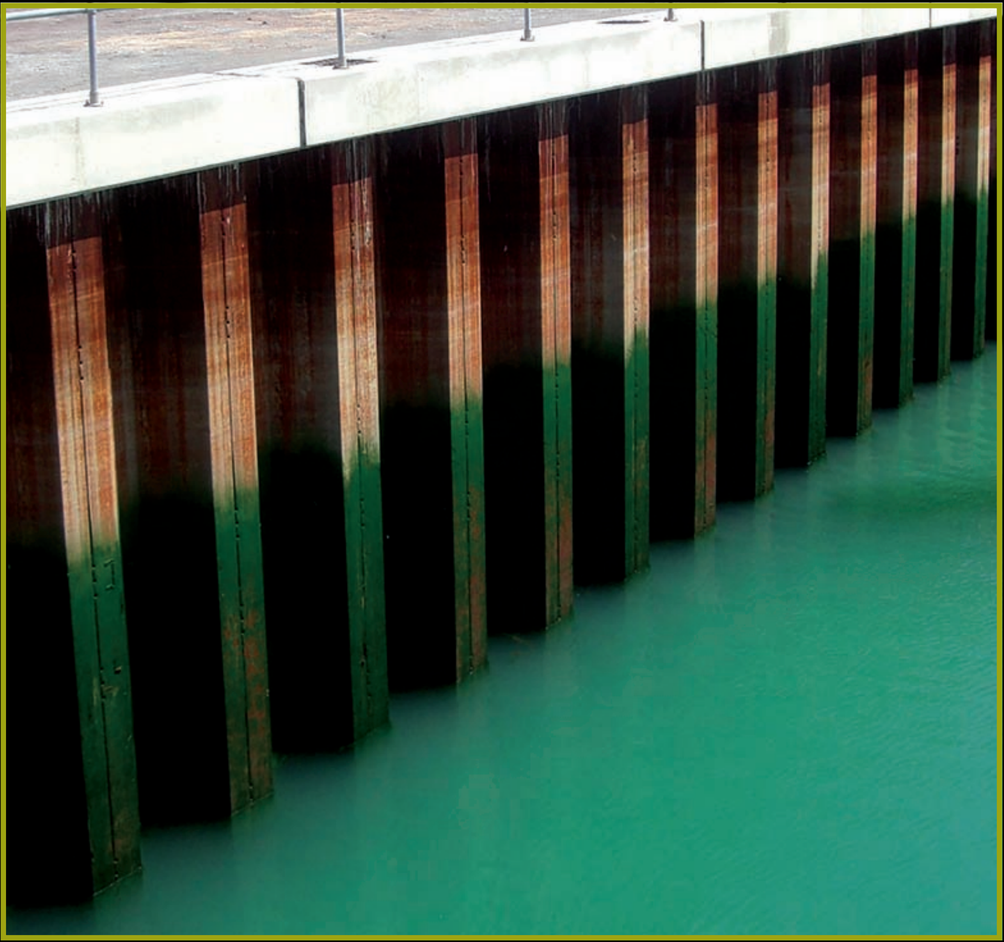
DURABILITY OF STEEL PILING



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The Steel Piling Group (SPG) was formed by British Steel in 1995 to promote steel piling and knowledge to the UK industry. The group has developed into a forum that provides a platform for discussion and an outlet for dissemination of steel piling knowledge to the UK industry.

Over the years, a key focus of the group has been to contribute technical expertise to UK industry publications and to identify and report technical issues with the use of the Eurocodes and to produce complementary guidance reflecting UK best practice. It also promotes the circular economy benefits of steel piling when considering the supply chain and whole life cycle issues.

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DURABILITY OF STEEL PILING

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FOREWORD

The Steel Piling Group (SPG) was formed by British Steel in 1995 to promote steel piling and knowledge to the UK industry. The group has developed into a forum that provides a platform for discussion and an outlet for dissemination of steel piling knowledge to the UK industry.

Over the years, a key focus of the group has been to contribute technical expertise to UK industry publications and to identify and report technical issues with the use of the Eurocodes and to produce complementary guidance reflecting UK best practice.

This publication provides to UK industry an overview of the corrosion process, outlines the corrosion performance of steel piling in various environments, and reviews the protective measures that can be taken to increase the life of steel piles where necessary.

The document was prepared by David Rowbottom (British Steel), David Baxter (ArcelorMittal) and the late Steve Cross (Royal Haskoning DHV), with contributions from Nancy Baddoo (SCI) and Ed Yandzio (SCI). It was reviewed by Graham Gedge (Arup).


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INTRODUCTION

This document was prepared by members of The Steel Piling Group and addresses the issue of the durability of steel piling.

In the majority of circumstances steel piles can be used without the need for corrosion protection but in more aggressive environments, protection may be required to ensure that the design life of the structure is achieved in the most economic manner. This document gives an overview of the corrosion process, outlines the corrosion performance of steel piling in various environments, and reviews the protective measures that can be taken to increase the life of steel piles where necessary.

CORROSION ENVIRONMENTS

2.1 General

The corrosion of steel can be considered as an electrochemical process that occurs in stages. Initial attack occurs at anodic areas on the surface, where ferrous ions go into solution. Electrons are released from the anode and move through the metallic structure to the adjacent cathodic sites on the surface, where they combine with oxygen and water to form hydroxyl ions. These react with the ferrous ions from the anode to produce ferrous hydroxide, which itself is further oxidised in air to produce hydrated ferric oxide (i.e. red rust).

However, after a period of time, polarisation effects such as the growth of corrosion products on the surface cause the corrosion process to be stifled. New, reactive anodic sites may be formed thereby allowing further corrosion. In this case, over long periods, the loss of metal is reasonably uniform over the surface, and this is usually described as ‘general corrosion’. A schematic representation of the corrosion mechanism is shown in Figure 2.1.

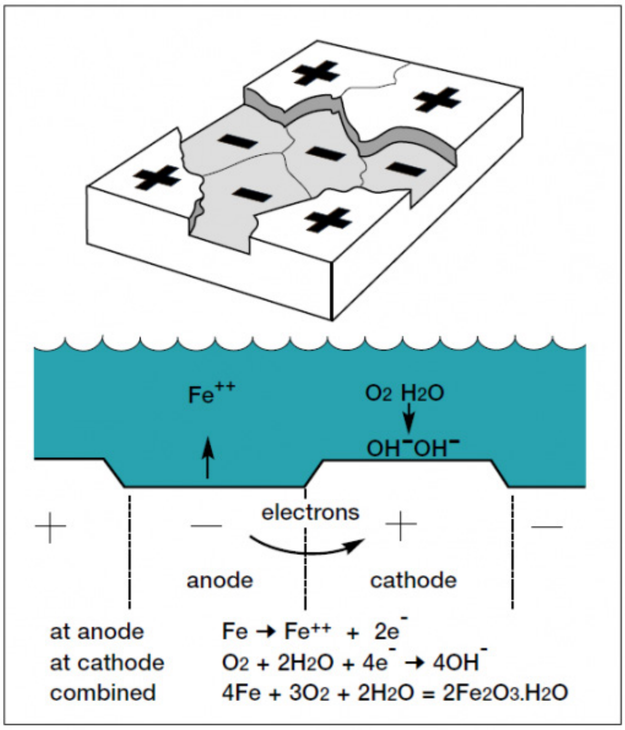

Figure 2.1 Schematic representation of the corrosion mechanism for steel

Courtesy: www.steelconstruction.info

The corrosion process requires the simultaneous presence of water and oxygen. In the absence of either, corrosion does not occur.

In determining the effective life of unprotected steel piles, the selection of piling section and the need for protection, it is necessary to consider the corrosion performance of bare steels in the different environments normally encountered in service.

Corrosion rates and allowances mentioned in this section apply to each face of the pile exposed to the specific environment. When considering the loss of section for a sheet pile, the nature of the structure is such that different corrosion conditions can apply to the front and rear faces of the pile. This is best demonstrated by considering a marine wall where the front face of the wall is exposed to seawater and tidal action but the back face may be in contact with soil. In such situations, assessment of corrosion loss is by summing the corrosion effects for each face of the pile at any given elevation.

Individual piles, such as H or tubular load bearing piles, will normally be exposed to the same environment around their entire perimeter at any given elevation although in the case of unfilled tubes, the potential for corrosion on the inside face of the tube must not be overlooked.

Corrosion is a naturally occurring process and is consequently variable in nature even in apparently similar situations. As a result, it is normal to analyse corrosion loss using statistical methods and for a given set of circumstances it is possible to derive mean values as well as values where the risk that they will be exceeded is minimised.

Mean corrosion values are most relevant to the design and performance of most steel foundations. The reasoning behind this assertion is that on any given structure it is not possible to predict with certainty where the maximum corrosion activity will occur and to design the entire structure for maximum corrosion loss would be prohibitively expensive. The recommendation is, therefore, to design the structure for mean corrosion losses and, where appropriate and feasible, adopt a maintenance regime that will identify and repair the areas that are subject to higher corrosion activity.

In circumstances where a steel element is safety critical (a tie rod for example) but inspection and subsequent maintenance will be difficult, it may be inappropriate to use the mean corrosion rate in design calculations and the designer may wish to adopt a corrosion value where the risk that the actual corrosion rate exceeds the assumed design value is minimised.

Corrosion rates or allowances for steel in different temperate environments are given in Eurocode 3: Design of steel structures, Part 5: Piling (EN 1993-5)[1], but information concerning steel in tropical conditions is less readily available. Consequently, corrosion rates and allowances in tropical conditions are given in the sections only where data exists. It should be noted that corrosion loss does not occur at a linear rate.

2.2 Corrosion in naturally occurring soils

The underground corrosion of steel piles has been studied extensively and a review of published data worldwide concluded that, unless the soils are strongly acidic ($pH<4$), the underground corrosion of steel piles driven into undisturbed soils is negligible, irrespective of the soil type and characteristics[2]. The insignificant corrosion attack is because of the very low dissolved oxygen concentration present in undisturbed soils and the very slow transport (by diffusion) of that dissolved oxygen through the pore structure of the soil to the steel surface even in the presence of ground water.

Most corrosion (via localised micro-cells or where differential aeration is present, via macro-cells) takes place above the water table. At the water table, some corrosion may sometimes occur if the water is mobile and replenished with oxygenated waters. Even in these circumstances, the water content of compacted natural soils is restricted (bogs are exceptional cases) and corrosion is usually apparent as isolated pitting in the water table zone.

Literature frequently reports pitting corrosion in the water table zone, but nowhere is this regarded as affecting the structural integrity of piling, except for some excessive pitting found in Norwegian marine sediments[3]. Evaluations by British Steel of piles extracted from UK sites, ranging from canal and river embankments to harbours and beaches, also demonstrate negligible underground corrosion losses[4], [5], [6], [7], [8]. A further evaluation in Japan of test piles driven at ten locations into natural soils which were considered to be corrosive, gave a maximum corrosion rate of 0.015 mm/year/side after ten years' exposure[9].

Recent measurements on 62 year old sheet piles driven in Singapore present the same values as recommended in EN 1993-5 for non-compacted and non-aggressive fills[10].

In general, underground corrosion rates for the soil types encountered in the United Kingdom are in the order of 0.01 mm/year/side. Similar results have also been obtained for soils elsewhere, suggesting that it is reasonable to suppose that underground corrosion test results will be applicable anywhere in the world, including tropical environments.

EN 1993-5 recommends a corrosion rate of 0.012 mm/year/side for piles driven into undisturbed soils.

2.3 Corrosion in infill and disturbed soils

2.3.1 General

Where digging and backfilling disturbs the soil, the situation can be quite different to that outlined above because filled soils are aerated and may include contaminants. In some instances, atmospheric oxygen can become trapped in isolated pockets or cells creating the potential for a localised anodic region. However, once the fill has been compacted, oxygen replenishment will be difficult, and the corrosion process will slow down naturally. One exception to this general case is if the fill or soil contains sulphides - on exposure to air these may react with oxygen to form sulphuric acid which is corrosive to steel. Where testing shows the presence of sulphides or high concentrations of sulphate in the fill, there is a risk of high corrosion rates and reclassification of the fill to “aggressive” may be appropriate. For undisturbed ground this should not be a risk because the driving of piles does not aerate the soil.

Traditionally, corrosion likelihood in fills has been evaluated based on the physical and chemical characteristics of the soil and parameters affecting corrosion potential are scored individually in terms of influence on corrosion severity. The collated results evaluate risk using empirical guides as to the likely corrosivity of the soil. Such general correlations provide guidance for materials selection but are too general to allow accurate prediction of damage at specific sites. Recent work has further refined these guidelines by showing that certain soil parameters, e.g. pH, resistivity, soluble salt content and internal drainage, can be used to classify a soil as non-aggressive or aggressive, in order for the appropriate corrosion rate to be determined[11]. DIN 50929 Part 3[12] may also provide additional guidance taking into account several parameters such as soil resistivity, water content, pH value, buffer capacity, presence of chlorides and sulphates.

Corrosion rates for fill soils have been published in EN 1993-5 for service lives up to 100 years in non-aggressive and aggressive compacted and noncompacted fills (long-term rates approximately 0.02 mm/year/side and 0.06 mm/year/side respectively).

2.3.2 Contaminated soils

Moves to redevelop brownfield sites in preference to greenfield locations mean that piles used on such sites are likely to be exposed to more aggressive conditions than would be expected in undisturbed soil. Most are old industrial sites such as, for example, chemical works, steel plants and railway land and the concentrations of soil contaminants can vary greatly from “trace” to near pure deposits. Typical industrial organic wastes are fuel oils, hydrocarbons and chlorinated hydrocarbons, whilst inorganic deposits such as lead, copper, asbestos, sulphates and nitrates can also be found in contaminated land.

Site surveys that determine soil resistivities, pH, the degree of soil drainage, fill soil structures and chemical concentrations and distributions are needed in order to determine whether there are likely to be any corrosion issues for steels in the contaminated land. DIN 50929 Part 3 gives advice in such situations.

2.4 Corrosion in water

2.4.1 Fresh water environment

Fresh waters are very variable and can contain dissolved salts, gases or pollutants that may be either beneficial or harmful to steel. The term ‘fresh waters’ distinguish these from sea or estuarine brackish waters with high salt concentration. The corrosion of steel in fresh waters depends upon the type of water, although pH has little effect over the range pH 4 to pH 9, which covers the majority of natural waters. Corrosion losses from fresh water immersion are generally lower than for seawater and effective lives are normally proportionately longer. EN 1993-5 gives the worst case corrosion rate for fresh waters of 0.014 mm/year/side for temperate climates. This worst case is for situations where there is a roughly constant water level and concentrated losses occur at this level. This maximum rate occurs at the water line, a special case reflecting differential aeration at the water surface.

There are no known data for tropical sites.

2.4.2 Marine environments

Marine environments normally encompass several different exposure zones and each one requires individual consideration, mostly due to the variation of water level and/or dissolved oxygen concentration. Nevertheless, corrosion rates derived from EN 1993-5 (approximately 0.03 - 0.11 mm/year/side) are appropriate for temperate climates. Recent measurements on sheet piles over 60 years old at a tropical site gave the same values as in EN 1993-5.

2.4.2.1 Below bed level

Where piles are below the bed level in temperate and tropical locations, very little corrosion occurs and the corrosion rate given for the underground condition is applicable, i.e. 0.012 mm/year/side.

2.4.2.2 Sea water immersion zone

Above the bed-level and depending upon the tidal range and local topography, there may be a continuous seawater immersion zone in which, with time, piling exposed to unpolluted waters acquires a protective blanket of corrosion products and marine growth, the latter consisting mainly of seaweeds, anemones and sea squirts.

In temperate and tropical locations, the recommended mean corrosion rate for design is in the order of 0.035 mm/year/side.

2.4.2.3 Low water zone

This is the zone between mean low water neap and mean low water spring tides. This zone, which is anodic to the tidal zone, will normally exhibit corrosion rates in line with those experienced in the splash zone.

In temperate climates, the recommended mean corrosion rate for design is in the order of 0.075 mm/year/side. In tropical climates, the recommended mean corrosion rate for design is slightly higher at 0.083 mm/year/side.

However, steel in marine environments at or slightly below lowest astronomical tide (LAT) may be subject to a particularly aggressive and localised form of corrosion. This phenomenon, which is often called Accelerated Low Water Corrosion (ALWC), a type of Microbially Induced Corrosion (MIC), is associated with microbial activity and reductions in steel thickness in the order of 1 mm per year have been experienced.

Although the loss of steel is severe when MIC occurs, its occurrence is somewhat random in that it does not affect every steel structure at a given location and similarly does not affect every pile in a given structure. When piles are subject to MIC, metal loss occurs on outward facing pile pans in the shoulder areas of Z shaped piles and the central area of U pile flanges. MIC may stop and restart randomly.

As metal loss at the rate indicated will soon affect the performance of individual piles (only at the low water zone location), it is recommended that regular maintenance inspections are carried out to ensure that design assumptions are not compromised and that preventive measures are still effective. More information is given in Section 4 and in CIRIA publication C634 *Management of accelerated low water corrosion in steel maritime structures*[13].

2.4.2.4 Tidal zone

This zone lies between the low-water neap tides and high-water spring tides and tends to accumulate dense barnacle growths with filamentous green seaweeds. The marine growths can again protect the piling by sheltering the steel from wave action between tides and by limiting the oxygen supply to the steel surface. The presence of macro-cells where the tidal zone is cathodic to the low water zone, may also limit the corrosion rate of steels to a level similar to that of immersion zone corrosion.

In temperate locations, the recommended mean corrosion rate for design is in the order of 0.035 mm/year/side. In tropical locations, the recommended mean corrosion rate for design is 0.04 mm/year/side.

2.4.2.5 Splash zone

This area above the normal tidal range is often wet from splashing by wave action and has a plentiful supply of oxygen. These two factors combine to produce a relatively aggressive environment. In this zone, thick stratified rust layers can develop and at thicknesses above about 10 mm these tend to spall from the steel especially on curved parts such as the shoulders and the clutches of sheet piles. Removal of the corrosion product exposes fresh steel substrate and corrosion proceeds at a much higher rate than where the corrosion product remains on the surface. The thickness of corrosion product is not a good estimate of section loss; corrosion products have a greater volume than the parent metal and steel corrosion losses may amount to no more than 7% to 10% of the rust thickness. The boundary between splash and atmospheric zones is not well defined but corrosion rates reduce rapidly with distance above wave height.

The elevated temperature in tropical conditions appears to have a serious effect on corrosion performance as corrosion rates are significantly higher than for temperate locations. The thickness of rust layers therefore reaches the point at which cracking and spalling may occur more quickly than in temperate climates. It is possible that enhanced expansion and contraction due to the temperature range experienced in tropical locations may also cause increased spalling leading to earlier exposure of the steel substrate to the environment and hence higher corrosion losses. Another explanation is that greater evaporation of water droplets leads to greater salt concentration on the steel substrate and increasing corrosivity.

In temperate locations, the recommended mean corrosion rate for design is in the order of 0.075 mm/year/side. In tropical locations, the recommended mean corrosion rate for design is significantly higher at 0.300 mm/year/side.

2.5 Corrosion in roadside environments

The environment adjacent to roads creates a unique environment due to the presence of road spray which may contain chlorides from de-icing salts in winter. Historically, in the UK, Highways England (HE) has taken an understandably conservative approach to the use of steel piles in this environment and assumed it is comparable to a marine splash zone environment for exposed and buried parts of piles. Recent research for HE has challenged this assumption based on the relatively short duration of exposure to de-icing salts in any given year and the beneficial effect of rain washing that will remove salts from the surface. This is supported by corrosion rate data from coupons exposed on safety barriers adjacent to the carriageway on the trunk road network. The results show relatively modest corrosion losses, which are approximately half that of the lower bound values for marine splash zones. The research also showed that a linear extrapolation of corrosion rates with time results in conservative estimates of loss over the life of a pile. Loss estimates using a power law equation, for example as given in ISO 9224[14] , provides a more realistic estimate of loss.

For atmospherically exposed surfaces of piles in a roadside environment, it is recommended that the assumed loss of thickness over 125 years is 2 mm. For buried parts of piles in either fill or undisturbed ground, the losses in thickness given in the UK National Annex to EN 1993-5 are appropriate. However, where design assumptions are made regarding the nature of existing or re-used fill, these should be validated by testing.

2.6 Atmospheric corrosion

At inland sites, piles used for foundation work may also be used as support structures above ground level. In such cases bare steel will corrode in the atmosphere at a rate that depends upon the site environment. This can be broadly classified as rural, urban or industrial. Similarly, piling at coastal sites may be subject to a marine atmospheric environment. EN ISO 12944-2[15] gives short-term (1 year) corrosion rates for these various environments. A linear extrapolation of these rates to longer times is both incorrect and likely to provide a significant over estimation of risk. To use the data to estimate long term rates, EN ISO 9223[16] and EN ISO 9224 provides an appropriate approach using the first year rate as an input.

Guidance on corrosion rates for atmospheric exposure of steel is given in EN 1993-5 for temperate climates. This code differentiates between what is classified as 'normal atmospheres' and locations where marine conditions may affect the performance of the structure. The lower values are more typical of long term values for rural or urban conditions and the marine figures are appropriate for coastal locations.

2.6.1 Data for temperate locations (EN 1993-5)

Traditionally, corrosion of steel piling in different environments was expressed in terms of a thickness loss per year per face, which implies that the corrosion rate throughout the life of a structure is uniform. Research has indicated that the gradual development of corrosion products on the surface of the steel tends to inhibit the corrosion process leading to a gradual reduction in the corrosion rate with time. Table 2.1 gives recommended thickness losses for steel in the specified environments for the given life of structure from EN 1993-5. These figures relate to temperate locations and take into account the corrosion rate reduction with time.

Climate		**Life of structure (years)**				
		5	**20**	**50**	**75**	**100**
Fresh water (river, ship canal)	Common (in the zone of high water attack [water line])	0.15	0.55	0.90	1.15	1.40
	Very polluted (in the zone of high attack [water line])	0.30	1.30	2.30	3.30	4.30
Sea water	In the zone of high attack (Low water and splash zones)	0.55	1.90	3.75	5.60	7.50
	In the zone of permanent immersion or in the intertidal zone	0.25	0.90	1.75	2.60	3.50
Natural soils	Undisturbed (Sand, silt, clay schist)	0.00	0.30	0.60	0.90	1.20
	Polluted industrial sites	0.15	0.75	1.50	2.25	3.00
	Aggressive (Swamp, marsh, peat)	0.20	1.00	1.75	2.50	3.25
Non aggressive fills (clay, schist, sand)	Compacted	0.09	0.35	0.60	0.85	1.10
	Non-compacted	0.18	0.70	1.20	1.70	2.20
Aggressive fills (ashes, slag)	Compacted	0.25	1.00	1.63	2.25	2.88
	Non-compacted	0.50	2.00	3.25	4.50	5.75
Note: The corrosion allowances are in mm thickness loss per face for the given life of the structure						

Table 2.1 Corrosion allowances for temperate climates

The loss of thickness due to atmospheric corrosion given in EN 1993-5 clause 4.4 is 0.01 mm/year/side. The loss of thickness is 0.02 mm/year/side in a marine atmosphere.

The UK National Annex to BS EN 1993-5: 2007 presents two tables providing the loss of thickness that should be allowed per face in soils and water for design lives up to 125 years. EN 1993-5 only presents thickness loss up to 100 years.

It should be noted that the values in EN 1993-5 are based on actual measurements for the shorter life spans and extrapolated values for the 50 to 100 year lives which includes for variability in corrosion rate over the life of the installation.

For intermediate values of design lives, an approximate value can be found by interpolating between the tabulated values. Longer design lives can be estimated by extrapolation, although this will not be accurate since the variation of loss of thickness over time is non-linear.

2.6.2 Data for tropical locations

The data for tropical locations reproduced in Table 2.2 is far less extensive than that obtained from EN 1993-5. Based on measurements taken from a number of marine structures in the Far East (Malaysia, Japan, Sri Lanka and Singapore), the figures relate to marine exposure zones. Again it should be noted that this does not take account of the non-linear relationship between loss of thickness and time.

Table 2.2 Corrosion allowances for tropical climates

Exposure zone	**Corrosion rate** (mm/year/side)
Splash	0.30
Inter-tidal	0.04
Low water	0.83
Immersion	0.035


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CORROSION PROTECTION SYSTEMS

In many circumstances steel corrosion rates are low and the use of protective systems may be unnecessary. However, where corrosion of steel piling is more significant, methods of increasing the effective life of a structure may need consideration. The measures that can be taken include the following:

a) Sacrificial steel
b) Higher strength steel
c) Corrosion resistant micro-alloyed steel (AMLoCor^{TM})
d) Applying a protective organic coating
e) Cathodic protection
f) Concrete encasement

3.1 Sacrificial steel

Engineering calculations will determine the critical performance criteria for a given steel member. The assumed section properties of the member must be present throughout the life of the structure for the factor of safety against failure assumed by the designer to be realised.

For a chosen steel element to be used in the pile design, its cross section properties (second moment of area, section modulus and cross-section area) will be known. However, the pile section chosen must be of a size which takes into account the thickness loss following corrosion. Based on the anticipated thickness loss, which may be derived by multiplying the corrosion rate by the life of the structure or by selecting a thickness loss from tables (e.g. Table 2.1), reduced section properties for the section can be determined. These reduced properties, however, must exceed the minimum requirements assumed in the design of the pile.

The effective life of a steel pile member can be increased using an additional steel thickness as a corrosion allowance. It is important to consider the stress distribution in the structure in order to locate the region where corrosion losses are most critical. It is possible that the zones subject to the highest corrosion rates will not coincide with the most highly stressed zone and therefore the use of a corrosion allowance can be a cost effective method of increasing effective life. Alternatively, it may prove more economical to increase the pile thickness locally by the attachment of plates.

When assessing pile durability, it is often beneficial to assess the pile driveability at an early stage because in some circumstances, the steel section required for pile installation may be heavier than that needed for structural reasons and the additional steel provided for driving can be utilised to provide the required design life.

There is a trend towards adding a sacrificial thickness of steel rather than painting piles in the UK because of the cost of shot blasting and painting piles and the potential damage to the paint coating during installation.

The design life can usually be achieved by adding a sacrificial thickness of steel, or in part by applying a paint coating with a 15 to 20 year life. For tropical splash zone areas, however, other measures of protection such as concrete encasement may be more appropriate (Section 3.6).

3.2 Higher strength steel

The effective life of a pile may be increased by retaining the same section but supplying it in a steel with a higher yield strength. The structural design may also exploit this higher strength. All grades of carbon steel have similar corrosion rates. However, the provision, for example, of grade S355GP sheet piles where the calculated stresses require grade S270GP (when the pile is new), will allow an additional 30% loss of thickness to be sustained without detriment. An even greater performance increase can be achieved by specifying S390GP, S430GP or S460GP steels to EN 10248 [17]. (Appendix A gives typical steel grades used in steel piling.)

However, care is required when considering using a higher grade steel and a corresponding smaller thickness. A reduction in the second moment of area for the thinner section will result in a greater deflection of the pile, which may not then be acceptable.

Special consideration may be required for other structural elements such as tie rods or anchors as steel grades can be used that are of significantly greater strength than grades used for piles. Higher strength steels may require protection from corrosion so sacrificial steel is not suitable, EN 1993-5 clauses 3.7, 7.2.2 and 7.2.5 give guidance on this.

3.3 Corrosion resistant micro-alloyed steel (AMLoCor™)

Sustained research and recent product development has led to a new micro-alloyed steel that performs better in the different zones to which a typical maritime quay wall is exposed.

AMLoCor™ is a micro-alloyed steel that displays favourable rates of corrosion in a marine environment compared to conventional sheet pile steels (in accordance with product standard EN 10248) [18]. Tests carried out in-situ have proven that the loss of steel thickness is reduced by a factor of three to five when compared to conventional sheet pile steels, depending on the exposure zone.

The maximum bending moment, and consequently the steel stress, is often in an area where corrosion rates are relatively low, such as the permanent immersion zone or embedded zone. However the Low Water Zone sometimes governs the design because of the higher rate of thickness loss in this area.

The use of AMLoCor™ results in a significant reduction in the corrosion rates in the Low Water Zone (LWZ) and in the Permanent Immersion Zone (PIZ). In addition, AMLoCor™ reduces corrosion rates associated with Accelerated Low Water Corrosion (ALWC) (Section 4). AMLoCor™ may also decrease the need for cathodic protection.

If AMLoCor™ is used, the reduced loss of thickness due to corrosion can be taken into account in the structural design verification. The loss of thickness data for conventional sheet pile steel grades in accordance with EN 10248 is presented in EN 1993-5. To obtain the loss of thickness using AMLoCor™ steel, the EN 1993-5 loss of thickness values are divided by a Corrosion Impediment Ratio (CIR), given in Table 3.1.

Table 3.1 Corrosion Impediment Ratio (CIR) for AMLoCor™ steel

Zone	Low water	Permanent immersion	Splash
CIR	5	3	1

As the mechanical properties of AMLoCor™ are fully equivalent to conventional sheet piling steels, design structural resistances can be determined according to all relevant design codes for steel sheet piling structures such as EN 1993-5.

Recent work has also shown better corrosion resistance of AMLoCor™ compared with conventional steel in soils. After a year of testing, a 20% decrease of the corrosion rate in silt loam soil was demonstrated. AMLoCor™ also performed better than steel protected with a hot dip galvanized layer in the same exposure conditions.

3.4 Protective organic coating

For some projects, additional corrosion protection is required to attain the desired product performance. Organic coatings offer a cost-effective approach to improved corrosion protection.

Coatings that are shop applied under controlled conditions are often more durable than site applied coatings. Since coatings can be damaged during transport, handling and pitching, appropriate on-site remedial treatment may be required. Driving in certain types of soil, e.g. gravels, may cause removal of some types of coatings, and this aspect should be considered when selecting an appropriate product.

The performance of a coating is affected by the quality of surface preparation prior to painting, the paint type and the thickness of coat applied. Paint manufacturers will generally give an indication in their product literature of the life to be expected from a given paint thickness. As a guide, a coating design life of the order of 15 - 20 years can be expected from an epoxy coating with a dry film thickness of 400 microns. A paint coating can be applied over part of piles such as the upper sections of the outer face only.

3.5 Cathodic protection

The design and application of cathodic protection (CP) systems to marine piled structures is a complex operation requiring specialist knowledge and experience. The design needs to provide protection to the structure and prevent detrimental effects (such as damage to high strength steels), both to the protected structure and any third party structures. It is recommended that specialist advice is sought when considering the use of cathodic protection for corrosion protection. The principals involved are outlined below.

Two systems are employed, utilising either sacrificial anodes or impressed DC currents. In normal electrochemical corrosion, all metal loss occurs at the anode and both types of CP system prevent corrosion by rendering the steel structure cathodic to externally placed anodes. Bare steel structures initially require an average current density of about 100 mA/m^2 in seawater, but this value normally falls over a long period of continuous operation to within the range 30 to 70 mA/m^2. Therefore, for a sheet piled structure of large surface area, the total current required could be considerable.

In many cases CP is used in conjunction with compliant coatings, hence if piles are coated below the water level then, depending upon the type of coating employed, current requirements are considerably reduced and can be as low as 5 mA/m^2.

Deterioration of the protective coating occurs with time, though this is counteracted to some extent by the deposition of protective calcium and magnesium salts on bare areas of the sheet piling and the growth of marine organisms.

However, in the long term, an increase in total current may be necessary and the CP system should be designed with an appropriate margin of capacity to cover this situation. This is explained in relevant design codes such DNV GL RP B401[19] which has breakdown factors for coatings and how that influences current density requirements. Not all protective coatings can be used in conjunction with CP. The coating should be of high electrical resistance, as continuous as possible, and resistant to any alkali which is generated by the cathodic reaction on the steel surface. The coating system suggested for sea water immersion can be used with CP.

When considering CP it should be borne in mind that this method is considered to be fully effective only up to the half-tide mark. For zones above this level, including the splash zone, alternative methods of protection are required.

Sacrificial anode or impressed current alone or in conjunction with CP-compatible protective coating systems have been evaluated and recommended as a method of protection against localised corrosion at the low water level in both Europe and Japan. These evaluations include bioreactor tests in the presence of bacteria.

It is considered that CP is effective at sea bed level where localised corrosion occurs due to sand eroding away the corrosion product layer (rather than the uncorroded steel surface). However, sand erosion prevents the deposition of protective calcareous deposits normally formed during CP and, therefore, the protective current density would be higher than typical values.

It is recommended that specialist advice is sought when considering the use of CP for corrosion protection.

3.6 Concrete encasement

Concrete encasement can be used to protect steel piles in marine environments. Often the use of concrete is restricted to the splash zone by extending the concrete cope to below the mean high water level. However, in some circumstances, both splash and tidal zones are protected by extending the cope to below the lowest low water level which also gives protection against Accelerated Low Water Corrosion (ALWC). Experience has shown that where the splash zone is only partially encased, a narrow zone of increased corrosion can occur at the steel-concrete junction. This is a result of electrochemical effects at the steel-concrete junction, i.e. a potential difference is generated between steel in concrete and in seawater which, combined with the effects of differential aeration at the junction, causes the exposed steel immediately adjacent to the concrete to become anodic and corrode preferentially.

Concrete is not itself always free from deterioration problems. It normally has a pH value of about 12 to 13 and within this pH range steel remains passive and corrosion is superficial. However, diffusion of chloride ions into the concrete from seawater can break down steel passivity and stimulate the corrosion reactions. Therefore, concrete for protecting steel in seawater must be of good quality, i.e. have high strength, good bonding characteristics, low permeability and be free initially from chlorides. It must also provide adequate cover and be properly placed and cured. If these requirements are not met, then rust formed from corrosion of the steel piles or steel reinforcement within the concrete can exert sufficient pressure to spall the concrete and expose the steel. In this case, the piles would need to be designed with a corrosion allowance. The exposure classification of the concrete should be determined according to EN 206 [20].

3.7 Inspection and repair

Since the rate of corrosion loss depends on many parameters, it is prudent to undertake regular inspections to control and validate the residual thickness and the mechanical properties of a piled installation. This is particularly important for port and harbour structures. Inspection can be carried out in the dry using a boat or hydraulic access platform or an underwater survey may be carried out using divers or an underwater camera.

Repair is discussed in Section 4.4.


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ACCELERATED LOW WATER CORROSION (ALWC)

4.1 What is ALWC?

Accelerated Low Water Corrosion (ALWC) is a form of microbially induced corrosion (MIC) that occurs as localised patches of accelerated metal loss on unprotected steel maritime structures in tidal waters, at or just below LAT. These ALWC patches are identifiable by their characteristic appearance, pattern of damage and high rates of metal loss.

The appearance is characterised by:

Surface Deposit

- A layered structure typically comprising a soft, spongy, bright orange outer layer with a thin, slimy, gelatinous, inner black liquid/paste layer (i.e. a black coloured iron sulphide bearing inner surface layer, indicative of sulphate reducing bacteria (SRB) activity).
- Less well adhered to the pile surface than surface deposits in surrounding areas.

Substrate Steel

- Bright, clean and shiny surface (indicative of high acidic environment) with extensive pitting.
- As pits deepen, they become more numerous and overlap. This produces a dishing effect in the metal surface which ultimately develops into a hole.

Pattern of Damage

- Whilst attack is random, both within and between installations, the pattern of damage is similar for particular pile geometries, irrespective of the geographic location of the installation.

Rates of Metal Loss

- High rates of localised metal wastage occur at ALWC patches, typically in the range of 0.3 to 1.2 mm/year/side, but rates could vary with time and location.

The presence of “orange” patches or high rates of metal wastage separately does not automatically confirm ALWC, although both together do.

The mechanism underlying this form of corrosion involves the conversion of sulphates in the water into hydrogen sulphide (H_2S) by SRB which causes direct corrosion of steel surfaces. The H_2S generated in this process also serves as an energy source for sulphide-oxidizing bacteria (SOB), which in turn convert the hydrogen sulphide into sulphuric acid (H_2SO_4). Hence the process requires both SRB and SOB to be present in mutually acceptable conditions which is the reason why ALWC is found near the low astronomical tide level (LAT) where anaerobic conditions exist for SRB and oxygen is available for SOB.

4.2 ALWC on steel components

4.2.1 Steel sheet pile sections

ALWC attack on sheet piles follows a distinct pattern; Z piles are attacked in the thinner web at the junction with the thicker flange but U piles are attacked in the middle of the outward facing flange.

Clearly the location of any holes will not only have a bearing on the ease with which repairs can be carried out but will also affect the design life of the structure. As the attack on Z sections removes material from the thinner web section, the section will perforate relatively quickly but holes in the web of the pile will have less effect on the section inertia (strength) than holes in the pile flange. However, holes in the thicker flange area will take longer to form. Clutches at the extremities of individual pile sections are rarely attacked.

4.2.2 Hot rolled steel sections

Attack occurs generally on the tips of flanges of H piles and other rolled structural sections, which will effectively reduce the cross-section area of the pile at the affected location resulting in overstressing and instability if precautions are not taken.

4.2.3 Steel tubular piles

ALWC attack can occur anywhere around the circumference of an isolated tube pile, but the severity of the attack tends to be uneven. Perforations will occur preferentially over a short section. While this degradation may not lead to instability in the pile, the loss of cross-section area could significantly increase direct stresses in what is normally a compression member.

4.2.4 Combi-walls

Combi-walls are formed by combining primary elements in the form of large diameter tubular piles or H piles such as High Modulus Piles, with secondary elements formed from lighter sheet pile sections acting as infill panels to form a continuous retaining wall. The design assumption is that the primary elements are the main retaining elements of the combined wall, carrying horizontal loads from soil and water pressures in addition to any vertical foundation loads. The intermediary sheet piles transfer horizontal loads, mainly due to water, to the primary elements.

4.3 Methods for control and prevention of ALWC

ALWC can be controlled by application of a number of techniques including provision of:

- sacrificial steel to the affected area,
- application of coatings,
- cathodic protection,
- wrapping techniques.

4.3.1 Sacrificial thickness

The sacrificial steel method gives acceptable results where corrosion rates are low and predictable, but is not fully appropriate for ALWC. The corrosion rate associated with ALWC is extremely variable and can exceed 1 mm per year. To be effective as a control method, pile thickness would need to be increased by a significant amount (a factor of 10 may be appropriate), which does not represent an economically viable solution, particularly as the problem is extremely localised yet the whole pile would be thickened. However, the use of plates fixed to the piles spanning the ALWC-susceptible zone can be effective. It is best to use plate material that is anodic to the sheet pile and will consequently corrode in preference to the sheet pile.

4.3.2 Coatings

Guidance on the selection of coatings for steel piling is given in Section 3.4.

4.3.3 Cathodic protection

Guidance on the selection of cathodic protection for steel piling is given in Section 3.5.

4.3.4 Wrapping

Wrapping offers a popular method of protection for isolated piles, although application may only be practical for tubular piles. Organic materials such as factory applied coatings, polyethylene resins and fibre-reinforced plastics are widely used as wrapping materials, their popularity resulting from their relatively low initial costs. Factory application avoids the problem of trapping anything deleterious between the material and the steel and permits good surface preparation, which is critical.

A system designed for field installation either underwater by divers or at low tide with minimal surface preparation is also available. An inner non-setting petrolatum mat with a resistant composite urethane jacket allows the substrate to be inspected but may be easily damaged, difficult to repair, and has a finite life.

4.4 Repair of structures

ALWC does not affect every pile or structure in a facility and the effect it will have on a particular structure is a function of the type of pile involved and the degree of damage suffered. Instability is a greater risk to structures supported on individual piles where loss of section will have a direct effect on the ability of the section to resist compressive and buckling stresses. In the case of a sheet piled structure, loss of section in an individual pile is unlikely to result in collapse of the whole structure but holes in several piles or loss of a tie rod could lead to structural failure and a hole will almost certainly lead to loss of fill material which will affect the serviceability of the structure.

It is therefore prudent to effect repairs at the earliest opportunity after ALWC is discovered because the longer it is left untreated, the more severe the loss of metal will be and in the extreme, the larger the hole in the structural member.

An inspection regime should be in place for port and harbour structures to ensure that ALWC, and any other situations, are detected at an early stage. Regular visual inspection of piles backed up by thickness measurements in areas where corrosion activity is found to be taking place will allow the condition of the piles to be monitored and a repair programme established to ensure that remedial measures are instigated before the loss of metal reaches 50% of the pile thickness as recommended by PIANC [21]. (It is easier to repair a pile with reduced thickness rather than one which is already perforated.)

The easiest repair method for steel piling is to weld plates to reinforce the damaged area. The plate thickness can be selected to suit the prevailing rate of loss of thickness but it is prudent to consider application of a coating in association with cathodic protection.

4.4.1 Access for repair

Repairs on the corroded zone should be effected at or below low water level. Divers will be required to carry out any underwater work, or a cofferdam can be installed within which the repairs can be carried out in the dry. The cofferdam could be created by installing temporary sheet piles in front of the affected structure but that would involve a substantial amount of pile driving and extraction, all of which take time. It is therefore more likely that the working area will be formed using a purpose-built mobile cofferdam or limpet dam. The limpet dam is positioned against the affected structure and internal water is rapidly evacuated so that the external water pressure forces it tight against the structure, allowing a seal to be made. Use of a cofferdam means that work is not limited by tide cycles and permits any remedial work to be inspected. It also creates working conditions suitable for painting or installing a sacrificial cathodic protection system.

4.4.2 Plating damaged areas

After filling any hole with fast-curing mortar or concrete and blast cleaning the surface of the piles, a steel plate is welded over the holes or areas where the steel thickness has reduced. To achieve a satisfactory weld, it is recommended that the pile and plate should be at least 5 mm thick.

Where section loss has occurred to the outpan, the recommended method of repair is to provide a plate that completely covers the affected area and extends along the pile webs towards the inpan areas. The distance that the plate extends towards the inpans is determined by the condition of the pile webs and in situations where the webs are too badly damaged for a suitable weld connection to be produced, the cover plates should extend back to the inpan with non-shrink grout filling any voids behind the plate. It is recommended that repair plates are pre-treated with a paint coating.

When the damage has occurred to the inpan areas or pile webs but the flanges are in good enough condition to weld, plates can be installed between adjacent outpans to act as a front shutter allowing the void to be filled with concrete to effect the repair.

4.4.3 Protective row of steel piles with concrete infill

An alternative to plating for situations where ALWC or corrosion is in an advanced state and weld repairs are impractical is to install a new sheet pile wall in front of the damaged one. The gap between the existing and new walls can be filled with concrete ensuring that further ALWC attack on the new structure will only expose the concrete protection.

4.4.4 Repair of steel tubular piles

Tubular piles may be repaired by welding a collar around the pile to cover the affected area. In the case of large diameter piles, a complete collar may not be necessary.


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CORROSION DESIGN WORKED EXAMPLE

This worked example comprises the design of a simple tied sheet piled wall taking into account the potential corrosion of steel. The steel grade of the sheet pile is S430GP in accordance with EN 10248. The proposed sheet pile is a Z section AZ 27-800.

The design life of the wall is taken as 50 years.

The following levels are relative to the datum at the top of the sheet pile (Figure 5.1).

- Mean High Water Spring level -2 m
- Mean Low Water Spring level -5 m
- Soil bed level -11 m
- Toe of wall -17.5 m

Calculations are performed in accordance with EN 1997[22] to ascertain the bending moment distribution at the ultimate limit state (ULS). These calculations, however, are outside the scope of this example. Full worked examples showing the geotechnical assessment and design of a sheet pile can be found in the ArcelorMittal Piling Handbook 9th Edition [23].

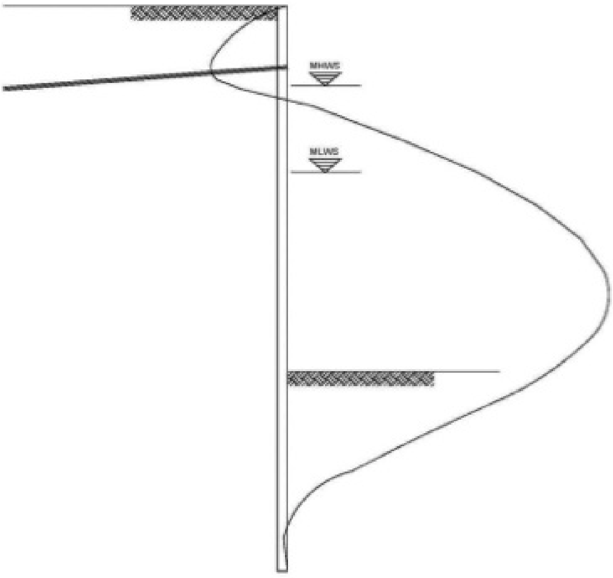

Figure 5.1
Tied sheet pile retaining wall showing ULS bending moment

Figure 5.1 shows the bending moment distribution along the pile at the ULS. Table 5.1 presents, at 1 m intervals, the bending moment magnitude and the corresponding loss of steel thickness at each level as obtained from EN 1993-5. Using Table 5.1 as a basis, two cases are considered; one at the location of the maximum bending moment and the other at the location of the maximum loss of steel thickness. Both cases are checked to see if the bending moment is less than the corresponding reduced cross-section bending resistance at that level. Table 5.2 shows that the chosen section is adequate.

Table 5.1
Corrosion losses at each level

Level (m)	ULS bending moment requirement (kNm/m)	Corrosion exposure zone*		Loss of thickness (mm)		
		Front	Rear	Front	Rear	Total
0	0	Splash	Soil	3.75	0.6	4.35
-1	42	Splash	Soil	3.75	0.6	4.35
-2	227	Splash	Soil	3.75	0.6	4.35
-3	-73	Intertidal	Soil	1.75	0.6	2.35
-4	-337	Intertidal	Soil	1.75	0.6	2.35
-5	-570	Intertidal	Soil	1.75	0.6	2.35
-6	-750	Low water	Soil	3.75	0.6	4.35
-7	-880	Permanently immersed	Soil	1.75	0.6	2.35
-8	-952	Permanently immersed	Soil	1.75	0.6	2.35
-9	-963	Permanently immersed	Soil	1.75	0.6	2.35
-10	-909	Permanently immersed	Soil	1.75	0.6	2.35
-11	-788	Permanently immersed	Soil	1.75	0.6	2.35
-12	-603	Soil	Soil	0.6	0.6	1.2
-13	-390	Soil	Soil	0.6	0.6	1.2
-14	-193	Soil	Soil	0.6	0.6	1.2
-15	-37	Soil	Soil	0.6	0.6	1.2
-16	12	Soil	Soil	0.6	0.6	1.2
-17	12	Soil	Soil	0.6	0.6	1.2

* The soil on both sides is taken as an undisturbed natural soil throughout this example.

Table 5.2
Sheet pile with sacrificial steel thickness only

Level (m)	Bending moment (kNm/m)	Total loss of thickness (mm)	Section modulus (cm^3/m)		Yield strength (N/mm^2)	Moment capacity (kNm/m)		Moment capacity > Design bending moment?
			New	Reduced		New	Reduced	
-6	-750	4.35	3200	2305	430	1376	991	Yes
-9	-963	2.35	3200	2715	430	1376	1167	Yes

A second example is presented whereby a lighter Z section sheet pile, AZ 28-750, is selected in conjunction with a protective coating applied to the face with marine exposure. The loss of thickness in the marine environment is therefore reduced to the corrosion loss anticipated in the 30 years following the lifetime of the coating. Anticipated thickness losses are as given in Table 5.3.

Verification of the moment resistance of the pile is as shown in Table 5.4. It is seen that the coated steel sheet pile section is adequate.

Table 5.3 Corrosion losses in each of the critical zones with 20 years paint protection

Level (m)	ULS bending moment requirement (kNm/m)	Corrosion exposure zone*		Loss of thickness (mm)		
		Front	Rear	Front	Rear	Total
-6	-750	Low water	Soil	2.27	0.6	2.87
-9	-963	Permanently immersed	Soil	1.07	0.6	1.67

Table 5.4 Sheet pile with painted outer face option

Level (m)	Bending moment (kNm/m)	Total loss of thickness (mm)	Section modulus (cm^3/m)		Yield strength (N/mm^2)	Moment capacity (kNm/m)		Moment capacity > Design bending moment?
			New	Reduced		New	Reduced	
-6	-750	2.87	2810	2210	430	1208	950	Yes
-9	-963	1.67	2810	2465	430	1208	1060	Yes

The relative costs of the two solutions can be compared and any practical implications and associated additional costs evaluated (such as protection of coating during transport, handling and installation). Such assessment will provide a preferred solution. Solutions comprising different sections and different steel grades can also be compared and contrasted.

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APPENDIX A COMMON STEEL GRADES USED FOR PILING

Table A.1 gives the appropriate steel product standards. Tables A.2 to A.4 give the mechanical properties for hot rolled and cold formed sheet piles and for tubular piles.

Table A.1 Common steel product standards used in piling

Element	Standard
Hot rolled sheet piles, box piles fabricated from hot rolled piles, hot rolled connectors for sheet piles, primary elements using box piles built up from hot rolled sheet piles or special I sections and secondary elements in combined walls.	EN 10248
Cold formed sheet piles, box piles fabricated from cold formed piles, primary elements using box piles built up from cold formed sheet piles and secondary elements in combined walls.	EN 10249
Hot formed tubular piles	EN 10210
Cold formed tubular piles	EN 10219

Table A.2 Nominal values of yield strength and ultimate tensile strength for hot rolled sheet piles according to EN 10248-1 Hot rolled sheet piling of non-alloy steels

Steel grade	Yield strength N/mm^2	Tensile strength N/mm^2
S240GP	240	340
S270GP	270	410
S320GP	320	440
S355GP	355	480
S390GP	390	490
S430GP	430	510
S460GP	460	550

Table A.3 Nominal values of yield strength and ultimate tensile strength for cold formed sheet piles according to EN 10249-1 Cold formed sheet piling of non-alloy steels

Steel grade	Yield strength N/mm^2	Tensile strength N/mm^2
S240GP	240	340
S270GP	270	410
S430GP	430	510
S460GP	460	550

Stockists can offer tubular piles which may be surplus from oil and gas projects and are specified as API grades which are not included in BS and EN standards. However the tubes may still meet the requirements of EN 10210 Hot finished welded structural hollow sections of non-alloy and fine grain steels / EN 10219 Cold formed welded structural hollow sections of non-alloy and fine grain steels.

Table A.4 lists these steels and their yield strengths for reference.

Table A.4 Nominal values of yield strength for API line pipe

Steel grade	**Yield strength N/mm^2**
API X52	358
API X56	386
API X60	413
API X65	448
API X70	483

DURABILITY OF STEEL PILING

This publication gives an overview of the corrosion process, outlines the corrosion performance of steel piling in various environments, and reviews the protective measures that can be taken to increase the life of steel piles where necessary. A worked example of a simple tied steel sheet pile wall is included which considers corrosion protection solutions to the steel.

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