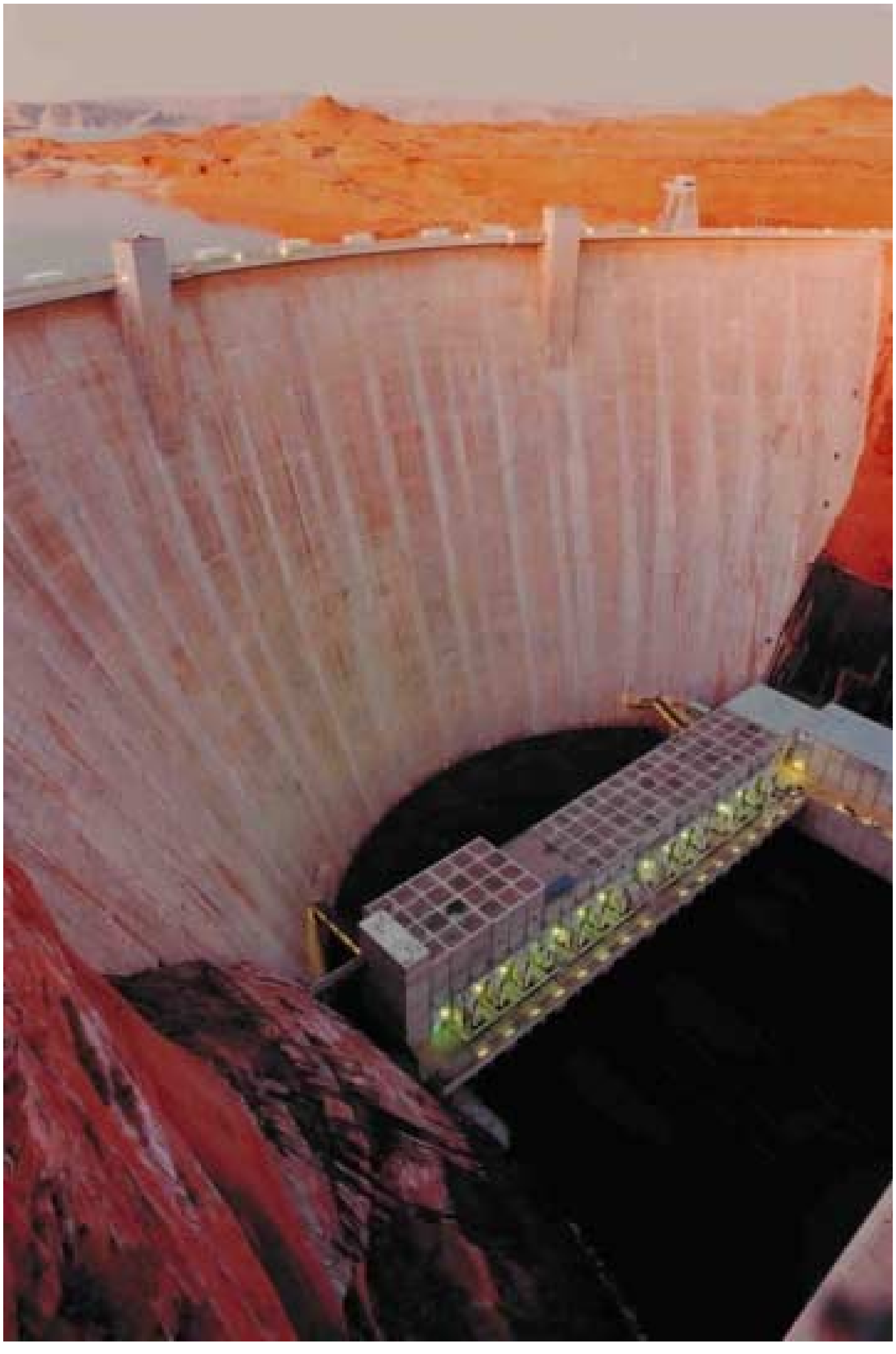
# APPENDIX F

# WATERWAYS AND PORTS



Port

Corroded columns at water line

Dam (concrete rebar corrosion)


Piling (steel corrosion)

# WATERWAYS AND PORTS

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## SUMMARY

The United States has approximately 40,000 km (25,000 mi) of navigable waterways, 600 ports and locks, and 10,000 waterfront facilities. Corrosion is typically found in piers and docks, bulkheads and retaining walls, mooring structures, and navigational aids. Corrosion occurs on structures exposed to both fresh water and saltwater conditions.

There is no formal tracking of the corrosion-related costs, and the estimates show that the annual expenditures for corrosion control to be as high as $293.4 million. Corrosion is primarily controlled by the surface coating systems and sacrificial cathodic protection systems.

Corrosion is seen as a significant issue within waterways and ports. Unfortunately, due to budgetary constraints, funds for structural maintenance to protect against corrosion are often in short supply. For example, the U.S. Army Corps of Engineers owned or operated 276 lock chambers at 230 sites in 1998; however, only 191 of these sites with 237 lock chambers received funding for maintenance.

Examples of neglected structures include single-pile navigational aids that are left in service until the corrosion is so severe that failure occurs. Subsequently, not only is a new $15,000 navigational aid necessary, but also the remaining pole that exists underwater becomes a hazard and must be removed.

Structures with higher initial capital costs are more likely to be protected either by coatings and/or cathodic protection. Structures such as lock gates, dam gates, and other water-containing devices are also protected to ensure their proper operation.

In the past 25 years, waterways and ports have benefited from advances in the quality of the available coating systems. The choice and development of coatings have also been affected by environmental regulations specifying which coatings can be exposed to water streams. For example, regulations have minimized the amount of volatile organic compounds that can be used in coatings.

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# SECTOR DESCRIPTION

The United States has more than 7,750 commercial water terminals, 192 commercially active lock sites with 238 chambers, and 40,000 km (25,000 mi) of inland, intracoastal, and coastal waterways and canals.(1) Forty-one states, 16 state capitals, and all states east of the Mississippi River are served by commercially navigable waterways.(2) Public and private works associated with waterways and ports have corrosion-related issues in both freshwater and seawater environments.

## Public and Private Works

Public works waterway structures, which are primarily operated and maintained by the U.S. Army Corps of Engineers, include locks, dams (see figure 1), navigational aids, levies, and dikes. These structures are on primarily freshwater lakes and rivers. Many freshwater public works related to irrigation and flood control are owned, operated, and maintained by state and local agencies such as the Tennessee Valley Authority (TVA) or the California Aqueduct.

Figure 1. Example of a steel-reinforced concrete dam.

Public docks, piers, and bulkheads are mostly owned and maintained by port authorities. These public agencies have structures in both fresh water and seawater; however, most of the larger ports are in marine locations.

In addition, there are also a significant number of private terminals for loading grain and commodities (e.g., coal) owned by shipping companies and railroads. These private terminals are located in both freshwater and marine environments. The large size of most structures at port facilities requires that they be built with steel-reinforced concrete, steel, or a combination of both. The environment at seawater locations is significantly more severe than that at rivers and lakes due to the high chloride content in the seawater.

Not included in this sector are military installations and utility-owned hydroelectric power generation dams. Military installations that include a large number of piers and shipyard facilities are addressed in the Defense sector (Appendix BB), while utility-owned hydroelectric power generation dams are described in the Electrical Utilities sector (Appendix L) of this report.

## AREAS OF MAJOR CORROSION IMPACT

### Seawater

The reinforced-concrete structures exposed to the marine environment suffer premature corrosion-induced deterioration by chlorine ions in seawater. Corrosion is typically found in piers and docks, bulkheads and retaining walls, mooring structures, and navigational aids.

The marine environment can have varying effects on different materials depending on the specific zones of exposure. Atmosphere, splash, tide, immersion, and subsoil have very different characteristics and, therefore, have different influences on corrosion.[3] Figure 2 shows the relative metal loss for steel piling after 5 years of exposure to seawater at Kure Beach, North Carolina.

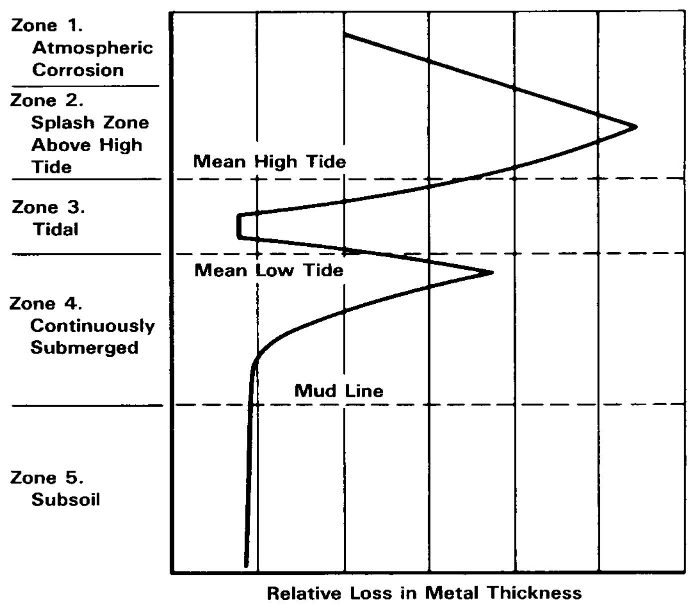


Figure 2. Corrosion profile of steel piling after 5 years' exposure in seawater at Kure Beach, North Carolina.[3]

Atmospherically exposed submerged zones and splash zones typically experience the most corrosion. These zones are found on piers and docks (ladders, railings, cranes, and steel support piles), bulkheads and retaining walls (steel sheet piling, steel-reinforced concrete elements, backside, and anchors on structures retaining dredged fill), and mooring structures and dams (steel gates, hinges, intake/discharge culverts, grates, and debris booms). Stationary navigational aids suffer from corrosion of support piles and steel-reinforced concrete pile caps. Floating steel buoys are subject to corrosion as well.

### Fresh Water

Airborne or splash zone attack is normally not a problem at freshwater facilities; however, air pollution can cause potential problems. Under certain flow conditions, such as turbulent flow or cavitation, fresh water can cause severe corrosion to submerged metallic elements. Ice damage also can limit the effectiveness of coatings on bulkhead walls and support piling.

Piers and docks, bulkheads and retaining walls, locks, dams, and navigational aids exposed to freshwater environment experience corrosion-related problems. The most common areas of attack include submerged and splash zones on support piles (piers, docks, and navigational aids) and steel sheet piling (bulkheads and retaining walls). These zones are also found on locks (steel gates, hinges, intake/discharge culverts, valves, and sheet pile walls), dams (steel gates, hinges, intake/discharge culverts, grates, and debris booms), and navigational aids (anchorages).

## Costs of Corrosion

### U.S. Army Corps of Engineers-Maintained Structures

Some cost of corrosion information on lock and dam structures can be obtained from the U.S. Army Corps of Engineers' maintenance and capital budgets. In a 1986 study,(4) the total cost of corrosion to the Corps of Engineers in the Ohio River Division, the Civil Works Component, was estimated to be between 4 and 7 percent of the total annual operation and maintenance (O&M) budget. Using a typical value of 5 percent of the total 1999 Corps of Engineers O&M budget of $1.4 billion, the total annual corrosion-related maintenance cost was estimated at approximately $70 million.(5)

The above study further indicated that a large number of the structures maintained by the Corps of Engineers are currently at the end of their design life, which would require staggering replacement costs.

### U.S. Public Ports

Public port authorities operate maritime cargo and cruise ship terminals along the Atlantic, the Pacific, and the Gulf coasts. Freshwater facilities are located in the Great Lakes region and on some major rivers. The American Association of Port Authorities (AAPA) also includes members from Canada and the Caribbean; however, the vast majority of seaports are located within the United States. The AAPA website(6) indicates that in the United States, there are 3,214 deep-draft ship berths located at 1,941 public and private terminals on coastal and inland waterways.

The AAPA Facilities Engineering Committee(7) indicated that corrosion costs are not tracked individually in O&M budgets and that cost data for the 1999 port expenditure survey were still being gathered. However, a previous survey revealed that the 83 port authority members in the United States had spent a total of $919 million on O&M in 1998.

The corrosion cost assessments can be made using the approximate cost (as a percentage of the total O&M budget) provided by the U.S. Corps of Engineers (5 percent). Since the Corps of Engineers maintains primarily freshwater structures, this value is most directly applicable to the freshwater ports.

Because marine structures are in a significantly more aggressive environment, corrosion costs are likely to be higher as coastal terminals have much higher atmospheric and splash zone corrosion rates. In addition, coating costs for berthing structures and cranes at saltwater marine terminals would be substantially greater than those for the freshwater facilities. Based on this information, it is estimated that approximately 5 percent of freshwater facility costs and 10 percent of saltwater marine port costs are corrosion-related.(5)

In 1998, about 20 percent of the 83 AAPA facilities were located in fresh water (mostly in the Great Lakes region); however, these freshwater structures were much smaller than the saltwater marine ports, such as New York or the Port of Long Beach. Adjusting for the size of the facilities, it is estimated that approximately 90 percent of the AAPA terminals are in saltwater environments and approximately 10 percent are in freshwater environments. Combined with the previous assumptions with respect to the fractions of the O&M budget attributable to corrosion, the estimated annual cost of corrosion-related maintenance in the U.S. public ports is $87.3 million.[2]

[2] Calculated as (10% x 90% + 5% x 10%) x $919 million

The AAPA website[(6)] further reveals that, between 1997 and 2002, the U.S. public ports will spend $1.9 billion per year on construction and modernization, and that much of this infrastructure construction is necessary to accommodate growth and handling of the larger modern container ships. Even if only 5 percent of this expenditure is spent on replacing corrosion-damaged berthing facilities, $95 million can still be attributed to the annual cost of corrosion.

The analysis above indicates that the annual cost of corrosion in the public port authority sector of the ports and waterways can be estimated at $182.3 million ($87.3 million + $95 million). It should be noted that as there was no available concrete data, the estimate is based on the assumptions made by the authors; therefore, the annual expenditures may differ substantially from the estimate.

## U.S. Coast Guard

The U.S. Coast Guard maintains navigational aids such as light structures and buoys that are continuously exposed to harsh environments in both fresh water and seawater.

According to the U.S. Coast Guard,[(8)] there are more than 21,000 navigation structures nationwide that range in size and complexity from simple unlit day beacons (a single wooden "telephone pole" driven into the bottom) to massive, multi-million dollar offshore lights and range structures.

The majority of the navigational aids are found in the Gulf Coast and are considered to be "simple" structures, such as a single-pile or a multiple-pile steel or wood construction.[(8)] Single-pile structures are not maintained and are, in fact, allowed to rust until they are replaced. Estimated costs are $15,000 per single-pile structure.[(9)]

Larger light structures are protected using epoxy coatings and zinc sacrificial anodes. New structure costs can range from $300,000 to $600,000, while the coating and sacrificial anode costs are estimated at $20,000 per system. The life expectancy of the coatings and sacrificial anodes are approximately 15 to 20 years.

Older lighthouses, initially constructed of iron in the 1800s and weighing approximately 600 tons, are still in use today. These massive structures require maintenance and sandblasting every 15 to 20 years at an estimated cost of $750,000 each.[(9)] There are 615 of these structures in the United States, with average annual routine maintenance expenditures of $750 per unit, for a total cost of $461,250 per annum. The combined cost of the lighthouse maintenance is therefore estimated at $23.5 million.[3]

The U.S. Coast Guard maintains foam, plastic, and steel buoys of different sizes and shapes in both fresh water and seawater. According to the U.S. Coast Guard,[(8)] approximately $2 million is spent each year to replace steel ocean buoys that cost between $15,000 and $18,000 each. It is estimated that there are 11,640 steel buoys with an expected service life of 40 years for each buoy. These buoys are often hit by boats and are continuously in harsh environments; however, epoxy and anti-fouling paints, which are to be reapplied every 6 years, can protect them. The estimated costs for labor and supplies to paint buoys are $5 million a year.

About 75 percent of river buoys are lost within a year of being put into service, the remainder of the river buoys often last 2 to 3 years.[(8)] The steel river buoys, made of sheet metal with a foam filling, cost between $170 and $330 each. Given the relatively small cost of the river buoys compared to the steel ocean buoys, river buoys are viewed as consumables and are replaced if they sink or are lost; therefore, they are not considered maintenance expenditures.

Annually, the U.S. Coast Guard spends approximately $2 million to purchase 5,000 to 7,000 replacement river buoys.[(8)]

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[3] Calculated as $750,000 / 20 x 615 + $460,000

### Corrosion-Related Maintenance Costs

In 1999, the U.S. Coast Guard spent an estimated $60 million on the east coast[(10)] and $31 million in the Pacific[(11)] on maintenance costs. These costs include maintenance performed on land and sea facilities, corrosion-related repairs, and any other activity necessary to maintain the safety of the waterways.

Applying the corrosion-related O&M budget fractions estimated for the U.S. Army Corps of Engineers (5 percent for fresh water and 10 percent for saltwater) and a similar assumption that 90 percent of the structures maintained by the U.S. Coast Guard are in a saltwater marine environment and the remaining 10 percent are in a freshwater environment, the annual cost of corrosion-related maintenance for 1999 can be estimated at $8.6 million.

## Total Costs

Total annual corrosion-related costs for this sector are shown in table 1.

Table 1. Total annual corrosion-related costs.

| CATEGORY | COST ($ x MILLION) |
|---|---|
| U.S. Army Corps of Engineers | |
| Maintenance @ 5% | 70.0 |
| **SUBTOTAL** | **70.0** |
| U.S. Public Ports | |
| Corrosion-Related Maintenance | 87.3 |
| Corrosion-Related Replacements | 95.0 |
| **SUBTOTAL** | **182.3** |
| U.S. Coast Guard | |
| Lighthouse Maintenance | 23.5 |
| Replace Steel Ocean Buoys | 2.0 |
| Paint Buoys | 5.0 |
| Replace River Buoys | 2.0 |
| Corrosion-Related Maintenance | 8.6 |
| **SUBTOTAL** | **41.1** |
| **TOTAL** | **$293.4** |

## CORROSION CONTROL METHODS AND MANAGEMENT PRACTICES

Typical corrosion control methods for freshwater structures include coatings for atmospherically exposed steel and corrosion allowances for submerged and splash zone steel. Dielectric coatings are normally used for structural steel above water, while galvanizing is often used for railings, ladders, gates, and gratings. Copper-bearing steel alloys are sometimes utilized for structural elements and sheet pile walls. These alloys, which form a tenuous oxide film in the atmosphere, provide little help when buried or submerged. Cathodic protection (CP) is occasionally used on submerged steel elements.

Marine corrosion control methods also include coatings for atmospherically exposed steel elements and a corrosion allowance for submerged and splash zone steel structures. Specialty marine dielectric coatings are normally used for structural steel above and often below water. Although galvanizing is used for railings, ladders, gates, and gratings, non-ferrous alloys provide better service in the aggressive saltwater marine conditions. Marine structures commonly use CP to control corrosion on submerged steel. CP is occasionally used on atmospherically exposed steel-reinforced concrete, particularly in warm climates [see additional discussion on the subject in the "Highway Bridges" sector (Appendix D) of this report]. The most cost-effective corrosion control on submerged and splash zone steel is achieved by using CP in conjunction with a heavy dielectric coating. Although corrosion allowances are often used for saltwater marine structures, they are not as helpful as in fresh water because the corrosion damage tends to be more localized in the tidal zone (wet/dry cycling) and at the mud interface zone.

While corrosion may be seen as a significant issue within waterways and ports, due to budgetary constraints, funds for structural maintenance to protect against corrosion are often in short supply. For example, the U.S. Army Corps of Engineers owned or operated 276 lock chambers at 230 sites in 1998, but only 191 of these sites with 237 lock chambers received funding for maintenance-related projects.[2]

Examples of the neglected structures include single-pile navigational aids that are left in service until the corrosion is so severe that a failure occurs. Not only is a new $15,000 navigational aid necessary, the remaining underwater pole becomes a hazard and must be removed as well.

Structures with higher initial capital costs are more likely to be protected either by coatings and/or CP. These include lock gates, dam gates, and other water-containing devices, which are protected to ensure their proper operation.

In the past 25 years, waterways and ports have benefited from advances in the quality of the available coating systems. New technologies that have been developed include metallizing, application of epoxies, and 100 percent solids coatings.

The choice and development of coatings have also been affected by environmental regulations specifying which coatings can be exposed to water streams (e.g., regulations have minimized the amount of volatile organic compounds (VOC) that can be used in coatings. Coatings with 100 percent solid content have been developed that contain no volatile solvents (before, coatings with 25 percent to 50 percent solid content were used). In addition to the epoxy coatings, anti-foulants are applied to submerged sections of the structure to prevent microbiologically induced corrosion (MIC).

Epoxy coatings cost approximately $4.7 to $5.3 per L ($18 to $20 per gal), while anti-foulants are much more expensive at approximately $11.8 to $21.1 per L ($45 to $80 per gallon).[12] Environmental regulations have also led to a decreased amount of chemicals released from industrial installations along waterways, especially corrosive ones such as chlorine. The materials of construction for some water structures have changed as well. Piers and docks are no longer being constructed with wood, but instead are being constructed with steel-reinforced concrete. To improve the lifespan of the structure and prevent corrosion of the reinforcing steel, fusion-bonded epoxy-coated reinforcement or corrosion-inhibiting admixtures are sometimes utilized in the concrete mix.

# REFERENCES

1. *An Assessment of the U.S. Marine Transportation System, A Report to Congress,* The Marine Transportation System (MTS), www.dor.gov/mts/report, September 2000.

2. "Navigation Data Center Publications and U.S. Waterway Data" CD, U.S. Army Corps of Engineers, Alexandria, VA, Volume 6, 2000.

3. J.A. Beavers, G.H. Koch, and W.E. Berry, *Corrosion of Metals in Marine Environments*, Metals and Ceramics Information Center, A Department of Defense Information Analysis Center, Batelle Columbus Division, Columbus, OH, June 1986.

4. C.C. Lozar, *Cost Analysis of Corrosion in Ohio River Division O&M Functions*, Champaign, IL.

5. A. Kumar, U.S. Army Corps of Engineers, Construction Research Laboratory, Personal Communication, 2000.

6. American Association of Port Authorities (AAPA), www.aapa-ports.org, September 2000.

7. E. O'Connell, Staff Liaison, AAPA Facilities Engineering Committee, Personal Communication, July 2000.

8. W. Danzik, Buoy and Structures Team Leader, U.S. Coast Guard, Personal Communication, September 2000.

9. Lieutenant S. Wagner, U.S. Coast Guard, Personal Communication, September 2000.

10. Lieutenant Commander J. Heinz, Executive Officer, CEU Miami, Atlantic Maintenance Logistics Command, U.S. Coast Guard, Personal Communication, September 2000.

11. Lieutenant Commander S. Powers, Pacific Maintenance Logistics Command, U.S. Coast Guard, Personal Communication, September 2000.

12. R. Bluffin, Devoe Coatings, Personal Communication, September 2000.