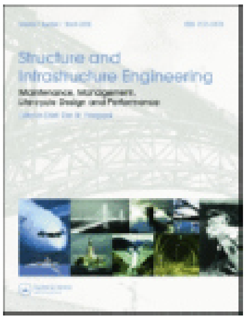
Upgrading of quay walls at the Ravenna port, Italy: evaluation of the steel piles degradation after a long working life



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# Upgrading of quay walls at the Ravenna port, Italy: evaluation of the steel piles degradation after a long working life

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**ABSTRACT**

In the context of a challenging project aimed at the upgrading of some old quays in the port of Ravenna (Italy) an extensive survey was conducted to determine the level of degradation of the most significative structural elements. The quays were essentially constituted by anchored sheet pile retaining walls in which the main structural elements were steel profiles. Therefore, the main point of concern was the degradation of the steel piles after a long-lasting exposure to the sea water. The corrosion of steel structures in marine environment is a well-recognized problem for maritime engineering, therefore nowadays a relevant part of the designing effort is oriented towards improving the durability and to minimize the cost of maintenance of infrastructures. However, data from real experience are not frequent. This paper presents some results of the inspection carried out on quays in the Ravenna port after an operative life between 21 to 29 years, focusing on the condition of the steel piles. Data include ultrasonic measurements of the thickness and laboratory analyses of steel samples. Although the environmental conditions were not particularly favourable, the results indicate that the degradation of the profiles in the permanently immersed zone was very limited.

**Keywords**
Durability, Corrosion, Ports, docks & harbours, Retaining walls, Steel structures, Maintenance & inspection

## 1 INTRODUCTION

A quay wall is one of the most challenging marine geotechnical structures, especially in port areas characterized by poor ground conditions. In these cases a profitable structural solution is based on the use of steel sheet piles because it offers a good balance between costs and performances, has the advantage of using precast structural elements of certified quality, allows an in-situ timely installation and, specifically from geotechnical perspective, favours the mobilization of the shear strength of weak soils thanks to the flexibility of the steel profiles. Moreover, recently improved profiles can be used to cater for heavy vertical load and large bending moment.

However, some concerns on the use of steel structures in aggressive environments for metals, that is marine water, appear justified. On more than one occasion corrosion processes have caused significant damage to steel structures shortly after their construction (Melchers, 2008; Greimann and Stecker, 1990). In this sense, the failures occurred to several quays, due to localised corrosion of the wall retaining systems, are emblematic (Barley, 1997; Ruggeri et al., 2013). These events highlight the diffuse underestimation of the durability aspects in many infrastructural works designed in the past and suggest taking more care with upgrading interventions for existing structures to achieve more demanding requirements (Roubos and De Gijt, 2013; Ruggeri et al., 2019). It is known that different interventions are possible to upgrade a quay (Franco and Noli, 1985; EAU, 2012; De Gijt and Broeken, 2013; Ruggeri et al., 2014; Bauduin et al., 2017; Ruggeri et al., 2019), but an appropriate knowledge of the current state of the structure is the basic condition to ensure the reliability of any design activity on existing structures.

The usual engineering countermeasures to ensure the required service life of sheet pile walls are the protection of the most exposed zone of the structure by coatings and the increasing of the thickness of the profiles where the corrosion rate is low. For operative quay walls in ports this means to use the coating for the splash and low water zones of the sheet pile and oversize the thickness in the immersed zone. Considering that sheet pile quay walls are often anchored structures in which the maximum bending moment takes place in the permanently immersed zone, exactly where the steel is directly exposed both to the soil and to the sea water, it is assumed that the safety of the geotechnical structure is guaranteed by the low progression of the corrosion of the steel profiles. The approach based on the use of sacrificial steel assumes that the corrosion process is uniform on the whole metal surface so that pit corrosion or other types of localised damaging process are not considered. In practice, a uniform loss of steel thickness is considered, whose amount is a result of the prescribed service life and aggressiveness of the environment.

Knowledge of the actual corrosion rate is thus a fundamental parameter when assessing the safety of the quay for its entire operative life. However, recent scientific literature offers a limited number of investigations on existing structures. Among others, Lee and Chang (2006), Bethencourt et al. (2007), Mackie (2009), Wall and Wadso (2013), Melchers and Jeffrey (2013), Solorzano (2018) present interesting surveys on corrosion aspects of steel marine structures.

This paper shows the results of an investigation aimed at evaluating the conditions after some decades of operative life for several sheet pile walls located in the port of Ravenna (Italy), in the Mediterranean Sea. The investigation aimed at providing reliable data to ensure safety for upgrading works of several quays. The survey was extended to the main structural components of the quay, that are steel profiles, concrete top beam, reinforcing bars and tendons. After a brief presentation of a typical survey on a quay, the paper focuses on the results of the investigation on the steel profiles. In particular, the results of in-situ ultrasonic measurements of the steel thickness performed by divers and laboratory analyses of some sample sheets, cut from the steel profiles, will be presented and discussed.

## 2 INVESTIGATIONS IN THE RAVENNA PORT

A comprehensive investigation on both the soil and the structures has been carried out to collect reliable data to design the upgrading works of several old quays in the Ravenna channel port.
In total, 5 different quays have been investigated, covering a length of about 1.750 m. After an overview of the port area, the main characteristics of the addressed quays and the typical investigation plan are presented. Details of the tests focusing the structural deterioration of the steel sheet profiles are then given together with a picture of the environmental conditions in terms of water chemical properties.

### 2.1 The port area

Ravenna is among the largest Italian ports, it is located along the eastern coast of Italy, on the Adriatic Sea, and it is developed along the banks of the "Candiano" channel (Figure 1a-b), an artificial waterway belonging to a natural lagoon. In Italian history, this port is one of the first in which sheet piles have been extensively used due to the very poor geotechnical properties of the subsoil that make the drivability of the piles easy.
The oldest large operative quays, designed for a seabed equal to 9-10 m, have been built between 1964 and 1971 and were formed by driven diaphragms precast with reinforced concrete, extending down to -20 m from sea level, back-anchored by a ribbed concrete slab sitting on a foundation of raked piles.
Since the 1980s, the driven concrete diaphragms have been substituted with steel profiles. Due to required seabed depth at the time, ranging from 10 to 12 m, the structural sections adopted for the operative quays typically consisted of a combined system of king piles (primary elements of H-shaped cross section) and infill sheets (secondary elements of Z-type cross section) back-anchored to anchor plates or retained by ground anchors.
In the Ravenna port area the subsoil includes granular deposits of loose sand and normal consolidated silty clay. Specifically, the current stratigraphy of the site, originated from a recent geological evolution of the Po Plain, is related to eustatic movements of the sea. Three main layers were identified in the area: the first, ranging from 8 to 15 m below sea level, is characterized by sands belonging to the most recent phase of the Holocene regression; below this layer and up to 25-26 m below sea level a layer of soft silty clay, with small lenses of sand and silt deposited in the marine environment during the extension of the Holocene transgression is found. Several samples of this layer contain between 5-10% of sands, but the overall behaviour is always matrix-sustained as demonstrated by several Authors (Irfan & Tang, 1993; Ruggeri et al., 2016). These two layers lie on a dense, grey sandy silts and silty sands that form the beginning of the continental depositional sequence in which granular layers take turn with cohesive strata. In Figure 1c is shown the geotechnical cross-section along the quays of the left side of the "Candiano" channel in which it is easy to identify the three mentioned soil deposits. Moreover, in the zone of interest, below the anthropic unit, some meters of soft clay, belonging to an old salt marsh, are present. Details on the geotechnical characterization of the port area can be found in Segato et al. (2010) and Ruggeri et al. (2020).
The tidal conditions of the port area have been defined thanks to the availability of the Porto Corsini tide gauge, an historical Italian tide gauge station located close to the entry port. As shown in Bruni et al. (2019) Porto Corsini tide gauge station was built in 1873 and today more than 140 years of readings are available. As demonstrated by the evolution of the medium sea level measured at Porto Corsini, the subsidence phenomenon that affect the port area is evident. The subsidence, partly of natural origin but mainly due to anthropic activities, determines a lowering of the port area of 10-15 mm/years. Considering the different factors, by evaluating the readings of the Porto Corsini tide gauge, it is possible to assume a HAT (LAT) value equal to +0.50 m on m.s.l. (-0.50 m on m.s.l.) and a MHW (MLW) equal to + 0.35 m on m.s.l. (- 0.35 m on m.s.l.).

## 2.2 Main characteristics of the investigated quays

The age and structural solutions of the five investigated quays allow to distinguish 3 groups of structures named A, B and C. All quays are back-anchored sheet pile walls, with the retaining system constituted by ground anchors. The seabed close to the walls was about 10 m below the medium sea level. None of the quays are or have been equipped with cathodic protection. The splash zone of each quay was protected by the concrete top beam and, even if not clearly indicated in the original project, the tidal and low water zones were protected by epoxy coating.

Quay A is a structure built in 1988 for a length of 240 m. During its construction, a new segment, named quay A1 of 130 m, extending towards North-East, was added to the initial segment. Both A and A1 quays are constituted by combined steel sheet piles manufactured by Arbed (now ArcelorMittal, Luxemburg), identified with the commercial code HZ775B/ZH9.5. This code means that king piles are H-shaped with total cross-section height equal to 775 mm, thickness of the flanges type B (19 mm thick) and intermediate Z-type profiles, identified by the code 9.5 that correspond to the thickness (in mm) of the steel plate.

Quay B is a structure built in 1992 for a length of 320 m. Soon after the construction of this quay, the same solution has been extended towards North-East for a length of 220 m, forming a new quay here identified as B1. For quays B and B1 the designers have adopted the same structural section used for quay A, identified with the code HZ775B/ZH9.5.

Quay C is the most recent geotechnical structure considered here, being built in 1996. It spans 840 m and its construction required a number of modifications of the project, originally defined in 1994. As a result of analysing the progress of the construction works it is evident that the selected sheet piles were installed in 1996. Quay C has been designed for heavy loads, according to a more recent design standard than that adopted for quays A and B. For these reasons, the selected sheet pile section was very robust HZ975C-14/ZH9.5 profile. This code indicates a large H-shaped king pile, with a cross section height of 975 mm, thickness of the flanges type C (21 mm thick) and strengthened by the adoption of 4 connectors at the edges of the flanges. Z-type profiles with thickness equal to 9.5 mm were used as intermediate elements. Moreover, the design drawings clearly indicate that the sheet pile face exposed to the marine water was protected by epoxy coating for 3 meters below the top beam.

Table 1 collects the main data of the steel profiles of the inspected quays, indicating years of construction, age of the structure (referred to the date of the investigation, summer 2017), total length of the quays, commercial code of the structural profile and nominal thickness of the king pile flange. Note that close to the nominal thickness of the king pile flange the tolerance specified by the manufacturer is given in the 1985 product sheet. The value of such tolerance is not negligible and may be a source of error when evaluating the corrosion rate of profiles for which the original thickness is unknown.

In Figure 2 a map of the sector of interest with the location of the investigated quays and the position of the inspection profiles is shown; such profiles are identified by a label ranging from P1 to P10. For each quay, a cross-section of the structure with the indication of the relevant stratigraphy and structural profiles are presented.

## 2.3 Typical investigation for a single quay

In Figure 3 the cross section of a considered quay with indication of the investigations carried out to verify the degradation of the structure are shown. In particular, the aspects of major relevance being addressed are:

- quality of the concrete of the top beam: some concrete's samples have been cored and subjected to compression tests;
- steel grade of the reinforcement bars: some rebar's specimens have been taken from the top beam and subjected to tensile tests;
- condition of the anchor head: some anchor's heads have been opened to inspect the degradation of the barrel-wedge devices holding the tendons;

- protection of the tendons along the free length: excavations have been made behind the top beam to visually inspect the protection system of the tendons (i.e. presence of the double protection system);
- electric isolation of the tendons from the ground/structure: by measuring the electric resistance between the tendons and the top beam (or ground) it is possible to evaluate the integrity of the plastic sheath protecting the tendons from corrosion;
- condition of the steel profiles: thickness measurements and mechanical tests on small specimens.

## 2.4 Specific investigations on the steel sheet pile walls

The investigations on the degradation of the steel sheet piles have been carried out during the summer 2017. Two kinds of tests have been performed:
- measurements of the steel thickness at different depths;
- laboratory testing on small steel portions cut from the flanges of the king piles.

The measurements of the thickness have been carried out by ultrasonic gauge (Cygnus 1 Underwater MK4, Cygnus Instruments Ltd, UK) operated by a diving team. Two king piles for each quay were inspected at depths of 0.50 – 2.50 – 4.50 – 6.50 – 8.50 m below the medium sea level. Before the execution of the measurements, the surface of the sheet pile has been properly cleaned by the divers, removing the marine fouling. It should be noted that beneath the tidal zone, where seaweeds and shellfishes were present, the piles surface was covered by a biofouling stratum of small thickness.
For 5 of the inspected profiles (namely P1, P3, P5, P7, P10 of Figure 2) a portion of the flange, approximately 200 x 500 mm (B x L), has been sampled from the king piles by oxy-arc underwater cutting. This sampling was carried out approximately at a depth of 2.50 – 3.00 m below m.s.l. where the bending moment is still low and the damage of the profiles could not affect the structural safety of the quay. The steel samples were used to assess the reliability of the ultrasonic thickness measurements and meanwhile to evaluate the material properties by tensile tests.

## 2.5 Quality of the seawater in the port area

It is known that environmental conditions have an influence on the rate of the corrosion process. Currently, a general picture of the situation in the port area can only be outlined, because data from long-term monitoring of the water quality are lacking. Some measurements of the chemical properties of the water are available thanks to the environmental survey carried out for planning the dredging activity of the port channel. Measurements carried out by a multiparameter probe in April 2014 indicate the following data for the channel water: salinity 28.5-29.3 g/l, temperature 16-17°C, pH 8.4-8.7, dissolved oxygen 7.0-9.0 mg/l. These data have been compared with those given by the climatological map of the Adriatic Sea produced by Lipizer et al. (2014); for the Ravenna coast, this map indicates: salinity varying from 29 (winter) to 34 g/l (summer), temperature of water ranging from 7°C (winter) to 24°C (summer), oxygen ranging from 8 (winter) to 6 mg/l (summer). Measured data are therefore well in agreement with the general climate parameters of the Adriatic Sea, with little differences probably related to the proximity of the port of Ravenna to the mouth of the Po river, that is the biggest Italian waterway. This justifies the relatively high concentration of Nitrates (up to 2.5 mg/l, that is about 0.56 mg N/l) observed by Corinaldesi et al. (2003) along the Ravenna coastline, especially in Spring and Autumn. Even if accurate measurements of Dissolved Inorganic Nitrogen (DIN) in the port area are missing, single measures of Nitrates, for water quality check investigations of the harbour, confirming the same figure.
For comparison, typical climatological data of other European seas (Brasseur et al., 1996; Janssen et al., 1999) are: Baltic Sea - salinity 4-8 g/l and a temperature of the shallow water (0-10 m depth) ranging from 0 to 16°C (winter/summer); North Sea - salinity of 32-34 g/l and a temperature ranging from 6° to 14°C (winter/summer) along the coast of Scotland and Norway and ranging from 3° to 18°C (winter/summer)

along the coast of Germany and Denmark; Mediterranean Sea – salinity of 37-39 g/l and a temperature ranging from 13 to 24°C (winter/summer) in the West side and from 17 to 28°C (winter/summer) in the East side. Figure 4 presents all the collected data: it results that salinity is very similar for all the considered seas (with the well-known exception of the Baltic Sea in which values are extremely low), whereas the temperature varies more significantly both in the seasonal and extreme values. Taking into account the dependence of the corrosion rate from environmental parameters, as clearly pointed out by Nevshupa et al. (2018), it is confirmed the importance of providing corrosion data for different environments of exposure.

## 3 CODES AND RECOMMENDATIONS: FOCUS ON CORROSION RATES

Designers generally take into account the corrosion problems by referring to technical codes such as Eurocode 3 part 5 (EN1993-5) and Recommendations of the Committee for Waterfront Structures – Harbours and Waterways (EAU, 2012). From the designers' perspective, the corrosion of the steel piles causes a progressive reduction of the section properties of the structural elements. Basically, codes and recommendations provide an estimation of the corrosion loss so that the designers can consider an initial over-thickness of the profiles to guarantee the safety of the structures for its entire life span without buckling or exceeding design stresses.

Generally, these standards provide different values of the corrosion rate for different zones of exposure with a rate progressively decreasing with time. This last assumption, recently confirmed by a widespread European research project (Houyoux et al., 2007), may be reasonably explained as the result of the protection offered by the corrosion products deposited over the metal surface that, when not removed by erosion, impedes oxygen to reach the deeper metal. This recalled European research project, by addressing several publications on marine corrosion of steel structures and by means of a number of laboratory trials, pointed out that the steel corrosion is a multi-factorial process dominated by age of exposure, water environment (temperature, salinity, dissolved oxygen) and acid content of water (pH). For this reason, it can be very useful to check the validity of such suggested rates with real measurements.

With reference to a sheet pile wall, specific zones with different levels of corrosion rate are defined in relation to their respective positions to the sea level, considering the tidal oscillation amplitude. Five distinct vertical zones are typically identified:

- Splash zone: from the deck plane to the level of mean high water level (MHW);
- Intertidal zone: area between mean high water (MHW) and mean low water (MLW) levels;
- Low water zone: from the mean low water level (MLW) to a depth of water of about 2 m;
- Permanently immersed zone: beneath the low water zone and till the seabed;
- Embedded zone: below the seabed on the sea side and over the entire ground side of the steel profile.

The proper identification of the tidal zone is not as simple as it would appear at first sight, as confirmed by Mackie (2009). It is useful to remember the main definitions of the tidal levels: HAT (LAT) – Highest (Lowest) Astronomical Tide, that is the highest (lowest) level that can be expected to occur under average meteorological conditions over a Metonic cycle (18.6 years); MHW (MLW) – Mean High (Low) Water, that is the arithmetic mean of the values of mean high (low) water springs and mean high (low) water neaps.

The corrosion rate in the embedded zone is always very low both according to EAU recommendations, in which the rate value of 0.01 mm/y is stated, and Eurocode 3, in which depending on the aggressiveness of the soil, the recommended rates ranges from 0.60 mm in 50 years (0.0012 mm/y) for undisturbed natural soil to 1.75 mm in 50 years (0.035 mm/y) for aggressive natural soils like marsh and peat.

Figure 5 compares the thickness of metal loss after 25 and 50 years of exposure according to EAU2012 and to Eurocode 3 for the previously defined zones. The given thickness losses refer to the outer flange of the king pile and include both the corrosion on the sea side and on the ground side, the latter refers to undisturbed deposits of natural soil. It should be noted that EAU 2012 provides a mean value and a maximum value of the thickness losses due to the corrosion process. It is evident that the values proposed by the Eurocode 3 match the corresponding mean values of EAU 2012. It is worth noting that the maximum value proposed by EAU 2012, often prescribed as reference for the design in some countries, is extremely severe for every surface exposed to the sea water.

A decrease in the corrosion rate when moving from the splash zone to the permanent immersion zone is expected, even though other factors may alter such simple behaviour: the typical macro-corrosion cell that takes place between tidal and low water zones tend to protect the tidal zone (cathode) at the expense of the low water zone (anode); the role played by pollutants (e.g. oil) floating on the sea surface, that may cover the steel in the tidal zone and modify the availability of oxygen and nutrients close to the metal; the aggression due to the growing of bacterial colonies.

It is well known that this last phenomenon is particularly dangerous in the low water zone, as shown by the PIANC report (Maritime Navigation Commission, 2005) that defines this kind of corrosion as "Accelerated low water corrosion" (ALWC). ALWC is a localised, aggressive corrosion characterized by a rate of 1 to 5 mm per year, typically occurring in the zone between the mean low water level (MLW) and the lowest astronomical tide (LAT), in which the environmental conditions favour the growth of bacterial colonies. The development of bacteria able to promote corrosion is associated to the microbial sulphur cycle in which the sulphates present in the environment are converted by sulphate reducing bacteria (SRB) into hydrogen sulphide (H2S) that is in turn converted into sulphuric acid by sulphide oxidising bacteria (SOB). So, it is this acid environment generated by the bacteria that enables the direct consumption of the steel. It should be noted that ALWC usually causes a pit corrosion leading to a strong degradation of the structural capacity that may become quickly dangerous without a proper protection of this zone.

Recently, under a different perspective, Melchers (2005) and Melchers and Jeffrey (2014) pointed out the general dependence of the corrosion process by the microbiological activity, not only in relatively shallow water but also in permanent immersed zone. These studies consider the availability of nutrients in the water, in particular the dissolved inorganic nitrogen (DIN), as the main parameter able to control the long-term steel corrosion process. Melchers (2003), Peng et al. (2017) and Melchers (2018) proposed a phenomenological model for the long-term corrosion loss based on a sequence of phases. At the beginning, the process is controlled by the amount of oxygen that reaches the metal surface, then the thickness of the corrosion product promotes the establishment of an anaerobic condition close to the fresh metal. Such anaerobic environment is favourable to the growth of sulphide reducing bacteria (SRB). Initially, this process proceeds with high corrosion rate, then it reaches a near steady state progression (i.e. linear with time) in relation to the availability of nutrients. In the long-term, the corrosion loss can be described as a linear process defined by the equation $c(t_e) = c_s + r_s t_e$ in which $c(t_e)$ is the corrosion loss at the exposure time $t_e$, $c_s$ represents the y-intercepts, and $r_s$ is the corrosion rate.

# 4 RESULTS AND DISCUSSION

## 4.1 Inspection of the flange samples

A picture of the outer surface of the samples taken from the flanges is shown in Figure 6a. The black epoxy coating of the surface of the plates is evident from the pictures, although not uniformly preserved. Note that the general rusty state of the surfaces is a consequence of the rapid oxidation of the metal after the oxy-arc cutting; this is confirmed by the picture of Figure 6b taken soon after the sampling in which no evidence of rust can be found. Moreover, it should be considered that the samples were taken 2.50 – 3.00 m below sea level that is very close to the permanent immersed zone and it is possible that in the low water zone the preservation of the coating was worse than on the sampled plates, especially for the oldest steel profiles.

Some specimens have been cut from the plates for tensile testing. Table 2 summarizes the results of such testing and compares the obtained values with the nominal properties of the steel. Figure 6c shows a specimen after tensile testing. An acceptable behaviour of the tested specimens in terms of yield stress, ultimate stress and elongation considering the possible disturbance caused by heating due to the oxy-arc cutting and to the lowered thickness of the samples can be observed. Moreover, no strength weakening (e.g. metal fatigue) has been observed.

### 4.2 Measurements of steel thickness

The measurements of the flange steel thickness are displayed in the graphs of Figure 7 for the three quays (A-A1, B-B1, C) together with the representative stratigraphy for each segment. Moreover, the measured thickness is compared with the nominal thickness of the king pile flange. Preliminarily, it should be noted that measurements on quays A-A1 and B-B1 indicate the reduction of the thickness with respect to the nominal values everywhere; on the contrary, the measured thickness for quay C resulted equal or slightly higher than nominal, therefore indicating an initial over-thickness of the profile.

Unfortunately, accurate measurements of initial thickness of the profiles are missing. This is a common problem of many old structures, related to the absence of any specific measurement of the size of the steel profiles in the inspection documents. To overcome this difficulty, it is possible to relate the size of the profiles to the original weight of the steel at delivering to the construction site. In fact, for every public work in Italy, the weight of any precast steel product must be checked by the Supervisor before installation and reported on the worksite book. This approach has been tested on the quay C. By examining the original official notes for the quay C, it resulted an extra-weight of the 3.4% in respect to the nominal weight of the steel profiles. For comparison, this value is much higher than the extra-weight resulting for quay A, which was equal to 0.4%. So, as a first approximation, by increasing 3.4% the nominal thickness of the king piles of the quay C (21 mm), the value of 21.7 mm is obtained. Such value fulfils the tolerance limit at delivering and can explain the actual thickness of the pile of quay C. However, this estimation is based on the unverifiable hypothesis that every plate of the steel profile is 3.4% heavier than the nominal. For these uncertainties, Quay C measurements were excluded from the corrosion rate assessment.

Apart from this aspect, it can be observed that the reduction of thickness is always very small and roughly uniform for the entire inspected depth. It means that for all the examined quays the structural safety after a long operative life is still not an issue. This result was meaningful for the designers when planning the upgrading of the quays, because the old steel structures resulted perfectly reliable.

Only in two points of the quay A-A1 it is observed a more pronounced reduction of the thickness in the low water zone with respect to those at greater depths. These findings could be related to the different present efficiency of the protection of the low water zone offered by the coating: on quay A-A1, the oldest one which was investigated (29 year of exposure), the coating began to end its protection, while on quay B-B1 (25 year old) and quay C (21 year old) the coating appears still capable of limiting the corrosion process. This observation is consistent with international standards, typically suggesting an extra life of 20 years due to coating protection only. Moreover, no significant effect related to the kind of soil in contact with the steel were observed in the present case, even if a thick anthropic deposit and some meters of marsh clay are somewhere part of the soil stratigraphy.

Focusing on the measurements of the quays A-A1 and B-B1, for which the nominal thickness appears representative of the original thickness, it is possible to estimate the corrosion loss. In Figure 8 the profile of the thickness loss has been displayed in comparison with the corrosion profile provided by Eurocode 3 after 25 years of exposure. On the other hand, for the low water zone 5 years of exposure is considered as the service life of the coating protection. It can be observed that, with the exception of the inspected profile P6, all the measured patterns indicate a corrosion loss smaller than expected in the permanently immersed zone. In the low water zone the effect of the coating has been substantial to limit the corrosion process as demonstrated by the quay B-B1 in which the measurements carried out exactly after 25 year of exposure agree very well with the expected 5 years figures. On the contrary, quay A-A1, after 29 years of exposure, shows the exhaustion of the coating protection and the beginning of the much aggressive corrosion in the low water zone. The anomalous behaviour of the inspected profile P6 (quay A1) may be attributed to an initial under-thickness of the profile, as suggested by the uniform thickness at different depths measured in the permanent immersed zone.

A different evaluation of the corrosion loss has been performed by following the approach suggested by Melchers. Climatological data of the Ravenna port indicate an average annual water temperature equal to 15°C. The concentration of dissolved inorganic nitrogen (DIN) is probably high: tentative values equal to 0.0, 0.25 and 0.5 mg N/l have been assumed to estimate the intercept ($c_s$) and the corrosion rate ($r_s$) of the linear model proposed by Melchers and Jeffrey (2014). The resulting trends of the corrosion losses with time of exposure are shown in Figure 9 for different dissolved inorganic concentrations and compared with the observed corrosion rates for the Ravenna quays A-A1 and B-B1. The measured corrosion losses are generally lower than expected and the proposed trends always overestimate the observed data. Considering that the model of Melchers and Jeffrey is based on a wide variety of data from many sources it is probable that some environmental aspect in the Ravenna port favored the preservation of the steel in the permanent immersed zone. The available data do not indicate peculiar characteristics of the site that could explain the observations: for example, the concentration of dissolved inorganic nitrogen is high, so the explanation has to be found elsewhere. The most unusual aspect at the Ravenna harbour in comparison with ports worldwide is the location along an artificial channel, in which both water flow and tidal oscillations are small. So, we can speculate that these aspects contribute to limit the supply of both nutrients and oxygen to the metal.

In conclusion, the experimental results indicate that in the permanent immersed zone the corrosion rates well compare with the average values recommended by international standards and by recent approaches, so proving the very low progression of the corrosion process in this specific environment and that steel structures can be considered fully operative for long-time. In particular, the measured corrosion losses are largely lower of the maximum values suggested by EAU recommendation. A monitoring activity in the future should be oriented to check the evolution of the corrosion in the low water zone where the present data give evidence of the progressive exhaustion of the coating protection.

## 5 CONCLUSIONS

With the aim of collecting information useful to design the upgrading of old quays in the port of Ravenna (Italy), an extensive survey has been carried out to evaluate the level of degradation of the main structural elements. The quays were formed by anchored steel sheet pile walls and the designers were strongly worried about the corrosion suffered by the main steel profiles after a long time of exposure to the sea water. The paper focuses on the results of the investigation carried out on the steel profiles: it includes measurements of the thickness of 10 king piles in the permanent immersed zone, where the bending moment is very high, and the evaluation of the mechanical properties of the steel for 5 specimens cut from the flange of the main profiles. The examined king piles belong to 5 quays with operative life ranging between 21 to 29 years. Measurements of the thickness were carried out by means of underwater ultrasonic probing. Results indicate the integrity of the steel profiles, with a thickness loss generally less than 1 mm, in substantial agreement with the average thickness reduction corrosion values suggested by the standards and by recent findings. As the thickness loss is so small, an exact evaluation of the corrosion suffered by the profiles is masked by the thickness tolerance declared by the supplier. However, some useful information can be obtained from the existing documentation prescribed for any Public work and particularly from the weight of the profiles always registered in official documents. Moreover, for a reliable maintenance plan of every new quay, the as-built documentation should include a record of the thickness of each installed steel profiles resulting from on site direct measurements.

In conclusion, the good performance of the steel sheet piles observed at the Ravenna port can be accounted for by:

- the effectiveness of the protection of the most exposed zone of the steel structures (i.e. splash, tidal and low water zones) by the epoxy coating and the concrete of the top beam;
- a behaviour in line with the expected figures according to the literature for the permanently submerged zone.

Some more detailed analyses of the environmental conditions are necessary to justify the good performance of the steel with respect to corrosion which wasn't expected in a water rich in nutrients.

Moreover, where the coating becomes less effective, as observed in the low water zone for quay A, the corrosion rate rises quickly. Although for tied back structures the stresses in this zone are relatively small, our results shown that the coating efficiency is a key parameter to be monitored for a sensible planning of maintenance works. In conclusion, for design purposes, due to the efficiency of the coating protection in the low water zones and the low corrosion rate occurring in the permanently immersed zone, the investigated structures still present a good structural reliability that allows considering their full capacity, for the design of upgrading works.

Considering that corrosion is a multifactorial phenomenon in which both the steel characteristics and the environmental site-dependent parameters (e.g. water composition, temperature, pollution)play a significant role, it is very important to progressively improve our knowledge from the observations made on existing structures as it was possible for this particular case study.

**Acknowledgments**

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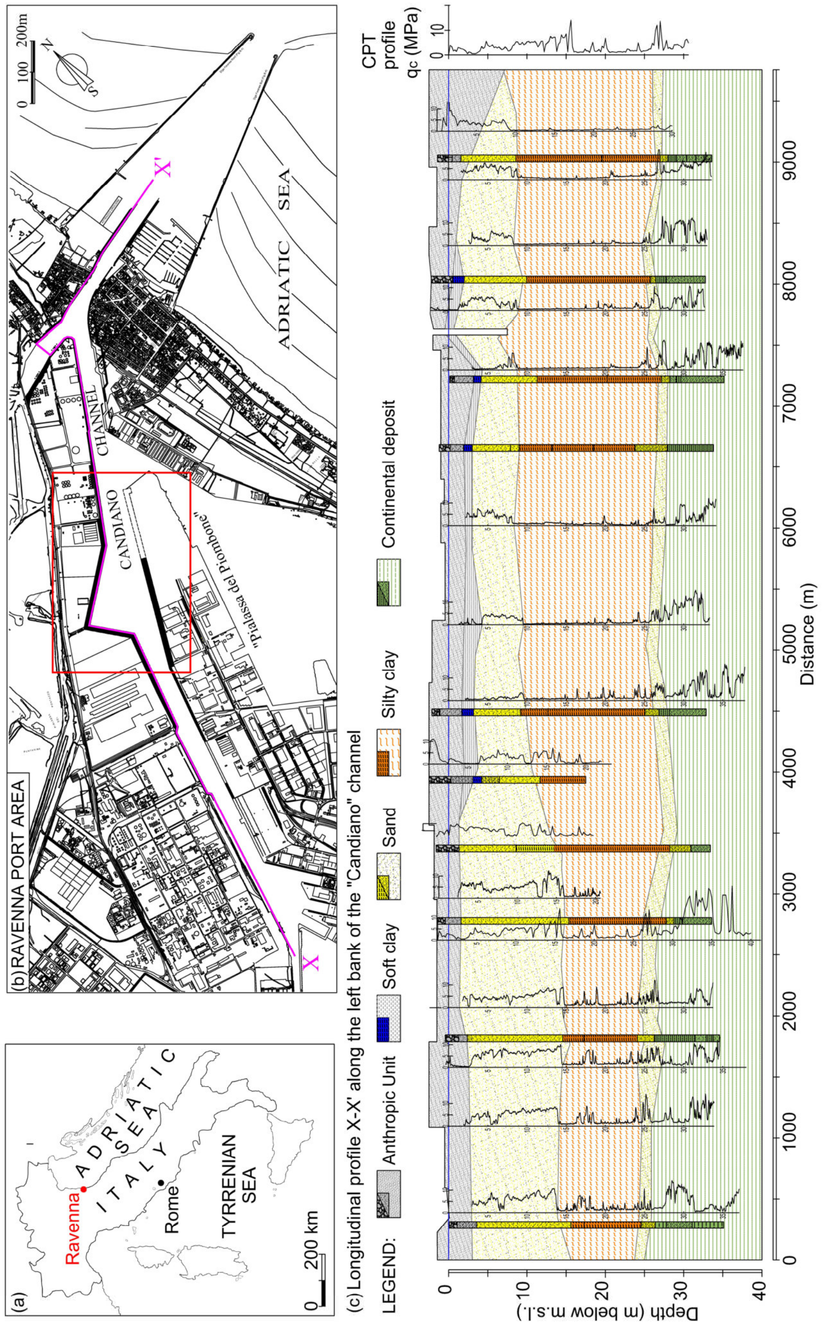
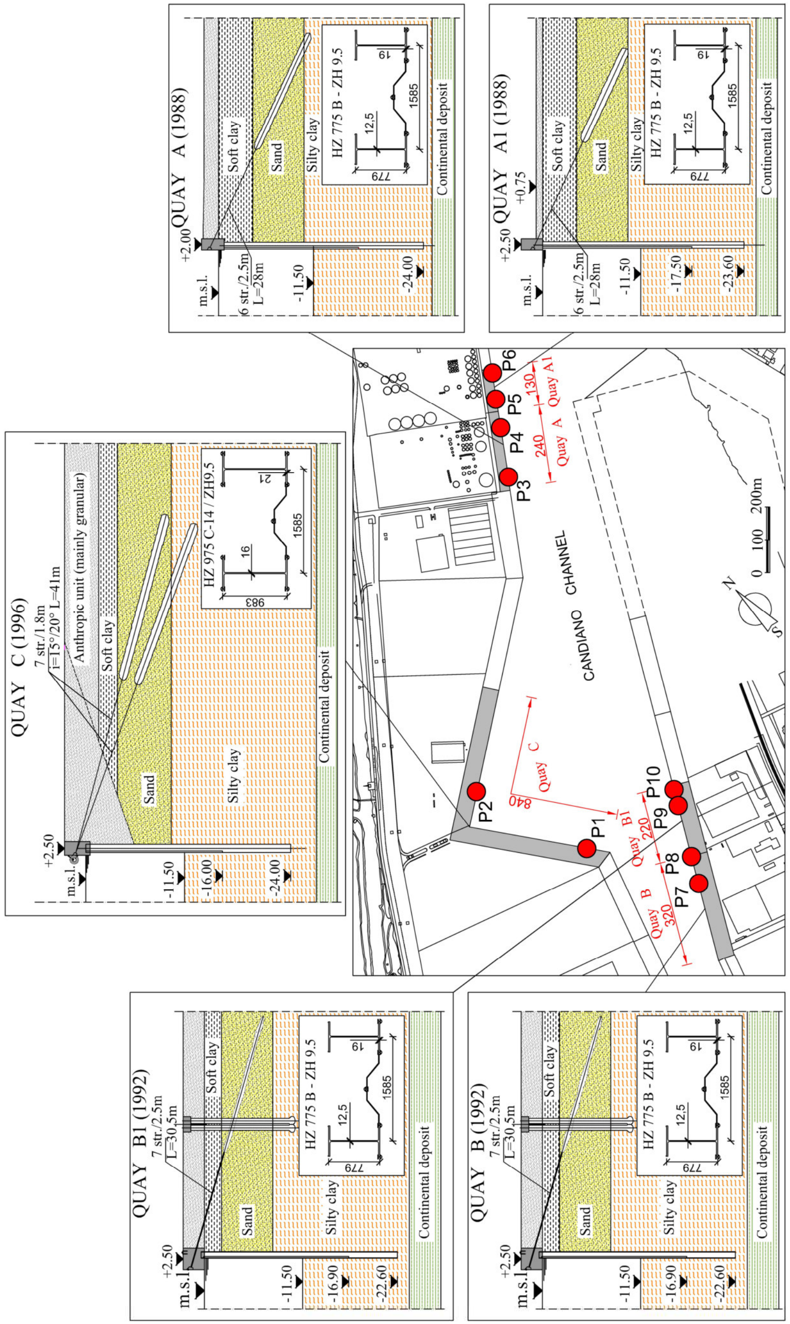
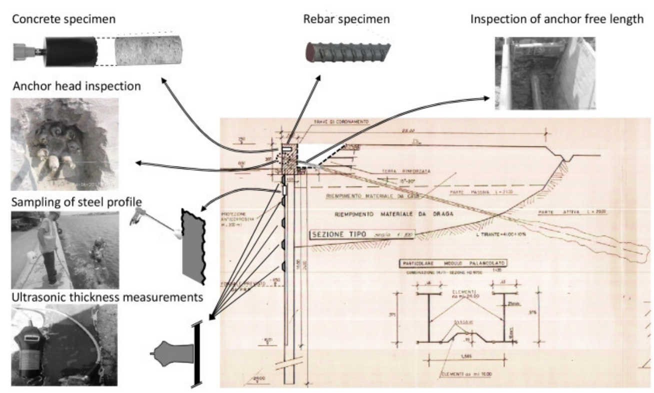

(a)
ADRIATIC SEA
ITALY
Ravenna
Rome
TYRRENIAN SEA
200 km
(b) RAVENNA PORT AREA
0 100 200m
N
S
X
X'
ADRIATIC SEA
CANDIANO CHANNEL
"Pialassa del Piombone"
(c) Longitudinal profile X-X' along the left bank of the "Candiano" channel
LEGEND:
Anthropic Unit
Soft clay
Sand
Silty clay
Continental deposit
CPT profile qc (MPa)
Depth (m below m.s.l.)
Distance (m)


QUAY A (1988)
QUAY A1 (1988)
QUAY C (1996)
QUAY B1 (1992)
QUAY B (1992)
Soft clay
Sand
Silty clay
Continental deposit
Anthropic unit (mainly granular)
HZ 775 B - ZH 9.5
HZ 975 C-14 / ZH9.5
6 str./2.5m
L=28m
7 str./2.5m
L=30.5m
7 str./1.8m
i=15°/20° L=41m
m.s.l.
+2.00
+2.50
+0.75
-11.50
-16.00
-16.90
-17.50
-22.60
-23.60
-24.00
CANDIANO CHANNEL
P1
P2
P3
P4
P5
P6
P7
P8
P9
P10
Quay A
Quay A1
Quay B
Quay B1
Quay C
240
130
840
220
320
0 100 200m

25/10/2019

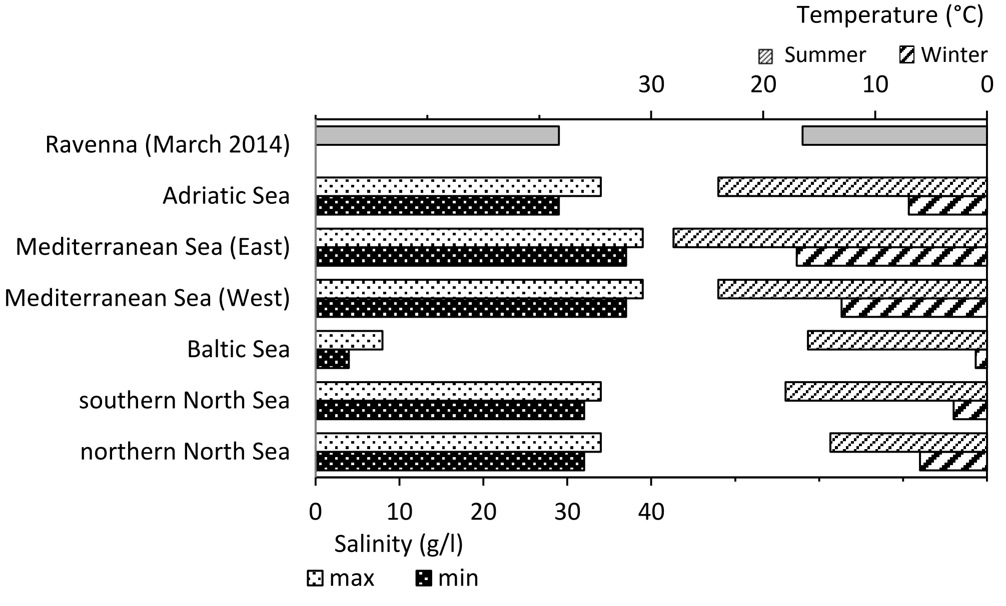



1

Figure 3. Typical investigations carried out on each quay

209x297mm (300 x 300 DPI)

# FIGURE 4


Temperature (°C)
Summer
Winter
30
20
10
0
Ravenna (March 2014)
Adriatic Sea
Mediterranean Sea (East)
Mediterranean Sea (West)
Baltic Sea
southern North Sea
northern North Sea
0
10
20
30
40
Salinity (g/l)
max
min

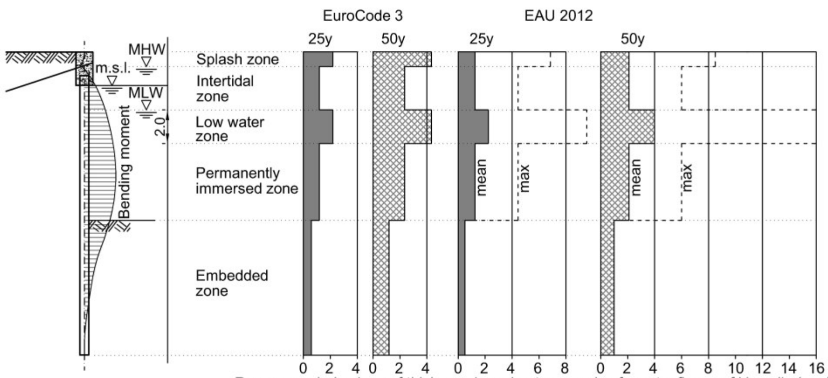



Figure 5. Vertical zoning of sea water on a sheet pile wall and recommended values for thickness loss due to corrosion according to Eurocode 3 and EAU 2012. Given values refer to 25 and 50 years of exposure for the outer flange of H-type pile

1749x2475mm (72 x 72 DPI)

**FIGURE 6**

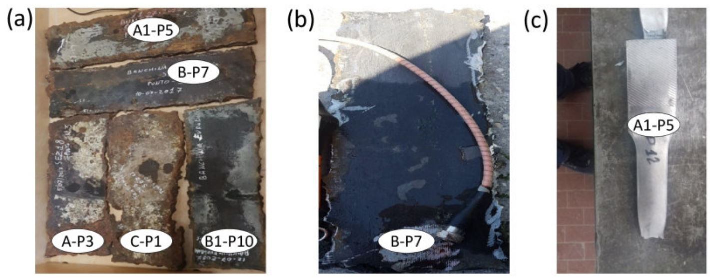



Figure 6

209x297mm (300 x 300 DPI)

**FIGURE 7**

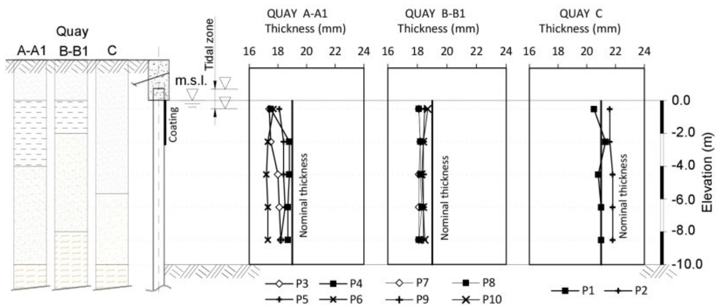



Figure 7. Measurements of the thickness of the steel profiles at different depth

209x297mm (300 x 300 DPI)

**FIGURE 8**

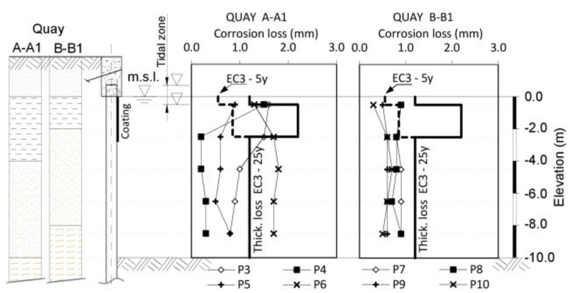



Figure 8. Corrosion loss evaluated from nominal thickness of the profiles compared with corrosion profiles suggested by Eurocode 3 for 25 y (□□□) and 5 y (- - -) of exposure

209x297mm (300 x 300 DPI)

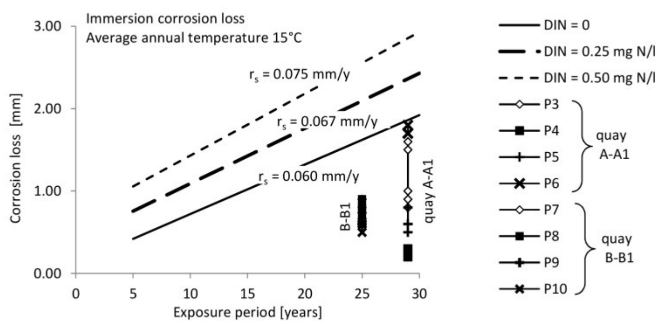



Figure 9. Measured corrosion losses compared with the linear model predictions according to Melchers and Jeffrey (2014)

209x297mm (300 x 300 DPI)

**TABLE 1**

| Quays | Year of construction | Age [y] | Total length [m] | Structural profile | Nominal flange thickness (mm) (± tolerances) |
|---|---|---|---|---|---|
| A | 1988 | 29 | 240 | HZ775B/ZH9.5 | 19 (+2.5/-1.5) |
| A1 | 1988 | 29 | 130 | HZ775B/ZH9.5 | 19 (+2.5/-1.5) |
| B | 1992 | 25 | 320 | HZ775B/ZH9.5 | 19 (+2.5/-1.5) |
| B1 | 1992 | 25 | 220 | HZ775B/ZH9.5 | 19 (+2.5/-1.5) |
| C | 1996 | 21 | 840 | HZ975C-14/ZH9.5 | 21 (+2.5/-1.5) |

Table 1. Main data of the inspected quays

190x274mm (284 x 284 DPI)

## TABLE 2

| Designation | Structural profile | Nominal flange thickness [mm] | Cross section of the speciment[+] B [mm] | W [mm] | Steel grade* | Minimum Yield Stress [N/mm$^2$] | Ultimate stress [N/mm$^2$] | Minimum elongation [%] |
|---|---|---|---|---|---|---|---|---|
| Nominal steel properties** | - | - | | | PAE 360 | 360 | 490 | 22 |
| Results of tested samples: | | | | | | | | |
| Quay A - P3 | HZ775B | 19 | 29.77 | 16.55 | PAE 360 | 412 | 569 | 26 |
| Quay A1 - P5 | HZ775B | 19 | 29.82 | 16.40 | PAE 360 | 349 | 487 | 27 |
| Quay B - P7 | HZ775B | 19 | 29.94 | 16.55 | PAE 360 | 344 | 481 | 31 |
| Quay B1 - P10 | HZ775B | 19 | 29.82 | 16.35 | PAE 360 | 354 | 488 | 34 |
| Quay C - P1 | HZ975C | 21 | 30.10 | 16.40 | PAE 360 | 412 | 548 | 26 |

[+] the thickness of the speciment has been reduced according to EN 10025 standard
*Designation according to NF 35.520 France standard
**Steel quality according to NF 35.520 France standard. Note that PAE360 corresponds to the Fe510B according to the EN 10025 standard

Table 2. Results of the laboratory testing

190x274mm (284 x 284 DPI)