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Accelerated low water corrosion (ALWC) of steel piling in harbours

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Abstract

Accelerated low water corrosion (ALWC) of steel piling in sea water harbours in the UK, Europe and elsewhere has been shown recently to be the result primarily of water pollution. Elevated levels of dissolved inorganic nitrogen in sea and brackish waters is responsible for microbiologically influenced corrosion of steel piling below the low water tide level. This is demonstrated in field data from 13 Australian experimental sites, 9 US naval sites and some severe sites in Australia, Norway, Japan and the UK. Localised perforation of sheet piling, often associated only with the webs of U and Z profile piles, is shown to be the result of centreline segregation, porosity and composition differences in steel profiles. These stem from the steel making process and are likely to be less severe for modern steels. The results explain most of the observations for actual steel piling in various harbours, both vertically and horizontally (i.e for U and Z and other pile profile types).

Keywords: Steel, corrosion, accelerated, seawater, bacteria, composition.

1. Introduction

Many seawater harbours use steel sheet piling as part of the structural system for quays and docks.¹ Typically the sheet piling retains the soil behind the sheet piling and also provides vertical support for the concrete quay deck. Corrosion of the steel piling may lead to significant loss of pile cross-section, perhaps causing structural failure and collapse or loss of the quay. The latter events could have significant operational and economic consequences for working ports.^{2,3}

During the 1980s several cases of severe corrosion of steel sheet piling, including complete perforation, just below low water was observed in some harbours in the UK and later in France, Australia, Canada, the Middle East. This caused considerable concern. It was described at an Institution of Civil Engineers conference¹ as ‘a matter of national importance’. The phenomenon was termed Accelerated Low Water Corrosion (ALWC) because corrosion rates of 1.0 mm/y or more were reported compared with the much lower conventional design allowance of 0.1-0.5 mm/y.

ALWC usually can be observed only at very low tide levels, either as orange rust at areas at risk before actual perforation becomes visible (Fig. 1a) or, worse, as actual perforation (Fig. 1b). In some cases large areas of perforation have occurred, particularly where regular inspection and repair had not been carried out.¹

Figure 1 here

Five aspects of ALWC have been identified:¹

(1) corrosion usually is more severe at an elevation just below low water tide level,

- (2) corrosion often appears to occur on the out-pans of U-profile sheet piling or sometimes at the corners or folds in the sheet piling (Fig. 2) or at the flange edges for H profile piles,
(3) ALWC appears to be more common for older steel piling,
(4) ALWC often is considered a modern phenomenon not observed in the earlier use of steel piling and
(5) perforation as a result of ALWC appears earlier on south facing sheet piling, at least in the UK.

Figure 2 here

To date most attention, both in practice and in research, has focussed on item (1). Already in the 1980s microbiologically influenced corrosion (MIC) was suspected as the main cause of ALWC.¹ However, early attempts to establish a link between ALWC and bacterial activity and water quality proved inconclusive.⁴ With hindsight most likely this was because the indicator of the occurrence of ALWC was taken as perforation of the sheet piling and when no perforation was observed ALWC was discounted.

Little attention has been given to items (2-5), although there has been some speculation¹. The present paper is concerned mainly the first 2 of the 5 aspects of ALWC listed above. Plausible explanations for the last 3 are proposed also. The next section provides a brief background to MIC and the factors involved. A summary is then given of recent test results on steel strips exposed along the East coast of Australia and also of much longer observations for sheet piling at US Navy bases. New results are then introduced for 6 locations involving steel structures up to 89 years in age and high concentrations of DIN. Possible reasons for the localized perforation of parts of some sheet piling and not others are then considered. Some remarks follow about the other issues (3-5 above).

2. Background

2.1 Microbiologically influenced corrosion of steel

The potential for MIC in natural environments such as seawater has been recognized for a long time, based largely on short-term observations in laboratory experiments.⁵ For seawater exposures correlation has been established between corrosion and the nutrients essential for microbiological activity, both short-term and for many years of exposure.⁶ In seawater the critical nutrient is nitrogen, usually present mainly as nitrates but ammonia and nitrites may be present also. The total inorganic nitrogen concentration usually is reported as dissolved inorganic nitrogen (DIN). For ALWC, recent tests in seawaters with various levels of nutrient concentrations have shown corrosion profiles consistent with ALWC, even after only a few years exposure and have shown good correlation between the severity of ALWC and DIN concentration.^{7,8} This is consistent with the strong emphasis in the ALWC literature on MIC.⁹ However, it is not the only influence. Already in the 1930s differential corrosion effects just below the water line were recognized, including in pure water.¹⁰ Thus bacteria could not have been involved. It follows that ALWC is not necessarily only the result of microbiological activity, although for long-term exposures bacteria have been associated repeatedly with corrosion in seawater.^{11, 12} This is considered to be the result of increased production of acidic materials.¹³

A plausible microbiological model to explain the ALWC phenomenon based on the alternate activity of aerobic and anaerobic bacterial species has been proposed by Gehrke and Sand.¹⁴

However, it does not provide estimates of the rates of consequential corrosion or the conditions under which microbiological activity causes a practical ALWC problem.

A different approach is to consider the relationship between the availability of nutrients for microbiological activity and the severity of the resulting corrosion and hence of ALWC.^{7,8} For corrosion of steel in seawater the initial mechanism controlling the rate of corrosion is the rate of diffusion of oxygen to the corrosion interface,¹⁰ for longer-term corrosion anaerobic conditions develop under rusts at the corrosion interface, permitting the possibility of anaerobic microbiological activity and microbiologically influenced corrosion.¹⁵ Under these conditions, the diffusion rate of nutrients through the rust layers is the likely rate-controlling process for the rate of corrosion, governed by the difficulty of the diffusion pathway and by the concentration of nutrients in the bulk water. As noted, for corrosion in seawater the critical nutrient is DIN and hence its concentration in the water immediately adjacent to the corroding steel will play a part in controlling the rate of corrosion. The concentration of DIN even in heavily polluted waters is much too low to have an influence on the usual purely electro-chemical corrosion processes.

2.2 Short-term field tests for ALWC

Since MIC of steel in natural seawater is known to occur both for in short-term exposures and in long-term exposures¹⁵ it follows that if microbiological activity is involved in causing ALWC in long-term exposures it should be evident also in the results from short-term exposure tests under realistic field exposure environments. Using this approach as a basis, short-term exposure tests were conducted at 13 different locations on the East coast of Australia, some selected because a suspected high nutrient presence. Mild steel strips suspended from timber jetties were exposed through the tidal zone for up to 3 years. The strips were exposed to the complete tidal range, with the lower part always immersed. Fig. 3 shows a typical corrosion profile obtained from mass loss measurements on 100mm long segments cut from the steel strips. It shows the higher corrosion loss in the region below the mean low tide (MLT), denoted *A*, and the average corrosion loss in the immersion zone, denoted *I*. The ratio $R=A/I$ was used to quantify the ALWC effect. Since both *A* and *I* are influenced by the local water temperature it is reasonable to assume that *R* is largely independent of water temperature.⁷

Figure 3 here

At each site the water quality was measured 3-4 times per year over the study period. The observed values of DIN were averaged to obtain annual means. Fig. 4 shows the *R* values plotted against the corresponding average DIN concentrations. There is a reasonable positive correlation.

Figure 4 here

2.3 US Navy base observations

For sheet piling exposed for periods ranging from 14 to 27 years at 8 different US Navy sites Brouillette and Hanna¹⁶ reported corrosion losses for samples taken at various elevations, ranging from above the mean high tide to below the mud-line. Using these observations estimates were made of *R* for each site.⁸ Seawater quality was not reported for any of the sites. However, extensive searches did reveal US Environmental Protection Agency (EPA) and

other reports with water quality data. Fig. 4 shows the values of R against the estimates for DIN. Evidently there is reasonably good correlation, after disregarding the two sites where oil was reported on the water surface.

Kumar et al.¹⁷ reported the corrosion performance of steel H piling after 5 years exposure at Buzzards Bay, MA. Fig. 5 shows the corrosion profiles for the two steel piles without cathodic protection or protective coatings for which R was estimated. The average DIN of the seawater at this site was estimated using EPA and other data.⁸ The resulting two points have been added to Fig. 4 and are consistent with the trend.

Figure 5 here

3. Some severe cases of ALWC

Subsequent to the analyses of the systematically-observed data extracted from the above studies, several other cases of ALWC became available, mainly in older literature. These cases are for severe ALWC and for very long exposure periods. They are considered below for consistency with the trends shown in Fig. 4.

3.1 Tokyo Bay and Yokohama Port, Japan

At Tokyo Bay, Japan, the steel tubular piles for the Toyomi dolphin were inspected and measured after 11 years seawater tidal exposure. The corrosion data was reported as rates.³ These were converted to corrosion losses and the profile plotted (Fig. 6). There is a distinct ALWC characteristic with R around 5.

Figure 6 here

Water quality data, including DIN, was obtained from a Food and Agriculture Organization report.¹⁸ This showed that outside the port area the nitrate (NO_3^-) concentration is around 1.5 mg N/L. To the south of the site it is about 1.2 mg N/L. This latter is considered more relevant in view of the currents in and out of the harbour (see Figs. 10.1 and 10.2 in reference 18).

In Yokohama Port, the same sources provide data for the corrosion profile shown in Fig. 7 for the tubular steel piles of the Yamashita wharf. The value of R is estimated at around 5. Also, DIN is around 0.75 N mg/L.¹⁹

Figure 7 here

3.2 Trondheim, Norway

The sheet piling of interest is in the Trondheim port area and more specifically near the mouth of the River Nidelva.¹⁹ Details are scarce but the first piling was constructed in 1948 and after 26 years significant losses were noted (Fig. 8). The second structure was built in 1950 and was inspected at the same time as the first. In both cases the same type of sheet piling had been used. The corrosion losses and profile for this case also are shown in Fig. 8. It is unclear why the corrosion losses are so different for the two cases. The R values are estimated at around 2.5 and 3 respectively.

Figure 8 here

Water quality data sources indicated that at one time fish processing facilities had existed in the area. There is no water quality information available for the period corresponding to exposure of the steel piling, but more modern data [reference 20, Part B Table 2 page 126] indicate a total seawater flow rate of around 8.8 million m³/d and a nitrate input of around 466 tonnes/y plus a small amount of ammonia (30 tonnes/y). From these figures the concentration at the mouth of the river can be estimated as around 0.15 mg N/L. Elsewhere in the report (Part B Table1-page 118) the DIN concentration was shown as around 0.1 mg N/L. These values almost certainly are too low for the exposure period.

3.3 Port Adelaide, South Australia

Corrosion loss data for older style steel sheet piling dating from 1925 in Port Adelaide and recovered in 1977 after 52 years continuous service were reported by Eadie and Kinson.²¹ Mass losses were estimated from samples cut from the recovered pile as well as ultrasonic measurements. Estimated were made separately for the sea- and the landside. Fig. 9 shows the estimated seaside web thickness losses as a function of elevation below the top of the pile. The ratio *R* is approximately 1.6. An analysis using the mass losses for the cross-sections (and therefore including the soil-side losses) produced a similar value for *R*.

Figure 9 here

Water quality data for Port Adelaide is not available for the exposure period. However, for 2005 the area of most relevance [reference 22, Table 2, Location 9] has a mean DIN around 0.5 mg N/L. Port Adelaide has a long history of industrial development and it is likely that nitrogenous pollution levels would have been quite low when the steel piling was installed in 1925, similar to trends elsewhere.²² Assuming that pollution levels increased linearly from 1925 to 2005 gives a rate of increase of around 0.0063 mg N/L per year. From this it can be estimated that the average DIN concentration over the 52 year life of the piling is 0.0063 x 26 = 0.16 mg N/L.

3.4 Harbor Island, NC, USA

Larrabee²⁴ reported corrosion profiles for 300 mm (12 inch) wide 7 m (20 foot) long steel strips exposed for 5 years from 1952 at Harbor Island at Wrightsville Beach, NC. One carbon steel and 6 low alloy steels were tested. The profiles shown in Fig. 10 were obtained from mass loss calculations on 300 mm (12 inch) squares cut from the strips. For these *R* is about 1.3. Observations of maximum and minimum remaining pile thickness show profiles generally similar to the mass loss profiles.

Figure 10 here

The region in which Harbor Island is situated (the Intercoastal Waterway) is listed in US Environmental Protection Agency documents²⁵ as subject to local sewage effluents. EPA records show sample levels for DIN between 'not detected' and as high as 2.5 mg N/L, although the average readings were much less - for the 363 readings in the period 2008 - mid-2012 the average is around 0.25 mg N/L. Assuming that DIN is proportional to contributing population and noting that the 1950s population was about 1/4-1/2 of the current population allows the relevant DIN concentration to be estimated as 0.06-0.12 mg N/L.

3.5 Newcastle upon Tyne, UK

The riveted steel plate caissons supporting the (now demolished) Redheugh Bridge at Newcastle, UK were assessed for corrosion when they were 89 years old. The remaining wall thickness profiles were reported.²⁶ To estimate the corrosion losses it was necessary to estimate the original thickness of the steel plates. The upper 5.5 m of the caissons was specified on old drawings of the bridge as constructed from plates '... 12/20 in ...' thick, which is equivalent to 15.2 mm. However, this nominal thickness does not allow for the almost inevitable over-supply of thickness of plate at the time.^{27,28} The plot of the remaining wall thickness after 89 years as obtained by ultrasonic measurements showed a remaining thickness of 16.2 mm on some parts of each of the two piers examined. In both cases this was in the atmospheric exposure zone where some of the bituminous coating remained. It is likely that this is the best estimate for the initial thickness of the steel plate.

Using 16.2 mm as the original wall thickness, Fig. 11 shows the corrosion loss profile for the upper part of one of the two caissons, using the data reported by Morley.²⁶ A similar profile was found for the second caisson. Fig. 11 shows that in the immersion zone the corrosion loss is around 0.5 - 0.6 mm and the loss in the ALWC zone, which corresponds closely with the low tide level, is about 3.6 mm. It follows that $R = 6-7.2$, ignoring the effect of bituminous coating as this may be assumed to be lost at about the same rate throughout the tidal and the immersion zones.

Figure 11 here

Estimating the water quality in the River Tyne at the bridge site during the 89 years of exposure proved more problematic. Nimmo-Smith et al.²⁹ refer to a European Environmental Agency (EEA) report that shows NO_3^- concentrations in the River Tyne averaging, for all the river monitoring stations, around 10 mg/L in the 1970s. These authors show that this is correlated with fertilizer consumption and that in the 1960s this was about half of the 1970s consumption, suggesting a correspondingly lower NO_3^- concentration in the river. Converting from NO_3^- to N gives $10 \text{ mg/L NO}_3^- \times 1/(4.4) = \text{approx. } 2.3 \text{ mg N/L}$ and adjusting for historical fertilizer usage yields about 1.15 mg N / L in the 1960s. It is possible that earlier in time the concentrations were even lower.

A separate estimate can be made from different data. Ahad³⁰ quotes NH_4^+ and NO_3^- inflows from the River Tyne into the estuary averaging around 80 mM but his own observations from several sampling programs in the estuary during 2002-3 show NH_4^+ plus NO_3^- to average about half of this. The sampling locations are not clearly defined and appear to be in the estuary itself rather than near the bridge site, which is supported by the observations of wide variations in salinity. This suggests that Ahad's³⁰ readings include the effect of dilution. Using his estimate of 40 mM NO_3^- and neglecting NH_4^+ and converting to DIN produces 0.56 mgN/L. The neglect of NH_4^+ is reasonable as the more recent readings in the estuary are influenced by the outflows from Howden sewage works, downstream of the site of the Redheugh Bridge. Such outflows are known to add considerable amounts of NH_4^+ but probably little NO_3^- to the receiving waters. With these assumptions and uncertainties, the best estimate of the conditions at the Redheugh Bridge caissons on average during their lifetime is $\text{DIN} \leq 1.15 \text{ mgN/L}$, $R = 6-7.2$.

3.6 Trend

Fig. 12 shows the estimates for R and DIN for each of the above cases added to the data and trend in Fig. 5. In each case the ellipse gives an indication of the uncertainty in the estimates for R and DIN. Despite the uncertainties, the locations of the ellipses are generally consistent with the extrapolated trend line through the experimental and the US data.

Figure 12 here

Fig. 12 reinforces the previous conclusions^{7,8} that for any given tidal seawater or brackish water site the proneness to ALWC of steel structures exposed bare and without cathodic protection can be estimated from knowledge of the water quality and in particular the annual average concentration of DIN. Alternatively, if DIN information is not available, or is difficult or inconvenient to collect, a simple corrosion experiment similar to those conducted in the Australian experimental project and lasting, say, two years, will give an indication of the likelihood of ALWC in the longer term, assuming, of course, that the water quality for the test program is representative.

4. Material and Orientation Effects

4.1 Preferential perforation

The second question concerning ALWC is why corrosion appears to be more severe in the webs and sometimes the corners of the sheet pile profile, that is, why there is preferential corrosion in the horizontal orientation? The first point to note is that perforation resulting from ALWC occurs below MLT (Fig. 2) and therefore the steel is fully and continuously immersed. This means there is no preferred orientation of the environment (except, perhaps, water velocity). This suggests local perforation most likely is the result of material properties.

The core region of steels is known to have some grain segregation and localized differences in composition with slightly elevated content of C, S, Mn and P typical. In hot rolled products such as steel sheet piling the core region usually is thin and parallel to the sides of the member. Heat treatment may reduce segregation and compositional differences but usually some remains³¹. For samples of actual U and Z profile sheet piling this was confirmed recently using detailed microscopic and composition examination. Direct evidence that the core region of sheet piling is more prone to corrosion was obtained by marine exposure of cross sectional samples of U and Z profile sheet piling. These samples were machine cut from actual piling, producing flat and smooth exposed cross-section surfaces. After 2 and 3 years exposure in temperate seawaters the cross sectional surfaces showed highly localized and severe corrosion along the centreline, corresponding to the location of the segregation and composition differences (Fig. 13). Away from the centre of the web no localized corrosion was evident. These observations showed that the existence of a region of material along the central region of the webs that is less corrosion resistant than the remainder. This is considered to be the reason for the earlier perforation of the webs as shown in Fig. 3.

Figure 13 here

Examination of the cross-sections of samples after seawater exposure revealed other regions of localized corrosion (Fig. 14). These were found to be at areas of local steel porosity and imperfections in grain structure³¹. They are more frequent near the corners or folds of the Z and to a lesser extent of the U profiles. These regions correspond to local perforation near corners (Fig. 2). Finally, the higher corrosion along the ends of flanges of H piles is the result

of relative energy considerations and the development of anodic areas at the edges. This mechanism was observed and explained already in the 1930s.¹⁰

Figure 14 here

4.2 Older and newer steels

It is sometimes claimed that the ALWC phenomenon is more severe and occurs earlier for piling made from older style steels.² Most likely this is the result of changes in steel making, with modern steels usually made by continuous casting. This produces less centreline and other segregation and smaller composition differences than was typical for the older steels.³¹

4.3 Pile steel composition

Steels with improved corrosion performance have been proposed. One example is the so-called 'Mariner' steel (ASTM A690). Fig. 4 shows its performance, measured in terms of parameter R , relative to the usual low alloy structural steel (ASTM A36) when exposed at the same location (Buzzards Bay) and over the same time period (5 years). The respective corrosion profiles (Fig. 5) show the A690 steel having somewhat higher corrosion losses overall compared to the A36 steel. This could be fortuitous because of the wide range of composition permitted under the A36 designation. It is noted that A36 has no upper limit on the content of P, noted above as implicated in the higher corrosion observed at centreline segregation.

The seven corrosion profiles in Fig. 10 also are of interest. For these Table 1 summarizes the R values and the alloys in the steel composition, together with data for the A36 and A690 steel piles at Buzzards Bay. There is no systematic influence on R except a slight increase with P (Fig. 15). However, overall corrosion losses, particularly in the immersion zone, are not very different from those of carbon steel (Fig. 10). This is consistent with well-established principles and practical observations for the effect of minor variations in composition for steel immersed in seawater.¹⁰

Table 1 here

Figure 15 here

4.4 Orientation

No systematic studies appear to exist to address the observation that ALWC appears to occur earlier on south facing sheet piling, at least in the UK.¹ However, it is known from studies of corrosion losses for individual steel coupons exposed for several years that those in the tidal and splash zone corrode more when they are oriented facing the late afternoon sun.³² It may be speculated that this could cause some drying of the surfaces of exterior rusts but the actual corroding interface is unlikely to be affected. Also, the slightly higher temperature is likely to cause corrosion to proceed at a faster rate compared to corroding surfaces not so heated. It is possible that a similar scenario applies for the upper part of the immersion zone and therefore affects ALWC. It remains an area for further investigation.

Discussion

Sometimes ALWC is considered a modern phenomenon¹ but this is not the case, although it when it was first observed its implications apparently were not recognized. Ellis³⁴ reported high rates of localized corrosion of steel piling in Kowloon Harbour (which undoubtedly was polluted at the time) and high corrosion losses were noted just below the water line for US naval vessels 'moth-balled' in the 1950s in San Diego harbor, considered to suffer from high rates of sewage pollution.³⁴ Also, in 1963 Arup and Glantz³⁵ reported high corrosion rates of sheet piling in 20 Danish harbours, with the greatest losses just below low tide and most severely in harbours with fish industries. A more modern interpretation immediately indicates a link with microbiologically influenced corrosion facilitated by the nutrient loading from the fish industry wastes.³⁶

One possible reason for the apparently unexpected and widespread discovery of ALWC in the 1980s may lie in the availability of DIN. The levels of water pollution in the North Sea and in the North Atlantic and thus the nutrient concentrations (including DIN) have risen considerably since the 1950s largely the result of water borne pollutants, fertilizer run-off and sewage plant effluents entering seawaters.²³ Most likely the steel piling located on these waters has been exposed to gradually increasing levels of nutrients and thus MIC. In this sense perforation is simply the last part of the ALWC process and is a legacy of many years of seawater pollution.

Usually not mentioned in the context of ALWC, but equally a legacy of the high levels of water pollution is the higher than normal corrosion in both the immersion and tidal zones. There is strong evidence that immersion and tidal corrosion is related directly to elevated nutrient levels.⁶ Importantly, the problem is not confined to sea and brackish waters. It can occur also in fresh waters, although the critical nutrients are different.

An immediate conclusion from these observations is that for management of corrosion of new and future steel infrastructure one approach is to control and if possible reduce nutrient loadings to waters in which steel infrastructure is located. For seawater this means reduction of the DIN entering seawater, such as through ammonia, nitrate and nitrite removal from sewage treatment plant effluents and reduction of fertilizer runoff. Such reductions may not be practical, politically possible or cost effective but understanding the implications is a potentially important aspect for decisions regarding steel infrastructure and environmental and pollution controls.

Improved corrosion performance of steel piling can be achieved by cathodic protection below the constantly wet regions and by protective coatings above, including concrete encasement. Apart from the traditional approach of using a sacrificial corrosion allowance, these are (still) the main techniques used in practice.¹ In this context it is noted that the corrosion rates specified in standard documents for the design of maritime structures, such as BS6349³⁷, in the main are inadequate to deal with ALWC since they do not consider water quality as an influencing factor.

Conclusion

The present study demonstrates that for steel piling exposed to tidal seawater the correlation established previously between the severity of Accelerated Low Water Corrosion (ALWC) and the concentration of dissolved inorganic nitrogen (DIN) in the surrounding seawater holds also for much higher DIN concentrations and for much longer periods of exposure than previously considered. This was demonstrated using literature data for steel structures

exposed for periods up to 89 years and under a wide range of mean seawater temperatures. The results support the previous inference that the vertical differential corrosion of steel piling in seawater (ALWC) largely is the result of microbiologically influenced corrosion (MIC). The localized perforation that is the long-term outcome of ALWC is consistent with localised differences in metal composition and grain-structure. There is insufficient evidence to claim that small changes in metal composition have a significant effect on the severity of ALWC. Further, ALWC is not a modern phenomenon as sometimes claimed and can be considered largely to be the result of increased anthropological water pollution.

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Accelerated low water corrosion (ALWC) of steel piling in harbours

Figure Titles

Figure 1. (a) Example of orange rust composed of iron hydroxides, (b) Example of a moderately sized perforation and the flow of ground water from behind the steel sheet piling.

Figure 2. Schematic view of sheet piling showing typical locations of perforation resulting from seawater corrosion.

Figure 3. Example of a profile of the corrosion losses, obtained from long strips divided into 100mm long segments for corrosion loss obtained from mass-losses.

Figure 4. Correlation between the ALWC parameter R and dissolved inorganic nitrogen (N) for the Australian experimental cases and the US Navy harbour piling.

Figure 5. Corrosion profiles for A36 and A690 steel piles at Buzzards Bay, MA, USA. Based on data reported by Kumar et al. ¹⁷.

Figure 6. Corrosion profile for piling of the Toyomi dolphin in Toyo harbour based n data reported by PIANC ³.

Figure 7. Corrosion profile for piling of the tubular steel piles of the Yamashita wharf, Japan, based on data reported by PIANC ³.

Figure 8. Corrosion losses and profile for original and subsequent sheet piling in Trondheim Port area. The type of sheet piling was the same in both cases.

Figure 9. Estimated seaside web thickness losses as a function of elevation below the top of the pile at Port Adelaide. Based on data reported by Eadie and Kinson ²¹.

Figure 10. Corrosion profiles for 7 grades of steel piling at Harbor Island, NC. Based on data reported by Larrabee ²⁴.

Figure 11. Corrosion profile for one of the caissons of the former Redheugh bridge at

Newcastle upon Tyne, UK. Interpreted from data reported by Morley ²⁶.

Figure 12. Correlation between R and DIN for all cases.

Figure 13. Two examples showing the highly localized corrosion in the central web areas of U and also of Z profile piles.

Figure 14. Localized corrosion at areas of local steel porosity and imperfections in grain structure for 18mm wall thickness. This sample is in the web-flange region.

Figure 15. Variation of ALWC parameter R as a function of phosphorous (P) content.

Accelerated low water corrosion (ALWC) of steel piling in harbours

Figure 1(a)

Figure 1 (b)

Figure 2.

Figure 3.

Figure 4.

Figure 5.

Figure 6.

Figure 7.

Figure 8.

Figure 9.

Fig. 10 a

Fig 10 b

Fig 10 c

Figure 11.

Figure 12.

Fig 13 a

Figure 13 b

Figure 14.

Figure 15.

Accelerated low water corrosion (ALWC) of steel piling in harbours

Table 1. Effect of alloying (% wt) on ALWC of steel sheet piling.

Location	Mark	Steel Code	C	P	Mn	S	Ni	Cu	R = A/I
Harbor Island	CS	Carbon Steel		0.04 max			-	-	1.2
	A	B01458		0.12			0.45	0.52	1.2
	B	B01389		0.17			0.55	0.22	1.39
	C	B01457		0.11			0.54	0.20	1.11
	D	B01459		0.14			0.55	0.20	1.26
	E	B01467		0.14			0.28	0.20	1.07
	F	B01456		0.17			0.28	0.22	1.44
Buzzards Bay		A36	0.26 max	0.04 max		0.05 max			2.2
		A690	0.22 max	0.08 0.15	0.60 0.90	0.04 max	0.04 0.75	0.50 min	2.5