HANDBOOK OF CORROSION PROTECTION FOR STEEL PILE STRUCTURES IN MARINE ENVIRONMENTS

Steel

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PREFACE

In the planning, design and construction of bulkheads, wharves, piers, loading docks, offshore platforms and other marine structures, it is usually desirable to achieve: (1) the required useful service life of the structure with minimal maintenance, and (2) the lowest total cost for initial construction and maintenance when equated in terms of the present value of all those expenditures. Therefore, the characteristics of the environment for the specific geographical location of the structure must be known, in addition to a knowledge of the physical and chemical properties of the structural materials available and the materials' behavior in that environment.

The design of piles and material selection for a marine structure are particularly critical because piles can be subjected to aggressive physical, chemical, and biological attack by various components of the marine environment.

Wood, concrete, and steel are the common materials of construction used for marine piles. Each of these is subject to deterioration due to various mechanisms found in a marine environment, as shown in Table I. It is obvious, from this tabulation, that protective measures may be required to prevent excessive damage and premature failure of piles made from any of these materials.

Steel piles are especially advantageous for building marine structures. They can be readily transported, are easily handled by standard lifting equipment, and can usually be driven readily into place. In the early use of such piles, corrosion protection was rarely specified. As a result, some pile installations have had to be rehabilitated or replaced prematurely, due to deterioration.

This Handbook provides information pertaining to evaluation of the need for corrosion control, the selection of methods for corrosion mitigation, the design and specification of such methods, and the estimation of costs. In addition, the rehabilitation of steel piles is discussed. This Handbook cannot, and is not intended to, replace the services of the experienced corrosion engineer. The Steel Pile Subcommittee of the Committee on Construction Codes and Standards, AISI, has developed this Handbook with the intention to familiarize the design engineer with the factors involved in the utilization of steel piles in marine environments.

TABLE I

ENVIRONMENTAL INFLUENCE ON PILES
IN MARINE STRUCTURES

Agent	Mechanism
Physical	
Tide	Thermal cycles
Wind	Fatigue and overstressing
Current	Erosion by sand
Wave action	Fatigue and overstressing
Ice	Overstressing (freeze-thaw cycles)
Ship impact	Overstressing
Chemical	
Brackish and seawater	Corrosion
(submerged, tidal and splash zones)	
Polluted water	Corrosion and direct attack
Fire	Burning
Fresh water	Corrosion
(submerged, tidal and splash zones)	
Biological	
Fouling organisms	Chemical by-products
Aerobic bacteria	Chemical by-products
Anaerobic bacteria	Chemical by-products
Marine borers	Ingestion

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Factors to be Considered in the Use of Steel Piling in Marine Structures; Fundamentals of Steel Corrosion; Design and Fabrication Practices; Steel Selection; Jacketing and Coating; Cathodic Protection

The material by Herman S. Preiser, P.E. was prepared in 1970-1971 in collaboration with C. Jay Steele, Corrosion Specialist. An earlier unpublished manuscript by the late Boris H. Tytell provided valuable background information. The material has been updated where applicable with certain additions and modifications.

The following engineers have contributed to the development of this Handbook by providing background data and reviewing some of the sections:

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TABLE OF CONTENTS

SECTION 1

FACTORS TO BE CONSIDERED IN THE USE OF STEEL PILING IN MARINE STRUCTURES

Herman S. Preiser, P.E.

Introduction

The factors to be considered during the planning and design of marine structures include service life, type and use of structures, existing and future environmental conditions, and level of inspection and maintenance. Consideration of the foregoing is necessary to construct an economical structure which can be used for the required function over an appropriate service life.

Deterioration caused by corrosion is a factor in determining service life and, therefore, the corrosion potential must be evaluated.

Corrosion potential may range from negligible to severe without protection systems. No matter what the corrosion potential, there are protection systems and many known methods available to retard or eliminate deterioration. It is apparent that under some conditions of limited service, or where corrosion is not significant, corrosion control measures would not be needed. On the other hand, in corrosive environments the economical method of achieving the required service life might well be the incorporation of corrosion control measures at the outset.

During the planning stage it is desirable to determine whether corrosion control is necessary and, if so, the degree of corrosion control that must be provided. This section offers guidance for evaluating the need for corrosion control and a listing of the methods used to provide that control.

1.1 Situations Where Corrosion Control Is Not Required

Consider the situations for which corrosion control would generally not be required for steel pile structures in marine environments: in temporary pile installations, in non-structural applications, in mildly corroding environments such as fresh water, and in portable or movable structures that are readily accessible for maintenance.

Temporary Service—There are many circumstances where temporary steel sheet piling is installed during marine construction, or where steel bearing and batter piles are installed as temporary supports while the main marine structure is being built. In these cases, the temporary piling need last only a relatively short time, usually less than five years, and, even at general corrosion rates of 10 mils per year (mpy) and random pitting of 20 mpy, no structural failures would be anticipated. No corrosion control is required in such cases, and it would be economically sound to install bare carbon steel piling.

Steel Forms—Sometimes lightweight steel pipe is used as a form for reinforced concrete piles poured in place. Such piles often are designed without consideration of the structural strength of the steel form and, therefore, once the concrete is cured the steel is expendable. Corrosion control of the steel pipe is consequently unnecessary.

Mild Environments—In unpolluted fresh water locations such as in natural lakes and inland rivers, steel pile structures are generally subject only to mild corrosion. While the average rates of corrosion in the immersion zone would not be significantly different from that in seawater (since the dissolved oxygen content, the controlling factor, is very nearly the same for fresh water as seawater), the pitting rate would normally be substantially less in fresh water. Because of higher

electrical resistance, fresh water corrosion cells operate on the microscale rather than on the macroscale, resulting in a corrosion pattern of general thinning rather than incipient localized pitting. In such circumstances, corrosion rates in the order of 5 mpy may be encountered and, therefore, with suitable design considerations, long-term service life can be assured without protective measures.

Portable Structures—Steel structures such as portable or movable piers, pontoons, and buoys which can be readily removed from the water for periodic inspection and repair can often be maintained more economically by patching and replacement of steel members than by the provision of corrosion control measures.

1.2   Situations Where Corrosion Control Is Required

Permanent Service—Many marine structures are expected to perform satisfactorily over long periods of time. Usually a minimum service life of at least 20 years would be planned before replacement of a permanent structure. Often 50-year and even greater service life is desired because of the physical difficulties of removing and replacing the old structure, the high cost of service disruption, and the renewal cost, which may be much greater than the original cost because of inflation. Long service life requirements usually dictate that corrosion protection be provided from the outset.

Impairment of Function and Safety—A corollary to long service life is that, while the structure is in use, it must retain its structural integrity to perform its designed function with an adequate margin of safety. Safety factors built into the design of a structure are usually necessary to compensate for flaws in material, fatigue cracking, excessive unpredictable transient loads, defects in workmanship, and ignorance of true service operating conditions. Corrosion often alters these design safety factors and increases the element of risk of permanent damage to the structure as well as increasing safety hazards to operating personnel. Therefore, corrosion protection may be called for where these safety factors appear in jeopardy over the intended service life.

Excessive Maintenance—Corrosion protection often is provided to avoid excessive costly maintenance procedures and loss of service and revenue from prolonged downtime. Usually, more options are available and costs are lower if negative bonding for future applications of cathodic protection or complete corrosion protection is installed at the outset. However, the decisions concerning the need and timing for such protection should be made by weighing the present value of the maintenance and downtime costs against the present value of the cost of protection installed at any given time. Periodic inspection can result in corrective measures with reduced downtime.

Appearance and Habitability—Often corrosion control above the waterline (where accessibility for maintenance is feasible) is provided for the esthetic purposes of appearance and habitability, rather than for economic reasons.

1.3   Corrosion Control Methods

Methods of corrosion control may vary, from good design and fabrication practices to use of combinations of coating and cathodic protection systems. However, knowledge of corrosion fundamentals and the economics of corrosion control are necessary before deciding on the level of protection applied. The following sections in the Handbook provide information which is useful to the engineer in the development of a corrosion control plan and some details of the design of protection systems. In addition, some existing marine structures are in need of protection or structural repairs and protection; therefore, a section devoted to the rehabilitation of steel piles is included.

SECTION 2

FUNDAMENTALS OF STEEL CORROSION

Herman S. Preiser, P.E.

Introduction

To properly consider corrosion protection measures, it is essential that some fundamental ideas about corrosion be understood. A brief review of some of these fundamentals as they apply to marine environments is provided herein. Additional discussion and data are continued in Section 5.

2.1 Nature of Corrosion[1,2,3,4,5]

Corrosion is a natural process. Most metals, in their natural state (ores), are combined with other elements such as oxygen, sulfur and silica to form stable compounds. The ores are refined by man (with large expenditures of energy, usually heat or electricity), alloyed for useful properties and ultimately fabricated into structures. Upon exposure to the natural environment, such as the atmosphere, the soil or the sea, these metals gradually revert to their original oxidized state. This undesirable destructive interaction of a metal with its environment is the *corrosion* process. Corrosion processes (similar to the refining processes) cause chemical alteration of the metal by transfer of thermal or electrical energy.

There are two general types of corrosion in marine environments that are of interest to the design engineer: uniform corrosion and pitting attack. Uniform corrosion is a general overall roughening of a metal surface resulting in its gradual thinning. This type of corrosion frequently occurs on steel piling exposed to low resistivity natural waters (see Figure 2.1). The more common pitting corrosion is a localized form of attack, and often occurs on piling immersed in saline waters (see Figure 2.2). In some cases (stress fluctuation) pitting may be more serious than uniform corrosion in that it forms sites where stresses on the structure can concentrate. Pitting corrosion rates are frequently five to ten times the uniform rates in the early stages of immersion, gradually tapering off to about three times the uniform rate over a longer period of approximately ten years.[6] Uniform rates are the normal criterion of corrosion of structural members used in waterfront structures.

2.2 Causes of Corrosion[7]

Corrosion occurs because of small physical and/or chemical differences present in metals or in the environment. The differential conditions in the metal arise from minor impurities, local composition variations, surface scratches and abrasions, breaks in the mill scale, locked-in thermal stresses, stray currents, galvanic couples and bacterial activity, to cite a few examples. Differential environmental conditions may arise from changes in amounts of dissolved oxygen varying with the depth of immersion, local fluctuation of velocity or non-uniform salt concentrations because of surface pollution. Such conditions create local dissimilar sites on the surface of the metal which interact electrochemically.

Corrosion reactions are most conveniently studied in a galvanic cell which is composed of two separate electrodes (see Figure 2.3), an anode and a cathode, which are immersed in a conducting solution called the electrolyte. A common flashlight battery is a good example of a galvanic cell. The cell is active when the two electrodes are connected together by an external wire. Corrosion occurs at the
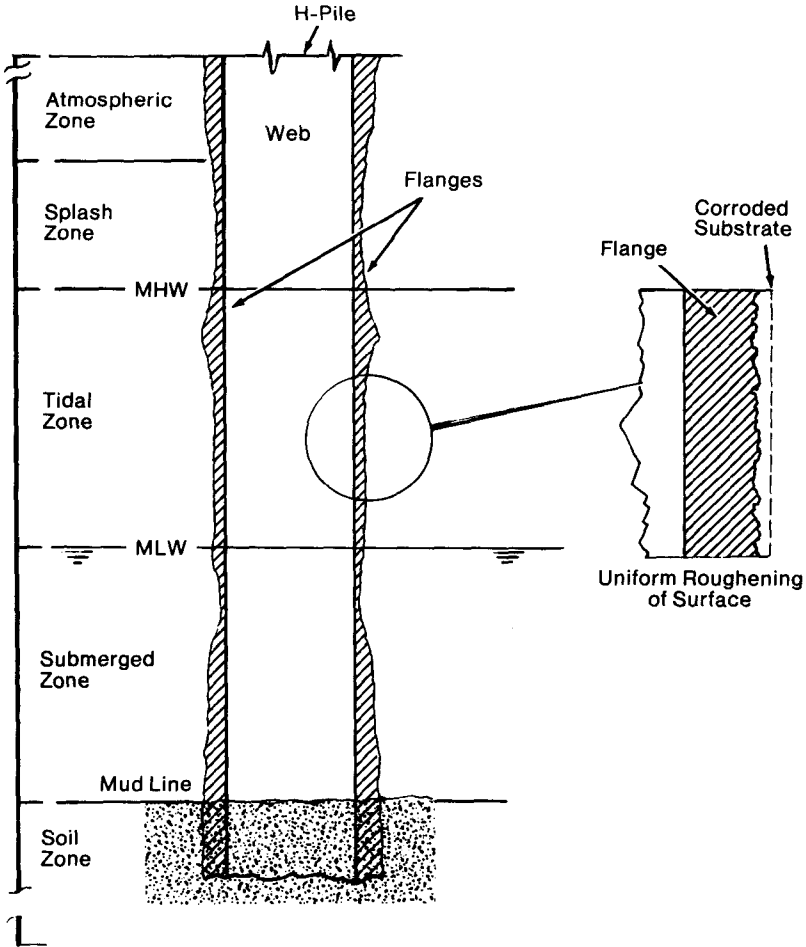
Figure 2.1   Uniform corrosion of a steel H-Pile (schematic).

anode and is accompanied by a flow of electrons through the external wire to the cathode. The voltage difference between the electrodes at any time determines the corresponding instantaneous corrosion current through the cell. These voltage differences change with the amount of current produced and the time the cell is operating, gradually reaching near-steady values.

2.3   Corrosion Mechanism of Steel in Seawater[8]

On steel piling in seawater, the more chemically active surface areas (anodes) are metallically coupled through the piling itself to the less chemically active surface areas (cathodes) resulting in a flow of electricity and corrosion of the anodic areas. General surface roughening occurs when these local anodic and cathodic areas continually shift about randomly during the corrosion process. Sometimes these

active local areas do not shift position and, therefore, the metal suffers localized attack and pitting occurs. In general, the depth of pitting is related to the ratio of the anodic sites to the area of cathodic sites in contact with the electrolyte (seawater); the smaller the anode area relative to the cathode area, the deeper the pitting.

The same destructive action occurs when two dissimilar metals, coupled together and immersed in seawater, form a galvanic cell (see Figure 2.4). Steel piles corrode if coupled with a less active (cathodic) metal in seawater.

Similar reactions occur within a corrosion pit (see Figure 2.3). The base of the pit becomes anodic to the surface of the metal because of a lack of oxygen in the pit. The metallic ions enter the seawater at these sites causing the pit to deepen. Electron flow in the metallic circuit proceeds from the anodic depths in the pit to the cathodic areas of surrounding metal. At the cathodic sites oxygen is reduced to hydroxyl
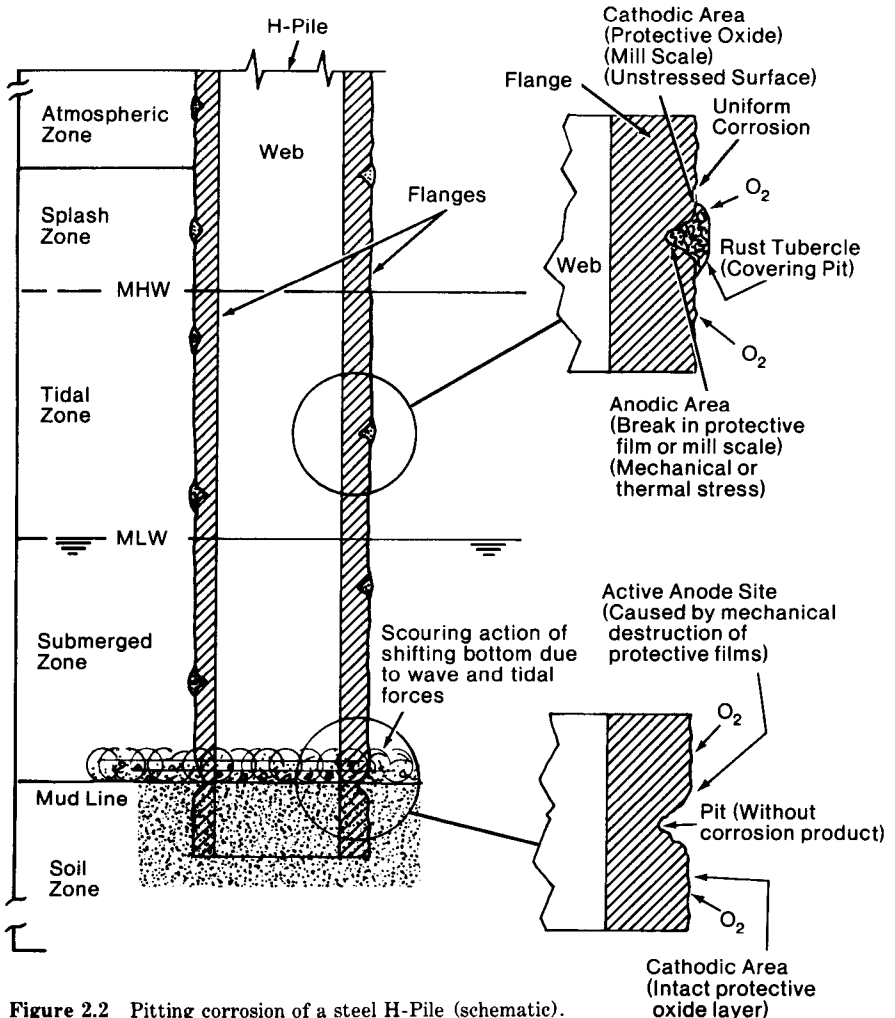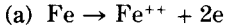

**Figure 2.2** Pitting corrosion of a steel H-Pile (schematic).

ions and combines with the iron ions to form gelatinous corrosion products which settle on the metal surface and offer some protection.

The chemical reactions taking place on iron (principal constituent of steel) corroding in seawater are as follows:
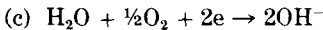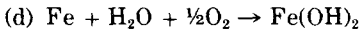
At the anode iron goes into solution:

(a) $Fe \rightarrow Fe^{++} + 2e$

The electrons flow to the cathode through the metallic circuit. At the cathode oxygen converts hydrogen atoms into water:

(b) $2H^+ + \frac{1}{2}O_2 + 2e \rightarrow H_2O$
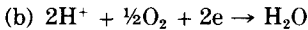
or converts water to hydroxyl ions:

(c) $H_2O + \frac{1}{2}O_2 + 2e \rightarrow 2OH^-$

By adding the above equations (a) and (c):

(d) $Fe + H_2O + \frac{1}{2}O_2 \rightarrow Fe(OH)_2$

Iron is converted to ferrous hydroxide. Other reactions can occur, such as conversion of ferrous hydroxide to ferric hydroxide $Fe(OH)_3$ by further reaction with oxygen.

2.4 Corrosion Mechanism of Steel in Marine Atmospheres

The corrosion of steel in marine atmospheres proceeds by two mechanisms: electroytic and direct chemical attack. The degree of wetting on the metal surface will greatly affect the corrosion rate.

A wet marine atmosphere, where condensed moisture is visible to the naked eye (corresponding to 100% relative humidity), is a very aggressive environment for steel. Under such conditions, the corrosion process is analogous to that of continuous seawater immersion except that the thin wet electrolytic film has a marked effect on the character of the corrosion pattern, the corrosion products, and the ease with which oxygen is transferred to the metal surface, resulting in accelerated corrosion.

In moist marine atmosphere (at relative humidities of less than 100%), the electrolytic films on the metal surfaces are invisible to the naked eye and extremely thin. Under these circumstances, dust, salt deposits and corrosion products enhance the corrosion process by entrapping moisture and allowing the electrolytic films to thicken and become continuous.

Under dry atmospheric conditions, least likely to be encountered in marine environments near the sea, steel corrodes chemically by reaction with a gaseous agent, in this case, atmospheric oxygen. The oxide films that form on steel grow rapidly to a limiting thickness and can remain stable and protective in nature if no wetting of the surfaces occur. In industrial marine atmospheres, sulfur compounds that are present enhance the oxide film growth to greater limiting thicknesses. These films also become stable and protective when maintained in a dry atmosphere. However, under moist conditions the presence of sulfur compounds on the metal surface will greatly accelerate the corrosion rate of steel.

In general, the thickness of the moisture films, the cleanliness of the metal surface, atmospheric temperature and rates of evaporation all influence the corrosion rate of steel above the high waterline. Figure 2.5 graphically illustrates the dependence of the atmopsheric corrosion rate on the thickness of the moisture film on the metal surface.
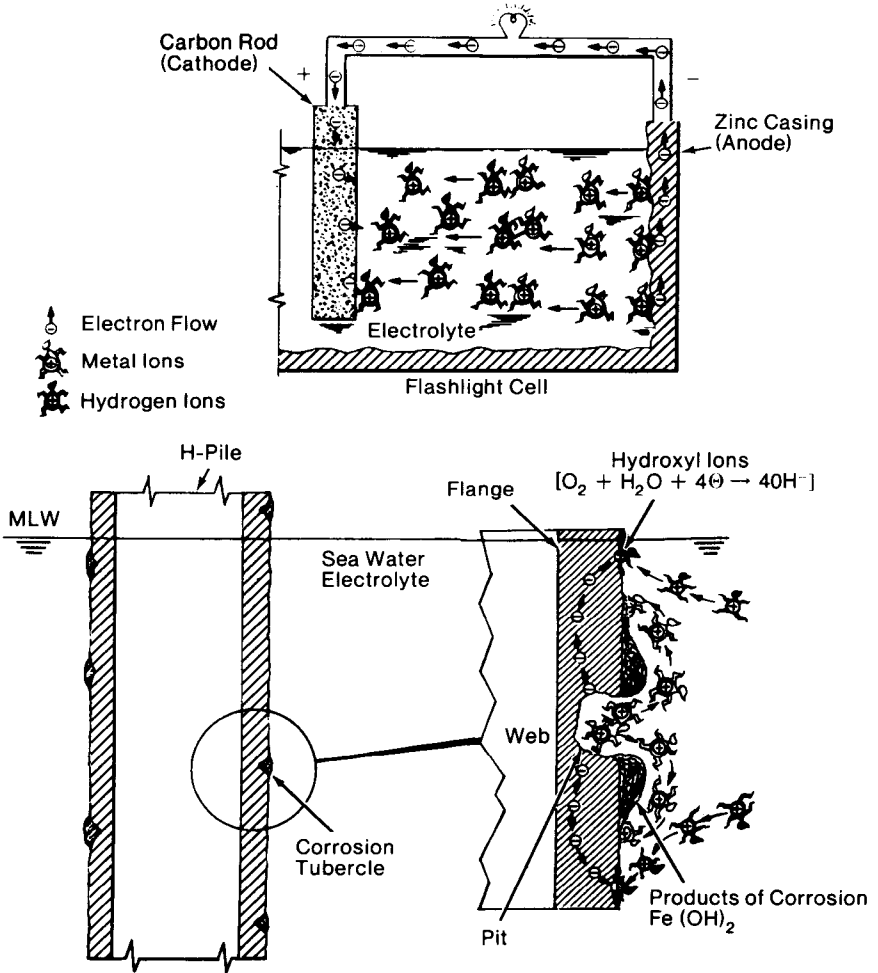
Figure 2.3   Simplified sketch of operation of galvanic corrosion cells. [Adapted from Navships 0919-000-4010, 1968][7]

2.5   Zones of Corrosion of Steel Piles[9]

Examination of corroded marine piles reveals several distinct areas of attack. It is convenient to divide these areas into five zones, each having a characteristic corrosion rate:

Atmospheric Zone—This is the area at the top of the piles which is continuously exposed to the atmosphere above the splash zone. This area is accessible for maintenance.

Splash Zone—This is the area from mean high water level upward to the bottom of the atmospheric zone. In this area moisture droplets and continuous water films are maintained on the pile surfaces exposed to the atmosphere. These areas are

accessible for maintenance, with some inconvenience, at low tide.

Tidal Zone—This is the area between mean low water level and high water level. This zone is subject to alternate periodic immersion owing to tide changes and is accessible for maintenance at low tide with difficulty.

Continuously Submerged Zone—This is the area of the piles which is always submerged extending from the mud line upward to mean low water level. (This zone does not exist in those locations where the mud line is above the mean low water level.) This area is not readily accessible for maintenance without recourse to cofferdaming techniques or specialized underwater painting techniques.

Soil Zone—This is the area of total burial in mud or soil and generally does not require maintenance.

It should be noted that the zones of one face of steel sheet piling frequently may differ from the opposite face, usually in the soil, splash and atmospheric zones.
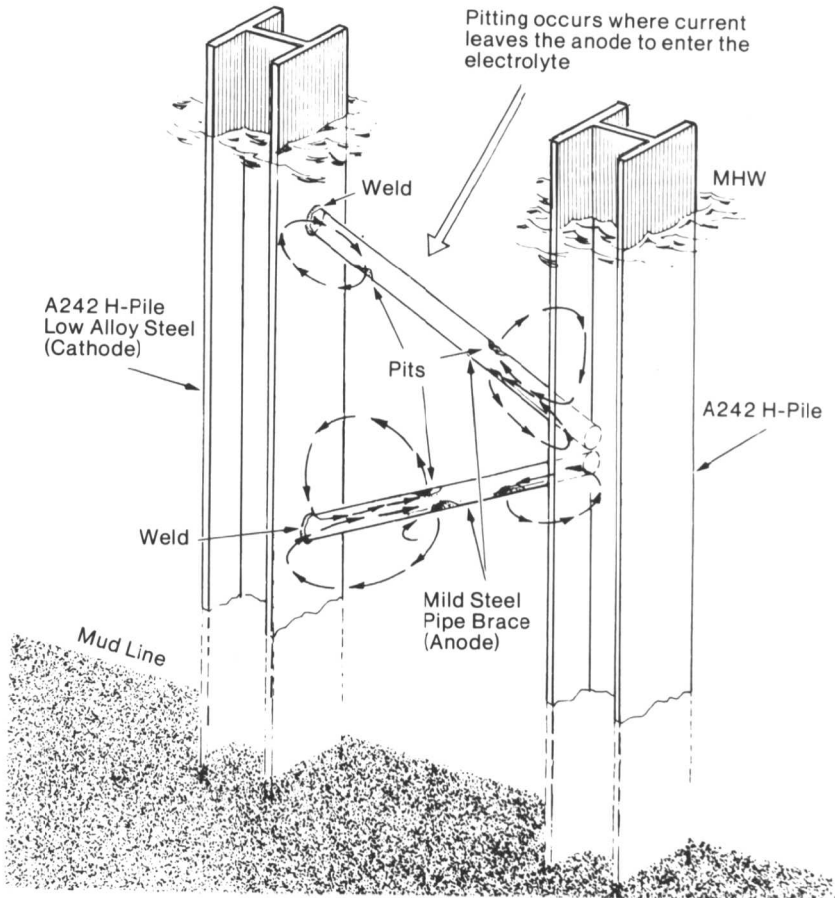
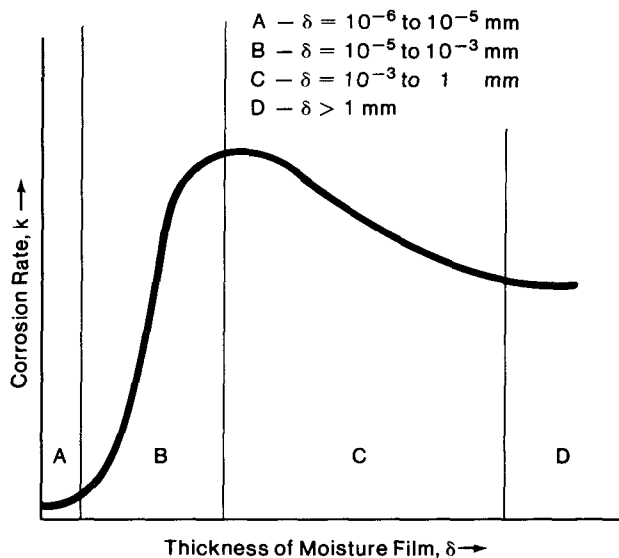**Figure 2.4**   Galvanic corrosion couples (dissimilar-electrode cells).

Figure 2.5   Dependence of atmospheric corrosion on thickness of the moisture film on the metal surface. [From Tomashov, 1966][5]

2.6   Environmental Factors Affecting Marine Corrosion Rates of Steel Piling

Corrosion Rates by Zone—The corrosion rates on steel piling surfaces normally vary considerably by zone. The corrosion rate profile for steel sheet piling, averaged for several harbor installations, is shown in Figure 2.6. The varying corrosion loss indicated in each zone is the average of eight harbor installations after 19 years' exposure. In general, the maximum reduction in metal thickness occurs in the splash zone immediately above mean high water level. A significant loss usually occurs a short way below mean low water in the continuously submerged zone.

With the exception of those few cases where scour is a factor, the least affected zone is usually found below the mud line, with higher losses at the water-mudline interface. Another low loss area exists in the tidal zone about halfway between mean high water and mean low water levels.

Corrosion loss is generally very low on areas of steel piling driven into undisturbed soils. An exception is where a porous backfill such as coral is used. Soil corrosion is discussed in more detail later in this Section.

Where steel sheet piling is exposed to water on one side, the average corrosion rate varies from 1 to 4.5 mils per year (mpy), reaching maximums of 3 to 14 mpy. Where steel sheet piling is exposed to water on both sides, the total rate of corrosion of the member is doubled. Pitting will cause localized corrosion attack at 1.5 to 3 times the average rates over an extended exposure period.

Erosion—Erosion derives from the Greek word "erodere" which literally means to wear away. Corrosion in the immersed zones in combination with erosion can produce severe localized attack. Steel in marine environments corrodes initially at a relatively high rate until protective films of corrosion reaction products form on the suface. In stagnant waters the film is effective; however, in estuaries for example, where the tide reverses, the protective film is eroded away leaving