL	Sheetpile	1.2	2.5
		Joint	1.9	3.5

It could be concluded from the previous table that the thicknesses for having failure, compared with the theoretical thicknesses of the piles, are in fact low, about 25%-30% of theoretical thickness. Thicknesses are greater for the joints compared to other sheet-piles. For the 18.6 m cells, sheet-piles above water require higher thicknesses compared to those below water, and the opposite is true for the 12.2 m cells.

2.4 Thicknesses measurements

The measurements from 2016, for the inside of the north breakwater, could be seen graphically in *Fig. 4*. In this graph, one section is considered per cell, so in cases with two sections measured per cell, conservatively the one with lower thicknesses was included in the figure. Levels are in meters from the LWL (lowest water level) so that effects of tides are recognized. Similar graphs were considered for the other exposition conditions i.e. south breakwater, and outside the basin.

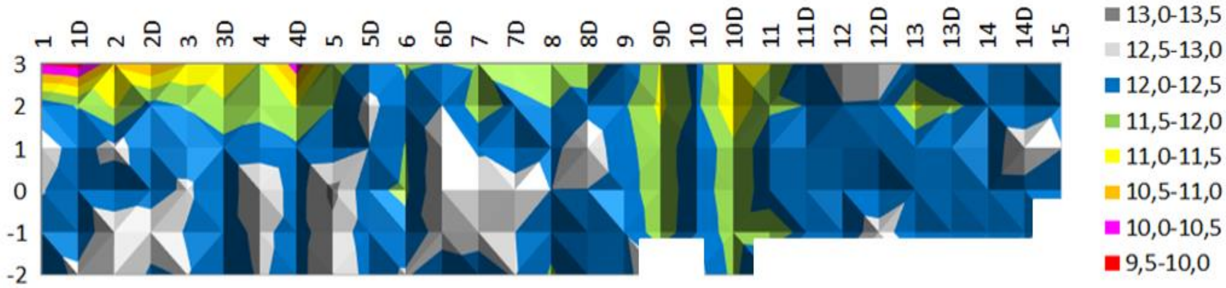
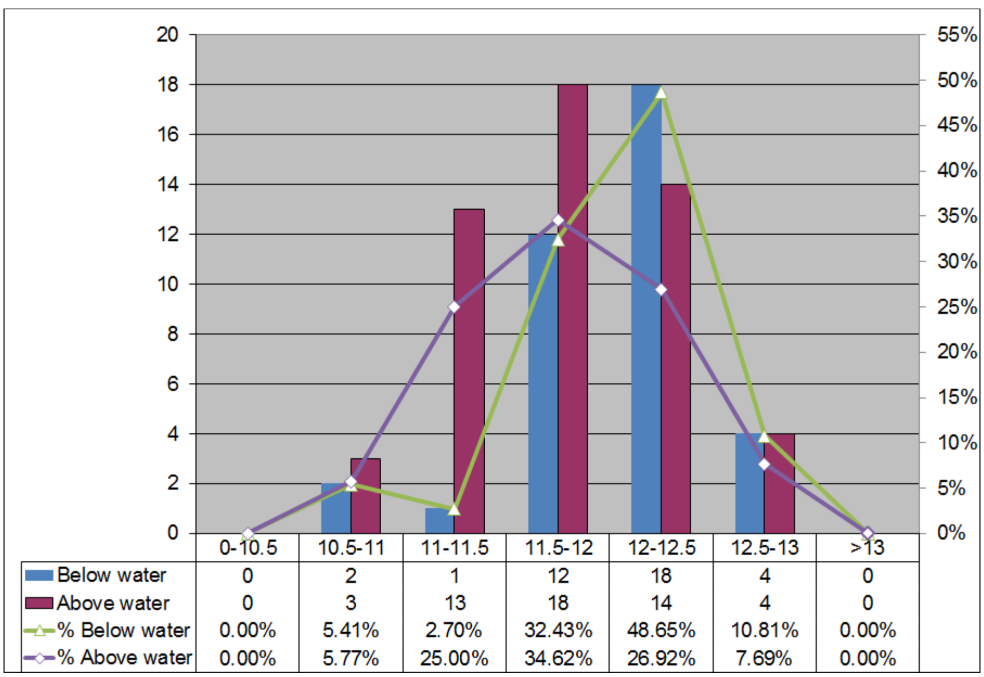


Fig. 4 Thicknesses (mm) at different elevations (from LLWL) and sections (one per cell) for the north breakwater inside the basin, 2016.

From these graphs, specific cells with lower thicknesses, i.e., higher corrosion could be identified, for example, above +1 m LWL inside cells 1-5 and above +1 LWL for outside cells 1-8. Also, statistically, the distribution of quantity of measurements for given ranges is also considered, as shown in *Fig. 5*. This graph shows the thickness measurements distribution for the north breakwater outside the basin, but similar graphs were calculated for other exposition conditions.



	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. 5 Thicknesses measurements distribution for north breakwater outside the basin, 2016.

Inside the north breakwater, 49% of measurements above LWL and 60% below LWL are between 12.0-12.5 mm, with a minimum measured thickness of 9.8 mm. Meanwhile, outside the north breakwater, 35% of measurements above LWL are from 11.5-12 mm, and 49% below LWL, are from 12-12.5 mm, with a minimum measured thickness of 10.6 mm. From the previous, and as expected, corrosion attack is higher above LWL, and lower below LWL.

2.5 Thicknesses versus time

The measurements of the all the 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. 6* shows the case corresponding to the inside part of the north breakwater. Similar cases were addressed for the other conditions i.e. north and south breakwater, and inside or outside the basin.

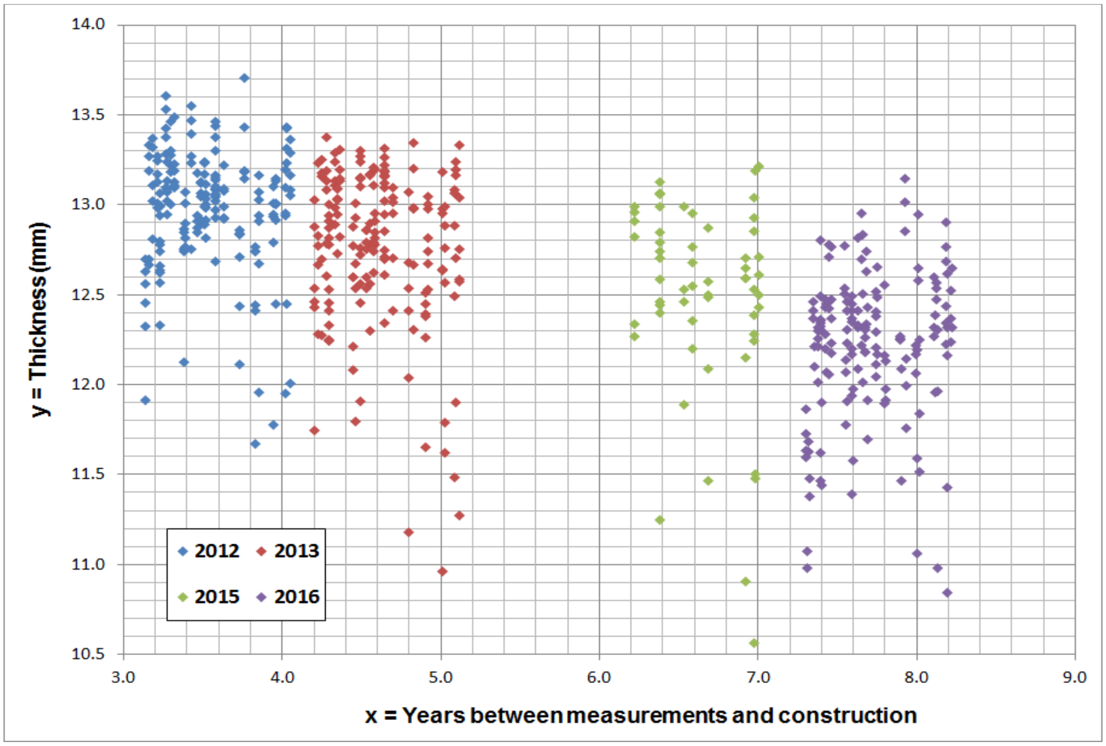


Fig. 6 Set of all thicknesses inside north breakwater vs. construction time, 2012 to 2016.

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

As expected, it is concluded that the general behavior of the sheet-piles after the construction of the breakwaters is loss of thickness (or corrosion), this no matter the exposition condition, North or South breakwater, inside or outside the basin. In general, in the north and south breakwaters, the lower thicknesses are in the sheet piles above +0 m LWL. The trend seems to be that higher up on the sheet-pile corrosion is greater.

In the north breakwater, the losses outside and inside the basin are in the same magnitude order. But on the south breakwater, this cannot be concluded because there is only one section in the inner part because rubble mound is laying in almost all the internal cells. Inside the basin, there is more corrosion in the curved part of the north breakwater, compared to the rest of the sheet piling. Outside this same breakwater, the corrosion is greater on the most exposed cells to waves.

Besides the general comparison, differences between data of the same measurement points from 2012 and 2016, were calculated. For the same point, the average differences are from 0.46 to 1.10 mm and maximum from 1.22 to 2.61 mm. Those differences are summarized on *Fig. 7*.

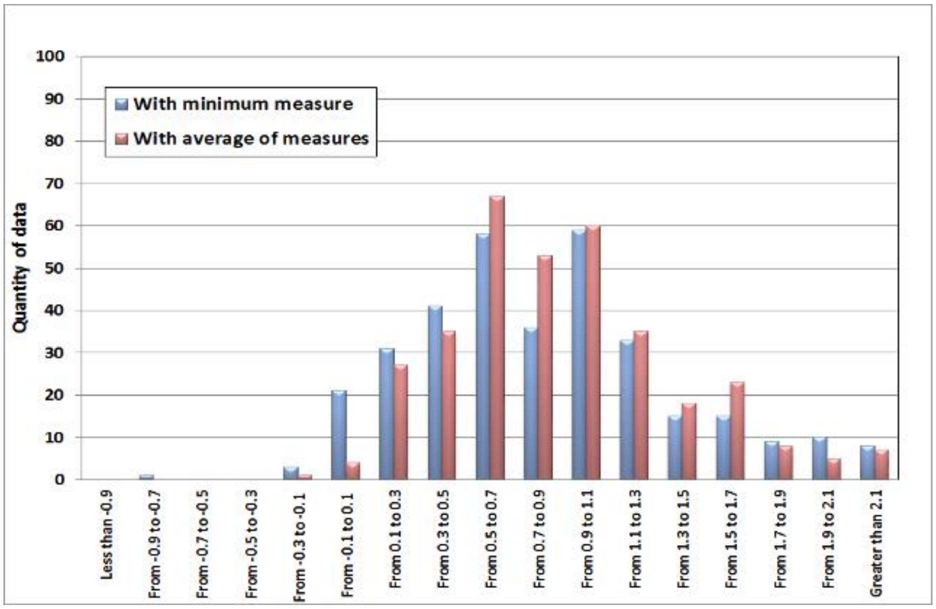


Fig. 7 Thicknesses differences of measurements, 2016-2012.

As shown, few measurements were higher in 2016 compared with the ones from 2012. That may be due to differences in equipment or cleaning, but also because, by procedure, measurements are directly on site, which never happens in the same exact spot. This is, for each measurement, an area of the sheet pile surface about 10 cm diameter, is cleaned, and the transducer is placed within this area. As the surface is irregular, some differences between measurements from different years are expected central cells.

2.6 Corrosion Rates

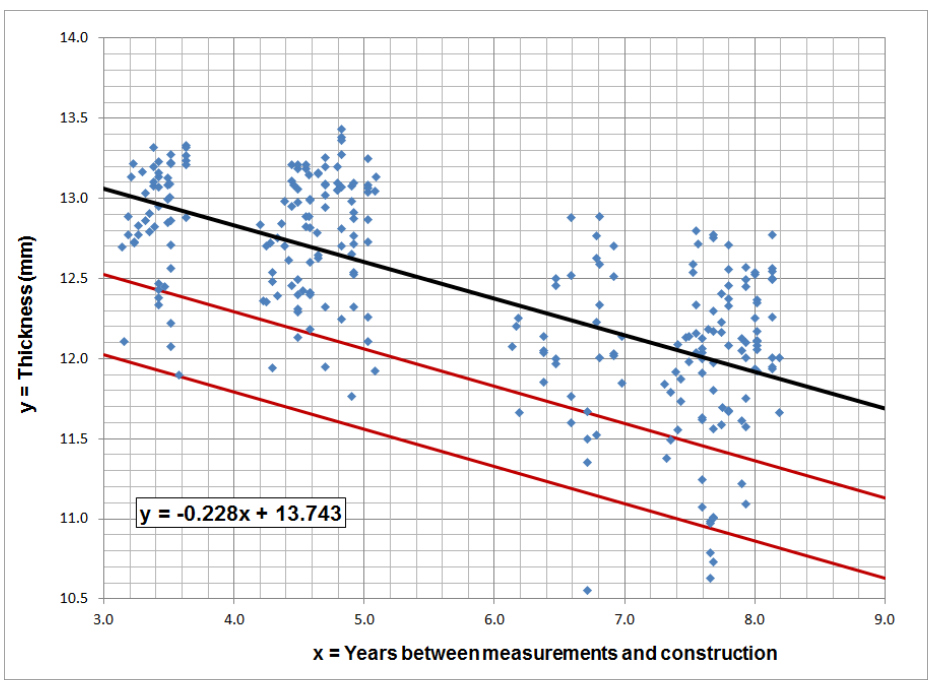


Fig. 8 Adjustment lines for the north breakwater outside and above waterline, 2012 to 2016.

With measurements from different years, corrosion rates could be calculated, as an average for some structure sectors, or for each measured point. Differences on thicknesses loses and corrosion rates were identified for conditions of exposition, i.e. outside and inside basin, above and below LWL, and due to the location along the breakwaters.

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 were included with a separation between them of 0.5 mm. *Fig. 8* shows the data and adjustment lines for the inside 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 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, it is 0.23 mm/year, which is high, but expected for tropics with no barrier or cathodic protection.

On the other hand, the estimates of the corrosion rates for each of the measured points, are based whether on the average of the measurements in each of the elevations or the minimum in the same section and elevation. For all the cases, the corrosion rates averaged from 0.11 to 0.26 mm/year, which are also high. It should be clarified that these rates have been calculated with a four-year term (2012-2016), and it is expected that the estimates will improve over the years, and more data.

2.8 Estimated Lifespan

Considering that the best fit lines, their parallel lines, and intersection with the minimum thicknesses, is possible to establish general lifespans (or useful lifes) for the steel breakwaters, considering each of the analyzed exposition conditions (combinations of north-south breakwaters, inside-outside the marina, or above-below sea level). The calculation shows estimated lifespans greater than 30 years in all cases, which is the about the time for ending the marina concession.

Also, from the safe structural thickness for each sector, lifespans could be calculated, based with the differences between the average measurements of 2012 and 2016 for each point. In general, these complies with the designed lifespan for the whole structure, however there are specific sectors with lifespans that are lower than required.

For each cell, the difference between the current measurement of the point, and the minimum safe thickness according the structural calculation, is a remnant of corrosion (available thickness that could corrode without failure of the structure). The time in years required for the estimated measurement thickness to corrode the remaining material up to the minimum thickness, in the calculated corrosion rate, is related to the lifespan for the sheet pile at that specific point.

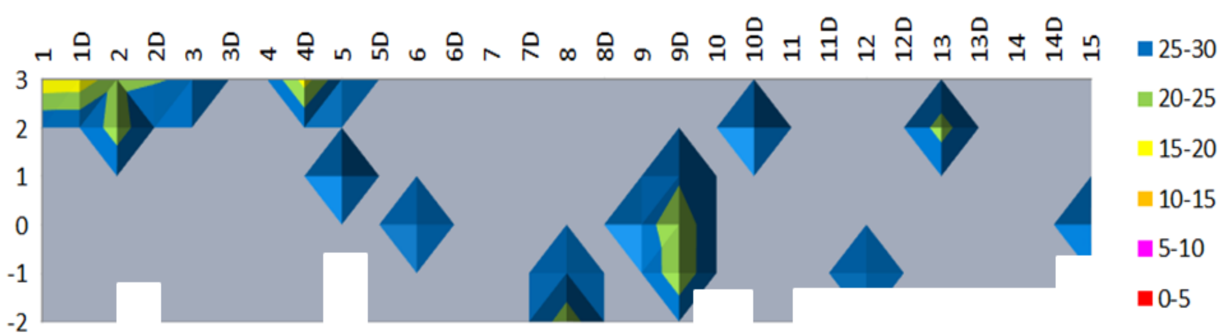
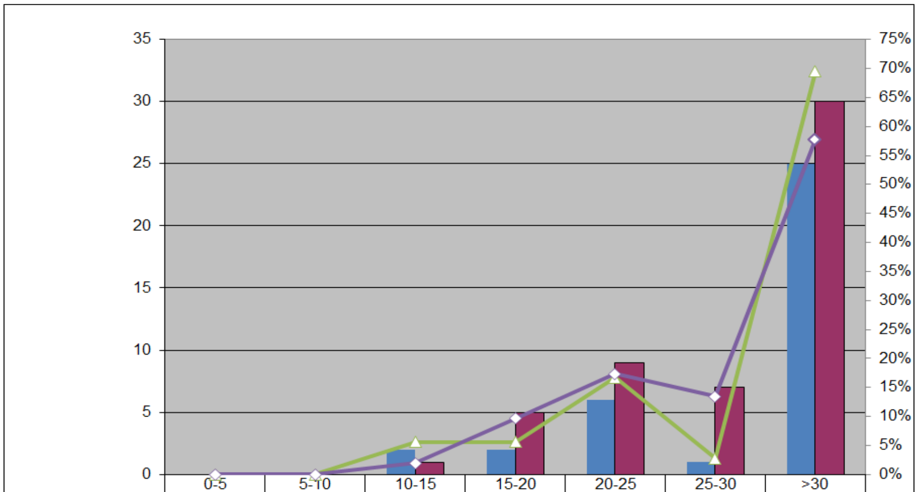


Fig. 9 Lifespans (years) for different elevations (from LWL) and sections (one per cell) for the north breakwater inside the basin, 2016.

The previous is summarized in Figs. 9 and 10, respectively for the north breakwater inside and the same breakwater outside. From these graphs it could be inferred that most of the points would have lifespans over 30 years. Similar graphs were obtained for all the combinations of expositions analyzed i.e. north-south breakwater, inside-ouside of basin, and above-below LWL.



	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. 10 Lifespans for individual measurements at north breakwater outside the basin, 2016.

The analysis shows that 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 have 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.

3. SHEET-PILE WALL AT CALDERA PORT

3.1 Descriptions

The principal bulkhead of Port of Caldera, includes three berthing positions Berth N.1-N.3 depths from -7.5 to -11 m LWL with a total length of 500 m, and was constructed in 1980 i.e. have 38 years of service (*Fig. 11*). An additional Berth N.4, which starts operation in 2014, corresponds to a pile supported pier, and is not included in this analysis.

The bulk-head is a steel sheet-pile retaining wall, with back filling composed of stone, and granular materials in the upper part. The sheet pile is anchored at +2.0 LWL level. An end cap of 2.6 m width was constructed between the levels +0.50 to +5.0 LWL, with the sheet pile embedded up to the level +3.0 LWL. These caps provide a barrier protection for the steel sheet-piles on the splash zone. Below water, sheet-piles are protected by sacrificial aluminum alloy anodes providing passive cathodic protection. In the attached *Fig. 12* there is a cross section through the Berth N.1.

According to construction plans sheet piles used were Z-25 type with 305 mm depth for berth N.3, and Z-45 with a depth of 360 mm for berths N.1 and N.2, both types of sheet-piles 400 mm wide. Regarding the galvanic anodes for the submerged part there are two rows of anodes for berth N.3 and 3 rows for berths N.1 and N.2. Each of the anodes weighs 137 kg, with external dimensions of 730 x 300 x 260 mm, and are placed on a steel plate welded to the sheet pile.

Fig. 11 Quay wall at Puerto Caldera, taken from the end of Berth N.3.

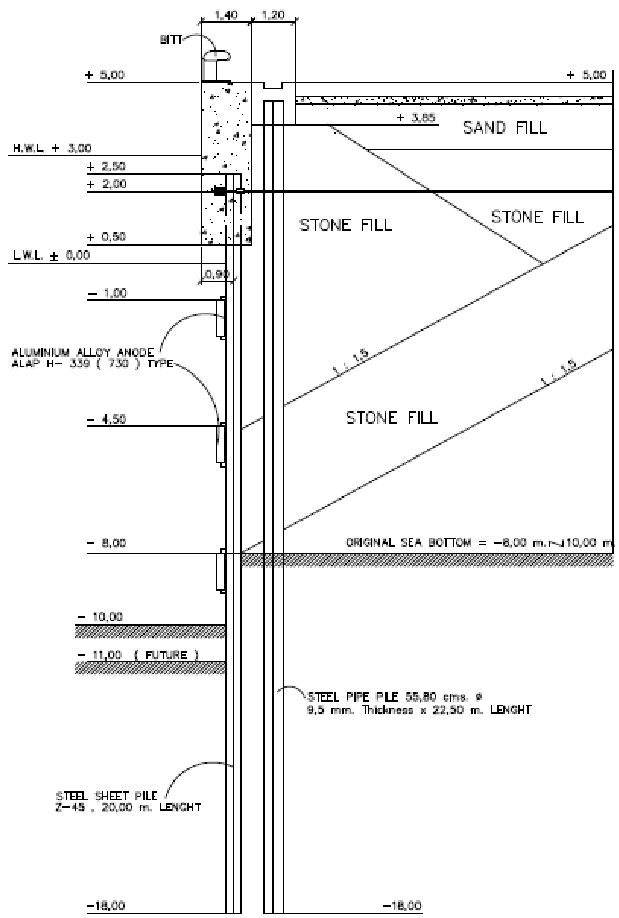


Fig. 12 Cross section trough sheet pile wall at Berth N.1.

3.2. Method Statement

Evaluations of sheet-pile thicknesses and electrical potential generated by the cathodic system were performed by others in 2003. Additional measurement campaigns, were executed from 2011 to 2015, and the last one in 2017. For horizontal location there were defined on 2011, reference points denominated W, P, E and located respectively in the west closure wall (E), main wall (P) and east closure wall (E), of the quay, located about 5 meters apart one from another.

Steel thicknesses measures, follows an analogous methodology as in the previous case study, with the difference that only measurements below water were executed, where there is no concrete cap. (*Fig.13*) Since the measurements from 2011, were taken as a base, longitudinal measurements were performed that year on sections every 10 meters. Based on the information from the campaigns of 2003 and 2011, follow up thicknesses measurements for following campaigns were executed at 8 control chosen sections.

Fig. 13 Example of thickness measurement at Caldera sheet-pile wall, 2017.

Electrical voltage assessment of the potential generated by the anodes of the quay wall, is used as maintenance evaluation to detect areas not complying with what is required for corrosion inhibition. Measurements are done in sections every 5 meters alongside the main and closure walls, and vertically every 50 cm from top to sea-bed. Also, on the campaign of 2011, a survey of the location of existing anodes on the wall was done.

Electrical potentials are measured with a voltmeter, in which the negative phase is connected to a special Ag/AgCl reference electrode and placed in the water, and the positive part to a plate that is connected inside the cap to the sheet-pile, as was originally planned by the Japanese to make these measurements. And scheme of the measurements and the equipment used is shown in *Fig. 14*.

In the procedure, first, the sea bottom is obtained measuring using a 30 m tape with a ballast weight. For the voltages measurements, with all connected, the reference electrode is located at the elevation +0.0 m LWL and lowered every 50 cm until the sea bottom previously measured is reached. With each increase in depth, the voltage value in the voltmeter is recorded. It was noted that the values were stable so it was not required to make several measurements at the same elevation.

The potential is adequate if it is more negative than -850 mV compared to a CSE reference electrode, which is equivalent to -800 mV to a Ag / AgCl electrode, or at least there is a negative change of 100 mV from the potential without anodes (in this case this information is not available). This is per the specifications established by the National Association of Corrosion Engineers (NACE) of USA [6], [7].

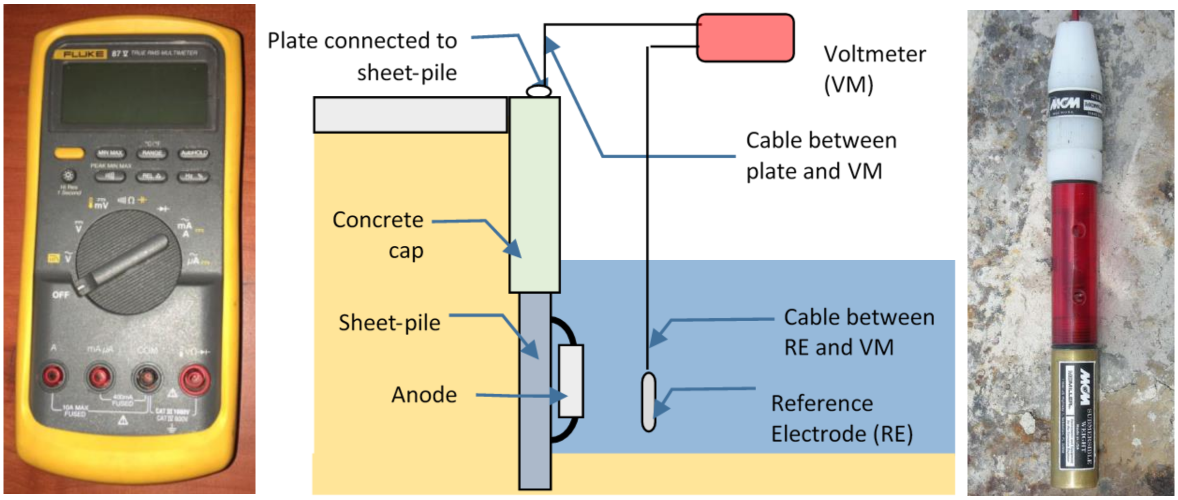


Fig. 14 Measurement of Anodes Potential (Left) High Impedance Voltmeter (Center) Equipment connection and Measurement Scheme (Right) Ag/AgCl Reference Electrode

This same procedure is repeated for the other sections beyond half the distance to the next plate. The previous so that the measurements could be verified, by overlapping measurements between plates, which did give similar results.

3.3 Thicknesses measurements

The averages of the four points measurements at each considered elevation, were calculated. The lowest average thickness in the sheet piles of Berths N.1 and N.2 is 20.01 mm, which is 1.79 mm less than the theoretical thickness. On the other hand, the smaller thickness in the sheet piles of Berth N.3 is 12.26 mm, 0.74 mm less than the theoretical. Thicknesses greater than the theoretical were also measured, which is possible considering the manufacturing tolerances of steel sheet piles.

Despite this is a structure with 38 years of construction, steel thicknesses compared to sheet-pile original specifications remain similar. It is then noted that in general, there has not been a significant loss of sheet pile thickness which is probably due to an effective cathodic protection.

3.4 Corrosion rates

For the corrosion calculations, the theoretical thickness of the sheet pile were taken as a basis, namely 21.9 mm for the sheet piles of the West closure wall and for Berths N.1 and N.2 walls, and 13 mm for Berth N.3 wall. To be consistent with the information presented, the corrosion rates have been calculated with the averages at each elevation. The corrosion rates calculated with the average are 97% less than or equal to 0.03 mm / year.

In addition to the rates calculated with averages, corrosion rates from the minimums measurementas at each elevation were also carried out. These calculations are more conservative, considering not only that it is done with the minimum, but because between two measurements at a given elevation, the minimum does not necessarily occur at the same point between annual or a previous measure.

Due to the time that has elapsed from the construction of the quay (38 years), it is considered that the rates considering the theoretical thicknesses of steel sheet piles as calculated are reliable. The premise is that, if up-date there have been no significant losses in the sheet piles, there is no reason for them to occur, as long as the required potential is maintained throughout the sheet-pile.

3.5 Potential measurements and countermeasures

As indicated before, the measurements of the voltages generated by the cathodic system, could be used to evaluate the provided protection to the sheet-pile. The campaign from 2011, is interesting since, the locations of the existing anodes were surveyed. When these locations are compared with the interpolation of the potential through the wall, it could be seen that the variations of the voltages ranges are related to the anodes location (*Fig. 15*). For example, an area outside specification was detected at middle of Berth 1, which is due to the lack of sacrificial anodes in the area.

Voltages scale:

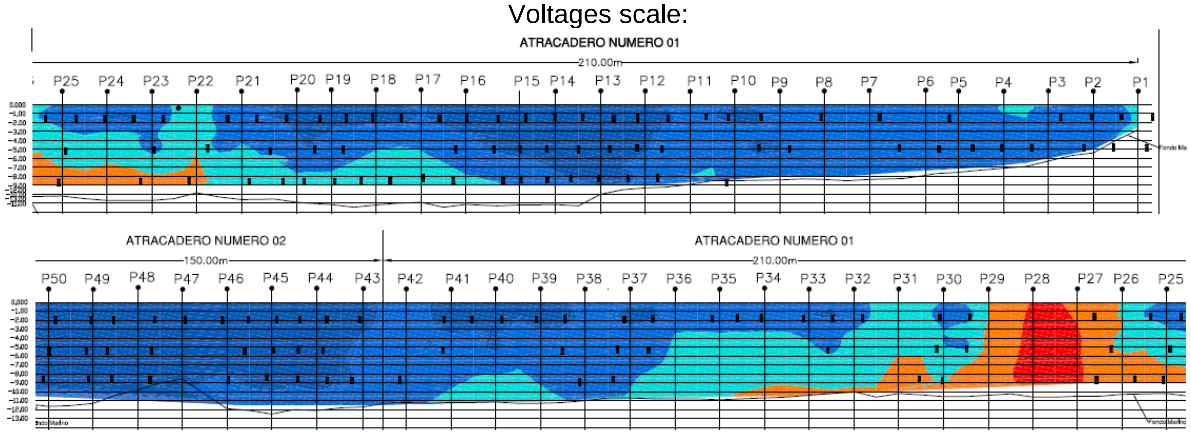


Fig. 15 Potential distribution and location of anodes in the sheet-pile wall on berth N.1, 2011.

If the potential is not what is required, additional anodes are welded to regain it. Also, after the new anodes were installed, electrical measurements are performed to confirm the protection. This approach minimizes maintenance costs since only the sections that need anodes would be re-protected with them, compared to replace anodes after certain mass loss despite the generated potential.

There had been other cases in which this happened. One was after the construction in 2012 of the underwater rock revetment at the Berth 3 corner, which was required for the slope protection between this corner and the dredging Berth 4. Because of the construction method for rock layers conformation, most of the anodes from the wall were ripped and potential measurements became inadequate.

After la installation of only 21 anodes in the bottom of the wall, the potential was regained. These could be seen in on *Fig. 16* for a portion of Berth N.3, with the location of the new anodes for more clarity. Above and below graphs are the conditions before and after the installation of the new anodes.

Voltages scale:

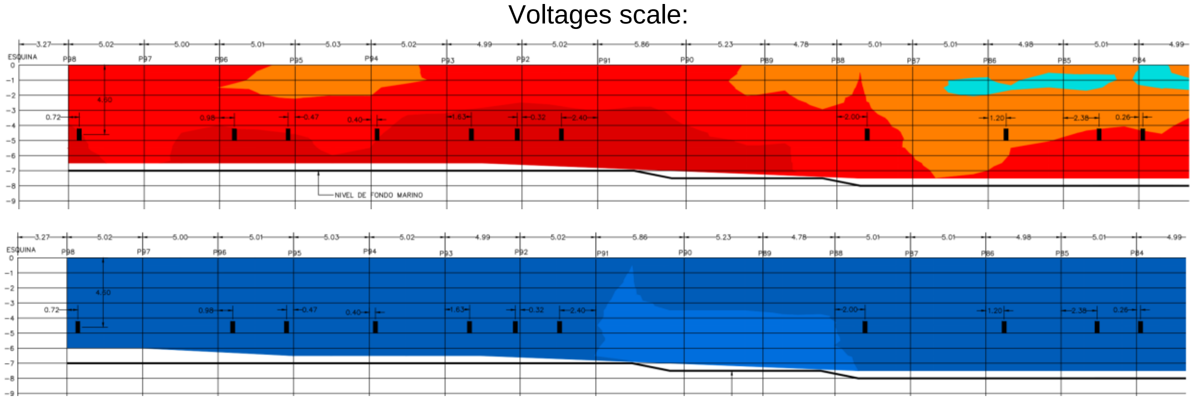


Fig. 16 Potential voltage measurements at a portion of Berth N.3
(Above) Before installation of anodes. (Below) After installation.

4. TRESTLE AT PUNTA MORALES PIER

4.1 Descriptions

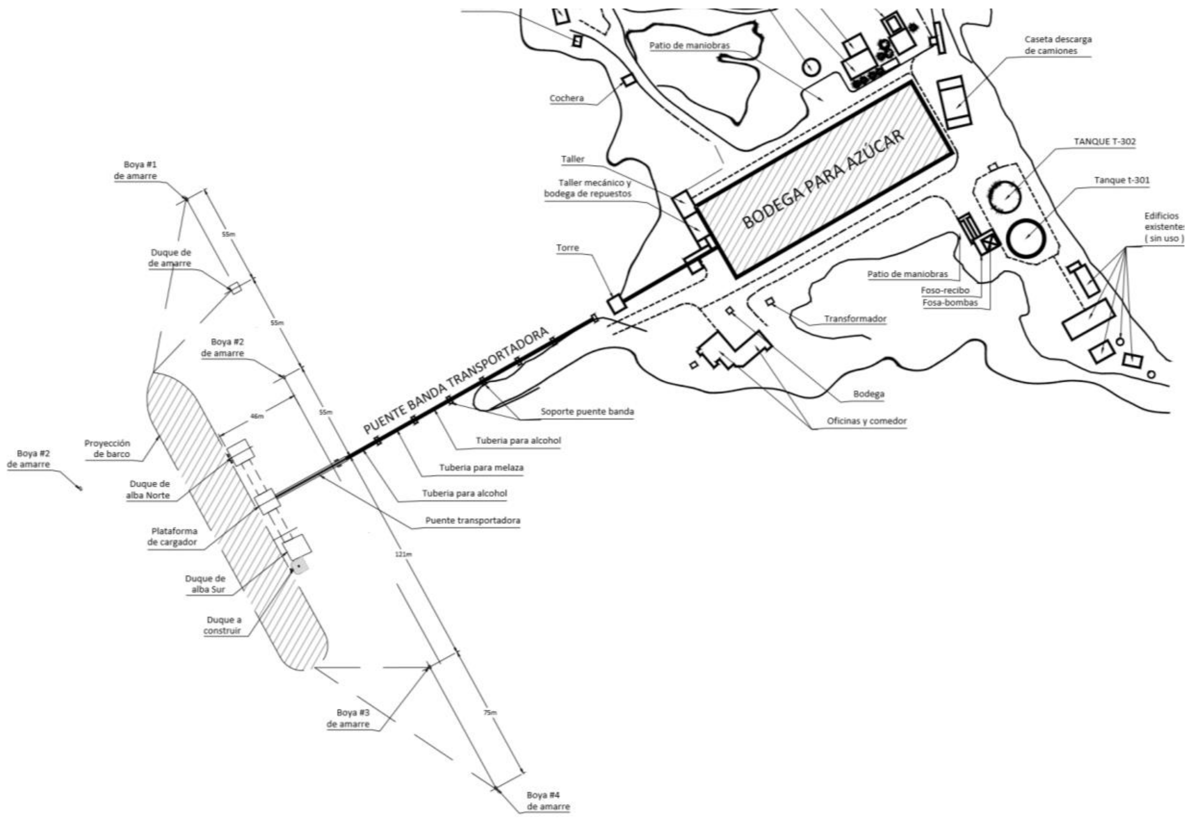


Fig. 17 Punta Morales Pier (Above) Layout of the pier including Charging Platform, Berthing Dolphins and Conveyor supports (Below) General View of Trestle Supports from land.

The Punta Morales pier, principally for sugar export, was constructed in 1980, and is a dolphin-type pier with a loading platform, all steel pipe piles. The sugar is transported from a warehouse on land to the loading platform by means of a conveyor belt. This belt is supported on (9) concrete caps, each one with (4) H-beam steel piles. In general, the piles were located with a certain horizontal inclination with respect to the axis of the conveyor belt, although the majority are with the flanges oriented in the direction of the belt axis. The layout of the pier including the conveyer support is shown on *Fig. 17*.

The first support of the conveyor belt from the pier, is different from the others, in cross section of the piles, and because there are some reinforce diagonals between piles. This support is in the deepest part, in addition to the band and catwalk are raised about 15 meters above the upper level of the upper part of the slab of the support, which probably explains the more braced structure.

The piles of the supports are protected with an active cathodic protection system of impressed current, wired at the top interconnected with the trestle superstructure. Cathodic protection condition would not be addressed in this paper.

In addition, piles are painted with epoxy products, with thicknesses from 0.2-0.4 mm as measured with the ultrasonic equipment. This represents an additional protection, whose effectiveness depends on how impermeable and continuous the layer is, so that ir being effective as a barrier protection for piles.

During routinely inspections, sections losses were viewed on the belt support piles, mostly near LWL, and possible due to abrasion. However, extend of the damages were unknown, especially below water. So, the recommendation was to measure steel thicknesses at each pile, every meter from top to sea-bottom, in the five outermost supports, which pile does not discover on low tide. According to measurements made on site, in these first (5) supports, the depths of the seabed from LWL are 9.0 m, 4.5 m, 3.0 m, 1.5 m and 1.0 m.

It should also be noted that this seems not to be a recent problem, since some piles have steel plates reinforcements welded principally in the flanges and the upper part of the piles. Its known that the site have important tide currents that carries nearby rivers sediments provoking abrasion and poor visibility.

4.2. Method Statement

Pile thickness measurements were made, vertically, at five points per elevation, each meter starting from the top of the pile below the support head (approximately at +3.0 m NMBS level) until it was closest to the bottom marine, or as far as visibility would allow.

In the scheme points 1,2, 4 and 5 are points taken on the pile's wings, while point 3 is taken at the beam's web, to differentiate conditions around the pile. By easiness to measure outside of the beam, was preferred, although in some cases, especially when there were existing reinforcement plates the measurements were done from the internal side (*Fig. 18*).

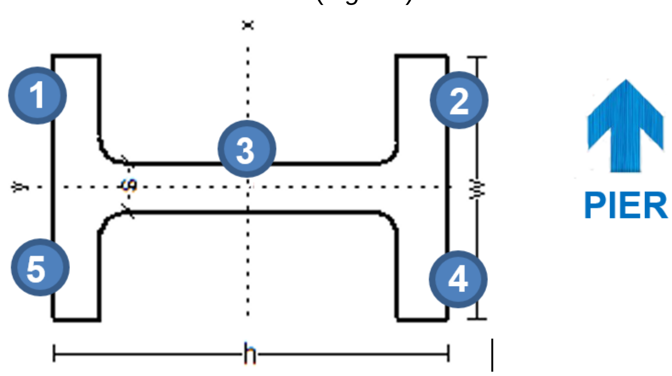


Fig. 18 Location of measurement points on H-pile flanges and web at each elevation

Due to visibility issues, it was not possible to reach the first of the supports from the ground to the seabed, but up to the level -7 m NMBS, which is about 2 meters above sea-bottom. In all other supports, measurements were made to the seabed. *Fig. 19* shows a thickness measurement in one of the piles on the first support from the pier.

Fig. 19 Thickness measurement in one pile of the first support from the pier

4.3. Thicknesses measurements

The thickness of the wings of the H-beams, are on average 20-21 mm, and 13-14 mm in webs. In general, from the analysis of the information there are piles that had lost 2 mm in thickness, compared with other measured elevations in which no corrosion is detectable. A single point on one of piles, gave a thickness of 17 mm, that is 3 mm less than the average.

The main losses are located coinciding with the low tide level (0 m of the NMBS), and about 3-4 meters below the level of the low tide. As demonstrated, thicknesses measures helped to detect areas with severe losses, and showed some losses below water, not necessarily detectable by divers.

As clarified, in some cases, there were some previous repairs with steel plates, for which there would be no problem, even if the thickness of the pile is much lower if some conditions are complied. These are that the plates are fairly welded, and that the plate reinforcement overlap to lower and upper sections of a pile in good condition.

4.2. Piles repair

Instead of prescribing substitution of the piles, which would probably be the recommendation without data, reinforcement of the piles with steel plates was proposed. Location of these reinforcements were accordingly, with the distribution of lower measurements from the study and in places without previous welded plates. These plates reinforcements were calculated following the shear flow concept [8], [9].

All this was implemented some months after the evaluation, and included underwater welding in difficult current and visibility conditions, but at low cost compared to a full substitution of piles. The piles were reinforced locally with 150 mm long 13 mm thick steel plates and with a width that allowed fillet welding between the plates and the top of the flanges or on the sides of the web. 21 plates were welded in the first 4 support H-piles in flanges, webs and in some cases in both. No intervention was considered for the fifth bent. *Fig. 20* shows the proposed reinforcement on Bent N.3 taken from the pier.

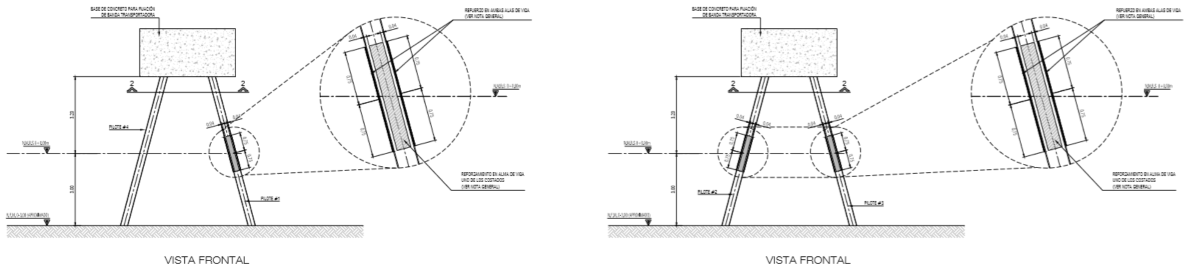


Fig. 20 Example of the proposed pile reinforcement at Bent N.3.

For additional protection, plates were painted with marine coating before installation, and the pile surface, where a plate goes, was cleaned from maritime life and corrosion, manually and using pneumatic tools.

Plates were placed in the intended position, secured and welded. Once the reinforcement plates were welded, the welds were toughly cleaned from slag, and from incipient marine life and corrosion. The borders of the plates were protected by a coat that could be placed and cured below underwater. This operation was performed once the welding was finished, which justifies the additional cleaning before coating. *Fig. 21* shows the general procedure of installation of reinforcement plates underwater.

5. CONCLUSIONS

In all these three study cases, thicknesses and electrical potential determination with maintenance measurements, helps to differentiate sectors of steel structures, where the phenomenon of corrosion and/or abrasion occurs with varied attack levels. With several campaigns of thicknesses measurements, along the years, it is possible to estimate corrosion rates and useful lives or lifespans, both general for structures, and specific for each level and section.

In turn, this allowed to identify maintenance priorities, defining possible sites where measures of corrosion protection should initiate, with barrier protection, or active or passive, cathodic protection systems, the need to apply other countermeasures as reinforcement or substitution of elements, as well in general, to have confidence in the structural capacity and safety of structures. Moreover, evaluation with discrete measurements along the structures had shown to be cost-effective reducing the costs for repairs and maintenance of the steel elements and cathodic protection systems.

6. REFERENCES

[1] Coburn, S. K. (2003). Corrosion Factors to be Considered in the Use of Steel Piling in Marine Structures. Pittsburgh: Pile Buck, Inc.
[2] U.S. Army Corps of Engineers (1989). EM 1110-2-2503 Design of Sheet Pile Cellular Structures Cofferdams and Retaining Structures. Washington, DC.
[3] Pile Buck, Inc. (1990). Cellular Cofferdams. Jupiter, Florida: Pile Buck, Inc.
[4] Arcelor RPS (Rails, Piles & Special Sections). Arcelor Group (2005). Piling Handbook. 8th ed.
[5] Bardi, J. (2012). Marina Pez Vela Cellular Cofferdam Evaluation. Washington: Berger Abam.
[6] National Association of Corrosion Engineers-NACE (2013) SP0169 Control of External Corrosion on Underground or Submerged Metallic Piping Systems.
[7] National Association of Corrosion Engineers-NACE (2012) STD TM0497 Measurement techniques related to criteria for cathodic protection on underground or submerged metallic piping.
[8] Creviston, Jonathon C. (2012) PDHonline Course S245 Steel Beam Reinforcement. PDHOnline, PDHCenter, Virginia.
[9] Dowswell Bo (2014). Reinforcing the point in Steelwise, January 2014.

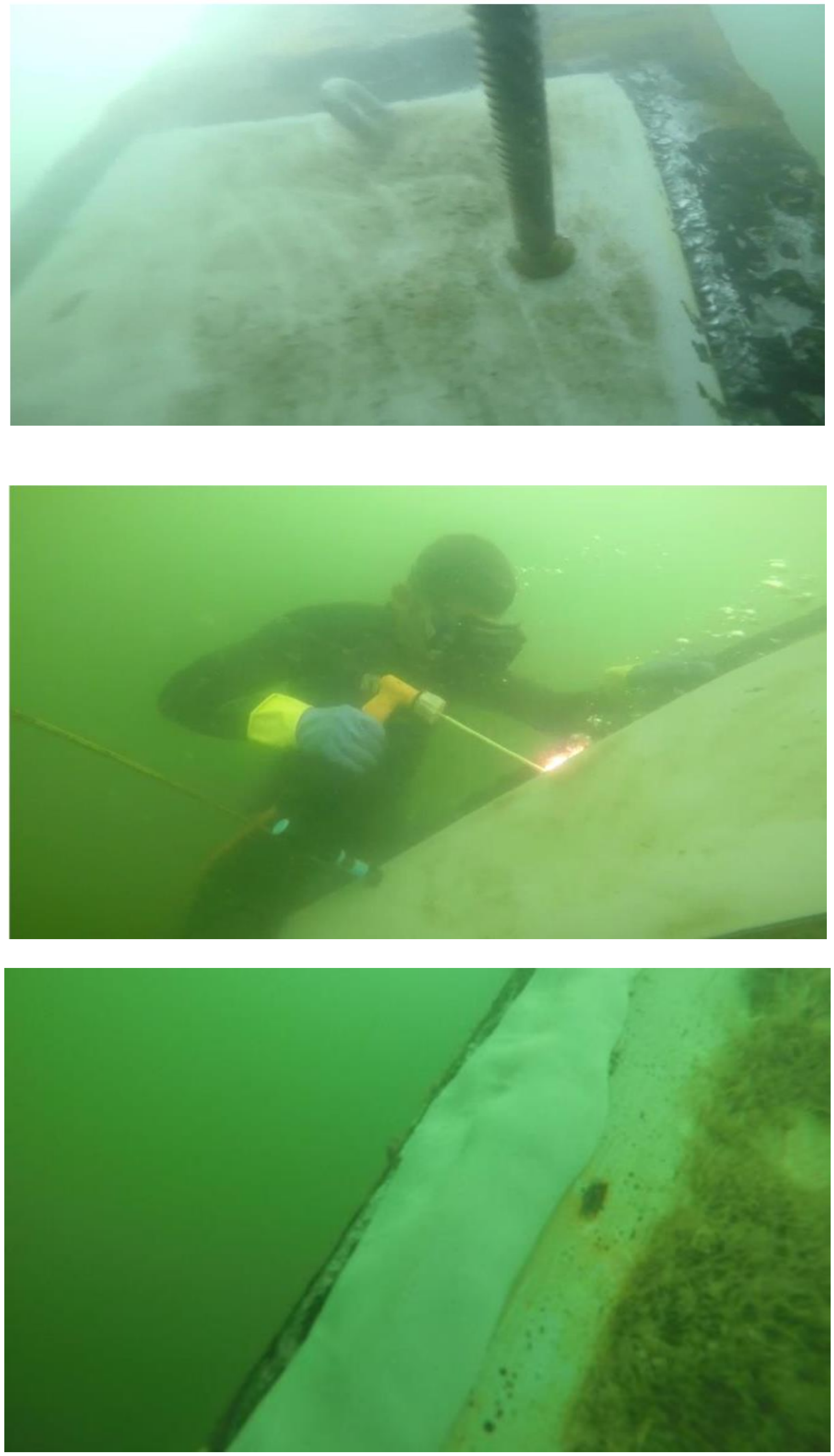


Fig. 21 Procedure for reinforcement of H-piles (Above) Installation of plates (Center) Underwater welding of plates (Below) Underwater coating of welds and plates borders.