Degradation of wire rope mooring lines in SE Asian waters

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Abstract

Steel wire rope has been used for mooring floating offshore production systems since their introduction nearly 30 years ago. In the majority of systems, unless fully sheathed in plastic, the life of the rope is less than that of the installation. This requires a policy of life prediction, inspection and replacement. The efficacy of various options such as zinc wires are discussed. Case studies are described illustrating how service life can be influenced by the local conditions. It is shown that primary factors in determining long term life are the weight of zinc coating on wires, the effectiveness of lubricant as a blocking compound, and especially the rate of zinc dissolution. There are clear indications from experience that this critical last issue is accelerated considerably by sea water temperature. This is a major difference between some SE Asia and other tropical locations and the N Sea. Experience in cold northern waters has been the basis for recommendations which are seen as inappropriate here.

1 Introduction

Wire ropes are widely used for mooring both floating production systems and mobile units, whether their role be drilling, accommodation or the provision of some other support function. These uses separate into two distinct classes:

- production systems which have permanent moorings where the ropes are only retrieved when due for discard; and,
- mobile units (classed as MODUs below) which have temporary moorings that are retrieved and redeployed whenever the vessel is moved to a different location.

These distinctions are significant with respect to the dominant degradation mechanisms and opportunities for inspection. Furthermore a higher degree of integrity is sought for permanent moorings.
2 Typical wire rope mooring systems

Wire rope moorings are by their nature of the compliant catenary type. At the inboard end there is generally a winch or other means of changing the length of rope deployed. This has the function of adjusting vessel position and controlling mean tensions. In very deep water the current trend is towards the use of polyester ropes avoiding the need for submerged buoys which can support some rope weight to effect better station keeping. Various different arrangements can be encountered at the outboard end of the line varying from simple concepts with the rope running right to the anchor, to complex compound systems with various combinations of chain and ropes of different constructions.

This discussion will focus on the issues of degradation in relation to the different parts of a conventional catenary system, which include some or all of:

- the inactive turns on the winch, i.e. those which remain on the winch but which may support overwound active wraps;
- the active rope on the winch, i.e. the part of the rope at the tangent point and rope which may be run on or off the winch during operations;
- rope in the splash zone which is wetted by seawater but also exposed to air and salt water spray;
- the fairlead region, i.e. the parts of the rope which are subjected to flexure as the rope moves on and off the fairlead sheave (or its equivalent) in response to fluctuations in tension, vessel motions, and winch operations;
- the mid catenary, i.e. that part of the system which remains submerged but contacts neither sea bed nor fairlead once deployed and tensioned;
- the touch-down zone, i.e. those parts of the line which make repeated contact with the seabed as a consequence of vessel motions and tension changes; and,
- ground line, i.e. that part of a rope mooring which, whilst deployed, remains permanently in contact with the seabed, is subject to relatively small axial movements in response to line tension changes, and is frequently buried to some extent.

The dominant degradation mechanisms vary significantly according to location within the system.

There are two primary wire rope constructions used for offshore mooring purposes: spiral strand (Figure 1(a)) and stranded rope (Figure 1(b)). Where stranded rope is used it will have
an independent wire rope core (IWRC) and invariably six outer strands (ropes with eight strands are much more dependent on IWRC for strength and have smaller outer wires than their six strand equivalents, which is not good for corrosion resistance).

![Figure 1](image)

**Figure 1:** Rope constructions - (a) spiral strand, and (b) six strand with IWRC.

Mobile units with wire rope moorings invariably use the more robust six-strand, while spiral strand is preferred for long-term permanent systems. Spiral strand constructions have the advantage that a polymeric sheath can be extruded over them to serve as a barrier to seawater. Such systems for protection are unknown on six-strand mooring ropes, and furthermore are inappropriate for use with conventional winch systems (Firth (1996) or Chaplin and Potts (1991)). The American Petroleum Institute (API RP 2SK (2005)) and Det Norske Veritas (DNV-OS-E301 (2004)) give recommendations for life expectancy of different constructions in terms of corrosion resistance, shown in Table 1, both require all wires to be galvanized though neither make reference to the different weights of galvanizing available.

**Table 1:** API and DNV recommendations for life in years of different rope constructions

<table>
<thead>
<tr>
<th>Rope construction</th>
<th>API</th>
<th>DNV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>replaceable</td>
<td>non-replaceable</td>
</tr>
<tr>
<td>six-strand</td>
<td>6 – 8</td>
<td>&lt; 15</td>
</tr>
<tr>
<td>unsheathed spiral strand</td>
<td>10 – 12</td>
<td>&gt; 15</td>
</tr>
<tr>
<td>unsheathed spiral strand + zinc filler wires</td>
<td>15 – 17</td>
<td>not mentioned</td>
</tr>
<tr>
<td>sheathed spiral strand</td>
<td>20 – 25</td>
<td>&gt; 15</td>
</tr>
<tr>
<td>sheathed spiral strand + zinc filler wires</td>
<td>30 – 35</td>
<td>not mentioned</td>
</tr>
</tbody>
</table>

API, DNV, Bureau Veritas (BV NI 493 (2004)), and International Organization for Standardization (ISO 1990-7 (2005)) all identify corrosion protection measures (galvanizing, lubricant as blocking compound, sheathing, zinc anode wires) and all draw attention to the need for special protection adjacent to terminations including additional anodes and electrical isolation of the rope, and the socket. As regards construction and protection ISO is not prescriptive stating that “typically” sheathing material is used for spiral strands, zinc anode
wires “may” be used, and diameter of ropes “typically” increased by 0.1 to 0.2 mm per
service year to enhance wear and corrosion protection. BV only insist upon galvanizing (or equivalent) and blocking compound, but they also state that diameter should be increased “where applicable” to allow for corrosion and wear.

3 Degradation mechanisms

3.1 Corrosion

The surface of the steel wire used in mooring ropes is (almost) always protected by galvanising. The thickness of the zinc coating (usually expressed as the weight in g/m²) depends on the class of galvanising, which may be “normal” or “heavy marine”: Class B or A respectively (BS EN 10244-2, 2001). As a matter of practicality the coating thickness increases with wire diameter as shown in Table 2. It is also common practice for the wire manufacturer to provide an average cover significantly in excess of the minimum required by standards, to allow for variation in the coating process. Class B galvanizing involves drawing after the hot-dip galvanizing, which gives better control of wire diameter and coating thickness; to achieve the greater thickness required for class A, the hot-dip is the final process which makes diameter more difficult to control and limits tensile strength.

<table>
<thead>
<tr>
<th>Wire Diameter $d$ in mm</th>
<th>Class A in g/m² (and $\mu$m)</th>
<th>Class B in g/m² (and $\mu$m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.50 ≤ $d$ &lt; 2.80</td>
<td>245 (34.5)</td>
<td>125 (17.6)</td>
</tr>
<tr>
<td>2.80 ≤ $d$ &lt; 3.20</td>
<td>255 (35.9)</td>
<td>135 (19.0)</td>
</tr>
<tr>
<td>3.20 ≤ $d$ &lt; 3.80</td>
<td>265 (37.3)</td>
<td>135 (19.0)</td>
</tr>
<tr>
<td>3.80 ≤ $d$ &lt; 4.40</td>
<td>275 (38.7)</td>
<td>135 (19.0)</td>
</tr>
<tr>
<td>4.40 ≤ $d$ &lt; 5.20</td>
<td>280 (39.5)</td>
<td>150 (21.1)</td>
</tr>
<tr>
<td>5.20 ≤ $d$ &lt; 8.20</td>
<td>290 (40.9)</td>
<td>-</td>
</tr>
</tbody>
</table>

As discussed below in detail, the zinc coating has a limited life essentially determined by its rate of dissolution. While experimental work by Yan Li (2001) has indicated that a useful extension may be obtained by using alternative zinc-aluminium alloys as an alternative to zinc, much longer term protection is more effectively provided by plastic sheathing which, however, is only practical for spiral strand. Even local puncturing of the sheath of a spiral strand rope is unlikely to result in significant corrosion since galvanising will provide the
necessary local internal protection and the conditions will be likely to ensure a slow
dissolution rate, which accounts for the service life recommendations in Table 1. The only
significant risk for a sheathed strand is through accidental damage over an extended length
incurred during installation or by heavy contact with other sub-sea hardware.

3.2 Wear
Abrasive wear of the exterior of a rope can only occur as a result of contact and sliding.
Under normal operating conditions, there are three points in a conventional system where
such conditions might occur: at the winch (discussed in the following section), at the fairlead,
and in the touch-down zone.

Relative sliding at the fairlead sheave will be associated with local rope stretch and is very
small. The sheave should have the correct groove profile to minimise contact stresses and
sheave flank interference. Frequent changes in the length of line deployed occasioned by
operational requirements mean that this is not a problem for MODUs. For permanent systems
occasional winch operations will shift the contact zones. However whilst this location is not
considered a problem, and there are no recorded observations of significant wear here, the
desirability to dispense with heavy deck-mounted winches and operate with more-or-less
fixed length mooring lines does lead to localised high contact forces. The tendency to use
small diameter sheaves increases contact pressure, and local rope movement due to vessel
motions or “flapping” of the fairlead sheave in response hydrodynamic loads have the
potential to induce wear. Increasing sheave diameter reduces contact pressure but increases
the length of rope bending on and off the sheave, the likelihood of sheave flank interference
and lateral hydrodynamic loads and thus the “flapping” amplitude.

Ground contact is only likely to become a serious problem when there is a contact with a hard
“fixed” object. Any reasonable planning procedure and bottom survey should eliminate
contact with man-made objects. Smaller rocks would normally be displaced by the rope, but
large boulders can be a problem if they escape a seabed survey. Moored vessels acting in a
support role to a fixed platform can encounter this kind of problem as a result of the need to
move between close and distant positions according to sea state. The resulting sweep of the
ground wire over the seabed can unearth previously buried obstacles. The rate of wear that
can result under these conditions is almost impossible to predict, being affected by so many
variables. The simplest solution is to use ground chain where there is any significant risk of ground contact with immobile hard objects.

Wear from dragging the rope over the seabed is rarely damaging in soft silts and muds, but can become significant in coarse sand seabeds which, rather like sandpaper, will abrade the zinc coating thus affecting corrosion resistance. However the extent of mooring line motions across the seabed is typically not great for most semi-submersible hull forms under most operating conditions since second order drift motions are typically small, though such motions can be substantial under more elevated seastates which occur infrequently. Ship-shaped FPSOs and FSOs exhibit significant second order drift motions, even under moderate operating conditions, whereby there is a greater potential for wire rope wear and abrasion in the touchdown and adjacent groundline.

3.3 Crushing and wear on a winch

The most common form of storage and tension control used for wire rope moorings is a winch onto which rope is wound in multiple layers. The large storage capacity of such winches is essential for mobile units, and can also be a factor in the installation of floating production systems. However the support of the active rope on underlying turns is a major source of degradation, especially given the $D/d$ ratios (drum to rope diameter) favoured for this type of installation which at typically 18:1 are much lower than recommended for any running rope application. Together with the potentially very high rope tensions these low D/d ratios give rise to locally very high contact pressure between wires, which, as shown by Chaplin (1994), is dramatically amplified at the turn crossovers where the rope steps from the valley between one pair of adjacent turns, to the valley between the next pair of turns (illustrated in Figure 2).

![Diagram of rope supported on underlying turns, but crossing over to adjacent valley, generally twice per revolution.](image)
The fluctuating tension in the rope induces elastic extension and recovery. Where the rope runs onto the winch this fluctuating tension and associated deformation is dissipated over an arc of contact extending back around the drum over a distance related to the tension levels. The small amplitude sliding of the rope relative to the supporting layers causes local wear, especially at the crossovers. Such wear can become so severe as to lead to significant numbers of localised wire breaks (Figure 3). These high contact pressures, under the action of high loading can also lead to crushing of the rope. The crushing can cause plastic deformation of surface wires, displacing them from their position in the rope construction. This permanent deformation can be such that, should this section of rope become deployed in the active part of the line, these wires are effectively slack and do not share in supporting the applied tensile load. This can have an extreme effect on tensile fatigue performance, though rope damaged in this way is likely to show little or no loss in tensile strength due to the ductility of the wire restoring load balance as the breaking load is approached.

![Image of rope damage](image.jpg)

**Figure 3:** Damage caused where the tangent point was close to a crossover on a 70 mm mooring line after 8 years of service on a floating production system (after cleaning).

Because of the high contact pressures under normal conditions on a winch drum, should there be any miscoiling of the rope in the turns underlying the tangent point of the rope to the drum, crushing in these area can be extremely severe. This is especially a problem when proving anchor holding capacity at installation, an operation that typically entails tensioning to 50% of rope breaking load. The subsequent relaxation to normal mean loads can result in crushed rope being deployed into the active line.

### 3.4 Torsion effects

Spiral strand ropes have a structure of concentric helical layers of wires with lay angles and sense of lay designed to minimise the net axial torque generated as a reaction to applied tension. The more conventional, and more rugged, six-stranded ropes do not have such a
torque balance. The result is that as tensile loading increases, so too does the torque reaction. If a rope is restricted from rotating by virtue of the attachments at either end, then there will be no rotation. However if there is no restraint, or if the restraint is compliant, there will be rotation until equilibrium is restored. Coupling components with different tension-torsion characteristics can result in counter rotation; this can be damaging. Torsion fatigue is a particular concern in mooring lines which combine six-strand wire rope and torque-balanced polyester ropes (Bradon et al. (2005).

The low torsional stiffness of ropes can lead to low natural frequencies for torsional oscillations. If such oscillations are excited and have the opportunity to achieve high amplitude this can lead to local “de-stranding” of the construction, and if the line slackens the de-stranding will be followed by “hockling” or kinking of individual strands. A common source of torsion problems is twist introduced into chain (due to handling at low tension with a six-strand work wire) which then migrates under tension to other components, especially spiral strand. The various torsional deformations which can be introduced to rope can result in gross reductions in strength by 50% or more, and even greater reductions in tensile fatigue performance.

3.5 Chasing
One of the most common causes of degradation seen in mooring ropes from mobile units is chaser damage. The more obvious signs of chaser damage are lines of crown wire breaks standing out from a band along one flank of a rope. These breaks initiate from brittle surface patches caused by the slip-stick motion of the chaser. This is one of the classic wire rope degradation mechanisms, first described by Stead (1911), in which high surface frictional heating followed by rapid quenching from surrounding material, can induce a metallurgical transformation to a brittle pre-stressed surface patch (which may in some cases be Martensitic) from which subsequent fatigue cracks are easily initiated. This form of damage is undetectable, at least until the wires start breaking.

Although the use of a roller chaser rather than a hooked chain chaser should avoid the problem, the efficacy of this alternative is by no means guaranteed and may not be practicable in many cases. So chasing should be a tool of last resort but may seem the only option following loss of an anchor pendant; if used aggressively the damage caused during the haste to recover a line is more than likely to curtail the useful life of a rope, and in the worst cases
lead to a subsequent service failure. Techniques involving pendant lines lying on the seabed in recorded positions, and which can subsequently be retrieved by grappling, offer a real alternative to a vulnerable buoyed pendant.

3.6 Fatigue
There are three fatigue processes relevant to wire rope moorings:

- conventional tension-tension (T-T) fatigue which is experienced by the whole active line, and where endurance is governed by the range of the cycling tension;
- interactive bending-tension (B-T) fatigue experienced locally at the fairlead, where the rope stretch associated with fluctuating tension induces small amplitude bending motions (which can be further amplified by vessel motions); and,
- torsion fatigue where cyclic tension generates a proportional cyclic torque in the rope, and the adjoining components do not have sufficient torsional stiffness to prevent rotation – life under these conditions is related to a combination of twist range and tension range.

The fatigue endurance in T-T can be reduced by as much as an order of magnitude once B-T effects are taken into consideration. However B-T fatigue damage is restricted to the short parts of the line moving on and off the fairlead sheave. B-T fatigue is therefore unlikely to be a problem for a mobile unit, and can be easily mitigated in permanent systems by occasional movements of the line. In the latter case the frequency of such adjustments should be limited to minimise the possibility of damaging the rope on the winch during adjustment.

In practice fatigue of wire rope moorings only becomes a problem when some other form of degradation, such as corrosion, crushing or wear, has severely reduced rope endurance locally. Torsional fatigue however has been observed in composite (six-strand wire and torque-balanced polyester) mooring lines, though these effects can be mitigated by designing polyester ropes with torsional characteristics which match those of the wire rope (Bradon et al. (2005)).

4 Corrosion protection from zinc
Of the different degradation mechanisms described above, provided abuse and accidental damage are avoided, for unsheathed wire ropes corrosion is dominant. Whilst intact the zinc coating is effective in providing a simple protective barrier to the steel. But with time zinc is
slowly dissolved where it is exposed, and its loss may be accelerated by external abrasion or at internal contacts between wires. Once steel is exposed the sacrificial protection begins involving a galvanic cell between the zinc and steel, via a seawater electrolyte. The sacrificial process leads to further consumption of zinc. So dissolution is an essential part of the protection process bringing the zinc ions to the exposed steel surface, but underwater proceeds whether steel is exposed or not, at a rate depending on local conditions. Steel loss will not commence until all the available zinc within a short range has been dissolved. The snag here is that the zinc must be available which means that the anodic zinc and protected cathodic steel must be exposed to, and connected by, hydrous electrolyte, with a return electrical path through the metals. Zinc on the wires within the heart of the rope construction, and protected by heavy marine grade lubricant which blocks out the seawater, cannot protect any exposed steel on outer wires from corrosion. In addition zinc “anode” wires which, for one reason or another, have no effective electrical connection to the steel cannot provide sacrificial galvanic protection. Furthermore if the rope is only wetted periodically, as in the splash zone, the electrolyte may be discontinuous.

The normal sequence of events therefore is that significant corrosion of outer steel wires only begins once all the exposed zinc on those wires has been dissolved. A typical pattern of corrosion which then follows is for the outer wires to corrode, not on the exposed crown, which is typically protected at this stage by zinc carbonate deposits, but along either side of the valley between them. As a result, in a severe case of corrosion, outer wires become almost rectangular in section, standing on edge with the gaps between them filled with corrosion debris (see Figure 4). At first sight, even to the experienced eye, such a rope appears comparatively undamaged as the outer surface looks to be in good condition.

It is also commonly found that the inner wires of a rope in this state are in near perfect condition, with a high proportion of original zinc remaining (see, for example, British Ropes (1979), Chaplin (1992) or MacGregor et al. (1994)) though some losses from the second layer particularly may occur if the blocking compound is sufficiently displaced, incidentally giving extended sacrificial protection. Wires in the IWRC of a six-strand rope are also initially protected by the blocking effect of the lubricant, but under severe conditions of extension and flexure, a “pumping” action can lead to this blocking compound being displaced from the relatively open structure of the IWRC. Once this has happened corrosion of IWRC wires will proceed.
Figure 4: Effects of external corrosion on 90 mm Class B galvanized MODU mooring rope after seven years of N Sea service; above as recovered and below after wet sand-blasting to remove all corrosion debris. Note characteristic “fin” profile of outer wires (Chaplin (1992)).

A dilemma for the rope maker is whether to use a heavy lubricant that will exclude seawater from the interior. Such a policy will obviously protect the interior, but will prevent zinc from within the rope protecting the outer wires. It is of course normal practice to use such a heavy lubricant, and so the critical factor for the onset of steel dissolution is the time taken to dissolve and consume the external zinc. For this reason an option used successfully in a number of installations is to use heavy marine grade (Class A) galvanizing for external wires, but lighter Class B galvanizing for all other wires (MacGregor et al. (1994)).

Figure 5: Left: corrosion and break-up of IWRC of 76 mm ungalvanized MODU mooring rope after five years service; right: IWRC of 90 mm galvanized MODU mooring rope after 7 years (from Chaplin (1992)).

Figure 5 (a) shows the state of corrosion of the IWRC of the mooring rope of a mobile drilling rig which had no galvanising, but which had been in service on different North Sea locations for five years. By comparison Figure 5(b) shows the IWRC of the same galvanized rope as shown in Figure 4, which has seen just under seven years service. The IWRC of the first rope is close to total disintegration, whilst the second sample retains lubricant and shows little sign of corrosion: the benefit of the galvanising is clear.
In addition to coating thickness local conditions can make an appreciable difference to the critical rate of zinc dissolution. Figure 6 shows two examples of ground wire from North Sea production installations which in one case has been in service for a record breaking 19 years before recovery, and in the second case 17 years. In both cases the outer wires, which both have Class A galvanizing, show barely the beginnings of corrosion whilst the IWRC is almost untouched. In both cases measurements indicate over half the original zinc is still present on outer wires – though the most exposed surface regions of outer wires have very little or no zinc remaining.

**Figure 6:** Left: A gal, 6-strand ground line from Brent Spar recovered after 19 years (Chaplin and Ridge (1996)); right: outer wires of A gal 6-strand ground line after 17 years - shown after wire brushing to remove loose debris.

Figure 7 shows detail of the IWRC and outer strands from the splash zone of a 13 year old six-strand mooring line from the same North Sea installation as Figure 6(b). Here the excellent state of lubrication from external strands and the IWRC can be seen, as well as light external corrosion and absence of internal corrosion.

**Figure 7:** Outer strand with 3 wires removed (above) and IWRC (below) from 6-strand upper segment of mooring rope with A-gal outer wires, after 13 years deployment in N Sea.
In contrast to the experience reported above from North Sea operations, Figure 8 shows the severely corroded state of a 115 mm six-strand wire rope mooring line retrieved from the Kumul SPM marine terminal some 50 km South of the Kikori river delta, Papua New Guinea.

![Figure 8](image)

**Figure 8:** Left: corroded and fractured outer A gal wires of 6-strand catenary line from Kumul SPM recovered after 4.5 years; right: the core of the same rope.

The rope photographed was removed during recovery of an adjacent broken line. Both lines had been in service some four and half years at the time of the failure which was primarily due to their advanced state of corrosion. The outer wires were Class A galvanized with an excess coating weight of some 50%, on the basis of which in a North Sea environment such a rope would be expected to last in excess of ten years.

![Figure 9](image)

**Figure 9:** Zinc “anode” wires recovered from the heavily corroded rope shown in Figure 8. Apart from fractures where the zinc has been trapped between outer strands and core, the wires have much the same diameter as when new.

These ropes also included solid zinc “anode” wires, laid between the outer strands and IWRC. Figure 9 shows the condition of the zinc wires recovered from this rope. It is apparent that whilst all the effective zinc coating has been lost from the steel, and presumably served to delay corrosion to some extent, there has been comparatively little loss from these zinc anode wires.
wires, which have therefore done nothing to hold back corrosion of the steel. The explanation for this is almost certainly the lack of any effective electrical contact between the zinc wires and the steel.

So the rate at which corrosion has advanced in the offshore PNG location is significantly faster than is typical of North Sea locations, which have tended to be the basis upon which recommendations are formulated. There are several features which make Kumul distinct from North sea experience as regards ropes operating at mid-catenary and splash zone locations:

- Probably of greatest significance, the water temperature is much higher, ~ 28° C.
- Kumul experiences quite high prevailing current flows of ~ 0.7 m/s, which are not seen consistently in North Sea locations.
- Since Kumul is a relatively shallow location (~30 m), it is probable that there will be a high oxygen content throughout the entire water column, comparable to splash zone.
- Furthermore, in view of the relatively shallow location, and the response of the SPM buoy, fatigue loading though not an issue in itself is nevertheless more severe than normal for North Sea locations. This accentuates any “pumping” action introducing the fine soil particles with which the water is laden, and displacing lubricant already softened by the higher temperature.

![Figure 10: Segment of failed mooring rope from the Kumul SPM, with two strands removed to show internal condition.](image_url)

Examination of part of the failed rope from this installation, shown in Figure 10, shows not only the high level of corrosion and break-up of the core, but also a total lack of residual lubricant (compare Figure 7) and heavy contamination from soil particles. The latter was evident in the record-breaking Brent Spar rope shown in Figure 6(a), but in that case the rope was essentially at constant load, buried in the mud and protected from any current. One effect...
of the high water temperature would be to soften the lubricant which, with the pumping action driven by tension fluctuations, would help displace lubricant from within the rope.

However in the Kumul SPM mooring the most significant factor is considered to be the effect of water temperature on zinc dissolution rate.

![Relative dissolution rates of zinc coating from steel wire constantly wetted with water, normalized to 1 at 5° C, derived from Suzumura and Nakumura (2004).](image)

**Figure 11:** Relative dissolution rates of zinc coating from steel wire constantly wetted with water, normalized to 1 at 5° C, derived from Suzumura and Nakumura (2004).

No guidance in respect of offshore moorings is available on seawater temperature effects, however experimental investigations have been conducted by Suzumura and Nakamura (2004) who were concerned with zinc dissolution rates from galvanized wires in suspension bridge cables. Figure 11 is derived from their work in which the continuously wet condition of galvanized wire within the suspension cable was reproduced, but with distilled water not sea water (which is not considered of great significance in this particular context). The tests at different temperatures indicate an order of magnitude increase in dissolution rate from 5° C (considered typical for ground wire in deep water of the North Sea) to 30° C (representing the conditions at the Kumul terminal).

This temperature effect is not wholly unknown, and has been commented upon elsewhere, but only in qualitative terms, as for example with awareness that wire rope used for hauling fishing nests corrodes more quickly in warmer waters to the North of Australia than to the South. The American Galvanizers Association website states that:
Seawater temperature can vary widely from 28 F (-2 C) at the poles to 95 F (35 C) near the equator. The higher the temperature the greater the dissolution of zinc in water. Tropical seawater (higher temperatures) yields higher corrosion rates, especially in polluted waters.

Tidal zones and fluid agitation are also important considerations in determining the corrosion protection delivered by galvanized steel. Often this motion of "washing" the carbonates off the zinc surface and not allowing them to form a protective film, along with zinc erosion, can be the cause for accelerated corrosion of zinc coatings.

The same website also tabulates data for rates of zinc loss from different samples immersed in seawater which, for periods in excess of 1 year, range from 4 to 48 μm/year (~ 30 to 340 g/m²/year). All these data are for flat plates or bar, from various locations and in various strengths of current. The data give no water temperature, but in so far as can be judged from locations, there is no obvious temperature effect, but also no great extremes are represented. However it should be noted that data for flat plates or bar, which have surfaces fully exposed to current, are bound to be conservative with respect to rates of dissolution from wire rope.

Studies into the service life of six strand ropes in the North Sea (Chaplin (1992) Chaplin and Ridge (1996) and, MacGregor et al. (1994)), indicated zinc consumption rates for different mooring line segments as follows:

- splash zone ~ up to 7 μm/year (50 g/m²/year)
- mid catenary ~ 4 to 6 μm/year (30 to 40 g/m²/year)
- ground wires ~ 1 to 4 μm/year (6 to 30 g/m²/year)

It may be noted further that in addition to different levels of current or water agitation, sea bed temperatures are typically lower than in mid-catenary or at the surface. The latter averaging some 10° C over a year.

These values are significantly lower than reported for plate or bar samples, reflecting differences in location and geometry as well as temperature, but the point remains that the effective mid-catenary rate of dissolution at the Kumul terminal is far in excess of the highest values recorded for North Sea installations, even in splash zones. The Kumul ropes were supplied with a mean coating mass of 430 g/m² (61 μm). To achieve the total loss of zinc and the state of steel corrosion observed after some 4.5 years the dissolution rate would have to have been greater than 15 μm/year (100 g/m²/year).

Zinc dissolution rates for galvanised wire ropes and roping wires from a series of immersion trials have been reviewed in Chaplin and Potts (1991). Temperate water immersion trials
(Swan(1970) and Kirk(1970)) indicate that the zinc consumption rate for galvanized wires is in the range of 10-15 μm/year, Kirk (1970) also reports a doubling of dissolution rate in a 0.6 m/s current compared with still sea water. Applying the relationship derived from Suzumura and Nakamura (2004) in Figure 11 to these data, together with the more recent data reported above, indicates the following mid-catenary consumption rates for different water environments:

- Cold Waters (5-15 deg C)  4-6 μm/year
- Temperate Waters (15-25 deg C)  10-15 μm/year
- Tropical Waters (20-30 deg C)  15-22.5 μm/year

The cold water consumption rates are based on the figures above and agree, for example, with the outer wire consumption rates of 3.8 μm/year reported by British Ropes (1979) for MODU rope after 10 years duty in the North Sea. Tropical exposure trials reported by Lennox et al (1970) indicated a consumption rate in the range of 20 to 30 μm/year.

The API and DNV recommendations detailed in Table 1 above limit the service life of six-strand rope to between six and eight years, where replacement is not possible. Yet it is evident from the reported assessment of North Sea six-strand ropes described above that far greater lives can be achieved without necessarily compromising rope integrity:

- MODU rope (89mm 6x49 IWRC) after 10 years duty in the North Sea examined by British Ropes (1979)
- FPU mooring rope after 13 years in the splash zone and 17 years as ground wire;
- Brent Spar FSU mooring rope in the North Sea after 19 years ground wire duty

Each of these six-strand ropes were of conventional construction with Class A galvanising and a marine grade lubricant/blocking compound. Whereas a Kumul SPM mooring rope, also with Class A galvanising but supplemented with zinc anode wires between the IWRC and outer strands, failed after only 4.5 years indicating a zinc consumption rate in excess of 15 μm/year. Although slightly lower, this latter rate is consistent with the wire rope immersion trials by Lennox et al (1970) in tropical water splash zone exposure conditions. Applying Suzumura and Nakamura (2004) and the 10-15 μm/year temperate water zinc consumption rate, to estimate the rate for 30° C water temperature as typical for the Kumul location gives 19-28 μm/year, consistent with reported experience.
5 Discussion

Corrosion is the most significant long term degradation mechanism for exposed steel wire mooring ropes. Zinc galvanizing can provide an effective protection against corrosion of submerged steel wire rope, but the duration of such protection is a function of several parameters in addition to coating mass. For zinc to be effective in preventing corrosion, it must be available to go into solution and electrically coupled to the steel. These facts have a number of consequences:

- Zinc coating on the inner wires contributes little to outer wire protection, at least while lubricant is in place and in reasonable condition.
- The practice of placing zinc anode wires within a rope construction surrounded by lubricant and with no effective electrical continuity to the steel wires means that they have little or no benefit.
- Parts of the surface of outer wires are protected from dissolution by contact with inner wires and lubricant. This zinc remains isolated from the seawater, so the effective availability of zinc even from outer wires is about two thirds of the total coating.
- Whilst immersed, areas of steel which have lost their zinc are protected by zinc from surrounding wires, but once removed from the water, the continuity of the seawater electrolyte may be lost and local surface corrosion can proceed. For this reason ropes which are bright when retrieved can quickly go rusty.
- Only once the available zinc has been exhausted, either through galvanic sacrificial action or simply by dissolution and abrasion, will corrosion of the steel proceed, and fatigue life then be shortened by interaction with corrosion.

It is apparent that, in addition to coating mass, there are several major variables relating to local conditions which must be taken into consideration:

- water agitation such as exposure to wave and current action;
- water temperature;
- exposure to wetting and drying under tidal or splash zone conditions;
- water oxygen content;
- presence of pollutants or nutrients from estuarine or river delta discharges; and,
- suspended abrasive particles and the chemistry of seabed sediments.

All of these apply wherever in the world moorings are deployed, but in terms of operations in SE Asian waters, temperature levels can be far higher than are typical of the locations which
have been most important in the past in determining recommendations. So whilst previous recommendations have indicated that even Class B galvanised ropes should have a service life of six or eight years, experience in a SE Asia location with high water temperature, strong current and water laden with soil particles, shows that wire with coatings exceeding the minimum Class A standard by 50% can fail by corrosion in less than five years.

6 Conclusions
1. The recommended service lives for steel wire mooring ropes in various design codes do not reflect the achieved lives of ropes in real service applications.

2. The service life duration of steel wire mooring ropes is governed by the integrity of the corrosion protection measures, and for unsheathed ropes, the longevity of the zinc coating on the wires.

3. Estimates of the longevity of the zinc coating and hence the service life of the rope, should take account of the mass of the zinc coating, seawater temperature and oxygen content, hydrodynamic action (ie. wave and current action), wetting and drying, mooring system configuration and loading on the mooring ropes, and abrasive constituents and chemistry of seabed sediments.

4. Zinc dissolution rates in tropical seas, typical for much of SE Asian, can be 3-4 times greater than for cold waters, the experience basis underlying current design code recommendations. Higher prevailing current actions will increase consumption rates by a further factor of 1.5-2.5, whereby zinc coating lives in tropical waters can be some 20-30% or even less of that expected from the cold water experience base.

5. Zinc anode wires have little or no effect unless electrical continuity with the steel can be assured whilst maintaining contact with the seawater electrolyte.

7 Acknowledgements
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8 References


BS EN 10244, Part 2, 2001, Steel Wire and Wire Products - Non-Ferrous Metallic Coatings on Steel Wire - Part 2: Zinc or Zinc Alloy Coatings.


