CORROSION OF ISOLATED AND ELECTRICALLY-CONNECTED STEEL COUPONS IN TEMPERATE COASTAL SEAWATER

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SUMMARY: Marine infrastructure such a sheet piling, bridge piles and the legs of offshore oil rigs often is exposed to the very corrosive tidal and splash zone environments. In these the corrosion losses are known to vary significantly with elevation and with the electrical conductivity between the areas of steel. Individual coupons typically show much more corrosion in the tidal zone that electrically connected coupons and continuous strips. Classical results are available as well as results from other locations but the potential for water pollution to be involved in the reported observations has not been clarified. Similarly, whether water velocity played a part in the results available in the literature also remains uncertain. As part of a program to develop guidelines for engineering and asset management purposes a new set of tests was conducted at Jervis Bay on the East coast of Australia in essentially clean coastal waters with very low water velocities. Isolated steel coupons, electrically connected steel coupons and continuous steel strips were exposed in the tidal zone. The corrosion profiles were found to be similar to the results available in the literature suggesting that water pollution and water velocity were not significant factors in the classical results.

Keywords: Steel, seawater, strips, coupons, water pollution, water velocity.

1. INTRODUCTION

Marine steel infrastructure such a sheet piling, bridge piles and the legs of offshore oil rigs often is exposed to very corrosive tidal and splash zone environments such as occur in of harbours, ports and offshore. In these zones protective coatings do not always work well and there are problems with keeping cathodic protection systems operational and in place for long periods and with minimal maintenance in these harsh environments. For these reasons and for (perhaps misplaced) reasons of cost it has been traditional to employ bare steel in many locations, particularly for sheet piling in harbours and for bridge piles. While such systems may be adequate for shorter term exposures there is increasing interest in ascertaining the extent to which they are still structurally viable, and if so, the remaining life of whatever is left.

At present the guidelines available to structural engineers for estimating the remaining steel thickness of sheet or other piling are rather general corrosion rates, experimentally obtained at site-specific locations and typically showing a high degree of variability. Moreover, there is, typically, considerable variation in corrosion loss with elevation relative to the mean waterline (Schumacher 1979, Kreysa and Eckermann 1992). The present project is part of an attempt to build better guidelines for engineering design and for the assessment of existing infrastructure. That attempt will build on information already presented in the literature but as will be shown, there is remarkably little quantitative information available in the corrosion literature for longer-term exposures and for the effect of various influencing factors. This is in strong contrast with the very extensive reports for corrosion in the immersion zone. One matter of considerable interest is whether it is adequate to use isolated, relatively small coupons to ascertain corrosion loss behaviour in the tidal zone. An important matter arising from the immersion tests and also from problems with ALWC (accelerated low water corrosion) of sheet piling is the possibility that microbiological activity can have a serious effect on the corrosion of steel in the tidal zone (Genim et al. 1993, Gubner 1998). Whether this is of importance for producing the classical corrosion profiles clearly needs to be established. Other matters of interest are effects such as water temperature and water velocity, previously shown to be critical for corrosion loss and maximum pit depths. Again, there is no information to indicate whether these issues have affected the classical (and other) corrosion profiles. For this reason it was considered desirable to conduct a set of new corrosion trials at a site known to be largely free from pollution and to have only low water velocities.

The next section provides an overview and assessment of material already in the literature for the corrosion of isolated coupons, electrically connected coupons and for continuous vertical strips. Particular attention is given to the variation of the corrosion loss with elevation (the so-called corrosion profiles). This is followed by a description of new test results obtained for isolated coupons, electrically connected coupons and for strips all exposed at the same site. The paper concludes by outlining the relationship of these test results to the results reported earlier in the literature as well as presenting an outline of the work remaining to be done to develop guidelines for engineering design and assessment.

2. REVIEW

Previous studies of steel coupons exposed in the coastal tidal zone appear to have commenced with Humble (1949) who reported corrosion losses for individual coupons as well as electrically-connected coupons. The complete trial consisted of 27 racks of coupons each rack with steels of different composition. The coupons were 300mm x 300mm in size and were exposed for about 6 months. The individual results derived from weight-loss measurements for untreated, sandblasted mild steel plates, coupled and uncoupled are shown in Figure 1. The corrosion profile is shown also. Note that the majority of the coupons were in the immersion zone, i.e. from mean high tide level, down to below the mud line. There are no panels in the atmospheric or splash zones. Even so, a significant difference is evident between the electrically connected and the isolated profiles in the vicinity of the mean water level. Both profiles have the greatest corrosion loss in the high water zone. There is also a higher corrosion loss at the mud line, some 1.8m below the MMT.

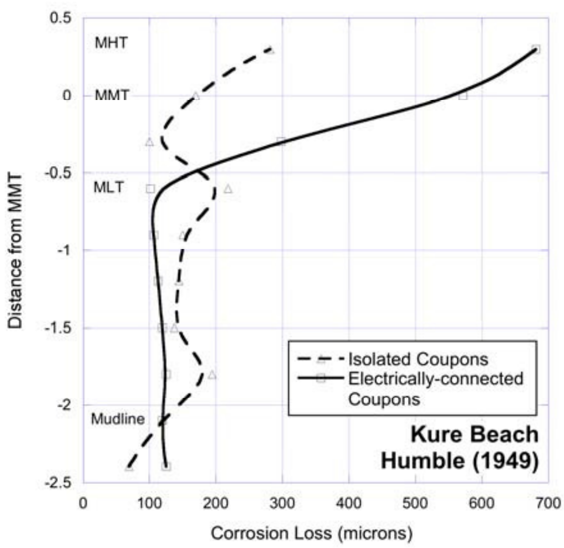

Figure 1 Corrosion profiles for coupled and isolated coupons exposed for about 6 months at Kure Beach, North Carolina. Trends based on date reported by Humble (1949).

Tests at the same test location (Kure Beach, North Carolina) but this time for isolated coupons and for continuous strips of mild steel were reported by LaQue (1951) for tests of 151 days duration (Figure 2). The coupons were 300 mm x 300 mm mild steel plates and the strip was 300 mm wide and 6m long. Corrosion loss was derived from mass loss, with the steel strip sectioned into 300mm lengths. It can be seen that the greatest loss for both strip and panels about 500 mm above the mid-tide mark although the loss on the panels is almost twice that on the continuous strip. Below average low tide level corrosion loss is similar. It will be noted that on the strip profile there are distinct high water (between MMT and MHT) and low water (between MLT and MMT) preferential corrosion zones. LaQue (1951) attributed the differing corrosion loss to differential aeration cells and calcareous deposits.

Subsequently, Larrabee (1958) investigating the ability of various compositions of steel to withstand the harsh tidal corrosion regime reported corrosion losses after 5 years of exposure at Kure Beach. Again the greatest losses were found in the zone between MHT and MLT, generally similar to the short-term test results. Somewhat surprisingly it was found that the low alloy steel performed better than higher alloy steels in the critical zone. The plots produced by Humble (1949), LaQue (1951) and by Larrabee (1958) have been reproduced in texts regularly. However, these are not the only investigations.

Because of the practical concern about pile corrosion, various longer-term average loss rates were investigated. Rayner (1952) reviewed field investigations of steel sheet piling at various locations on the US Atlantic coast. Ayers and Stokes (1961) reported average corrosion rates at 2-3 foot elevations on steel piling that had been exposed in-service for 13-27 years at 8 different harbours in the USA. Some piles had bituminous coatings applied prior to installation. This renders direct comparisons difficult, although the vertical corrosion profiles were generally similar to those shown for continuous strips in Figure 2. The authors noted failures of the protective coatings within 2 years and also that higher corrosion rates could be associated with warmer waters and with sewage polluted waters. A subsequent study (Kumar and Wittmer 1979) reported primarily on coating performance in the tidal zone but also provides results for 5 years of exposure in seawater at Buzzards Bay, USA (Kumar et al. 1981).

Arup and Glantz (1963) made observations about the corrosion rates of steel sheet piling in Denmark, obtaining results not inconsistent with the US results. Takamara et al. (1971) reported both field and laboratory observations for low alloy steel. The field samples were exposed on an offshore ore-wharf dolphin in Osaka Bay, Japan. More recently Li et al. (2004) reported on tidal zone corrosion loss observations taken off an offshore oil platform in the Chengdao Offshore Oil Exploration Area. Figure 3 gives an example. Owing to the inevitable presence of pollution at offshore oil platforms (Odom 1993), these data may not be comparable to data from natural seawaters. Studies using continuous vertical metal strips to simulate the corrosion of sheet piling have also been reported from China (Zhu et al.1997).

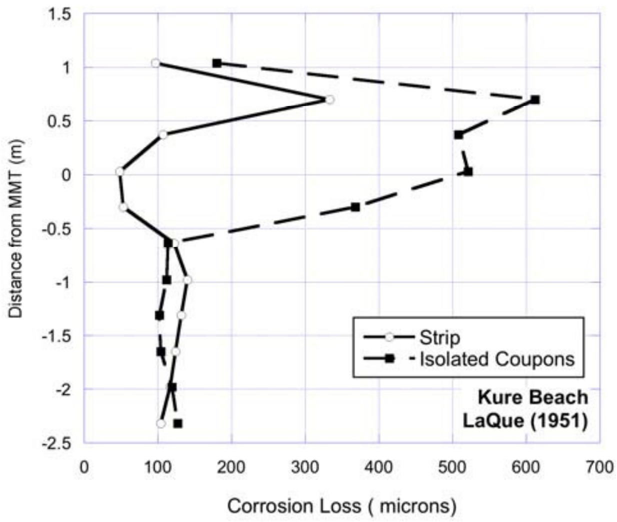

Figure 2 Corrosion profile as derived from exposed steel strip and individual coupons exposed for 151 days at Kure Beach, North Carolina. Based on data reported by LaQue (1951).

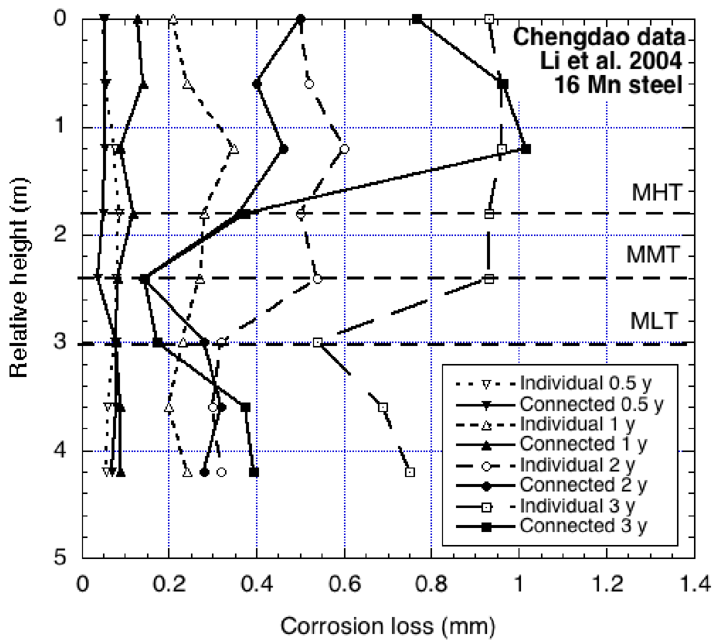

Figure 3 Comparative corrosion profiles for steel (16Mn) coupons isolated and electrically connected exposed at Chengdao Offshore Oil Exploration Area, based on data reported by Li et al. (2004). The profiles for other steels were generally similar.

Observations for individual vertical, closely-spaced coupons exposed for approximately 7 months to coastal seawaters at Taylors Beach and Newcastle Pilot Station has been reported previously by the authors (Jeffrey and Melchers 2007). The trials were conducted to ascertain the possible effect of shielding and of water velocity on the vertical corrosion profiles. This was confirmed. In the splash zone the upper coupons in the shielded condition were found to have corroded more than expected relative to the lower coupons. This was attributed to the effect of rainwater, although earlier Tomashev (1966) had proposed that a similar effect observed by others on continuous steel piling might be the result of differential aeration.

The following describes a field trial conducted at Jervis Bay on the east coast of Australia to attempt to confirm the findings obtained by others that there is a distinct difference in the corrosion loss profile for isolated as opposed to electrically connected coupons and that the profile for the latter corresponds closely to that for continuous strips. Despite the extensive work conducted elsewhere, such a simple comparison appears not previously to have been conducted. The other aspect of interest was the potential influence of water pollution and thus the possibility that microbiological activity may have influenced previous observations. As noted, the corrosion profiles for the previous investigations were all obtained in harbours or waters with a high degree of potential for pollution. Similarly, the potential for there to have been an effect of water velocity on the overall pattern of the corrosion profile could not be ascertained for the classical (and other) results. For this reason a site with low water velocities was used for the present study.

3. EXPERIMENTAL PROCEDURE

The field tests were conducted at Jervis Bay Naval Station, a secure site. Two sets of ten (100 mm x 50 mm x 3 mm) mild steel coupons were each attached to a 50 mm wide 3m steel strips. In turn these were suspended from the timber jetty at the Naval Station. The coupons were acid cleaned and weighed prior to deployment. The strips were exposed in as-rolled condition. Both sets were insulated from the holding strips with nylon bolts and spacers and one set of coupons was continuously electrically connected by short lengths of copper wire, attached using the holding bolts. The lower coupons were permanently immersed and the upper coupons were above the annual high tide level. All test pieces were exposed for a period of 373 days.

The Naval Station is located inside a National Park. There is little or no known agricultural surface water run-off, hence the waters were expected to be nominally free from elevated levels of nutrients (Beckman 1991). Table 1 gives a summary of water quality, measured at various intervals during the exposure period and at other times. It confirms the low level of nutrients in the water. At the exposure site the water velocity is very low (< 0.05 m/s). The tidal range is about 2m. Water temperature was recorded as ranging from 14°C to 26 °C and averaged 18.7°C over the period of exposure.

Table 1 Water quality and other parameters at the Jervis Bay exposure site

Parameter	Units	Typical value (range)
Ammonia	ppm	0.009 – 0.045
Nitrate	ppm	< 0.005 – 0.022
Nitrite	ppm	< 0.003 – 0.036
Sulfate	ppm	2300 – 2800
Total P	ppm	0.007 – 0.008
Ca	ppm	374 – 392
Cl	ppm	21,000
Alkalinity	ppm $CaCO_3$	130
Salinity	ppt	29.0
pH		8.2

On recovery the coupons and strips were taken to the laboratory for cleaning and mass loss determination. The strips were guillotined carefully into 100 mm lengths. The original mass was estimated from the original dimensions and the density of steel. Both coupons and cut strips were acid cleaned and weighed to the nearest 0.1g. The overall error in mass loss determination and hence in corrosion loss is estimated at ± 2%.

4. RESULTS

The data points and the corrosion profiles obtained from them for the two strips are shown in Figure 4. Similarly, the data and the profiles for the insulated and for the connected coupons are shown in Figure 5.

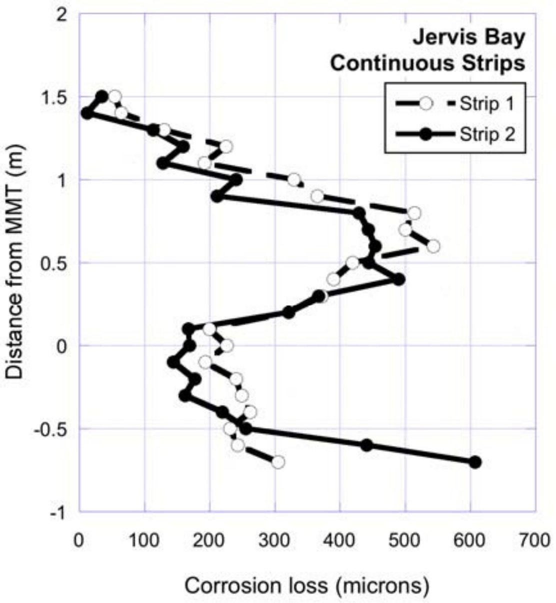

Figure 4 Corrosion profiles for strips

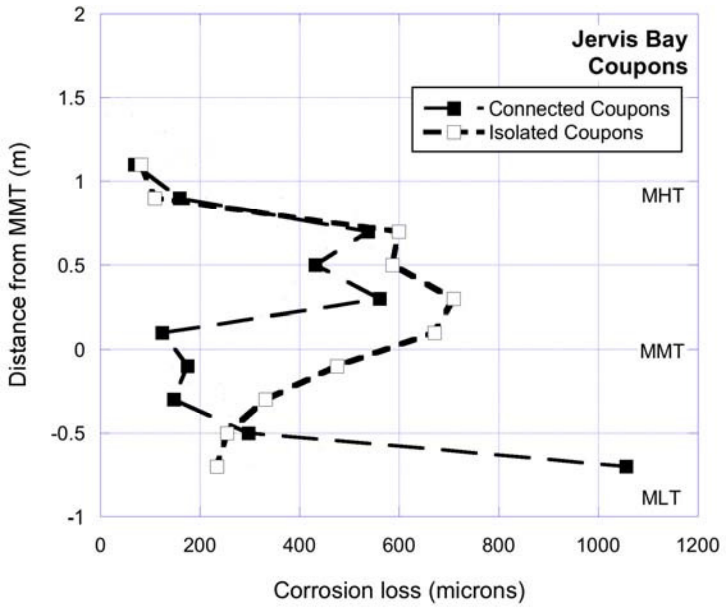

Figure 5 Corrosion profiles for insulated and connected coupons

Evidently, the profiles in Figure 4 are very similar, both showing a distinct increase in corrosion loss in the upper tidal zone and at the lowest section of the strip, consistent with the profiles reported previously (Jeffrey and Melchers 2008). The increased loss above mid tide level has been attributed to maximum availability of the two key factors governing corrosion – availability of oxygen and the presence of a suitable electrolyte. Strips that are embedded in the river or sea bed tend to have a relatively even profile below the annual low tide level – as reported by Humble (1949) and Laque (1951). The addition corrosion loss at the lowest section of the strips reported here has been observed also on strips that are suspended only from the top and are relatively free to move with the current (unreported observations).

The corrosion profiles obtained from the corrosion losses of the two sets of coupons are shown in Figure 5. The corrosion losses in the atmospheric zone are almost identical. Between the maximum high tide level and lowest low tide level (the tidal zone) the profiles are similar but the losses on the isolated coupons are up to twice those of the connected coupons.

Losses at low tide level are very similar. However, in the immersion zone, the few coupons exposed here show very different corrosion losses, with the electrically connected coupons having losses at the lower extremity almost five times those of the electrically isolated coupon. The reason for this difference is unclear. One possibility may be an anodic effect as a result of the coupons being connected to the other coupons. In this case a similar effect might be expected for the strips – indeed these also show evidence of very high corrosion losses at the ends. Shorter strips, not covering the entire vertical range as in Figure 4, also have been found to show a generally similar but less severe effect (Jeffrey and Melchers 2009).

Figure 6 gives a comparison of all the data and all trends. It is apparent that apart from corrosion loss on the lowest connected coupon, the corrosion profile derived from the electrically connected coupons is similar to that of the steel support strips.

5. DISCUSSION

The present results reinforce the observations previously available in the literature that there is a considerable difference in corrosion loss for individual, isolated coupons such as often used in field investigations for ease of handling and corrosion loss determination, and results for connected coupons and continuous strips. The latter are particularly difficult to handle in field investigations and require careful cutting and analysis to estimate corrosion losses and derive corrosion profiles. In contrast, electrically connected coupons are rather easier to handle and to analyse and are here shown to provide results essentially undistinguishable from those for continuous strips. This is the case provided care is taken to select appropriate materials and not cause local galvanic action at the locations where the coupons are connected together.

The corrosion profiles obtained in the present study, as well as those obtained previously by others, illustrate the considerable variation in corrosion loss with elevation, irrespective of whether isolated coupons or strips are considered. This highlights the importance of considering the orientation and elevation of the structure relative to the mean tide and the tidal range. Of particular concern should be the very high losses observed at the lower ends of the strips and coupons. This has been observed also for other, shorter, strips exposed in the tidal zone (Jeffrey and Melchers 2009). As noted the reason for this observation have not yet been identified. It was not, apparently, observed in the classical studies that used much larger coupons (300mm x 300mm) and this may be one reason for it not being observed. Interestingly, the lower parts of the corrosion profiles given in Figure 3 for isolated and connected coupons exposed at an offshore oil platform appear to show higher corrosion losses also. This aspect clearly is one that requires further investigation.

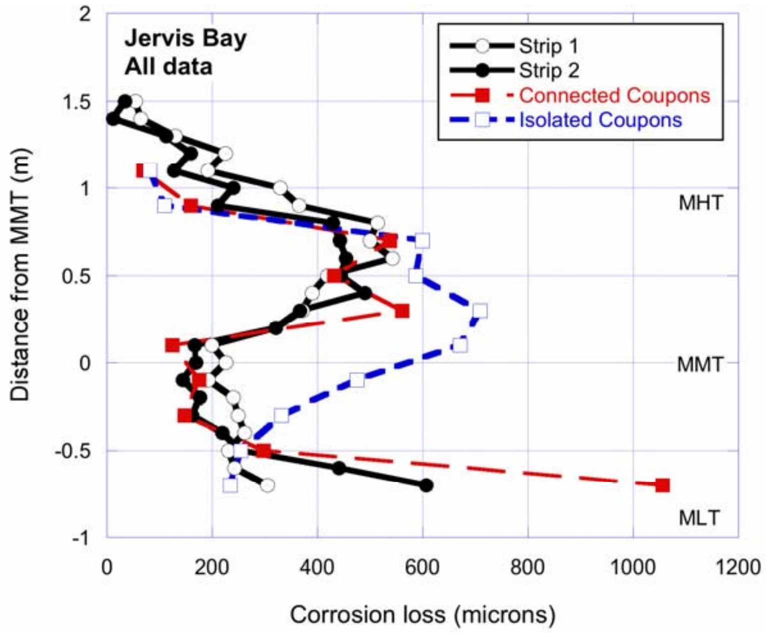

Figure 6 Comparative corrosion profiles for strips and coupons exposed at Jervis Bay.

When the results shown in Figures 4-6 are compared with the classical profiles of Humble (1949), LaQue (1951) and Larrabee (1958) as well as the profiles published by others subsequently, it is clear that the profiles for isolated coupons are all very similar, irrespective of location. Similarly the results for electrically connected coupons are similar to those for continuous strips and also are similar to the classical profiles. Thus it may be concluded that the profiles for the classical results all likely to be applicable to unpolluted coastal seawaters, a matter not previously clarified as water quality was not defined and in some cases there could easily have been local water pollution. Given this conclusion it becomes possible to use the available information together with the Jervis Bay and other data being collected on the east coast of Australia

(Jeffrey and Melchers 2008) to develop trends for the effect of water temperature, the variable so far not accounted for in the data. The outcome of this calibration work will be reported in due course.

6. CONCLUSION

The present results confirm that the corrosion losses in the tidal zone for isolated coupons exposed are more severe than the losses for electrically connected coupons and for continuous strips. This is in accordance with classical results. The present results were obtained in coastal waters with very low pollution levels and with low water velocities. This indicates that the classical results are likely to have been obtained under similar conditions.

7. ACKNOWLEDGMENTS

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9. AUTHOR DETAILS

Robert Jeffrey is a research scientist at The University of Newcastle, Australia where for the last ten years he has been investigating corrosion in marine, tidal and atmospheric conditions. Robert is also a director of Pacific Testing Pty Ltd, a company specializing in corrosion problems. He is a past president of the ACA and has been on the committee of the Newcastle branch for twenty years. He has presented papers at all ACA conferences for the last two decades. He co-authored a paper that won the prestigious T P Hoar Prize (Institute of Corrosion, UK, and co-authored with R Melchers) and has twice been presented with the ACA's Marshal Fordham award for corrosion research.

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