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Corrosion rate measurements in Steel Sheet Pile Walls in a marine environment

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Abstract

Corrosion of steel structures in the marine environment is a major problem. The deterioration of this kind of structures is costly and difficult to predict both when designing new structures and when estimating the remaining service life time for existing structures. The aim of this investigation was to find indicative values for the corrosion rate of steel sheet piles on the Swedish west coast. Such corrosion rates (mm/year) can be used both when designing new structures by oversizing the steel thickness and when estimating the bearing capacity of existing sheet pile structures. Earlier investigations on the corrosion rates along the Swedish east coast – with salinity from about 0.2% - 0.8% – are still used today as guidelines for the corrosion rate of all steel structures in the Swedish maritime environment even though the salinity on the west coast can be as high as 3.0%.

Steel sheet pile wharfs located in the port of Halmstad on the Swedish west coast were inspected by ultrasonic measurements. Three wharf structures with a total length of about 700 m were inspected. None of the inspected wharfs had or have had cathodic protection. The thickness measurements of the steel sheet pile structures were performed by divers.

The age of the three inspected sheet pile structures ranged from 36 to 51 years. The dimensions of the original sheet pile sections are known. One of the quay structures is located along a river. The salinity at all wharfs varied from low values at the surface to approx. 2% at the bottom (also in the river outflow).

The measured average corrosion rates were in the same order as the design values in the European code. However, the results indicate increased corrosion rates about one meter below the mean water surface and at the level of the propellers from the ships berthing the most frequented of the inspected wharfs, 3 to 6 meters below water surface.

The tolerances of steel sheet thicknesses – usually in the order of ±6% – are often neglected when investigating the remaining thickness in steel sheet piles. A simple calculation model shows that the sheet pile must be almost 50 years of age before an accurate estimation on the corrosion rate can be made, considering the tolerances, if the true original sheet pile thickness is not known.

Keywords

Corrosion rate
Sheet pile
Marine corrosion

1. Introduction

1.1. Background

A large part of the international trade in the world is today transported at sea. The higher volume of transported goods by sea, along with larger freight vessels, set increased demands on the quays and ferry berths in our harbors. Since the loads on the quay decks increase with increased handling of goods and the deterioration in form of corrosion reduces the bearing capacity of the sheet pile structure, this can lead to a collapse. Figure 1 shows some typical quays in industrial harbors.

Many of the quays in Swedish harbors have reached an age of 60 to 70 years and have – according to the original design criteria based on assumed corrosion rates – reached their design life time. Even though most of these quays and wharfs are actually still in good condition there is a need for inspections and predictions of remaining life time for these structures in order to plan for renovations and the design of new quays.

FIGURE 1 (TWO PICTURES NAMED LEFT AND RIGHT)

The service life time of new sheet pile structure is usually fulfilled by oversizing the steel thickness in the sheet profile. Knowledge about the corrosion rate is also important when verifying the remaining bearing capacity of existing structures, and estimating the remaining service life time according to bearing capacity. When oversizing the structure, a certain corrosion rate (mm/year) is assumed. The corrosion is also assumed to be even all over the surface and pit corrosion or other types of uneven corrosion are not accounted for. In practice the corrosion rate is also assumed to be a linear function of time by most engineers. However, a report from a European research project [1] concludes that the corrosion rate decreases with time. The values on corrosion rates in this report are also given in reference [2] and are used by practicing engineers in Europe today when designing new steel structures. According to this report, the corrosion rate needs to be treated statistically. It is probable that a decreasing corrosion rate will be found if the protective layers of corrosion products formed are not damaged or eroded [3].

One way to estimate the corrosion rate at a certain site is to perform measurements on remaining goods thickness on existing structures. With knowledge about the original sheet pile dimensions and the year of installation, it is then possible to estimate the average corrosion rate. Having knowledge about the average corrosion rate in individual harbors gives both economic and environmental gains as this kind of structures can then be optimized based on the actual rate of loss of materials.

When investigating existing steel sheet structures, one usually measures the uniform corrosion rate over a certain area of the structure. This is, however, a simplification of how the corrosion process takes place, since there is also often pit corrosion, which is concentrated to small areas. Pit corrosion can give very misleading results when measuring the steel thickness with the commonly used ultrasonic gauges. It is also commonly found that the most severe corrosion in sheet pile structures appears in the splash zone, while much lower corrosion rates are found a couple of meters below mean water level. This could indicate the presence of accelerated low water corrosion (ALWC) as described in references [4] and in [5] among others. No obvious signs of the presence of ALWC have however been found in the investigation presented in this paper. The above factors complicate the estimation of the status of harbor structures.

1.2 Principles of design of a sheet pile quay

When designing a new sheet pile quay there are several aspects to consider. The geotechnical conditions are for example of importance for the final operation of the structure. Sometimes it is necessary to replace natural weak soils behind the quay wall with coarser filling material with higher bearing capacity. Two other design criteria are the prescribed ground load from trucks and mobile cranes on the quay deck behind the sheet pile wall (cf. Fig. 1), and the prescribed service life time of the quay.

One of the most common quay structures today is the back-anchored steel sheet wall as shown in Fig. 2. The wall is back-anchored either in bedrock or in anchor plates in the backfilling behind the wall. The material used in the tie rods is steel and the anchor plates are usually precast concrete slabs or steel sheet piles. The tie rods are protected against corrosion, e.g., by a bitumen lining.

FIGURE 2

The most commonly used sheet pile sections in harbor constructions are Z- and U-profiles (Fig. 3). The sheet piles are delivered in steel grades with minimum yield strength between 240 and 460 MPa. The thickness on standard profiles varies between 6 and 20 mm in the flanges and between 8 and 16 mm in the web. Maximum standard rolling lengths depends on the profile type chosen and varies between 16 and 33 m.

FIGURE 3

The most sensitive section (with respect to the bending moment capacity) in a back-anchored sheet pile wall occurs at about one third of the excavation depth from the sea bottom, as this is where the highest bending moment normally occurs (Fig. 4). However, the largest shear force is located at the level of the attachment of the rods. Because of this it is important to detect potential weaknesses in the flanges below the water surface *and* in the web at the location of the attachment of the tie rods. If the sheet pile wall supports the direct vertical load from for example a crane, the corrosion of the whole section is to be considered since this load case gives rise to additional compression stresses over the whole sectional area.

FIGURE 4

When designing a sheet pile wall for a certain location, it would be of interest to be able to consider all the factors that influence the corrosion rate: temperature, salinity, oxygen concentration, biological growth, erosion etc. This is not feasible, but we can focus on the most important factors to optimize a design for a certain location.

In Sweden we have rather large variations in temperature over the year and the salinity ranges from approx. 0.2% at the north east coast, to 0.8% at the south coast, to around 3.0% at the upper north-west coast. This unique gradient in salinity – seen nowhere in the world on this scale – could serve as a test ground for studies of how salinity influences corrosion rate in harbors. It is well known that temperature and salinity, together with several other physical and chemical parameters, influences the corrosion of mild steel in sea water, see for example reference [6]. However, this study is based on laboratory measurements and does not take for example biological growth into account; under natural exposure it has been proposed that temperature is the main variable governing corrosion of marine structures [7].

1.3 Current design values on corrosion rates

Different values on corrosion rates on steel in marine structures are used in different parts of the world. Information on recommended rates is in some cases available in national or international building codes. In Fig. 5 recommended corrosion rates for steel in marine environments are summarized for USA, Australia, Europe and Sweden.

It is well-known that the corrosion on steel in a marine environment is not linear, see for example the measurements presented in the report on which the Eurocode is based [1]. Several models for describing the non-linearity has been developed during the years; one of the more refined models is that presented by Melchers [7]. The non-linear behaviour is however most obvious during the first three years of exposure, at least in the Nordic colder climates and the maximum corrosion rate during this period is about 0.13 mm/year with a mean water temperature over the year of 10° C, Fig. 5. Since new harbour structures are designed to last for at least 50, but often 100 years, it is reasonable to assume that the corrosion rate over this time is linear.

FIGURE 5

1.3.1 North America

In the United States the U.S. Army Corps of Engineers states that the corrosion rate in marine environment on steel sheet piles is between 2 and 10 mils/year [8], which corresponds to approx. 0.05 to 0.25 mm/year. Garlich notes [9] that existing U.S. data on corrosion rates are old and inconsistent and points out that the Eurocode 3 (part 5: piling) gives a better guidance.

1.3.2 Australia

In Australia guidelines for corrosion rates in marine environment are given in the Australian standard, AS 2159 [10]. The submerged zone in sea water and sea water in the tidal/splash zone in cold water, is classified as “severe” and the tidal/splash zone in tropical/subtropical water is classified as a “very severe” environment. The “moderate” classification is for soft running fresh water.

1.3.3 Europe

New design codes for steel structures including guidelines for thickness loss due to corrosion is available in Eurocode 3 [2]. For sheet pile structures situated with different media on the two sides of the sheet pile wall, which is the natural situation for a wharf, values for corrosion of steel in different kind of soils are also available. These values are to be combined with the corrosion rates in Fig. 5. However, the corrosion values given for steel in soils do not cover all the soils possible in harbor constructions.

As an example of a case that is available in the Eurocode, the corrosion rate in an undisturbed soil of sand, clay or shale is given as 1.2 mm in 100 years. For a steel sheet pile wharf back-filled with this kind of soil, the total corrosion in 100 years would be 8.7 mm in the high attack zone and 4.7 mm in the immersion zone.

1.3.4 Sweden

Corrosion of steel sheet piles along the Swedish east coast has been investigated earlier, see for example references [11, 12]. In reference [11], which is based on an extensive survey of corrosion data on steel piles and sheet piles in soil and water, guidelines are given for the corrosion rates in freshwater, brackish water and in sea water. No data on corrosion rates along the west coast has been collected. Since the environmental loads in the marine environment along the Swedish coast differs a lot, these guidelines are probably too rough to be generally applicable. As mentioned earlier the salinity is significantly lower at the east coast than at the west coast. Yet the same guidelines are used when designing new structures on both sides of the country.

In reference [11] it is recommended the corrosion of the steel facing the back-filling in a wharf with natural soils behind it, can be set to 10% of the corrosion on the side facing the water. This a similar discussion as in the Eurocode [2] but with lower corrosion rates in soils.

2 Investigations in a Swedish harbor

The investigation was performed in the harbor of Halmstad on the Swedish west coast, (Figs. 6 and 7). In total 3 different wharfs where investigated with the purpose of determining the remaining steel thickness in the sheet pile walls. The three wharfs are frequently berthed by ships and one of them is located along the outflow of a river (Fig. 7). The salinity in the sea outside Halmstad varies between 1.5% and 2.5% [13] depending on water depth and wind direction. The salinity in the harbor changes from low values at the surface to approx. 2% at the bottom; this is true for all locations in the harbor.

FIGURE 6

FIGURE 7

The three inspected wharfs are here named A, B and C. As seen in Table 1, wharf B was built in three stages between 1960 and 1975. Wharf A is located along the outflow of a river, while wharfs B and C are located in a basin east of the river with direct contact to the sea of Kattegat. None of the wharfs in the harbour are or have been equipped with cathodic protection. Typical tolerance for steel thickness today is ±6% of the nominal thickness. Since no data on tolerances before 1975 has been found, we assume that ±6% is true also for older sheet piles.

TABLE 1

The measurements were performed by a diving team with one diver and two assistants using an ultrasonic gauge (Cygnus Underwater, Cygnus Instruments Ltd., Dorchester, UK). The investigation was monitored by the corresponding author. Measurements were performed every even meter on the sheet pile walls with starting from the water level going down to the bottom of the basins. The top level of the cap beams are known and the water level was measured with the cap beam as a reference with a measuring tape. The measuring tape was then lowered down so it reached from the top of the cap beam down to the sea bottom. The depth along the inspected wharfs varied from approx. 9 m at wharf B and C down to approx. 6 m along wharf A.

In total 15 sections were inspected, three along wharf A, nine along wharf B (three along each part of the wharf) and three along wharf C. The inspection was performed during a three-day period in late autumn 2011. The visibility in the water was rather poor, sometimes less than one meter, due to turbidity caused by the ships operating in the harbor.

Parts of the sheet pile wall were cleaned by the diver before the measurements. Shells and algae were removed manually with a steel scraper. Three palm size areas (on the outer flange, on the web and on the inner flange) were cleaned every meter from the water surface down to the bottom.

With the purpose of testing the precision of the instrument used, three values in each palm sized area were measured in selected sections. These measurements showed very little scatter except in a few points that probably were influenced by pit corrosion.

3 Results

In Fig. 8 the results from the inspection are presented as corrosion rates in mm/year which has been calculated from the known ages of the inspected sheet piles. The graphs show average corrosion rates, calculated from each three sections along each specific wharf.

The different parts of the sheet pile are here named (cf. Fig. 8):

P1: Outer flange of sheet pile facing the basin
P2: Web of sheet pile
P3: Inner flange of sheet pile

FIGURE 8

The standard deviations of the values given in Fig. 8 are between 0.00 mm/year and 0.04 mm/year. This is rather high compared to the measured corrosion rates (between approx. 0.01 mm/year and 0.07 mm/year). However, the present standard deviations are in the same order as in other studies, see for example references [1, 14].

4 Discussion

As seen from the graphs, the average corrosion rates for the outer flanges on the sheet pile walls of wharf A peaks about one meter below the mean water surface. Since the effect of tidal water in Sweden is very small (only a few centimeters) it seems that the higher corrosion rate at this level could be water line corrosion as described in [15].

Another interesting observation is that there is also a peak on the average corrosion rate on the outer flanges at the level between -3 and -6 m along the most frequented wharfs, wharf B parts 1 and 3 and wharf C. This level corresponds to the level of the propellers of the ships that frequent the harbor. We hypothesize that the increased corrosion rates at this level are caused by erosion by the water movement from the propellers.

A complicating factor is the tolerances of the steel thickness of the new sheet piles. These tolerances are in most cases ±6%, i.e., ±0.6 mm for a 10 mm initial thickness. This means that the actual corrosion loss of the steel sheet measured on 50 year old structures (like the ones investigated in the present study) is of the same magnitude as the tolerances. This makes it difficult to accurately assess corrosion rates before the corrosion has removed significantly more than 6% of the steel thickness, which brings us close to the end of the service life. Highly accurate ultrasonic measurements combined with the significant uncertainty in the initial thickness, results in that accurate predictions of the remaining service life are difficult to make, while it is easy to assess that a structure has come to the end of its service life. The future solution to this problem is to measure the true initial thickness of the steel sheet piles used to build a new harbor structure. With accurate initial thickness values it will be possible to make good service life predictions – assuming that the corrosion rate does not change unpredictably – on wharfs that are only a few decades old.

If one assumes that the initial thickness is the same in each sheet pile (or even in several sheet piles in a part of a wharf that was constructed at the same time), accurate comparisons can still be made between values measured at different depths on one sheet (or between different sheets on the same part of a wharf). This means that although the true corrosion rate can have a high uncertainty. For each corrosion rate profile in a sheet, the shape is essentially correct, but its location in the thickness-direction is uncertain. This is illustrated in Fig. 9A-B for two of the rate profiles used to calculate the mean values in Fig. 8. Figure 9A shows a profile representing the majority of profiles measured in Halmstad, while Fig. 9B shows an extreme case were the apparent corrosion is negative. In this (extreme) case the corrosion rate has probably been calculated with a too low initial thickness, so that even after several years of exposure, many of the calculated rate values become negative. This is mainly a problem for lower corrosion rates; the higher corrosion rates have a higher relative precision. However, if we assume that the shape of the profile is correct and that it is unlikely that we have negative or zero corrosion rates, the uncertainty can be reduced somewhat as we can assume that the initial thickness must in this case have been greater than the nominal thickness (Fig. 9B).

Calculation of the corrosion rate from measurements with respect to the nominal thickness and with consideration of the tolerances can be modeled as follows:

$$D_t = D_0 - Rt \qquad (1)$$

Here, D_t (mm) is the thickness at time t, D_0 (mm) is the thickness when the profile was new, R (mm/y) is the actual corrosion rate, and t (y) is the time. Then:

$$R = \frac{D_0 - D_t}{t} \qquad (2)$$

However, if there is an uncertainty in D_0 of d (mm) this will result in an uncertainty also in R and the latter equation will instead look like:

$$R \pm r = \frac{D_0 \pm d - D_t}{t}, \qquad (3)$$

where r (mm/year) is the uncertainty in the measured corrosion rate and D_0 is the nominal thickness. This can be written:

$$r = \pm \frac{d}{t}. \qquad (4)$$

The above reasoning is illustrated in Fig. 9C were the solid line is the actual corrosion rate and the dashed lines indicate the limits inside the result of a corrosion rate measurement will be found. It is seen that the sheet pile must be almost 50 years of age before a good estimate of the corrosion rate can be made if the true original sheet pile thickness is not known.

FIGURE 9

Considering the above discussion on the influence of the uncertainty of the initial thickness, the service life of a sheet pile structure can be handled in the following way:

1. When a wharf is built, the thicknesses of all piles are measured in positions P1, P2 and P3 (Fig. 8). This measurement can be made with an ultrasonic thickness meter or with a caliper.
2. After a certain fraction of the design service life time, for example 20%, a first inspection of the wharfs is made by divers using ultrasonic thickness gauges. Based on the results from these measurements and knowledge about the initial thickness, a first revision of the expected service life time is made.
3. Depending on the results on the corrosion rates found in the second step, the time for next inspection is decided on. Higher corrosion rates than used in the design of the wharf leads to more frequent inspections.

The above proposal for wharf inspections is based on a belief that it is important for a harbor to have a good knowledge of the remaining service life times of their quay structures, also for those structures that are relatively new. The economic value of a quay structure is also so high so that the cost of a diver inspection is easily justified. Note that the above is only relevant for uniform corrosion; other measures have to be taken for other types of corrosion or mechanical damages resulting from, e.g., collisions with the quay.

In reference [11] the proposed design value for corrosion rate in the submerged zone is set to less than 0.1 mm/year, regardless of the environmental loads on the wharf. The average corrosion rates shown in this investigation are lower than 0.1 mm/year in all the investigated submerged zones. Comparing the results from this investigation with the proposed design values in reference [11] and the design values in the European building code [2], the average corrosion rates found in this study are in reasonable agreement with the values given in the Eurocode [2], but lower than the Swedish guidelines [11]. The values on average corrosion rates in reference [8] are too general to be useful as design criteria. The recommended design values on corrosion rates in the Australian code [10] seems low considering that the water temperature is relatively high in Australia. However, the structural designers in Australia as – in other countries are – free to use higher values on the corrosion rates if necessary.

5 Conclusions

The conclusions from this investigation of corrosion of steel sheet piles are:

- There is a tendency that the average corrosion rate on the outer flange reaches a peak between 3 and 6 m below the mean water level at the most frequented wharfs. This level correlates with the level of the propellers on the ships berthing the wharfs. Since this is the level where the maximum bending moment occurs, this information is essential for the structural designers.
- The tolerance of the steel thickness, usually ±6%, is not often considered in the literature when discussing corrosion rates and service life times of steel sheet pile structures. A simple model including the tolerances of the initial steel thickness shows that the age of the sheet piles should be almost 50 years before a good estimation of the corrosion rate can be made if the true original thickness is not known.
- The average corrosion rate measured in this investigation is generally lower than the recommended values in the Swedish guidelines, but are similar to the values given in the Eurocode and by Melchers [7].

Acknowledgement

The work presented in this paper is a part of an ongoing Swedish research project on corrosion of steel sheet piles in marine environment. The authors would like to thank SBUF (The Development Fund of the Swedish Construction Industry) and Skanska Sweden AB for their financial support of this project. The authors would also like to thank Mr. Lennart Pettersson at the Port of Halmstad for letting us perform the investigation of the sheet pile structures in the harbor. The discussions of corrosion issues with Prof. Robert E. Melchers at the University of Newcastle in Australia are also acknowledged and very appreciated.

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Tables

Table 1
Construction data for the inspected wharfs.

Wharf	Year of Construction	Age (y)	Total length (m)	Profile	Nominal flange thickness (mm) (± tolerances)	Nominal web thickness (mm) (± tolerances)
A	1968	43	200	BZ IV N 50	14.0 ± 0.84	10.0 ± 0.60
B part 1 (middle)	1960	51	300	BZ IV N	14.0 ± 0.84	10.0 ± 0.60
B part 2 (inner)	1966	45	180	BZ IV N	14.0 ± 0.84	10.0 ± 0.60
B part 3 (outer)	1975	36	70	BZ 450	13.2 ± 0.79	10.0 ± 0.60
C	1974	37	220	Larssen III s	14.1 ± 0.85	10.0 ± 0.60

Figures

Fig. 1. Examples of vertical loads on quay decks

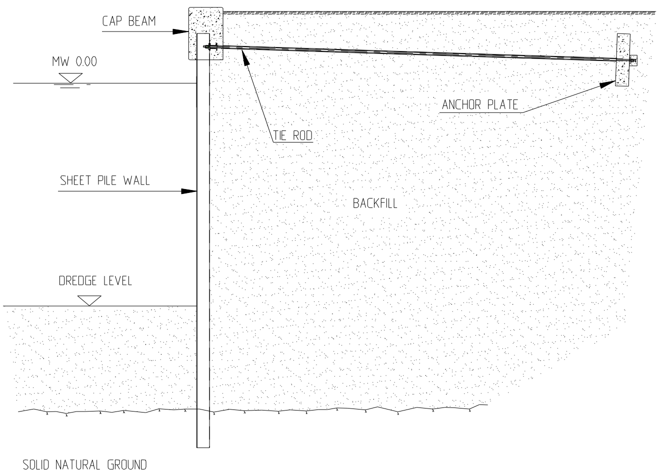

Fig. 2. Cross section of a standard back-anchored steel sheet pile wall

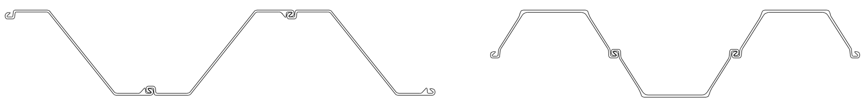

Fig. 3. Examples of sections of sheet piles: Z-profile (type BZ and AZ) on the left and U-profile (type Larssen) on the right

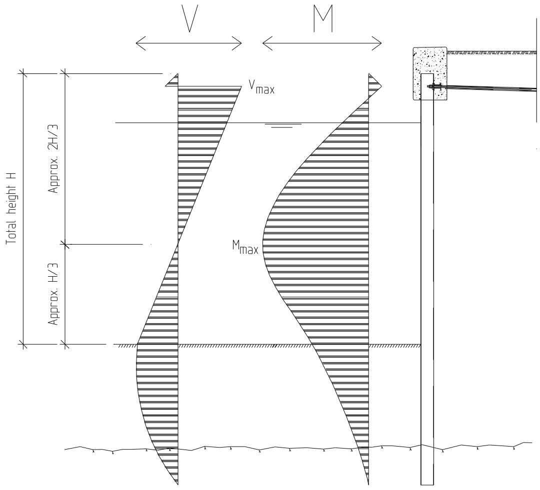

Fig. 4. Bending moment (M) and shear force (V) diagrams for a standard back-anchored sheet pile wall

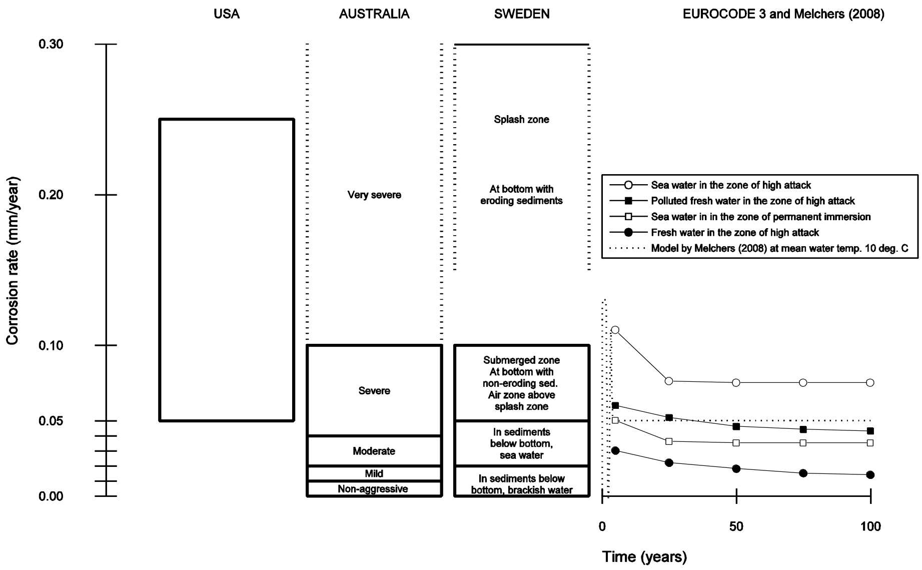

Fig. 5. Recommended design corrosion rates for steel in marine environments in different parts of the world [2, 7, 8, 10, 11]

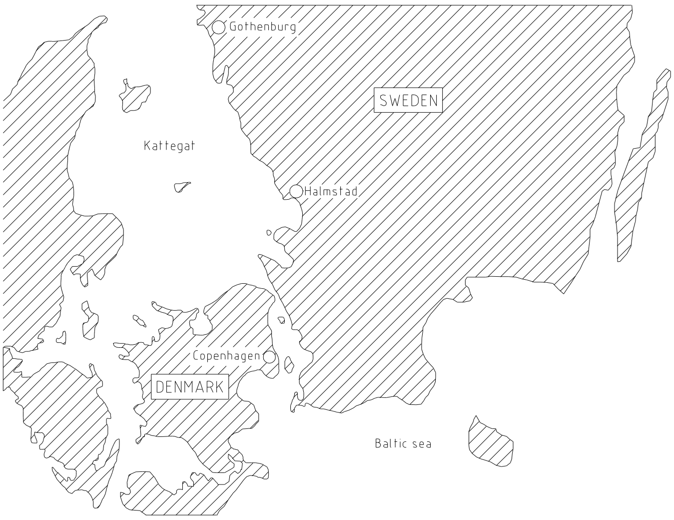

Fig. 6. Location of Halmstad

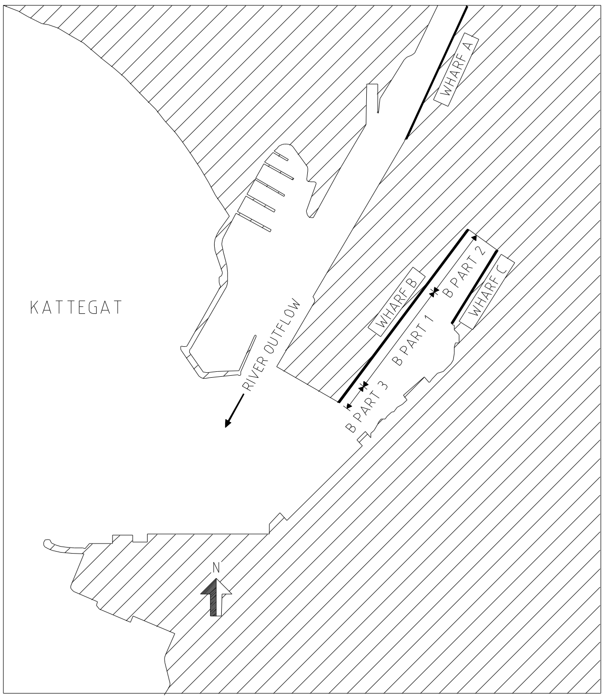

Fig. 7. Location of the inspected wharfs

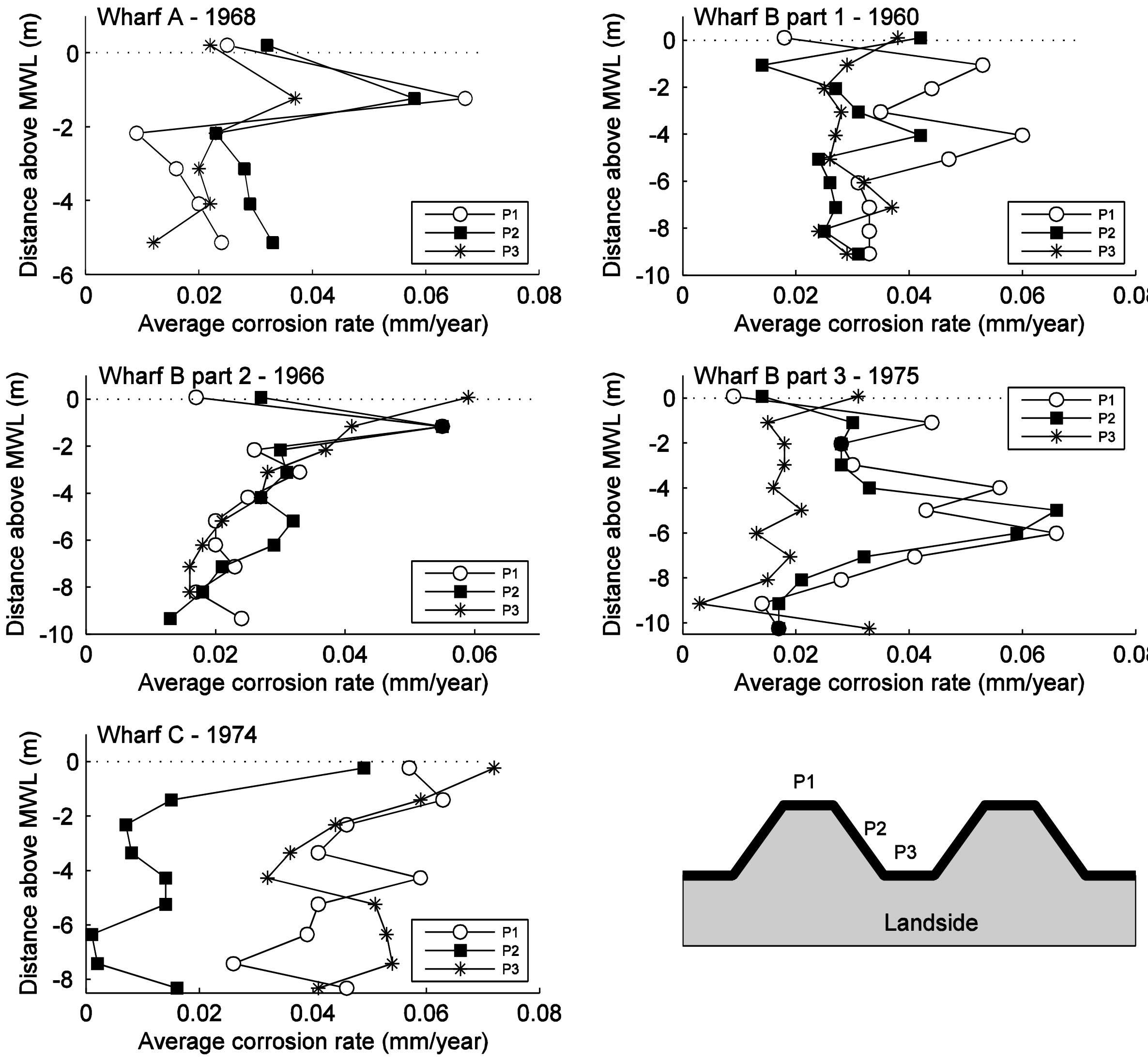

Fig. 8. Corrosion rates (average values) on sheet pile walls in Halmstad harbor. The measurement points are illustrated in the bottom right figure.

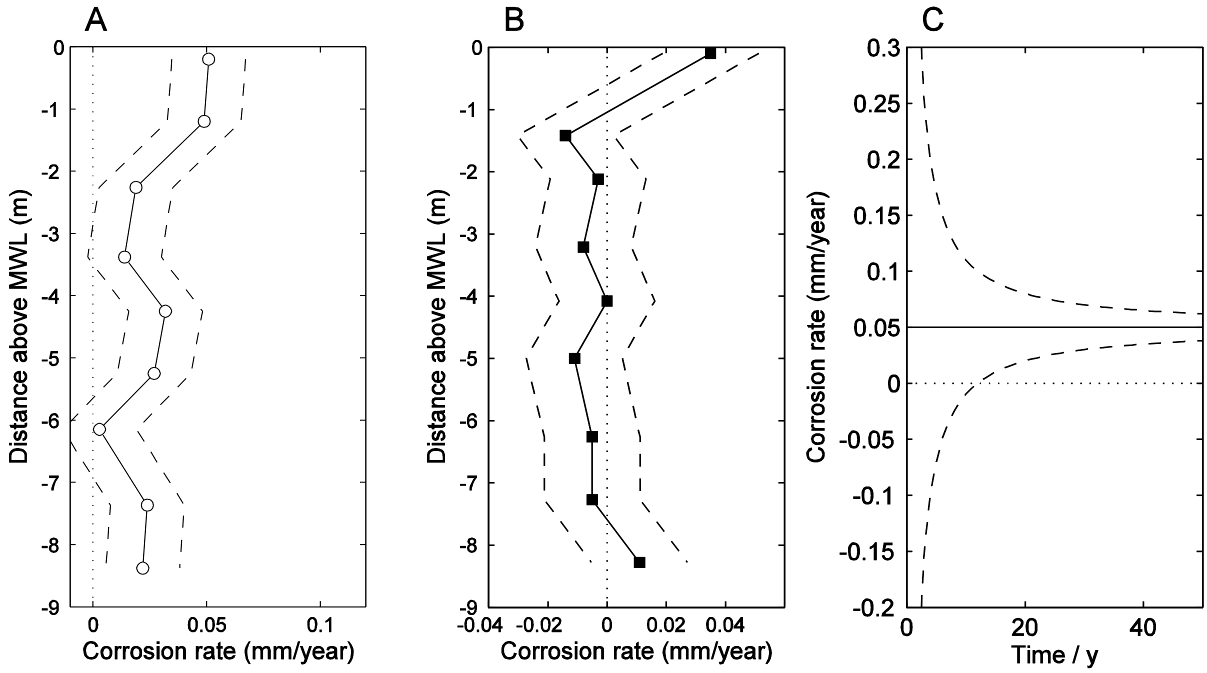

Fig. 9. A. A measured corrosion rate profile (one of the webs, P2, in wharf C) calculated assuming the nominal initial thickness (open circles) and the limits within which the true rate profile will be found assuming an uncertainty of 6% in the initial thickness. B. Similar to A, but with apparent negative corrosion probably due to large thickness tolerances on the positive side. C. An alternative way to look at the influence of an uncertainty in the initial thickness of a sheet. Uncertainties in evaluated corrosion rates as a function of time, for a sheet with a nominal original thickness of 10 mm, an uncertainty in this value of 6%, and an actual corrosion rate of 0.05 mm/year. The dashed lines indicate the limits within which the measured corrosion rate will be found (Eq. 4.).