ERDC/CERL TR-08-DRAFT

US Army Corps of Engineers®
Engineer Research and Development Center

DoD Corrosion Prevention and Control Program

In-Situ Coating for Sheet Piles

Interim Report on Project FO-8-AR06 for FY08

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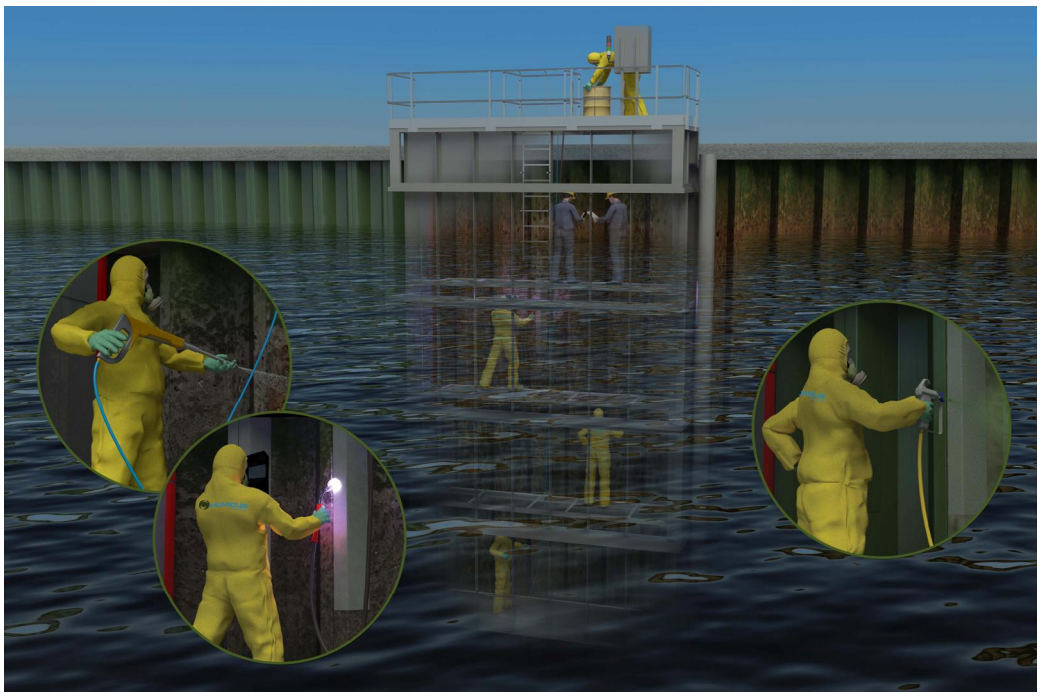
December 2009



Construction Engineering Research Laboratory

In-Situ Coating for Sheet Piles

Interim Report on Project FO-8-AR06 for FY08

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Interim report

Prepared for Office of the Secretary of Defense (OUSD(AT&L))
3090 Defense Pentagon
Washington, DC 20301-3090

Under Military Interdepartmental Purchase Request XXXXX-XXXXX-XXX

Abstract:

The In-situ Coating for Sheet Pile project demonstrated a state of the art technique to repair and preserve submerged steel sheet piling walls. The technique deploys a portable limpet cofferdam and applies a high performance amine epoxy system. This report is a source document for planning, estimating, and performing technical maintenance and repair work of immersed steel sheet piling from a limpet. It includes tools for evaluating economic and technical benefits in comparison to traditional methods of bulkhead preservation and repairs. Recommendations include updating the Unified Facilities Criteria for Maintenance of Waterfront Facilities (UFC 4-150-07) and qualifications based specifications for competitive bidding.

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Preface

This demonstration was performed for the Office of the Secretary of Defense (OSD) under Department of Defense (DoD) Corrosion Control and Prevention Project SOW 08T0070, "In Situ Coatings for Sheet Piles". The proponent was the U.S. Army Office of the Assistant Chief of Staff for Installation Management (ACSIM), and the stakeholder was the U.S. Army Installation Management Command (IMCOM).

The work was performed by the Engineering and Materials Branch (CEERD-CF-M), Facilities Division (CF), U. S. Army Engineer Research and Development Center (ERDC) – Construction Engineering Research Laboratory (CERL), Champaign, IL. The ERDC-CERL technical monitors were Dr. Ashok Kumar and Dr. Larry Stephenson. Project manager was Mr. Al Beitelman, Director Paint Technology Center. The program manager was Mr. Lawrence Clark, Mandaree Enterprise Corporation (MEC). Significant portions of this work were performed by Mr. Eric Van Draege and Kurt Claeys of Acotec NV. The contributions of the Roen Salvage Company personnel are also acknowledged.

The following persons are gratefully acknowledged for their support and assistance in this project:

- Daniel Zrna, Department of Public Works, Torii Station, Okinawa
- David Rozène Acotec Inc. co-editor of the report .

This project entailed the demonstration of a limpet cofferdam, repair methods, and amine epoxy coating on 50 immersed sheet piles in the Port Naha, Okinawa, Japan. The limpet cofferdam, called the **DZI,** and the amine epoxy coating called **Humidur®** is manufactured by Acotec NV (Erembodegem, Belgium).

The contractor, Mandaree Enterprise Corporation (MEC) from Warner Robbins CA subcontracted the work to Acotec NV, a Belgium firm. Acotec pioneered the system in the early 1980's. Acotec has treated more than 300,000 m² of immersed steel sheet piling with the Humidur® Coating system from their portable limpet cofferdams (brand name **DZI**). Acotec is ISO 9001 certified for repairing and maintaining steel sheet piling. The

U.S. Army Corp of Engineers pre-qualified the Acotec system[i,ii]. Acotec teamed with Roen Salvage , offering an opportunity of acquiring experience in this field of work. Roen Salvage is marine contractor with headquarters in Sturgeon Bay Wisconsin.

Executive Summary

The “In-situ Coating for Sheet Piles” project demonstrated a state of the art technique to repair and preserve submerged steel sheet piling walls. The technique deployed a portable limpet cofferdam, called the **DZI**, and applied a high performance amine epoxy coating, called **Humidur®**. The **DZI** limpet allowed dry access to submerged pilings. It created a workshop environment for inspection, repairs, and coating application. Contractors repaired a sheet piling wall in bad conditions to a high standard. The **Humidur®** Coating System is expected to extend the service life of treated areas more than 25 years.

Limpet cofferdam design and contract work requires specialized skills. On-site competent personnel with requisite experience can provide necessary training.

The method of work allows thorough inspection and cost effective renovation of immersed steel surfaces while minimizing disturbance to harbor activities.

When structures are treated in-situ before the onset of heavy corrosion, the renovation can easily achieve an additional 30 years of service life and a 10-20% reduction in life cycle costs. Price data from the open market is not available or sufficient for calculating costs. The report provides financial tools to evaluate the cost-benefit ratio of repair techniques with a limpet cofferdam to other methods.

Unit Conversion Factors

Multiply	By	To Obtain
degrees Fahrenheit	(F-32)/1.8	degrees Celsius
feet	0.3048	meters
gallons (U.S. liquid)	3.785412 E-03	cubic meters
gallons (U.S. liquid)	3.7854	liters
inches	0.0254	meters
mils	0.0254	millimeters
square feet	0.09290304	square meters
psi	0.070028	bar

1 Introduction

1.1 Problem statement

The task order is a field test of a system to renovate a corroded bulkhead in poor condition. Figure 1 and Figure 2 show the visible condition of the structure. Conditions below the waterline are unknown prior to the start of the project.

Figure 1 - Southwest view of bulkhead above the waterline

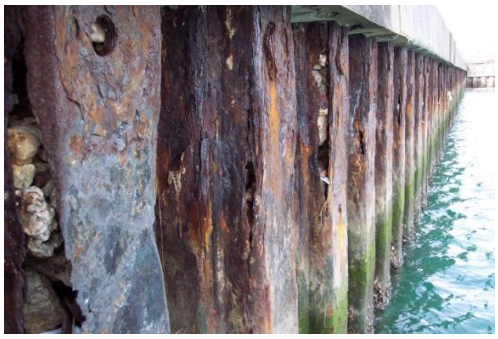

Figure 2 - Northeast view of bulkhead above the waterline

The method of work is novel to U.S. Department of Defense Agencies and U.S. Contractors. Project designers and estimators lack historical data for evaluating economic and technical benefits in comparison to traditional methods of bulkhead preservation and repair.

The Department of Defense spent approximately US$ 60,000,000 maintaining and repairing steel bulkhead sheet piling in the first half of 2009. A major reason for repairs is that steel bulkhead sheet piles are subject to an aggressive form of corrosion that is commonly referred to as Accelerated Low Water Corrosion (ALWC). In a 1967 report to Naval Facilities Command in New York (NAVFAC Report), Peat, Harwick, Livingston & Co stated “no economical technique for (repairing and) recoating the under-

water surfaces, alternative means[1] for the maintenance and repair of the bulkhead must be employed. An effective technique for underwater application of substantial coatings is needed."[iii (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[2] 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."[iv] 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."[v]

"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 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

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[1] 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.

[2] Kilometric ton is annual gross metric tons per kilometer of navigable waterway

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."[vi]

1.2 Objective

The objective of this task order report is to provide a source for planning, estimating, and performing technical maintenance and repair work of immersed steel sheet piling. The following test objectives provide guidance for performance specifications. The cost data contributes information for life cycle cost analysis of steel bulkheads. The method of work also allows on-site evaluation of corrosion mechanisms. Lessons learned will provide guidance for future project planning.

- Demonstrate that a proven limpet cofferdam system with competent on-site personnel can repair badly corroded piles to a high standard.
- Confirm that application of a high performance marine epoxy coating on dry, near white steel is an effective and long term solution to stop further corrosion above and below the waterline.
- Define technical factors necessary for successful project outcome.
- Implement measures to evaluate the service life of corrosion protection.
- Collect cost data for a meaningful comparison to other repair methods, including replacement.
- Conduct on-site inspection that includes root cause analysis of Accelerated Low Water Corrosion (ALWC) and Microbially-Influenced Corrosion (MIC).

1.3 Approach

The contractor deploys a working platform for dry access to submerged areas of steel bulkhead sheet piling. After bulkhead cleaning and initial surface preparation, the contracting team determines the best method to repair the structure. Following repairs, an inspector makes a visual assessment, collects physical measurements, and records photographic evidence of the condition of the bulkhead. The inspection includes a bacteriological field investigation.

Following final surface preparation and inspection, the contractor coats the bulkhead with a high performance marine epoxy. High-build barrier epoxy coatings are proven effective against Accelerated Low Water Corrosion (ALWC) when applied on properly prepared steel. Surface preparation is the single most significant factor for coating performance. Epoxy coatings are much less likely to fail when applied on dry, near white surfaces free of salts. A limpet creates a dry, work shop environment to achieve these conditions. The task order includes two follow up inspection at six month intervals.

2 Technical Investigation

2.1 Project overview

Limpet dams or movable cofferdams provide dry access to damaged areas below the low-water level. Limpets are normally manufactured and operated by specialist contractors. A dry working environment is possible throughout the tidal range and down to a predetermined depth.

The Acotec **DZI**[1] limpet cofferdam shown in Figure 3 was selected for executing the task order. The **DZI** is a proven to safely and rapidly achieve a dry, salt-free surface underwater. The **DZI** also functions as a containment enclosure and contain all debris and fugitive emissions.

Acotec had sole responsibility to supply a safe and suitable limpet cofferdam. The limpet was shipped with all necessary auxiliary equipment in two containers. A third party engineering firm certified the structural integrity and suitability of purpose. The limpet included requirements for safety, form design features, structure, method and materials for construction, fitting out, stability, and operational efficiency.

Acotec provided project engineering assistance and training for on-site competent supervision.

A 600 micron layer of high performance marine epoxy coating is an effective method of stopping ALWC. The coating should have a service life of more than 25 years. A single coat, high-build coating that can cure underwater eliminates the time for prime or intermediate coats and drying.[vii] One such product is the **Humidur®** Coating System. Independent Inspection reports verify a service life of more than 24 years.

The **Humidur®** Coating System was selected for corrosion protection. **Humidur®** is a two-component, solvent free and coal tar free epoxy system. It has high corrosion and abrasion resistance that universally pre-

[1] "DZI" is the Flemish acronym for "Dry Setting Installation".

vents corrosion from underwater to above the splash zone. Technical data sheets are found in appendix (A).

Figure 3 - **The Acotec "Pacific Flyer" DZI limpet cofferdam**

The **Humidur®** Coating System being applied in Figure 4 is formulated specifically for protecting marine steel structures exposed to severe corrosion environments and ALWC[viii, ix]. It is a waterproof barrier coating comprised of a solvent-free and coal tar-free modified epoxy. **Humidur®** is the result of extensive research and development at Acotec's in-house facilities. In addition to more than 25 years of claim-free history, the product has the following performance features:

- Independent inspection reports such as the report in appendix (B) provide at least 20 years of historical coating performance under similar conditions.
- The manufacturer has the ability to warrant the coating project against coating failure for 10 years.
- Properties include excellent chemical, abrasion & impact resistance.
- **Humidur®** cures at low temperatures and it is temperature tolerant after curing
- Standard spray equipment can apply a single layer up to 1,000 microns (40 mils). Coating requires no prime coat.

- The coating cures underwater and the contractor has no wait time prior to immersion.
- The coating is comprised of 100 per cent solids and contains no solvents.
- Independent toxicology reports confirm that the coating is safe to marine life during and after curing.
- The coating includes compatible brush and putty variants for filling voids and stripe coating.
- The coating is compatible with cathodic impressed current systems.

The extent of surface cleaning and repairs were unknown at the onset of the project. Actual conditions of the bulkhead underwater were unknown. Estimating the costs and duration of were difficult prior to deployment of the limpet. Cleaning and welding repairs significantly impacted project duration and costs.

Figure 4 - *Humidur®* coating on submerged steel sheet pile

2.1.1 Site conditions

The bulkhead is located at Port Naha Okinawa, Japan and pictured in Figure 5. The hot rolled structural steel sheet piles were installed in 1950's. The sheet pile was manufactured in Japan. Metallurgical reports are not available. No corrosion prevention methods were previously applied. The type of sheet pile is unknown.

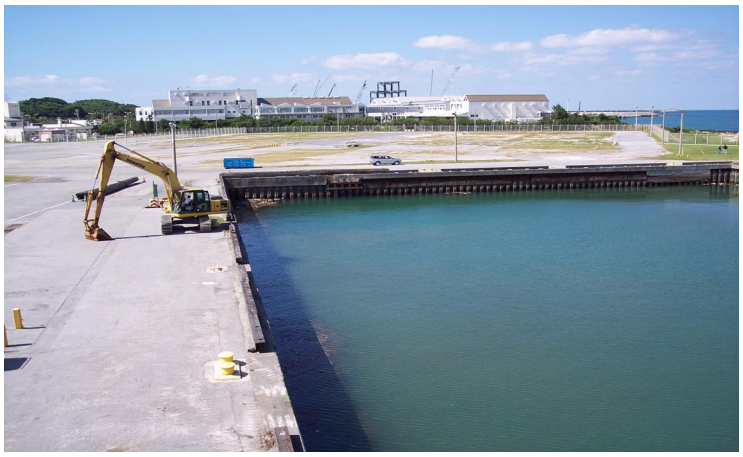

Figure 5 - Bulkhead at Port Naha Okinawa, Japan

Earlier methods to repair the bulkhead include steel plates and concrete. The non-coated steel plating was bolted-on . These plates are in mean-while in their turn heavily corroded and holed , proving the necessity of corrosion protection .

Figure 6 - Earlier Repairs to Bulkhead

Minimum site criteria for prosecution of work included the following items:

- Adequate access to the site location (either from shore or water)
- Sufficient and secure area for assembling equipment and staging material
- Available fresh water for rinsing salts and wet blasting operations

- Sufficient overhead clearance for transport and lifting operations
- Adequate load bearing capacity for equipment along the bulkhead for shore access

The mud bottom is illustrated in Appendix (C) and varies between -5.0 to -8.0 meters.

2.1.2 Scope of Work

The task order was a negotiated procurement for in-situ coating of immersed steel bulkhead sheet piling. The contract work consisted of the following items of work: clean to near bare metal and inspect steel bulkhead sheet piling; repair holes/leaks watertight in sheet pile wall for the proper application of new coating; and, coat with a single coat, two-component solvent free polyamine cured epoxy. All work had to be conducted in a dry environment from a limpet cofferdam enclosure. The project included inspections six (6) and eleven (11) months after project completion.

The task order consisted of inspection and contract work on approximately forty (40) linear meters of steel sheet pile bulkhead between a concrete cap (elevation 0.00 m) to approximately 2.0 meters below mean low water (elevation -4.0 meters). The total coverage area was approximately 270 m^2 of steel bulkhead sheet piling.

The task order was divided into the following major tasks.

(1) Submit project documentation.
(2) Inspect bulkhead and perform contract work. Inspection included non-destructive technology (NDT) to record statistically significant measurements of the steel bulkhead structural condition. Bacteriological investigations were conducted for the presence of bacteria known to accelerate steel corrosion. A photographic and video record of bulkhead conditions and work were prepared.
(3) Install test coupons of steel sheet piling material (mild steel) so that they are exposed to the same conditions as the sheet piling that is to be coated under this task order.
(4) Conduct final inspections after 6 and 12 months. Submit a final report.
(5) Correct any deficiencies and submit any warranty and service period information.

2.1.3 Submittals

Bid submittals included a description of work methods, table of contents of recommended health, safety and environmental plan, material safety data sheets, technical specifications, and other supporting documentation sufficient to describe work methods, including the following:

- Proposed containment system
- Staffing requirements and qualifications
- Schedule of work and description of tasks
- Equipment and utility requirements for the following activities
    - Deployment of work platforms
    - Bulkhead Repair
    - Surface preparation
    - Coating application
- Project References with contact information
- Environmental mitigation methods
- Health and safety plan, Table of Contents

Project submittals included the following additional documentation

- List of products and materials with detailed descriptions and material safety data sheets, where applicable.
- Manufacturer's published Material Safety Data Sheets
- Manufacturer's published Technical Specifications
- Drawings showing locations of specific work areas
- Health & Safety Plan
- Communications Plan
- Environmental Compliance Assessment

2.1.4 Description of Tasks

The typical work sequence included the following activities.

1. Deploy and seal limpet.
2. Initial Cleaning & Inspection
    a. Clean to SSPC-SP 3 (hand tool and power tool clean to remove loose rust)
    b. Abrasive blast to SSPC-6 (commercial blast cleaning) , sufficient for inspection and weld repairs
    c. Inspect Structure
3. Repairs

a. Above mean high water
    i. Apply reinforcing plates
    ii. Fill voids and holes
        1. Reconstruct deteriorated piles (closing holes)
        2. Inject grout between doubling plates and bulk-head .

b. Below mean high water (splash zone and below mean low water)
    i. Patch weld wet holes
    ii. Weld reinforcing plates over areas where residual steel thickness is less than 50% of original thickness, or as directed by the Agency.

4. Abrasive blast to SSPC-SP10 (near-white blast cleaning)
5. Measure residual steel thickness and inspect surface preparation (clean steel, surface profile) and test for salts, moisture.
6. Mix and apply coating: caulk, stripe, spray (one coat that cures underwater)
7. Visually inspect for holidays and measure wet film thickness
8. Re-position limpet to next location

2.1.5 Project Schedule

The task order was to repair and coat between elevations -0.00 (under side coping beam) to -4.0 meters of 50 consecutive sheet piles in 26 days. The schedule assumed an experienced contractor would provide a proven limpet cofferdam design and on-site assistance. The coverage area was 270 m². Actual work took 32 days. Two unforeseen conditions below the waterline extended the project duration.

1. The piles had a thick layer of amorphous rust, more than 10 mm thick .
2. Numerous small holes .
3. Two piles were separated from their interlocks.

88 steel patch plates 200 x 200 x 6 mm were welded over leaking holes. Time needed for stopping water leaks varied and occasionally took as much as 30 minutes per hole. 50 reinforcing plates were welded over the piles above the waterline. Reconstruction of corroded out-pans and welding doubling plates over each pile required more than two hours per pile. The average duration of project work for one set-up of four piles was approximately 3 days. Progress accelerated as the crew gained experience.

- 1 day for cleaning and stopping leaks
- 1 day for welding patch plates and reinforcing plates
- 1 day for surface preparation and coating application

Table 1 - Project Milestones marks project milestones. The project schedule is summarized in appendix (D). Appendix (E) shows details of project progress.

Notice to Commence	6/16/2009
Deliver Limpet FOB, Antwerp	9/9/2009
Mobilization of Equipment and Personnel	10/22/2008
Kick-off Meeting	10/23/2008
Assembly of Limpet	10/26/2008
First Deployment	10/29/2008
Start Contract Work	10/31/2008
Work Complete	12/12/2008
Demobilization & Clean-up	12/16/2008
6 Month Inspection	6/8/2009
11 Month Inspection	12/8/2009

Table 1 - Project Milestones

2.1.6 Health & Safety

No specific safety and occupational health standards refer to portable limpet cofferdams. The manufacturer of the cofferdam provided a comprehensive Health and Safety Manual.

Portions of Code of Federal Regulations 29 CFR Chapter XVII paragraph 1926 and the U.S. Army Corps of Engineers Safety & Occupational Health Standard EM have transferrable criteria.

2.1.7 Environmental Compliance

Discharge of pollutants into water was prohibited. The DZI limpet was the primary containment enclosure for pollutants, corrosion products spent blast media, and air-borne particulate matter. The enclosure provided localized containment at the point of collection and conformed to the surface. Secondary method was to channel debris within the enclosure to a central removal location.

The **DZI** was used to confine spent materials, aerosols, dust and other debris generated:

- during abrasive blasting operations;
- when cleaning the steel surfaces on the structure in preparation for coating application;
- when collecting and removing debris;
- when applying the new coating.

2.2 Installation of the technology

The contractor deploys and dewaters the **DZI** limpet for dry access to submerged areas of steel bulkhead sheet piling. After initial cleaning and surface preparation, the contracting team determines the best method to repair the structure. Following inspection and final surface preparation, the contractor coats the bulkhead with a high performance marine epoxy. High-build barrier epoxy coatings are proven effective against Accelerated Low Water Corrosion (ALWC) when applied on properly prepared steel. The task order includes two follow up inspection at six month intervals.

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

2.2.1 Description of the equipment

2.2.1.1 Heavy Equipment

- Acotec had sole responsibility to supply a safe and suitable limpet cofferdam.
- Lifting equipment for assembling and deploying the limpet from shore side.
- Forklift for material handling

2.2.1.2 Portable Equipment with accessories and spare parts

- Generator
- Air compressor
- Abrasive blasting Pot
- Air pollution control equipment
- Welding machines
- High Pressure Airless Paint Sprayer, 5000 psi (360 bar) and 2.4 gpm (9 liters/min), 60:1 Pump ratio, Wagner 560 spray gun, or similar
- High pressure washer 300 bar
- Fresh water tank

2.2.1.3 Other Equipment

Two (2) working platforms for work above the water line

2.2.1.4 Secure Storage area for the following items

- On-site office and sanitary facilities
- 2 x 40 ft. containers
- 2 x 12 cubic yard waste disposal containers (non hazardous materials)
- Hazardous material storage

2.2.1.5 Tools

- 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

2.2.1.6 Special Materials

- Rapid-cure cement
- **Humidur®** Marine epoxy coating with compatible putty and brush variants
- Tools and materials for sealing wet holes
- Steel plates for reinforcing thin steel

2.2.1.7 Consumables

- Fuel
- Cleaning solvents
- Abrasive blast media
- Fresh water

2.2.2 Contractor Services

The task order required contractor services with the following capabilities.

2.2.2.1 Competent Person

Deployment of a pre-fabricated limpet requires a competent person (usually from the manufacturer). (If a competent person is not explicitly 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 operations from a limpet cofferdam. A competent person shall be able to demonstrate the following:

- Training, experience, and knowledge of design, assembly, deployment and work operations of a limpet;
- Use of protective systems;
- Ability to detect:
    - Conditions that could result in structural failure
    - Failures in protective systems;
    - Hazardous atmospheres; and
- Other hazards including those associated with working from a limpet; and,
- have the Authority to take prompt corrective measures to eliminate existing and predictable hazards and stop work when required.

2.2.2.2 Welding services

- Seal and patch weld all wet holes prior to surface preparation for coating application.

- Weld reinforcing (doubling) plates over thin sections where steel thickness is less than 50% of original thickness, or as directed by the Agency.
- Overlay doubling plates to match the original contour of the sheet piling. Doubling plates shall extend at least 8 inches over steel with thickness greater than 70% of the original steel thickness, or as directed by the agency. Use 6 mm (¼ inch) weathering structural steel in conformance with ASTM A242/A242M.

2.2.2.3 Structural Steel Coating Services

- Surface preparation and quality control in accordance with the coating manufacturer's instructions.
    - Hydro blast clean to remove marine growth, loose corrosion products
    - Manual and power tool cleaning to SSPC SP-3
    - Abrasive blast clean to SSPC-SP10 (SSI-Sa2 ½, or NACE # 2), 2-3 mil profile
    - Mix pre-packaged, two-part epoxy coating
    - Apply coating with high-pressure airless spraying equipment
- Welding services with following capabilities
    - Welding certification, AWS or approved equal
    - Portable DC welder, 225-300 amp , Diesel
    - Cutting and arc welding tools and accessories
- Personal protective equipment to conduct work

2.2.2.4 Coating Inspector

The coating manufacturer provided inspection services.

2.2.3 Mobilization

The **DZI** limpet and all auxiliary equipment were delivered in two 40' HT containers (Figure 7 and Figure 8). The staging area for the DZI Limpet was approximately 40 x 20 m (Figure 9).

Figure 7 - DZI limpet arriving on site in containers

Figure 8 - Unloading DZI limpet from containers

The contractor was able to assemble the limpet in two days (Figure 10). The contractor did not have to make any modifications. The limpet satisfied all environmental and safety regulations. Initial deployment and safety training began on the third day after the equipment arrived.

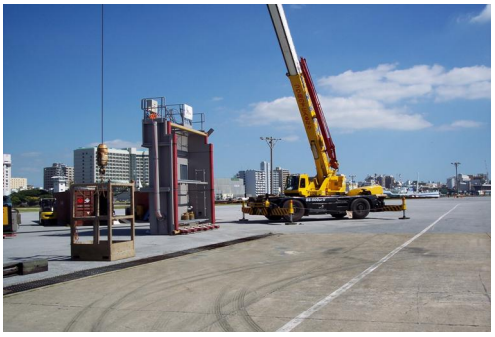

Figure 9 - Staging area for the DZI limpet

Figure 10 - Assembling the DZI

2.2.4 Working Platforms

In order to organize the work as efficiently as possible, the contractor executed work from several platforms. The atmospheric zone of the SSP directly under the capping beam was clearly visible and severely corroded. The condition of the steel under water was unknown.

The contractor deployed two swing platforms for overwater work and one **DZI** limpet for underwater work. The platforms and DZI are shown in Figure 11 and Figure 12. The underwater part of the work from the **DZI** went faster than the overwater work. The **DZI** was dewatered up to 4.6 meters under the concrete cap

Another method to increase productivity is to deploy multiple DZI's. One crew can do repair work in one DZI while another crew can perform grit blasting, quality control and coating in another.

Figure 11 - Overwater working platforms

Figure 12 - DZI limpet and overwater working platform in operation concurrently

2.2.5 Bulkhead Cleaning and Inspection

The team had to remove thick layers of amorphous rust and marine fouling. The work was time consuming and labor intensive. The 300 bar pressure washer was not powerful enough to remove the thick solid layers. Mechanical impact was required to break up the thick layers. Workers used hammers and pneumatic tools to remove thick layers of corrosion products as shown in Figure 13 and Figure 14. All debris was collected in the sump of the **DZI**.

2.2.6 Bulkhead Repairs

Prior to weld repairs, all leaks were sealed watertight. Steel reinforcing plates were welded over any unsound metal. Patch plates were welded over any holes below the waterline. After welding, voids behind the reinforcing plates shall be injected and filled with cement grout or epoxy resin. Appendix (F) depicts locations of repairs. Appendix (G) is an inventory of repair materials. Appendix (H) are picture s of the repair work.

Figure 13 - Manual removal of corrosion products

Figure 14 - Pneumatic removal of corrosion products

2.2.6.1 Bulkhead Repairs above the waterline

2.2.6.1.1 Overwater Work (Splash Zone up to Concrete Cap)

The contractor installed two work platforms at low tide. Brackets to support the platform were prepared in advance and shipped over. The platforms had "teeth" to match the SSP profile in order to collect rust scales and debris as shown in Figure 15. Brackets were welded to the out-pans of the piles to support the platforms as shown in Figure 16.

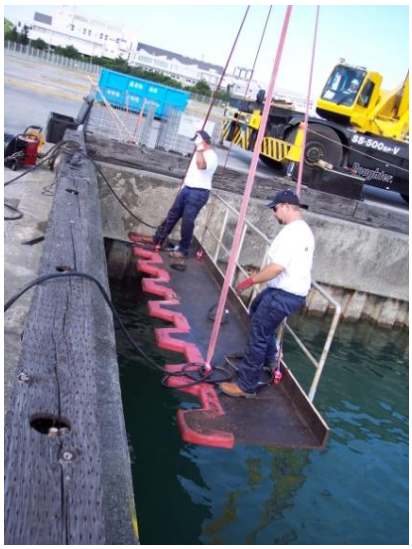

Figure 15 - Platform for overwater work

Figure 16 - Workers repairing piles overwater

After manual and mechanical removal of rust, workers used grit blasting to remove tightly adhering rust particles. Bulkhead cleaning and inspection

preparation revealed extensive holing and loss of steel in a 1.0 meter band above the waterline. The condition is shown in Figure 1, Figure 2, and Figure 17.

Figure 17 - Corrosion in the Atmospheric Zone

Each pile was heavily corroded and there were holes in the area between the splash zone and the underside of the concrete capping beam. All holes were situated at the corners and webs of the out-pans, in a band of approximately 0.8 m under the capping beam. The steel of the in-pan was only holed in a couple of places and remaining steel thickness was on average about half of the original thickness, or approximately 10 mm. The remaining steel was thick enough to dry weld reinforcing plates to it. Small isolated holes were plugged with special cement.

A lot of backfill had fallen out. Larger stones remained in place. The scope of work did not include refilling voids behind the piles. The contractor injected polyurethane foam in lieu of replacing backfill (Figure 18). After the holes were filled, the contractor remodeled the piles with a proprietary cement as shown in Figure 19. The remodeled piles were liquid tight.

Figure 18 - PU injection into voids behind piles above the waterline

Figure 19 - Restoring the pile shape with cement

Either non-shrink grout or epoxy resin was injected between the doubling plate and the pile. This provided better structural reinforcement. A close fit between the doubling plates and piles and reduced the amount of injection material and associated costs. Appendix (I) are diagrams depicting bulkhead repairs above the waterline.

Figure 20 - Remodeled corners prior to attaching doubling plates

The contractor prepared one hundred (100) plates 6 mm thick and 1 meter high to reconstruct fifty (50) piles. Figure 21 shows the material staged at the site. A local workshop rolled the plates to fit the original pile as closely as possible. A 10 mm hole was drilled in each plate to allow injection of either non-shrink cement grout or epoxy resin in the gap between old and

new steel, shown in Figure 22. This was the reason why the holed piles needed to be remodeled liquid-tight.

Figure 21 - Doubling plates

Figure 22 - Drilling injection hole

Two workers installed and tack-welded the plates with use of an inverter welding set (welding rods), Figure 23. A third person finished the welding with a semi-automatic welder using Lincoln Intershield 1.4mm wire, Figure 24.

Figure 23 - Tack welding plates

Figure 24 - Continuous welding of plates.

After welding, the contractor injected **Humidur®** into any voids between old steel and the new doubling plates. The material protected the new steel from the back side. A spray hose was screwed into the 3/8” hole at the top of each plate and epoxy pumped-in till it discharged from the hole at the opposite side of the out-pan . The holes were plugged with 3/8” bolts.

Abrasive blasting operations were later conducted in the **DZI**. The **DZI** is a primary containment enclosure. Forced ventilation and air pollution control equipment maintained emissions within published standards.

2.2.6.2 Underwater work

*2.2.6.2.1 **DZI** Deployment*

The contractor used a 60 Tons hydraulic crane from the shore to hoist and position the **DZI**. When shore access is not feasible or practical, the contractor can work from a barge and use either a crane or gantry system.

Prior to deploying the **DZI**, the contractor scraped the bulkhead with an excavator. After scraping the out-pans with a flat edge bucket, the contractor welded a blade on the bucket that matched the contour of the in-pans. This reduced the time for bulkhead cleaning and removed barnacles that tear up seals.

After the **DZI** was dewatered, water immediately spouted from larger holes. Only after initial cleaning did pin holes, such as those in Figure 25 and Figure 26 appear. Water leaked out of some interlocks and tie-rod anchor plates. All wet holes and leaks were sealed watertight before welding repair plates.

Figure 25 - Level -3.5 m after initial cleaning

Figure 26 - Pin holes revealed after initial cleaning

2.2.6.2.2 Bulkhead Repairs below the waterline

Deep pits, craters and unusual corrosion patterns were found below high water mark as shown in figures 9 through 20 of appendix (J).

Numerous holes of various sizes and shapes were found throughout the sheet piles. Water from the backside of the piling spouted out of the holes. Water leaked out of some interlocks and tie-rod anchor plates. All wet holes and leaks must be sealed watertight before welding repair plates. The contractor attempted various techniques including plugging with various materials, foam injection, and quick-setting cement. These methods were time consuming and did not always provide satisfactory results. More effective proprietary techniques were also applied to increase production and ensure a dry surface.

50 mm diameter holes were found at -2,5 m and -3,5 meters. The location of most holes was on the out-pans of each pile as seen in Figure 27. . The holes were likely made at the time of construction for tie rods. Subsequently, the tie rods were installed on the in-pans and the holes were left open. Only few real corrosion holes were identified under the water line. These holes were patch welded with 200 x 200 x 6 mm plates, Figure 28.

Figure 27 - Example Hole on out-pan

Figure 28 - Example of patch weld.

2.2.7 Surface Preparation and Cleaning

Surface preparation is the primary factor that determines coating effectiveness. After repairs, the contractor cleans steel surfaces to at least ISO 8501-1, Sa 2 ½ (near white metal) and at least ISO 8503-2 segment 1 nominal roughness profile (2.0 mils to 3.0 mils). All surfaces must be clean and structurally sound, free of dirt, dust, abrasives, grease, oil, paint, etc

High pressure washing with tap water removes salts. Adequate forced ventilation provides dust control. Air pressure and clean brushes remove surface dust.

The Contractor measures soluble salts and dust on steel surfaces to be coated to insure that the concentrations of these contaminants are less than the levels allowed by the coating manufacturer.

Maximum allowable chloride concentrations and soluble salts were set by the contractor on respectively 60 mg/m² and 90 mg/m². The method for determining these values is described in ISO 8502-6 and ISO8502-9. Admissible amount of dust was quality degree 3, class 2 per ISO 8502-3. A cigarette paper test was normally sufficient for evaluating surface dryness. A surface temperature 2°C/5°F above the prevailing dew point was normally sufficient to prevent condensation from forming.

2.2.8 Coating Application

Prior to coating application, deep pits, voids and interlocks are filled with a **Humidur® P**, compatible putty variant of the coating. Deep pits can be seen in Figure 29. If these are not filled, an air pocket may form under the

coating. This may lead to coating failure at the pit, Figure 30. The interlocks between piles are caulked, Figure 31. The contractor brushed all sharp edges with **Humidur® BAML,** Figure 32. Stripe coating is necessary because spraying will blow off coating on sharp edges.

Figure 29 - Deep pits

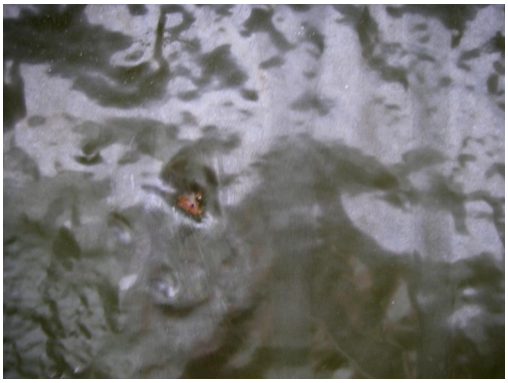

Figure 30 - Holiday over a deep pit

Figure 31 - Treating interlocks with *Humidur®* P and BAML

Figure 32 - Brushing *Humidur®* BAML on sharp edges

Painters have better control over the spray pattern when the coating temperature is constant at the spray nozzle. **Humidur® ML** has the best spray performance when the temperature is 38° C at the nozzle. To achieve optimum spray performance at lower ambient temperatures, the **Humidur®** is heated in a 40° C bath. Spray hoses are wrapped with heating cables and insulated.

The contractor applies **Humidur®** in accordance with the manufacturer's instructions. The nominal recommended coating thickness is 400 microns on new steel. On heavily pitted steel, a nominal thickness of 600 microns

is recommended to adequately cover the peaks and valleys of the rough surface. Pits, interlocks, and repair plates increase the surface area. Actual coverage rates of coating can increase to more than 50 per cent of the theoretical coverage rate. After application, the inspector visually checks for holidays and measures wet film thickness measurements.

Humidur® cures underwater. The contractor immediately floods the **DZI** and hoists it out of the water. The sequence of work is continued down the bulkhead. Figure 33 is the bulkhead before the task order. Figure 34 is the bulkhead after completion of work.

Figure 33 - Original Bulkhead

Figure 34 - Renovated Bulkhead

2.2.9 Containment

The **DZI** served as a primary containment enclosure. It prevented visible emissions or releases of spent materials, dust or other debris into the environment. All debris that fell to the bottom of the DZI was collected. After work was complete, the **DZI** was slowly refilled with water, then hoisted out of the water. It is parked on the dock and allowed to drip out overnight. In Figure 35, the cofferdam was hoisted over the waste container and emptied manually with shovels and brooms

Figure 35 - Emptying waste material collected in DZI

2.2.10 Installation of Reference Coupons

In order to monitor the coating behavior after the completion of the work, the contractor installed twenty four (24) coupons on the face of the seawall underwater for exposure. Figure 36 shows the contractor installing the reference coupons.

The reference coupons were approximately 8x23 cm and fabricated of mild steel. Twelve (12) coupons were coated with **Humidur®** using the same process that was used for the sheet pile on the seawall. The other twelve (12) were installed untreated.

The contractor placed one coated and one untreated coupon at level -1.0 m and -2.5 m of in-pan between the following piles: 0 – 1, 7 – 8, 15-16, 31-32, 39-40, and 47-48. These locations are where corrosion was found to be most aggressive. Figure 37 shows treated and untreated coupons side by side.

Figure 36 - Installation of Reference Coupons

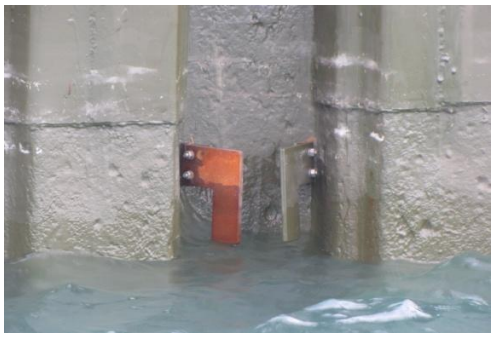

Figure 37 - Treated and Untreated Coupons installed on Bulkhead

2.3 Technology operation and monitoring

2.3.1 DZI Limpet Performance

Efficient sealing was a critical design element. The patented sealing system of the **DZI** proved highly effective at water depths over 3 meters. With one exception, deployment and de-watering occurred in less than-thirty minutes, without the use of divers.

A competent person on-site provided techniques to seal a cofferdam when installed sheet piles were outside industry standard tolerances: plumb tolerance 1/8" per foot of pile length for sheet pile and alignment tolerance of 1" per 30 feet lineal distance.

The exception was due to an unforeseen condition; a sheet pile was driven out of its interlock with an adjacent pile. The limpet was unable to seal the **DZI** between piles 22 and 26. A diving inspection revealed that the inter lock between piles 24 and 25 was open from – 3,5m down to the mud bottom. Pile 24 was standing out from the face of the wall. The opening between the piles at the mud line was approximately 60 cm. The backfill had washed out. The gap provided a direct connection between the seawater and the inside of the cofferdam. The gap was plugged temporarily under water until the contractor could dewater the **DZI**. The part of the gap that extended into the cofferdam was plugged with cement. The defect originates from the time of construction and was probably never noticed. Because of the low visibility under water, it was not possible to document the defect with pictures or video. The split between the piles is illustrated in Appendix (F).

2.3.2 Steel Thickness Measurements

Prior to coating, the inspector performed ultrasonic thickness measurements of the piles. Before the work started, all sheet piles are numbered and marked for reporting and monitoring purposes. At each of the 50 sheet piles, 42 measurements were taken at four surfaces, in-pan, out-pan and webs between level -1,0 meter and -4.0 meter below the concrete cap.

Each of the 42 measurements was the average of 4 measurements in a 2" diameter area. In total 2100 average steel thickness recorded out of 8400 measurements taken, Figure 38 Locations of deep pits were identified and measured, Figure 39.

The test instrument was a calibrated Krautkrämer DM4E.

Figure 38 - Measuring steel thickness

Figure 39 - Measuring Pits

2.3.3 Bacteriological field investigation

Bacteriological field investigation was conducted with the Bart-Test described in appendix (K). The Bart test identifies the presence and type of bacteria. The presence of the certain bacteria can indicate the occurrence of microbially influenced corrosion (MIC).

2.3.4 Surface Preparation and Coating

The coating manufacturer conducted quality control tests of the surface preparation in accordance with coating manufacturer's specifications. Appendix (L) is the coating manufacturer's log book.

2.4 Follow-up Inspections

2.4.1 Reference Coupons

After six (6) months, the contractor removes three (3) treated and three (3) untreated coupons for inspection. After eleven (11) months, the contractor removes and inspects six (6) more coupons. The remaining coupons remain on the bulkhead for long-term exposure analysis. The inspection includes photographs and evaluation per ASTM D610, ASTM D 714, and ASTM D 1645. Results are discussed in section 3.3.

2.4.2 Adhesion Test

The inspector conducted one adhesion test at -2.0 m on pile number 46 with a pull-off adhesion tester as shown in Figure 40. The coating was applied on November 21, 2008 and tested on December 4, 2008. The dolly shows glue failure with a little bit of green pigment from the surface of the coating. The dolly glue failed before the coating detached. The coating was not fully cured at the time of the tests. Full cure time for Humidur® is 3 weeks at 20°. The results show very good adhesion.

Table 2 - Adhesion Test Results, -2.0 m at Pile No. 46

Dolly	Location	Reading (MPa)	Failure
1	Out-pan	12.0	100% glue
2	Out-pan	14.1	100% glue
3	In-pan	10.8	100% glue

Figure 40 - Adhesion Test

2.5 Warranty

Acotec warrants the coating performance for ten years. Appendix (M) is the HDI Gerling Insurance Certificate.

3 Discussion

3.1 Metrics

Measurements are in metric units.

Structural inspections conformed to the following specifications:

Specification	Description
ASTM E 797	Standard Practice for Measuring Thickness by Manual Ultrasonic Pulse-Echo Contact Method
ASTM D610	Standard Test Method for Evaluating Degree of Rusting on Painted Steel

Weld repairs conformed to the following specifications

Specification	Description
ASTM A242/A242M	High-Strength Low-Alloy Structural Steel
AWS D1.1	Structural Welding Code – Steel
AWS Z49.1	Safety in Welding and Cutting and Allied Processes

Surface preparation and coating conformed to the manufacturer's specifications for coating application and included the following specifications.

Specification	Description
ASTM D 4417	Test Methods for Field Measurement of Surface Profile of Blast Cleaned Steel, Method B
ASTM D 1186	Nondestructive Measurement of Dry Film Thickness of Nonmagnetic Coatings Applied to a Ferrous Base
ASTM D 4541	Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers

Specification	Description
ISO 8502-3	Preparation of steel substrates before application of paints and related products -- Tests for the assessment of surface cleanliness -- Part 3: Assessment of dust on steel surfaces prepared for painting (pressure-sensitive tape method)
ISO 8502-4	Preparation of steel substrates before application of paints and related products -- Tests for the assessment of surface cleanliness -- Part 4: Guidance on the estimation of the probability of condensation prior to paint application
ISO 8502-6	Preparation of steel substrates before application of paints and related products -- Tests for the assessment of surface cleanliness -- Part 6: Extraction of soluble contaminants for analysis -- The Bresle method
ISO 8502-9	Preparation of steel substrates before application of paints and related products -- Tests for the assessment of surface cleanliness -- Part 9: Field method for the conductometric determination of water-soluble salts
ISO 8503-2	Preparation of steel substrates before application of paints and related products -- Surface roughness characteristics of blast-cleaned steel substrates -- Part 2: Method for the grading of surface profile of abrasive blast-cleaned steel -- Comparator procedure
ISO 19840	Paints and varnishes -- Corrosion protection of steel structures by protective paint systems -- Measurement of, and acceptance criteria for, the thickness of dry films on rough surfaces
SSPC-VIS	Digital photographs & comparison to photographic reference standard of surface condition
SSPC-AB	Abrasive Specification No. 1 for Mineral and Slag Abrasives
SSPC-VIS 1-89	Guide To Visual Standard for Abrasive Blast Cleaned Steel (Standard Reference Photographs)
SSPC SP-2	Surface Preparation Specification No. 2 for Hand Tool Cleaning
SSPC SP-3	Surface Preparation Specification No. 3 for Power Tool Cleaning

Specification	Description
SSPC-SP 6/NACE No. 3	Joint Surface Preparation Standard for Commercial Blast Cleaning
SSPC-SP 10/NACE No. 2	Joint Surface Preparation Standard for near-white blast cleaning

Health and safety plan conformed to the Acotec Health & Safety Manual and applicable section of the following regulations. Applicable sections included regulations and standards for conventional cofferdams, trench shields, floating platforms, contractor equipment and services.

- Code of Federal Regulations 29 CFR Chapter XVII paragraph 1926
- U.S. Army Corps of Engineers Safety & Occupational Health Standard EM 385-1-1.

Environmental Compliance conformed to the following specifications.

- No discharge of pollutants into the environment.
- No discharge into the atmosphere from abrasive blasting for a period aggregating more than three minutes in any one hour which is dark or darker in shade as that designated as No. 2 on the Ringlemann Chart, as published by the United States Bureau of Mines.
- 40 CFR Subchapter C, parts 100-149 - Federally Promulgated Water Quality Standards

3.2 Results

3.2.1 Steel Thickness

Original estimated steel thickness at the in-pans and out-pans is 20 mm. Original estimated steel thickness at the webs is and 15 mm. Appendix (N) is a record of residual steel thickness for piles 1-25. Appendix (O) is a record of residual steel thickness for piles 26-50. The results are printed in three different colors:

1. GREEN: Steel thickness is more than 8 mm (1/3 of the original thickness).
2. ORANGE : Steel thickness is between 6 and 8 mm
3. RED : Steel thickness is less than 6mm and deeply pitted

The depth of the pits is found by subtracting its value from the thickness of the surrounding material.

3.2.2 Corrosion Profile

Maritime structure design has traditionally considered corrosion conditions in distinct vertical zones in relation to the sea. These zones, and their typical corrosion conditions and rates are described below and illustrated in Figure 42. The loss of steel from -1.00 m to -4.00 m is between 23% and 60%. Flanges on the in-pans and out-pans suffer 15 – 25% more loss of steel than the webs. Pitting corrosion is prevalent from -1.00 m to -2.50 m. On piles 13 – 26 and piles 32 – 50.O, pitting corrosion extends to -4.0 m.

3.2.3 Uniform Corrosion

Approximately 50% loss of steel appears to occur uniformly. The medium thickness for areas in green is approximately 11 mm with a 20% variance. The uniform loss of steel corresponds to a minimum of 0.2 mm (10 mils) per year, assuming loss of steel started immediately after construction (which in reality starts only years later, assuming 10 years, in figure 41).

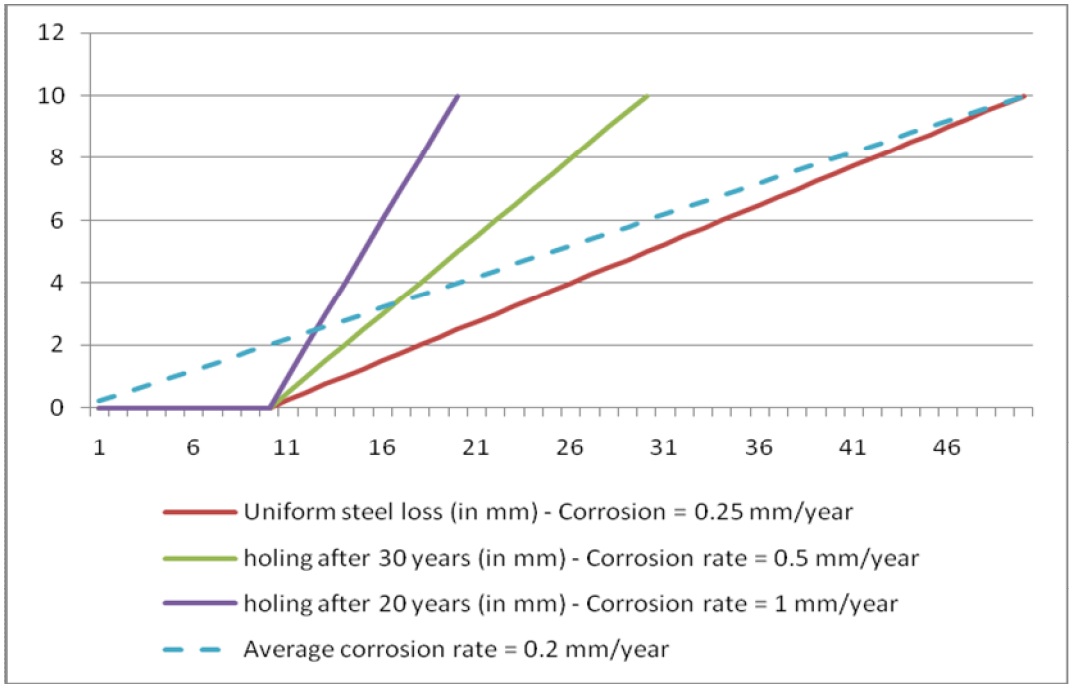

Figure 41 - Corrosion rates

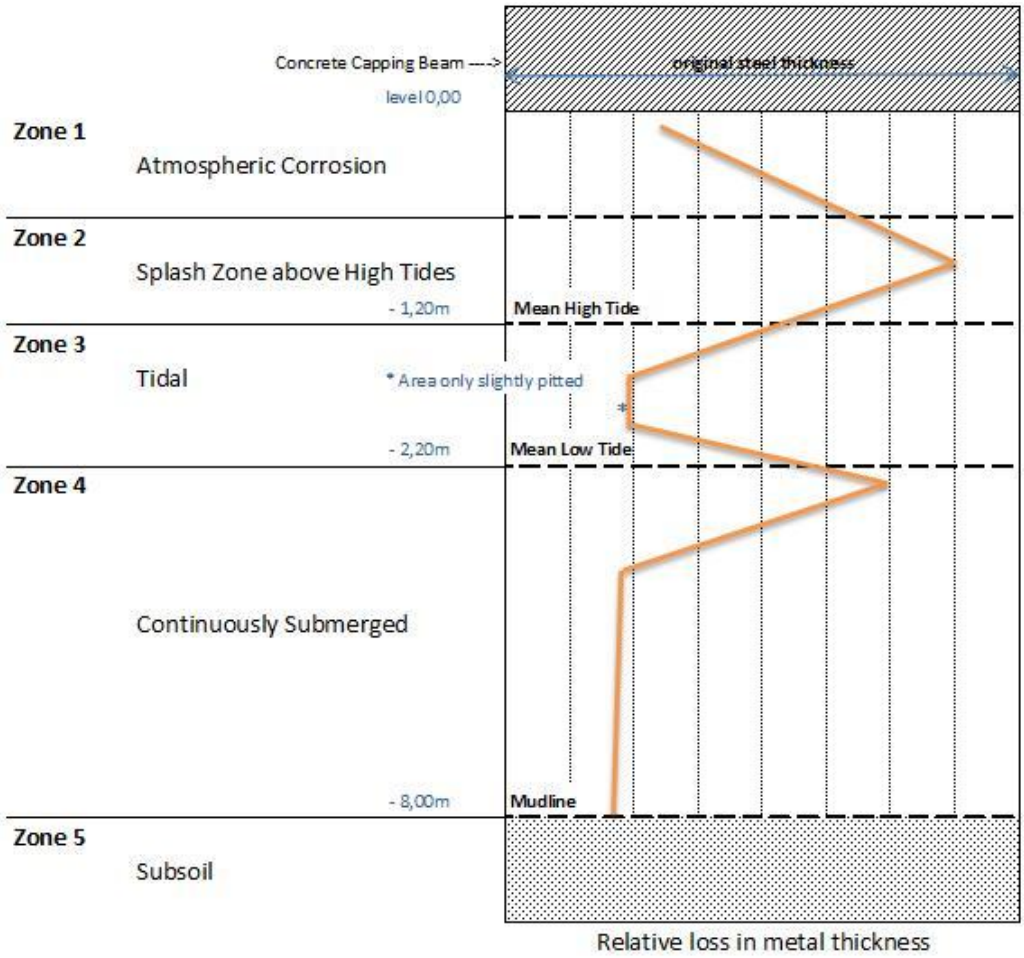

Figure 42 - Typical Corrosion Profile of Steel Pilings in Ocean Tidal Water.

3.2.4 Atmospheric Zone

The atmospheric zone extends from approximately 0.0 m to -0.8 m. The deterioration of the piles is clearly visible. Thick rust scales on all surfaces of the profile (webs and flanges). Between -.060 m and -0.80 m, steel has completely corroded away on the water-side corners. Deep localized pitting is observed on the in-pans. Piles were remodeled with cement and reconstructed with doubling plates of one meter high.

3.2.5 Splash Zone

The splash zone extends from approximately -0.8 to -1.2 (mean high tide). The splash zone had general pitting with very small perforations.

3.2.6 Tidal Zone

The tidal zone extends from approximately elevations -1.2 m at mean high water to -2.2 m at mean low water. Prior to cleaning, the region between -1.00 m and – 1.5 meter appeared sound. The sheet piles have little marine fouling as seen in figure 43. Below -1.50 m the piles are completely covered with shells and vegetation, figure 44Figure 44.

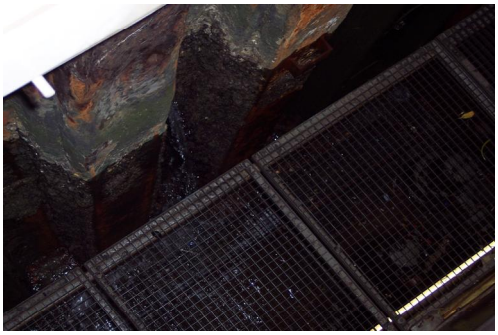

Figure 43 - Tidal zone between -1.0 m and -1.5 m

Figure 44 - Tidal zone below -1.5 m

Cleaning revealed a thick layer of amorphous rust more than 10 mm thick. The thick rust layer was very difficult to remove. Between -1.5 m and -2.0 m, the intact steel underneath was only slightly pitted.

3.2.7 Low Water Zone

The low water zone extends from approximately -2.0 m to at least -4.0 m. The condition of the bulkhead was unknown prior to deployment of the DZI. The thick layer of amorphous rust extended from the tidal zone to the low water zone. Between -2.0 m and -4.0, the intact steel underneath was heavily pitted. Appendix (J) includes pictures of the pits and various striated patterns of corrosion. The unusual striations are parallel grooves running at 30 – 45 degrees from the vertical. Some patterns cross each other symmetrically. The striations are likely a fingerprint of microbiologically influenced corrosion (MIC).

Bacteriological field investigation show the presence of the bacteria associated with the corrosion damage. These types of bacteria are known to promote corrosion of iron through reactions leading to the dissolution of

corrosion resistant oxide films (passive layer) on the metal surface. Pits grow at a much higher speed than the general corrosion rate.

3.3 Follow-up Inspections of Treated Areas

3.3.1 Inspection after Six (6) months

3.3.1.1 Bulkhead Inspection

The contractor inspected the bulkhead on June 8, 2009, six (6) months after completion of work. Figure 45 shows the general condition of the bulkhead. Figure 46 is a closer view. Below is a summary of inspection results after six (6) months.

- Degree of Rusting: ASTM D610-08 Grade 10, less than 0.01% of total surface.
- Degree of Blistering: ASTM D714-02, 10, less than 0.01%

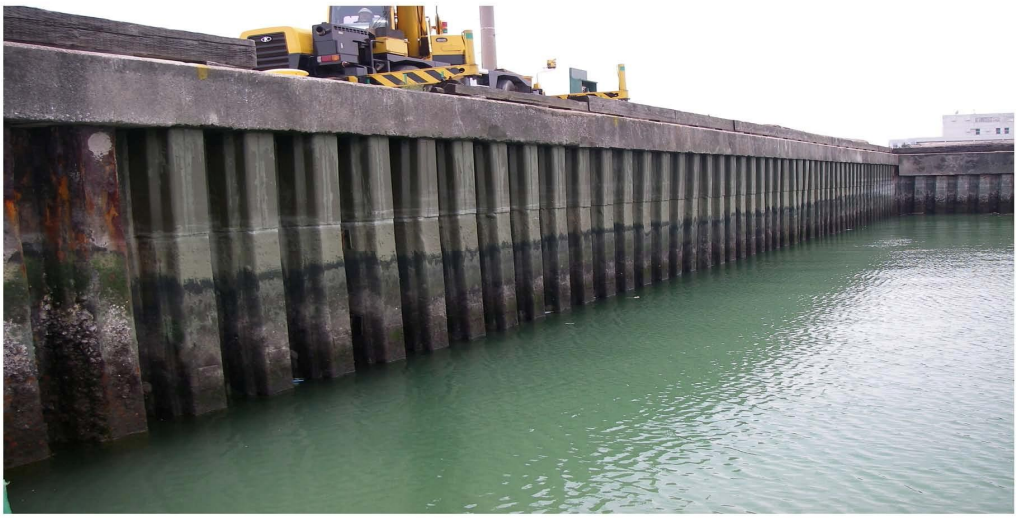

Figure 45 - General Condition of Bulkhead Six Months after Renovation

From level 0.0 to -1.5, some pinholes and minor mechanical damage appeared. From -1.5 to approximately -3.0 meters, no defects were observed. Examples of pinholes are shown in figure 47 and figure 48. Appendix (P) is the six (6) month inspection report, with the dry coating thickness measurement in Appendix (Q).

Figure 46 - Closer View of completed work after 6 months

Figure 47 - Two small pinholes visible after cleaning

Figure 48 - Rust Stain at Pile #23

3.3.1.2 Coupon Inspection

The contractor removed and inspected one (1) treated and one (1) untreated coupon from the following locations for a total of six (6) coupons: two (2) coupons on pile 8 at elevation -2.5 m; two (2) coupons on pile 16 at elevation -1.0 m; one (1) coated coupon on pile 32 at elevation -2.5 m and one (1) un coated coupon on pile 32 at elevation -3.0 m.

Test and evaluation report of these coupons are in Appendix (R). The coupons were in excellent condition and showed no sign of rust or blistering. After field inspection, the coupons were sent to Acotec's laboratory.

3.3.2 Inspection after Eleven (11) Months

3.3.2.1 Bulkhead Inspection

The contractor inspected the bulkhead on December 6, 2009, eleven (11) months after completion of work. Below is a summary of inspection results after eleven (11) months.

- Degree of Rusting: ASTM D610-08 Grade 10, less than 0.01% of total surface.
- Degree of Blistering: ASTM D714-02, 10, less than 0.01%

Appendix (S) is an evaluation of the coating condition after eleven (11) months. All pinholes and mechanical damage observed during the six (6) month inspection have been repaired.

3.3.2.2 Coupon Inspection

The contractor removed and inspected one (1) treated and one (1) untreated coupon from the following locations for a total of six (6) coupons:

Test reports of these coupons are in Appendix (T) The coupons were in excellent condition and showed no sign of rust or blistering. After field inspection, the coupons were sent to Acotec's laboratory.

3.4 Lessons learned

Costs are a direct function of project duration. The major factors that impacted project duration include sealing efficiency of the limpet, contractor experience, and the extent of repairs.

The extent of repairs had significant impact on estimated project costs and duration. The condition of the bulkhead was difficult to ascertain prior to deploying a limpet. An accurate estimate for repairs was impractical without a basis upon which to estimate. The following conditions were not known until after the project commenced.

- Extent of the thick, amorphous rust in the tidal and low water zones,
- Split between piles 24 and 25 near the mud bottom,
- Size and location of leaks and holes, and
- Amount of lost backfill.

3.4.1 Sealing Efficiency

With one exception, deployment and de-watering occurred in thirty minutes or less without the use of divers. The exception was due to an unforeseen condition; a sheet pile was driven out of its interlock with an adjacent pile. A 60 cm gap below the waterline between adjacent piles had to be repaired and sealed. This increased the project duration approximately 10 hours and required the use of a dive team.

3.4.2 Sealing Leaks and Wet Holes Watertight

Some methods to seal wet holes proved time consuming and initially stalled project progress. The results often allowed some seepage of water. The consequences are premature coating failure. These methods included plugging holes with various materials such as foam, oakum, quick-setting cements, and fast curing epoxy. Acotec provided novel techniques for efficiently sealing wet holes. Acotec also supplied special cement for sealing leaks at tie-rod backing plates, pile interlocks, and small pin holes. Better techniques for sealing leaks decreased the time to seal leaks from an average of more than 4 hours per hole to less than 30 minutes per hole. The results were a completely dry surface.

3.4.3 Repairs

A unit price for repairs was difficult to establish at the onset of the project. Techniques and costs to repair holes varied according to geometry and location. Techniques to repair large, irregular holes above the waterline differed from those of small holes below the waterline. Repairs at corners and other non-planar surfaces required more effort than on flat surfaces. Reinforcing plates had to be bent to fit the piles.

3.4.4 Surface cleaning

A 10 mm thick layer of amorphous rust was revealed after commencement of work. The steel underneath was pitted (see Appendix (J)). Removing the rust layer increased surface preparation time 2-3 hours per pile.

The fatiguing work had a significant impact on crew efficiency. Initial progress was slow. The duration of project work for one set-up of four piles was approximately 3 days. Progress accelerated as the crew gained experience. The work crew increased progress to approximately 2.5 days per set-up. The scope of work was not sufficient to consider the value of increasing the crew size to increase productivity.

Ultra high pressure water blasting (2,000 bar) may have been faster. This type of equipment was however not foreseen and also not available on the island of Okinawa.

3.4.5 Coating

Pinholes appeared in the coating over areas of sever pitting. Air trapped under the coating expands during the curing process and forms a bubble. When the bubble bursts, coating integrity may be lost. The contractor filled most fill deep pits and voids with a brush or Humidur P (a putty variant). Some pits were missed. These small defects are difficult to detect during coating applications. They were repaired during the 11th Month – inspection (see Appendix (S)).

4 Economic Summary

4.1 Costs and Assumptions

Table 3 is a summary of direct costs. To achieve the objectives of the task order within the allowable budget, the contractor provided the following items at no extra cost:

- Repair of unforeseen conditions
  - Interlock failure between two piles that created a large gap in the bulkhead below the waterline
  - Extra work for removal of 12 mm of amorphous rust
  - Systematically repair and remodeling with doubling plates of all (50) pile outpans in the upper zone

Table 3 - Summary of Direct Costs (Price List Task Order)

Item	Description	No. Units	Unit	Unit Cost US$	Exten-sion US$
1	Modifications to the **DZI** limpet	1	LOT		28,275
2	Mobilization of equipment, travel, per diem	1	LOT		101,415
3	Repairs, Surface Preparation, & Coating Application from shore	270	M^2	963.10	260,037
4	Follow-up Inspections after 6 and 12 months	1	Lot		18,375
	TOTAL COST				408,102

These costs assume the following:

- The 4 person work crew has prior experience and qualified competent person on-site;
- The limpet will seal in less than 30 minutes and without the use of divers;
- Access to the bulkhead is from the land and the site is not obstructed;

- The contractor can stage materials at the location of work.
- Freshwater is immediately available.
- The bulkhead has no existing coatings or hazardous materials;
- Prevailing wages apply to labor rates, per diem and travel costs; and,
- The multi-functional crew did not include a qualified dive team.

The repair, surface preparation and coating applications costs are further broken down in Table 4. Repair costs include the inventory of labor, plate steel, welding gasses and wire tabulated in appendix (G). Final surface preparation and coating application are the approximate costs to apply corrosion protection on a bulkhead in fairly good condition with few or no holes.

Table 4 - Breakdown of actual costs of Repairs and Coating Application

Item	Description	No. Units	Unit	Unit Cost US$	Extension US$
3a	Extra time to complete the work : Labor and equipment to remove amorphous rust and solve the inter lock failure .	6	Day	7,724	46,344
3b	Structural repairs: Fit, install and weld doubling plates 1,000 x 500 x 6 mm, bent to fit contour of piling.	50	piles	2,642	132,100
3c	Repair holes below waterline: Seal holes watertight. Fit, install and weld patch plates over wet holes, 200 x 200 x 6 mm	88	plates	636	55,968
3d	Final surface preparation, inspection and coating application. Included extra time for scale removal	270	M^2	582	157,710
				Actual costs	**362,122**

Financial results of the task order indicate that the costs to remove the thick layers of amorphous rust and remodeling the complete upper part with doubling plates are almost 2 times the cost of inspection and coat-

ing. Preventive maintenance measures before the onset of ALWC will significantly reduce life cycle costs.

The fixed costs, item 1 and 2 from table 3, are very high, compared with the small size of this project and the remote location and are therefore not taken in consideration .

The unit cost trend for labor efficiency will decrease and progress will accelerate as the contractor gains experience, site supervisors improve crew coordination and project management improves resource allocation.

4.1.1 Relative Costs for Bulkheads in Various Conditions

Total costs under the task order are less than $3,000 per linear foot. The actual cost according table 4, not considering the fixed costs (items 1 and 2) is about $2,723 per linear foot. Including these cost, the linear foot cost amounts to $3,700 . The fixed costs represent here approx. $1,000 per LFt .
The cost to inspect and coat the same sheet piling in fair condition with minor repairs will be much less to half this cost. Table 5 projects the relative cost to renovate bulkheads in various conditions.

Table 5 - Relative Costs to Renovate Bulkheads in Various Conditions

Bulkhead Condition	Welding	Relative Cost	Expected Additional Service Life
Good - Excellent	-	0.9 – 1.4	25 – 50 years
Fair – Good	~	1.3 – 1.8	25 – 50 years
Poor – Fair	X	1.8 – 2.0	Please see Section4.1.4 below
Bad – Poor	XX	> 2.0	

4.1.2 Indirect Positive Effects

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

- Indirect cost savings of <u>not losing revenue</u> because of interruption of port operations during contract work. (Loss of income of an operational commercial quay may vary from hundreds to thousand (s) of dollars per linear foot per month.)

- Hard metrics that evaluate the total impact on energy consumption, pollution, and material recycling, such as:
  - Lower demand for energy resources compared to new steel fabrication; and
  - Recycle 100% of installed materials (non polluting process).
- Soft metrics that evaluate the total impact on community benefits such as
  - perceived good will and local economic stimulus;
  - maintain or create productive job opportunities that utilize traditional labor skills; and,
  - benefits of spending less on bulkhead repairs and reallocating the cost savings to more critical activities in support of relevant missions.

4.1.3 Baseline Configuration

"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]

The initial installation cost is the initial outlay for the wall and it should include the material costs, transportation costs, and on-site handling and driving costs. For a bulkhead, it is customary to include the cost of anchors, tie-rods, and wales, as well as excavation and backfilling costs.

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[1]. This is an estimate of only installation cost, excluding mobilization and inspections. 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 make civil repairs on the land side.

The life cycle cost comparisons in section 4.1.4. use US$ 5,500 per linear foot for initial installation cost (P).

4.1.4 Financial Tools for Evaluating Repair Systems in Extending Bulkhead Life

Price data from the open market is not available or sufficient for calculating costs. 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. The 1967 NAVFAC Report includes a method to make comparisons when cost data is not available.

Typical service life of steel bulkhead sheet piling in a marine environment is between 30-40 years. "The end of lifetime is defined by any one of the following three conditions: (1) collapse or buckling of a significant portion of the bulkhead; (2) gross loss of backfill through holes in the bulkhead; (3) or frequent and expensive maintenance to keep the bulkhead in service." [iii (p. 92)].

"A sheet pile bulkhead wall deteriorates unevenly. The area from slightly below the tidal zone to the splash zone may be approaching failure, while

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[1] (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.

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]

Inspections 15 years after in-situ treatment with **Humidur®** indicate that "the lifetime of the sheet piling will last for another 15 years and thus may be estimated to be at least 30 years" (see Appendix (B)). 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 treated steel sheet pile wall at least 30 years.

4.2 Economical Analysis

The annual life cycle cost savings as a function of renovation cost, original service life, and additional years of service life are compared in Table 6.

When structures are treated in-situ before the onset of heavy corrosion, the renovation investment is much less. Conclusions from Table 6A are that design engineers can easily achieve an additional 30 years of service life and a 10-20% reduction in life cycle costs.

"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”[x]

Conclusions from Table 6D are that approximately 50% of the original installation cost can be spent for ten more years of life if the original life is less than 30 years.

Table 6 - Life Cycle Cost Comparisons to Evaluate when Renovation Costs can Justify Service Life Extension

Table A. Renovation Cost per linear foot (L) = 20% of Initial Installation Cost, (P)

Additional Years of Service Life (Y)	Annual Life Cycle Cost Savings (%)					
	Original Service Life, (n) Years					
	25	*30*	*35*	*40*	*45*	*50*
+50	23%	18%	14%	11%	8%	6%
+40	22%	17%	13%	10%	8%	6%
+30	20%	15%	11%	9%	7%	5%
+20	16%	15%	11%	9%	7%	5%
+10	9%	6%	5%	3%	2%	2%

Table B. - Renovation Cost per linear foot (L) = 30% of Initial Installation Cost, (P)

Additional Years of Service Life (Y)	Annual Life Cycle Cost Savings (%)					
	Original Service Life, (n) Years					
	25	*30*	*35*	*40*	*45*	*50*
+50	21%	16%	12%	9%	7%	6%
+40	20%	15%	11%	9%	7%	5%
+30	18%	13%	10%	8%	6%	4%
+20	14%	13%	10%	8%	6%	4%
+10	6%	4%	3%	2%	1%	1%

Table C. Renovation Cost per linear foot (L) = 40% of Initial Installation Cost, (P)

Additional Years of Service Life (Y)	Annual Life Cycle Cost Savings (%)					
	Original Service Life, (n) Years					
	25	*30*	*35*	*40*	*45*	*50*
+50	19%	14%	11%	8%	6%	5%
+40	18%	13%	10%	7%	6%	4%
+30	15%	11%	8%	6%	5%	4%
+20	11%	11%	8%	6%	5%	4%
+10	4%	2%	1%	1%	0%	0%

Table D. Renovation Cost per linear foot (L) = 50% of Initial Installation Cost, (P)

Additional Years of Service Life (Y)	Annual Life Cycle Cost Savings (%)					
	Original Service Life, (n) Years					
	25	*30*	*35*	*40*	*45*	*50*
+50	17%	13%	7%	7%	5%	4%
+40	16%	11%	6%	6%	5%	4%
+30	13%	9%	5%	5%	4%	3%
+20	9%	9%	5%	5%	4%	3%
+10	1%	0%	-1%	-1%	-1%	-1%

5 Conclusions and Recommendations

5.1 Conclusions

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. In-situ repair method from a limpet cofferdam can use the non-corroded steel as a basic part of a life extension system. Corrosion protection will stop further corrosion and extend the service life.

The task order successfully demonstrated that the proven limpet cofferdam ("DZI") with competent on-site personnel can repair badly corroded piles to a high standard. Application of the Humidur® high performance epoxy coating, specially developed for this type of underwater protection, and allowing applications at freezing temperature. It is a, for 25-years proven, effective and long term solution to stop further corrosion above and below the waterline.

Financial results of the task order indicate that the costs to remove thick corrosion products and make repairs are 2-3 times the cost of final surface preparation, inspection and coating. Preventive maintenance measures before the consequences of severe corrosion or the onset of ALWC will significantly reduce life cycle costs.

Actual bulkhead conditions are difficult to ascertain before work begins. The true structural condition of the steel was not revealed until all corrosion products were removed over a large area. The project should meet operational goals.

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.

5.1.1 DZI Cofferdam

The mobile limpet cofferdam is a state of the art technique to repair and preserve steel sheet piling walls. Pictures of the DZI are shown in Appendix (U). The **DZI** limpet is a benchmark for establishing design, performance and safety criteria for a limpet cofferdam.

- Sealing is a critical design element of the limpet. The contractor used a patented sealing design that is proven to work. Other designs were not evaluated. Project designers should note that the **DZI** sealing technology is protected under U.S. Patent number 5,292,206, Device for Sealing a Caisson in a Watertight Way.
- The **DZI** was a best management practice to prevent visible emissions or releases of spent materials, dust or other debris into the environment. The contractor was able to contain and collect debris that fell into the bottom of the **DZI**. Repairs eliminated the flow of sediment and other constituents from the backfill into the waterways through underwater holes.

5.1.1.1 Advantages

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

5.1.1.2 Disadvantages

Intrinsic barriers and long cycle time for introducing 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 for this method of work among engineers and consultants

5.1.2 Unique factors and Special Skills

Limpet cofferdam design and contract work requires specialized skills and technology not commonly available in the United States, nor easily duplicated.

Repairs required special skills usually acquired through experience. On-site competent personnel with requisite experience provided novice **DZI** users with the necessary training. The special skills included the following techniques:

- Assemble and deploy the **DZI** limpet with little or no modifications in 3 days.
- Seal the **DZI** limpet against Z-piling without the use of divers in 30 minutes or less.
- Seal leaks watertight. The time to seal each leak was from 5 to 30 minutes, depending on the size, location, and amount of flowing water.

5.1.3 Corrosion Protection

The **Humidur®** Coating System is a benchmark for steel sheet pile coating specifications. Initial inspection results of the **Humidur®** coating after 25 years are very satisfactory. A third party insurance company will guarantee satisfactory long term performance for ten years. Prior inspections of the coating supported claims that the service life will extend thirty or more years. Surface preparation followed standard methods and practices for abrasive blasting heavy structural steel. Field supervisors provided assistance to ensure a dry, salt free surface.

5.1.4 Underwater Corrosion Inspection

The inspector was able to perform all standard measurements with no difficulty. Additionally, the inspector was able to collect and preserve biological samples and perform laboratory analysis. This is critical for a finding root cause analysis of the corrosion mechanism.

Corrosion patterns and bacteriological field tests show the presence of micro-organisms associated with the underwater corrosion damage

- Sulfur Reducing Bacteria (SRB). SRB's are anaerobic bacteria that produce highly corrosive products.
- Sulfur Oxidizing Bacteria (SOB). SOB's are able to use the S-compounds produced by SRB if oxygen or other electron acceptors like Fe^{3+} or NO_3^- are available. By their metabolism, the Sulfur compounds are oxidized to sulfuric acid, a corrosive agent.
- Metal reducing bacteria (MRB). MRB's are slime formers that may produce concentration corrosion cells on steel surfaces.

These types of bacteria are known to promote corrosion of iron through reactions leading to the dissolution of corrosion resistant oxide films (passive layer) on the metal surface. Pits grow at a much higher speed than the general corrosion rate. MIC corrosion rates can exceed 0.5 mm per year. At cruising speed, corrosion occurs at on the order of millimeters of steel loss per year.

5.2 Recommendations

5.2.1 Applicability

The limpet dam or **DZI** and corrosion-resistant, rapid -cure epoxy coating should be used to ensure a durable and quick rehab of the steel pile structure, and is available commercially. Acotec NV has developed the **Humidur®** line of anti-corrosion coating products. This coating can be applied by a limpet/mobile cofferdam which creates free access to the site, and enables thorough inspection - optimum maintenance and repair works on steel surfaces below water in the dry, while minimizing disturbance to harbor activities.

The additional installation cost to coat a new bulkhead system in-situ can be justified economically through similar life cycle cost comparisons. Design engineers should consider this when a wharf 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.

The following recommendations are for a safe and successful project outcome.

- Conduct an initial dive inspection for unforeseen conditions and general condition of the bulkhead. Section 5.2.2 recommends information that should be part of a good assessment.
- Define a baseline for estimating repairs.
- Include safety standards for trench shields for work from a limpet cofferdam.

5.2.2 Conduct an Initial Site Assessment

An initial site investigation 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 de-

sign 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.

When prior inspection documents are not available, the design engineer should consider include a Level I inspection over the entire bulkhead and a Level II inspection over a statistically significant representation of bulkhead that has been equally exposed to similar conditions.

The design engineer should record obvious major damage or deterioration due to overstress (collisions, ice), severe corrosion, or extensive biological growth attack.

Good site assessment includes the following information:

- Describe and measure the extent of marine fouling and corrosion.
- Confirm water levels, depths, and current.
- Sound the mud bottom to locate any submerged obstructions.
- 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.

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.

5.2.3 Baseline for Estimating Repairs

Actual bulkhead conditions are difficult to ascertain before work begins. Contracting officers should define a baseline for repair specifications against which contractors can bid.

5.2.4 The Unified Facilities Criteria for Maintenance of Waterfront Facilities (UFC 4-150-07)

This report provides supporting rationale for recommending in-situ coating as a method for inclusion in the Unified Facilities Criteria for Maintenance of Waterfront Facilities (UFC 4-150-07). UFC 4-150-07 describes various methods to repair and maintain underwater steel structures that suffer ALWC.

5.3 Implementation

FAR Subpart 15.3 prescribes policies and procedures for selection of a source or sources in competitive negotiated acquisitions. The objective of source selection is to select the proposal that represents the best value. Contracting by negotiation allows more flexibility in awarding a contract. The contracting officer may engage in discussions with offerors and, in evaluating proposals, he or she may also consider non-cost factors (such as managerial experience, technical approach, historical data, and past performance. Appendix (V) proposes a synopsis for Requests for Proposals and Solicitations. It includes special clauses that contracting officers may consider for solicitation documents. The proposed synopsis includes provisions whereby offerors can protect proprietary and patented information. Appendix (I) diagrams the vertical and horizontal cross sections of common bulkhead repairs above the waterline.

Appendix (W) proposes language for revisions to the Unified Facilities Criteria for Maintenance of Waterfront Facilities (UFC 4-150-07).

Appendices

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*

2. REPORT TYPE

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE

Authors are urged to leave this form alone because it can be unpredictable in terms of word processing. An editor will fill it in for you.

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

Corrosion Prevention and Control

6. AUTHOR(S)

5d. PROJECT NUMBER

CPC XXX-XXX

5e. TASK NUMBER

MIPR5CCERB1011, MIPR5CROBB1012

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

U.S. Army Engineer Research and Development Center
Construction Engineering Research Laboratory
P.O. Box 9005
Champaign, IL 61826-9005

8. PERFORMING ORGANIZATION REPORT NUMBER

ERDC/CERL TR-0X-XX

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER** *(include area code)*
Unclassified	Unclassified	Unclassified		181	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. 239.18

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