DEPARTMENT OF THE ARMY
MISSISSIPPI VALLEY DIVISION, CORPS OF ENGINEERS
P.O. BOX 80
VICKSBURG, MISSISSIPPI 39181-0080

REPLY TO
ATTENTION OF:

16 Dec 2009

CEMVD-RB-T

MEMORANDUM FOR Commander, Hurricane Protection Office

SUBJECT: HSDDRS Design Guidelines - Waiver for Steel Piles Corrosion Protection

1. Reference enclosed memorandum, CEMVN-HPO, 4 Dec 2009, subject same as above.

2. The request to use sacrificial steel as an alternate to coal tar epoxy coating for corrosion protection is approved subject to the recommendations in paragraph 3.

3. This office recommends conservative assumptions in determining the sacrificial section to ensure project life requirements are met. Even though the majority of the pile length will be embedded in oxygen deficient soils, the potential exists for subsidence-induced settlement exposing pile tops to atmospheric conditions below the T-Wall bases. Measures may be developed to mitigate this concern, but can not be fully depended on to eliminate exposure to atmospheric conditions for the project life. For this reason corrosion rates based on similar situations and exposure to atmospheric conditions should be assumed in the design.

4. In the enclosed referenced memorandum, MVN-HPO provides a thorough evaluation of corrosion protection alternatives for steel piles and sheetpiles. This includes historical information from a report prepared by Melvin Romanoff for the U.S. Department of Commerce, National Bureau of Standards dated 24 October 1962. This report includes data from projects in South Louisiana where piles were extracted after many years of use. To augment this information, MVD recommends the inspection of existing T-Wall structures with uncoated steel piles and in-place for many years. Spot-checks in various locations will reveal pile conditions and corrosion rates which should be similar to those expected in the proposed design. This information, in conjunction with information already available, will provide a sound basis for design assumptions.

5. Even though this memorandum provides approval to deviate from current HSDRRS Design Guidelines, coal tar epoxy should be the

preferred option for corrosion protection when the schedule allows its use. This is based on consultation with Dr. Larry D. Stephenson, subject matter expert with ERDC-CERL.

6. The vertical team has been engaged in this waiver request. Ms. Anjana Chudgar is the HQUSACE representative. For additional information, the MVD POC is Mr. Allen Perry at (601) 634-5883.

Encl

MICHAEL J. WALSH
Brigadier General, USA
Commanding

CF:
CECW-CE (Mr. Dalton, Mr. Pezza, Ms. Chudgar)
CEMVN-ED (Mr. Baumy)
CEMVN-HPO (Mr. Grieshaber)
CEMVN-TFH (Mr. Park)
CEMVD-RB-T

DEPARTMENT OF THE ARMY
HURRICANE PROTECTION OFFICE, CORPS OF ENGINEERS
P.O. BOX 60267
NEW ORLEANS, LOUISIANA 70160-0267

REPLY TO
ATTENTION OF

CEMVN-HPO 4 Dec 09

MEMORANDUM FOR BG Michael J. Walsh, Commander, Mississippi Valley Division, U. S. Army Corps of Engineers, 1400 Walnut Street, Vicksburg, MS 39180-3262

SUBJECT: HSDRRS Design Guidelines – Waiver for Steel Piles Corrosion Protection

1. Reference MVN Hurricane Storm and Damage Risk Reduction System (HSDRRS) Design Guidelines, dated 12 June 2008.

2. Request a waiver to the HSDRRS Design Guidelines to allow the use of sacrificial steel as an alternate to coal tar epoxy for the corrosion protection of steel piles. Current requirements in the HSDRRS Design Guidelines, dated 12 June 2008, state that "Only coal tar epoxy shall be used." This waiver will afford the opportunity to eliminate any delays associated with coating the top portion of steel piles and sheetpile sections with coal tar epoxy. Your prompt action on this request will allow maintaining the schedule to provide hundred year level of protection attainment by hurricane season 2011.

3. Our evaluation team for this request included participants from MVN and HPO and our evaluation of corrosion protection requirements has been documented in the enclosed 4 December 2009 memorandum, SUBJECT: Evaluation of Corrosion Protection Alternatives for Steel Piles and Sheetpiles. We have coordinated the proposed action with representatives from HQUSACE, ERDC-CERL, MVD, and MVP. The enclosure reflects the outcome of our discussions.

4. Based on the aforementioned discussions, we requested a conditional approval to be followed by a formal request through official channels. The conditional approval was received from MVD-RB-T, Mr. Jimmy Waddle, Chief, Business Technical Division, on 4 November 2009. This memorandum formalizes this waiver request.

5. My point of contact for this request is Dr. John B. Grieshaber, (504) 862-2979.

Encl

ROBERT A. SINKLER
COL, EN
Commanding

CF:
Commander, New Orleans District (CEMVN-EX) (w/encl)
Director, Task Force Hope (CEMVN-TFH) (w/encl)
Chief, RB-T MVD, Jimmy Waddle, P.E. (CEMVD-RB-T) (w/encl)
Chief, Engineering Division MVN, Walter Baumy, P.E. (CEMVN-ED) (w/encl)

CEMVN-HPO 4 December 2009

MEMORANDUM FOR RECORD

SUBJECT: Evaluation of Corrosion Protection Alternatives for Steel Piles and Sheetpiles

1. INTRODUCTION

As we finalize the design of projects for the Hurricane and Storm Damage Risk Reduction System (HSDRRS), the subject of corrosion mitigation for steel piles and sheetpiles has been identified as an issue that should be re-analyzed due to schedule impacts. The current HSDRRS Design Guidelines do not allow for alternate systems of corrosion protection, other than coal tar epoxy coating (bitumen). Corrosion protection is typically applied at a location other than the steel mill and there are very limited facilities that can apply this corrosion protection treatment. Previous attempts to apply the bitumen coating locally, in a smaller quantity, were not successful. We anticipate that steel piles and sheetpiles will be sent from the mill to an out-of-state facility to be coated, and then transported to the job site. This paper discusses the various aspects of alternate methods for corrosion protection, effectiveness relative to the soil conditions for the HSDRRS projects, possible impacts on the construction schedule, and offers a recommendation for a reasonable modification to the HSDRRS Design Guidelines.

Current requirements in the HSDRRS Design Guidelines, dated 12 June 2008, are as follows (note that "painting" refers to corrosion protection):

> **"5.6.8 Painting**
> Only coal tar epoxy shall be used.
>
> Steel sheet, H and Pipe pilings that will be installed in new fill, disturbed materials or fluctuating water tables shall be painted with a coal tar epoxy system. The H-piles and sheet piling shall be painted 3 inches above the stabilization slab and to a 5 ft. minimum below new fill material, disturbed soil or the lowest elevation of fluctuating water tables. Piles exposed in water (i.e. cutoff pilings in breakwaters) shall be coated the full height exposed to water plus a 5' embedment length. Use engineering judgment for final painting requirements."

Moreover, the Early Contractor Involvement (ECI) contractors have expressed concerns about construction schedule delays due to the application of coal tar epoxy for corrosion protection. The following comments were received from a construction contractor with a cost estimate:

- Currently there is a severe shortage of qualified coating facilities.
- The current coating facilities are at full capacity and are overwhelmed with the volume of orders and this is prior to any material orders from St. Bernard's ECI Contractors.
- Current work schedule for coating facilities are six-day work-weeks.

Enclosure

It is proposed that an alternate method for providing corrosion protection, i.e., sacrificial steel or increased section thickness, be allowed in HSDDRS projects, whenever site and design conditions are favorable.

2. GENERAL

Due to the requirements of a long project life, safe, reliable, and cost effective civil works structures, it is necessary to address corrosion aspects of steel pile and steel sheetpile foundations in soil and water. The standard practice has been to provide a coating of coal tar epoxy to the steel surface for the length that warrants corrosion protection. Coated surfaces are typically from the top of the pile to a safe distance below the lowest groundwater table level or new fill placement. In some instances, it is more practical to protect the entire element, especially for relatively short steel sheetpiles used for seepage management.

Due to the unusual requirement for such a large quantity of coated piles and sheetpiles and site-specific circumstances, we explored alternate ways to provide a safe, reliable, less time consuming, and cost effective corrosion mitigation plan for steel piles and sheetpile for HSDRRS projects. We reviewed many publications, but the focus of this paper is on studies that have similar application and soil conditions to the New Orleans area, undisturbed deposits, clay deposits that are oxygen-deficient and do not allow oxygen to reach the steel readily and pile installation conditions where the piles are fully embedded in the soil. This in itself mitigates greatly our problem of corrosion exposure because the most severe steel pile corrosion problems occur on exposed piles, where the opportunities for oxygen availability, either through the atmosphere or water, which promotes the corrosion mechanism, exists. Another condition that greatly increases corrosion is when piles are embedded in new fill that is oxygen rich. Most authors agree that oxygen availability is one of the most significant factors that should be considered in corrosion evaluation. For example, in coarse-grained soils corrosion rates may approach those of atmospheric conditions. In clays, the deficiency of oxygen would result in conditions approaching those of submerged conditions, where very little corrosion occurs (Foundations in Engineering Practice by Shamsher Prakash and Hari D. Sharma). New Orleans area soils are generally clays and would fall in the latter category, i.e., the corrosion rates would tend to be near the low end of published data.

The following methods for providing corrosion protection are discussed in this paper:

a. Coal Tar Epoxy
b. Increase Material Thickness
c. A-690, Marine Steel
d. A-572 Steel
e. Splice Thicker Section on Top Portion of Pile

3. CORROSION OF STEEL PILES

Our limited research of the subject indicates that the corrosion rate of steel piles embedded in soil is influenced by a number of corrosion related parameters, in addition to oxygen availability. These include soil minimum resistivity, pH, chloride content, sulfate content, sulfide ion content, and soil moisture content within the soil. Measurement of these parameters can give an indication of the corrosivity of a soil. Unfortunately, because of the number of factors involved and the complex nature of their interaction, actual corrosion rates of driven steel piles cannot be determined by measuring these parameters. For example, the California Department of Transportation has eliminated the minimum resistivity criteria, since it is only an indicator of possible corrosion. Many authors and agencies recommend making an estimate of the potential for corrosion by comparing site conditions and soil corrosion parameters at a proposed site with historical information at similar sites. This is the approach followed on this paper.

In general, the corrosion behavior of structural steel embedded in soil is divided into two categories, corrosion in disturbed soil and corrosion in undisturbed soil. A disturbed or freshly placed soil is defined as a soil in which digging, backfilling, or other soil upheaval has taken place allowing the creation of an oxygen-rich environment. Driven steel piles generally have the majority of their length in undisturbed soil. However, excavation and backfilling for footings and pile caps create a region of disturbed soil near the top of the piles, increasing the availability of oxygen and the opportunity for corrosion.

As mentioned above, a major contributor to increased corrosion rates of driven steel piles in soil is the availability of oxygen. In general, oxygen content is greater near the upper portion of the pile, greater in disturbed soils, and greater in soil near a ground water surface. Soil disturbance in the upper region of the pile may create areas of differential aeration within and just below the disturbed soil zone. This may lead to increased pitting corrosion of the steel piles within or near the disturbed zone and has been recognized in the HSDRRS Design Guidelines by including provisions for freshly placed soils, i.e., new fill material or disturbed soil.

Many agencies and authors recommend the use of a sacrificial metal thickness for steel pile foundations. Sacrificial metal or corrosion allowance is the thickness of metal (above what is structurally required for the pile) needed to compensate for the loss of metal that will occur as the pile corrodes. This extra metal thickness is added to all surfaces of the pile exposed to the corrosive soil or water. In the case of steel piles in soil, this is the most common method to account for expected corrosion penetration. During our evaluation, we identified corrosion rates presented in various studies to assist in determining a corrosion rate for the New Orleans area, as discussed below:

- Swedish Commission on Pile Research. According to the Swedish Commission on Pile Research, the optimal solution for steel piles in soil is to account for the loss of wall thickness due to corrosion penetration. The optimal solution for steel tube piles in corrosive water, where accounting for corrosion penetration may not be sufficient, is probably the use of PE-cover. If the PE-cover is combined with cathodic protection and sacrifice anode, the additional cost is often marginal. (Corrosion and protection of steel piles and sheet piles in soil and water, Excerpt and translation of Report 93, Swedish Commission on Pile Research, by Göran Camitz)

- Japan Experience (Ohsaki 1982), Corrosion of Steel Piles Driven in Soil Deposits. While abundant data on the corrosion of steel and other metallic materials are available from laboratory tests on disturbed soil samples, information about the corrosion of steel piles driven in natural, undisturbed soils is limited. A study was conducted in Japan (Ohsaki 1982) to determine the corrosion rate of piles driven into undisturbed soils ranging from alluvial clay to coastal reclaimed soils, in an area from the southern to the middle portion of Japan. About 130 steel piles, 15m long, were driven into natural soils of varying conditions. The piles were withdrawn at 2, 5, and 10 years after driving and the corrosion rates were evaluated. The results obtained during the 10 years of research indicate that:

- The withdrawn piles were generally in excellent condition, corrosion effects were minimal and independent of soil conditions.
- Average corrosion rate was approximately 0.01 mm/year per both faces of a pile over the 10 year period.
- Corrosion of the inner face of a pipe pile seems to be the same as the outer face.
- It was difficult to find any particular soil parameters which decisively influenced the corrosion rate.
- Effects on corrosion due to steel composition (mild steel, copper-bearing steel or weathering steel) cathodic protection or protection by painting was not evident. Influences of welding, cold-working, and underground electric current leakage were insignificant.

The author summarized that "Fortunately, however, the corrosion rate itself is so small, regardless of soil condition, that no serious consequence would be encountered if a slight thicker cross-section is chosen at the design stage to accommodate sacrificial thickness for anticipated corrosion losses."

- <u>California Department of Transportation Corrosion Guidelines (Version 1.0)</u>. According to the California DOT, local corrosion cells may exist in some miscellaneous fills that can lead to increased corrosion rates of driven steel piles. These miscellaneous fills include combinations of natural soils (clays and sands), construction debris, ash and cinder material, as well as waste inorganic materials. Increased corrosion rates have been documented in these fills where soil pH was low, 5.5 or less. Historically, the Department has defined a corrosive area in terms of the resistivity, pH, and soluble salt content of the soil and/or water. Since resistivity serves only as an indicator parameter for the possible presence of soluble salts, it is not included to define a corrosive area. For structural elements, the Department considers a site to be corrosive if one or more of the following conditions exist for the representative soil and/or water samples taken at the site: Chloride concentration is 500 ppm or greater, sulfate concentration is 2000 ppm or greater, or the pH is 5.5 or less. If a site is corrosive based on the definition listed above, then corrosion mitigation is required.

- <u>Florida's LADOTD Requirement for Additional Sacrificial Steel Thickness (dot.state.fl.us)</u>

Application	Subsurface Environment	
	Slightly Aggressive	Moderately Aggressive
Pipe and H-Piles completely buried in ground without corrosion protection measures	0.075 inches	0.15 inches

- National Bureau of Standards (Bowles 1982). A study for the National Bureau of Standards (Bowles 1982) on sheetpile and bearing pile substructures indicated that if piles are driven into undisturbed natural soil deposits, then pile corrosion is not great enough to affect the strength of the piles significantly. The piles that were studied had been in service from 7 to 40 years. Undisturbed soils were found to be oxygen-deficient from a few feet below the ground surface. The diffusion of oxygen in undisturbed soil, and particularly below the water line, is sufficiently low that the corrosion process is effectively stifled. The role of oxygen in an undisturbed soil overrides the effects of soil resistivity, pH, and other factors (Chaker and Palmer). Oxygen deficiency was attributed to be the primary cause for the reduced corrosion rate of piles driven into undisturbed soil deposits.

4. CORROSION OF STEEL PILES IN THE SOUTH LOUISIANA AREA

The following information is from a report prepared by Melvin Romanoff for the U.S. Department of Commerce, National Bureau of Standards, October 24, 1962. Bonnet Carre and Chef Menteur Pass are cases where the piles were extracted and Berwick Lock and Algiers Lock are cases where the pilings were exposed by excavation.

As a basis for more accurate estimates of the useful life of steel pilings in soils, the National Bureau of Standards, in cooperation with the American Iron and Steel Institute and the U.S. Corps of Engineers, undertook a project to investigate the extent of corrosion on steel piles after many years of service.

a. Bonnet Carre Spillway, New Orleans, Louisiana

History: A 12-in., 65-lb, test H-pile was driven to a depth of about 122 ft below natural ground surface in a swamp near the river side toe of the west approach ramp to the Airline Highway Bridge across Bonnet Carre Spillway.

Date pile driven: 1933
Date pile pulled: 1950
Age of piling: 17 years
Piling exposed: Elevation +2.0 to -120 MSL.
Ground line at +2.5ft; water line at 0 feet.

Soil characteristics:
+2.5 to -7 ft: Soft dark gray organic silty clay.
-7 to -40: Very soft dark gray highly organic clay and silt layers with few thin layers of peat and few layers of fine gray sand.
-40 to -62: Very soft dark gray clay and silt layers, slightly organic.
-62 to -67: Dense yellowish brown silty sand with hard clay layers at bottom.
-67 to -120: Light bluish gray plastic clay, hard at top, very stiff at bottom.

Condition of pile: The space between the flanges of the pile was completely filled with soil and a layer of soil adhered to the outer edges of the flanges. Examination after cleaning showed no measurable corrosion. Mill scale was intact over almost the entire surface except for the 3-ft section in the area of the water table between elevation +1.5 to -1.5 feet. In this zone a crust of light colored hard substance coated the metal. Slight metal attack was found under the crust.

b. Chef Menteur Pass, New Orleans, Louisiana

History: In connection with construction work on the Simpson-Long Bridge across the Chef Menteur Pass on U.S. Highway 90, about 11 miles west of New Orleans, it was necessary to pull about 60 tons of sheet pilings. The pilings formed a retaining wall for the abutment of the bridge. The sheet piles were 33 ft in length, arch type with a driving width of 19-5/8 in, and a thickness of 3/8 in. at the center of the web.

Date pile driven: 1929
Date pile pulled: 1961
Age of piling: 32 years

Piling exposed: Elevation +6 to -27 feet: Water side, +6 to +3 in atmosphere; +3 to 0 ft. (mud line) in brackish salt water. Soil side, +6 to +4 ft. in atmosphere; ground line at +4 ft.

Soil characteristics:
+4 to -4 ft: Light gray loose silty sand.
-4 to -27: Very tight gray clay.

Condition of piles: Detailed examination of four lengths of pilings showed that the degree and pattern of corrosion were similar. The condition of the pile exhibiting the maximum amount of corrosion is reported herewith. Both sides of the top 4 ft. sections of the piles were coated with a protective aluminum-type paint and an undercoat of red lead.

Water side:
+6 to +4 ft: Paint was intact, unaffected by corrosion.
+4 to +2 ft: Rust and slight metal attack, two pits measured 23 and 38 mils in depth, other pits about 10 mils.
+2 to 0 ft: Thick crust of corrosion products on the finger interlock edge between 25 and 40 mils thick, localized pitting and metal attack beneath the crust, some pits between 40 and 50 mils in depth. Thin layer of corrosion products on flanges, web and thumb interlock with pitting less than 10 mils in depth, except for a few pits between 25 and 60 mils on one side of the flange at 1 feet. Mil scale almost completely removed from this zone.
0 to -1 ft: Metal attack and slight pitting (less than 10 mils) on interlock only.
-1 to -14 ft: Mill scale intack over 95% of surface. Flanges and webs unaffected by corrosion. Slight metal attack and three scattered pits (maximum depth, 70 mils) on finger interlock at -11 to -12 ft.
-14 to -17 ft: Metal attack and 6 pits ranging in depth between 60 to 145 mils along finger interlock. No measurable pits on the web or flange. Mill scale intact over 80% of surface.
-17 to -19 ft: Slight metal attack, mill scale intact over 80% of surface.

-19 to -20 ft: Mill scale intact over 75% of surface. Four pits between 33 and 88 mils in depth on the thumb interlock and flange; two pits, 95 and 58 mils in depth, on other flange.

-20 to -27 ft: Mill scale intact over 90% of surface. Only two measurable pits, 80 and 104 mils in depth, at -26 on finger interlock.

Soil side:

+6 to +4 ft: Uniform thin layer of rust, no measurable pits.

+4 to 0 ft: Uniform layer of rust and scale over surface to a thickness of 40 mils. No measurable pits.

0 to -27 ft: Metal attack in many areas. About 75% of surface covered with mill scale. No measurable pits greater than 10 mils, except at elevation -24 where a few pits were found on the finger interlock of one pile. Maximum pit depth, 25 mils.

c. Berwick Lock, Berwick, Louisiana

History: Two excavations were made to expose steel pilings in the cutoff walls on the west side and east side of the north end of the Berwick Lock which is located between the Lower Atchafalaya River and Berwick Bay near Berwick, Louisiana. The arch-type steel sheet pilings had a driving width of 19-5/8 in, and 3/8 in. wall thickness.

Date pile driven: March 1949
Date of inspection: April 1960
Age of piling: 11.1 years

(1) North End of Lock – West Side

Piling exposed: A 5-ft width of pilings was exposed between elevation +3.5 and -1.5 feet. One side of the pilings which was uncoated, was totally exposed to the soil environment. The other side of the pilings had a coal tar epoxy coating and was exposed to water.

Surface elevation: +5 feet.
Water table elevation: -0.5 feet.

Soil characteristics:

+5 to +2 ft: Fill material consisting of a mixture of gray and brown silty clay containing some gravel and small shells.

+2 to -1.5 ft: Natural soil consisting of tight bluish gray impervious plastic clay with patches of tight brown clay dispersed throughout the profile.

Condition of piles:

+3.5 to 1.5 ft: Mill scale was intact over 40 percent of the surface. The remaining surface was uniformly attacked and had many shallow pits less than 25 mils in depth, and some deeper pits. A few pits ranged between 55 and 61 mils in depth, and many others ranged between 25 and 55 mils. The average reduction in wall thickness observed on the three most corroded areas was between 6 to 8 percent.

+1.5 to -1.5 ft: Mill scale was intact over about 60% of the surface. Slight uniform corrosion was present on the remaining surface and there were many pits which did not exceed 25 mils in depth. There was slight general metal attack and pitting over the entire coated side of the pilings which was exposed on the water side. The river water had a resistivity of 2,500 ohms-cm, and salt content of 40 ppm.

(2) North End of Lock – East Side

Piling exposed: A 5-ft width of the wall was exposed between elevation +3.5 and 0 feet.
Surface elevation: +5 ft.
Water table elevation: +1 ft.

Soil characteristics:
+5 to +3 ft: Fill consisting of a mixture of slightly friable reddish brown and gray tight clay containing gravel and many stones.
+3 to 0 ft: Natural soil consisting of brown fat plastic clay.

Condition of piles:
+3 to +1 ft: Mill scale was present on 40% of pile surfaces. There was uniform corrosion and pitting where the mill scale was missing. The three deepest pits were between 75 and 90 mils in depth. About 30 pits measured between 20 and 75 mils in depth, and many other pits were shallower than 20 mils. The average reduction in pile thickness observed in the three most corroded areas was between 8 and 11 percent.
+1 to 0 ft: About 75% of the mill scale was intact in this zone. The pile surfaces were smooth, had little metal attack, and all pits were less than 20 mils in depth. The corrosion of the coated pile exposed to the water was similar to that described for the piling on the west side of the lock.

d. Algiers Lock, New Orleans, Louisiana

History: An excavation was made to expose type Z 32 sheet pilings in the cutoff wall on the east side of the south end of Algiers Lock, which is located on the Algiers Canal at the Mississippi River, New Orleans, Louisiana. The piles have a driving width of 21 in. and a wall thickness of 3/8 in. at the web and 1/2 in. at the flanges.

Date pile driven: May 1948
Date of inspection: April 1960
Age of piling: 11.9 years

Piling exposed: A 5-ft width of the cutoff wall was exposed between elevation +3.5 feet to +1 foot.

Surface elevation: +5 feet.

Water table elevation: +2 feet.

Soil characteristics:
+5 to +3.5 ft: Brown silty clay fill material.
+3.5 to +1 ft: Brown silty clay with pockets of tight plastic grayish blue clay dispersed throughout the profile with large quantities of organic matter, rotted wood, gravel, and small stones.

Condition of piles: Mill scale was present over approximately 85 percent of the surface. Nodules of clay adhered to the steel surface in scattered small areas, generally not exceeding 1 square inch in size, beneath which were light metal attack or pitting. The deepest pit measured 40 mils in depth. Nine pits measured between 22 and 32 mils in depth, and other pits measured less than 30 mils. The average reduction in wall thickness measured on the three most corroded areas of the sample pile section cut from the wall was between 3 and 4 percent.

The following are excerpts from the discussion paragraph of Monograph 58 (Romanoff):
"Previous investigations on soil corrosion conducted by the National Bureau of Standards have been restricted to the behavior of metals in disturbed soils; trenches or excavations were dug and backfilled after installation of the specimens. Because no prior systematic investigation pertaining to the behavior of metals in undisturbed soils had been conducted, it became general practice because no other data were available to apply the information provide by the NBS soil investigations as a guide to estimate the corrosion of metals in all types of underground installations, under both disturbed and undisturbed soil conditions.

One of the most interesting characteristics of underground corrosion is the irregular nature of the attack. A section of pipe is often penetrated at only one or more points and practically no corrosion is found elsewhere on the section. Usually the loss of ferrous metal is too small to be of importance if it were uniformly distributed over a metal surface.

The major cause of the corrosion can be attributed to the non-uniformity of the distribution of oxygen and moisture along the surface of a buried metallic structure.

The pitting type of corrosion is of major importance in pipelines or other structures designed to carry liquids or gases. On the other hand, for underground structures that are primarily load-bearing the depth of pitting is of less interest than the overall loss in weight or strength. Hence, in relating corrosion damage to the useful life of pilings the most important measurement involves the amount of uniform corrosion that will result in a reduction of the cross section.

Any attempt to estimate the corrosiveness of the soils to which the pilings were exposed by association of the soil properties and characteristics with data obtained from similar soil environments from either NBS field tests, or actual service history of the structures in disturbed soils, could only lead to expectations of severe corrosion at most sites.

The major difference between the soils at the NBS test sites and the soils into which the pilings were driven appears to be the oxygen content. The data from the early soil-corrosion tests and most corrosion data reported previously on service structures were obtained on specimens or structures located in backfilled soils. The backfilling causes a drastic disturbance in the oxygen content of the soil and promotes corrosion of iron and steel by differential aeration. On the other hand, the oxygen concentration of undisturbed soils is not sufficient to cause appreciable corrosion of pilings that are driven into the ground."

The following is the entire summary of the cited document:

"Steel pilings which have been in service in various underground structures for periods ranging between 7 and 40 years were inspected by pulling piles at 8 locations and making excavations to expose pile sections at 11 locations. The conditions at the sites varied widely, as indicated by the soil types which ranged from well-drained sands to impervious clays, soil resistivities which ranged from 300 ohm-cm to 50,200 ohm-cm, and soil pH which ranged from 2.3 to 8.6.

The data indicate that the type and amount of corrosion observed on the steel pilings driven into undisturbed natural soil, regardless of the soil characteristics and properties, is not sufficient to significantly affect the strength or useful life of pilings as load-bearing structures.

Moderate corrosion occurred on several piles exposed to fill soils which were above the water table level or in the water table zone. At these levels the pile sections are accessible if the need for corrosion protection should be deemed necessary.

It was observed that soil environments which are severely corrosive to iron and steel buried under disturbed conditions in excavated trenches were not corrosive to steel pilings driven in the undisturbed soil. The difference in corrosion is attributed to the differences in oxygen concentration. The data indicate that undisturbed soils are so deficient in oxygen at levels a few feet below the ground line or below the water table zone, that steel pilings are not appreciably affected by corrosion, regardless of the soil types or soil properties. Properties of soils such as type, drainage, resistivity, pH or chemical composition are of no practical value in determining the corrosiveness of soils toward steel pilings driven underground. This is contrary to everything previously published pertaining to the behavior of steel under disturbed soil conditions. Hence, it can be concluded that National Bureau of Standards data previously published on specimens exposed in disturbed soils do not apply to steel pilings which are driven in undisturbed soils."

5. EVALUATION OF ALTERNATIVES

The following is a summary of the evaluation results for each alternative, including details regarding advantages and disadvantages for the various alternatives:

a. Coal Tar Epoxy. Although the use of coatings on driven steel piles is the default alternative for a corrosion protection strategy, it is not free of problems. When this alternative is selected, the designer must address the need to protect the coating from damage during the driving operation, coating repair strategies, and the method of field coating pile splice sections. While applying a bitumen coat to a pile is simple, it is costly and the implementation results in a prolonged pile driving schedule. Coal tar epoxy for corrosion protection is typically applied at a location other than the mill, which causes additional handling of the steel piles prior to e arrival at the job site, impacting the schedule and cost for the projects. These logistical problems will be exacerbated due to the need for steel pile and sheetpiles for HSDRRS projects for both the

Project Restoration Office (PRO) and the Hurricane Protection Office (HPO), which are working to complete the 100-year level of protection by 1 June 2011. This demand for resources will place a tremendous strain on industry as we increase the volume of material ordered in similar timeframes. In addition, we explored the possibility of treating the piles locally but there are very limited facilities in the New Orleans area that can apply this corrosion protection treatment and they most likely would be overwhelmed if a significant portion of this work is performed locally.

Coal tar epoxy coating will also reduce pile capacity, which is an undesirable effect. A literature search for the reduction of shaft resistance in the coated area revealed that most studies conclude that the reduction can be up to 90%. This is normally not a significant issue for piles driven from existing ground because very little, if any, frictional capacity is obtained in the upper soft soil layers. This is the case for floodwalls at the West Closure Complex and the IHNC Lake Borgne Barrier. However, for floodwalls built on existing levees, piles will be driven through compacted embankments that have been in place for many years and afford friction capacity to the pile. This is the case for the St. Bernard floodwalls and, for these cases, the piles should be lengthened to account for this reduction in capacity. A rough calculation indicates that piles will need to be approximately 15 feet longer (including batter) for the first reach of LPV-145 to compensate for the loss of shaft capacity in the H-pile zone that is coated with bitumen.

b. Increase Material Thickness . Another method to account for the effects of corrosion that is recommended by many researchers and agencies is to use a thicker pile section. It is the normal practice to provide sufficient cross-section area of steel to allow for wastage over the useful life of the structure while still leaving enough steel to keep the working stresses within safe limits (Blake). This method is very practical for an environment comprised of oxygen-deficient clay materials in an undisturbed condition. The HSDDRS projects are in this type of environment. To quantify the required increase in thickness for both H-piles and sheetpiles, we have performed basic calculations based on published corrosion rates, as shown in the table below:

TABLE 1 - SUMMARY OF YEARLY CORROSION RATES

Environment	Corrosion Rate (in. per year)	Reference
130 steel piles driven into undisturbed soils ranging from alluvial clay to coastal reclaimed soils.	0.00039	Ohsaki
Harbor bulkheads driven into sand, earth or other cover. Both surfaces are covered by soil.	0.00047*	Gaythwaite
Undisturbed Soil	0.00047	Eurocode 3
National Bureau of Standards in USA. Not known if it is the same study cited by Bowles.	0.0003 – 0.003	Blake
Bonnet Carre Spillway, LA., National Bureau of Standards Rpt.	Negligible	Romanoff
Chef Menteur Pass, LA., National Bureau of Standards Report	Not Reported	Romanoff
Berwick Lock, LA., National Bureau of Standards Report	0.002 – 0.0027	Romanoff

* Computed based on ratio of corrosion of both surfaces covered/one surface covered for Beach Bulkhead (0.0017/0.0094*0.0026).

Example calculations of sacrificial steel for an HP14x89 pile (not coated) compared to a new HP14x73 pile and PZC 14 (not coated) versus PZ 22:

Corrosion rate = A value of 0.00047 in./year is used since it is the value recommended by Eurocode3, Gaythwaite, and for all practical purposes by Ohsaki.

(1) HP14x89 pile versus HP14x73 pile.

HP14x89	HP14x73
(thickness of flange = thickness of web)	
tf = tw = 0.615 in	tf = tw = 0.505 in

Available sacrificial layer = 0.615 - 0.505 = 0.11 in

Duration of sacrificial layer = 0.11/0.00047 = 234 years

(2) PZC 14 sheetpile versus PZ 22. PZC 14 is used because it is the next higher section in terms of weight per square foot of wall that has a thicker section than PZ 22.

PZC 14	PZ 22
Web thickness = 0.420 in	Web thickness = 0.375 in

Available sacrificial layer = 0.420 - 0.375 = 0.045 in

Duration of sacrificial layer = 0.045/0.00047 = 96 years

Since the sheetpile's function is to cutoff flow and erosion protection and not as a structural support member, even a PZ 22 section may be sufficient. A PZ 22 section would last significantly longer than the 50-year project life at the estimated corrosion rate. Even using the recommended Eurocode3 loss of thickness value of 3.5 mm/100 years for sea water, the PZ 22 section would last over 270 years. The slightly heavier PZC 14 section would offer an additional 96 years of corrosion protection than the PZ 22 section and should take less time to install, since the width of each sheet is 27.88 inches compared to 22 inches for the PZ 22.

c. A-690, Marine Steel. This alternative was initially considered during our evaluations but it was not further pursued because it does not appear to have any significant advantages over regular steel piles. The American Society of Testing and Materials (ASTM) requires corrosion protection for steel in the ground, including A-690 steel.

d. A-572 Steel. This alternative does not appear to be beneficial for steel piles, since the ASTM requires corrosion protection for steel in the ground, but it looks promising for a sheetpile section. The PZC 14 section provides a slightly thicker section at a slight increase in weight. The extra thickness would offer corrosion protection for numerous years.

e. Splice Thicker Section on Top Portion of Pile. An alternative that places the thicker section where it is required most for corrosion protection. Although, a portion of the pile has a smaller section, it requires a mill or field weld (splice). Field splices would slow down the construction process and questions about the quality and strength of the weld would be hard to verify for a weld at each pile. Also, the location of the splices would be a consideration since it is advisable to avoid locating all splices at the same elevation. Mill scale retards the corrosion rate of piles in the ground. Welds are more prone to corrosion, since a weld will not have mill scale, and thus, it is advisable to locate all welds below the groundwater table.

f. Other Coating systems. These were considered initially but were not pursued in detail since their costs are higher than for the standard coal tar epoxy coating system and the logistics associated with its application are more complicated. There are questions about whether some of the coatings are as resistant to abrasion as the coal tar epoxy in embedded conditions. Special coatings, other than coal tar epoxy, appear to be more suited for piles exposed to the atmosphere, such as the splash zone in marine facilities. Another disadvantage is that many of the products do not have a long history of use compared to coal tar epoxy. As such, some of the products would require testing before wide use in a significant civil works project. Finally, at this time, it is questionable whether the limited specialty facilities can meet production needs.

6. COORDINATION

a. USACE. An early draft of this paper was offered for review to several members of USACE Structural and Geotechnical Engineering Communities of Practice. Subsequently, we had a discussion by telephone on 03 November 2009 to discuss comments and concerns from all participants. Review participants included:

Anjana Chudgar – HQUSACE	Angela Desoto-Duncan – HPO
Marty Goff – HQUSACE	Tom Hassenboehler – HPO
Dr. L.D. Stephenson[1] – ERDC-CERL	Francisco Duarte – HPO
Allen Perry – MVD	Luis A. Ruiz – HPO
Ken Klaus – MVD	Darryl Bonura – MVN
Kent Hokens – MVP	Carl Balint – MVN
Mark Gonski[1] – MVN	Richard Cordes – MVN

[1]Did not participate on Conference Call

Dr. L.D. Stephenson, ERDC-CERL, who is a subject matter expert, could not participate on our telephone discussions. However, he reviewed the draft paper and advised that “In consideration of your scheduling requirements, I support the recommendations that sacrificial thicknesses be used for the HSDRRS projects.” All participants concurred on the recommendation to allow the use of sacrificial steel thickness as a corrosion protection alternative to coal tar epoxy. It was also agreed, that we would request a conditional approval from MVD to allow all projects to move forward and meet the 01 June 2011 deadline. The conditional approval was received from MVD, Mr. Jimmy Waddle, Chief, Business Technical Division, on 04 November 2009, subject to formalizing the paperwork. Based on the feedback received during the conference call, the draft paper was finalized and will be forwarded to MVD to complete the HSDRRS Guidelines formal waiver request process. In addition, the revised HSDRRS Guidelines paragraph on corrosion protection will be revised accordingly and transmitted to all PDTs, A-Es and MVD Region districts for implementation.

b. Non-Federal Sponsor. This paper was coordinated with representatives for the Southeast Louisiana Flood Protection Authority-East (SLFPAE) and the Louisiana Office of Coastal Protection & Restoration. The state representatives expressed concerns regarding the proposed corrosion protection alternative, which were focused on future maintenance of the flood protection facilities, especially the potential for exposure of the piles to the atmosphere if differential settlement occurs between the bottom of the T-wall bottom slabs and the ground surface, leading to accelerated corrosion rates.

They offered for our consideration an ASCE paper (Decker et al, March 2008) describing a study conducted in Salt Lake Valley, Utah to evaluate corrosion rates for steel piles that were abandoned during reconstruction of I-15. According to the ASCE paper, corrosion rates were measured for 20 piles extracted from five sites after service lives of 34-38 years. The results of the evaluation are presented below in Table 2. The first three sites in the report were evaluated for comparison of the corrosion rate with the proposed value in this paper.

Table 2 - Corrosion Rates from Utah Study Versus Proposed Rate

Location of Samples	**Corrosion Rate** (in/yr)	**Proposed, this paper** (in/yr)
2100 South	Maximum = 0.00024 Average = 0.000095	0.00047
South Temple	Maximum = 0.00059 Average = 0.00025	0.00047
2nd South	Maximum = 0.00051 Average = 0.00024	0.00047

SLFPAE representatives submitted their internal review comments and concerns on the draft paper and hired Halcrow, Inc. of Baton Rouge, LA to evaluate the draft copy of the corrosion paper. HPO addressed all comments in the SLFPAE memo and the evaluation by Halcrow, Inc. In summary, Halcrow, Inc. did not disagree with the proposed corrosion protection alternative proposed in the paper and in fact, their statements tend to indicate that we are being conservative in providing corrosion protection for our conditions. For example, the following excerpts from Halcrow's evaluation of the corrosion paper illustrate this point:

(1) "Corrosion Allowance in Cross-Section: Halcrow has long practiced using an increased pile section as a corrosion allowance. However this is invariably due to the expected coating breakdown and high corrosion losses within the submerged (non-embedded) and atmospheric sections. If pilings were not exposed to these environments, there would be no need to employ a corrosion allowance"

(2) "From the cited studies, it would appear to be wasteful to specify a corrosion allowance for piling that is not subjected to water or atmospheric corrosion."

(3) "From a cursory examination, it would appear that no corrosion mitigation would be needed for completely embedded piling."

A meeting was held at New Orleans District with representatives from the state agencies, District and HPO representatives, and Halcrow Engineers, to address outstanding concerns about proposed corrosion protection alternative. The major outstanding concern from SLFPAE and Louisiana Office of Coastal Protection & Restoration is the potential for corrosion due to settlement of the soil below the base slab. The state representative asked Halcrow to submit materials that show that there is more corrosion at the steel and concrete interface than at any other location. HPO reviewed the information and concluded that the sites were in open ocean or gulf environments with high salt concentrations and are not representative of the job sites where the steel will be used. In order to reduce or eliminate the introduction of oxygen to the steel, in case of settlement below the slab, HPO plans to add a key at each end of the base (mud) slab that will penetrate approximately one foot into the levee section to prevent the exposure of the piles to atmospheric effects in case of differential settlement.

7. CONCLUSIONS

a. In general, the corrosion behavior of structural steel embedded in soil can be divided into two categories, corrosion in disturbed soil and corrosion in undisturbed soil. Most authors agree that oxygen availability is one of the most significant factors that should be considered in corrosion evaluation. A study for the National Bureau of Standards revealed that pile corrosion in undisturbed soils is not great enough to affect the strength of the piles significantly.

b. Many agencies and authors recommend the use of a sacrificial metal thickness for steel pile foundations. The author of a very comprehensive study in Japan summarized that "Fortunately, however, the corrosion rate itself is so small, regardless of soil condition, that no serious consequence would be encountered if a slight thicker cross-section is chosen at the design stage to accommodate sacrificial thickness for anticipated corrosion losses."

c. Florida's LADOTD requires an additional sacrificial steel thickness of 0.075 inches for slightly aggressive conditions and 0.15 inches for moderately aggressive conditions. According to the corrosion rate in the Japanese, Eurocode3, and other studies, the extra 0.11 inch thickness of a HP14x89 uncoated pile would provide an additional 234 years of corrosion resistance when compare to new HP14x73 pile. The 0.11 inch thickness is more than the 0.075 inch that is required for slightly aggressive soil conditions by the Florida Department of Transportation and Development.

d. Construction delays due to the coating process are not quantified due to the many variables that would have to be analyzed, such as the production rate of current facilities, location of coating facility relative to steel mill and construction site, transportation delays, production problems due to labor or material shortages, and quantity of coated steel that is required at any given time. The only thing that is easy to quantify is that allowing the use of a sacrificial layer for corrosion protection eliminates all of the delays associated with coating the steel sections.

8. RECOMMENDATIONS

a. Based on this evaluation, we recommend that sacrificial steel represented by a larger steel cross-section be allowed for steel piles and that PZC sheetpiles be used for HSDRRS projects to compensate for corrosion during the life of the structures. This alternative would afford the opportunity to eliminate any delays associated with coating the top portion of steel piles and sheetpile sections with coal tar epoxy. It is imperative to eliminate design and construction schedule delays to maintain the very aggressive schedule for HSDRRS projects.

b. The following table summarizes the equivalent uncoated pile shapes compared to the coated counterparts:

EQUIVALENT COATED & UNCOATED SHAPES			
Steel H-Piles		**Steel Sheetpiles**	
Coated	**Uncoated**	**Coated**	**Uncoated**
HP 14 x 73	HP 14 x 89	PZ 22	PZC 14
HP 14 x 89	HP 14 x 102	PZ 27	PZC 19
HP 14 x 102	HP 14 x 117	PZC 14	PZC 25
Note: For circular steel piles, either longitudinally or spirally welded, add 1/8-in to the thickness of the required coated shape for uncoated use.			

c. When site conditions are encountered where a coal tar epoxy coat is a better choice, then the designs will be revised accordingly.

8. REFERENCES

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