STEEL BULKHEAD

An Illustrative Steel Bulkhead Structural Components Vary with Design Requirements.

Illustration 6.

STONE TOE PROTECTION

GRANULAR BACKFILL

STEEL SHEET PILING
no corrosion problems occur, but if the anode is smaller than the cathode corrosion tends to be localized and severe damage may result in the form of pitting. Pitting is not considered a problem in piles, as the strength reduction is usually minimal. But pitting in pipelines, especially high-pressure ones, can cause problems. Since corrosion cells develop between areas of different aeration, it seems likely that the method of placing piles or steel members in the ground would be reflected in their rate of corrosion. The difference in the degree or rate of corrosion in undisturbed soils and that in disturbed backfill soils is indicated in Romanoff (1972), who notes that corrosion is higher in the disturbed soils because of nonuniformity of the entrapped air. Chellis (1961) notes that electrolytic action could occur in coastal environments, well below the line of free air, because of the presence of salts.

Other factors known to influence corrosion are: pollutants, in the form of dust and smoke acid; water, depending on its degree of salinity, pollution, and temperature; oxygen content; and the presence of sulfate-reducing bacteria.

Certain tests can identify some of these corrosive features. Electrical resistivity is used to investigate the corrosion potential of a soil. The conductivity of the soil is a measure of the soluble salt concentration: microbiological examination can be used to determine the presence of bacteria. If the area of interest is in the tidal flat region, a full chemical analysis with pH included should be conducted (Tomlinson 1963).

The rate of corrosion varies with the soil texture, composition of the soil, depth of embedment, and moisture content (Chellis 1961). Chellis also states that in coarse-textured soils, where air can circulate, the corrosion rate may approach the atmospheric condition, and in heavy clays, where there is oxygen deficiency, the corrosion rate is similar to the submerged rate. From Tables 4 and 5 it can be concluded that the atmospheric rate is higher than the buried rate and the abrasion zone is the area of greatest corrosion. This zone is in a surf where continued sand movement allows no protective corrosion cover to form. The pitting action in the abrasion zone indicates that a very short life span for sheet piles would be expected.

Protection from corrosion is usually self-forming. The formation of rust and the impregnation of the surrounding soil with corrosion residue both tend to reduce the rate of corrosion. Generally corrosion is within a few feet of the groundline, either up or down the pile, and concreting this zone should increase the life of the system. Cathodic protection, which utilizes the electropotential-forming corrosion, has proved successful. Zinc bars act as anodes with the steel cathodic structure, so the zinc can be used for the reaction instead of the steel.

Alaskan soils have also been used to test sheet piles (Romanoff 1972). Test piles were located in soils ranging from silts to clays, with a pH range of 5.4 to 7.6, and resistivities from 1,350 to 11,500 ohm-cm. The conclusions were: 1) the piling was unaffected by corrosion in permafrost regions, 2) in the active thaw region, the effect of pitting and corrosion was insignificant, 3) below the groundwater table, in undisturbed soils, regardless of the soil types and properties, no appreciable corrosion occurred, and 4) in fill materials above the groundwater table, soil corrosion was variable but not
<table>
<thead>
<tr>
<th>Pile location</th>
<th>Rate of thickness change in/yr</th>
<th>mm/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>soil</td>
<td>0.0003 to 0.003</td>
<td>0.008 to 0.08</td>
</tr>
<tr>
<td>sub-sand</td>
<td>0.001</td>
<td>0.03</td>
</tr>
<tr>
<td>abrasion zone</td>
<td></td>
<td></td>
</tr>
<tr>
<td>general</td>
<td>0.117</td>
<td>3.0</td>
</tr>
<tr>
<td>pitting</td>
<td>0.373</td>
<td>9.5</td>
</tr>
<tr>
<td>seawater</td>
<td>0.0005 to 0.005</td>
<td>0.013 to 0.13</td>
</tr>
<tr>
<td>atmosphere</td>
<td>0.011</td>
<td>0.28</td>
</tr>
<tr>
<td>Cover</td>
<td>Harbors bulkheads in/yr&lt;sup&gt;1&lt;/sup&gt;</td>
<td>Beach bulkheads in/yr</td>
</tr>
<tr>
<td>------------------------------------------------</td>
<td>-------------------------------------</td>
<td>-----------------------</td>
</tr>
<tr>
<td>No cover on either surface of pile (NN)</td>
<td>0.0075</td>
<td>0.027</td>
</tr>
<tr>
<td>One surface never covered, other covered part-time (NP)</td>
<td>0.0076</td>
<td>0.020</td>
</tr>
<tr>
<td>One surface only covered (NC)</td>
<td>0.0026</td>
<td>0.0094</td>
</tr>
<tr>
<td>One surface always covered, other covered part-time (PC)</td>
<td>0.0065</td>
<td>0.0057</td>
</tr>
<tr>
<td>Both surfaces covered part-time (PP)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Both surfaces always covered (CC)</td>
<td>0.0017</td>
<td>0.0026</td>
</tr>
</tbody>
</table>

<sup>1</sup> 1 in = 2.54 mm.
serious.

The above studies lead to the following conclusions:

- The corrosion of commonly used ferrous metals is of the same type and order of magnitude within a given soil environment.

  Corrosion of ferrous metal in different soil environments varies widely.

- Well-drained, high-resistivity soils have a high initial rate of corrosion which decreases in a few years to pitting.

- Poorly drained, low-resistivity soils have a low corrosion rate that is nearly constant with time.

- The oxygen differential, caused by the differences in aeration in backfills, is the major factor that causes corrosion when compared to the same soil in the undisturbed state.

- In general, soil type, drainage, soil resistivity, pH, and chemical composition of soils are of little importance in determining the corrosion of steel pilings driven in undisturbed soils. The resulting corrosion is not significant enough to affect the strength or useful life of pilings as load-bearing structures (Romanoff 1972).

  Table 6 gives a general summary of Romanoff's results, which are in agreement with the above conclusions.

**Seawater**

The seawater environment affects the corrosion rate of steel in many ways. Watkins (1969) describes the corrosion process as dependent on the following:

- water temperature;

- concentration of oxygen in electrolyte (seawater);

- pH value of the seawater;

- marine fouling on piling (for example, barnacle growth);

- salinity of the seawater;

- velocity of the water relative to the structure;

- and galvanic effect of unlike metals.

There are two basic protection systems used to prevent corrosion: isolation by barrier, and causing an electric current to flow to the steel from an anodic source. The latter is cathodic protection; the former uses
TABLE 6 Summary of Inspections on Steel Piling (Romanoff 1972)

<table>
<thead>
<tr>
<th>Location</th>
<th>Age of piling</th>
<th>Soil types</th>
<th>Piling exposed</th>
<th>Soil resistivity</th>
<th>pH</th>
<th>Partial chemical composition (mg-Cr/g/100 g soil)</th>
<th>Condition of piling</th>
<th>Surface with original mill scale intact</th>
<th>Maximum reduction of thickness in local areas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extracted Pile</td>
<td>17</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>Oka-cul</td>
<td>513</td>
<td>10,000</td>
<td>14.5</td>
</tr>
<tr>
<td>Honegill Creek</td>
<td>18</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>Fill-sand, silt and clay</td>
<td>1,300</td>
<td>12,400</td>
<td>7.7</td>
</tr>
<tr>
<td>Sunnys Point, Md.</td>
<td>18</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>Fill-sand, silt and clay</td>
<td>1,300</td>
<td>12,400</td>
<td>7.7</td>
</tr>
<tr>
<td>Ganges River</td>
<td>40</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>Fill-sand, silt and clay</td>
<td>1,300</td>
<td>12,400</td>
<td>7.7</td>
</tr>
<tr>
<td>Lack No.</td>
<td>12</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>Fill-sand, silt and clay</td>
<td>1,300</td>
<td>12,400</td>
<td>7.7</td>
</tr>
<tr>
<td>Ganges Dam; North Isle</td>
<td>12</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>Fill-sand, silt and clay</td>
<td>1,300</td>
<td>12,400</td>
<td>7.7</td>
</tr>
<tr>
<td>Sadie Dam</td>
<td>20</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>Fill-sand, silt and clay</td>
<td>1,300</td>
<td>12,400</td>
<td>7.7</td>
</tr>
<tr>
<td>Chilhowee Pass</td>
<td>32</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>Fill-sand, silt and clay</td>
<td>1,300</td>
<td>12,400</td>
<td>7.7</td>
</tr>
<tr>
<td>Williamsburg Terminal</td>
<td>32</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>Fill-sand, silt and clay</td>
<td>1,300</td>
<td>12,400</td>
<td>7.7</td>
</tr>
<tr>
<td>Laflour River</td>
<td>37</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>Fill-sand, silt and clay</td>
<td>1,300</td>
<td>12,400</td>
<td>7.7</td>
</tr>
</tbody>
</table>

*See sections 4.1 and 4.2 for additional information pertaining to location, type and length of piling examined. (Romanoff 1972)*

*In "x" indicates the soil level with reference to the water table in which piling was examined. The water table range below 2 ft above and below the water line. A dash indicates that piling was not examined at that level.*

*Includes all soil resistivity determinations measured by Shepard Cane, 4-pin method, or in the laboratory.*

*Condition of piling is described in accordance with the following code:* U, no corrosion, surface is entirely unaffected as indicated by the presence of mill scale over practically the entire surface. The surface may be roughened in small areas but no pits have a depth greater than the thickness of the mill scale.

M, uniform metal attack induced by removal of mill scale over large areas and roughening of the surface. 1/2" depths do not exceed the thickness of the mill scale.

2, shallow metal attack, sufficient corrosion to have removed a perceptible amount of metal in localized areas. Pits do not exceed 1/2" in depth.

P, pitting, grooving or scaling to a depth greater than 25 mils. The numbers indicate the maximum pit depth in mils.

Pit should be noted that the average reduction in thickness does not refer to the entire piling section, but to a very small area, usually 1 in. of the most corroded area of the piling. Refer to section 2.3 for further explanation. "Nil" indicates that the reduction in thickness is negligible.

Pitting passed through a sand and gravel stratum at a depth of about -11 ft. A 3 ft section of the pile at this level showed moderate corrosion as indicated in section 4.1.

*This was the only coasted pile inspected.*
barriers of organic or inorganic coatings and concrete encasement.

Concrete encasement is sometimes used to protect steel in marine structures. To protect steel effectively from corrosion, the concrete must be of good quality, properly placed and cured, and of adequate thickness. According to Watkins (1969), a 4 inch (102 mm) concrete jacket is needed as a minimal thickness.

If poor quality concrete or an inadequate concrete thickness is used, seawater may permeate through the concrete and cause corrosion of the steel. Since corrosion produces a greater volume than the initial steel volume, pressure is exerted on the surrounding concrete. If this pressure exceeds the tensile strength of the concrete, cracks and spalling will occur. Watkins notes that corroding metal can exert expansion pressures up to 4,700 psi (32.4 MN/m²) on the concrete.

A good concrete for jacketing steel in marine structures should have high strength, be relatively impermeable, and have good bonding characteristics. Seven and one-half sacks of cement per cubic yard of concrete and 5 gallons (0.019 m³) of water per sack of cement are recommended for corrosion protection in splashing water or alkaline soil (Watkins 1969). If jacketing is in a freezing area, entrained air of 10 to 12 percent is best in seawater exposures.

Procedures suggested for minimizing the deterioration of reinforced concrete should be applicable to concrete-jacketed steel. Watkins (1969) suggests the following ways of preventing deterioration of reinforced concrete in coastal structures:

- Use durable cements (from the chemical standpoint, those with low tricalcium aluminate content) and aluminous cements.
- Use tough and well-graded aggregate.
- Use high-quality, maximum density concrete of 1:1:3 (cement, sand, gravel) or 1:1:2 mixes.
- Restrict working stresses to reasonable values.
- Use a cover of not less than 2 inches (51 mm), but preferably 3 inches (76 mm); avoid square edges on beams or piles.
- Allow thorough air curing before exposure to tides or splash.
- Remove mill scale from the steel before installation.
- Use water-cement ratios as low as possible.
- Avoid segregation of the concrete upon placement.
- Use vibrators to obtain maximum consolidation.

37
Coatings

The first 8 years of a field study on organic coating, inorganic coating, and cathodic protection are described in Escalante et al. (1977). Table 7 describes the coatings tested and Figure 4 illustrates the zones of attack, indicating the splash zone as the most corrosive.

The effects of the coatings are to be compared against bare steel piles, which were used for control. During their 6 years of ocean exposure, these bare piles showed extensive corrosion that was fairly constant with time. Two major areas of corrosion occurred: 1) above the high water line, and 2) within the erosion zone near the mudline. Figures 5, 6, 7, and 8 give a profile of the average flange thickness and an indication of the depth of pitting for the control piles.

Organic Coatings

As a group, the coal tar epoxy paints did not perform as well as expected. The coal tar epoxies on the H-piles showed considerable deterioration in the atmospheric zone, but below the mudline the deterioration was insignificant. In a comparison of H-piles and pipe piles, the pipe piles had fewer coating failures but deeper pitting. Figures 9 through 14 illustrate the results of flange reduction and pitting.

The second group of nonmetallic coatings consisted of coatings of polyvinylidene chloride, phenolic mastic, and polyester glass flake. As Figures 15, 16, and 17 illustrate, these coatings showed a good resistance to deterioration. The maximum rate of corrosion for this group, 0.15 mils per year, was located just below the mean high water line. A window in the atmospheric zone, the worst location, only suffered moderate undercutting. Of the three coatings in this group, the polyvinylidene chloride gave the least amount of protection.

Inorganic Coatings

When metal coatings of aluminum-pigmented coal tar epoxies were tried, the most damage occurred in the erosion zone. The degree of pitting damage was minor over most of the pile, with some undercutting of the window in the atmospheric zone. Figures 18 and 19 indicate the corrosion, suggesting fairly good performance.

The combination of nonmetallic coatings on metal-filled coatings was tested. Metallic zinc powder was used in the metal-filled undercoatings, in combination with five different electrically insulating top coatings. The test specimens (Figures 20, 21, and 22) had low corrosion rates of 0.2, 0.1, and less than 0.1 mils per year, respectively. Figures 21 and 22 indicate an increase in thickness of the flanges, but this occurred because not all of the protective coating had been removed. This also indicates that these two coating systems were in excellent condition when removed for measurement. Pile 19A (Figure 23) showed general attack the full length of the pile, with more
### TABLE 7 Description of Steel Pile Systems Exposed to the Atlantic Ocean at Dam Neck, Virginia (Escalante et al. 1977)

<table>
<thead>
<tr>
<th>Piling System Number</th>
<th>Description</th>
<th>Number of Costs</th>
<th>Average Coating Thickness on Each Pile (mils)</th>
<th>Coating Thickness Range (mils)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>BARE CARBON STEEL</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>BARE CARBON STEEL WITH ZINC ANODES</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Protected beneath waterline with two zinc anodes(c)</td>
</tr>
<tr>
<td>3</td>
<td>BARE CARBON STEEL WITH ALUMINUM ANODES</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Protected beneath waterline with two aluminum anodes(c)</td>
</tr>
<tr>
<td>4</td>
<td>POLYAMIDE CURED COAL TAR EPOXY</td>
<td>2</td>
<td>A-16</td>
<td>A+11-20</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>S-16</td>
<td>S+10-22</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>C-16</td>
<td>C+13-22</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>POLYAMIDE CURED COAL TAR EPOXY</td>
<td>2</td>
<td>A-20</td>
<td>A+13-30</td>
<td>Protected beneath waterline with two Zinc anodes(c)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>S-20</td>
<td>S+12-30</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>C-19</td>
<td>C+11-27</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>POLYAMIDE CURED COAL TAR EPOXY</td>
<td>2</td>
<td>A-16</td>
<td>A+12-20</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>S-15</td>
<td>S+10-28</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>C-13</td>
<td>C+7-20</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>POLYAMIDE CURED COAL TAR EPOXY</td>
<td>2</td>
<td>A-15(33)(q)</td>
<td>A+7-32(20-40)(q)</td>
<td>Third coat and Aluminum Oxide applied between 16&quot; and 22&quot; from bottom of piles only</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>S-21(35)</td>
<td>S+17-31(20-41)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>C-21(35)</td>
<td>C+16-30(25-40)</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>ALUMINUM PIGMENTED COAL TAR EPOXY</td>
<td>1</td>
<td>A-27</td>
<td>A+17-35</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>S-25</td>
<td>S+14-40</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>C-25</td>
<td>C+15-40</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Anode Cured, Red-Leg Pigmented, Coal Tar Epoxy Primer</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Anode Cured Coal Tar Epoxy</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Intermediate</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Anode Cured, Aluminum Pigmented, Coal Tar Epoxy Finish</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>ALUMINUM PIGMENTED COAL TAR EPOXY</td>
<td>1</td>
<td>A-19</td>
<td>A+12-35</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>S-18</td>
<td>S+12-35</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>C-18</td>
<td>C+13-27</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Epoxy Primer</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Anode Cured Coal Tar Epoxy</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Intermediate</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Anode Cured, Aluminum Pigmented, Coal Tar Epoxy Finish</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>HOT DIPPED ZINC (GALVANIZED)</td>
<td>1</td>
<td>A-9</td>
<td>A+5-13</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>B-8</td>
<td>B+5-15</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>C-8</td>
<td>C+5-16</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>HOT DIPPED ZINC (GALVANIZED)</td>
<td>1</td>
<td>A-7</td>
<td>A+4-12</td>
<td>Protected beneath waterline with two zinc anodes(c)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>B-9</td>
<td>B+4-15</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>C-7</td>
<td>C+3-18</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>POLYVINYLIDENE CHLORIDE</td>
<td>7</td>
<td>A-7</td>
<td>A+5-13</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(Alternate Orange and White Coats)</td>
<td></td>
<td>S-5</td>
<td>S+3-12</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>C-7</td>
<td>C+3-11</td>
<td></td>
</tr>
<tr>
<td>Piling System Number</td>
<td>Description</td>
<td>Number of Coats</td>
<td>Average Coating Thickness on Each Pile (mils)</td>
<td>Coating Thickness Range (mils)</td>
<td>Remarks</td>
</tr>
<tr>
<td>----------------------</td>
<td>-------------------------------------------------------</td>
<td>-----------------</td>
<td>-----------------------------------------------</td>
<td>--------------------------------</td>
<td>----------------------------------------------</td>
</tr>
<tr>
<td>22</td>
<td>COATED ZINC INORGANIC SILICATE</td>
<td>1</td>
<td>A-10</td>
<td>A+6-16</td>
<td>Low Alloy Steel HPiles</td>
</tr>
<tr>
<td></td>
<td>Zinc Inorganic Silicate Primer</td>
<td></td>
<td>B-8</td>
<td>B+4-17</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(Post Cured)</td>
<td></td>
<td>C-13</td>
<td>C+7-28</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Strontium-Chromate, Iron-Oxide</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Vinyl Phenolic Primer</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Vinyl Mastic Finish</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>BARE MARINER STEEL</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Low Alloy Steel HPiles</td>
</tr>
<tr>
<td>24</td>
<td>BARE MARINER STEEL WITH ZINC ANODES</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Protected beneath waterline with two zinc anodes(c)</td>
</tr>
<tr>
<td>25</td>
<td>POLYAMIDE CURED COAL TAR EPOXY</td>
<td>2</td>
<td>A-17</td>
<td>A+6-40</td>
<td>Low Alloy Steel HPiles</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>B-16</td>
<td>B+8-28</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>C-17</td>
<td>C+10-30</td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>BARE CARBON STEEL</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Carbon Steel Pipe Piles</td>
</tr>
<tr>
<td>27</td>
<td>POLYAMIDE CURED COAL TAR EPOXY</td>
<td>2</td>
<td>A-20</td>
<td>A+15-28</td>
<td>Carbon Steel Pipe Piles</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>B-17</td>
<td>B+15-24</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>C-24</td>
<td>C+17-30</td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>POLYAMIDE CURED COAL TAR EPOXY</td>
<td>2</td>
<td>A-21(40*)</td>
<td>A+13-30(40*)</td>
<td>Carbon Steel Pipe Piles</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>B-21(32)</td>
<td>B+12-30(30-40)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>C-16(40*)</td>
<td>C+16(40*)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Coal Tar Epoxy and Aluminum Oxide</td>
<td></td>
<td></td>
<td></td>
<td>Third coat and aluminum oxide applied between 16' and 22' from bottom of piles only</td>
</tr>
<tr>
<td>29</td>
<td>FLAKEGLASS FILLED POLYESTER</td>
<td>1</td>
<td>A-32</td>
<td>A+18-40</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>B-30</td>
<td>B+17-40</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>C-34</td>
<td>C+15-40</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>BARE CARBON STEEL</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>31</td>
<td>BARE CARBON STEEL</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

(a) All piles were carbon steel "H" piles unless noted otherwise.
(b) Piles in each system were coated as follows:
   A-Piles - Completely coated except for six 1" x 6" bare windows located at intervals along the outside face of the ocean flange of piles.
   B-Piles - Completely coated.
   C-Piles - Top 23 feet completely coated; bottom 12 feet left uncoated.
(c) Anodes on A and C-piles located in water below HLW; Anodes on B-piles located in the sand.
(d) Values in parenthesis indicate total thickness after application of third coat of Coal Tar Epoxy and Aluminum Oxide between 16' and 22' from bottom of piles.
FIGURE 4 Zones of Deterioration
(Escalante et al. 1977)
FIGURES 5-8 Results of Coating Test on Steel (Escalante et al. 1977)

**FIGURE 5**
1A BARE CARBON STEEL

**FIGURE 6**
30A BARE CARBON STEEL

**FIGURE 7**
31A BARE CARBON STEEL

**FIGURE 8**
25A BARE CARBON STEEL (PIPE)
FIGURES 9-12 Results of Coating Test on Steel (Escalante et al. 1977)

FIGURE 9

6A COAL TAR EPOXY

FIGURE 10

4A COAL TAR EPOXY

FIGURE 11

7A COAL TAR EPOXY PLUS ARMOR

FIGURE 12

25A COAL TAR EPOXY ON MARINER STEEL
FIGURES 13-14 Results of Coating Test on Steel (Escalante et al. 1977)

FIGURE 13
27A COAL TAR EPOXY (PIPE)

FIGURE 14
28A COAL TAR EPOXY WITH ARMOR (PIPE)
FIGURES 15-17 Results of Coating Test on Steel (Escalante et al. 1977)

**FIGURE 15**

17A PHENOLIC MASTIC

**FIGURE 16**

29A POLYESTER GLASS FLAKE

**FIGURE 17**

12A POLYVINYLIDENE CHLORIDE
FIGURES 18-19 Results of Coating Test on Steel (Escalante et al. 1977)

FIGURE 18
9A AI PIGMENTED COAL TAR EPOXY

FIGURE 19
8A AI PIGMENTED COAL TAR EPOXY

DASHED LINE IS ORIGINAL SURFACE

AVERAGE FLANGE THICKNESS, in

DEPTH OF DEEPEST PIT, in

% - AREA Pitted

MEAN HIGH WATER

MEAN LOW WATER

MUD LINE

% - AREA Pitted

MEAN HIGH WATER

MEAN LOW WATER

MUD LINE

% - AREA Pitted

MEAN HIGH WATER

MEAN LOW WATER

MUD LINE
FIGURES 20-21 Results of Coating Test on Steel (Escalante et al. 1977)

FIGURE 20

18A COAL TAR EPOXY / Zn RICH ORGANIC

FIGURE 21

20A EPOXY POLYAMIDE / Zn RICH INORGANIC
FIGURES 22-24 Results of Coating Test on Steel (Escalante et al. 1977)

**FIGURE 22**

**21A EPOXY TAR / ZN RICH INORGANIC**

- Mean high water: 1%
- Mean low water: 1%
- Mud line: 10%

**FIGURE 23**

**19A VINYL / ZN RICH INORGANIC**

- Mean high water: 1%
- Mean low water: 10%
- Mud line: 5%

**FIGURE 24**

**22A VINYL MASTIC / ZN RICH INORGANIC**

- Mean high water: 15%
- Mean low water: 5%
- Mud line: 65%

**Data Summary**

- Average flange thickness: 0.6 in, 0.7 in
- Depth of deepest pit: 0 in, 0.1 in
attack in the erosion zone than indicated because of the method of measurement. The average corrosion rate for pile 19A in Figure 23 was 0.2 mils per year. Pile 22A (Figure 24) performed very well, with some general deterioration in the tidal zone and an overall deterioration rate of less than 0.25 mils per year. In general, the coatings on piles 19A and 22A performed very well with average corrosion rates less than 0.2 mils per year.

The nonmetallic-on-metallic coatings produced a nonconducting cover over the conducting secondary cover of the three tested. The average rates varied from 0.05 to 0.1 to 1.5 mils per year for piles 13A, 15A, and 16A (Figures 25, 26, and 27), respectively. In most of the double coating systems, if the first one breaks down, the second one generally provides the protection. In the case of pile 16A, when the outer coating broke down the second layer also began to deteriorate. At the time of testing, this coating system was only 50 percent effective.

Overall, the nonmetallic-on-metallic coatings, although they display a wide spectrum of results, provided good protection, except for pile 16A.

The results of tests with two metallic coatings, a hot-dipped galvanized and a flame-sprayed aluminum coating, are presented in Figures 28 and 29. In a study of the galvanized coating, the rate of corrosion decreased for the first 3 years and then began to increase, after 8 years nearing that of the bare steel. Pile 1uA, with galvanized coating, shows some corrosion in the atmospheric zone and considerable corrosion in the erosion zone, although the average corrosion rate was less than 0.15 mils per year. The flame-sprayed aluminum, on the other hand, revealed some metal loss in the erosion zone and practically no pitting anywhere. The atmospheric zone remained in excellent condition, but damage below the mudline was more extensive as Figure 29 indicates. Overall, the metal coatings began to show deterioration after 5 years, although the piles were in excellent condition after 8 years, with only minor damage in the abrasion zone.

In summary, every coating system reduced the corrosion of steel piling in seawater. The reduction in corrosion ranged by factors of 22 to 2, as compared to the bare piles. In Table 8, the coatings are listed in order of increasing corrosion, with the average corrosion rates for the different zones indicated. It should be noted that no one class of coatings performed entirely satisfactorily. In general, the coal tar epoxies were near the bottom of the list of protective coatings.

Cathodic Protection

Cathodic protection is another method of reducing the rate of corrosion of metal structures in an electrolyte such as seawater. This method is suitable for protecting the immersed zone of the piling, but because of the high resistance of fresh water, cathodic protection is not usually feasible in fresh water (US Coast Guard 1967; Watkins 1969).

The two general methods of cathodic protection are: 1) galvanic protection, and 2) impressed-current protection. These methods operate on the same principle as corrosion. Figure 30 presents an example of a corrosion cell, which basically consists of two unlike metals in an electrolyte. In most
FIGURES 25-27 Results of Coating Test on Steel (Escalante et al. 1977)

FIGURE 25
13A VINYL/Al FLAME SPRAY

FIGURE 26
15A POLYVINYLIDENE CHLORIDE/ZINC FLAME SPRAY

FIGURE 27
16A VINYL/ZN FLAME SPRAY

AVERAGE FLANGE THICKNESS, in

DEPTH OF DEEPEST PIt, in

% AREA PITTED

MEAN HIGH WATER

MEAN LOW WATER

MUD LINE

DASHED LINE IS ORIGINAL SURFACE

0.6 0.7 0.1

0 10 15 20 25 30

0 10 20 30 40

0 10 20 30 40 50
FIGURES 28-29 Results of Coating Test on Steel (Escalante et al. 1977)

FIGURE 28

10A GALVANIZED

FIGURE 29

14A AI FLAME SPRAY

% AREA Pitted

LENGTH OF PILE, ft

AVERAGE FLANGE THICKNESS, in

DEPTH OF DEEPEST PIT, in

DASHED LINE IS ORIGINAL SURFACE

MEAN HIGH WATER

MEAN LOW WATER

MUD LINE

% AREA Pitted

LENGTH OF PILE, ft

AVERAGE FLANGE THICKNESS, in

DEPTH OF DEEPEST PIT, in

DASHED LINE IS ORIGINAL SURFACE

MEAN HIGH WATER

MEAN LOW WATER

MUD LINE

10%

22%

12%

12%

44%

4%

8%

7%
## TABLE 8 Corrosion Rates of H-Piles Based on Flange Thickness Measurements (Escalante et al. 1977)

<table>
<thead>
<tr>
<th>SYSTEM</th>
<th>COATING DESCRIPTION</th>
<th>Overall Average Corrosion Rate,</th>
<th>Average Corrosion Rate Within Zone,</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>mg/a</td>
<td>Zone 1 9 to 12 ft, b</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Zone 2 13 to 15 ft, b</td>
</tr>
<tr>
<td>21</td>
<td>Coal Tar Epoxy/Zinc Rich Inorganic</td>
<td>-0.01</td>
<td>-0.01</td>
</tr>
<tr>
<td>13</td>
<td>Vinyl/Flame Sprayed Aluminum</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>20</td>
<td>Enamel Poly-resin/Zinc Rich Inorganic</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>8</td>
<td>Aluminum Pigmented Coal Tar Epoxy</td>
<td>0.07</td>
<td>0.07</td>
</tr>
<tr>
<td>22</td>
<td>Polyester Glass Flake</td>
<td>-0.10</td>
<td>-0.10</td>
</tr>
<tr>
<td>15</td>
<td>Polyvinylidene Chloride/Flame Sprayed Zinc</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td>10</td>
<td>Galvanized</td>
<td>0.14</td>
<td>0.14</td>
</tr>
<tr>
<td>17</td>
<td>Phenolic Mastic</td>
<td>0.14</td>
<td>0.14</td>
</tr>
<tr>
<td>14</td>
<td>Flame Sprayed Aluminum</td>
<td>0.16</td>
<td>0.16</td>
</tr>
<tr>
<td>9</td>
<td>Aluminum Pigmented Coal Tar Epoxy</td>
<td>0.18</td>
<td>0.18</td>
</tr>
<tr>
<td>18</td>
<td>Coal Tar Epoxy/Zinc Rich Organic</td>
<td>0.19</td>
<td>0.19</td>
</tr>
<tr>
<td>19</td>
<td>Vinyl/Zinc Rich Inorganic</td>
<td>0.20</td>
<td>0.20</td>
</tr>
<tr>
<td>22</td>
<td>Vinyl Mastic/Zinc Rich Inorganic</td>
<td>0.24</td>
<td>0.24</td>
</tr>
<tr>
<td>4</td>
<td>Coal Tar Epoxy</td>
<td>0.53</td>
<td>0.53</td>
</tr>
<tr>
<td>25</td>
<td>Coal Tar Epoxy on Casing Steel</td>
<td>0.63</td>
<td>0.63</td>
</tr>
<tr>
<td>7</td>
<td>Coal Tar Epoxy plus Armor</td>
<td>0.95</td>
<td>0.95</td>
</tr>
<tr>
<td>6</td>
<td>Coal Tar Epoxy</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>16</td>
<td>Vinyl-Resin Lead/Flame Sprayed Zinc</td>
<td>1.4</td>
<td>1.4</td>
</tr>
<tr>
<td>12</td>
<td>Polyvinylidene Chloride</td>
<td>2.4</td>
<td>2.4</td>
</tr>
<tr>
<td>10</td>
<td>Bare Carbon Steel</td>
<td>4.9</td>
<td>4.9</td>
</tr>
<tr>
<td>1</td>
<td>Bare Carbon Steel</td>
<td>6.0</td>
<td>6.0</td>
</tr>
<tr>
<td>31</td>
<td>Bare Carbon Steel</td>
<td>7.3</td>
<td>7.3</td>
</tr>
<tr>
<td>26</td>
<td>Bare Carbon Steel</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>27</td>
<td>Coal Tar Epoxy</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>28</td>
<td>Coal Tar Epoxy plus Armor</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

*For front: mils per year x 0.38 = milligrams per square decimeter per day.

**Distance from bottom of pile:**

---

Notes:
- Flange thickness measurements not made on pile piles.
FIGURE 30 Example of Galvanic Corrosion Cell (Watkins 1969)

- Cathode material does not corrode.
- Anode material corrodes.
- Ions from Anode are neutralized by Electrons from Cathode.
- Electrically charged particles (Ions) break away from Anode material and move through Electrolyte to Cathode.
- Container
metal structures only one metal is used, but corrosion cells are developed because of the difference in electrical potential caused by different environments (air, seawater, soil) surrounding different parts of the structure. Electrically charged particles flow from the anode to the cathode causing a loss of material at the anode. If the anode is larger than the cathode, a minimum of corrosion occurs. But if the cathode is larger than the anode, a small area is required to satisfy the potential for a large area and severe corrosion can occur.

The basic difference between the two cathodic protection systems is that, in the galvanic system, the source of the required electric current is the difference in electrical potential between two connected unlike potential areas; in the impressed-current system, direct current of sufficient magnitude is supplied by an outside source to force an area to be either anodic or cathodic as desired.

Corrosion of marine structures can be caused by a nonhomogeneous surface, a nonhomogeneous electrolyte, or biological action.

- A common nonhomogeneous surface is a break in the paint coating or a break in the mill scale of new steel, either of which will cause a concentration of corrosion.

- A nonhomogeneous electrolyte is created when another liquid flows into the water in which a structure is submerged. This is a frequent cause of corrosion near river mouths, discharge outlets of factories, or sewage treatment plants. Differences in entrapped air caused by the wave action against a structure also result in a nonhomogeneous electrolyte.

- Biological organisms that adhere to a metal structure can also cause corrosion. Severity is dependent on the type of organism. Sulfate-reducing bacteria actively influence corrosion; barnacles and mollusks create a corrosion condition by damaging the protective coatings or by creating oxygen depletion or concentration cells. Antifouling paints may be used to protect against marine organisms, but these paints generally contain metal and if they are placed on bare metal a galvanic cell may be formed that can cause more damage than the organisms.

Six corrosion zones may exist in a marine structure; the corrosion tendency and method of protection are zone-dependent (US Coast Guard 1967).

- The atmospheric zone is the area of the structure above the maximum normal wave at mean high tide. This area is subjected to normal atmospheric corrosion with local pockets of corrosion forming in crevices and surface pits. Both types of corrosion will be accelerated by the salty environment. These areas are protected by paint or other coatings and by the elimination of areas where water can collect.

- The splash zone is the region above the mean high water line that is subject to wave attack. Corrosion tends to be accelerated here because of the removal of any protective coatings by the wave action; the latter directly determines the severity of corrosion. Because paints or
other coatings are difficult to maintain in this region, additional thickness is commonly provided to the metal.

- The tidal zone is the area on the structure between mean low and mean high water level. The area around mean low water is always submerged, but in an oxygen-rich environment it is usually cathodic compared to the areas above or below it. Therefore the area just below the low water level, which acts as an anode, is generally subjected to the most severe corrosion of any area on the structure. Cathodic protection or coatings combined with cathodic protection have been used to prevent corrosion in this zone. Since the corrosion is generally severe, an increase in metal thickness is usually allowed for in the design.

- The permanent immersion zone is located between the mean low water and the mudline. The rate of corrosion in this zone is generally small and uniformly distributed. Heterogeneous metal, heterogeneous electrolyte, and biological action cause corrosion in this zone. Cathodic protection, a protective coating, or a combination of the two has been used for corrosion protection.

- The mudline zone is also prone to corrosion, caused by the change in electrolyte between the water and mud, and debris or sediments that tend to scour off protective coatings. Bacteria that contribute to corrosion are also located here. Cathodic protection is usually effective.

- The soil zone is the embedded portion of the structure. Corrosion is usually light unless the soil contains a high concentration of metal compounds or corrosive bacteria. This zone tends to be self-protecting, although cathodic protection may sometimes be needed.

The preceding sections have shown that steel structures can be protected in many ways. The options for a particular structure need to be weighed in the context of site conditions, water conditions, and economics.
ASBESTOS CEMENT

The asbestos normally used for cement products is a hydrated magnesium silicate commonly known as chrysotile, a fibrous form of serpentine having fibers a few centimeters long (Orchard 1979). Because of their crystalline structure, the fibers show a clear tendency, under mechanical treatment, to split into ever thinner fibers. This tendency enables the cement particles to envelop all fibers or small bundles of fibers, permitting full anchorage of the reinforcement (Krenchel 1974).

Asbestos cement, a mixture of fibers, cement, and water, is highly resistant to chemical corrosion and abrasion (Klos 1975), with no evidence of deterioration in its bending strength over long periods. Still, the impact strength of asbestos cement sheets falls to about 50 percent of its initial value after 10 to 15 years (Majumdar 1975).

Asbestos cement sheets have been used in the marine environment as bulkheads for protection against wave and current erosion. This material is subject to three types of corrosion attack: 1) sulfate attack; 2) carbon dioxide attack; and 3) the freeze/thaw cycle (Watson, Machemehl, and Barnes 1979).

Sulfates in the seawater react with calcium hydroxide, Ca(OH)$_2$, in the concrete, which is produced by hydration of normally cured Portland cement. The reaction of the sulfates and Ca(OH)$_2$, produces gypsum:

\[
\text{Ca(OH)}_2 + \text{SO}_4^{2-} + 2\text{H}_2\text{O} = \text{CaSO}_4^{2-} + 2\text{H}_2\text{O} + 2(\text{OH})^{-}
\]

Gypsum in turn reacts with the tricalcium aluminate (C$_3$A) in cement to form ettringite, a mineral with a volume 36 percent greater than the original materials, by the reaction:

\[
3\text{C}_3\text{A} + 3\text{CaSO}_4 + 31 \text{H}_2\text{O} = 3\text{C}_3\text{A} \cdot 3\text{CaSO}_4 \cdot 31 \text{H}_2\text{O}
\]

The creation of this material produces internal swelling and eventual cracking of the cement, leading to deterioration (Watson, Machemehl, and Barnes 1979).

Carbon dioxide (CO$_2$) corrosion alters the cement makeup as the water passes through the concrete, causing deterioration, strength loss, and leaching. CO$_2$ will deplete the surface of the cement of Ca(OH)$_2$ leaving it open for calcium carbonate (CaCO$_3$) to dissolve. After the above reaction occurs, the cement is conducive to leaching of other constituents.

The freeze/thaw cycle is very destructive to low-density, permeable cement products such as asbestos cement.
Watson, Machemehl, and Barnes (1979) conclude:

- Severe deterioration occurs through the reaction of aggressive CO₂ with CaCO₃. The resulting calcium bicarbonate, Ca(HCO₃), is leached out of the structure, decreasing its density.

- Asbestos cement is vulnerable to carbonic acid attack in areas where biological decay produces excessive CO₂ and the water pH is less than 7.

- Autoclaved asbestos cement is not as susceptible to carbonic acid as normal asbestos cement because of its nonreactive silica content, which may delay extensive deterioration.

- Autoclaved asbestos cement is subject to corrosion in seawater, possibly because of the sulfate concentration.

Not only is asbestos cement questionable for waterfront construction because of deterioration problems, but asbestos itself has come under question. The demand for asbestos is exceeding the supply, and recent studies suggest possible health hazards. Although asbestos products have been used for years in the building industry, and although the material is highly chemical- and abrasion resistant, its use as a waterfront construction material requires further study including long-term tests.
ALUMINUM

Aluminum is a high-strength, corrosion-resistant alloy that produces a durable, low-maintenance structure. It is used for boat hulls and dock systems, and retaining walls, bulkheads, and groins. Aluminum sheet piles are relatively lightweight and therefore easy to handle and install. Aluminum was first used in seawater in 1970.

There is little or no environmental reaction in normal conditions. The trade literature indicates that use is suitable within a pH range of 4 to 9, with an allowable soil resistivity of 500 ohm-cm or greater. For installation, free-draining soils (sand) are preferred for structural reasons; this type of soil will also allow an oxide barrier to form rapidly whenever the pile is attacked. Electrolysis is not a concern as long as no electrical outlets are grounded near the structure where stray electrical currents might cause damage. However, metal-hulled boats, other than aluminum, tied alongside and in direct contact with an aluminum structure may cause electrolysis to occur.

Although aluminum is an active metal, its behavior is stable because of the protective, tightly adherent oxide film on its surface. When disturbed, this film begins to re-form immediately if oxygen or air is present. As long as this oxide film remains intact and continuous, or can re-form after damage, the aluminum will maintain a high resistance to corrosion.

Although studies by the industry have minimized many potential problems, corrosion is still possible in aluminum structures. It is caused by the flow of electric current between various anodic and cathodic regions. The current flow, and therefore the rate of corrosion, are affected by: alloy constituents, metallurgical and thermal treatments, pH, galvanic corrosion, stray currents, and soil resistivity.

Aluminum alloys are subject to many types of corrosion; uniform and pitting are the most common. If the type of corrosion is known, the problem can be analyzed and solved.

In uniform corrosion, the metal corrodes evenly. Strong acid or alkaline electrolytes that dissolve the oxide film and prevent its re-formation usually cause this type of corrosion. The attack is characterized by superficial etching and staining, to rapid dissolution of the metal. The attack can be evaluated by measuring the weight loss or decrease in thickness of the material.

Corrosion by pitting is most common. Exposure to weather, fresh or saltwater, or other electrolytes may cause pitting at localized discontinuities in the oxide film. Pitting often appears more severe than it actually is because of the buildup of corrosion products that occupy several times the volume of metal removed. Pitting is difficult to evaluate, although the rate may be indicated by measuring the pits.
ALUMINUM GROIN

An Illustrative Aluminum Groin. Structural Components Vary with Design Requirements.

Illustration 7.
Long-term tests of aluminum alloys in industrial, chemical, seacoast, tropical, and many other environments indicate that although the rate of corrosion may at first appear severe, it decreases during the early months and years to a relatively slow rate. The corrosion also tends to spread laterally along the surface of the pile rather than deepening.

Aluminum sheeting, like other materials, has its advantages and disadvantages. It may work well in protected or semi-protected areas, but has been used very little in areas of severe wave attack. Aluminum sheeting should be considered as an option during the feasibility study of a project.
GABIONS

The first factory-fabricated metal gabion was erected in 1894 to seal a breach in the bank of the Reno River near Bologna, Italy (Rodie 1976). Since then gabion use has spread almost worldwide.

A gabion is a simple wire and rock structure used for erosion control and soil stabilization. For erosion control, a wire mesh mattress is used with a thickness commonly 9 to 12 inches (229 to 305 mm) and a 6.5 foot (2.0 m) width with 6, 10, and 12 foot (2.4, 3.0, and 3.7 m) lengths. In the mattresses, the stone size is normally 4 to 6 inches (102 to 152 mm); uniformly graded, hard, durable, clean stone of nearly any shape can be used. Filling may be by hand or machine, depending on local labor economics. Gabion mattresses have been used for stream bank protection, channel liners, spillway and culvert aprons, and bridge abutment protection systems.

Gabion baskets may be used in conjunction with the mattresses or by themselves in revetments, weirs, groins, or gravity-retaining structures. The baskets are commonly 3 feet (0.9 m) wide, 5, 9, or 12 feet (1.8, 2.7, or 3.7 m) long, and 1, 1.5, or 3 feet (0.3, 0.5, or 0.9 m) thick. Depending on the site conditions, a variety of standard sizes of gabions exist that essentially act as a flexible gravity protection structure. The rock size in the baskets is normally 4 to 8 inches (102 to 203 mm) of hard, durable, sound rock with angular surface.

If the soil conditions are such that a migration of fines may occur from beneath the structure, a filter cloth may be desired to prevent this. If vehicles will be driven over the gabions, such as in boat ramps, or if severe deterioration is likely to occur, as in a weir, a concrete cap 2 to 3 inches (51 to 76 mm) thick may be poured over the gabions. After the gabions have had time to trap soil particles, an esthetically enhancing vegetation of the system often occurs.

The contemporary gabion is a compartmental, rectangular container made of thick steel wire that is woven with a triple twist at all intersections. The hexagon-shaped openings are approximately 3.25 by 4.25 inches (83 by 108 mm wide), and each gabion unit is wired to its neighbor to form a variety of gravity protection structures.

Gabions have been used in all climates. They are constructed of 11-gauge galvanized steel suitable for land applications and fresh water where the pH of the fluid in contact with the structure is not less than 7 nor greater than 12. In saltwater, polluted streams, or highly corrosive areas, 12-gauge steel wire is used with a polyvinyl chloride (PVC) coating over the galvanizing.

The advantages of gabions are: 1) they are highly flexible and will adjust to uneven ground or settlement; 2) they can be filled and placed underwater with minimal problems; and 3) since they are permeable, drainage is not restricted and a hydrostatic head is not likely to develop. In many cases, sediments gradually fill in the voids and vegetation growth occurs, increasing
GABION REVETMENT
An Illustrative Gabion Revetment. Structural Components Vary with Design Requirements.

Illustration 8.
the integrity of the structure. A potential disadvantage is that if the PVC coating is damaged during placement or by sustained sediment abrasion, the wire will be exposed to corrosion.
SYNTHETIC FABRICS

Synthetic fabrics are becoming a common item in the construction business for use as filter fabrics, as grout- or sand-filled bags for erosion protection, and as form work for pile jackets. They are usually made from nylon, polyester, polypropylene, polyamide, polyethylene, or combinations of these, either by the traditional weaving method of the fibers or by bonding by a mechanical, thermal, or chemical process into a nonwoven form. Nylon is commonly coated with a polyvinyl chloride or acrylic to prevent fiber deterioration by ultraviolet rays (Welsh and Koerner 1979).

Coastal protection systems have used fabric sacks of various shapes and sizes to provide either temporary or long-term protection. The temporary protection systems use sand to fill the fabric sacks; the long-term systems use either mortar or cement. The sacks may be interlocked to form a continuous barrier or placed individually depending on the protection required. Common names for these fabric sacks are Fabriflow molded blocks, Durabags, and Bolsacretes.

In waterfront protection systems, filled fabric sacks have been used for groins, underwater pipe racks, and as soil retaining structures. Fabric sections have even been used as pile jackets: a fabric sleeve is zipped up around a pile, enclosing the pile and a reinforcing mesh banded off at the top and bottom, and pumped full of mortar or concrete. Another design is a mattress 4 to 8 inches thick (102 to 203 mm) to be used as a channel liner, bridge abutment protector, or revetment.

The forms that the fabric can take are virtually unlimited, and since the fabric is filled with either sand or a concrete mix, almost any shape can be constructed. No heavy equipment is needed for filling these sacks, mattresses, or pile jackets, some type of slurry pump normally suffices.

Although a variety of protection systems use synthetic fabrics, there are four basic forms: 1) filter cloth; 2) tube forms; 3) erosion control mattresses; and 4) pile jackets.

Filter cloth is used to prevent the leaching out of fines or for retaining a separation of materials while allowing free drainage. Filter cloths have been used extensively under riprap, making graded filter stones unnecessary. In road subgrades, filter cloth is used to keep materials separated; and behind waterfront protection structures, filter cloth allows drainage but prevents a migration of the fine soil particles.

Tube forms of the synthetic fabrics have been inflated with concrete to a height of 3 feet (0.9 m) and a length of over 100 feet (30.5 m) (Welsh and Koerner 1979). These tube forms, either above or below the water, will assume a shape with the height equal to one-half the width. They may be filled with either sand or concrete and may be of almost any dimension.
There are two types of erosion control mattresses. The first is the uniform thickness mattress, constructed of two layers of cloth connected by internal spacer threads that dictate the thickness that will be obtained upon filling. These mattresses are relatively impervious, although filter points for weep holes may be included. The second type of mattress is made up of two layers of fabric connected on 5 or 8 inch (127 or 203 mm) centers with filter points. This gives a cobblestone appearance to the finished mattress and allows for drainage while preventing material migration.

Pile jackets are needed in marine environments, where all piles suffer varying rates of deterioration. Piles of wood, steel, and concrete are all affected differently in this environment, but they are all commonly repaired with some kind of concrete or grout sleeve. The fabric pile jackets can be made in any size and installed with less manpower and equipment than steel forms.

Synthetic fabrics work well in many waterfront construction or repair projects, and should be considered during project feasibility studies.
REINFORCED SOIL

Birds and some animals have always used reinforced soil for habitat construction. Man has reinforced soil since biblical times to strengthen adobe bricks, and the Gauls used alternate layers of earth and logs to build fortifications (Chang and Forsyth 1977).

Reinforced soil has been defined as a construction material composed of soil fill strengthened by the inclusion of rods, bars, fibers, or nets that interact with the soil by means of a frictional resistance (Lee, Adams, and Wagner 1973). There are two basic soil reinforcement concepts in use today: 1) using a single layer of foreign material to act as a separator between the original ground surface and the fill material being placed; and 2) using a multilayered system of reinforcing material and soil.

Separators have consisted of materials such as: 1) bamboo bundles to support embankments on soft, marshy lands; 2) log mats for support of road surfaces over swamps or areas of poor soil; 3) polyethylene tubes cabled together to form a mat for vehicle support in snow or soft mud; and 4) plastics or paper sand-filled cells for use in road subgrades (Holtz 1978). Some of these systems perform the same task as filter fabrics. The purpose of the separators is to take up the shearing stresses applied by the fill to the foundation (Holtz 1978).

The multilayered concept is the Reinforced Earth* system currently finding wide acceptance in highway embankments, earth- and slope-retaining structures, platform supporting structures, underwater structures, and such fresh- and saltwater marine structures as seawalls and bulkheads. The horizontal reinforcing elements provide the soil mass with tensile strength, and the vertical-facing elements to which the reinforcement is attached enclose the soil mass and help prevent sloughing of the face.

The reinforcing elements so far proposed for use in these structures include aluminum and alloys, mild steel (bare and organic-coated), galvanized steel, aluminized steel, stainless steel, copper alloys, glass reinforced plastics (GRP), synthetic organic webbings and woven fabrics, and reinforced concrete planks (King and Nabizadeh 1978). Metals and reinforced plastics are not the only reinforcing members being tried; tire sidewalls are also being tested in a California road embankment (Forsyth 1978). The facing elements are usually precast and can be easily placed in the field. They are produced in a variety of sizes, shapes, and materials.

To obtain a reinforced soil structure that is effective, the fill material and the reinforcing material must be compatible. Minimizing cost requires a design that can use local fill, the minimum reinforcement of the cheapest material, and the fastest construction procedure (King and Nabizadeh 1978). But finding a local fill material that is compatible with the cheapest reinforcement strips may not be easy. It is possible that the local fill is corrosive or will react in some way with many of the reinforcing strips, so

*Reinforced Earth is a company that specializes in soil reinforcement; many other approaches are in use.