March 12, 2022

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SUBJECT: Fidalgo Marina - Breakwater Corrosion Control Evaluation

Mr. Pilling,

Northwest Corrosion Engineering completed a series of corrosion control tests at the Fidalgo Marina. The purpose of this testing was to provide supplemental corrosion protection related information in conjunction with a recent visual dive inspection of the submerged metallic surfaces.

This work of this testing included determination of quantity of protective current needed to provide effective corrosion control, electrical continuity status of the breakwater structures, and stray current testing. This report outlines the results of the field testing and provides preliminary design information and rough order of magnitude costs for both a galvanic and impressed current cathodic protection system.

It is noted that the City of Anacortes has a breakwater in close proximity to the North and East Breakwaters. These structures were designed and built in the same manner at the same time. Testing was not completed on the City owned breakwater, however; it is reasonable to expect that the same information gathered during this inspection would apply.

BACKGROUND

The North and East Breakwater structures are constructed using vertical H-piles (HP 14 x89) and 12.75-in diameter steel pipe batter piles. A single batter pile is welded to an individual H-pile. Previous reports also note that each batter pile incorporates a 40-ft minimum length HP 14 x 73 H-pile welded to the bottom-most embedded portion of the pile. All piles were installed with a galvanized coating.

A recent diving inspection revealed that majority of the North Breakwater was in poor condition with significant corrosion section loss. The East Breakwater was in slightly better condition, also with significant corrosion section loss. The galvanized coating on all submerged surfaces was noted as being effectively consumed.

TEST PROCEDURES

Electrical Continuity

Electrical continuity is an important consideration when selecting the proper means of corrosion control. The flow of cathodic protection current requires a metallic path connecting the anode and the structure (cathode). For galvanic systems, this involves directly connecting the anodes to the structure by welding or bolting the anode core to the metal surface. Steel structures not electrically continuous with the anode will not receive current.

The vertical steel H-piles and steel pipe batter piles are welded together, providing electrical continuity. In this manner, a galvanic anode can be connected to either of the two structures and current will flow to both surfaces. However, without provisions for electrical continuity, an anode installed on one H-pile/steel pipe batter pile support will not provide current to an adjacent support. In this case, individual anodes would need to be installed at each of the H-pile/steel pipe batter pile supports.

To test for electrical continuity, a DC potential measurement was taken between two adjacent steel support plates (welded to the H-pile) located on top the breakwater structure. Potential differences between piles of 2.0 millivolts or less indicate electrical continuity. Potential differences greater than 10 millivolts suggest electrical isolation. Between these values, additional testing is required for interpretation.

Electrical potential measurement between adjacent supports to determine electrical continuity

Structure-to-Electrolyte Potentials

Electrical potential measurements are used to determine if the structure being tested meets corrosion protection criteria. For marine environments, a silver-silver chloride (SSC) reference electrode is placed into the water and a DC potential is measured between the electrode and the structure. Polarized potentials that are at or more negative than -790 millivolts indicate that corrosion control is being afforded at the test location. For this testing, potentials were measured at the waterline, midway down the submerged pile, and at the seafloor.

Typically, electrical potentials of carbon steel in a seawater environment without cathodic protection will be in the range of -400 to -600 millivolts. If the structure has an effective galvanized coating, the potentials will be shifted in the negative direction and be on the order of -800 to -900 millivolts. Carbon steel with a deteriorating galvanized coating will reside in the -600 to -700 millivolt range.

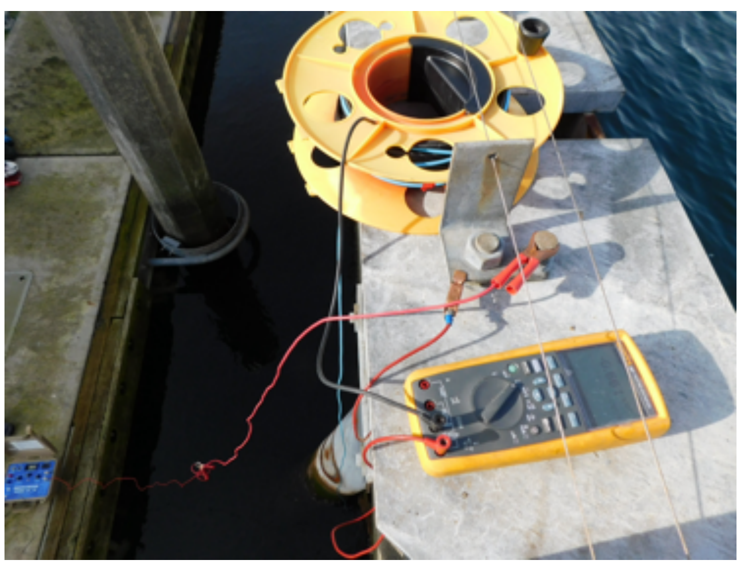
Current Requirement

The quantity of DC current needed to provide complete corrosion control is a function of the surface area being protected. For a steel pipe with an effective dielectric coating, such as coal tar epoxy, the current demands will be low. The dielectric coating acts as an electrical barrier between the seawater and underlying carbon steel surface. If the steel is not in direct contact with the seawater, corrosion will not occur.

For bare or galvanized steel structures, the protective current demand can be very high due to the large amount of surface area exposed to the seawater and because flowing seawater is a highly corrosive medium. Industry standards recommend a protective current density of 15 – 30 milliamps per square foot of exposed steel in medium flow (3 – 5 ft/second) seawater.

For a dielectric coated steel pile, the total cathodic protection current needed to protect the small coating defects may be on the order of 50 – 200 milliamps. For a bare or galvanized 1-ft diameter steel pile, the current demand can be 3 – 6 amperes (3,000 – 6,000 milliamps).

Current requirement testing conducted on representative pipe piles involved inserting a temporary anode into the water and connecting it to a pipe pile though a variable current output source. Cathodic protection current was allowed to discharge from the anode to the structure for 4 minutes. After this time, measurements were made to determine the shift in electrical potential. To meet corrosion protection criteria, the structure must achieve a polarized potential of -790 millivolts SSC or more negative, or the electrical potential of the structure must have shifted a minimum of 100 millivolts.



Current requirement and potential measurement setup

Stray Current Analysis, Cell-to-Cell Survey

Voltage gradients within an electrolyte such as seawater can drive ionic current flow from areas of high (negative) potential to areas of low potential. Stray currents are those currents flowing in unintended paths. For example, if an electrical grounding condition exists, current can flow through the water or soil onto a steel structure that is not electrically continuous with the current source. If stray current is picked up, it must also discharge off the interfered with structure, causing accelerated corrosion at the location of current discharge. As an example, one ampere of DC current discharging off a steel structure for a period of one year will result in 20 pounds of steel loss. A brief review of the extensive corrosion damage observed at the North Breakwater suggests that stray current may have been present, particularly given the noted areas of complete section loss.

Since current flow cannot be directly measured through the water, the most common means of detecting the presence of current is by measuring voltage gradients, as voltages are required to "push" current through a medium. To measure voltage gradients, two matched reference electrodes are spaced approximately 4-ft apart an inserted into the water. Changes in potential between the reference electrodes are attributable to voltage gradients.

Testing was conducted in this manner at representative locations around the docks, with particular attention paid to the areas in the immediate vicinity of the North Breakwater and the dock-mounted transformers placed throughout the facility.

<u>TEST RESULTS AND DATA ANALYSIS</u>

Electrical Continuity

Electrical continuity testing was completed between multiple supports at the North Breakwater. Test results are included in Table 1.

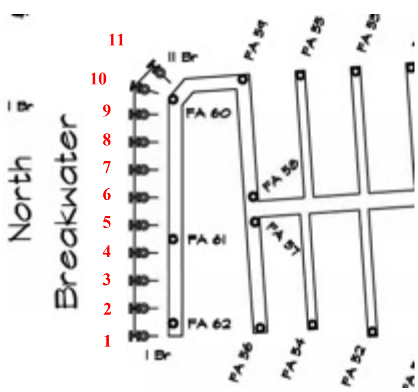


Figure 1: North Breakwater Test Locations

Table 1: Continuity Testing

Support	Support	Potential	Comment
2	3	3.6 mV	Likely not continuous
8	9	33.0 mV	Not continuous
4	5	29.2 mV	Not continuous
9	10	2.3	Likely continuous

The continuity testing shows that adjacent H-pile/steel pipe batter piles were not intentionally bonded together to create an electrically continuous structure. Should the use of an impressed current cathodic protection system be desired for corrosion control, all support structures will be required to have a bonding jumper installed to provide electrical continuity to all metallic components.

Continuity testing could not be completed on the East Breakwater structure due to limited access. However, the two breakwater structures were designed in the same manner and it is expected that electrical continuity along the East Breakwater also was not provided for.

Current Requirement

Native state electrical potentials were recorded prior to test current application such that the polarization characteristics of the structure components could be determined. Protective current was then applied and ON and Instant Off (polarized) potentials were measured. The ON reading contains an error component that must be accounted for by momentarily cycling the current off (Instant Off). As previously described, the polarized potential must be at or more negative than -790 millivolts or a minimum shift of 100 millivolts between the Native state and Polarized potential values must occur for corrosion protection criteria to be satisfied.

For this testing, the temporary current output was adjusted to 1.8 amperes. Data was collected with the reference electrode and the temporary anode on the moorage side of the North and East Breakwaters at the indicated supports. For support 9 (North Breakwater) and 71 (East Breakwater), potential data was measured on both the moorage and seaside of the wall with the temporary anode on the moorage side, to determine how well current was reaching the backside of the H-piles. It was observed that polarization was similar on both the moorage and seaside of the structures.

Results of the testing are presented in Table 2.

Table 2: Current Requirement Testing

	Potential in mV, with Temporary Anode Output Set at 1.8 Amperes			
Site	**Native, mV**	**On, mV**	**Polarized, mV**	**Shift, mV**
North Breakwater Support 1: Anode and reference electrode on moorage side of breakwater				
Waterline	-644	-689	-657	13
Mid	-645	-667	-654	9
Seafloor	-643	-654	-651	8
North Breakwater Support 6: Anode and reference electrode on moorage side of breakwater				
Waterline	-651	-702	-666	15
Mid	-648	-669	-658	10
Seafloor	-646	-654	-650	4
North Breakwater Support 9: Anode and reference electrode on moorage side of breakwater				
Waterline	-652	-696	-666	14
Mid	-651	-663	-659	8
Seafloor	-651	-661	-657	6
North Breakwater Support 9: Anode and reference electrode on seaside side of breakwater				
Waterline	-630	-644	-640	10
Mid	-631	-645	-642	11
Seafloor	-633	-647	-646	15
East Breakwater Support 71: Anode and reference electrode on moorage side of breakwater				
Waterline	-646	-695	-661	15
Mid	-642	-686	-661	19
Seafloor	-642	-671	-657	15
East Breakwater Support 71: Anode and reference electrode on seaside side of breakwater				
Waterline	-630	-658	-643	13
Mid	-628	-657	-643	15
Seafloor	-632	-663	-649	17

Test current applied for 4 minutes at each location prior to taking On and Polarized potentials.

Stray Current Analysis, Cell-to-Cell Survey

Figure 2 shows the locations and measured values of the cell-to-cell survey. The data shows only slight changes throughout the testing area, generally less than 15 millivolts. Concern would be raised had the voltage gradients been on the order of 100 or more millivolts. While this testing was completed, there was a vessel moored at the south side of the East Breakwater. There were no large vessels moored adjacent to the North Breakwater.

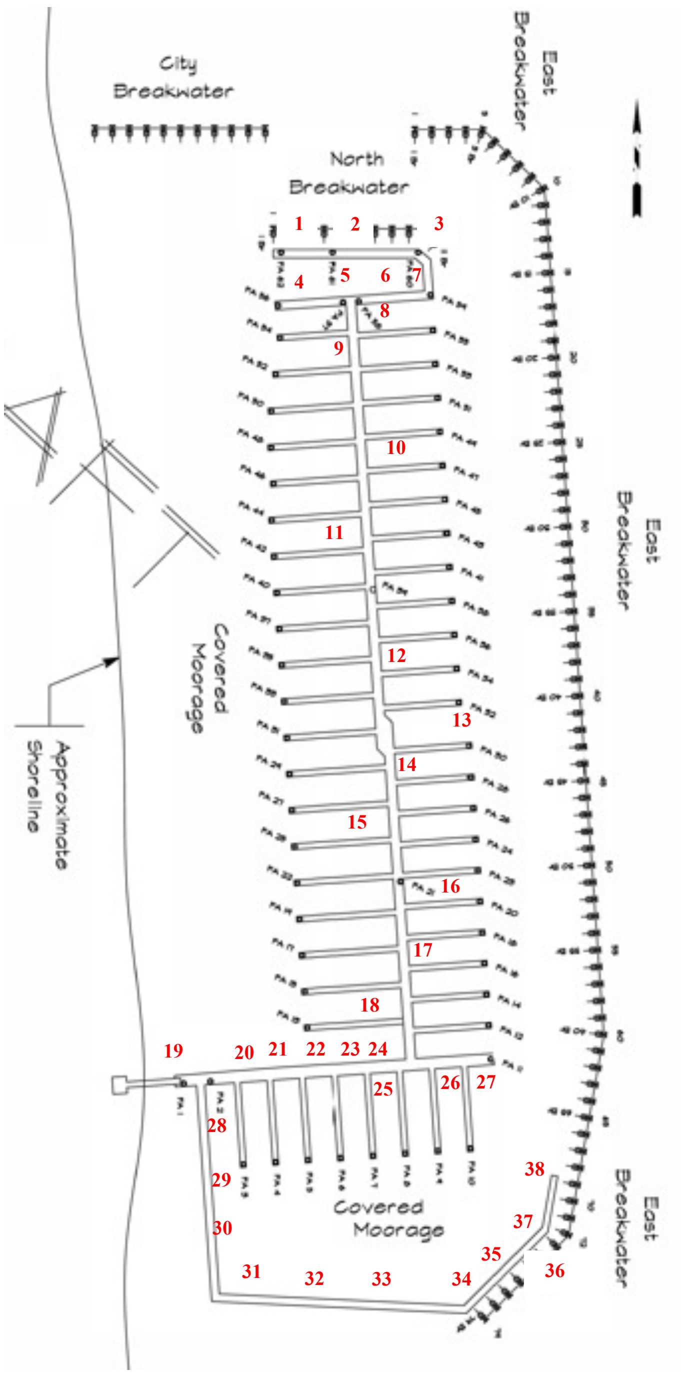


Figure 2: Voltage Gradient Test Locations

Table 3: Gradient Testing

No.	Delta V	No.	Delta V
1	31.6	20	12.5
2	31.3	21	29.0
3	9.7	22	10.8
4	12.2	23	20.1
5	36.8	24	11.2
6	34.3	25	9.9
7	30.1	26	10.2
8	13.5	27	17.1
9	12.8	28	11.9
10	16.3	29	12.2
11	3.7	30	12.1
12	3.8	31	11.5
13	5.9	32	11.5
14	6.5	33	11.2
15	3.5	34	10.3
16	1.1	35	11.3
17	1.0	36	11.3
18	2.5	37	10.5
19	23.0	38	9.0

Notes: Readings 5, 6, 7, 10, and 14 are adjacent to transformers.

CORROSION CONTROL OPTIONS

Protective Coatings

Galvanized Coatings

Galvanized steel provides a high degree of corrosion protection when exposed to atmospheric conditions. The thin layer of zinc embedded into and on the surface of the carbon steel substrate during the galvanizing process will initially corrode producing a layer of zinc oxide that provides a high degree of corrosion protection. However, if the zinc oxide layer is removed, as what will occur during tidal flow or splashing events, the newly exposed underlying zinc will degrade to develop additional zinc oxide. Continuing this process over an extended period will lead to complete loss of zinc and exposure and subsequent corrosion of the carbon steel parent material. This is a common occurrence in a marine environment where the galvanized surfaces above the splash zone tend to hold the zinc oxide film and experience very little surface loss. In the tidal and slash zone, continual buildup and breakdown of the zinc oxide layer leads to loss of corrosion protection afforded by the galvanizing. Galvanized surfaces below the areas of tidal influence tend to have a longer life, but degradation is expected as the zinc is consumed. Furthermore, areas that experience complete loss of zinc will become cathodic to areas that are still zinc coated. This instance leads to accelerated loss of the zinc as current will be driven from the zinc to adjacent bare steel area, resulting in a loss of zinc material. This is the same process experienced with zinc anodes installed on a vessel to protect the submerged metallic surfaces.

Zinc coatings, such as zinc rich epoxies incorporate zinc dust directly into the liquid coating. The coating is then applied to the prepared steel surface and will provide a high degree of corrosion protection in atmospherically exposed areas.

Dielectric Coatings

Dielectric liquid coatings provide an electrical barrier between the surface on which they are applied and the environment. In this manner, corrosion is halted as the flow of ionic current is stopped. However, defects in the coating will allow for corrosion at the location of damage. Dielectric coatings do not contain zinc and therefore do not provide a degree of corrosion control in the form of galvanic protection. At coating defect sites, surface corrosion will occur which typically results in disbondment of adjacent sound coatings as corrosion products force normally adherent coatings from the surface. Because of this, when dielectric coatings are used in a submerged service, the application of cathodic protection is also recommended to act in conjunction with the coatings for effective corrosion control.

Galvanic Anode Cathodic Protection

Galvanic anodes use the energy inherent in their material make-up to provide corrosion protection current to metallic surfaces. The difference in voltage potential between the anode and the steel (cathode) surface results in electrical current flow from the anode to the steel. During this current exchange, the anode will deteriorate as it sacrifices its energy to protect the steel.

Electrical current collection on a steel surface results in the development of a polarization film which acts as a barrier slowing or halting the corrosion process on the surface of the steel. In a marine environment, the flow of water over the steel surface disrupts the polarization film resulting in additional current flow from the anode, consuming the anode quicker. This same effect is noticed as zinc anodes on a vessel at rest will last longer than when that same vessel is moving.

Given these limitations, galvanic anodes are most effective when used in concert with a protective dielectric coating. The coating significantly reduces the amount of surface area requiring protection allowing the anode to operate for a longer time.

Galvanic anodes can be designed to protect large surfaces in marine environments; however, the anodes will be large and will have a limited life, typically on the order of 15 years.

Galvanic anodes have the advantage in that they do not require an external power source, they are easy to replace, require minimal maintenance, and they are not generally a source of stray current interference.

<u>Galvanic Anode Cathodic Protection System</u>

1. 3 each 250# aluminum anodes per H-pile / pipe batter pile, total of 273 anodes.
2. Anodes to be welded directly to H-pile and pipe batter pile surface.
3. Materials and labor costs: $480,000. Price does not include contingency or applicable taxes.
4. System life: 15 – 20 years

Pros

1. No ongoing maintenance aside from period testing and inspection.
2. No power requirements.
3. Does not require electrical bonding of piles.
4. Will not cause stray current interference.
5. Will provide protection against stray current, but anodes will be consumed faster.
6. Easier installation compared to an impressed current system.

Cons

1. Shorter life than impressed current system.
2. Lower driving voltage reduces current distribution, hence additional anode material required.
3. Current output is not adjustable.

Impressed Current Cathodic Protection

Unlike galvanic anodes, an impressed current system uses a power source (rectifier) to operate inert anode materials. These systems have the advantage of supplying significantly more protective current and will have a longer life than galvanic anodes. While a galvanic anode system will require anodes to be installed at each H-pile location, an impressed current system will use fewer anodes spaced out evenly along the breakwater structure.

For an impressed current system to be effective, all steel structures to receive cathodic protection current must be made electrically continuous through the installation of jumper bonds. Other considerations include the routing of lead wires to each anode, installation of junction boxes, and housing multiple rectifiers at various locations on the docks.

Because impressed current systems use higher voltages, the opportunity for stray current corrosion damage exists. Voltage requirements can be reduced through the design of the anode system, but if the system is not properly monitored and maintained, significant damage to foreign structures (boats) can occur.

Impressed Current Cathodic Protection System

1. Bond all metallic components together.
2. Total of 30 – 40 impressed current anodes installed on Breakwaters.
3. 3 – 4 transformer rectifiers positioned on dock.
4. Reference electrodes, junction boxes, conduit, etc.
5. Materials and labor costs: $400,000. Price could vary by +/- 20% based upon final design.
6. System life: minimum 30 years.
7. Ongoing power costs for rectifiers, estimate total of $500/month.

Pros

1. Adjustable current output.
2. Fewer anodes required.
3. Longer life compared to a galvanic anode system.
4. More effective protective current distribution.

Cons

1. Can be a source of stray current interference if not properly maintained and monitored.
2. Bonding jumpers are required to make all metallic components electrically continuous.
3. All anodes will have lead wire connections, increasing the chance for mechanical damage due to floating debris.
4. Installation may require anchoring anodes to concrete panels.
5. Ongoing power costs for rectifiers.

CONCLUSIONS

The following conclusions are based upon the results of our testing.

1. The metallic support structures were not made to be intentionally electrically continuous. Testing shows that several adjacent pile segments are electrically isolated.
2. The native state potentials of the H-pile/steel pipe batter piles are consistent with a carbon steel parent metal having a deteriorating galvanized coating.
3. Current requirement testing showed minimal polarization of the steel components with 1.8 amperes of applied current. To provide complete protection, current output ranging from 9.5 – 20 amperes per combination of H-pile and batter pile will be required. This high current demand is consistent with a deteriorated galvanized coating.
4. The application of cathodic protection current will provide corrosion control to the submerged surfaces of the steel members. Because the tidal and splash zones are not continually submerged, continued loss of galvanizing and corrosion of the underlying carbon steel within these zones will continue. To completely protect the surfaces in these areas, a dielectric protective coating would need to be applied from a lower tide level to the top of the splash zone.

5. Using the cell-to-cell test, there were no instances of stray currents noted at the 38 tested locations within the marina. It is possible that stray current influence could have occurred with a different vessel setup than what existed during our testing.
6. The Fidalgo Marina currently has a project ongoing that will install a high strength protective barrier around deteriorated steel batter piles. The application of this barrier material will reduce the surface area exposed to the seawater and decrease the number of anodes required for corrosion protection. The preliminary designs offered in this report do not take into account the installation of this CarboSleeve system.

RECOMMENDATIONS

1. Design and install a cathodic protection system to provide corrosion control to the submerged surfaces of the steel support structures.
2. Apply a protective coating to the pile members in the tidal and splash zone.

We appreciate the opportunity of assisting you with this important project. Please feel free to contact our office if you have any questions or would like additional information.

Sincerely,
Northwest Corrosion Engineering

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