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 seafloor 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 of the sheet-piles, 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 surrounding the basin (or the inside), are mixed, with combinations of rubble mound slope breakwaters (rocks and precast concrete units), and steel plain sheetpile cells in circular arrangements, known as cellular cofferdams (Figs. 1 and 2).

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

- 737 m breakwater at north (named North Breakwater) with a 353 m rubble mound section, and 16 circular cells of 18.6 m in diameter;
- 219 m at south-east (called 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 of the cells are Arcelor AS-500 type, 500 mm width. The thicknesses vary as per the diameter of the cells, being 11.0 mm on the 12.2 m cells, and 12.7 mm on the 18.6 m cells.

The steel of these sheet piles is ASTM A690, which is “marine” steel, with a yield strength of 345 MPa. It is recognized that on the splash zone (wave and tidal exchange), this steel type has a corrosion resistance of 2-3 times more than normal steel, but not in the submerged part, where normal and marine steel have similar corrosion rates [1].
The sheet piles were not protected by a barrier, i.e., with no paint or coatings prior to their installation, nor with concrete or other material once constructed. Also, no anodes were placed for cathodic protection of the submerged parts. As a 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, without affecting the capacity of the cells. This leads to the need to follow up the corrosion of the sheetpiles, 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, in a number of one section per cell or arch inside and two sections per cell or arch outside, with the purpose of being controlled annually.

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

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, by previously excavating the gravel and sand. This was made to understand the behavior of these sections compared to exposed cells.

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 the top of the cell down. At each elevation, 4 points were measured as shown in Fig. 3, so that minimum and average values could be considered for statistical purposes.

Defining the measurements in such way allows re-staking each section and points in a simple way, so that they could be repeated during annual campaigns.

When the measurements were above the water, access to the measuring points was done with stairs and platforms. On the other hand, 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 at each measurement point to clean the sheet-pile surface from marine life and corrosion, at each measurement point. The cleaning was done in a circle with 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 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. 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, included in this
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Fig. 5 Underwater thicknesses measurement with ultrasonic sensor.

paper, finished on April 2016, when the sheet piles had from 7-8 years of being installed. 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 rubble mound;
- June 2012 thicknesses measurements in the diaphragm wall, or inside the fill of the cells;
- February 2013;
- January 2015.

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]:

\[ F_{t, Rd} = \min \left( \frac{0.8 \cdot R_{k, s} \cdot t_m \cdot f_y}{S.F. \cdot S.F.} \right) \]

\[ F_{t, Ed} = P_{m, Ed} \cdot R_d \]

\[ F_{t, Ed} \leq F_{t, Rd} \]

where,

- \( P_{t, Rd} \) is the admissible tension;
- \( r_m \) is the cell radius;
- \( t_m \) 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.

Critical elevations could vary from cell to cell and could be either above or underwater. 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 is lower.

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 relationship between the measured thickness and the maximum tension that theoretically can support the connection. This is based on ARCELOR design manual as per Ref. [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, are summarized minimum thicknesses in the inner and outer exposed cells of main and connecting arches, as well for the connecting yees (or joints).

In addition to the 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 toward the outside of the cell and the resultant hoop tension of the sheet-piles.

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 3-4 times higher.

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.

3.2 Thicknesses Measurements

The measurements from 2016, for the inside of the north breakwater, could be seen graphically in Fig. 6. 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 LLWS (lowest water level spring) so that effects of tides are recognized. Similar graphs could be considered for the other exposition conditions i.e. south breakwater, and outside the basin.

From these 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.

Also, statistically, the distribution of quantity of measurements for given ranges is also considered, as shown in Fig. 7. This graph shows the thickness measurements distribution for the north breakwater outside the basin, but graphs are similar for other exposition conditions.

Inside the north breakwater, 49% of measurements above LLWS and 60% below LLWS are between 12.0-12.5 mm, with a minimum measured thickness of 9.8 mm.

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

| Location | 12.2 m cells | 18.6 m cells |
|----------|--------------|--------------|
| Outside  |              |              |
| Above water | Sheeptile | 1.8 | 1.4 |
|   | Joint | 2.5 | 1.9 |
| Below water | Sheeptile | 1.4 | 2.4 |
|   | Joint | 2.2 | 3.4 |
| Inside   |              |              |
| Above water | Sheeptile | 1.3 | 1.6 |
|   | Joint | 2.0 | 1.9 |
| Below water | Sheeptile | 1.2 | 2.5 |
|   | Joint | 1.9 | 3.5 |
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 sheet piles 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, i.e., north and south breakwater, and inside or outside the basin.

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 of the lowest spring tide (LWWS). 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. Outside the south breakwater, and depending on height, corrosion is concentrated on central cells.

### 3.4 Thicknesses Differences

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 in Fig. 9.

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.

### 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 were included with a separation between them of 0.5 mm.

![Fig. 9  Thicknesses differences of measurements, 2016-2012.](image)
Fig. 10 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 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, it 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 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 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.

3.5 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).

Lifespans can also be calculated based with the differences between the average measurements of 2012 and 2016 for each point. 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.

The previous is summarized in Figs. 11 and 12, 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.

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 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.

6. Future Activities

6.1 Measurements Follow-up

Sheet piles should be monitored in accordance with the guidelines explained herein. Comparisons with new annually campaign measurements, must be done. In this regard, measurements, that will have more time from the baseline (year 2012), will help determining a more exact corrosion rate for the sheetpiles.

As sheet piles are losing thickness on the future, more attention should be paid to subsequent thickness measurement campaigns to detect problems.

6.2 Sheetpile Protections

Quantifying the conditions of the cell piles, by sections and points, including the general and specific lifespans, makes it 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.

Based on the current results, it is being recommended only the application of a barrier protection in the areas above water with higher overall corrosion. This could vary if there are important changes in corrosion rates or behavior in future campaigns.

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

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, if 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 recommendation 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

For concrete covers, to warranty the complete adhesion of the concrete to the surface, it 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 to support an internal reinforcing steel mesh. Thicknesses of covers are variable and starts 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 performed prior to formwork and final coating casting, as required.

It is recommended to use concrete with a minimum resistance of 350 kg/cm², 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 concrete covers.

Primarily, the segregations and washes of the concrete should be avoided, including if necessary, the use of impermeable forms, 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 others.

6.5 Underwater Cathodic Protection

The area and location of the surface to be protected, water resistivity, and time of protection, drive the size and quantity of sacrificial anodes required per design. The anodes are placed on the surface, which, when it is 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 that they protect. Accordingly, they are usually
referred to as sacrificial anodes.

The 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 anodes will be placed, must be cleaned either by manual means (rackets and wire brushes), and/or pneumatic and hydraulic procedures (compressor and grinders or escalators).

The area must be clean of marine life, and corrosion products. The cleaning must be such that there is a free minimum area around anodes legs, so that they could be welded.

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, it is advisable to make a record of several aspects of welding as location, polarity, amperage, voltage, electrode characteristics, and so on. Also, welds must also be inspected after 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 using 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 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 that the phenomenon of corrosion is being presented in all the steel sheet piles.

However, this corrosion is not homogeneous and there are different behaviors 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 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, taking as the initial thickness of the sheet pile, the measurement of 2012.

Thus, the difference is obtained with the measurements of 2016, which represents the thickness losses 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 requirement 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. For these sections specific and directed solutions, could be accounted for, to protect those specific sections of sheet-piles, rather than apply general solutions.

In maintenance, this in turn, allows to make a more efficient, economic and safe use of the resources, principally applying them when they are required.

In general, the protection of sheet-piles could be done, above water in the intertidal and splash zones by barriers (coatings or concrete cover), and below water using cathodic protection.

At current time, the protection from corrosion, of the steel surfaces, by a barrier is what is recommend, since structurally thicknesses are above for what is required, as minimum as calculated by design.

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