UNDERWATER STEEL STRUCTURES: INSPECTION, REPAIR AND MAINTENANCE

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ABSTRACT

Immersed steel structures in the splash zone are subject to an aggressive form of corrosion that is commonly referred to as Accelerated Low Water Corrosion (ALWC). Inspection, repair, and maintenance are both difficult and labor intensive. The Unified Facilities Criteria for Maintenance of Waterfront Facilities (UFC 4-150-07) describes various methods to repair and maintain underwater steel structures that suffer ALWC. This document complements UFC 4-150-07 with a system to rapidly inspect, repair, and maintain submerged components of waterfront structures, such as steel sheet piling on bulkheads. The system deploys a mobile cofferdam to access underwater steel structures in a dry environment.

The purpose of this document is to provide a source for planning, estimating, and performing technical maintenance and repair work of immersed steel sheet piling. It compiles historical data, long-term results and lessons-learned from the deployment of mobile cofferdams at various locations throughout the world for the past twenty years.

Technical Sections identify unique requirements of mobile cofferdams and include

- Site conditions for deployment of a cofferdam
- Performance criteria for structural design, ventilation, lighting, sealing, de-watering, and deployment of a mobile cofferdam.
- Safety and environmental considerations
- Unique skills and special materials for executing work

Project Sections include guidelines to assist Facilities Corrosion Management and include

- Tools for estimating project costs and duration
- Comparisons to related technologies
- General labor, equipment and material requirements
- Repair Procedures

Keywords: limpet cofferdam, steel sheet piling, corrosion, inspection, repair, maintenance,

INTRODUCTION

Accelerated low water corrosion (ALWC) attacks steel sheet piling just below the water line. Traditional repair methods are either very expensive, not proven effective against ALWC, or both.

Little et al note that "accelerated low water corrosion (ALWC) … is a particularly aggressive form of localized corrosion. It has become a high profile problem, associated with unusually high rates of metal wastage of unprotected, or inadequately protected, steel sheet pilings. Sheet piles are used as retaining walls, wharfs, and piers. Corrosion rates in the low water level are typically 0.1 mm/year. Average corrosion rates in the range of 0.3 to 1.2 mm/side/year are typically reported for ALWC."[1]

A mobile limpet cofferdam allows cost-effective inspection, repair and protection of steel sheet piling walls subject to corrosion, especially accelerated low water corrosion (ALWC). Project results include the following benefits:

- Restore the existing steel sheet pile walls to original working capacity and possibly to near design capacity (figure 1).
- Extend the service life of steel sheet piling walls longer than traditional methods
- Significantly reduce the life cycle costs of steel bulkhead sheet pile
- Root cause analysis of corrosion mechanisms that include bacterial activity on the water and land side of a bulkhead.

Figure 1. Worker reparing steel sheet piling in a limpet cofferdam

This technique has the potential to save agencies that are responsible for maintenance of waterfront structures millions of dollars annually in corrosion repairs, extend the service life of steel bulkhead sheet piles for 30 years, and arrest further ALWC.

Background

In a 1967 report to Naval Facilities Command in New York (NAVFAC Report), Peat, Harwick, Livingston & Co (since merged with KPMG) reported that that "the steel in the region very near the water surface is cathodic to an area some distance below the water surface. Because of continual wave action, the water near the active electrolytic zone normally contains considerably higher entrapped oxygen content than water at greater distances from the surface. This situation leads to the formation of oxygen concentration cells in which the area where oxygen is less available becomes the anode, and the cathode is formed where oxygen is abundantly available. Iron ions continually go into solution in the sea water electrolyte at the anode, thus leading to a gross loss of metal in the region just below the oxygen-rich surface layer."[2(p. 10)]. The NAVFAC report identified ALWC as "oxygen concentration cells". The root cause analysis reflected the prevailing expertise of corrosion engineering in the maritime industry of the early 1960's.

More recently, Borenstein[3], Dexter[4], Little and Lee[5], Heitz, Flemming[6] and others established the relationship between ALWC and microbial influenced corrosion.(MIC). Bacterial groups known to cause deterioration of steel include APB (Acid Producing Bacteria) SRB (Sulfate Reducing Bacteria), IRB (Iron Related Bacteria), and HAB (Heterotrophic Aerobic), and SLYM (Slime Forming Bacteria).

ALWC/MIC occurs in salt, brackish and freshwater throughout the world.[7] Soil or freshwater normally contain sulfate in only very small concentrations. Because of sulfate limitation, metabolic activity of SRB in soil or freshwater habitats is mostly very limited. Graf reports that this limitation can be overcome by a special microbial mechanism, the collaboration of SRB and sulfur oxidizing bacteria (SOB)". From a portable limpet cofferdam, he was able to investigate the backfill where ALWC perforated a steel bulkhead sheet pile wall. He concluded that the "corrosion process is a mixed form of direct anaerobic corrosion carried out by sulfate reducing bacteria and partly of acid corrosion due to sulfuric acid formed by sulfur oxidizing bacteria (SOB)".[8] Hicks reports a "pattern of corrosion (that) is consistent with the appearance of microbiologically influenced corrosion (MIC)" on submerged steel sheet piling at the Duluth-Superior harbor in Wisconsin.[9]

The NAVFAC Report noted that there was "no economical technique for (repairing and) recoating the underwater surfaces, alternative means[i] for the maintenance and repair of the bulkhead must be employed. An effective technique for underwater application of substantial coatings is needed."[2 (p. 158)] In 1978, the Belgian Ministry of Waterway Infrastructure and Marine Affairs solicited proposals for a solution to ALWC of steel sheet piling along more than 70,000 kilometric tons[ii] of canals. The Ministry also could not find an acceptable solution until 1984. Van Damme and Vrelust recount that "based on the knowledge that bacteriologic attack below the water level was limited in depth…the idea for dry setting installation (with a limpet cofferdam) for inspection, repair and application of corrosion protection was born… development (of the limpet cofferdam and corrosion protection) took about 7 years for long lasting protection of steel sheet piling below the water, in the splash zone, and in the atmospheric zone."[10] The Ministry instituted a maintenance program with limpet cofferdams and has continuously deployed them for more than 25 years.

In 2001, the limpet cofferdam came to the attention of DePasquale, Heary, and Voight at the Philadelphia District of the U.S. Army Corps of Engineers. After conducting an evaluation of a limpet cofferdam, they concluded that it reduced the need for underwater work. "The (limpet cofferdam) replaces the work of divers…it allows dry inspection and maintenance of submerged structures – in this case steel sheet pilings."[11]

In 2008, Stephenson, Kumar and Beitelman at the U. S. Army Engineer Research & Development Center (ERDC), Construction Engineering Research Laboratory (CERL) consulted on the corrosion of structural sheet piles and in-situ repair methods. "Occurrences of ALWC have been noted in the literature as far back as the first half of the 20th century in Europe, Japan, and the US…. Limpet dams or movable cofferdams can provide access to damaged areas situated below the low-water level.

A (limpet) dam provides good access for cleaning, measurement, repairs, and coating operations as well as facilitating full workshop-standard quality and quality assurance procedures

[i] The Unified Facilities Criteria for Maintenance of Waterfront Facilities (UFC 4-150-07) describes common methods currently used to repair and maintain underwater steel structures that suffer ALWC.
[ii] Kilometric ton is annual gross metric tons per kilometer of navigable waterway

based on direct inspection. The environment created is effectively a confined space, so safety precautions related to such should be applied (ventilation, means of escape, etc.).

High tide inspections force water from behind into the dam thus revealing holes that are otherwise difficult to detect. Residual water ingress from holes or ill-fitting dam seals is continuously evacuated by the pumps, but in extreme cases temporary repairs or sealing may be necessary to stem water ingress. The use of limpet dams is a very specialized area in terms of system design, safe and effective operation, and commercial sensitivity where patents apply. In practice it is found that the larger the scale of application, then the more cost-effective per unit of measurement the limpet dam becomes."[12]

DESCRIPTION OF PORTABLE LIMPET COFFERDAM

The limpet cofferdam is a portable, three-sided rectangular steel box similar to one shown in figure 2. A modular design can facilitate future modifications. It will also allow storage and shipment in containers. Seals are a critical design element. They should allow for misalignment of sheet. Poor sealing efficiency will adversely impact progress, costs, and quality. Other design features include dewatering equipment, egress openings and ladders, platforms and railings, containment of fugitive emissions, provisions for ventilation and illumination. Auxiliary equipment includes dust collectors and water filters. Advance designs will allow field retrofit of the limpet to various bulkhead configurations.

Figure 2. On-site assembly of a modular prefabricated limpet

How the limpet cofferdam works

The limpet is lowered into place by gantry or crane, with the open side against the face of the bulkhead. The work site can be on the shore or a spud barge. The entire work site can readily moved out of the way of ship movements, stevedoring activities, and other port operations. A crane or gantry lowers the limpet cofferdam alongside a bulkhead. Various deployment options are shown in figures 3 and 4.

Figure 3, Shore crane deploying a limpet

Figure 4, Limpet and gantry on a barge

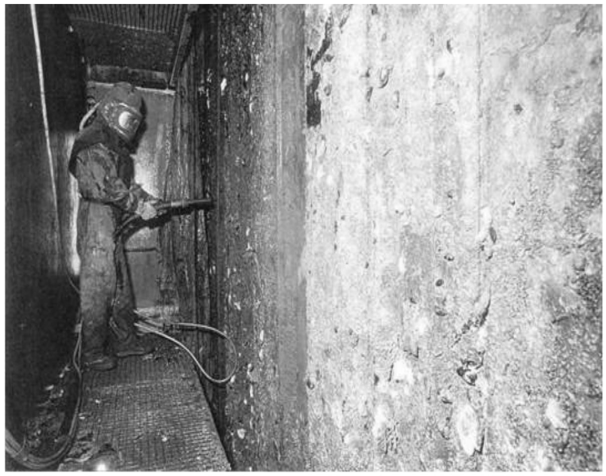
Dewatering equipment evacuates the limpet in few minutes. Once installed, loose rust and corrosion products are manually and mechanically removed. The surface is cleaned for inspection and welding repairs. An inspector conducts structural and corrosion inspections, shown in Figure 5. Structural inspection for steel thickness and holes, and Figure 6. Corrosion inspection of surface condition, shown in Figure 6

Figure 5. Structural inspection for steel thickness and holes

Figure 6. Corrosion inspection of surface condition

Figure 7. Abrasive blast cleaning inside a limpet. Adequate personal protection equipment, ventilation and illumination are essential.

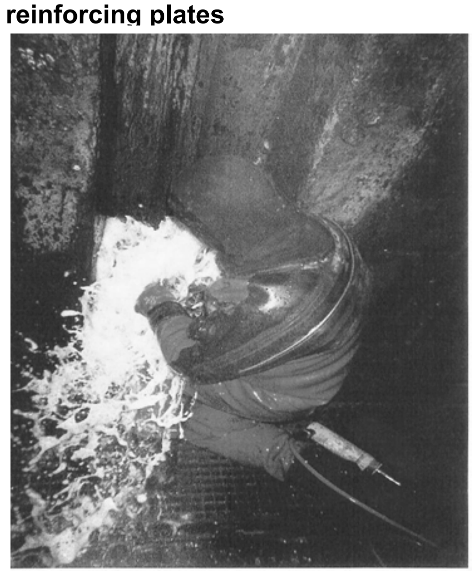
Figure 7. Abrasive blast cleaning inside a limpet



A common result of ALWC are localized regions of holes, pitting and thin sections of steel from mean low water to approximately 2 meters down. After de-watering, water from the backfill will flow through the holes. These wet holes must be sealed dry prior to welding patch plates (figure 8) Reinforcing, or doubling steel plates are welded over thin sections (figure 9). Thin sections are typically areas where residual steel thickness is less than 50% of the original thickness.

Figure 8. Sealing wet holes

Figure 9. Welding structural reinforcing plates



After completion, the portable limpet is flooded and re-positioned to the next location. Typical duration for an experienced crew at each position, or "set"[iii] is one day for minor welding repairs. Larger sets and steel in poor condition will require several days of repairs. After surface preparation to near white metal, corrosion protection is applied.

[iii] A set is the dry working area under the limpet cofferdam.

PROJECT EXECUTION

Two Phase Approach

Project design engineers may wish to consider a two phase approach. Executing a project from a mobile, limpet cofferdam is a new technique the United States. Actual costs for repair work underwater are very difficult to estimate prior to cofferdam deployment. Furthermore, very few consultants or marine contractors have experience with this method of work. Novice users of a limpet cofferdam will have insufficient data to accurately estimate or schedule a project. A two phase approach gives the design engineer and contractor better cost control over a project.

Phase One: Phase One is repair and corrosion protection on a representative section of the steel sheet piling wall. This section is usually 60 – 100 consecutive linear feet, but can vary with site conditions. Phase One includes an underwater inspection that is higher than level III of the UFC 4-150-07. The project design engineer may increase the scope of Phase One if they determine that differences in the manufacture of the steel sheet piling, the dates of installation, prior corrosion protection, or other factors could impact the corrosion rate. During Phase One, initial productivity of novice limpet users is usually low. As a project progresses, the contractor realizes labor efficiencies. They acquire skills and techniques to increase productivity and lower operating costs.

Phase One Inspection: During phase one, the inspector records and measures the data listed below. The data is used to assess the structural integrity of the bulkhead and evaluate corrosion protection. Prior to inspection, the structure should be abrasive blast cleaned to SSPC SP10 to reveal pin holes.

- Analysis of existing coatings for hazardous materials
- Residual steel thickness using “Standard Practice for Measuring Thickness by Manual Ultrasonic Pulse-Echo Contact”, ASTM E797
- “Standard Test Method for Evaluating Degree of Rusting on Painted Steel”, ASTM D610 including “Standard Test Method for evaluating Degree of Blistering of Paints”, ASTM D714
- Digital photographs& comparison to photographic reference standard SSPC-VIS
- Size and location of holes
- Remove samples of corrosion products and analyze type of corrosion common to carbon steel
- Origin of corrosion from the water and from the land side of the wall.
- Mitigating and aggravating factors that influence corrosion
- Other observed conditions
- Digital photographs and descriptive text
- Conduct field tests for bacteria that are known to cause deterioration of steel.

Phase One Expected Outcome: Phase One should provide the project designer and the contractor sufficient experience and data to generate accurate repair estimates. (Other methods of allocating repair costs include pre-negotiated rates and unit pricing. In practice, a two phase approach is more sensible.) At the completion of Phase I, the project designer may wish to revise the project schedule and evaluate potential change orders to continue repairs and implement corrosion protection. The Contracting Agency may wish to reserve the right to continue on the original or revised scope, terminate work, or suspend work until more funding is available. Mobilization and demobilization costs of this type work are low compared to contracts for major repair projects.

Phase Two: During Phase Two, the project manager may wish to deploy a second cofferdam. The decision will depend on the extent of welding repair that a project requires, time constraints to complete a project, financial resources, and labor resources. Welding repairs greatly impact project duration and cost. Extensive repairs and surface preparation may increase project costs 50 - 100%. A second cofferdam reduces the project duration and associated equipment costs. Multi-disciplined work crews who are qualified in commercial diving, welding, and capable of abrasive blasting can lower labor costs. When this is not possible, a second cofferdam reduces the standby time of single trade workers and increases the rate of progress.

Phase Two Expected Outcome: The renovation costs should reduce annual baseline maintenance costs and increase the service life at least as long as other repair methods. Computational analysis for cost analysis and comparison are discussed later in this report.

- Repairs should return the structure to near original working capacity.
- Corrosion protection should stop ALWC.
- The project should meet operational goals.
  - Allow normal port operations to continue uninterrupted.
  - Allow agencies who maintain waterfront assets to reallocate available resources to more critical activities in support of their relevant missions.
- The project should meet national goals.
  - Lower demand for energy resources
  - Recycle 100% of installed materials
  - Increase labor efficiency - maintain or create productive job opportunities that utilize traditional labor skills
- A final report should document Inspection results and offer root cause analysis of corrosion.

Typical Work Sequence

The typical work sequence from a limpet includes the following activities:

1. Deploy and seal limpet
2. Clean to SSPC-SP 3 (hand tool and power tool clean to remove loose rust)
3. Abrasive blast to SSPC-SP10 (near white)
4. Patch weld wet holes
5. Weld reinforcing plates over areas where residual steel thickness < 50% of original thickness (to be confirmed with structural engineer.)
6. Re-blast as necessary
7. Inspect surface preparation (clean steel, surface profile) and test for salts, moisture.
8. Mix and apply coating: caulk, stripe, spray (preferably one coat that cures underwater)
9. Visually inspect for holidays and measure wet film thickness
10. Re-position limpet to next location

Project Duration

The major factors affecting project duration are the sealing efficiency of the limpet, contractor experience, and the extent of repairs.

Sealing Efficiency: Deployment and de-watering should occur rapidly and without the assistance of divers. Excessive time spent sealing a cofferdam will adversely impact project duration and increase project costs. Contractors may be unable to efficiently achieve a dry, salt free surface for coating application.

Contractor Experience: Some of the work from a limpet may require special skills. Special skills include both project management skills and trade skills. The design engineer may have limited data for estimating project duration, labor, equipment, and material. The contractor may need special trade skills to accomplish the following tasks efficiently:

- Deploy and seal a portable limpet cofferdam
- Seal and repair irregular wet holes that have water flowing through them.
- Achieve a dry, salt free surface in an underwater environment.

Repair of steel bulkhead sheet piling is novel to many contractors. Design engineers should expect that suppliers of limpets include technical assistance.

Extent of repairs: Projects that require moderate or major repairs may take 2-3 times as long to complete as projects that require very minor, or no repairs. The design engineer should provide realistic information on the condition of the structure below the waterline to avoid miscalculating the project scope.

Factors Affecting Repairs

Repair specification: The design engineer should specify 3/8 inch ASTM A36 carbon structural steel for repairs. All welding should be in accordance with AWS D1.1/D1.1M, Structural Welding Code, latest edition. All holes should be sealed and dry prior to welding repair plates. The contractor should weld reinforcing plates on steel less than 50% of original thickness, or as directed by the design engineer.

Estimate of structural repairs. The design engineer should provide a baseline estimate of holes below the water line. An example of an estimate of structural repairs per 100 square feet (CSF) (9.3 m^2) is provided Figure 10:

Figure 10: Example of an estimate for structural repairs

Hole diameter	Frequency per CSF	Patch Size
diameter < 0.25 inch	0.85	16 in^2 (103 cm^2)
0.25 inch < diameter < 2.0 inch	0.21	25 in^2 (161 cm^2)
2.0 inch < hole diameter	0.14	100 in^2. (645 cm^2)

The estimate of thin steel sheet piling that shall require reinforcing plates is 5% of coverage area.

Contractor Services

Equipment and labor requirements vary according to site location and access. The limpet cofferdam deployment typically requires the following equipment and services.

Heavy Equipment

- Hoisting equipment for assembly, lifting and positioning the limpet
- Barge if water access is desired or necessary.
- Forklift and operator for material handling
- Excavator may be necessary if depth under limpet is insufficient

Portable Equipment

- Generator
- Air Compressor

- High pressure water blaster
- Hydraulic power unit
- Abrasive blasting equipment
- Dust collector
- Welder
- Paint Sprayer and mixing equipment

<u>Tools</u>

- Power tool cleaning: pneumatic chipping hammers, wire brushes, grinders, rotopeen, needle guns etc.
- Power tools for assembling limpet, impact wrenches
- Job box with tools typical for minor mechanical, carpentry and electrical work.

<u>Labor</u>

- Welding services with following capabilities
  - Welding certification, AWS or approved equal
  - Cutting and arc welding
- Industrial marine coating services with following capabilities:
  - Certification, SSPC or approved equal
  - Hydro blast clean to remove marine growth, loose corrosion products
  - Power tool cleaning
  - Abrasive blast clean to SSPC-SP10 in an enclosure
  - Mix pre-packaged, two-part epoxy coatings
  - Apply coating with high-pressure airless spraying equipment
  - Portable air compressor with filtered breathing air capability
- Coating Inspector
- Dive team on standby (available with 24-48 hour notice)
  - Dive team can also perform the services described above to the extent permitted by law or local labor agreements.
- Competent person
  - Occupational Health and Safety Standards may require a competent Deployment of a pre-fabricated limpets may require a competent person (usually from the manufacturer)
  - If a competent person is not currently required, the design engineer should consider adding this requirement
  - A competent person is one with training, experience, and knowledge of design, assembly, deployment and work from a limpet cofferdam

DESIGN FACTORS FOR A LIMPET COFFERDAM

Site Assessment

A site visit is highly advisable for a feasibility analysis, site conditions, cost estimates, and verification of design details. The design engineer should request safe access from both the water side and the land side.

Site assessment is a general inspection that may impact design or deployment of a limpet. The design engineer may obtain site data directly from the project owner and project documents, and then verify the information with an on-site investigation. When available, the design engineer should review prior inspection documents.

The on-site investigation relies primarily on visual and/or tactile observations to make condition assessments. The design engineer should record obvious major damage or deterioration due to overstress (collisions, ice), severe corrosion, or extensive biological growth attack.

Site assessment includes the following information:

- Confirm water levels, depths, and current.
- Sound the mud bottom with a rod to locate any submerged debris.
- Confirm type of sheet piling and length of bulkhead.
- Confirm geometric measurements of wales, caps, fendering systems and other appurtenances.
- Evaluate site accessibility from either the shore or from the water.
- Presence and identification of potentially hazardous materials
- Presence and identification of potential obstructions.
- Determine the rust condition that is visible above the waterline.

Site assessment data provides essential information to evaluate the following critical factors:

- Feasibility of deploying a limpet
- Limpet design and cost
- Initial estimate of equipment, labor and material to renovate bulkhead.

Design Considerations

The working area from a limpet cofferdam should extend from at least the mean high water mark down to 2.0 meters below mean low water.

Anderson[13] explains design loads on circular and rectangular limpet cofferdams. Design loads include hydrostatic forces and buoyancy forces. Design engineers may wish to exclude impact forces from barge collisions, wave activity and ice. These may not be practical factors for application to limpet design calculations.

Design details and performance of a pre-fabricated limpet are typically the responsibility of the manufacturer. Equipment should include consideration for egress, ventilation, pollution control, worker safety, worker comfort, and illumination.

Sealing is critical. The contractor should be able to deploy a limpet without the use of divers.

Environmental Considerations

State, local and federal regulations, environmental concerns or Agency specifications may require air and water pollution control measures. Sources of pollution can arise from abrasive blasting operations and petroleum products that have leached into backfill (especially marine oil terminals). Leakage water may contain a small amount of sediment that arises from work activities in the limpet.

The limpet should have provisions for the following:

- Filtering and testing of seepage water before returning it to its source.
- Containment, ventilation and collection of airborne particulates

Before removing existing coatings, the design engineer should analyze the constituents for hazardous material. If hazardous materials are identified in the coating, then the project may require environmental remediation. State of the art techniques other than abrasive blasting might be cost justified for coating removal.

Where coating removal and coating application is being conducted, special care should be provided to capture material removed from the coated area. The limpet cofferdam is a primary containment enclosure used to confine spent materials, aerosols, dust and other debris generated:

(1) during abrasive blasting operations;
(2) when collecting and removing debris and
(3) when applying the new coating.

If turbidity rises above background levels and exceeds allowable limits, the contractor can channel debris within the enclosure to a central removal location.

If toxicity levels in water adjacent to the limpet rise above background levels and exceeds allowable limits, the design engineer will need to determine the source. The source may be from abrasive blast media, equipment or facilities on the project site. The contractor should take immediate corrective action. The source may be from adjacent property or unrelated construction activities. Water contaminated with oil or other hazardous materials may flow from the backfill through holes in a bulkhead and into the limpet. Where existing hazardous materials require remediation, the design engineer should consider provisions to filter and test seepage water before returning it to its source.

Excessive seepage of water around sealing will adversely impact environmental control measures.

Safety Considerations

State, local and federal regulations, occupational safety concerns and other specifications may require that a Competent Person design, fabricate, and deploy a limpet cofferdam. A Competent Person should be able to demonstrate the following:

- Training, experience, and knowledge of design, assembly, deployment and work operations of a limpet cofferdam.
- Knowledge of applicable occupational health and safety requirements.
- Ability to detect:
  - Conditions that could result in structural failure
  - Failures in protective systems;
  - Hazardous atmospheres; and
  - Other hazards including those associated with confined spaces.
  - And have the Authority to take prompt corrective measures to eliminate existing and predictable hazards and stop work when required.
- Proposed methods for preventing damage to man-made facilities or natural features designated to remain within or adjacent to the construction rights-of-way;
- Controlled flooding plan
- Fall protection
- Access/egress
- Evacuation procedures

COST ANALYSIS AND COMPARISON

In the absence of cost data, project design engineers need tools to evaluate the cost-benefit ratio of repair techniques with a limpet cofferdam to other methods. The1967 NAVFAC Report includes a method to make comparisons when cost data is not available.

“<u>Baseline Configuration:</u> When the annual cost variables can be projected with some accuracy, all alternatives for bulkhead construction and repair can be estimated and compared with each other. When one or more variables cannot be projected with accuracy, comparisons can best be drawn against a base line configuration which represents a normal bulkhead situation with known costs and lifetime. In this report, the baseline condition is a sheet-steel bulkhead installed with no protective coatings or cathodic protection and no maintenance prior to the time of repair or replacement. The annual cost of a sheet-steel bulkhead can be calculated using the formula:

$$\text{Annual base line cost} = P\,[\, i*(1+i)^n / (1+i)^n - 1] \qquad (1)$$

where:
p = installation cost in dollars per linear foot
n = lifetime in years
i = time value of money in percent

Formula (1) assumes that there will be no salvage value at the end of functional lifetime."[2, pp. 94-95]

"Evaluation of Repair Systems in Extending Bulkhead Life: "A sheet pile bulkhead wall deteriorates unevenly. The area from slightly below the tidal zone to the splash zone may be approaching failure, while the top and bottom of the bulkhead are still serviceable. The steel piling driven below the mud line, which is not corroded, can be a very strong foundation for additional construction. There are repair methods that can be used near the end of the normal life span of the bulkhead which use the non-corroded steel as a basic part of a life extension system.

A formula for determining how much can be spent at the end of normal life to extend the lifetime by some period of years is follows:

$$P*[\, i*(1+i)^{n+y} / (1+i)^{n+y} - 1] \;+\; L*[\, 1 / ((1+i)^n\,] \;*\; P*[\, i*(1+i)^n / (1+i)^n - 1] \;\leq\; P\,[\, i*(1+i)^n / (1+i)^n - 1] \qquad (2)$$

where:
L = maximum investment ($/linear feet) in renovation of wall at the end of n years which will extend the life of the wall by "y" years, and n, i and P are as defined previously)... Raising the interest factor will make additional investments to achieve longer life even more attractive, while lower interest rates will require a longer payout period.."[2, pp. 105-106]

A set of solutions for the maximum dollar renovation investment are shown in Figure 10. The results shown in this figure are based on an initial investment of P, and values of L (are from 20% of P to 80% of P

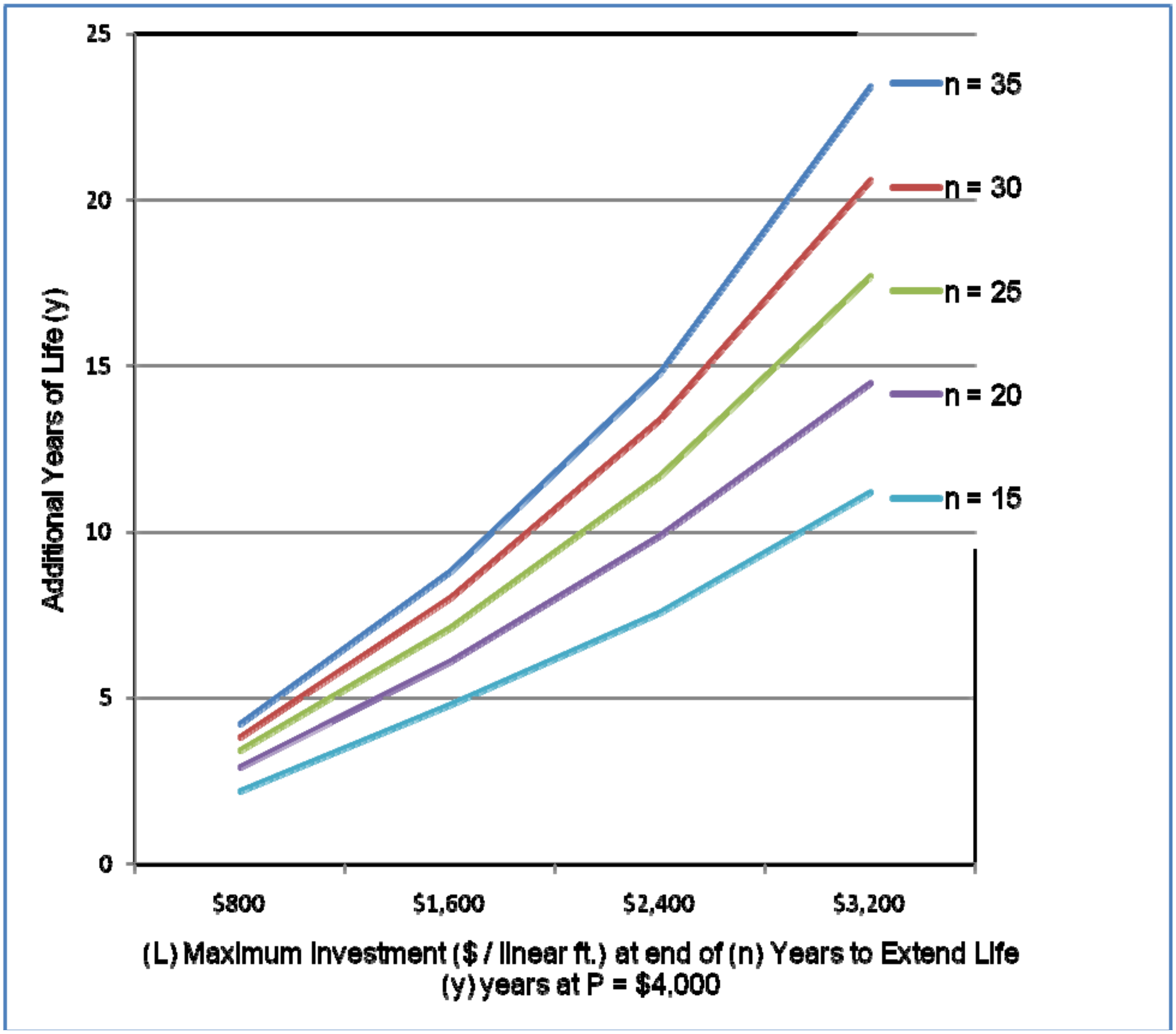
Interesting conclusions to be drawn from analysis of this data include the following:

- Over 50-percent of the original cost can be spent for ten more years of life if the original life is less than 30 years.
- The possibility exists for repairs each 10 to 15 years if the structural integrity of the sheet steel foundation and tie rods remains intact."[2 (pp.105-107)]

Inspections after 15 years indicated that "the lifetime of the sheet piling will last for another 15 years and thus may be estimated to be at least 30 years".[10] The project design engineer should request independent inspection reports of completed projects and verify claims. In 2007, further inspections support the Ministry's estimate of at least 30 years. With competent persons executing a project, the design engineer should expect that renovation will extend the service life of a steel sheet pile wall at least 25 years.

Recent estimates of the cost to install new Z piling over 50 feet in length in the first quarter 2009 range from $6,500 to $ 9,000 per linear foot[iv]. This is an estimate of only installation cost. Additional costs of engineering, design, geological surveys, and other professional services may range from 10 and 20% of the installation cost. The design engineer should also add in the additional cost to replenish backfill and make civil repairs on the land side.

Figure 10. Example of how much can be spent at the end of normal life to extend the lifetime of a structure by different periods of years.



[iv] (a) NAVFAC Solicitation N40085, Repairs to W306 and W305 Bulkhead at Naval Station, Norfolk, VA, average of line item 0001H price; (b) Port of Seattle Memorandum dated Jan. 13,. 2009; (c), J. Berry, "Unsafe Harbor Restricts Access" Cape Cod Times Apr. 24th, 2009, p. 1(d) NAVFAC Solicitation N6945009R1259, Design and Construction for P999 Warf Alpha Improvements at Naval Station Mayport, FL, 50% of project value is estimated to replace of 900 ft of sheet piling.

Based on values where cost per linear foot of new sheet piling, P = $6,800; expected service life, n = 30 years; time value of money, i = 5%, expected additional service life, y = 20 years, and; cost or repair does not exceed, L = $3,000, the annual baseline costs will decrease at least 10% per linear foot per year. The service life at working capacity should increase more than two-thirds.

Renovation investment with a limpet cofferdam can offer significant economic benefits when compared to other methods. With efficient limpet design and sealing, proper assistance of a competent person, and a proven coating product, renovation repairs will extend the service life longer than traditional methods.

"The difficult part appears to be encouraging port and berth owners to take a close look in the first place. If they do, and catch the corrosion early enough, the long-term financial savings in maintenance versus the possibility of complete replacement or reconstruction is very significant"[14]

Additional Installation Costs (pre-coating new piles in-situ): Evaluation of systems with additional installation costs for extending bulkhead life, a bulkhead system which will cost more than conventional pre-coating methods, can be justified economically through similar life cycle cost comparisons. An example is to apply corrosion protection in-situ, after piles are driven. The design engineer should consider this when a platform or pier will be installed over a bulkhead/tie back wall. Future access may not be readily available. The cost of future repairs will be much more expensive.

Other Measures of Justification

The project design engineer may also wish to monitor other indirect costs, for example:

- hard metrics that evaluate the total impact on energy consumption, pollution, and material recycling.
- soft metrics that evaluate the total impact on community benefits such as perceived good will and local economic stimulus.

CONCLUSIONS

The mobile limpet cofferdam is a state of the art technique to repair and preserve steel sheet piling walls. Contractor experience and limpet sealing efficiency are critical factors that impact project success. Treating steel bulkhead sheet piling before it is allowed to deteriorate to poor condition will significantly reduce project duration and lifetime costs.

Advantages

- Excellent access to critical areas of piles irrespective of tide.
- Inspection and repairs can be carried out efficiently and concurrently.
- True structure condition is revealed.
- Standard workshop environment is provided.
- Containment of debris and airborne particulates

Disadvantages

- Intrinsic barriers and long cycle time for introducing new repair techniques of a limpet cofferdam due to the following factors:
  - Limited cost data and contractor experience in the United States
  - Lack of source planning documents for design engineers
  - Lack of awareness among engineers and consultants
- Reluctance of design engineers to impose additional costs of coating sheet piles in-situ before installation of a platform or pier over a bulkhead/tieback wall.

ACKNOWLEDGEMENTS

Photographs courtesy of Acotec NV

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