Construction of Waterfront Structures

This course is based on excerpts from the:
US Corp of Engineer's publication, #UFC 4-150-07, September 2012,
"Maintenance and Operation of Waterfront Facilities"

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Chapter 1: Types of Waterfront Facilities

Types of Facilities

Types of waterfront facilities include:

Berthing Facilities
for mooring and for providing support to ships and craft.

Drydocks
used for construction of ships and to expose the underwater portion of the ship for repair, modification, inspection, or maintenance.

Coastal Protective Structures
designed to protect shorelines or harbors.

Components of Waterfront Structures

The components of a waterfront facility:

- Fender systems
- Piling
- Dolphins
- Utility distribution systems
- Deck and mooring hardware
- Fleet moorings

Berthing Facilities

The basic facilities to provide berthing support for ships and craft are piers and wharves. These facilities provide a safe space for ships to moor and receive shore utilities and other hotel services.

They provide a platform for loading and unloading cargo and personnel, transferring ordnance, receiving fuel, and performing ship maintenance; repair; and fitting out.

Berthing facilities are also provided for tugboats, small craft, barges, and harbor support equipment.

Piers

These are berthing facilities that extend outward from the shore into the water. Piers may be used for berthing on one or both sides of their length.

There are three types of pier structures with distinct differences in configuration:

- Open
- Closed
- Floating Piers

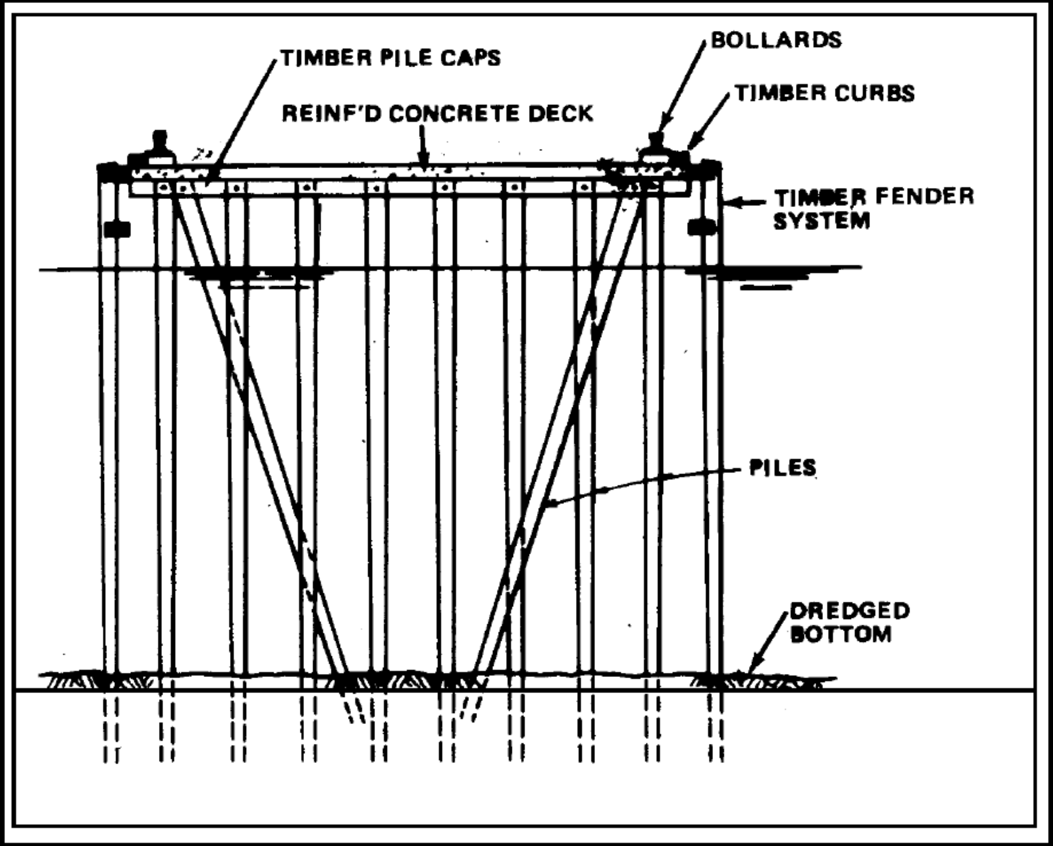
Combination Piers – (combine open and closed configurations)

Open Piers

are pile-supported platform structures that allow water to flow underneath.

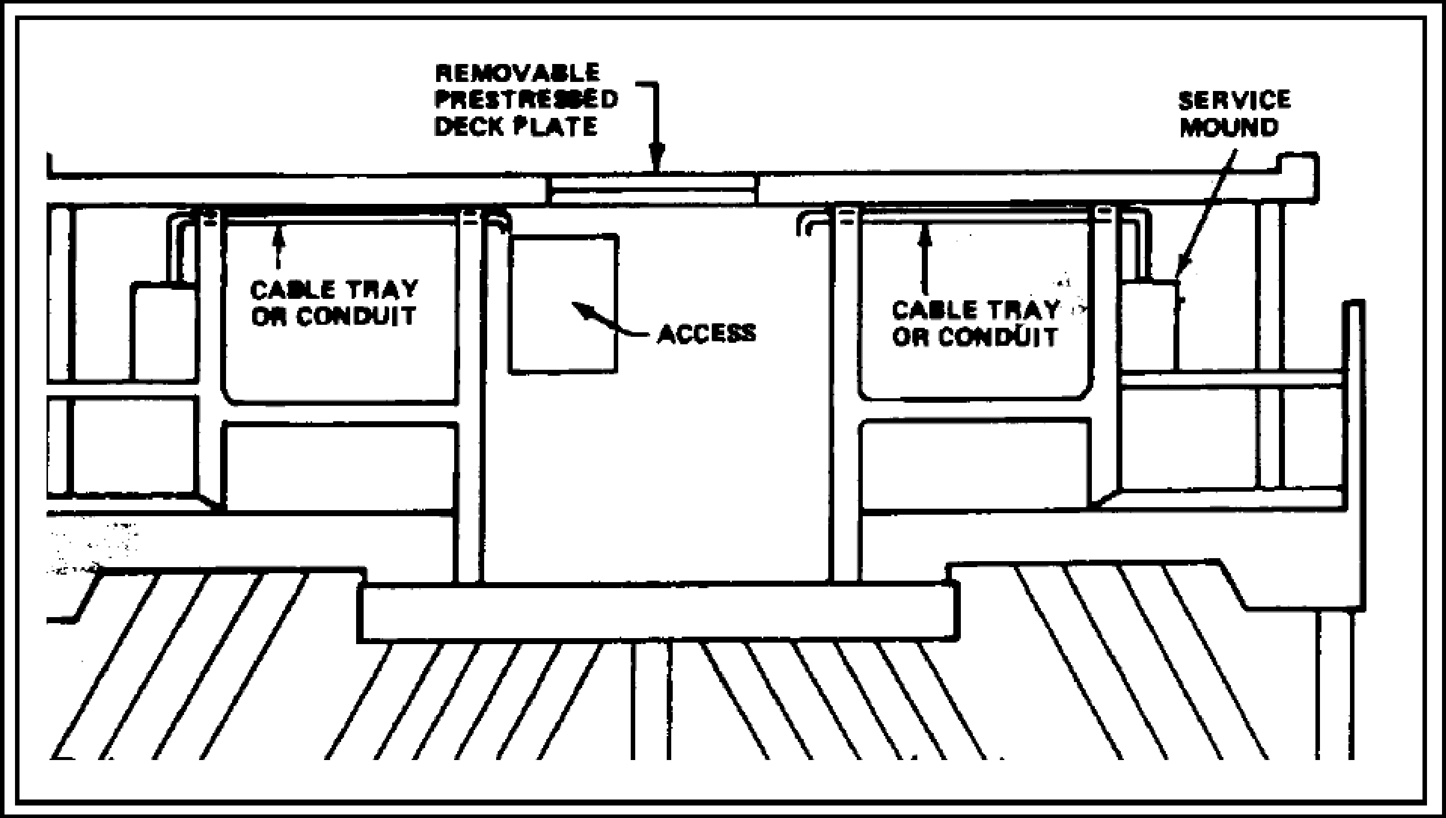
Pile supported piers can be single-deck or double-deck structures.

The image to the right, shows a diagram of a single-deck, open pier.



Open Piers (Double Deck)

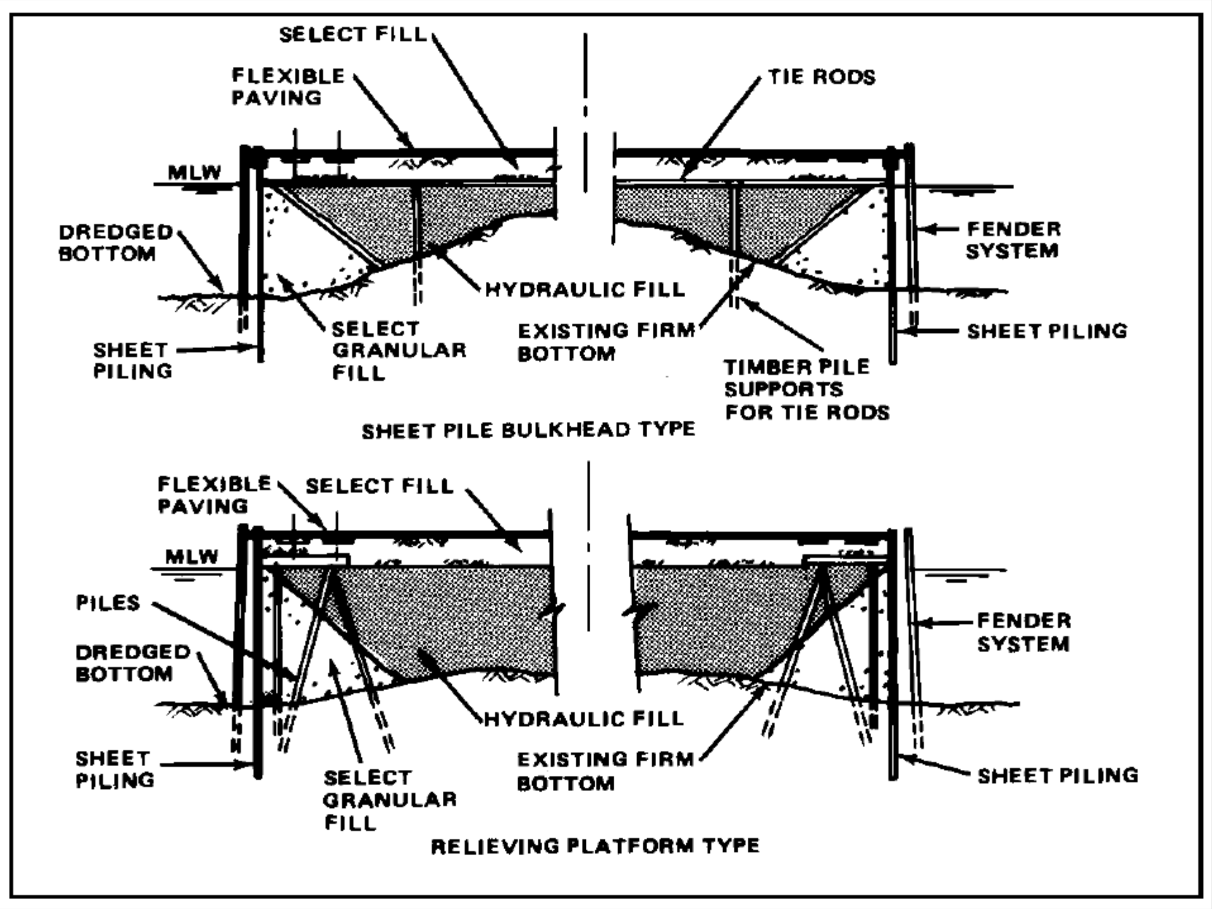
The image below shows a diagram of a double-deck, open pier.



Closed Piers, or Solid Fill Piers

are constructed so that water is prevented from flowing underneath. The solid fill pier is surrounded along the perimeter by a bulkhead to hold back fill.

The image below shows a diagram of a solid fill pier.



Moles or Mole Piers

A special type of solid fill pier is a mole pier. Mole piers are earthen structures that extend outward from the shore.

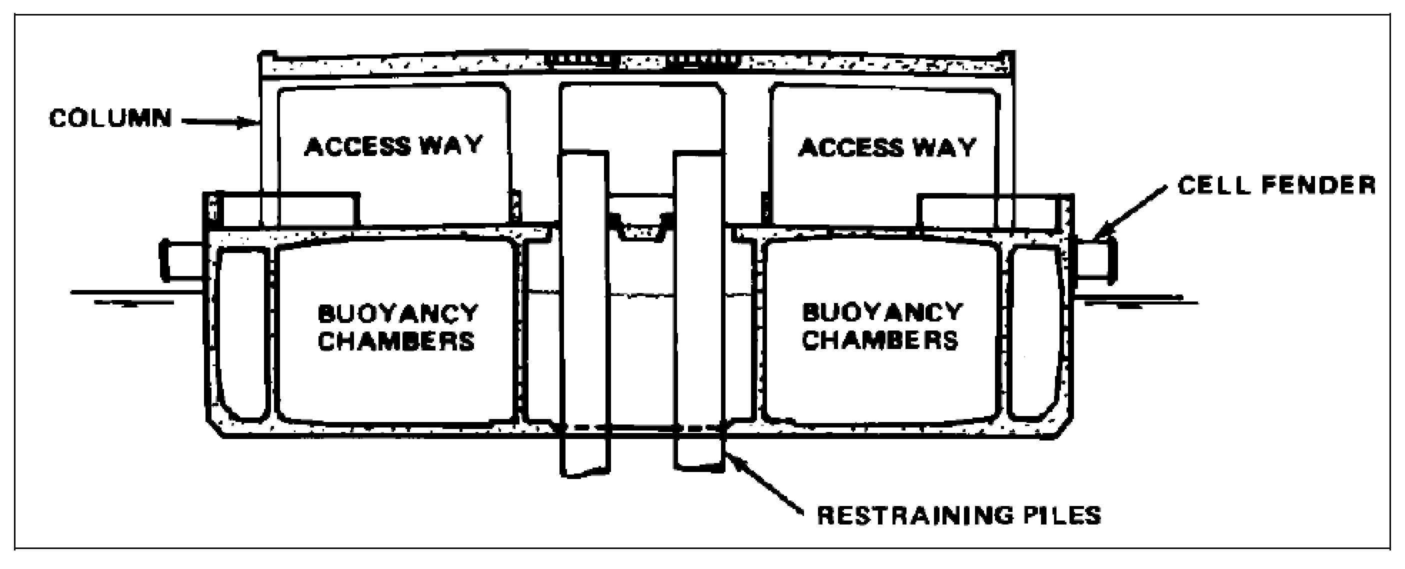
The sides and offshore end of the pier are retained and protected by sheet piles, circular cells or walls of either masonry or concrete. If the water is deep, the pier can be used to berth ships.

Floating Piers

are constructed of steel or concrete and are connected to the shore with access ramps.

Guide piles in the center of the pier, or a chain anchorage system, prevent lateral movement and allow the pier to move up and down with the tide. The floating pier may be a single-deck or a double-deck structure.

A floating pier design concept developed by the US Navy is shown below.

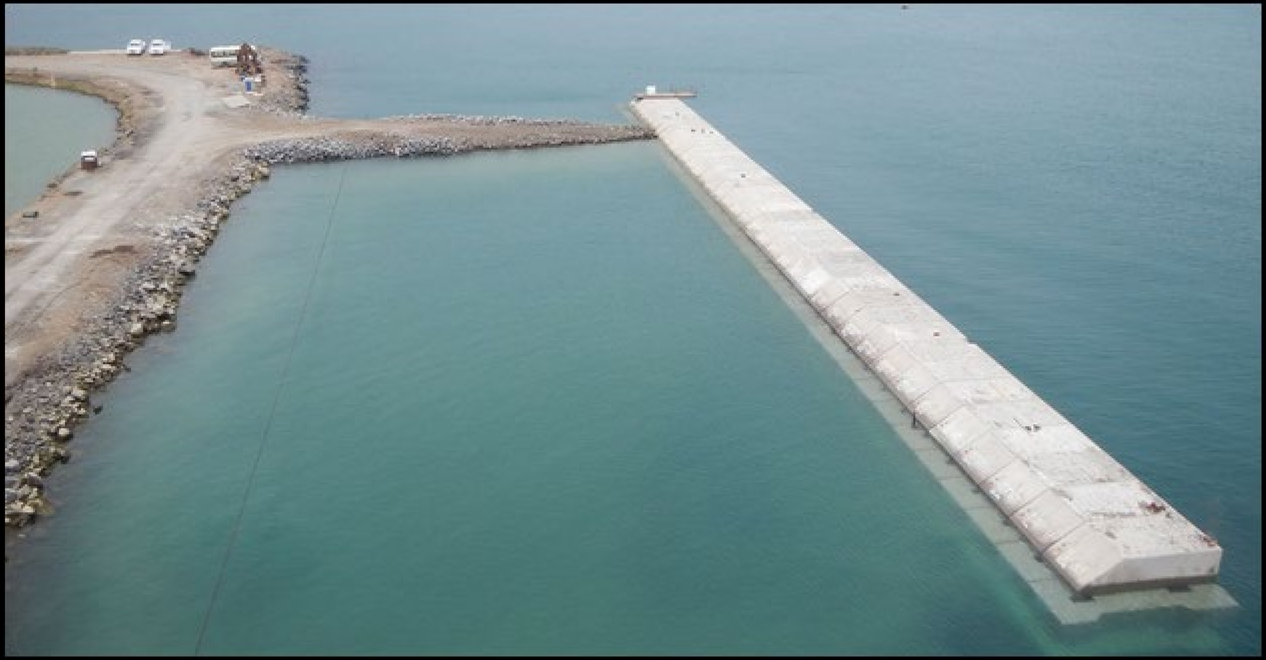


Wharves and Quaywalls

Wharves are berthing facilities that are parallel to the shore. They are normally connected to the shore along their full length, and a retaining structure is used to contain earth or stone placed behind the wharf.

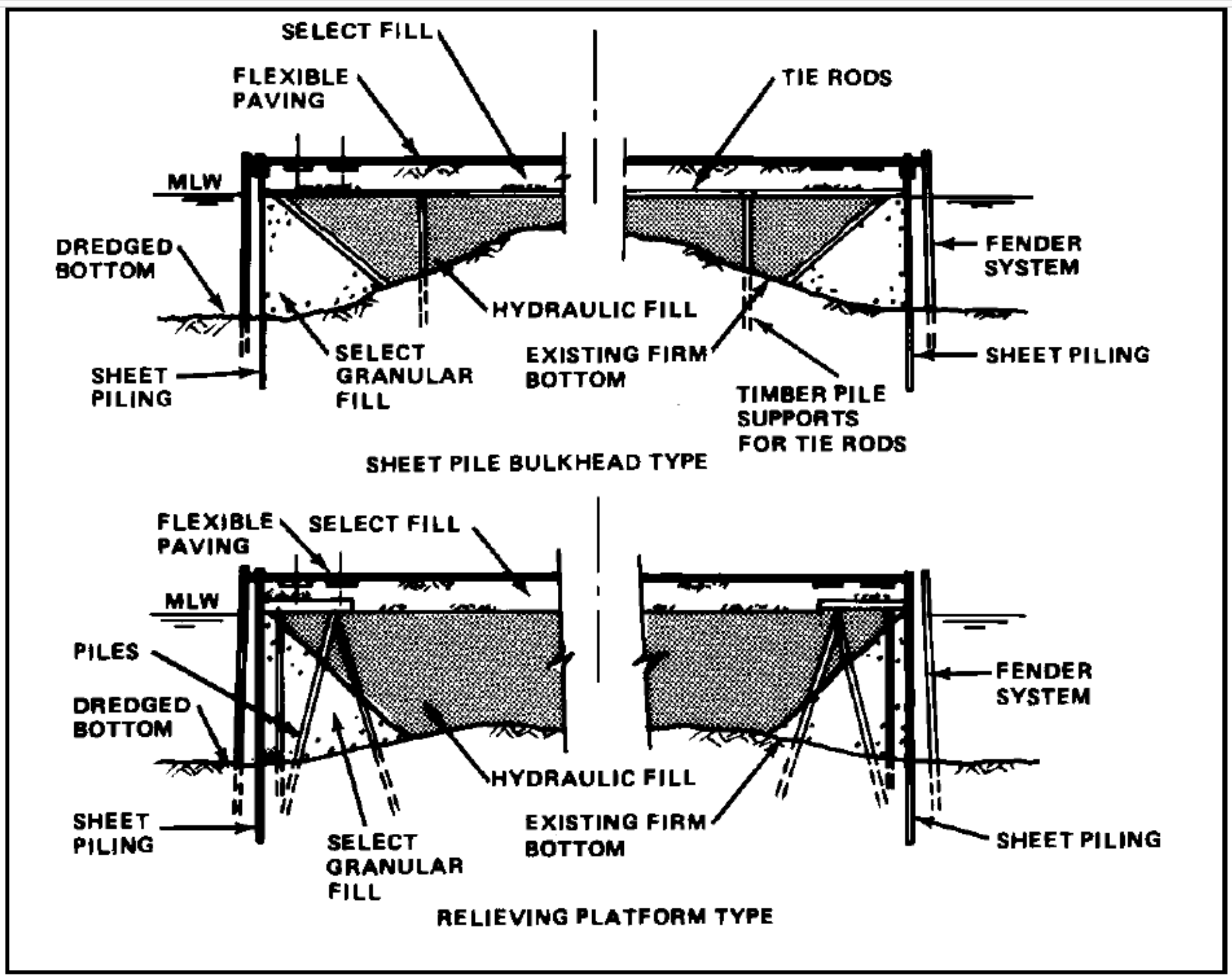
This retaining structure is often referred to as the quaywall or bulkhead.

Ships are moored along the outshore face of the wharf. The wharf types are the same as the basic pier types and include open and closed (or solid fill) configurations.



Solid Fill Pier

The image below shows a solid-fill pier with a configuration similar to a closed wharf.



Drydocking Facilities

Drydocking facilities are used to expose the underwater portion of ships for repair, modification, inspection, or maintenance.

Several different types of drydocks exist, including:

- graving drydocks
- floating drydocks
- marine railways
- vertical ship lifts

The image to the right shows the A graving dock housing the USS Greenville (US Navy) submarine.

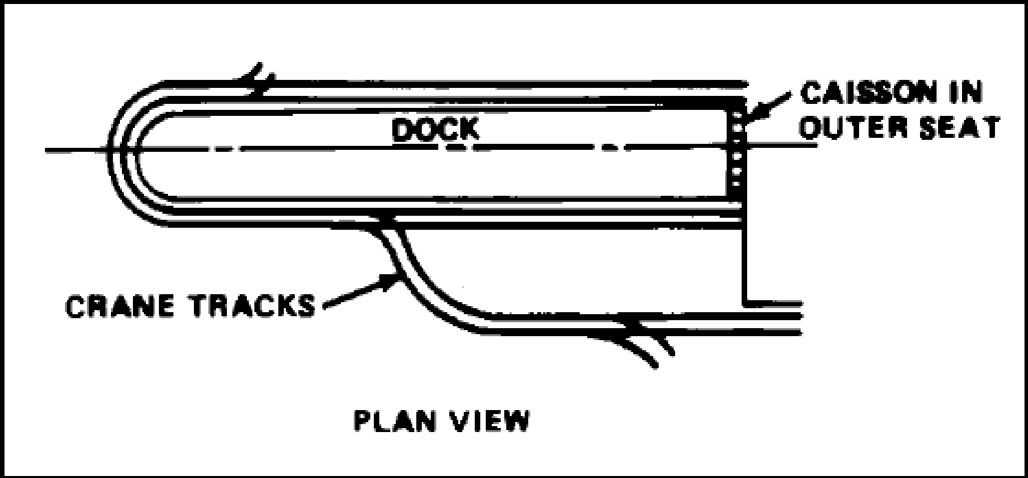
Graving Drydocks

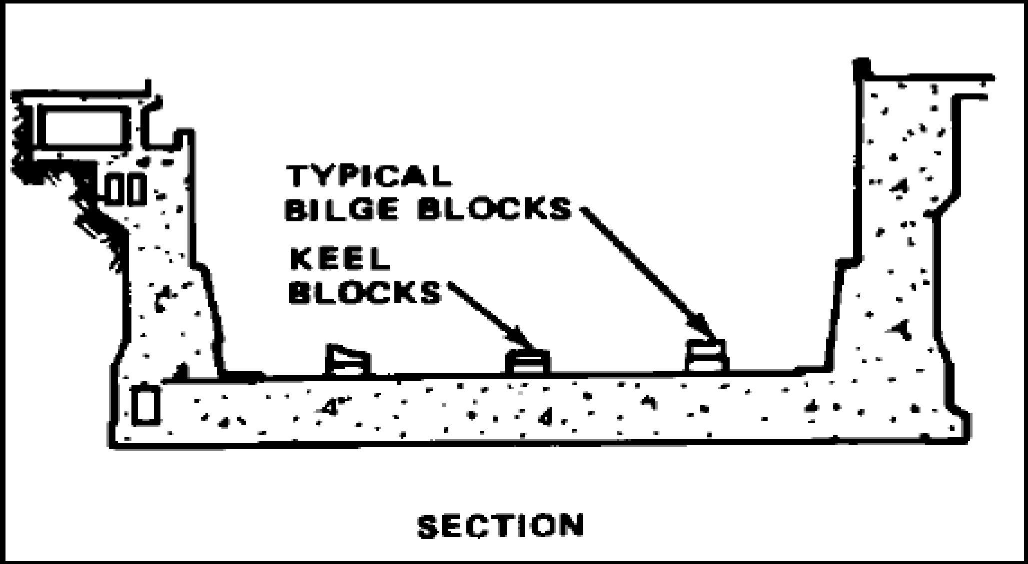
These are fixed basins adjacent to the water's edge and are constructed of stone masonry, concrete, or sheet pile cells.

They can be closed off from the waterway by a movable watertight barrier (entrance caisson or flap gate).

After closing the barrier, the basin is pumped dry, which allows the ship to settle on blocking set on the dock floor.

The images to the right show the plan and section views of a graving drydock.





Floating Drydocks

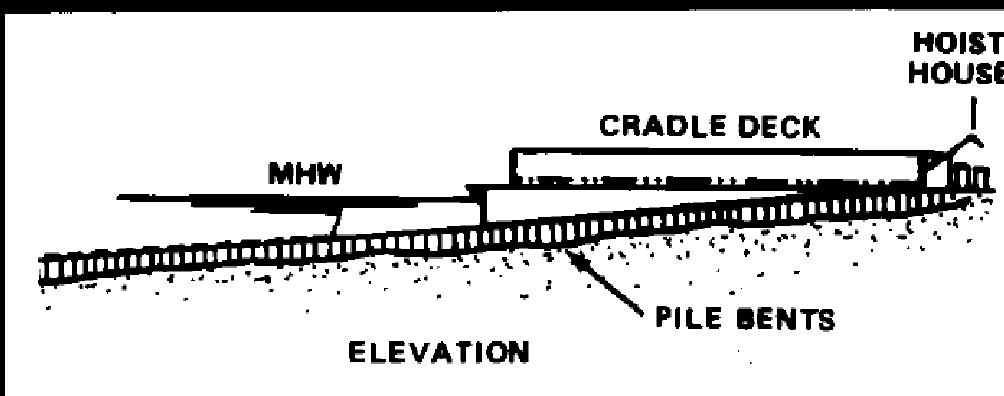
are ship or U-shaped structures that are sub-merged by flooding to permit a vessel to enter and then pumped dry to raise the vessel out of the water.

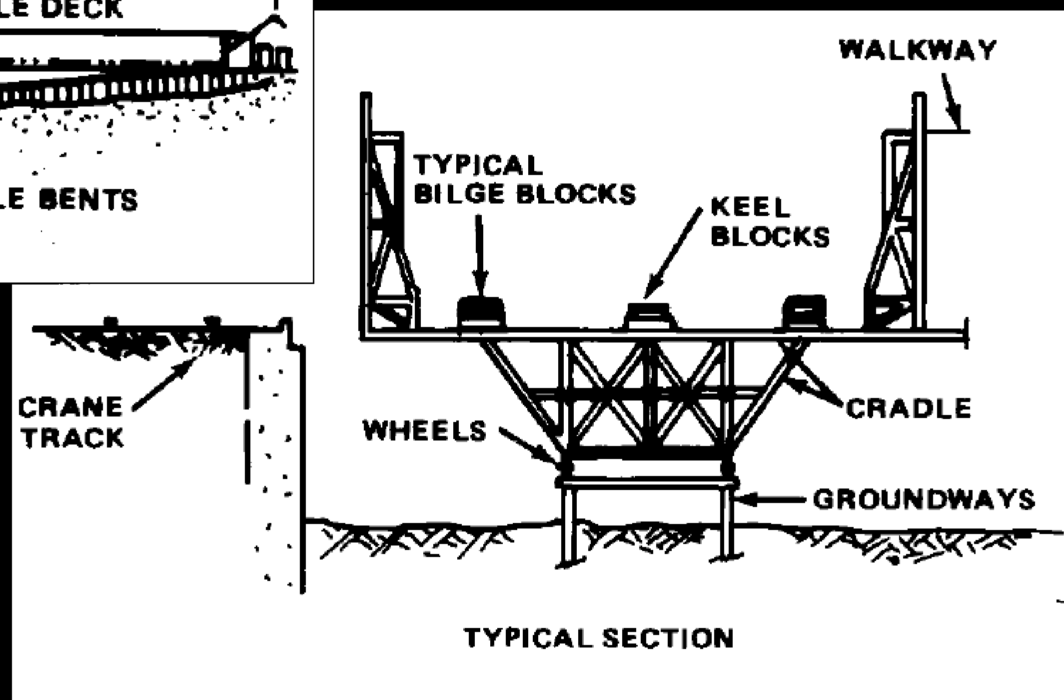
The image below shows three floating drydocks in a port in Gydnia, Poland.

Marine Railways

These consist of a ramp extending into the water, a mobile ship cradle on wheels or rollers, groundway ship cradle tracks, hoisting machinery, and chains or cables for hauling the ship cradle endwise or sidewise.

See images below of a marine railway.



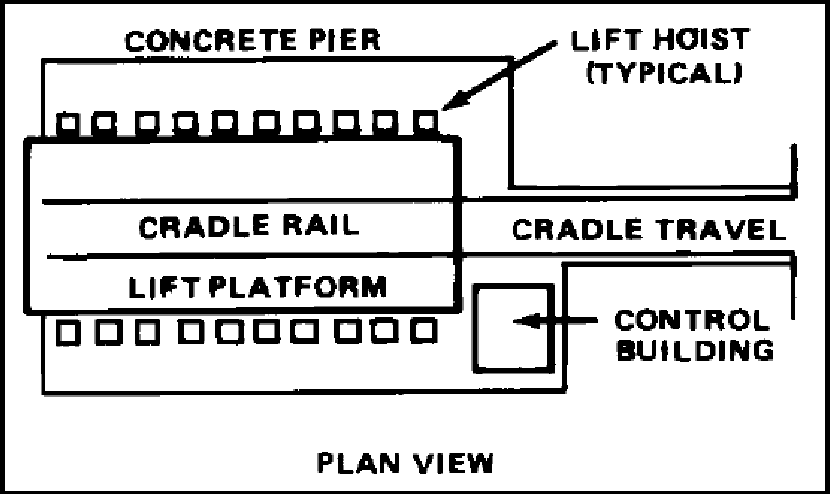


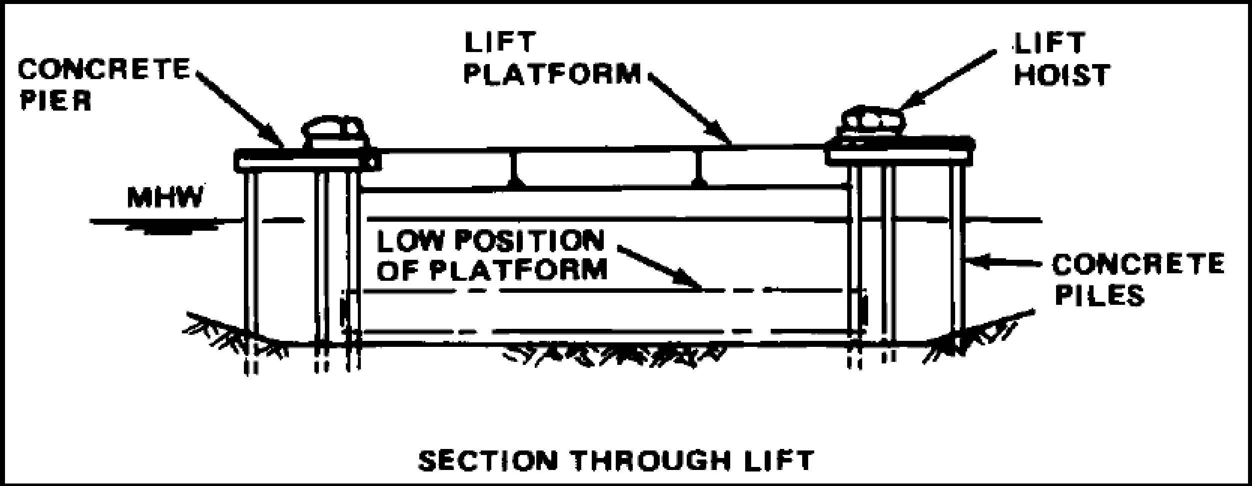
Ship Lifts

These consist of platforms that are lowered into the water to receive ships.

The ship is then lifted out of the water on the platform by electrically powered hoist equipment.

The images show a vertical ship lift drydocking system, also known as a "Syncrolift".





Coastal Protection Structures

Structures designed to reduce the erosive effects of wave action, or to protect harbors from excessive wave action and the formation of sandbars, are classified as coastal protection structures.

The common coastal protection structures are:

- Seawalls
- Groins
- Jetties
- Breakwaters

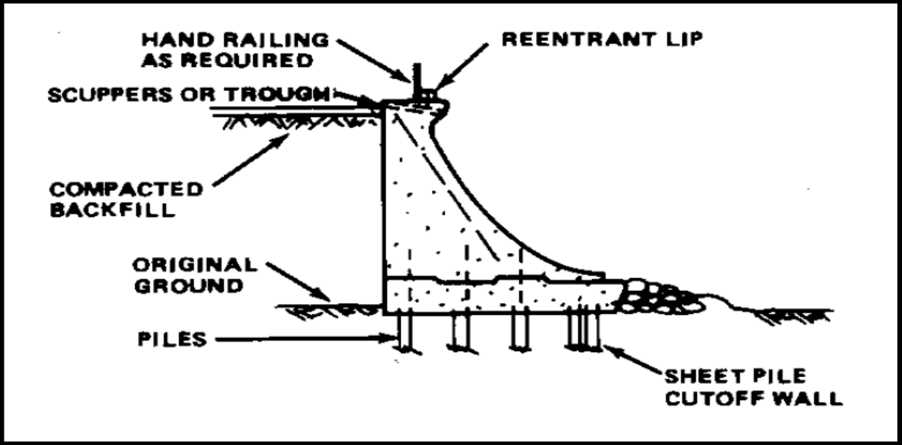
Seawalls

Seawalls (image below) are massive coastal structures built along the shoreline to protect coastal areas from erosion caused by waves and flooding during heavy seas.

Seawalls are constructed of a variety of materials including rubble-mounds, granite masonry, or reinforced concrete.

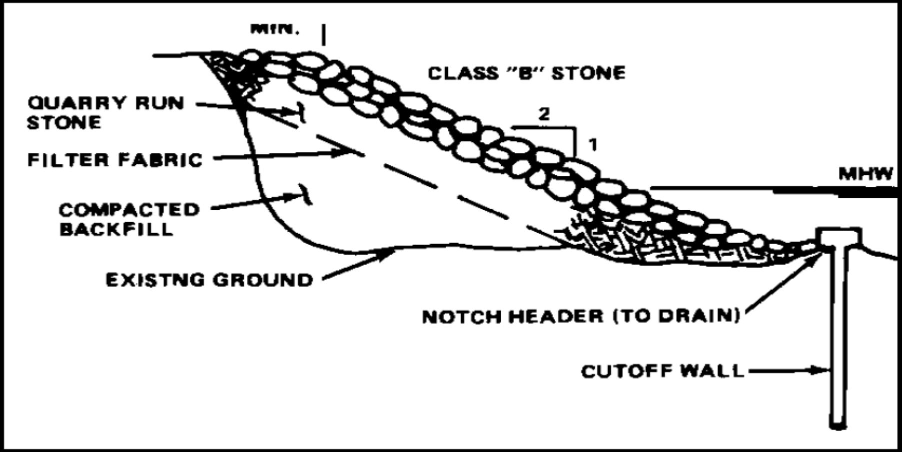
They are usually supplemented by steel or concrete sheet pile driven into the soil and are strengthened by wales and brace-type piles.

The following page shows three types of seawall configurations.



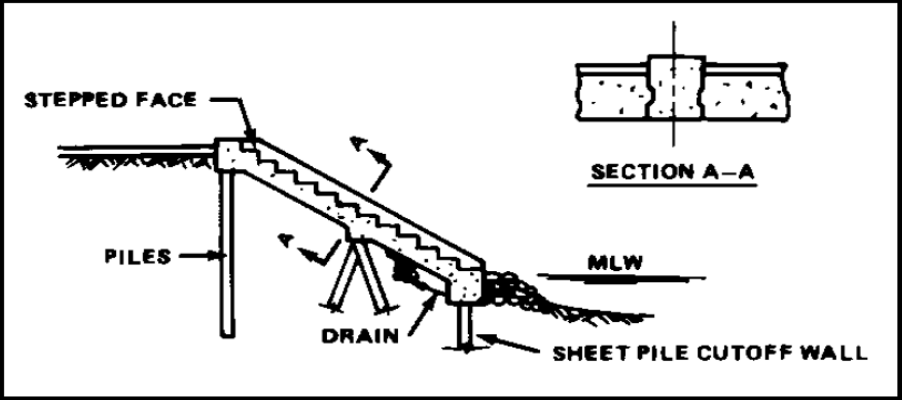
Curved Face Seawalls

The image shows a curved face or (concave) seawall configuration.



Stone Revetment Seawalls

The image shows a stone revetment seawall configuration.



Stepped Face Seawalls

The image shows a stepped face seawall configuration.

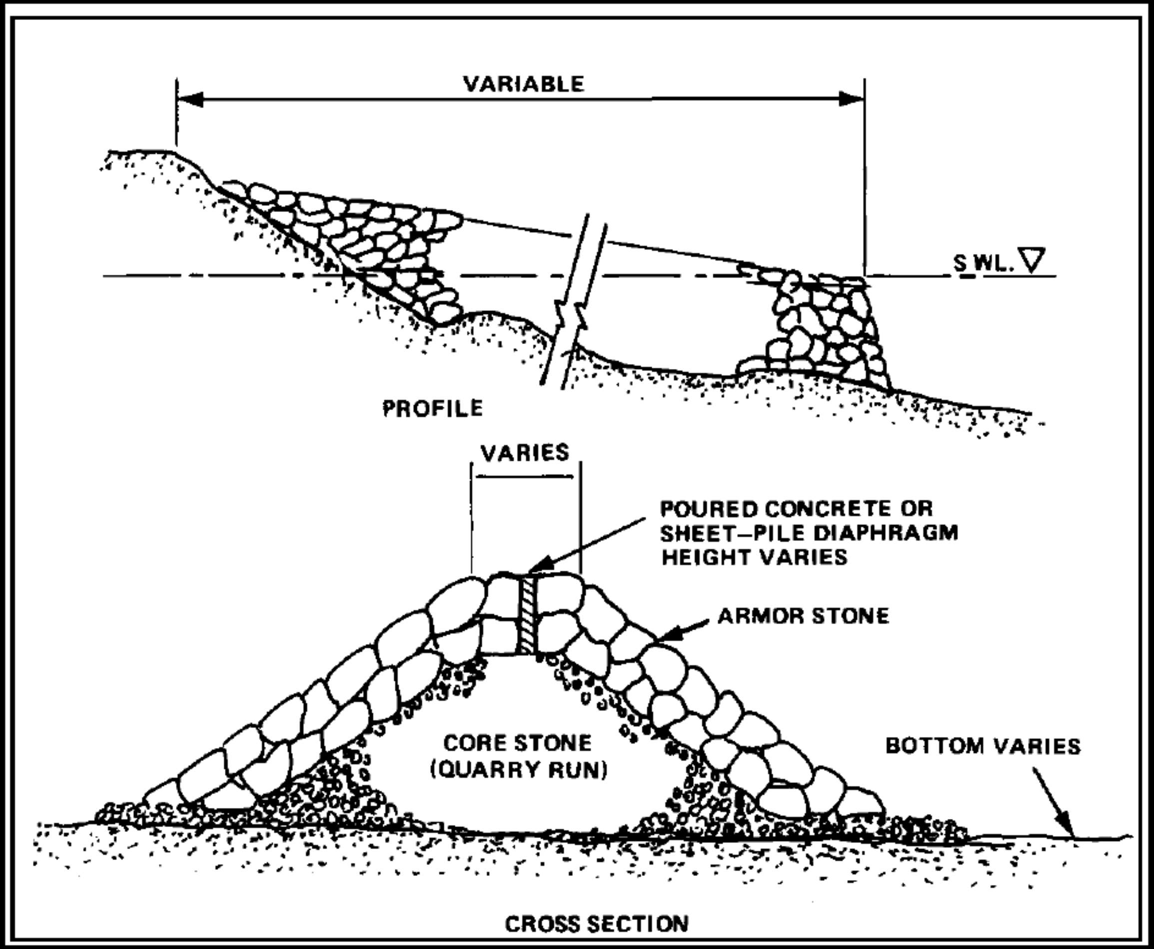
Groins (or Groynes)

Groins are structures designed to control the rate of shifting sand by influencing offshore currents and waves so that erosion of the shoreline is minimized.

The image below, shows an example of a series of groins in Sitges, Catalonia, Spain.

Groins

Groins project outward, perpendicular to the shoreline, and are constructed of large rocks, pre-cast concrete units, reinforced or prestressed concrete piles, steel sheet piles, or timber cribbing filled with rock.



Jetties

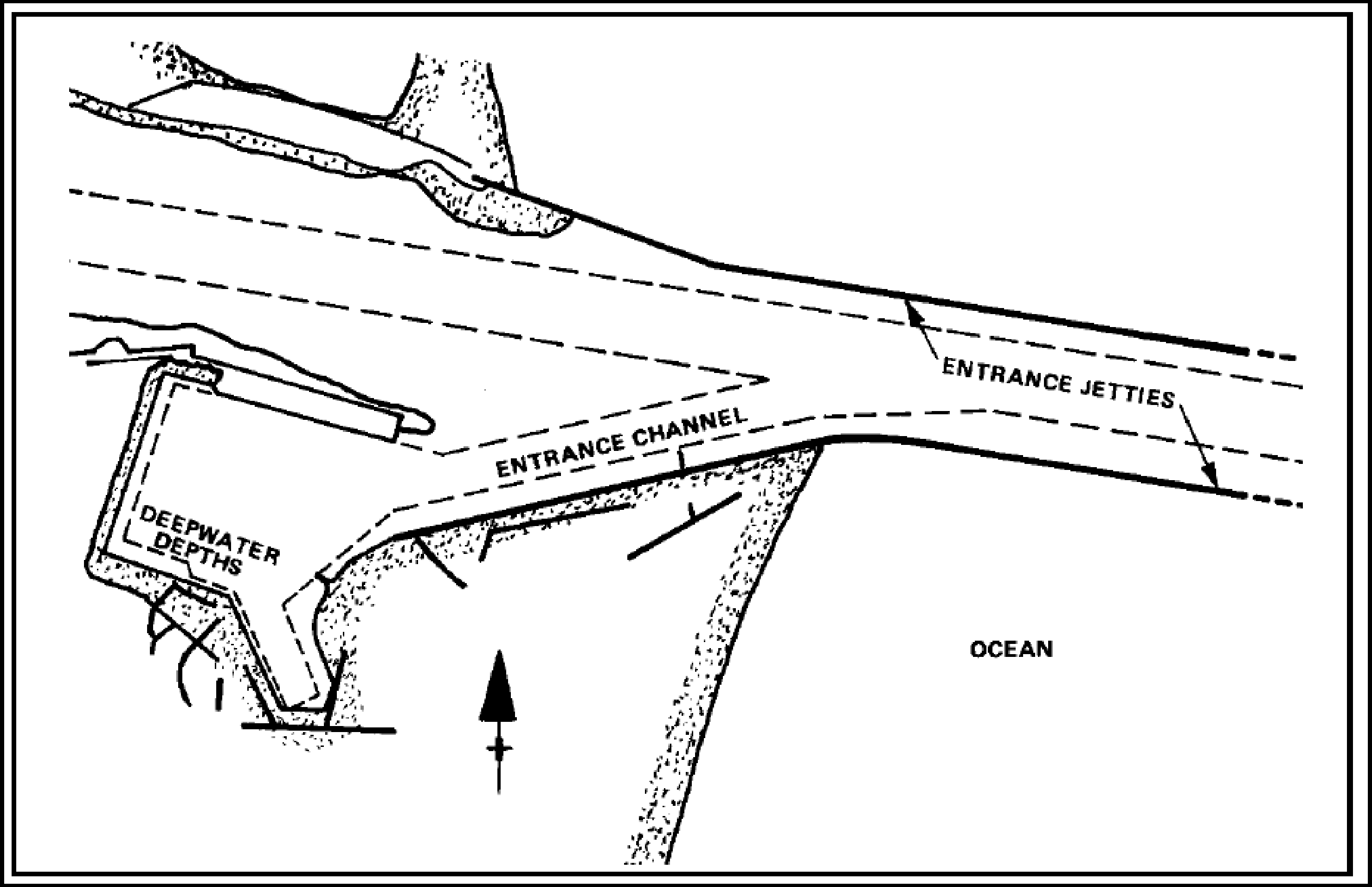
Jetties are structures that extend from the shore into deeper water to prevent the formation of sandbars and to direct and confine the flow of water due to currents and tides.

These structures are normally located at the entrance to a harbor or a river estuary. Jetties are usually constructed of mounds of large rubble about a meter above the high tide mark.

The image shows the position of jetties at the harbor entrance to Humboldt Bay, in northern California.

Wing Dams

A form of jetty, wing dams, are extended out opposite one another, from each bank of a river at intervals, to contract a wide channel and by concentration of the current to produce a deepening.



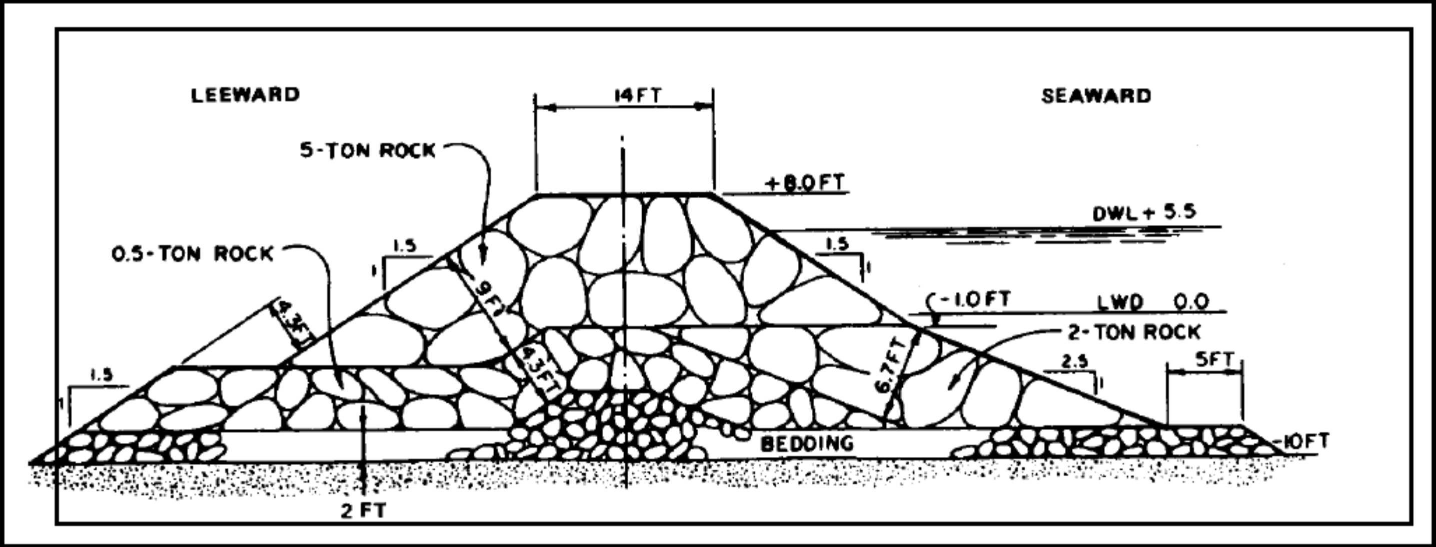
Breakwaters

Breakwaters (see image for cross section) are large rubble-mound structures located outside of a harbor, anchorage, or coastline to protect the inner waters and shoreline from the effects of heavy seas.

These barriers help to ensure safe mooring, operating, loading, or unloading of ships within the harbor. Breakwaters may be connected to the shore or detached from the shore.

The types of breakwaters, depending on the angle of the exposed face, are either:

- Vertical or partially vertical
- Inclined or partially inclined



Chapter 2: Components of Waterfront Facilities

Components

Numerous components of basic facilities are present at the waterfront to aid in port operations. These components are integral parts of piers and wharves.

They include: fender systems, piling, dolphins, deck and mooring hardware, and utility distribution systems.

They may also be offshore systems vital to ship operations, such as mooring systems (see image above).

Fender Systems

Fender systems (image) are used on piers to protect the ship and the pier during berthing operations and while the ship is moored.

The most widely used fender system consists of timber fender piles, timber wales, and chocks, with rubber compression fender units between the system and the pier to absorb berthing impacts.

This type of system is the highest maintenance cost portion of the pier. The trend is toward using longer lasting and more resilient fender systems with less reliance on treated timber because of environmental concerns.

Types of Fenders and their Components

The main types of fenders, and their components, that may be found installed in ports are:

- Fender pile systems
- Fenders (fixed to the pier)
- Resilient, floating pneumatic and foam-filled fenders (connected or suspended from the pier or backed up by closely driven steel or concrete fender piles)

Types of Fenders Systems

Fender pile systems:

- Timber
- Steel
- Concrete
- Composite Piles

Fenders fixed to the Pier

Fenders fixed to the pier come in a variety of shapes and sizes:

- Rubber-in-compression units: cylindrical, rectangular, trapezoidal, wing-type, and D-shaped units.
- Rubber-in-shear fenders: rectangular rubber column and Raykin fender.
- Buckling fender: buckling column fender and cylindrical cell fender.
- Recycled Tires

(Note: “rubber” refers to various elastomeric plastic materials)

Resilient, Floating Pneumatic and Foam-filled Fenders

Resilient, floating pneumatic and foam-filled fenders connected or suspended from the pier or backed up by closely driven steel or concrete fender piles.

Piling

Piling (image) is an integral part of all open piers and wharves.

The exposure of piling makes it susceptible to severe environmental attack from:

- Corrosion
- Marine borers
- Erosion

Piling is made from concrete, wood, steel, or composite materials and requires protective coatings, preservatives, or wraps to ensure a long life.

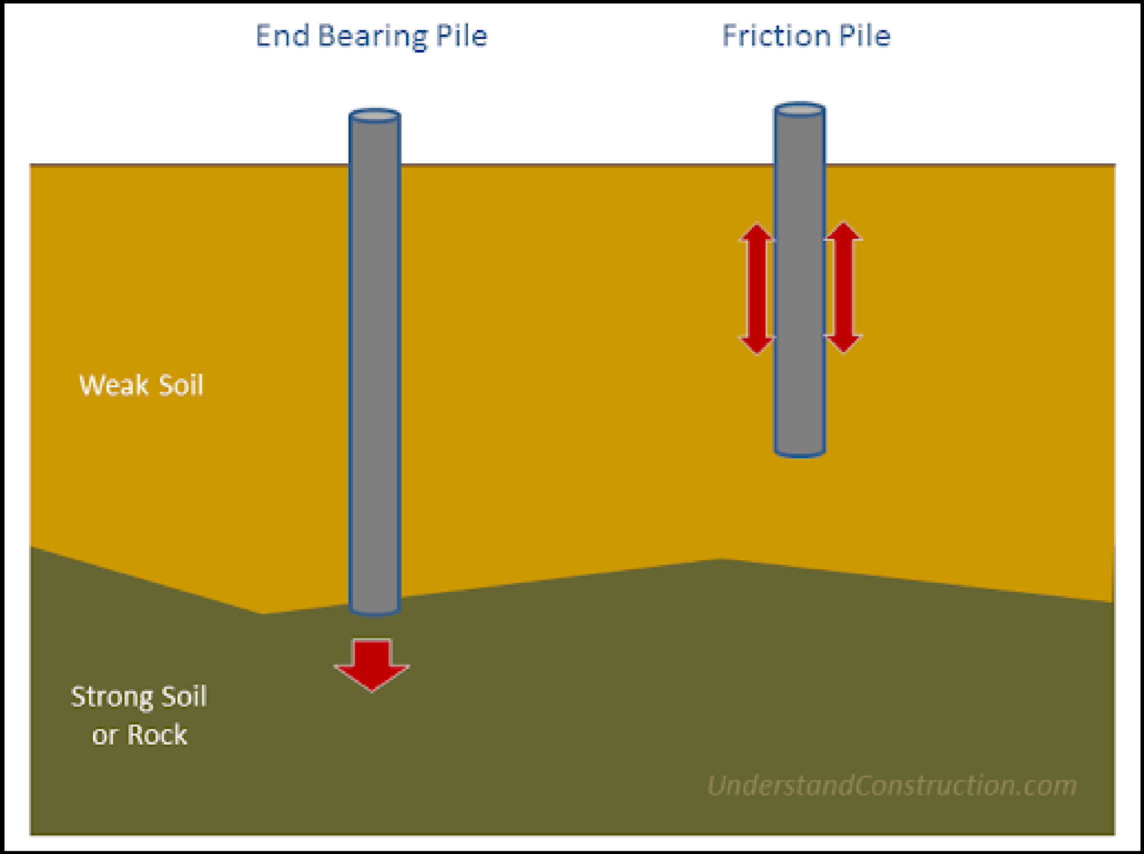
Four Functional Types of Piling

There are four functional types of piling:

- Vertical bearing piles
- Batter piles
- Fender piles
- Sheet piles

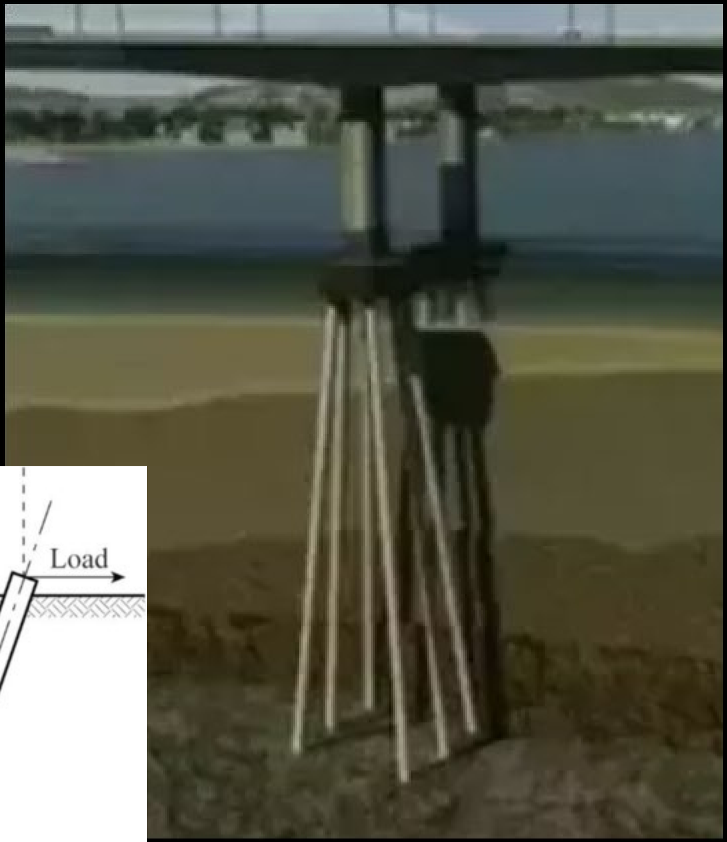
Bearing Piling

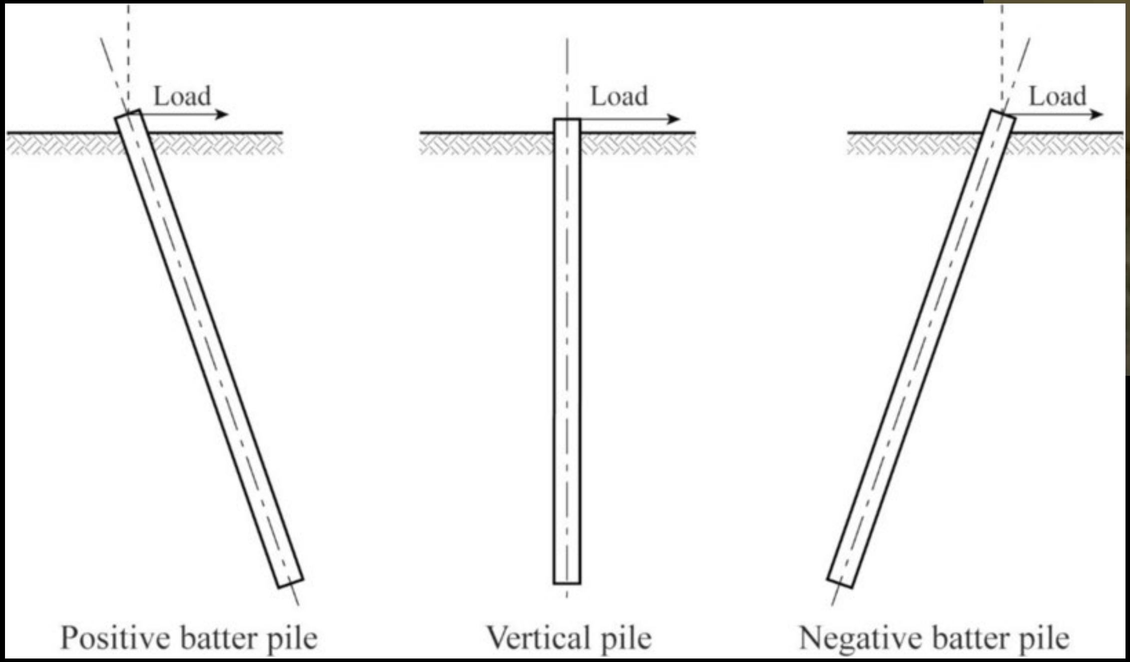
are used to support the weight of the pier and loads on the pier.



Batter Piling

provide lateral and longitudinal stability.





Fender Piling

are used to absorb the impact of berthing ships.

Sheet Piling

is used for various waterfront structures, e.g., quaywalls to retain fill.

Dolphins

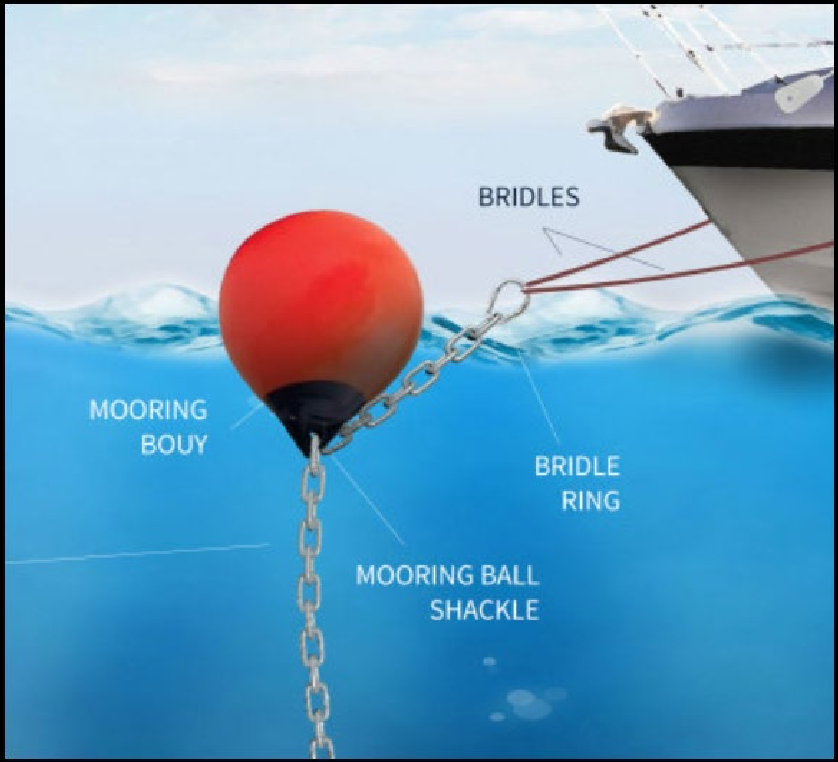
A dolphin (image) is a group of piles placed near piers and wharves, or in turning basins and ship channels.

These structures are used to guide vessels into their moorings, to mark underwater structures (shoals or shore), and to support navigational aids.

Fleet Mooring

A fleet mooring is an offshore anchoring system that consists of various hardware items:

- Chain
- Cable
- Sinkers
- Anchors
- Buoys



The offshore anchoring system is placed in a fixed location so that vessels, when entering the port, can anchor to the buoys.

Deck and Mooring Hardware

Various deck and mooring hardware are used on piers and wharves, such as:

- Gratings
- Handrails
- Bollards (image-left)
- Bitts
- Cleats
- Chocks (image-right)
- Rings

These items require inspection and maintenance to ensure personnel safety and adequate mooring facilities for ships.

Utility Distribution Systems

Utility distribution systems are provided on most piers and wharves to service the ships.

Utilities available at most piers and wharves might include:

- Steam
- Potable water
- Saltwater
- Sewage and oily waste collection
- Compressed air
- Electricity
- Fuel
- Telephone service
- Fire alarm systems

Typically, routine maintenance is required on the following utility system components:

- Conduit
- Piping
- Valves
- Expansion joints
- Drains
- Regulators
- Insulation

Chapter 3: Wood and Timber Components

Wood and Timber Members

Wood and timber members have been used for construction and maintenance of waterfront facilities due to availability, economy, and ease of handling relative to other construction materials.

Common wood products used include:

- Dimension lumber
- Timber
- Piles
- Poles

Engineered wood products such as glued and laminated timbers (glulam) are common and, if, properly preserved or protected, may be used.

Plastics and composites can be used as substitute materials for non-load bearing wood members.

Primary Applications

The primary applications at the waterfront include:

- Older piers, wharves, bulkheads, and quaywalls built from timber piles.
- Fender systems built from timber and round timber piles.
- Pile dolphins built from round timber piles.
- Floats and camels* built from logs, timber, dimension lumber, glued and laminated wood, or miscellaneous forms.
- Groins built from timber and round timber piles.

**(camels are floats which are attached to the sides of ships; see image below)*

Connection Hardware

One critical aspect of timber construction is connection hardware, where typically bolts are used.

Problems observed from hardware misalignment and corrosion are exhibited in terms of:

- "Necking down" of bolt shank
- Distortion/enlargement of washer holes
- Bolt heads popping off or being drawn through the washer

Maintenance

Maintenance of wooden structures involves replacing decayed or damaged wood with properly treated wood or other suitable material.

If repairs are to be reduced in the future, exposed wood and pile caps must be treated with an effective preservative to retain its strength and longevity against destructive fungi, marine organisms, insects, and bacteria attack.

Wood Species are used for Treated Dimension Lumber

Many wood species are used for treated dimension lumber and timber in the US. Primarily, Douglas fir (image on left) is used on the West Coast and Southern Pine (image on right) is used on the East Coast due to availability.

Round timber piles for marine use are also usually made from Douglas Fir or Southern Pine according to availability and size requirements for piling.

All wood products, including treated wood, must be inspected by agencies certified by the American Lumber Standards Committee (ALSC) and must be properly graded and marked before acceptance.

Wood Deterioration

Biological and physical deterioration of wood can bring about rapid destruction of waterfront facilities.

Improper design and construction procedures that lead to biological deterioration include:

- Inadequate preservative treatment
- Improper handling of treated wood
- A design that promotes retention of water
- A design that unnecessarily places wood timbers below water

Wood Deterioration

Major design deficiencies, which promote physical deterioration, include:

- Insufficient strength of piles resulting in overloading (loss of strength and embrittlement caused by treatment with salts and other preservatives are an important design considerations).
- Improper connection hardware or pile connections that restrict load transfer to other parts of the structure.
- Inability of sheet pile walls to retain backfill or insufficient strength in the soil foundation that results in sheet pile movement.

Biological Deterioration

Wood-destroying organisms infest wood structures both above and below the waterline.

Marine borers are the principle cause of deterioration in the immersed zones and are found in harbors and estuaries worldwide.

Marine fouling organisms found on the wood surface do not cause wood deterioration and may even serve to retard marine borer damage.

Insects and fungi are the main wood-destroying organisms above the waterline.

Marine Borers

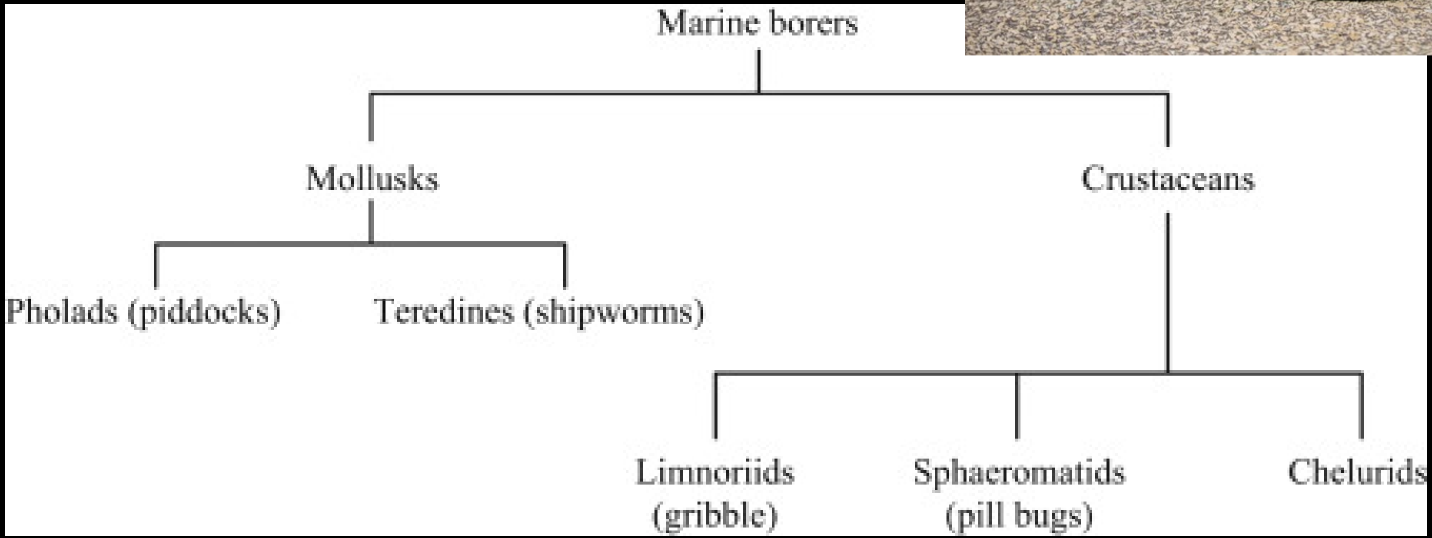
There are two general types of marine borers that attack marine timbers:

Crustaceans

The major wood-boring crustaceans are the Limnorians.

Mollusks

The principle wood-destroying mollusks are the Teredines (Teredo and Bankia) and the Pholads (Martesia).



Marine Borers

Wood-Boring Crustaceans

Three common crustacean wood borers are:

- Limnoria (image is of the Limnoria quadripunctata)
- Sphaeroma
- Chelura

Limnoria is considered to be the most economically important. These borers burrow just below the wood surface forming a network of interlacing tunnels. The weakened wood is easily eroded by wave action often resulting in a characteristic "hourglass" shape.

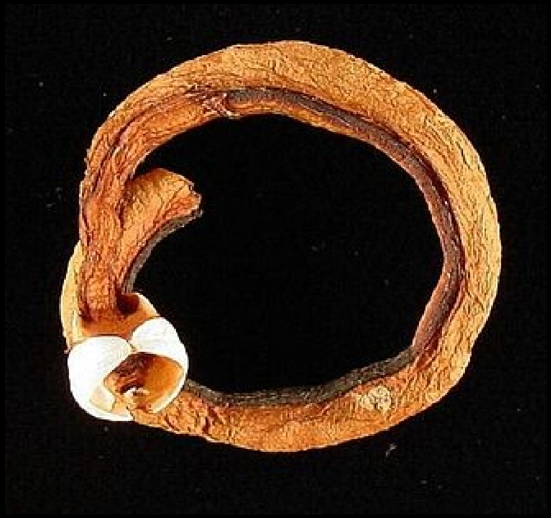
Limnoria tripunctata is of particular importance because it can attack creosoted wood.

Marine Borers (Teredines)

Teredines: Wood-Destroying Mollusks
Teredines are commonly referred to as "shipworms" because of their wormlike appearance (image). Penetration of the wood occurs during the microscopic larval stage.

As the shipworms grow, their tunnels increase in diameter and length while the entrance holes remain about the same size.

Attacked piles may appear sound on the surface, yet be completely riddled.

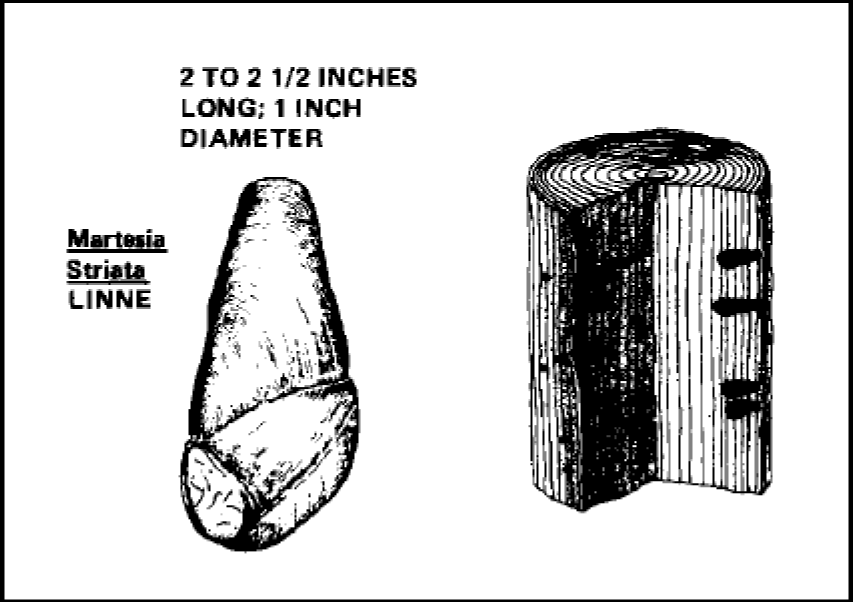


Marine Borers (Pholads)

Pholads: Wood-Destroying Mollusks
Pholads (image) bore into wood, soft rock, or concrete for protection.

These clams have pear-shaped shells that can reach 6 cm in length.

Like the Teredines, Martesia can cause considerable structural damage to wood, but both of these mollusks can be more effectively controlled by creosote preservative treatment than the Limnorians.



Insects

Termites (see image above) are the most destructive wood-destroying insects found on waterfront structures. Other insect pests include: wood-boring beetles, ants, and bees.

An insect frequently associated with damage to piers and docks is the wharf-borer, Nacerda, a beetle about 0.32 inch (8 mm) long, yellowish-brown to dark red in color.

Some insects, such as termites, require wood for food and shelter; others, such as carpenter ants, require wood for nesting only. Most wood-destroying insects thrive under damp conditions.

Fungi

Three categories of wood-decay fungi are:

- White rot, which tends to bleach the affected wood
- Brown rot, often termed "dry rot," which produces a brown, crumbling type of decay (the image below shows an example of wood decay caused by Serpula lacrymans; called true dry rot, which is a type of brown-rot).
- Soft rot, which softens the wood

Slight strength reduction of infected wood can be caused by stain fungi, which produce bluish black to steel gray or brownish discoloration of the wood.

Molds

Molds also produce a discoloration of the wood surface (see image) and are regarded as merely a blemish, but their presence indicates that conditions may be favorable for decay organisms.

Most wood-destroying fungi require damp conditions for growth.

Physical Deterioration

Physical deterioration of timber piles and other wood structures is generally due to the following causes:

Abrasion

Abrasion of timber piles occurs principally in the intertidal zone. The rate at which piles are destroyed by abrasion depends on the amount of floating debris in the harbor, the velocity of water moving past the piles, ice in the harbor, and the action of marine borers. Fender piles are also abraded by camels and ships.

Overload

Overloading of piles may result from a continuous heavy load or infrequent, severe loads. Overloading may be caused by vertical and horizontal loads. Failure of one pile requires the adjacent piling to carry the extra load. Continual overloading can lead to collapse of the entire structure.

Connection Failure

When a timber pile connection fails, the structure is free to move and will eventually fail. If untreated wood is exposed, connection failure may first allow the entry of marine borers if below the waterline, or insects and fungi if above the water line.

Timber Wall Movement

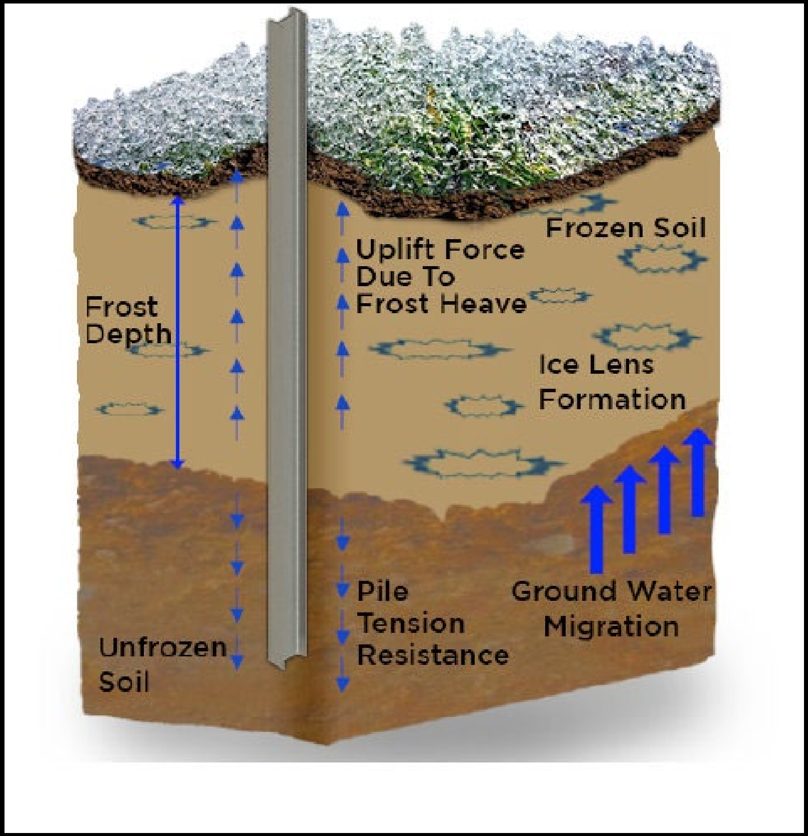
Outward wall movement can result from horizontal loading of the backfill material caused by excessive loading behind the structure or failure of tie-backs.

Timber Wall Movement

Loss of backfill material can result in movement in the opposite direction. If either condition continues, the structure will fail.

Single Timber Piles

Single timber piles or those used in light structures may be lifted by ice freezing to the pile and pulling it as the ice moves with the tide.



Preventive Maintenance for Wood and Timber

The primary preventive maintenance (PM) measure at the waterfront is to select the type of wood best suited for the particular use and to purchase wood products and timber piles that have been treated with quality preservatives and methods.

Field Techniques

should be used to eliminate or minimize cuts and holes made in the members at the site, particularly for those members to be placed below water. If cuts and holes must be made, special field PM preservative treatment is required.

In addition, there are other PM measures applicable to timber piles using encasements and retardants.

The most important field PM for the exposed wood of waterfront buildings and related structures is the application of paint and other coatings.

Pressure Treatment

Pressure treatment of the outer sapwood of timbers with preservatives is the most important and effective method of protecting wood.

Using pressure treatment allows the preservative to uniformly penetrate deeper and allows closer control of retention levels.

The preservative penetrates the wood from .39 to 3.93 inches (1 cm to 10 cm), depending on the type of wood, and provides protection from fungi, marine borers, insects and bacteria.

American Wood Protection Association (AWPA) Standards

These are standards which govern the treatment processes that must be performed on wood used in waterfront areas.

The choice of preservative treatment depends on how and where the wood is to be used.

Wood preservatives are classified in three categories:

- Creosote preservatives
- Oil-borne preservatives
- Water-borne preservative

Creosote

Creosote preservatives have been the most commonly used preservatives at the waterfront because they are not easily leached from the wood and are not corrosive to metals.

Creosote and creosote-coal tar solutions, both derived from bituminous coal, can be used for immersed wood. Creosote is commonly diluted with petroleum oil for treatment of wood not subject to immersion.

The image below shows a bundle of creosote treated posts, used for fencing applications.

Disadvantages of Creosoted Piling

An important disadvantage of creosoted piling, however, is that it is readily attacked by the marine borer, Limnoria tripunctata.

In addition, creosote and creosote solutions cannot be used where it may come in contact with people or where local environmental concerns have restricted its use in the marine environment.

Consult the local environmental office for the latest policies and regulations in regards to its allowed use.

Oil-Borne Preservatives

Oil-borne preservatives are dissolved in a petroleum solvent and include pentachlorophenol, copper naphthenate (image), tributyl tin oxide, and copper-8-quinolinolate.

Oil-borne preservatives are suitable for wood members out of the water for protection against insects and fungi but does not provide adequate protection against marine borers and, thus, cannot be used for immersed wood.

Painting Treated Wood

Treated wood can be painted, does not swell and distort, is easily handled, and will not corrode metal.

Before the solvent evaporates, it is more flammable than untreated wood. Pentachlorophenol is the most effective of these preservatives but is also highly toxic.

Water-Borne Preservatives

Water-borne preservatives are toxic metallic salts dissolved in water for easier application.

Commonly used water-borne preservatives include:

- Chromated copper arsenate (CCA) (see image below, for CCA-treated posts)
- Ammoniacal copper zinc arsenate (ACZA)
- Ammoniacal copper arsenate (ACA)

Wood treated with one of these water-borne preservatives can be used either above or below the waterline (wood used below the waterline is treated at higher retention levels).

Other Water-borne Preservatives

In addition, these salts in combination with creosote (dual treatment) are more effective in preventing marine borer damage than any single treatment.

Other water-borne preservatives for use above the waterline include:

Acid copper chromate (ACC)
Ammoniacal copper citrate (CC)
Ammoniacal copper quat (ACQ)-Type B

Negative Aspects

All preservative treatments have drawbacks that should be considered.

Metallic salts, for example, will seriously embrittle wood. More importantly, these toxic chemicals present environmental and personnel safety concerns.

All treated wood should be supplied with a Consumer Information Sheet that provides use, handling, and disposal precautions. Proper safety procedures should be carefully followed.

Disposal of Treated Wood

Plans for handling pressure-treated wood removed from service should be carefully considered, especially in areas where the disposal of treated wood may be restricted.

Alternatives to landfilling include reuse as landscape timbers, recycled as fuel, etc. Wood treated with CCA should never be used as a fuel, and treated wood should not be recycled as mulch. Other restrictions may apply.

Field Treating Exposed Areas of Wood Before Installation

Cut surfaces of wood members, pile cutoffs, bolt holes, and any other exposed surfaces of treated wood members must be treated in the field before installation.

All exposed, untreated wood should be treated in accordance with the:

> **American Wood Protection Association, Standard U1 -**
> Use Category System: User Specification for Treated Wood

Treatment of Bolt Holes

Treat holes for bolts and wood plugs inserted in piles and timbers with the same general type of wood preservative originally used for the member.

Bolt holes should be treated under pressure with a mechanical bolt hole treater, if available, or thoroughly saturated.

Wood preservatives are restricted-use pesticides and must be applied in compliance with applicable standards.

Field Treating of Piles

Pile Tops

Timber pile tops, cut off after the pile is driven, expose the untreated heartwood of the pile to rapid decay. AWPA Standard U1 provides recommendations for preservative treatments for pile tops.

Creosoted Piles

may be field treated with creosote solutions, or where particularly heavy coatings are required, a coal-tar roof cement meeting ASTM D4022/D4022M, Specification for Coal Tar Roof Cement, Asbestos Containing.

Piles treated with ACA, ACZA, or CCA

can be field treated with any of the water-borne preservatives.

After Field Treatment

the pile top must be covered with a cap or bonnet consisting of two layers of tar saturated fabric, tar paper, or fiberglass cloth, which shall overlap the side of the pile at least 2 inch (5 cm) and securely fastened.

Remedial Treatment of Wood

There are a variety of different types of remedial wood treatments available.

These include:

- Fumigants
- Brush On
- Liquid Internal
- Solid Rod
- Encasements and Retardants

Fumigants (Pesticides and Preservatives)

Fumigants are used to prevent or eradicate fungal decay of large (6 by 6 inch (15 by 15 cm) or greater cross-sectional area) wood members.

These products may be an available option in your area for waterfront structures.

They are highly toxic, restricted use pesticides, and can be handled only by certified personnel.

The most widely available product currently available is applied only by the manufacturer. Generally, an inspection of the prospective treatment site and a treatment plan is carried out by the contractor prior to actual treatments.

Consult your environmental and safety offices before using these products.

Brush On Preservatives

Brush on preservative pastes and bandages are commonly used as a remedial groundline treatment for southern pine utility poles. They may have some application to waterfront timbers.

Diffusion of the preservative ingredients into the decayed portion of the wood depends on the moisture in the wood. Typically, the level of preservative penetration and long-term efficacy of these products is less than that of fumigants.

Liquid Internal

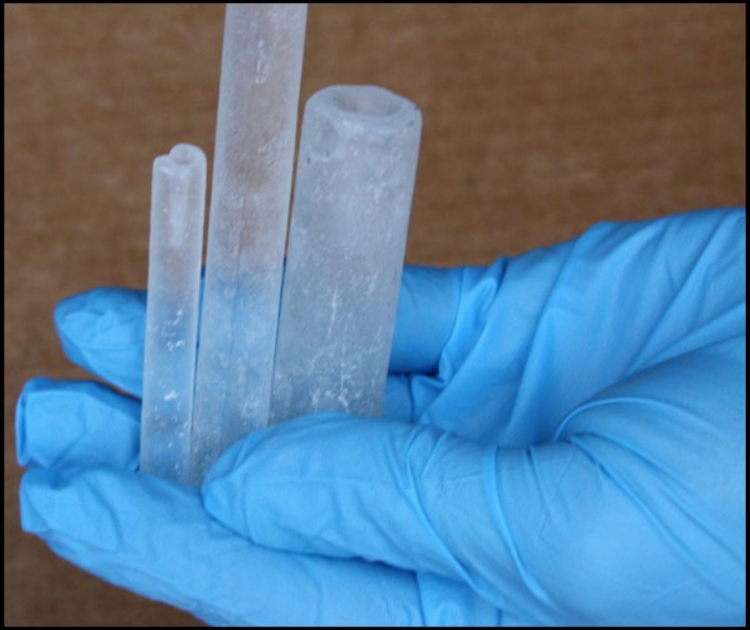
Liquid internal treatments are sometimes used when voids and cavities are present in wood.

This treatment is not generally recommended for waterfront timbers. If voids and cavities are present, replacing the wood member is advisable.

Solid Rod

Solid rod treatments commercially available today are fused borate rods available in a variety of sizes. They are relatively easy and safe to handle.

Like brush on pastes and preservative bandages, diffusion of the borate in these rods depends on wood moisture and the level of preservative penetration and long-term efficacy of these products is less than that of fumigants.



Encasements and Retardants

Two methods are available to protect timber pile tops by using encasements and retardants, which include:

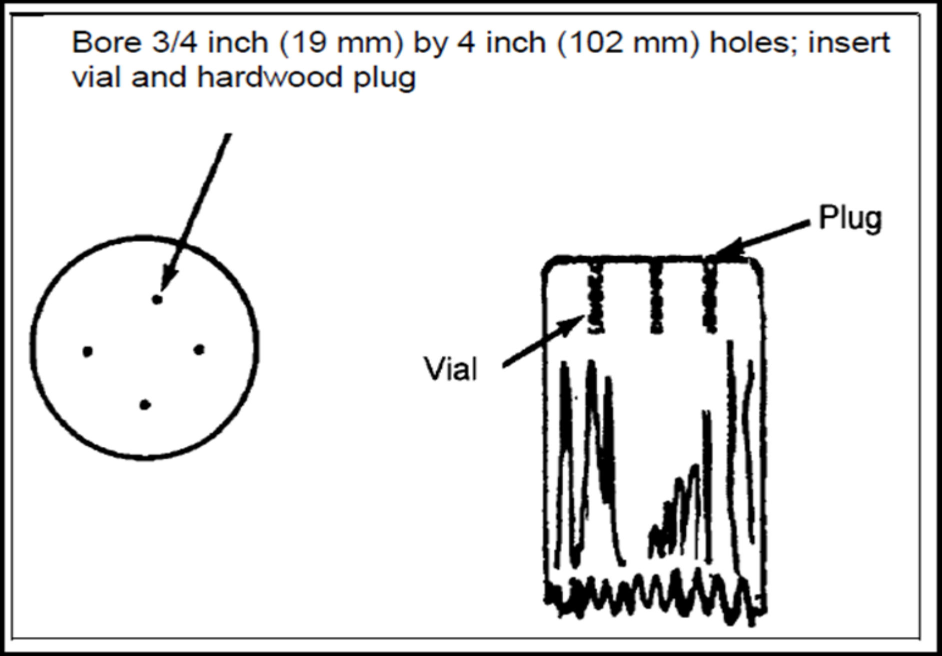
- Remedial Treatment with Fumigant Vials
- Pile Top Bonnet

Also pile caps (coned cap shown in image) can be used to protect the top of a timber pile.

Remedial Treatment with Fumigant Vials

Commercial fumigant vials are embedded in the cut top of timber piles and slowly leach into the pile to retard and prevent rot. Holes are bored in the top of the pile, vials inserted, and the holes plugged with hardwood (image).

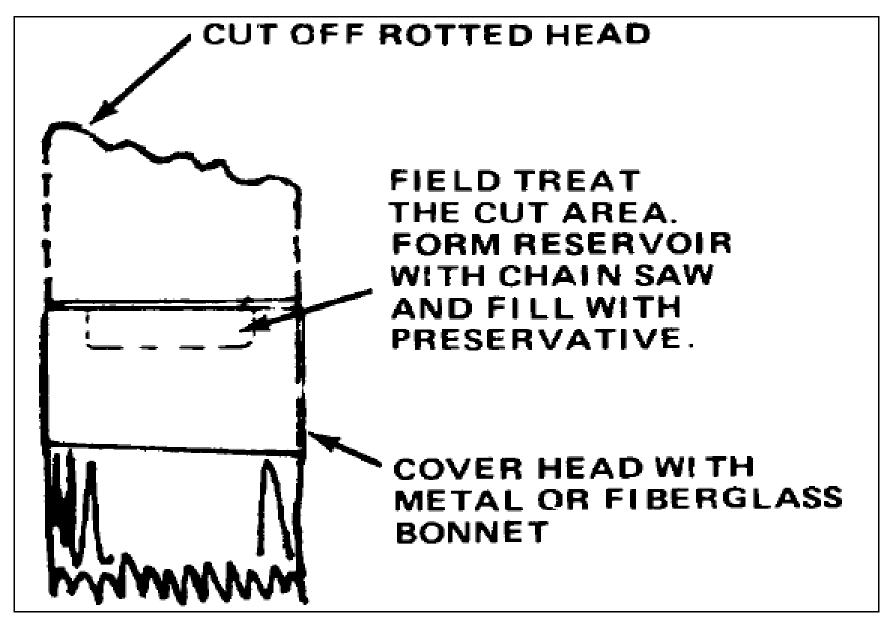
A pile cap can be after fumigants are applied. This method is useful where the pile top is accessible and subject to wetting by rain or spray. These are restricted use pesticides; application of fumigants over water is restricted in California and other areas. Consult your environmental or safety office before using.



Pile Top Bonnet

This method uses liquid preservative in the pile top and a protective bonnet or cap fabricated of two layers of tar saturated fabric or tar paper or fiberglass. Formation of a reservoir is optional.

This method can be used to repair a rotted pile top, as shown in the image below, or as a preventive measure on a sound pile.



Coatings for Wood Buildings

Surface preparation of either previously coated wood or uncoated wood may consist of the following procedures:

- 100% removal of biological growth
- Removal of unsound coatings
- Removal of surface contamination such as oil, grease, dirt
- Light sanding of sound coatings and exposed wood

Two Coating System

This may be used for either previously coated wood or uncoated wood as follows:

- 40% volume solids, exterior latex (water-based): 1 or 2 coats at 1.97 to 5.9 mils (0.05 to 0.15 mm) dry film thickness (DFT)
- 55% volume solids, flexible acrylic waterborne (water-based): 1 or 2 coats at 3.94 to 11.81 mils (0.1 to 0.3 mm) DFT.

Wooden structures continuously immersed in seawater or those which are subject to immersion during tidal changes are not usually painted except for marking identification or location.

In general, coating wood is confined to structures such as buildings located in waterfront areas to protect the wood from weathering and for appearance.

Protection of Timber Piles

All timber piling in the marine environment, including piling properly treated, are eventually attacked by wood destroying organisms. Pilings are also commonly subjected to ice lift and abrasion.

As a result, protection with plastic wraps is often required, in order to minimize the impact of these environmental factors.

In tropical environments, such as Puerto Rico, even dual-treated pilling should be wrapped.

Plastic Timber Pile Wraps

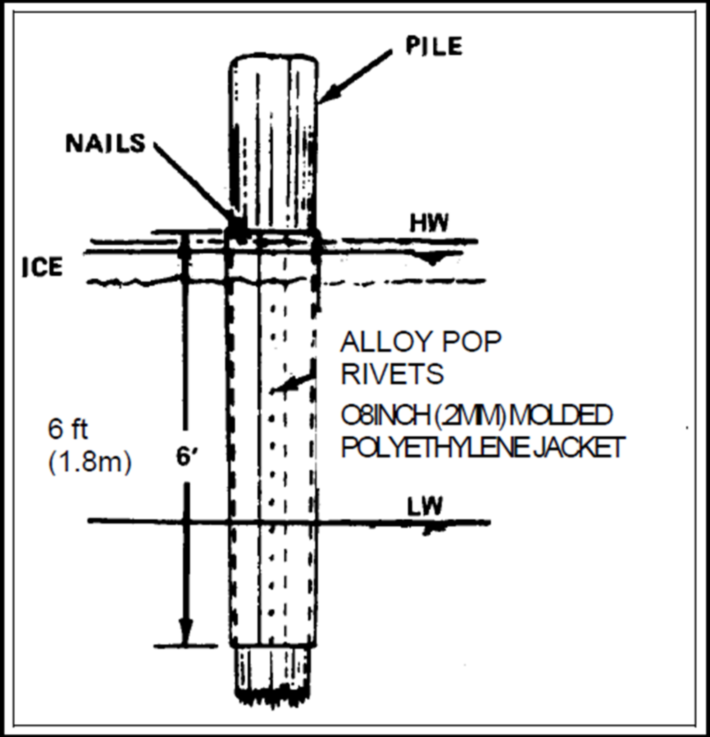
The use of plastic wrapping to protect piling against marine borer damage, at and below the waterline, does offer considerable economic benefit by effectively eliminating borer damage, reducing future repair costs.

The polyvinyl chloride (PVC) or polyethylene wrapping smothers borers already in the wood and prevents the entry of more borers.

Fender piles pre-wrapped with a thick, heat-shrink polyethylene provides a slippery surface that prevents exposure of untreated wood due to wear from camels.

Use of Pile Jackets for Protection

These are designed for to strengthen and extend the life span of timber, concrete and steel piles. They provide a quick and economical solution to repairing deteriorated pilings. The images to the left are jackets made of nylon (top) and fiberglass (bottom).



Chapter 4: Reinforced Concrete Components

Reinforced Concrete

Reinforced concrete is the predominant construction material for waterfront facilities due to its durability, strength, and economy as a bulk construction material.

Steel and wood do not have the bulk properties and adaptability of concrete. In addition, basic components to make reinforced concrete are readily available at most locations.

Applications of reinforced concrete

Applications of reinforced concrete at the waterfront include:

- Seawalls, bulkheads (quaywalls), and revetments.
- Piers and wharves
- Groins
- Breakwaters
- Submerged structures
- Floating structures
- Drydocks

Seawalls, Bulkheads (Quaywalls), and Revetments

Seawalls, bulkheads (quaywalls), and revetments use reinforced concrete as the dominant material of construction.

It is used as the facing material to absorb wave impact, retain fill, and reduce the erosive effects of wave action. Concrete is used in piles, curved-faces, sheet piling, and other forms.

Piers and Wharves

Piers and wharves are usually built with reinforced concrete. Concrete is also used to protect wood or steel from corrosion, weathering, fungal decay, or marine organism attack. Prestressed concrete fender piles are effective and long lasting.

Groins

Groins are built from concrete sheet piles and panels. The piles or panels are usually prestressed units and are tied in place with a concrete cap. The image below shows a series of prefabricated concrete groins.

Breakwaters

Breakwaters use various shapes of precast concrete.

Submerged Structures

Submerged structures use reinforced concrete that are cast in place or precast and used to support pilings and structures.

Floating Structures

Floating structures use reinforced concrete for pontoons, quays, wharves, piers, and facilities for small boats.

Drydocks

Drydocks are made of reinforced concrete.

Deterioration

Deterioration of reinforced concrete near or in seawater is due to corrosion of the reinforcement.

This corrosion can be accelerated due to improper concrete mix, insufficient concrete cover (thickness of concrete over the reinforcing steel), improper curing, operational loads, chemical attack, and volume changes.

Using well established mix designs and construction practices, however, will enhance reinforced concrete durability.

ACI-318 Standard – Code for Structural Concrete

Reinforced concrete in waterfront facilities must meet the criteria set by the American Concrete Institute (ACI) Standard 318, Building Code Requirements for Structural Concrete. This standard covers the building code requirements for concrete with and without reinforcing.

Components of Concrete

Concrete is a mixture of Portland cement, coarse and fine aggregate, and water.

Various admixtures, and pozzolans may be used to improve the strength, workability, and service life.

Preparation and proportioning of concrete mixtures should follow the recommendations of the:

Portland Cement Association's (“Principles of Quality Concrete “)

and

ACI 211 (Recommended Practice for Selecting Proportions for Concrete)

Portland Cement

Five types of Portland cement are described in ASTM C150 / C150M, Standard Specification for Portland Cement.

For concrete structures exposed to seawater, Types II and V should be used. Type II is a sulfate-resisting cement. Type V, however, is no longer being produced.

Low alkali cements should be used with potentially reactive aggregates.

Do not use any product containing sodium or calcium, as it will likely accelerate the onset of rebar corrosion.

Aggregates

Aggregates are used in concrete mixtures to improve durability and reduce costs. They usually make up 60 to 80 percent of the volume of the concrete. The shape and size of the aggregate should meet the requirements specified in ASTM C330/C330M.

Aggregates are a mixture of sand and rock.

Marine aggregates, such as coral, should not be used. However, if marine aggregate is the only available material, it must be washed thoroughly with freshwater to remove the salt.

Aggregates

In some applications, special aggregates may be used to make lightweight concrete for lightweight structures.

Most lightweight concretes have a density between 79.9 and 109.87 pounds/cubic foot (1,280 and 1,760 kg/m3) compared to 149.83 pounds/cubic foot (2,400 kg/m3) for normal weight concrete.

Lightweight aggregate concrete is generally more durable in the marine environment than concrete made with normal weight aggregate.

Water

Water quantity and quality will affect the durability, strength, and workability of concrete. In practice, use water which is equal in quality to that of drinking water.

The ratio of water to cement has a direct effect on the strength of the concrete and its permeability.

A maximum water-to-cement ratio of 0.40 by weight is crucial for concrete used in a marine environment.

Seawater should never be used for making concrete because the salts will dramatically increase the corrosion rate of reinforcing steel.

Admixtures

A variety of chemical admixtures are incorporated into the mix, to give specific properties to the concrete to improve durability, finishability or workability.

If admixtures are required, they should meet the appropriate ASTM or ACI specifications.

Water Reducing

Water-reducing admixtures are available to allow a reduction in the water-to-cement ratio while maintaining a workable slump.

Normal range water reducers and superplasticizers are admixtures that permit the reduction of the water-to-cement ratio.

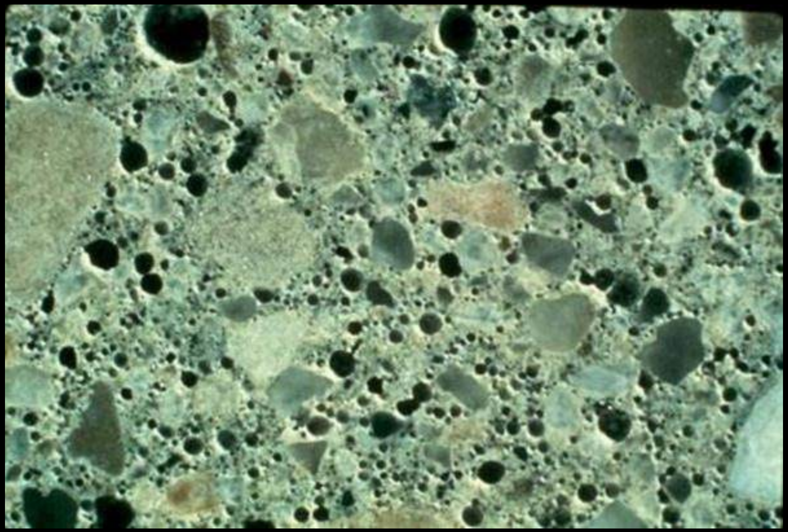
Air-Entraining

Air-entraining admixtures are available to improve the concrete's ability to resist freeze-thaw conditions and enhance workability.

Air-entraining agents should be used to incorporate from 5 to 7 percent of entrained air into the concrete.

ASTM C233 / C233M, Test Method for Air Entraining Admixtures for Concrete, covers the air-entraining agents.

Air-entraining agents also improve the workability of the concrete.



Accelerator

Accelerator admixtures are available for rapid setting products.

These increase the early strength of concrete but have little effect on the final strength.

Accelerators containing excessive chloride should not be used since they increase corrosion of reinforcing steel.

Pozzolan Minerals

Pozzolan minerals (fly ash Class F) are highly recommended as a replacement of 25% of the Portland cement.

The ash reduces permeability, eliminates alkali-silicon reactions, and improves workability.

Silica fume can reduce permeability but may cause finishing problems and surface cracks.

Avoid silica fume dosages about 5% by weight to concrete.

Reinforcing Steel

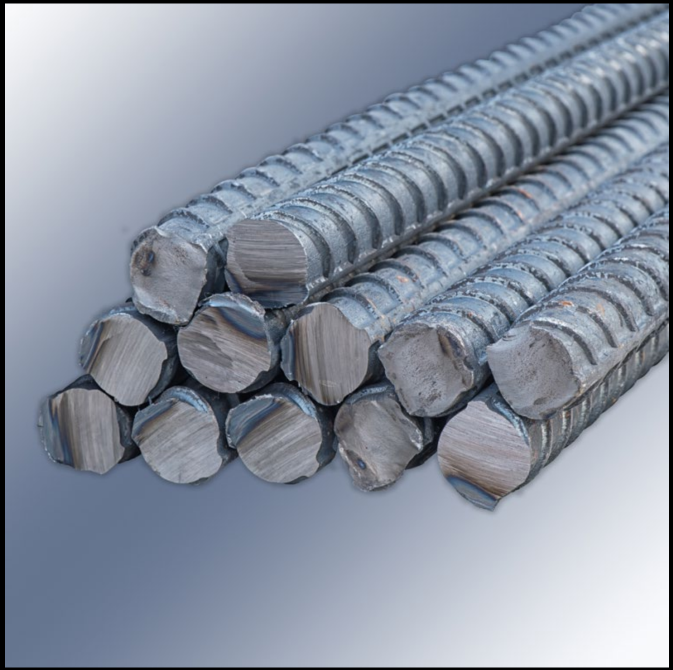
Reinforcing steel for concrete in waterfront facilities is the same as for conventional concrete structures.

It's use should conform to:

ASTM A615
Specification for Deformed and Plain Carbon Steel Bars for Concrete Reinforcement.

or

ASTM A996/A996M
Specification for Rail-Steel and Axle-Steel Deformed Bars for Concrete Reinforcement.



Special Types of Concrete Mixtures

Special concrete mixtures include polymer concrete and polymer-Portland cement concrete.

Concrete mixtures containing polymers are useful for repairing concrete and may provide improvements over conventional concrete mixtures when used and applied correctly.

Polymer Concrete Mix

Polymer concrete does not contain Portland cement.

Epoxy concrete is one common type of polymer concrete that is readily available and possesses excellent bond and tensile strength qualities.

Use extreme caution when using polymer concretes for structures subject to thermal resistance due to a high coefficient of thermal expansion that often results in repair failure.

Fiber Reinforced Concrete Mix

Fiber reinforcements may improve the tensile strength, toughness, and ductility of concrete.

In general, steel fibers (image) should not be used in the marine environment. Polypropylene fibers avoid the corrosion problem of steel fibers and improve impact resistance.

Fiber should not be considered as a replacement for the reinforcement.

Causes of Concrete Deterioration

Cracking and spalling of concrete are the results of:

- Chemical Attack
- Rebar Corrosion

Chemical Attack

The most common chemical attack is from sulfates in seawater that cause a softening of cement paste.

Other causes of chemical attack are poor quality aggregates reacting with alkali in the cement (alkali-aggregate reaction). The alkali-aggregate reaction expands the aggregate and results in cracking throughout the concrete in the presence of moisture.

Use of 25% Class F fly ash (image) is extremely effective in reducing chemical attack.

Corrosion of Reinforcing Steel

The high alkalinity of cement paste protects steel from corrosion.

With improper mix designs, chloride contamination and carbonation eventually reduce the alkali film around the steel. Corrosion will then occur if sufficient moisture and oxygen are present (image).

In the splash zone, the wet and dry cycles provide conditions for the chloride and oxygen to corrode the steel. Accordingly, steel corrosion in concrete is most severe directly above the mean low water (MLW).

When steel corrodes, the rust product increases in volume many times over its original volume. Expansion of the rust causes cracking of the concrete. These cracks run parallel to the reinforcement. Eventually, concrete covering the reinforcing steel spalls off.

Cracking of Concrete

As concrete dries it shrinks, which in turn, can cause cracks. These cracks may increase in size as the internal water is lost over time and the concrete cannot contract freely.

Temperature changes can also cause cracking.

In addition, freezing water in the concrete can lead to deterioration, cracking, and spalling. Overload conditions can cause cracks. Waterfront structures are subject to settlement conditions. When settlement is uneven, cracks usually result.

Cracking of Concrete

Shrinkage cracking can be minimized by proper curing and using a minimum amount of cement and water in the mix.

Temperature cracking can be controlled in concrete by using expansion joints and temperature reinforcement.

Air entrainment is critical to minimize freeze-thaw damage.

Prevention and control of cracking may be improved by proper design of the concrete structure and measures taken during construction.

Preventive Maintenance for Concrete

Measures to minimize deterioration of reinforced concrete must be taken during design of the structure and during construction.

Proper design for concrete is contained in ACI standards and service design manuals.

The main objectives of preventive maintenance are to:

- Keep water out of the concrete
- Protect the reinforcing steel
- Prevent and control cracking
- Prevent chemical actions

The primary PM measure that should be considered for existing reinforced concrete structures is the application of a surface coating.

Coatings should be reapplied periodically to concrete that was coated when new.

This measure can be applied to old concrete but rebar corrosion, the principal cause of concrete deterioration and the reason these PM measure are applied, will not likely be inhibited.

Surface Coatings for Concrete Waterfront Structures

Sound concrete piles and other waterfront concrete structures are generally left uncoated and provide years of excellent service.

Existing concrete structures, above the splash zone, however, may be successfully coated for aesthetics, for marking purposes, and for protection against wind driven rain and sand, and salt spray.

The application of a coating over a penetrating sealer is not recommended because the sealer reduces the bond strength of the coating to the concrete.

Surface Coatings for Concrete Waterfront Structures

It is both difficult and labor intensive to coat immersed concrete and concrete in the splash zone.

These areas require using either cofferdams or divers to apply “splash zone mastics,” high performance coatings that cure underwater, and other specialty coatings.

The benefit of applying these coatings, however, may not warrant the high cost.

Coatings for Deck Marking

For use in identifying walkways and traffic lines, the following marking paints may be applied to clean/dry concrete decks.

- 54% volume solids, solvent-based, chlorinated rubber: 1 coat at 7.87 to 9.84 mils (0.2 to 0.25 mm) DFT
- 50% volume solids, solvent-based alkyd: 1 coat at 7.87 to 9.84 mils (0.2 to 0.25mm) DFT
- 60% volume solids, waterborne acrylic (water-based): 1 coat at 7.87 to 9.84 mils (0.2 to 0.25mm) DFT

Other Coatings

Concrete buildings above the splash zone may be coated for aesthetics and protection against wind driven rain.

Surface preparation of concrete surfaces may consist of the following sequential procedures:

- 100% removal of biological growth
- Removal of unsound coatings
- Removal of surface contamination such as oil, grease, dirt, and efflorescence
- Removal of weak surface cement (laitance)
- Removal of surface chloride contamination
- Brush-off blasting of sound coatings
- Light abrasive blasting of uncoated concrete

Other Coatings

The below acrylic system may be used as an overcoat for sound coating systems whereas all three systems are acceptable for use on uncoated concrete.

- 55% volume solids, flexible acrylic waterborne (water-based): 1-2 coats at 3.94 to 15.75 mils (0.1 to 0.4 mm) DFT
- Two-component, epoxy polyamide primer followed by two coats of a flexible acrylic topcoat: 3 coats at 19.67 mils (0.5 mm) total DFT (5.9 mils (0.15 mm) primer, 7.87 mils (0.2 mm) topcoat
- Two-component, epoxy polyamide primer followed by two coats of a two-component, aliphatic urethane topcoat: 3 coats at 9.84 mils (0.25 mm) total DFT (5.9 mils (0.15 mm) primer, 3.94 mils (0.1 mm) topcoat, 3.94 mils (0.1 mm) topcoat)

Treatment of Cracks

Cracks in concrete are typically caused by shrinkage during curing, thermal expansion and contraction, rebar corrosion, operational loading, or structure settlement.

Cracks are routed out and repaired using a flexible elastomer over bond-breaker tape.

Hairline cracks may be repaired by pressure injecting polyurethane or methyl methacrylate through injection ports.

Chapter 5: Steel Components

Steel

Steel is used extensively in construction and repair of water-front facilities due to availability, cost, ease of fabrication, physical and mechanical properties, and design experience.

Structural steel and cast or fabricated steel are used in all areas of the waterfront.

Applications of Steel

Typical applications include:

- Piers and wharves use steel H-piles or pipe piles to support or brace the structure. Structural steel shapes are used for framing.
- Bulkheads and quaywalls use interlocking steel sheet piling with tie rods and wales. Steel sheet piling is used to retain fill.
- Fender systems incorporate steel H-piles.
- Mooring hardware such as cleats, bollards, bitts, and chocks are made from cast or fabricated steel.
- Other items such as utility lines, grating, opening frames, manhole covers, fences, bolts and nuts, handrails, and concrete reinforcement are made of steel.
- Steel components are used in some camels.

Maintenance of Steel

Maintenance of steel structures and components will entail repair or replacement of damaged or corroded steel, periodic coating of steel surfaces for corrosion protection, and maintenance of cathodic protection systems.

Although physical damage from impact or loading may occur, corrosion is the major cause of the deterioration of steel structures.

Material Selection

The extent or severity of corrosion will vary with the exposure zone of the material; that is, whether it is in the atmospheric zone, the splash or tidal zone, or the submerged zone. The selection of materials for waterfront use must consider each of these varied conditions.

Additionally, instances of failure of steel structures, i.e. sheet pile bulkheads with interior wales resulting from galvanic incompatibility have occurred. Consult NFESC metallurgist for proper selection of materials.

The use of steel should follow design guidelines in the American Institute of Steel Construction’s Manual of Steel Construction.

The material specifications of ASTM and other organizations document chemical and physical characteristics of the various types of steel. Material selection and procurement should conform to these specifications.

Steel for Waterfront Construction

Carbon steel and carbon steel alloys are the most important types of metals used for construction of waterfront facilities.

In general, only low carbon steels with a carbon content less than 0.35 percent by weight are used due to welding characteristics.

Carbon Steel

Carbon steel is an alloy of iron and carbon with a carbon content less than 2 percent.

The requirements for structural carbon steel are contained in:

ASTM A36/A36M

This grade is suitable for welding.

Carbon steel will corrode in all exposure zones, but the most severe corrosion occurs in the splash zone and just below the MLW (mean low water) boundary.

Coatings and cathodic protection are necessary to prevent excessive corrosion of steel in the waterfront environment.

Low-Alloy Carbon Steels

Corrosion resistant, low-alloy carbon steel may be used instead of carbon steel if greater corrosion resistance is required.

Low-alloy carbon steels contain small amounts of other elements such as copper, chromium, nickel, molybdenum, silicon, and manganese. Up to 1.5 percent of these elements is added for increased strength or heat treatment capability.

These alloys have a better resistance to corrosion because the rust does not easily break away from the metal surface.

Specifications for Low-Alloy Carbon Steels

ASTM Specifications for common low-alloy steels include:

ASTM A690/A690M
Specification for High-Strength Low-Alloy Nickel, Copper, Phosphorus Steel H-Piles and Sheet Piling with Atmospheric Corrosion Resistance for Use in Marine Environments (also called "Mariner steel").

ASTM A572/A572M
Specification for High-Strength, Low-Alloy Columbium-Vanadium Structural Steel.

ASTM A242/A242M
Specification for High-Strength, Low-Alloy Structural Steel.

ASTM A690/A690M
Steel conforming to this specification is recommended for steel H-piles and sheet piling, because of its greater corrosion resistance over plain carbon steel in the splash zone.

Coated, Cathodic Protected, or Composite Steels (for Submerged Use)

The previously mentioned low-alloy steels offer no more resistance to corrosion than ordinary carbon steel, when submerged. Under submerged conditions, the low-alloy steels require coatings or cathodic protection, or both. Coatings for, and cathodic protection of, low-alloy steels are the same as for plain carbon .

ASTM A690/A690M and ASTM A36/A36M
(Specifications for Carbon Structural Steel)
Composite piles made from these 2 steel types may be used when more resistance in the splash zone is required.

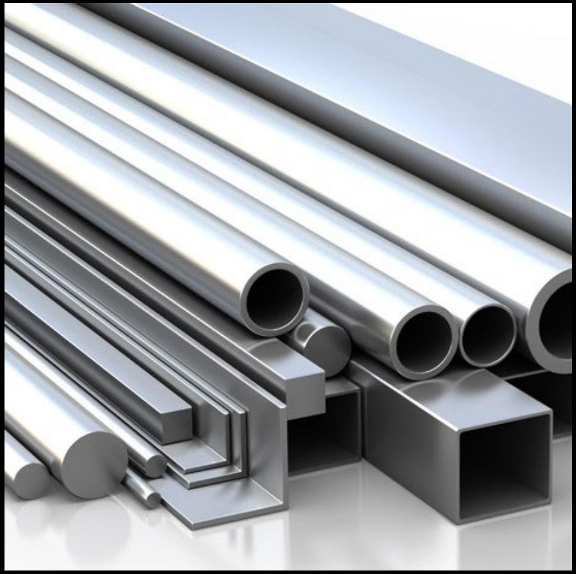
ASTM A242/A242M
Steels which are specified here, are not recommended for buried structures, submerged conditions, and marine atmospheres unless they are exposed to the wind, rain, and sun.

Stainless Steels

Stainless steels have application in the marine environment under certain conditions. They do well when exposed to wind, rain, sun, or high-velocity conditions in seawater.

In calm or stagnant waters, salt spray zones, or in buried conditions, corrosion is likely to occur. Stainless steels in the 300 series (302, 304, 316) are substantially more corrosion resistant than the 400 series stainless steels.

Except in certain atmospheric environments, stainless steels should only be used for specialized applications where performance experience has been superior to more commonly used materials to justify the high cost.



Deterioration of Steel

Although exposure to the atmosphere, severe temperature changes, and wind erosion all contribute to the deterioration of steel in waterfront facilities, exposure to saltwater is the major concern.

Corrosion rates of metals exposed to seawater are much higher than those of similar metals exposed to freshwater.

Biological fouling, (image) the growth of marine organisms on the steel, also contributes to increased corrosion.

This type of fouling can be decreased by using antifouling coatings.

Major Causes of Deterioration of Steel

Other major causes of deterioration are:

- Wave and current effects
- Abrasion from objects
- Elements in the seawater

Preventive Maintenance for Steel

The primary preventive measures available to increase the life of steel are protective coatings and cathodic protection.

The decision of which approach to use is a function of location on the waterfront structure (submerged or not) and economics.

The use of cathodic protection is restricted to submerged or buried structures. The image below shows the use of a galvanic anode used to provide protection of concrete and steel piles in a marine environment.

Protective Coatings for Steel

Steel in a marine environment will corrode freely if left unprotected and without a coating system.

Coating systems are designed according to three marine zones:

- Constantly submerged
- Intertidal and splash zone
- Above the splash zone

Steel in the submerged zone is best protected through a combination of a coating system and cathodic protection.

Maintenance coating systems are employed as follows:

- Overcoats on sound coatings
- Repairs to coating systems with spot failing
- Complete reapplication where coating systems have failed

Protective Coatings for Steel

Surface preparation of previously coated steel may consist of the following sequential procedures:

- 100% removal of biological growth
- Removal of unsound coatings and rust
- Removal of surface contamination such as oil, grease, dirt
- Removal of surface chloride contamination
- Brush-off blasting of sound coatings
- Abrasive blasting of uncoated steel to produce an angular anchor profile between 2 to 3 mils (0.05 to 0.08 mm)

Coating Systems

The below coating systems have displayed high performance and may be used for either spot repairs or complete reapplication.

It is recommended that a coating specialist be contacted prior to specifying one of the below coating systems for overcoating sound coatings.

DOD and other Federal activities may wish to contact an NFESC coating specialist.

Submerged Zone

- Underwater cure, two-component, 100% solid liquid epoxy: 1 to 2 coats at 7.87 to 11.81 mils (0.2 to 0.3 mm) DFT (dry film thickness)

- Underwater cure, two-component, 100% solid epoxy putty: 1 coat at 118.1 to 236.22 mils (3 to 6 mm) DFT

Intertidal/Splash Zone

- Two-component, coal tar epoxy: 1 to 2 coats at 7.387 to 15.75 mils (0.2 to 0.4 mm) DFT
- Single-component, coal tar urethane: 1 to 2 coats at 3.94 to 11.81 mils (0.1 to 0.3 mm) DFT
- Three-component, aggregate-filled epoxy: 1 coat at 118.1 to 236.22 mils (3 to 6 mm) DFT

Above Splash Zone

- Two-component epoxy polyamide primer followed by two coats of a two-component, aliphatic urethane topcoat: 3 coats at 9.84 mils (0.25 mm) DFT (5.9 mils (0.15 mm) primer, 3.94 mils (0.1 mm) topcoat, 3.94 mils (0.1 mm) topcoat)

- Single-component, zinc-rich urethane primer followed by two coats of a single-component, aliphatic urethane topcoat: 3 coats at 7.87 mils (0.2 mm) DFT (3.94 mils (0.1mm) primer, 3.94 mils (0.1 mm) topcoat, 3.94 mils (0.1 mm) topcoat)

- Two-component epoxy polyamide primer followed by two coats of a flexible acrylic topcoat: 3 coats at 19.67 mils (0.5 mm) DFT 5.9 mils (0.15 mm) primer, 7.87 mils (0.2 mm) topcoat, 7.87 mils (0.2 mm) topcoat)

Cathodic Protection of Steel

The natural corrosion of steel structures immersed in water or buried in soil can effectively be controlled by using anodes and direct current systems to minimize or stop the corrosion process, by establishing the steel as a cathode.

Cathodic protection systems are best installed when the structure is constructed, but can be added to existing structures.

They can effectively stop corrosion but cannot restore the material already lost by corrosion.

Galvanic Anode

Galvanic anode cathodic protection systems rely on the corrosion of active metals such as zinc, magnesium or aluminum to generate the electrical current needed to protect buried or submerged steel structures.

Since these anodes (image) are sacrificed to protect the structure, they are known as sacrificial anodes.

Galvanic Anode (continued)

The anodes must be buried or submerged near the structure to be protected and electrically connected to it with a low resistance bond.

As the anodes are consumed, they must be periodically monitored and replaced when over 80 percent of the metal is consumed, or when they will be consumed before the next scheduled inspection.

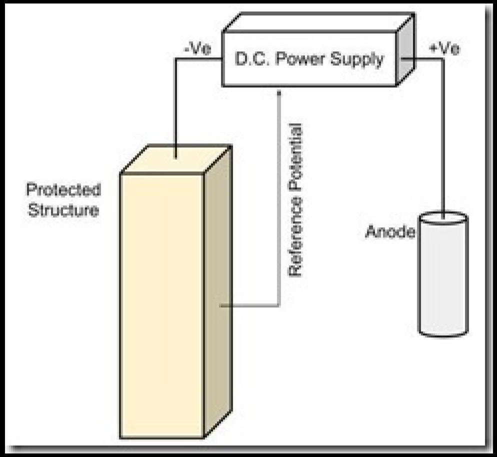
The level of protection provided can be determined by measuring the potential of the structure being protected by comparison with a standard reference electrode.

Impressed Current

Impressed current cathodic protection systems use an external source of electrical alternating current, and a rectifier, to provide the protective direct current to be impressed across the system.

This system also requires anodes buried or submerged in the vicinity of the structure being protected, but these anodes can last much longer than galvanic anodes, since they only conduct the protective current into the water or soil and are not the source of the current.

Impressed current cathodic protection systems also require periodic inspection and maintenance to ensure effectiveness in controlling corrosion.



Chapter 6: Nonferrous Metals and Alloys

Common Nonferrous Metals

A variety of materials are available that, if used properly, are more resistant to corrosion by seawater and marine atmosphere than steel.

These materials are used for specialized applications and are not used as much as steel due to higher costs.

The common nonferrous metals are:

- Aluminum
- Copper
- Nickel
- Titanium
- And alloys of each

Aluminum

Many alloys of aluminum are available for applications requiring high corrosion resistance to the marine atmosphere as well as good strength-to-weight ratios.

The common uses of aluminum at the waterfront include: Brows and platforms, decking and catwalks, and light poles and bases. Aluminum should not be used as a substitute for steel solely for its corrosion resistance quality.

Aluminum and its alloys are subject to pitting and crevice corrosion in marine environments, especially in submerged conditions. If pitting can be tolerated and crevices eliminated, aluminum alloys may be used successfully where low weight and other unique properties are required.

ASTM specifications define compositions and mechanical properties of aluminum alloys.

Alloys 5083, 5086, 5052 and 6061 are the most popular alloys for structures exposed to the marine atmosphere.

Copper

Copper and copper alloys are suitable for waterfront use because of their uniform, low corrosion rate.

Copper is used for electrical conductors, pipe, sheathing, and many hidden uses on supporting equipment at the waterfront.

The copper alloys usually selected for marine corrosion resistance are:

- Copper
- Cupro-nickel 90-10
- Cupro-nickel 70-30
- Arsenical admiralty brass
- Most true (zincless) bronzes

These alloys form films of corrosion products that provide protection even in flowing water.

Nickel

Nickel base alloys have good corrosion resistance to seawater and to cavitation damage.

These materials are used for specialized applications in:

- Springs
- Cable connectors
- Expansion joints
- Rupture disks
- Valves
- Fasteners
- Heat exchangers
- Piping

The high cost of these materials makes them unsuitable for bulk construction at the waterfront.

Common Nickel Alloys

The most common nickel alloys used are:

- Inconel Alloy 625 (nickel-chrome alloy)
- Hastelloy Alloy "C" (nickel-chrome-molybdenum alloy)
- Monel 400 (nickel-copper alloy)

Inconel and Hastelloy "C" are essentially immune to corrosion in marine environments.

Monel 400 has good corrosion resistance when it has been cathodically protected with a more active metal. If not protected, Monel will develop pitting and crevices.

Deterioration of Nonferrous Metals and Alloys

Nonferrous metals and alloys will corrode and develop pits and crevices under normal atmospheric conditions. In general, these metals are not given preservative coatings, but may be painted for color/appearance in certain uses.

Corrosion rates can be greatly accelerated when two or more dissimilar metals are in contact with each other and exposed to a corrosive environment.

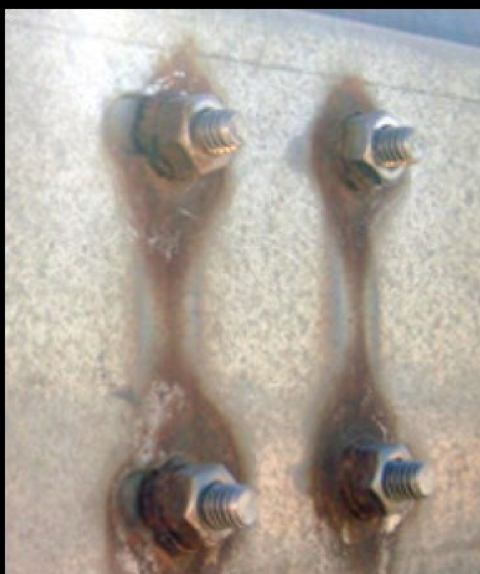
Galvanic Corrosion

Particularly when they are buried or submerged, accelerated corrosion of one of the metals can occur due to an electrochemical reaction called galvanic corrosion.

Galvanic corrosion rates depend on the metals' electrical properties and the medium in which the metals are exposed.

Corroded metal considered to be anodic (less noble) + / Protected paired cathodic metal (more noble) -	Platinum	Gold	Stainless steel 18-9	Silver	Mercury	Nickel	CuZn23Ni22 alloy	Copper	Copper-Aluminium Cu Al10	CuZn brass CuZn39Pb	Bronze CuSn12	Tin	Lead	Fe Ni25	Aluminium-Copper AlCu4Mg	Cast iron	Carbon steel	Screw-cutting light alloy	Light cast alloy	Aluminium A5	Carbon steel for heat treatment XC80	Al Mg alloy	Cadmium	Pure iron	AlMgSi alloy	Chrome	Al Zn Mg alloy	Sn Zn white metal	Zinc	Manganese	Magnesium
Platinum	0																														
Gold	130	0																													
Stainless steel 18-9	250	120	0																												
Silver	350	220	100	0																											
Mercury	350	220	100	0	0																										
Nickel	430	300	180	80	80	0																									
CuZnNi alloy	450	320	200	100	100	20	0																								
Copper	570	440	320	220	220	140	120	0																							
Copper-Aluminium	600	470	350	250	250	170	150	30	0																						
Brass CuZn	650	520	400	300	300	220	200	80	50	0																					
Bronze CuSn	770	640	520	420	420	340	320	200	170	120	0																				
Tin	800	670	550	450	450	370	350	230	200	150	30	0																			
Lead	840	710	590	490	490	410	390	270	240	190	70	40	0																		
Fe Ni25	930	800	680	580	580	500	480	360	330	280	160	130	90	0																	
Aluminium Copper	940	810	690	590	590	510	490	370	340	290	170	140	100	10	0																
Cast iron	950	820	700	600	600	520	500	380	350	300	180	150	110	20	10	0															
Carbon steel	1000	870	750	650	650	570	550	430	400	350	230	200	160	70	60	50	0														
Screw-cutting light alloy	1000	870	750	650	650	570	550	480	400	350	230	200	160	70	60	50	0	0													
Light cast alloy	1065	935	815	715	715	635	615	495	465	415	295	265	225	135	125	115	65	65	0												
Aluminium	1090	960	840	740	740	660	640	520	490	440	320	290	250	160	150	140	90	90	25	0											
Carbon steel for heat treatment	1095	965	845	745	745	665	645	525	495	445	325	295	255	165	155	145	95	95	30	5	0										
Al Mg alloy	1100	970	850	750	750	670	650	530	500	450	330	300	260	170	160	150	100	100	35	10	5	0									
Cadmium	1100	970	850	750	750	670	650	530	500	450	330	300	260	170	160	150	100	100	35	10	5	0	0								
Pure iron	1105	975	855	755	755	675	655	535	505	455	335	305	265	175	165	155	105	105	40	15	10	5	5	0							
AlMgSi alloy	1105	975	855	755	755	675	655	535	505	455	335	305	265	175	165	155	105	105	40	15	10	5	5	0	0						
Chrome	1200	1070	950	850	850	770	750	630	600	550	430	400	360	270	260	250	200	200	135	110	105	100	100	95	95	0					
Al Zn Mg alloy	1275	1095	975	875	875	795	775	655	625	575	455	425	385	295	285	275	225	225	160	115	130	125	125	120	120	25	0				
Sn Zn white metal	1360	1230	1110	1010	1010	930	910	790	760	710	500	560	520	430	420	410	360	360	295	270	265	260	260	255	255	160	135	0			
Zinc	1400	1270	1150	1050	1050	970	950	830	800	750	630	600	560	470	460	450	400	400	335	310	305	300	300	295	295	200	175	40	0		
Manganese	1470	1340	1220	1120	1120	1040	1020	900	870	820	700	670	630	540	530	520	470	470	405	380	375	370	370	365	365	270	245	110	70	0	
Magnesium	1950	1870	1700	1600	1600	1520	1500	1380	1350	1300	1180	1150	1110	1020	1010	1000	950	950	885	860	855	850	850	845	845	750	725	590	550	480	0

Below the red line, the metal listed in the vertical column will be attacked:
- the metal combined is not subject to galvanic corrosion – on the contrary, it benefits from a protective effect
- the galvanic effect is influenced by the interaction between the surfaces of the two metals in contact – if the surface of the metal considered is the smallest, its corrosion increases, and vice versa



Galvanic Series Tables

Galvanic series tables (above) have been developed indicating lists of metals in order of decreasing corrodibility when exposed to a certain solution or medium.

Generally, the closer one metal is to another in the galvanic series, the lower the corrosion rate with the more active metal, and conversely, the further apart, the greater will be the corrosion rate of this metal.

Preventive Maintenance for Nonferrous Metals and Alloys

PM measures depend on whether or not dissimilar materials are involved:

Similar Nonferrous Metals and Alloys

The only formal PM measure is regular and careful inspection to determine the condition of the component. In the later part of a component's life expectancy, it may prove economical to coat the metal to prevent further corrosion rather than to replace the component.

Avoiding Galvanic Corrosion

Galvanic corrosion can effectively be eliminated by making the structure out of as much of the same metal as possible, placing a protective insulator between the two dissimilar metals, and by providing cathodic protection if buried or immersed.

When galvanic corrosion cannot be effectively eliminated, it can be reduced by using appropriate protective coatings on the steel, ensuring not to coat the anodes.

Preventive Maintenance (Dissimilar Metals)

Detailed information on treatments of galvanic corrosion is given in:

MIL-STD-889B

Dissimilar Metals for metal exposed to the saltwater environment.

If dissimilar metals must be joined, the following preventive measures should be taken:

- Choose metals close together in the galvanic series.
- Keep the cathodic area small in relation to the anode area; for instance, bolts or screws of stainless steel for fastening aluminum sheets, but not the reverse.
- Provide a protective insulator between the two metals.
- Use special coatings on the metals.

Chapter 7: Synthetic Materials

Synthetic Materials

Numerous synthetic materials are used in waterfront facilities and components. They are extremely versatile in application and serve as a structural material, coating material, or buoyancy material.

In general, these materials do not corrode in the marine environment, but deteriorate due to other reasons, such as water absorption and swelling and degradation by ultraviolet light.

Deterioration of these synthetics, other than physical damage, increases with aging; plastics crack or separate, some become brittle; foams crumble with age and lose resiliency; and elastomers stretch and deteriorate from the effects of sun and exposure.

In general, no preventive maintenance measures are performed other than inspection.

Certain materials and components can be economically repaired when damaged.

The common synthetic materials include:

- Wood Plastic Composites
- Fiber-reinforced plastics (FRP)
- Foams, rubbers, and elastomers
- Plastic pile wraps and piping
- Synthetic fibers
- Adhesives

Wood-plastic Composites (WPCs) are composite materials made of wood fiber/wood flour and thermoplastic(s) such as PE, PP, PVC, or PLA.

In addition to wood fiber and plastic, WPCs can also contain other ligno-cellulosic and/or inorganic filler materials.

WPCs are a subset of a larger category of materials called natural fiber plastic composites (NFPCs), which may contain no cellulose-based fiber fillers such as pulp fibers, peanut hulls, coffee husk, bamboo, straw, digestate, etc.

Chemical additives provide for integration of polymer and wood flour (powder) while facilitating an optimal processing condition.

Fiber-reinforced Composites (FRC)

This is a composite building material that consists of three components:

- fibers as the discontinuous or dispersed phase,
- matrix as the continuous phase, and
- fine interphase region, also known as the interface.

This is a type of advanced composite group, which makes use of rice husk, rice hull, and plastic as ingredients.

This technology involves a method of refining, blending, and compounding natural fibers from cellulosic waste streams to form a high-strength fiber composite material in a polymer matrix.

Fiber-reinforced Plastics (FRP)

Carbon fiber sheets, strips, and rods are used to upgrade existing pier decks. The sheets and strips can be used by bonding them to the underside of the deck and the rods embedded into the top deck for negative reinforcement.

These techniques can increase the shear capacity of the deck to permit greater loads. FRP are a composite of resin and fibrous material.

The common resins are polyester and epoxy. Polyester resins are general purpose resins that cost less than epoxy.

Epoxy resins have superior strength properties, greater resistance to chemical and water degradation, and lower shrinkage during curing.

Materials used as reinforcement for FRP include:

- Continuous strands
- Woven cloth
- Chopped fibers
- And in some cases, glass flakes

Applications of Fiber-reinforced Plastics

FRPs are used for applications requiring high strength-to-weight ratios and a resistance to deterioration.

Applications such as:

- Pile jackets for steel, concrete, and timber piling to reduce corrosion or erosion; for reinforcement; and to prevent marine borer attack.
- Lightweight, sandwich construction for small buildings and containers.
- Floating structures, such as buoys and landing floats, when used in combination with closed-cell foams.
- Deck hardware such as lighting posts, grating, utility line hangars, and handrails on piers.
- Filament wound piping for lightweight, low temperature pipelines transporting steam condensate, seawater, freshwater, sewage, oil, and potable water.

Plastic and Fiberglass Piles

Piles made primarily of plastic or fiberglass are being used as replacements for timber fender piles.

Among the plastic piles are recycled plastic piles of which there are two basic types. One type uses a steel pipe core encapsulated in a mixture of high density and low density polyethylene.

The second uses either steel or fiberglass rebar as the reinforcement in high-density polyethylene (HDPE).

Early versions of the plastic piles had problems associated with cracking of the outer skin. Later editions of the plastic piles have had fewer cracking problems attributed to them.

In addition to the plastic piles, there are fiberglass piles that consist of a fiberglass tube, which can be filled with concrete for increased strength. The fiberglass piles have performed extremely well as fender piles.

Plastic and Fiberglass Piles

In general, the fiberglass tube type piles that are filled with concrete provide more stiffness than the plastic piles. However, the fiberglass piles are vulnerable to abrasion.

High- density polyethylene or ultra high molecular weight polyethylene (UHMW) should be used as a rub strip on the fiberglass fender piles.

Both the plastic and composite fender piles have been employed successfully at many Navy piers.

Most of the plastic and composite piles have been used as part of the secondary fendering system.

It is recommended that the plastic and composite piles not be used as the primary fendering system at this time.

Furthermore, the plastic and composite piles are not recommended for use as bearing piles. Currently, there are no ASTM or other industry standards for these piles, but they are being developed.

Marine Foams

Foams are used at the waterfront as filler material for sandwich construction, to provide buoyancy for buoys; landing floats; and floating brows, and in foam-filled fenders to absorb the energy of berthing ships.

Foams are resistant to deterioration in the marine environment if encased in an impermeable, durable material.

Types of Foams

The common foams are:

Polyurethane foams
can be foamed on-site. However, before the foam hardens it is unstable in direct sunlight and is flammable.

Polystyrene foams
are relatively inexpensive compared to polyurethane. They can be purchased in large quantities and cut to shape.

Polystyrene foams
are used in decks for buoyancy of small boat moorings in marinas.

Closed cell cross-linked polyethylene foams
are used in foam-filled fenders.

Ionomer foams
have been used in buoys and fenders. The outer skin of the products is a denser version of the low-density encased foam. The foam, encased in an elastomer cover, absorbs the impact energy of berthing ships.

Rubber and Elastomers

Numerous natural and synthetic rubbers and elastomers are used at the waterfront in hose lines, gaskets, fender system components, and other specialized applications.

These materials are resistant to the marine environment provided the appropriate rubber or elastomer is used.

The more common material is a urethane elastomer as used for the shell of foam-filled fenders.

The elastomer ethylene propylene dimonomer (EPDM) is used in arch-type rubber fenders.

Other Synthetic Materials

Synthetic materials are also used at the waterfront for pile wraps, piping, and as adhesives.

Pile wraps are made of flexible polyvinyl chloride (PVC) or polyethylene (PE) films and prevent growth of wood boring organisms.

PVC piping is widely used for numerous applications, as it is lightweight and corrosion resistant. Some degradation of the piping will occur if exposed to sunlight and other weathering factors. Normally, PVC pipe becomes brittle as it ages.

Adhesives, coatings, and putties made from epoxy have been developed for bonding to damp and underwater surfaces.

They are used to bond structures or components, connections, joints, and other metal configurations susceptible to corrosion; to fill voids; and to protect surfaces.

They can also be used to patch holes above the water or underwater.

Chapter 8: Soil Fill For Quaywalls and Moles

Soil

Soil is the most common backfill material behind quaywalls, shoreline walls, and solid fill/mole piers; dikes; and levees.

A complete description of a soil includes:

- Classification
- Density
- Shear strength
- Moisture content
- Mineralogic content

For soils used in waterfront structures, it is often sufficient to classify them according to size (clay, silt, sand, and gravel.)

The density, plasticity, and moisture content are important for the finer-grained soils, while soundness and gradation are applicable to the coarser-grained soils and rock fills.

Particle Size

The particle size, which marks the boundary between the fine-grained, generally cohesive soils (silts and clays) and the coarse-grained, granular soils (sands and gravels), is approximately the minimum size retained on the No. 200 standard sieve.

Organic soils, such as elastic silts and peats, are never used in the construction or repair of engineering structures.

Issues with Finer-grainer Soils

Maintenance problems increase as the grain size of the soil gets smaller.

Finer-grained soils in the cohesionless range are extremely susceptible to leaching and erosion, whereas fine-grained cohesive soils are difficult to compact satisfactorily and may undergo undesirable shrinkage or swelling.

Soil Gradation

With granular soils, gradation is important. Uniformly graded soils with a narrow range of particle sizes are difficult to compact, are extremely porous, and have lower densities and strengths than soils with a broader distribution of particle sizes.

However, where compaction of sands and gravels is involved, large, oversize cobbles (image) can interfere with the compaction of the finer materials present.

Such large particles should be removed from the compacted fills and used as riprap or slope protection.

Chapter 9: Environmental Compliance

Federal, State, and Local Environmental Compliance

Environmental compliance is a facility's or project's status with respect to a wide variety of federal, state, and local environmental regulations in existence to protect our environment.

Environmental compliance involves aspects that affect the operation of a project, such as:

- Wastewater discharge
- Noise abatement
- Air quality attainment
- Hazardous waste (HW) management
- Hazardous materials (HAZMAT) management

Environmental Regulations

Environmental regulations have increased considerably over time, due to an ever-growing concern about the environment.

All shore activities are now regulated by a number of federal, state, regional, and local agencies. Thus, compliance to all of the applicable regulations for a particular project can vary greatly depending on the project's nature and location.

Environmental Topics

Some of these specific environmental topics including:

- Management of ozone-depleting substances
- Clean air ashore
- Clean water ashore
- Drinking water and water conservation
- Oil and hazardous substances contingency planning
- PCB management
- Pesticide compliance
- Noise prevention
- Installation restoration
- Natural resources management
- Solid waste management

National Environmental Policy Act (NEPA)

National Environmental Policy Act (NEPA)
The National Environmental Policy Act (NEPA), first enacted in 1969, is the national charter (within the US and its territories) for protection of the environment.

It establishes policy, sets goals, and provides a means for carrying out environmental policy within the United States and its territories.

NEPA impacts a wide variety of existing environmental legislation including the:

- Clean Water Act (CWA)
- Clean Air Act (CAA)
- Pollution Prevention Act (PPA)
- Coastal Zone Management Act (CZMA)
- Endangered Species Act (ESA)
- Marine Protection Research and Sanctuaries Act (MPRSA)

Environmental Documentation (3-Tiered Approach)

Under the NEPA Council on Environmental Quality (CEQ), a three-tiered approach of environmental consideration and documentation has been established:

- Categorical Exclusion (Cat. Ex)
- Environmental Assessment (EA)
- Environmental Impact Statement (EIS)

Categorical Exclusion

This is a statement that the intended project work or action does not have, under normal circumstances, individually or cumulatively, a significant effect on the environment.

If a categorical exclusion is allowed, an EA or EIS will not be required.

Categorical Exclusion

Categorical exclusions include:

- Routine repair and maintenance of facilities and equipment to maintain existing operations and activities, including maintenance of improved and semi-improved grounds.
- Alteration and additions of existing structures to conform or provide conforming use specifically required by new or existing applicable regulations.
- Routine actions normally conducted to operate, protect, and maintain military-owned or controlled properties.
- New construction that is consistent with existing land use and, when completed, complies with existing regulatory requirements.
- Routine movement, handling, and distribution of materials, including HAZMAT or HW that is moved, handled, or distributed under applicable regulations.
- Demolition, disposal, or improvements involving buildings or structures neither on nor eligible for listing on the National Register of Historic Places.
- Actions which require the concurrence or approval of another Federal agency, where the action is a categorical exclusion of the other Federal agency.
- Maintenance dredging and debris disposal where no new depths are required, applicable permits are secured, and disposal will be at an approved site.

Categorical Exclusion

Even though a proposal generally fits the definition of a categorical exclusion, the categorical exclusion will not be used if the proposed action affects public health and safety, or involves an action that is determined to have the potential for significant environmental effects on wetlands, endangered species, HW sites, or archeological resources.

When it is unknown beforehand whether or not the proposed action will significantly affect the human environment or be controversial with respect to environmental effects, a categorical exclusion cannot be used.

Environmental Office Documentation

The Environmental Office must document the categorical exclusion(s), the facts supporting their use, and specific considerations of whether the exceptions to the use of categorical exclusions are applicable.

This Record of Categorical Exclusion need not be more than a page or two, but must be signed by the Commanding Officer or a designee.

The signed Record of Categorical Exclusion must be retained within the project files and be available for review during environmental compliance evaluations.

Additionally, many Environmental Officers will prepare an Environmental Review Document (ERD), an in-house document listing impacts, or lack thereof, of the project on several environmental areas.

Even though a categorical exclusion is granted, it does not mean the end of the environmental compliance process. Local, regional, state, and federal agencies may require permits for certain operations, or for a specific type of equipment.

It is the Environmental Officer’s responsibility to obtain these permits, using the technical input from the project team. When work is contracted out, the contractor is responsible for providing an environmental protection plan, along with applicable permits and reports via the Contracting Officer.

Permits

Waterfront maintenance projects usually do not require permits unless special construction is required. Additionally, they will not need a new categorical exclusion if the work has been previously reviewed by the Environmental Officer. However, the Environmental Officer needs to be informed of any work taking place at the waterfront to ensure that environmental procedures are being followed.

Annual Inspection of Waterfront Structures

Normally, maintenance projects evolve from an annual inspection of waterfront structures by the Public Works Centers. The repair and/or maintenance requirements are then relayed to the facility customers who then submit a summary of the proposed work to the Environmental Office.

Environmental Assessment

An environmental assessment (EA) is an analysis of the potential environmental impact of a proposed action.

An EA is prepared for projects or actions that do not fall under one or more of the listed categorical exclusions and that have the potential for significant environmental impacts. If significant impacts are obvious, an Environmental Impact Statement is directly prepared.

Environmental Assessment (EA)

An EA discusses the need for the action, alternatives, impacts, and any environmental monitoring required. Additional information may be required of the project coordinators and other project planners to complete the EA.

No Impact Found:

If after completion of the EA, it is determined that the proposed project will not significantly impact the environment, a Finding of No Significant Impact (FONSI) will be prepared and the project implemented.

An Environmental Impact was found:

If it is determined that the proposed project will significantly impact the environment, an EIS must be prepared.

Environmental Impact Statement (EIS)

An EIS is a detailed document that provides a full discussion of significant environmental impacts and informs decision makers and the public of reasonable alternatives that would avoid or minimize adverse impact, or enhance the quality of the human environment.

An EIS can be lengthy and are frequently prepared by contractors who can provide an unbiased analysis, thus avoiding a conflict of interest.

The likelihood that an EIS would be required for a normal waterfront maintenance or repair project is small.

Working in Compliance

Once all permits for a project have been obtained and all documentation has been completed, the environmental official will issue a “site-approval.”

Generally, those performing maintenance or repair on a waterfront facility will not start work until a site approval has been issued.

Often, contact with the activity’s Environmental Office during planning and execution of waterfront maintenance and repair projects is all that will be required to assure compliance with environmental regulations.

Project personnel in some circumstances, however, may need to establish direct contact with the various permitting and regulatory agencies concerned with the work.

These might include but are not limited to:

- Port officials
- State Department of Health
- Department of Fish & Game
- State EPA office
- Coast Guard
- Army Corps of Engineers

Treated Wood - Environmental Issues

Since there is extensive use of treated wood at waterfront facilities, and since wood preservatives likely constitute the greatest percentage of chemicals used on the waterfront, a special mention about the environmental issues is warranted.

In recent years, using treated wood in the marine environment raised concerns about its effect on surrounding aquatic life.

Currently, wood preservatives are registered by the EPA for use in the marine environment, and treated wood is not considered a hazardous waste nor banned from landfills, according to Federal law.

However, local and state regulations are more restrictive.

The Environmental Office should be consulted for applicable restrictions at the waterfront facility of interest.

This concludes our course on "Construction of Waterfront Structures".
You may now proceed to the final exam located on the course page.

Thank you for taking this course with Online-PDH!