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EXECUTIVE SUMMARY

The successful performance of hot-rolled steel sheet piling is well documented in many and varied environments. Regardless of the structure's exposure and service life, a steel sheet piling system can be designed to provide a solution. For some projects, the best system for the job includes some supplemental corrosion protection. In many applications, however, steel sheet piling does not require any additional protection. These projects typically include temporary structures, structures in most atmospheric exposures, structures driven into undisturbed soils, and structures which are continually submerged in either fresh or salt water. On the other end of the corrosion spectrum is the splash zone of steel sheet piling structures in marine environments, where wave and wind action remove the protective rust coating resulting in the highest corrosion rates. Between these two extremes are a wide variety of conditions, with a corresponding wide variety of protection alternatives to ensure the steel sheet piling meets the project requirements.

Although every structure has its own unique set of exposure conditions, design requirements, service life, aesthetic goals and economic requirements, this report provides general information on steel sheet piling corrosion and basic guidelines for evaluating the need for supplemental corrosion protection for new steel sheet piling structures. These general guidelines should be applied with care, taking into account local environmental conditions and exposures. Local experience with corrosion in similar structures is perhaps the most valuable guide in decision-making.

INTRODUCTION

Steel sheet piling has long been valued for its high strength, long life, economy and durability. Properly evaluating the corrosion potential of a steel sheet piling wall can help determine the most economical means of ensuring the piling's integrity over the life of the structure. Although corrosion is a natural process for steel in many installations, the presence of rust in no way signifies a loss of integrity. Rather, the designer must evaluate the steel loss due to corrosion in terms of its effect on the steel section and its structural properties. In many applications, the loss of steel due to corrosion is small enough that no supplemental corrosion protection measures need be applied. This can be true even for structures with long design lives. In a series of widely published National Bureau of Standards studies (ref. 1), steel pilings were pulled after six to fifty years in service from various geographic locations. The overall conclusion was: "in general, steel pilings are not significantly affected by corrosion in undisturbed natural soils, regardless of the soil types and soil properties." Similarly, construction in West London recently unearthed pilings over eighty years old. When pulled from the native wet soil, the pilings were so well preserved, the original rolling marks could be seen (ref. 13).

The need for corrosion protection is a function of both the exposure (which determines the projected loss of steel due to corrosion) and the design life of the structure. Structures with shorter design lives may be capable of maintaining structural integrity without supplemental protection even in corrosive environments, while structures with very long design lives may benefit from supplemental corrosion protection even in relatively mild exposures.

This report can help identify when supplemental corrosion protection may be required, and provide basic information on some of the more common protection systems. If the projected corrosion losses are low, no additional corrosion protection may be required.

A flowchart is presented in Figure 2 that provides an overview of the decision making process, based on current industry best practices on the use of supplemental corrosion protection for steel sheet piling. The flowchart leads the user through a series of questions which can help determine if supplemental corrosion protection measures should be considered.

THE BASICS OF CORROSION

Corrosion is a natural electro-chemical reaction that affects all metals to some degree. Corrosion occurs under action similar to that of a battery, where a small electric current flows between a positive electrode (anode) and a negative electrode (cathode) in the presence of an electrolyte (typically water in the case of steel sheet pilings). As the current flows from anode to cathode, the anode (the steel in this case) corrodes, resulting in rust formation. As the steel corrodes, it loses thickness. Steel corrosion becomes a design concern when the projected loss of steel thickness over the design life impacts the structural capacity of the piling.

Although many factors can contribute to the corrosion process, the most important are moisture, oxygen and chlorides (principally salt from seawater). Moisture is perhaps the most important element necessary for corrosion, as it acts as the electrolyte, allowing electrons to move between the anode and cathode. For this reason, pilings subject to atmospheric exposures tend to have much lower corrosion rates than those in wetter environments. The second major factor is oxygen, which stimulates the cathodic reaction in the presence of moisture. Chlorides, primarily found in marine environments, are the third major factor affecting steel sheet piling corrosion. Chlorides increase the electrical conductivity of the water, allowing corrosion to proceed at a higher rate.

Theoretically, factors such as the electrical resistivity of the soil or water, and the soil/water pH can impact corrosion. In practice, however, corrosion losses have been found to correlate primarily to exposure. In some cases, such as pilings driven into undisturbed natural soils, factors such as soil resistivity and pH appear to have no effect on corrosion losses.

Corrosion can either occur relatively evenly over the structure's surface, or can be localized to a particular area. This localized corrosion often takes the form of pitting. Pitting corrosion is more common than uniform loss on steel pilings (ref. 11), but also has a lower potential to impact the structural capacity because the piling can transfer stresses around the pitted area. The small potential loss of retained material due to pitting is not typically a concern. Where the steel pilings are being used to contain heavily polluted or contaminated material and pitting is a concern, a high-quality coating can be applied to prevent pitting.

Although stray electric current has been shown to produce pitting in pipes, there is little evidence to suggest that stray electric current produces widespread corrosion (ref. 11). Alternating stray currents are of little consequence to piling corrosion, however direct stray currents should be eliminated, or the structure properly grounded to the negative return leg of the stray current source (ref. 2).

In most cases, the rate of steel sheet piling corrosion tends to decrease over time, due to the formation of rust and fouling in marine environments, both of which have protective properties. In exposures where the protective layer of rust is removed, such as by wave action in the splash zone of marine environments, corrosion rates do not decrease over time. Hence, these areas tend to have the highest overall corrosion rates. Other conditions that remove the protective layer, such as abrasion due to propeller wash, or that may change the exposure conditions, such as erosion, also need to be considered in the overall corrosion evaluation. The reader is referred to *Sheet Piling Design and Handbook of Corrosion Protection for Steel Piling Structures in Marine Environments* (refs. 2, 14) for more complete discussions of potential corrosion factors for steel sheet piling.

HOW THE ENVIRONMENT AFFECTS STEEL SHEET PILING DURABILITY

Environments are generally classified as atmospheric, soil or water. Within these broad classifications, various levels of corrosion potential exist. The following section summarizes relative corrosion losses in various environments.

TABLE 1. Loss of Thickness Due to Corrosion for Steel Sheet Pilings (Ref 4) [A]

Soil, with or without groundwater:	DESIGN LIFE:				
	5 years	25 years	50 years	75 years	100 years
Undisturbed natural soils	0.00 mm	0.30 mm	0.60 mm	0.90 mm	1.20 mm
Polluted natural soils and industrial grounds	0.15 mm	0.75 mm	1.50 mm	2.25 mm	3.00 mm
Aggressive natural soils (swamp, marsh, peat...)	0.20 mm	1.00 mm	1.75 mm	2.50 mm	3.25 mm
Non-compacted and non-aggressive fills [B] (clay, schist, sand, silt...)	0.18 mm	0.70 mm	1.20 mm	1.70 mm	2.20 mm
Non-compacted and aggressive fills [B] (ashes, slag...)	0.50 mm	2.00 mm	3.25 mm	4.50 mm	5.75 mm
Water[C]:					
Common fresh water (river, ship canal-,...) in the zone of high attack (water line)	0.15 mm	0.55 mm	0.90 mm	1.15 mm	1.40 mm
Very polluted fresh water (sewage, industrial effluent-,...) in the zone of high attack (water line)	0.30 mm	1.30 mm	2.30 mm	3.30 mm	4.30 mm
Sea water in temperate climate in the zone of high attack (low water and splash zones)	0.55 mm	1.90 mm	3.75 mm	5.60 mm	7.50 mm
Sea water in temperate climate in the submerged zone or tidal zone	0.25 mm	0.90 mm	1.75 mm	2.60 mm	3.50 mm

A. Values are provided for general guidance only. Local knowledge may lead to the use of other values for design. The values given for 5 and 25 years are based on measurements, whereas other values are extrapolated.

B. In compacted fills, these corrosion losses should be divided by two.

C. The highest corrosion rate is usually found at the splash zone of marine environments or at the low water level in tidal waters. However, in most cases, the highest bending stresses occur in the submerged zone.

ATMOSPHERIC ENVIRONMENTS

In most atmospheric exposures, moisture from the air causes an initial coating of rust, which tends to inhibit further corrosion. Also, the absence of an electrolyte in atmospheric applications leads to low corrosion rates. In many atmospheric exposures, therefore, supplemental corrosion protection measures are unnecessary. The presence of salts or chemicals in the air, however, can lead to a greater loss of steel due to corrosion. For the purpose of evaluating steel sheet piling corrosion potential, atmospheric exposures are typically classified as rural, industrial/urban or marine. Rural exposures are considered minimally corrosive and coatings, when used, are typically applied only for aesthetic reasons. Note, however, that even in rural exposures, specific conditions such as a bridge abutment subject to road salt spray may warrant a coating or other corrosion protection. Air in marine environments contains chlorides, and is the most corrosive atmospheric exposure, although corrosion rates decrease significantly with distance from the beach. The Eurocode (ref. 9) assigns a corrosion rate of 0.02 mm/yr in marine atmospheres, twice the rate of rural atmospheres, although still low in comparison to most soil and water environments. Urban or industrial exposures may have corrosive chemical elements which can accelerate corrosion. These exposures should be evaluated based on the specific site conditions.

SOIL ENVIRONMENTS

The potential corrosiveness of soil exposures is primarily dependent on the presence of oxygen in the soil. As noted in the introduction, steel sheet pilings driven into undisturbed natural soils do not require supplemental corrosion protection.

For the purposes of this report, undisturbed soils are those which are naturally occurring (not fills) and are not significantly disturbed during the project under consideration.

The lack of corrosion in undisturbed soils is primarily attributed to the lack of oxygen in the soil.

Soil oxygen content also explains why compacted fills are assumed to produce only about half the projected corrosion as non-compacted fills (ref. 9). It is also interesting to note that sand backfill is itself protective, because it forms a protective ferrosilicate film on the steel (ref. 2). Although oxygen is the primary indicator of soil corrosiveness, the presence of corrosive materials such as cinders, salts, organic fills or high pollution levels can also be expected to increase the projected corrosion rates.

WATER ENVIRONMENTS

Water exposures are typically classified, in ascending order of corrosion potential, as fresh water, brackish and marine. Polluted water, fresh or salt, can be less or more corrosive than any of the other types of water, so an analysis should be done on contaminated water. Similarly, the aggressiveness of brackish water varies depending on the salt content. Fresh water and marine environments are discussed in more detail below.

Clean fresh water has been shown to have low corrosion potential, and supplemental corrosion protection is typically not warranted. One notable exception can occur in non-tidal situations, such as canals, where the water level does not change significantly. In these cases, localized accelerated corrosion can occur at the water line, and this area may require special consideration. Where the water level varies, low overall corrosion can typically be expected.

Steel pilings placed in marine environments are exposed to higher corrosion rates due to the presence of salt. Note, however, that exposures and corresponding corrosion rates vary significantly along the height of the piling. These various exposure zones are shown in Figure 1 and described below.

Marine buried soil zone: This is the underground exposure, and is typically treated as for any other soil exposure.

WATER ENVIRONMENTS (CONTINUED)

Marine immersed submerged zone: This is the area continuously below water, which often acquires a protective layer of marine growth. In addition, corrosion rates decrease rapidly with water depth, so are typically considered to be low in this zone. In the case of shallow tidal estuaries, however, sand and mud movement at the mud line can remove the rust at that point, which may require additional corrosion protection.

Marine tidal zone: The tidal zone, between the lowest low tide and highest high tide levels, is exposed to cyclical wetting and drying. Like the immersed zone, this area also tends to acquire a dense barnacle and seaweed layer, which helps protect the steel. Corrosion rates in the tidal zone are considered to be similar to the seawater immersion zone (ref. 4), with the exception of the area at the low water level. At this point, there is no protective marine growth, and higher corrosion rates can occur. Some manufacturers recommend periodic inspections of the low water level.

Marine splash zone: The splash zone extends from the top of the high tidal zone to the peak wave height. Steel in this area is subject to the highest corrosion rates because it is exposed to salt spray and to wave action, which can remove the protective surface rust.

Marine atmospheric zone: This zone is primarily exposed to air-borne chlorides, which make marine atmospheric environments more corrosive than non-marine atmospheric environments. Note, however, that the overall marine atmospheric corrosion rates are still low in comparison to most soil and water environments. In practice, if supplemental corrosion protection is used for the splash zone, it is often extended through the atmospheric zone as well.

STRATEGIES for DURABLE SSP

When evaluating supplemental corrosion protection methods, the economics of each system must be evaluated for the structure under consideration. Balancing the structure's design life, projected corrosion losses and corrosion protection system requirements is important to making proper design decisions. The choice of protection system may also vary with need for and accessibility for maintenance. For example, a coating with a ten-year life may be a good choice in an atmospheric exposure where it is easy to inspect and recoat, but not for a submerged section that would require temporary dewatering or other techniques to allow for inspection and maintenance.

Weighing these various factors will lead the designer to one of four main approaches: uncoated steel sheet piling; providing local protection to the area(s) most at risk; providing global protection to the entire structure; or using some combination of these strategies.

UNCOATED SSP

With the first option uncoated steel sheet piling is installed allowing for some initial rusting. As stated previously, this rust then acts as protection, decreasing future corrosion. This is a good approach for temporary structures (those with a design life of four to five years or less (refs. 9, 14)), pilings driven into undisturbed soil, pilings in many atmospheric exposures where the appearance of rust is acceptable, and for many submerged and buried applications as well.

LOCAL PROTECTION: *COATINGS*

Local protection strategies include coatings and, less commonly, concrete encasement. Coatings are the most commonly used sheet piling corrosion protection method. When compared to other corrosion protection strategies, coatings typically have the lowest initial cost, and can have a useful life of fifteen to twenty years depending on the coating system and its exposure. Surface preparation is typically required prior to applying the coating, and application procedures and cure times vary with the coating system. When it is determined that a coating is appropriate, factors in evaluating specific coatings include the design life of the structure versus coating life, appearance, ease of application and repair, and matching the coating to the exposure,

(i.e. resistance to chemical attack or organic acids for contaminated fill; resistance to abrasion in areas subject to abrasion). Tolerances on the driven depth of pilings make it necessary to apply the coating to an area larger than the area requiring protection to ensure the zone of concern is protected. For example, when driving pilings into disturbed soils, the Army Corp of Engineers recommends coating the depth to be underground plus two feet (ref. 8). Aesthetics often drive the use of coatings in atmospheric conditions.

LOCAL PROTECTION: *ENCASEMENT*

In some cases, a section of piling is encased in concrete to protect it from corrosion. Like a coating, this is a barrier-type protection that is applied to only a portion of the piling. Most often, encasement is used for the marine splash zone, but sometimes for both the splash and tidal zones. Maintenance on a spalled or damaged concrete encasement can be difficult and expensive, so the concrete should have high strength, good bonding characteristics to steel, low permeability and be initially free from chlorides. A seal coat over the concrete can help protect it from seawater entry and prolong the life. A concrete encasement should typically extend to about one meter below the mean high water level. As the tidal range increases, encasement tends to be less economical, since a larger area must be encased. At the top and bottom of the encasement, a two-foot wide coating should be applied to insulate the concrete from the steel, hence minimizing the potential for a corrosion cell to form at the steel/concrete interface which could result in increased corrosion.

GLOBAL PROTECTION: *SACRIFICIAL HIGHER STRENGTH or CORROSION-RESISTANT STEEL*

Global protection strategies are those that protect the entire piling. Global strategies often include protection to areas where it is not required, but they tend to require less maintenance and repair than local strategies. A common global protection strategy is to specify a thicker steel section than that required for the structural design.

Rather than trying to prevent corrosion, as is the case with coatings and encasement, using a thicker section allows corrosion, but ensures that the structure can perform as intended after the steel loses thickness. A similar approach is to specify a higher strength steel than is required. This also builds in a corrosion allowance, although in terms of strength rather than section thickness. For example, specifying A 572 Grades 60 or 65 (with yield strengths of 60 and 65 ksi, respectively) for a piling designed for Grade 50 (with a yield strength of 50 ksi) can provide 20% to 30% more strength to the steel sheet piling structure.

Specifying a corrosion-resistant steel is another option which retards the steel loss due to corrosion. Steels manufactured for increased corrosion-resistance, such as ASTM A 588 and A 690, include metals such as chromium and copper, and/or other alloying elements to enhance corrosion resistance. A 588, sometimes referred to as COR-TEN (ref. 5), provides improved performance primarily in atmospheric exposures. A 690, or mariner steel, is a high-strength low alloy steel developed specifically for marine environments.

GLOBAL PROTECTION: *CATHODIC PROTECTION SYSTEMS*

Cathodic protection is another option for global protection, although because of the complexity, high initial cost and need for periodic maintenance over the life of the structure, cathodic protection is typically only used on critical structures, for example commercial port or harbor structures. On these types of structures, future installation of a cathodic protection system is often provided for by electrically connecting the pilings during construction, either by welding a flat or reinforcing bar across the tops of the pilings, or by welding the piling interlocks for a suitable length. As discussed previously, corrosion occurs because the steel is the anode in an electro-chemical cell. Cathodic protection works by making the steel the cathode of the battery. The system requires application of an external current, electrical continuity along the length of the piling structure, and installation and maintenance of sacrificial anodes.

GLOBAL PROTECTION- (CONTINUED)

In addition, because cathodic systems rely on water as the electrolyte, they are only effective in continually submerged areas, although they are considered partially effective in the tidal zone. It is recommended (ref. 4) that a company familiar with these systems be retained to design and install the system because of their complexity. Structures with a large surface area may require substantial current, but a coating can greatly reduce the amount of current required.

COMBINATIONS of PROTECTION STRATEGIES

Combinations of the above strategies are often utilized, most commonly by using a coating with one of the global protection strategies. For example, the combination of a coating with a cathodic protection system provides a very durable protection system for critical structures. With the coating in place, cathodic protection is unnecessary. Once the coating begins to break down, the cathodic protection system can be activated, and the remaining coating greatly reduces the current requirements of the system. Note that not all coatings are compatible with cathodic protection.

When the projected corrosion rate over the structure's design life exceeds the acceptable steel loss of even a thicker or higher strength steel section, a coating can be applied to reduce the corrosion losses. In this application, the coating is designed to be sacrificial. It is used to delay the onset of the steel corrosion, allowing the structure to reach its intended service life.

CORROSION PROTECTION DECISION MAKING

The decision making process begins with the type of structure and the role of aesthetics. Temporary and non-structural piling installations, for example, only include supplemental corrosion protection if mandated by the project's aesthetic requirements. For permanent structural installations, the user must first evaluate the environment the piling will be subject to, keeping in mind that the environment may vary over the length of the piling. In addition, if opposite sides of the piling are subject to different environments, then each side should be evaluated separately.

Projected loss of steel thickness values due to corrosion for various exposures and design lives are shown in Table 1. Rust typically has a protective effect on steel corrosion, so these values are tabulated according to design life in years, rather than given as an annual rate that is then multiplied by the design life. For example, steel pilings in fresh water have a fifty-year corrosion loss of 0.90 mm, 40% less than that determined by a straight-line extrapolation of the five-year rate of 0.15 mm. Note that these loss of thickness values apply to each face of the piling being exposed to the given environment. Corrosion losses for both sides must be added together to evaluate the total loss in thickness.

If it is determined that some supplemental corrosion protection is required, the overall approach to determining the amount or level of protection entails evaluating the projected loss of steel over the life of the structure and comparing this to the structural capacity and requirements of the section. Structural requirements, and in some cases the projected corrosion losses, vary along the height of the steel piling. Therefore, a series of analyses at various heights along the piling, comparing the post-corrosion section to the structural requirements at that height, must be performed. There is not always an obvious critical section, since the highest bending stresses and hence highest structural requirements, typically occur where the piling is permanently immersed in soil and hence subject to low corrosion. Such a series of analyses is beyond the scope of this work. However, the reader is referred to the *Designing for Durability* presentation and Durability software (refs. 3, 15) for more detailed guidance and tools to facilitate this process.

An appropriate corrosion protection strategy for a given project will be one that allows the structure to function as intended over its design life in an economical manner. Considerations for repair and maintenance, and associated costs, should be included in this evaluation.

The cost and ease with which a structure can be repaired while in service, and the associated costs of rebuilding or removing the wall must be taken into account.

The flowchart presented in Figure 2 provides an overview of the decision making process, based on current industry best practices. The chart leads the user through a series of questions which can help determine if supplemental corrosion protection measures should be considered.

For a retaining wall in a typical suburban environment, we would apply Figure 2 to each side separately. The retaining wall is a permanent structural application, so the lower portion of the figure, the area divided into the broad categories of atmospheric exposure, soil exposure and water exposure, is applicable. Considering first the buried side of the wall, it becomes clear that if the sheet piling is driven into undisturbed soil, no further evaluation or protection is required. If, however, the area behind the piling is backfilled, further evaluation of the backfill materials is required before a decision on corrosion protection can be made. On the front face of the piling, the side exposed to air, the left-most branch of the flowchart indicates that, barring an aesthetic coating requirement or a corrosive atmosphere, coating or other protection methods will not be required.

Note that individual exposure conditions within any one category, such as "Fresh Water" or "Disturbed Soil" can vary substantially. As such, the user is cautioned to use the flowchart as a general guide to begin evaluating the corrosion protection needs for any given project. Project specific conditions should always govern the choice of a particular approach. Where available, local experience with steel corrosion in similar exposures is invaluable in determining corrosion protection requirements.

QUALITY ASSURANCE for DURABILITY

Quality assurance provisions will vary with the importance of the structure, the environmental exposure, and the type of corrosion protection system employed.

Most coating manufacturers recommend, at a minimum, inspection of the surface preparation prior to coating application, as well as inspection after the coating is applied to ensure proper and uniform coating application. Any areas not adequately coated should be recoated to meet the project specifications. Once coated, the steel pilings should be handled with care to avoid damaging the coating prior to or during installation.

For cathodic protection systems, the *Handbook of Corrosion Protection for Steel Piling Structures in Marine Environments* (ref. 14) recommends:

- A weekly or biweekly check that the rectifiers are operating continuously,
- Every three months recording rectifier data, such as voltage and current,
- An annual visual inspection of all pilings and anodes, and replacement of any anodes that are 85% consumed or more,
- An annual measurement of the potential between the structure and a reference electrode to identify any anomalies, and
- A complete survey every three to five years to evaluate the system performance and recommend corrections, if necessary.

FIGURE 1. CORROSION PROTECTION CONSIDERATIONS for MARINE ENVIRONMENTS

Reference Wall

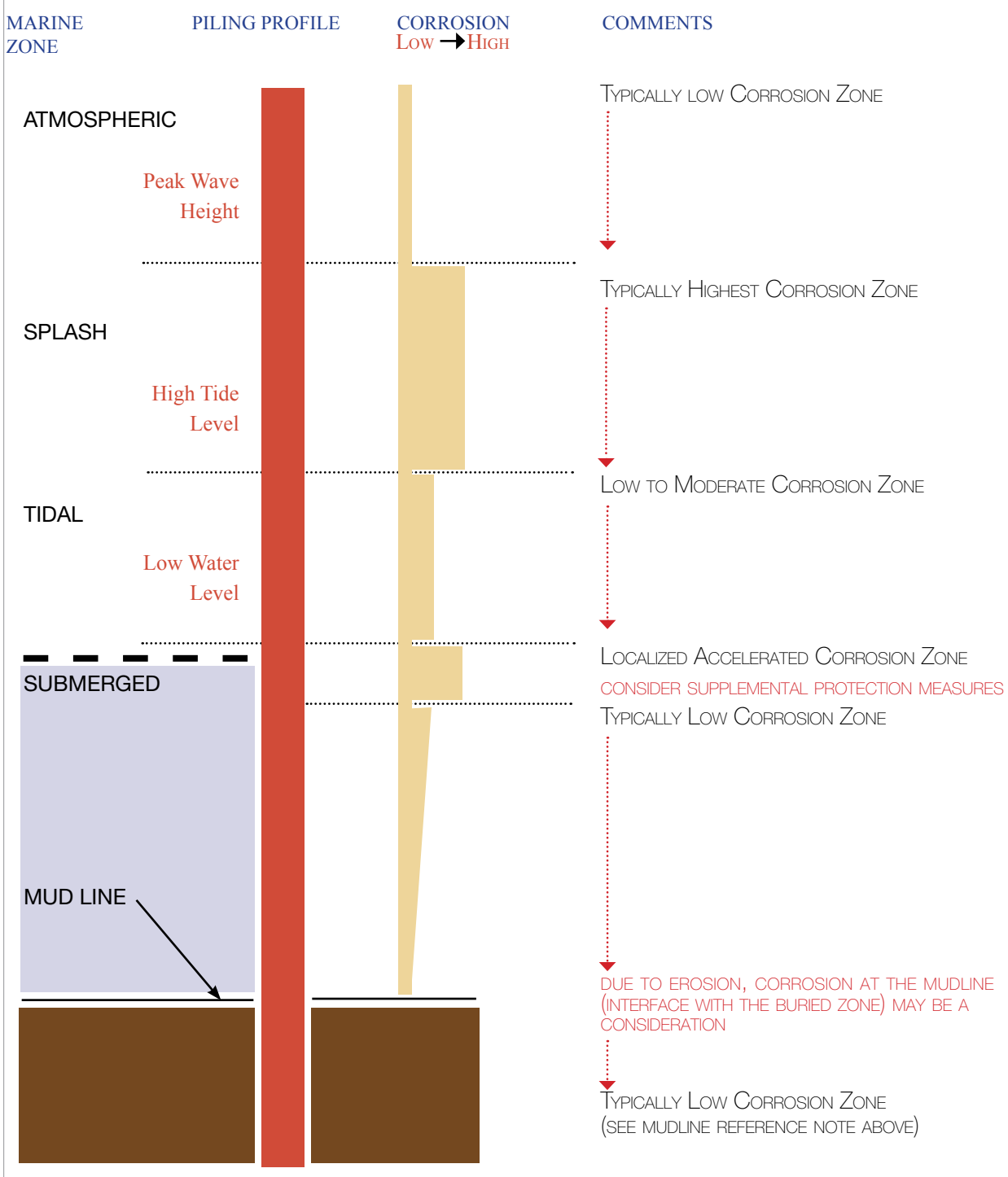
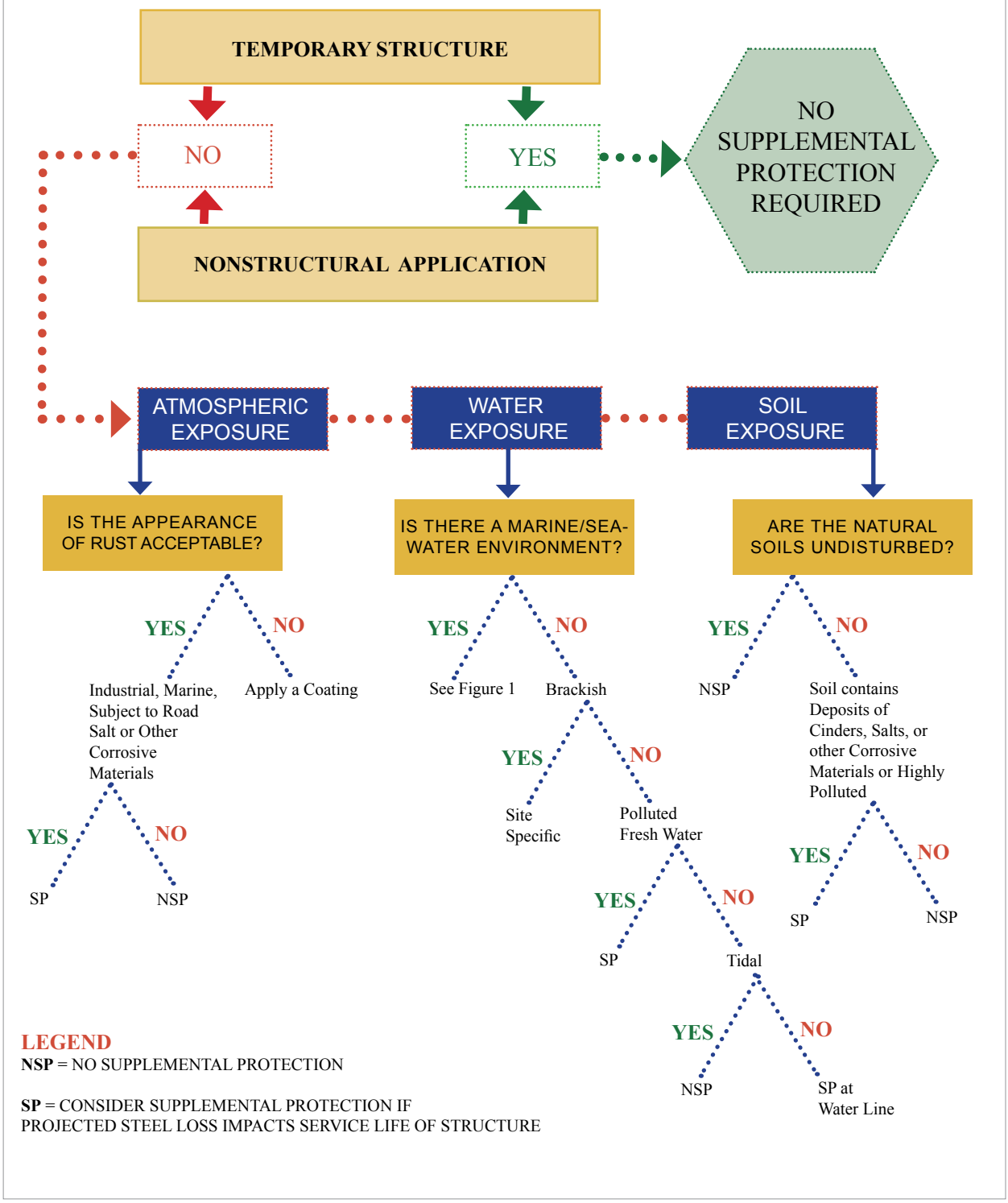


FIGURE 2. CORROSION PROTECTION CONSIDERATIONS

Decision Diagram



LEGEND

NSP = NO SUPPLEMENTAL PROTECTION

SP = CONSIDER SUPPLEMENTAL PROTECTION IF PROJECTED STEEL LOSS IMPACTS SERVICE LIFE OF STRUCTURE

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