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CORROSION OF VERTICAL STEEL STRIPS EXPOSED IN THE MARINE TIDAL ZONE AND IMPLICATIONS FOR ALWC

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ABSTRACT

Accelerated Low Water Corrosion (ALWC) particularly of steel sheet piling in harbors has been documented in various parts of the world. It is thought to involve microbiological influences but the precise mechanisms involved remain to be explained. This paper reports in-situ field investigations for the corrosion of long lengths of mild steel strips exposed at 10 locations on the Eastern Australian seaboard for up to 3 years. Preliminary results show that corrosion below the mean low water level was more severe for higher average concentrations of total nitrogen concentration in the bulk seawater. This is consistent with earlier findings that elevated nitrogen levels increase corrosion, an observation earlier attributed to microbiological influences. The results presented allow the prediction of the likelihood of the occurrence of long-term ALWC through short-term corrosion profile experiments or when measurements are available of bulk water nutrient concentration. It is proposed that the influence of bacteria also holds for freshwater conditions although the rate controlling nutrients are likely to be different.

Keywords: Steel, seawater, tidal, strips, microbiological corrosion, nutrients.

INTRODUCTION

Accelerated Low Water Corrosion (ALWC) of sheet and other steel piling used for port infrastructure such as wharves and bridge and jetty supports has in recent years become a topic of much discussion and also considerable research, as described in more detail below. Despite this, the problem is still not fully understood. ALWC is the corrosion of steel piling in the region below about the mean low tide (MLT) level for tidal marine waters (or an equivalent location). This can lead to premature or unexpected failure of the sheet piling by bending or to loss of back-fill behind sheet piling, with consequent potentially sever economic losses for port authorities. The problem is of interest for

structural engineers because of the need to predict likely durability and safe operation of such facilities.

The marine tidal zone region is well-known to be severe for the corrosion of unprotected steel. The earliest studies, conducted during the late 1940's to mid-1950's on the US East coast, showed that the greatest amount of corrosion loss occurred locally at around the high water mark and with relatively low losses around the mean tide region. For coupons that are not connected together there was a similar effect but also considerable corrosion losses through the whole of the tidal zone. Figure 1 shows some typical results, for quite short (around 6 months) and somewhat longer (5 year) exposures[1,2]. However, even the latter are quite short compared with the expectations usually placed on the durability of civil infrastructure, where 50- or 100-year lives normally are demanded.

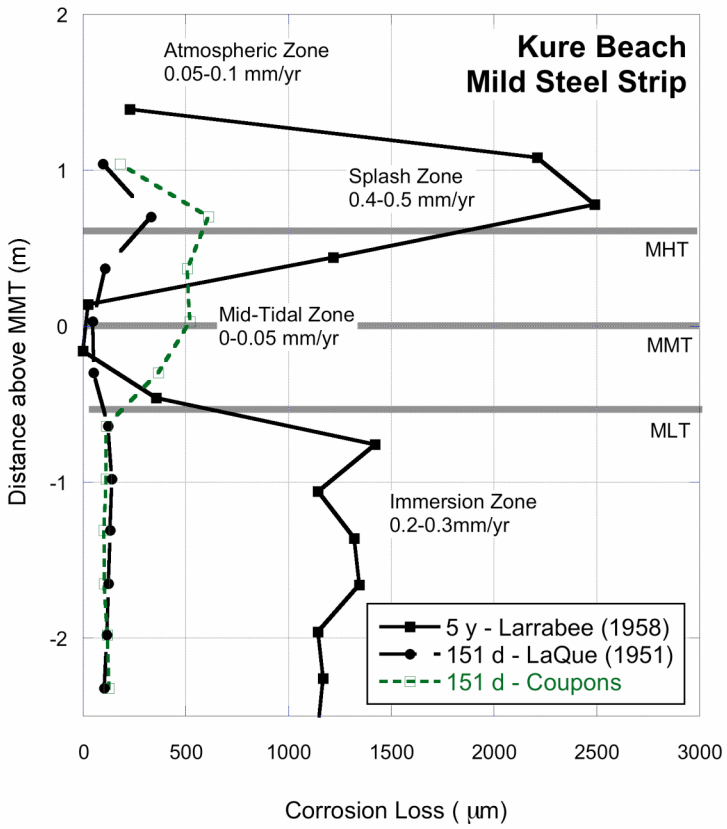

FIGURE 1 - Some classical data and trends for exposure of mild steel strips and coupons in the Atlantic Ocean at Kure Beach, USA.

While ALWC often is considered a relatively 'modern' problem, sometimes associated with changes in steel composition, there are clear antecedents. Thus the high local corrosion immediately below the waterline was studied already in the 1920's and, according to Evans[3], was eventually attributed by JN Agar to the then newly discovered phenomenon of differential aeration. Differential aeration also may have contributed to the severe corrosion losses observed immediately below the waterline of naval ships 'moth-balled' in San Diego harbor[4]. However, this was eventually attributed largely to high levels of (sewage) water pollution[5].

There is evidence that the ALWC phenomenon for steel sheet piling in the marine tidal zone was observed already in the 1950's at some isolated locations. Although there is little in the corrosion literature from that era, some corrosion specialists with considerable practical experience recall seeing the characteristic yellowish corrosion products that are now known to overlie gey rust products that are easil removed to reveal bright steel[6]. Arup and Glantz[7], in a paper that appears largely to have gone

unnoticed in the ALWC literature, observed cases in Danish harbors of steel sheet piling that had perforated after 25-35 years operation and that showed pitting corrosion rates of some 0.25-0.5 mm/year. Steel sheet piling in some 20 Danish harbors was surveyed during 1961-2 using ultrasonics to determine remaining wall thickness at various locations between MWL and the mud-line and along the sheet pile wall. The study, covering piling ranging from 15 to 35 years old, found the highest corrosion losses to occur some 0.3-0.6m below MWL. Since the tidal range in Danish waters is 'slight', this can be taken to correspond closely with MLT. In passing, the authors noted that 'the highest corrosion rates have been found in harbors with fish industries' but did not elaborate. The authors also noted that similar work to theirs had been done in Norway and South Africa but had not been published.

More recently interest in ALWC has grown, particularly for European marine ports[8] but it has now been observed in many other locations (e.g. Ref 6) as well as the fresh water port of Duluth on the Great Lakes in the US[9]. Moreover, although not noted as ALWC[10], it can be seen also in data for the corrosion losses on some oil production platforms, particularly for electrically connected coupons (Figure 2).

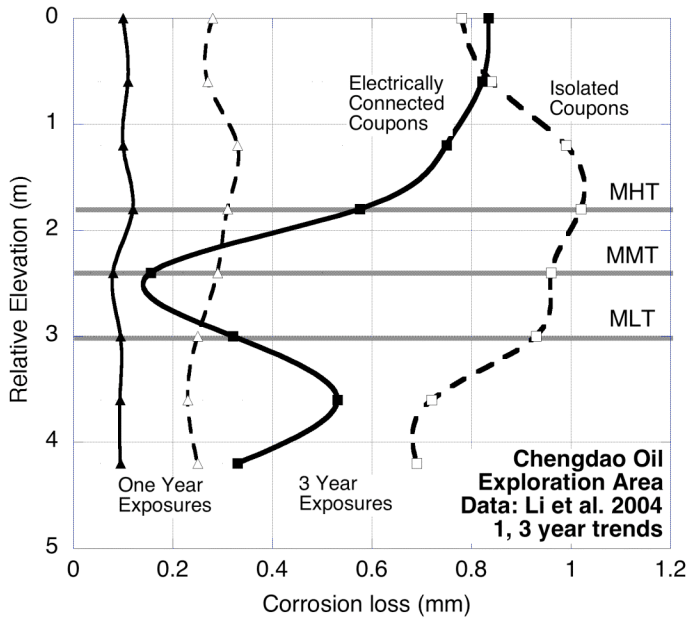

FIGURE 2 - Corrosion profiles for coupons and strips in the Chengdao Oil Exploration Region showing evidence of ALWC after 3 years exposure. MHT, MMT and MLT denote mean high, mean and low tide levels respectively. Data from [10].

Several European studies have implicated microbiologically influenced corrosion (MIC) as a causative mechanism for ALWC[11,12,13,14]. Generally they found high bacterial counts whenever ALWC was present. The bacteria usually associated with marine corrosion are the sulfate reducing bacteria (SRB)[15] but these invariably are part of bacterial consortia that include sulfur oxidizing bacteria (SOB), often considered to enhance the metabolism of SRB and therefore potentially causing greater corrosion damage[16]. While there is much understanding of the influence of bacterial activity on corrosion while the SRB reside in anaerobic niches in the biofilm that forms very quickly after steel is first exposed to seawater[17], the situation is less clear for longer term exposures when there is already a considerable amount of rust product formed on the steel surface. Thus in a study of 22 sites in harbors in Europe including 10 where the sheet piling apparently was not suffering from ALWC, no clear correlation was established between bacterial counts and ALWC[13]. Most of the piling studied was some 30-40 years old and already considerably corroded. Iron sulfide, normally a product of SRB activity, was detected at all locations. However, for the ALWC sites somewhat elevated levels of organic carbon, nitrogen and hydrogen were noted. Beech and Campbell[18] recently have given an extensive overview of the

complexity of the problem. It is clear that a sound understanding is still lacking of why ALWC occurs at some locations and not at others. Moreover, there is also no logical explanation of why sheet piling of different geometries corrode in different ways. For example, Larssen (U-shaped) sheet piling usually corrodes through in the trough of the U shape. On the other hand, Frodingham (Z shaped) sheet piling often is found to have corroded through in the middle of the Z shape. Similarly, there are observations of more severe ALWC effects on one side of quay harbours compared with the lesser effects on the other side[18].

It is evident from the above that the corrosion of steel piling is a long-term corrosion problem and therefore not one easily studied in the laboratory. It is now recognized that laboratory studies are unable to replicate the precise conditions required for a realistic study of microbiological activity and its potential influence on seawater corrosion, including that of steel[19]. Earlier, it had been proposed that long-term corrosion loss and maximum pit depth in marine environments can be, and should be, modeled using only field data and corrosion science principles[20,21]. In particular, it is now clear that MIC if it is involved will be influential on the corrosion of steel within a very short period after initial exposure[22]. It can be involved also again later, in long-term corrosion, provided the environmental conditions are appropriate[20,21]. It follows that if MIC is involved in ALWC, this longer-term bacterial component of the model will be associated with it.

To date the field observations of ALWC have invariably considered older piling and looked for both evidence of bacterial activity[11] or nutrients or other water quality indicators[13] and evidence of localized corrosion around the MLT level. There appear to have been no studies of a possible correlation between water quality and ALWC of steel piling or steel strips in shorter-term exposures in the tidal zone. Such correlation would be expected since MIC is known to occur on steel surfaces soon after the steel is first exposed to natural seawater[22,23]. Moreover, elevated levels of nutrients have been demonstrated to increase marine corrosion loss and maximum pit depth for steel in marine immersion conditions. This is the case both for early corrosion[23] and for longer-term exposures[24]. It is therefore reasonable to suppose that this phenomenon will be reflected also in ALWC. This is the first hypothesis for the present work.

Both the rate of early corrosion and longer-term corrosion are functions of water temperature, and this appears to extend to some degree also to the rate of bacterial metabolism[20]. Empirical data collected from a variety of natural seawater exposure experiments suggests that the early effect of MIC tends to be less severe than for subsequent corrosion[21] and for maximum pit depth. This suggests that any ALWC effect that can be attributed to MIC and also to differential aeration is not likely to be clearly discernible in short-term experiments, particularly in colder waters[7]. However, longer duration experiments, particularly in warmer waters, could be satisfactory in indicating proneness to ALWC. This is the second hypothesis for the present work.

EXPERIMENTAL PROGRAM

As noted, it is increasingly evident that laboratory experiments cannot replicate natural seawater corrosion, largely because of the difficulty in replicating biological influences[19]. For this reason, and in common with earlier work[25,26], field exposures were chosen as the best means for attempting to obtain information about ALWC.

The experimental program consisted of exposing 3 and 6 m long strips of mild steel, 50 x 3 mm in cross section, at 10 different locations along the East coast of Australia for up to 3 years (Figure 3). The program is not yet complete and only the results for up to 2 years are reported here. Typically the strips were simply attached to a timber jetty using steel bolts. This provided insulation from surrounding structures. Owing to the difficulty of preparing the surfaces of these long strips to conventional corrosion testing standards, the strips were exposed in the 'as-delivered' condition apart from being degreased prior to exposure. All the strips showed a uniform smooth grey surface mill-scale finish.

Previous studies have shown that the presence of mill-scale has only a temporary, short-term effect on corrosion loss.

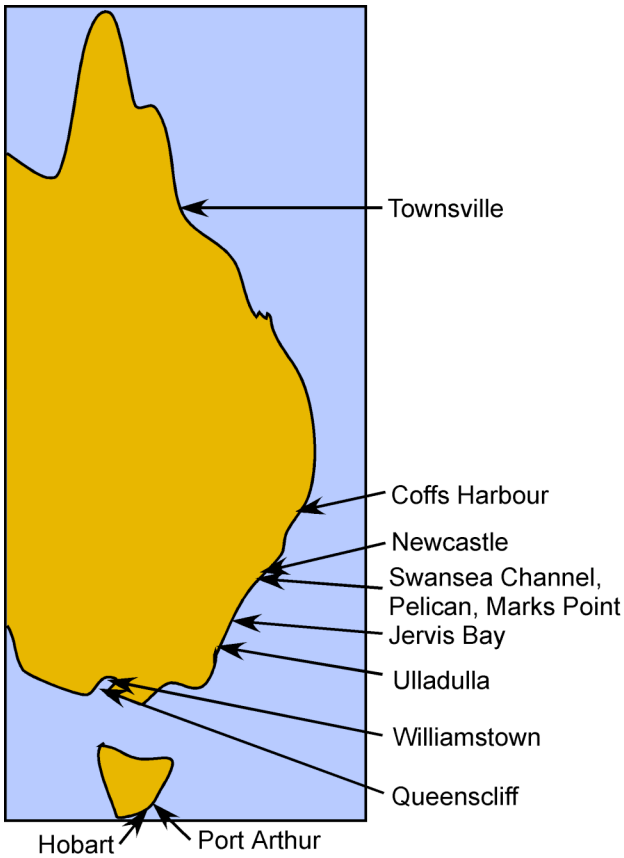

FIGURE 3 - Map of eastern Australian coastline showing corrosion testing sites.

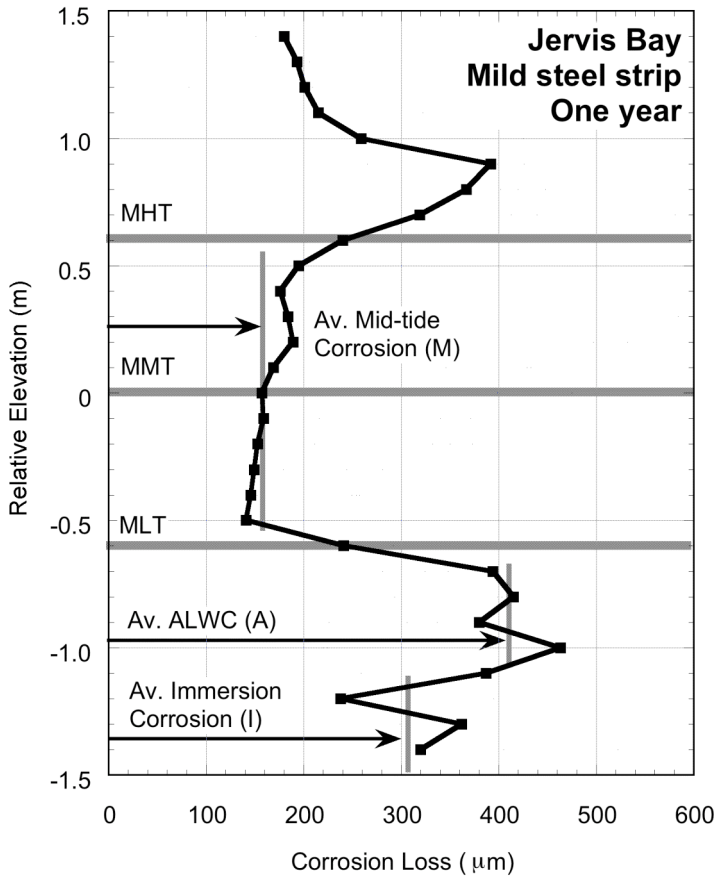

FIGURE 4 - Corrosion loss profile for one-year exposure at Jervis Bay, showing tide levels and parameters M, A and I used in the analysis.

After a predetermined exposure period the strips were recovered from each site, cleaned of marine growth and fouling and loose rusts were knocked off. The strips were then repatriated to the laboratory where they were immediately guillotined to individual segments each very closely 100 mm long and number-punched sequentially as they were cut. Each segment was then cleaned to remove rusts according to ASTM G3 and the mass of each segment ascertained. The mass loss over the exposure period was then calculated, with the original mass of each section estimated from the density of the steel and the original dimensions (allowing where necessary for any fixing holes). The uncertainty in mass loss was estimated to be about 1%, governed mainly by accuracy in the cutting of the strips to segment lengths. The equivalent corrosion loss for each segment was then calculated from the individual mass losses. The information so obtained permitted the plotting of a corrosion loss profile relative to the mean tide (MMT) and mean high (MHT) and mean low (MLT) tide levels at each site. Figure 4 gives an example for the Jervis Bay site. It shows the individual corrosion losses for each segment plotted at the mid-height elevation of each segment. Also shown is a best-fit curve constructed through the data points. Where possible the ALWC region was identified as well as the mid-tide corrosion region and the immersion corrosion region. This was done for all sites. Table 1 shows a summary of the results for the exposure periods for one year or more and for which currently data are available.

TABLE 1

Corrosion Loss and Environmental Data for Australian Sites

Column (1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Site	Exposure Period (months)	ALWC (A) (microns)	Immersion Corrosion (I) (microns)	Mid-tide Corrosion (M) (microns)	Ratio R1 = A / I = (3)/(4)	Ratio R2 = A / M = (5)/(4)	Mean Total N[a] mg N/l
Townsville	12	520	320	240	1.63	2.2	0.06
	18	540	500	260	1.08	2.2	0.06
	24	1060	800	300	1.33	3.5	0.06
Coffs Harbour	12	630	500	300	1.26	2.2	0.065
Newcastle	6	250	180	100	1.39	2.5	0.067
	12	300	250	100	1.20	3.0	0.067
Swansea Channel	12	480	350	200	1.37	2.4	0.085
Pelican	12	300	210	140	1.43	2.1	0.085
Marks Point	12	480	350	160	1.37	3.0	0.085
Jervis Bay - slow[b]	12	470	340	120	1.38	3.9	0.045
- medium	12	480	350	150	1.37	3.2	0.045
- fast	12	520	400	150	1.30	3.5	0.045
Ulladulla	12	420	300	90	1.40	4.2	0.13
Williamstown	12	220	150	100	1.46	2.2	0.14
	18	660	350	120	1.88	5.5	0.14
	23	750	500	180	1.50	3.1	0.14
Queenscliff	13	570	320	200	1.78	2.9	0.155
	18	710	380	200	2.30	3.6	0.155
Hobart	13	560	370	180	1.51	3.1	0.08
	18	760	450	170	1.69	4.5	0.08
Port Arthur	13	470	300	130	1.57	3.6	0.11
	18	550	300	150	1.83	3.7	0.11

Notes:
[a] Mean Total N based on average between summer and winter levels or best estimate thereof. Surface seawaters tend to be lower in nutrient concentrations during summer months.
[b] Slow, medium and fast refer to relative water velocities at sample locations.

To relate the corrosion losses with nutrient loads in the seawater at each site, periodic water quality monitoring was carried out at all sites. Seawater samples were tested for nutrients including total N in a commercial water-quality testing laboratory. Where possible Summer and Winter nutrient levels were measured, based on these typically being the extreme variations of nutrient loading[27]. However, Spring and Fall readings were taken also at sites where there is known to be a temporary nutrient bloom during the Spring period. The nutrient information is not yet complete for all sites. Table 1 gives the range of values based on current data, and the best estimate for the annual mean N load.

In general bacterial activity is controlled by the rate of bacterial metabolism and this is particularly relevant for the sulfate reducing bacteria that appear to be the main influence in immersion corrosion of steel in seawater[11,15,18]. Of the various nutrients that could be rate-limiting, the nutrient of most interest for bacterial activity in seawater is nitrogen and this has previously been shown to be correlated with early and with later MIC in seawater[23]. It is reasonable to suppose that the same will hold for any MIC involvement in ALWC. Table 1 shows the total nitrogen concentration in the water, including ammonia, nitrate and nitrite. Normally only the first of these is significant.

ANALYSIS

The corrosion loss data was analyzed as follows. Because the environmental conditions at the exposure sites are all different, control over the experimental conditions is less than ideal and this could lead to some level of variability not captured in the two key parameters considered in the present study - water temperature and nutrient loading. The former was handled by considering not the actual corrosion losses in the ALWC region (i.e. immediately below MLT) but by considering the ratio *R1*, defined as:

$$R1 = (\text{av. ALWC loss}) \ / \ (\text{av. immersion loss}) = A / I \qquad (1)$$

where 'av. ALWC loss' (*A*) and 'av. immersion loss' (*I*) are defined in Figure 4. Evidently, some degree of judgment was required in assigning values to these terms. The use of *R1* rather than the actual losses is an attempt to by-pass the influence of water temperature. It is well known that water temperature has a significant effect on immersion corrosion loss. For longer-term corrosion losses this can be accounted for by considering only the annual mean seawater temperature[20]. Since it is highly likely that the water temperatures in the ALWC zone and in the immersion zone will be closely similar, the use of a ratio of corrosion losses is likely to eliminate the effect of water temperature. Whether the experimental results bear this out will be considered again below.

Figure 5 shows the corrosion loss ratio *R1* plotted against the average annual total nitrogen load (Table 1) for each of the sites, as marked.

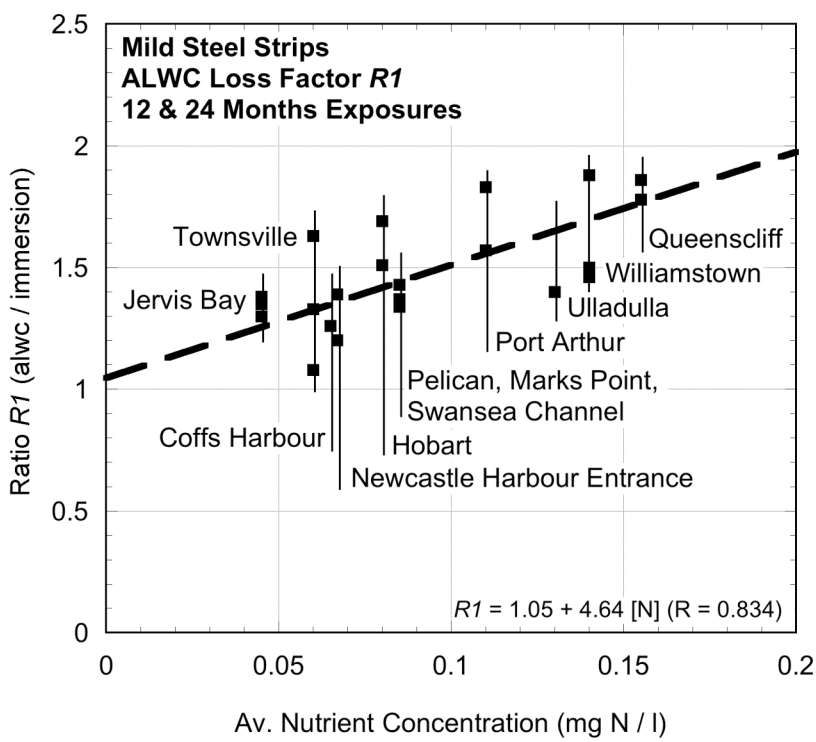

FIGURE 5 - Effect of nutrient concentration in bulk seawater on ratio *R1* between maximum low water and immersion corrosion losses.

A second parameter, the ratio *R2* also was defined:

$$R2 = \text{max / min corrosion loss} = M / A \qquad (2)$$

where the 'av. mid-tide corrosion loss' *M* is defined in Figure 4. Again, a degree of subjective judgment was involved, but the error clearly is not large. This ratio is plotted in Figure 6, again as a function of average annual nutrient load (Table 1).

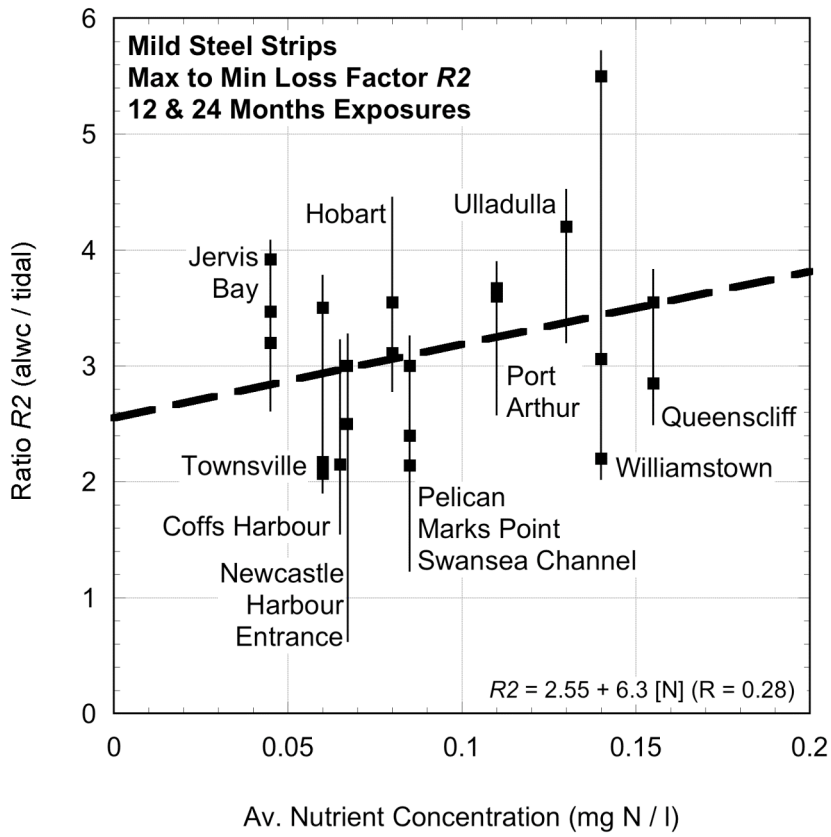

FIGURE 6 - Effect of nutrient concentration in bulk seawater on ratio *R2* between maximum and minimum corrosion losses.

DISCUSSION

Figure 4 shows that for the Jervis Bay site the ALWC phenomenon was (just) evident already after only one year of exposure, with R1 being slightly greater than zero. Similarly from Figure 5 it can be seen that *R1* > 0 also for all the other sites in the present study, for which the longest exposure period was only 2 years. This is considerably shorter than the detection time for ALWC reported in any previous investigation. The main reason for this is that previously it tended to be thought that ALWC is a phenomenon that becomes evident only after long-term exposures. However, the present work has commenced form the hypothesis that if bacteria are involved in the corrosion process, as variously proposed based on their identification with ALWC and the presence of certain corrosion products, then evidence of ALWC ought to be available reasonably soon after first exposure in seawater, since it is well-established that bacterial activity is active already soon after first exposure.

Direct evidence that the bacteria associated with areas of corroding steel are actually involved in the corrosion process and hence contribute to either pitting or corrosion loss or both generally is difficult to

obtain. This is because while some corrosion may be the result of the influence of bacteria, there is another possibility, expressed in the acronym CIM - Corrosion Induced Microbiological activity[28]. It recognizes that iron (Fe) is a critical nutrient for most biological processes[15] and therefore it is possible that the bacteria are where they are found because the local environment is favorable. It has been proposed that to establish whether microorganisms are involved in the corrosion process it is necessary to ascertain whether there is a relationship between nutrient availability and corrosion loss or pitting, irrespective of precisely which bacteria are involved[21]. Such relationships are precisely what Figures 5 and 6 attempt to show.

In part, the scatter in the data in Figures 5 and 6 most likely is the result of having used data collected from in-situ field experiments. For these there are only limited possibilities for experimental control and none on influencing parameters such as water temperature and water quality variations. As in earlier work by the authors, the variations in these parameters may be assumed to be composed of an annual cycle with year-to-year variability. For this reason the data for just 6 months observations largely have been excluded from the analysis at this time, but may be included at a later date once there is sufficient data to represent within-year variations. This is particularly important for water quality influences for which the present data base needs considerable augmentation. Despite this, changing the estimated values for N concentration in Table 1 within the range of observed values and allowing for when these were observed was found to have relatively little effect on the trend lines shown, even though the ordering of sites was not identical always to that shown in Figures 5 and 6.

In part, also, the scatter in the data in Figures 5 and 6 may be due to the use in the present analysis of bulk water nutrient concentration. This was entirely for practical reasons. The nutrient concentration of direct relevance for bacterial metabolism is that in the immediate vicinity of the organisms involved, that is within the biofilms or similar locations. However, to measure or estimate bacterial metabolism is clearly difficult and also raises the issue of interference by the experimental techniques in the very processes being studied. For this reason the bulk water nutrient content was used, despite its surrogate nature. Nevertheless, it might be expected from considerations of species diffusion that the bulk water nutrient concentration will be reflected, on average, in the local nutrient concentration adjacent to microorganisms. Evidently, this will not necessarily be the case for all locations and for all microorganisms present. Moreover, there is likely to be interaction between different microorganisms and between different levels of nutrients - the precise details of these interactions are, of course, of much interest. Whether they have a significant influence on the longer-term corrosion processes remains to be elucidated through further research. Neglecting this aspect implies an additional degree of uncertainty in the data and in its interpretation. Nevertheless, Figures 5 and 6 do demonstrate that despite the neglect of these more detailed aspects there is correlation between nutrient load and corrosion loss profiles. It is this aspect that is of most direct practical interest.

Comparison to Table 1 for mean annual water temperatures for the respective exposure sites shows that there is no obvious pattern that correlates *R1* or *R2* with average seawater temperature. Despite the data limitations, the tends shown in Figures 5 and 6 are easily demonstrated to be not very sensitive to quite considerable, but reasonable variations about the nutrient values shown in Table 1. Thus, despite the uncertainties in the data, the qualitative aspect of trends in Figures 5 and 6 can be considered to be quite clear. As more data become available the quantitative aspect of the trends is expected to become more defined. However, even at this stage some observations about the trends can be made.

The trend line for *R1* in Figure 5 is a reasonable fit to the data, indicated by the correlation coefficient R = 0.83. Evidently, at zero nutrient concentration *R1* is approximately unity. This means that there is then no ALWC effect and that immersion corrosion is roughly the same within the upper immersion zone and into the tidal zone. In contrast, the trend line for *R2* in Figure 6 is a relatively poor fit (R = 0.28). Nevertheless, extrapolating it to zero nutrient concentration shows that *R2* there is approximately 2.5. This is essentially the result obtained at Jervis Bay, Townsville and at Coffs Harbour, all sites considered in previous studies to be close to unpolluted and free from agricultural fertilizer runoff and

from fishery-related activities[25]. The *R2* value in this case reflects the effect of differential aeration on corrosion loss in the tidal zone, compared to corrosion loss in the immersion zone. A similar effect can be seen clearly in the classical corrosion profile given by LaQue[2] for steel strip immersed for 151 days at Kure Beach at a time when water pollution in the area would have been very low.

The practical implications of these findings are two-fold. The first is that, with properly observation of the corrosion loss of steel strips or specific experiments along the lines of these presented here, it should be possible to determine from short-term corrosion loss observations on steel strip (or electrically connected coupons) whether ALWC is likely to be an issue in the long term. Evidently, proper surveys of sheet piling wall thickness at any time after just a few years also should reveal whether the corrosion profile has the characteristic ALWC corrosion pattern seen in Figure 4.

Because the early rate of corrosion is strongly dependent on mean water temperature as shown earlier for in-situ data from a wide variety of sources[20], short term tests of say one year duration may not always be adequate to reveal the possibility of ALWC. Thus Arup and Glantz[7] obtained corrosion profiles from experimental field trials on isolated and electrically connected coupons, each 300 x 250 mm x 3 mm thick, exposed for one year in Copenhagen harbor that has an average seawater temperature of about 9°C. Figure 7 shows the corrosion profile and it is evident that while there is some evidence of ALWC, it is not strong. Similarly, the corrosion loss profile for one year in the Chengdao Oil Exploration Area (Figure 2) shows that when compared to the profile for isolated coupons, the electrically connected coupon profile (equivalent to a continuous strip) shows a hint of ALWC at about the MLT level. However, in this case the physical size of the coupons involved tends to smooth the overall trend curve. This is therefore an important aspect to consider in experimental design.

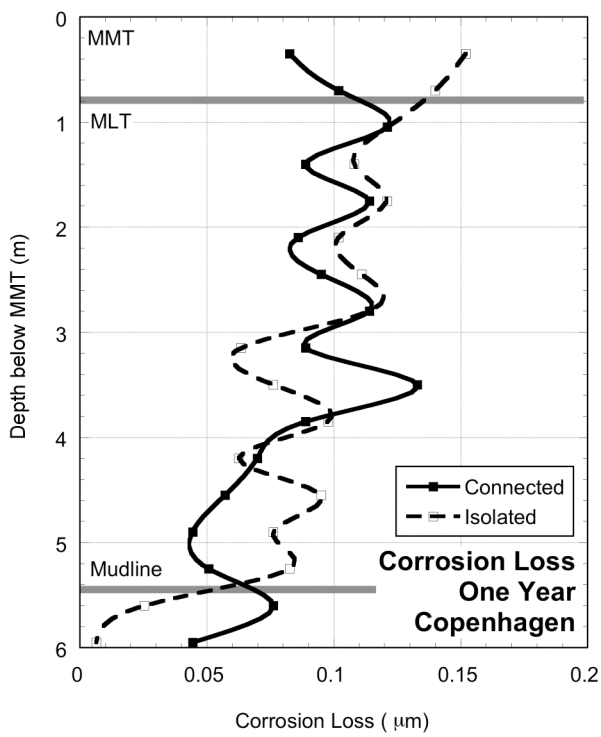

FIGURE 7 - Corrosion loss profile for sheet piling in Copenhagen harbor (data from Ref 7).

The second practical implication of the present findings follows from Figures 5 and 6. They show a clear relationship between corrosion loss in the LWT region and total N concentration in the bulk water, even though there is considerable scatter in the data. This means that elevated total N in seawater is

likely to result in ALWC. It is reasonable to suppose that higher N levels will result in the earlier occurrence of ALWC but this remains to be ascertained by further research and through model development and calibration.

As noted in the Introduction, ALWC is not a modern phenomenon as sometimes assumed, having been noted in Danish harbors already in the 1950's if not earlier[7]. Nevertheless, its relatively recent widespread appearance in ports along the North Sea and also in Atlantic Ocean ports, both in the UK and elsewhere, appears to have been quite unexpected[29]. A possible explanation for this can now be offered, given the above analysis showing that a crucial aspect of ALWC is MIC controlled by the availability of appropriate nutrients. Environmental studies have shown that water pollution, and thus nutrient loading, in the North Sea and the North Atlantic coastal zones rose considerable since about the 1950's [30] although there is now evidence that this has peaked and may be declining [27]. However, long-term corrosion integrates the influences of environmental variables over many years of time. This means that is likely that the deterioration of sheet and other steel piling increasingly becoming evident in recent years is simply the legacy of earlier periods of high nutrient loadings (i.e. water pollution). This may be the simple explanation for the puzzle of the apparently 'modern' nature of ALWC - it is simply the outcome of earlier decades of high levels of water pollution.

The discussion above has focused only on the ALWC phenomenon for marine exposure conditions and the evidence that this involves MIC. As noted, ALWC also has been observed in the fresh waters, most notably in Duluth-Superior Harbor on Lake Superior in the USA. The preliminary report was uncertain about the possibility of MIC being involved[9]. However, it has been suggested[31] that even in freshwaters MIC is a causative agent in ALWC, such as for inland freshwater harbors in Europe. This is supported by observations of bacterial activity and high levels of corrosion under some conditions in freshwaters[32], including in a study of the corrosion of steel along the river Thames in the UK for which corrosion loss was found to be correlated to sewage inflows and that sulfate was the limiting nutrient[33]. This observation was consistent with sulfate being the rate-controlling nutrient required for the metabolism of SRB and other bacteria in the bacterial consortia associated with SRB in freshwater. The implication of these observations is that for fresh waters, too, water pollution is likely to be a decisive factor in ALWC. Evidently, scope exists for investigations along the lines reported herein for fresh (and brackish) waters.

The present results offer no insight regarding the orientation of the perforation of steel sheet piling, and for the different corrosion patterns observed for Frodingham and for Larssen piles. An experimental program currently is in progress that attempts to provide experimental support for a plausible hypothesis to explain these phenomena.

CONCLUSION

The following conclusions may be drawn from the investigations reported herein:

1. The present results show that despite scatter in the data there is correlation between bulk water nutrient content and ALWC (as given by the two proposed measures). This immediately offers a practical approach for assessing the risk of long-term ALWC problems.

2. Since bacterial activity is known to have some influence on the corrosion of steel in seawater already from soon after first immersion, the potential for long-term ALWC can be detected from the corrosion profile of steel tests strips exposed for only a short-term (one - to two year) period. This also offers an immediate practical approach for assessing long-term risk of ALWC.

3. The increased occurrence of ALWC reported in recent years is most likely the result of elevated levels of water pollution in the waters to which the steel piling has been exposed over its lifetime, irrespective of whether water pollution is currently decreasing,

4. It is proposed that ALWC observed in freshwaters also is likely to involve bacterial activity, based on earlier observations of elevated corrosion losses for steel exposed in natural fresh waters with high bulk water nutrient concentrations.

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