March 25, 2023

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SUBJECT: Fidalgo Marina Breakwater - Post Cathodic Protection Installation Checkout

Mr. Hill,

Northwest Corrosion Engineering completed a post installation cathodic protection system checkout of representative breakwater steel H-piles and pipe batter piles that comprise the North and East Breakwater structures at the Fidalgo Marina. The checkout was performed to verify the operation of the recently installed aluminum galvanic anodes used to provide corrosion protection to these submerged steel materials. The checkout was conducted on all piles associated the North Breakwater and batter piles 1 and 69 – 79 on the East Breakwater.

In addition to the cathodic protection system checkout, a voltage gradient test was conducted at locations surrounding the marina. The purpose of this testing was to determine if the conditions at the time of testing were favorable for supporting stray current corrosion. Testing was completed at the same locations as our previous test conducted in March 2022 prior to anode installation.

Lastly, a visual inspection, completed from a Jon boat, of all H-pile and pipe batter piles was made to verify placement of the individual anodes.

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 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 diving inspection performed in 2021 revealed that a majority of the North Breakwater was in poor condition with significant corrosion section loss. The East Breakwater was in slightly better condition, but still experiencing significant corrosion section loss. The galvanized coating on all submerged surfaces was noted as being effectively consumed. Results of the dive inspection are included in the June 2021 Echelon Engineering report "Underwater Inspection & Assessment of Piles & Floats Fidalgo Marina Anacortes, WA".

To provide structural support to the existing pipe batter piles associated with the North Breakwater, in 2022/2023 a Denso SeaShield repair system consisting of a composite fiber-reinforced plastic (FRP) jacket installed over each batter pile from the seafloor to near the top of the high water mark was installed. The annular space between the FRP and steel batter pile was then filled with grout. This installation serves multiple purposes: 1) the SeaShield system adds strength to the corroded piles and, 2) because the FRP jacket is non-conductive, the amount of steel surface area exposed to the saltwater environment is eliminated in all areas where the jacket is installed. This decrease in surface area exposure reduces the amount of cathodic protection current needed to provide corrosion control, allowing for additional life of the galvanic anodes.

TEST PROCEDURES

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 with the reference electrode placed at the waterline and seafloor. Potential data was collected between 10:30 am and 1:00 pm on March 24th, 2023.

Typically, electrical potentials of carbon steel in a seawater environment without cathodic protection (native potentials) 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.

Stray Current Analysis, Cell-to-Cell Survey

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 during the 2021 dive inspection suggests that stray currents 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 and inserted into the water. Changes in potential between the two reference electrodes are attributable to voltage gradients.

For comparison purposes, cell-to-cell testing was conducted at the same representative locations measured during our March 2022 survey. Particular attention was paid to the areas in the immediate vicinity of the North Breakwater where the most extensive corrosion damage was observed as well at as the dock-mounted transformers placed throughout the facility.

TEST RESULTS AND DATA ANALYSIS

Electrical Continuity

As part of the March 2022 assessment completed by Northwest Corrosion Engineering, electrical continuity testing between adjacent H-pile/pipe batter pile testing was conducted. Results of that testing showed that intentional electrical continuity was not provided between adjacent H-pile/pipe batter pile structures. Due to this condition, the installation of an impressed current cathodic protection system would have required the installation of jumper bonds between each of the H-pile/pipe batter pile structures along the length of both the North and East Breakwaters.

At each individual support, the pipe batter pile is welded to its associated H-pile allowing for electrical continuity between these two elements. Due to this electrical continuity, the installation of a galvanic anode on the H-pile will provide corrosion protection current to both the H-pile and steel batter pile.

Structure-to-Electrolyte Potentials

North and East Breakwater electrical potential data is provided in Tables 1 and 2. The collected data shows that the addition of the aluminum anodes has shifted the ON potential of the carbon steel structures in the electrically negative direction resulting in an increase in corrosion protection. Because the anodes are directly welded to the H-piles, the ON potential readings include an error component due to electrical current flow. The only manner in which this error can be eliminated is to momentarily remove the anode from the circuit resulting in a polarized potential of just the carbon steel. The directly connected anodes do not allow for this type of measurement. However, the significant negative shift in the anode/carbon steel metallic couple does show that protective current is flowing the steel. Generally, with the low DC driving voltage of the aluminum anode and the low resistivity seawater environment, the error component of the ON potential will be no more than 100 millivolts. This suggests that ON readings at or more negative than -890 millivolts indicate corrosion protection criteria is being met.

Table 1: Structure-to-Electrolyte Potential Data, North Breakwater H- and Batter Piles

Site	Native, mV March 2022	ON, mV March 2023		Potential Shift, mV
North Breakwater	Moorage Side	Moorage Side	Seaside	
Support 1 – West End				
Waterline	-644	-987	-982	343
Seafloor	-643	-1004	-1007	361
Support 2				
Waterline		-980	-968	
Seafloor		-999	-995	
Support 3				
Waterline		-985	-958	
Seafloor		-1003	-993	
Support 4				
Waterline		-969	-957	
Seafloor		-987	-953	
Support 5				
Waterline		-987	-955	
Seafloor		-999	-983	
Support 6				
Waterline	-651	-986	-966	335
Seafloor	-646	-992	-994	346

Site	**Native, mV March 2022**	**ON, mV March 2023**		**Potential Shift, mV**
North Breakwater	**Moorage Side**	**Moorage Side**	**Seaside**	
Support 7				
Waterline		-983	-965	
Seafloor		-990	-988	
Support 8				
Waterline		-988	-971	
Seafloor		-1083	-1007	
Support 9				
Waterline	-630	-972	-970	342
Seafloor	-633	-1047	-1047	414
Support 10				
Waterline		-995	-969	
Seafloor		-990	-984	
Support 11 – East End				
Waterline		-1005	-1005	
Seafloor		-1012	-1009	

Table 2: Structure-to-Electrolyte Potential Data, East Breakwater Batter Piles

Site	**Native, mV**	**ON, mV**	**Potential Shift, mV**
East Breakwater	**Moorage Side**	**Moorage Side**	
Support 1 – Northwest End			
Waterline		-948	
Seafloor		-947	
Support 68			
Waterline		-1040	
Seafloor		-1021	
Support 69			
Waterline		-1045	
Seafloor		-1030	
Support 70			
Waterline		-1027	
Seafloor		-1003	
Support 71			
Waterline	-630	-1018	388
Seafloor	-632	-1010	378
Support 72			
Waterline		-1016	
Seafloor		-1006	

Site	Native, mV	ON, mV	Potential Shift, mV
East Breakwater	Moorage Side	Moorage Side	
Support 73			
Waterline		-1016	
Seafloor		-1007	
Support 74			
Waterline		-1004	
Seafloor		-1010	
Support 75			
Waterline		-1015	
Seafloor		-1001	
Support 76			
Waterline		-991	
Seafloor		-974	
Support 77			
Waterline		-1013	
Seafloor		-994	
Support 78 – Southwest End (adjacent to last pile Support 79)			
Waterline		-1017	
Seafloor		-1015	

Stray Current Analysis, Cell-to-Cell Survey

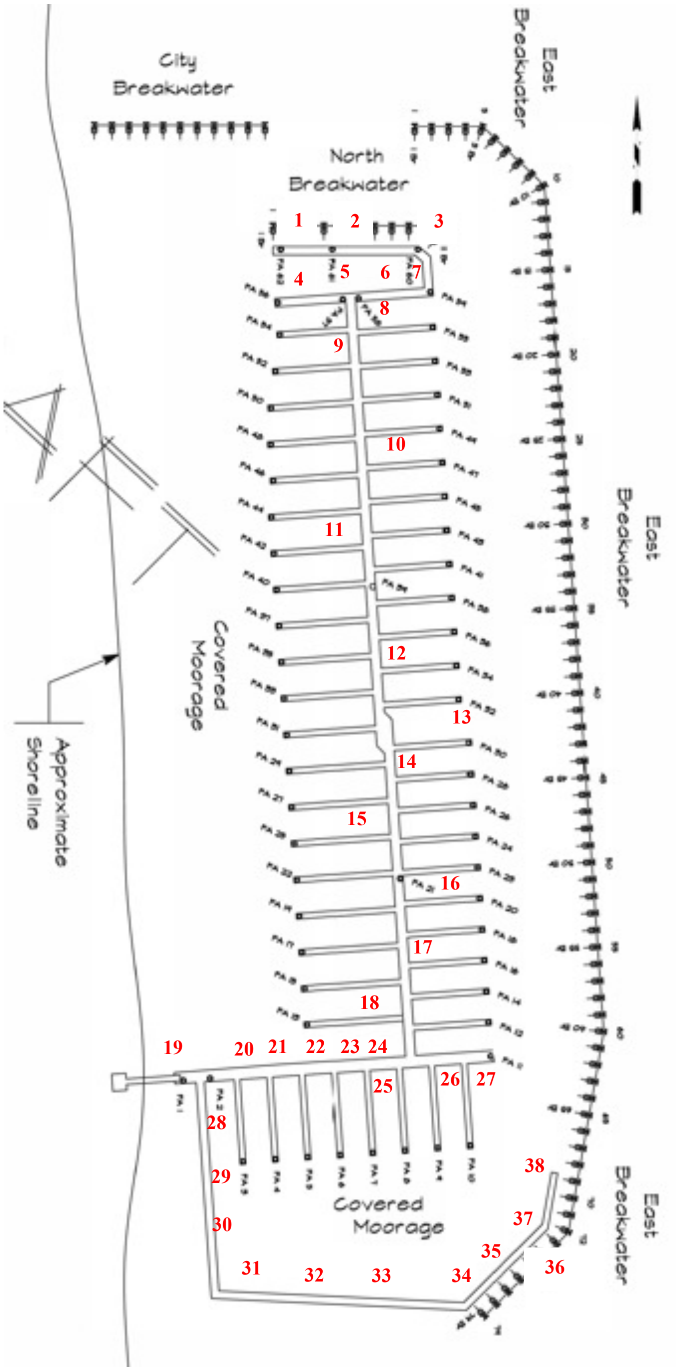
Table 3 provides data collected during both the March 2022 and March 2023 cell-to-cell survey with locations of the testing included on Figure 1. The data shows only slight voltage gradients throughout the testing area, generally less than 15 millivolts in March 2022 and generally 1 – 2 millivolts during the March 2023 testing. Concern would be raised had the voltage gradients been on the order of 100 or more millivolts. During the March 2022 testing, a vessel was moored at the south side of the East Breakwater. There were no large vessels moored adjacent to the North Breakwater. During the 2023 survey there were vessels moored at both the south side of the East Breakwater (not connected to shore power) and adjacent to the North Breakwater (the vessel was plugged into shore power).

The low voltage gradients indicate that current flow through the water was not occurring at the time of testing. Instances that could cause significant current flow (such as that which would cause stray current corrosion on the steel breakwater components) would be a grounding condition that did not allow for return of all current through a dedicated electronic path or foreign impressed current cathodic protection systems. Stray current could be in the form of either AC or DC, with DC (unidirectional) current causing approximately 99.5% more corrosion damage than the same magnitude of AC (sinusoidal) current.

It is important to note that results of the voltage gradient testing are for the conditions of the marina at the time of testing and will vary with differing conditions such as electrical grounding issues.

Table 3: Voltage Gradient Testing

Location	March 2022 Delta, mV	March 2023 Delta, mV	Location	March 2022 Delta, mV	March 2023 Delta, mV
1	31.6	1.8	20	12.5	1.6
2	31.3	1.7	21	29.0	0.6
3	9.7	4.8	22	10.8	1.5
4	12.2	1.7	23	20.1	1.5
5	36.8	2.5	24	11.2	1.5
6	34.3	1.9	25	9.9	2.4
7	30.1	0.3	26	10.2	1.9
8	13.5	1.6	27	17.1	1.7
9	12.8	1.8	28	11.9	2.1
10	16.3	1.2	29	12.2	2.0
11	3.7	2.7	30	12.1	1.9
12	3.8	1.7	31	11.5	1.6
13	5.9	1.8	32	11.5	1.4
14	6.5	1.8	33	11.2	0.6
15	3.5	2.3	34	10.3	2.3
16	1.1	2.2	35	11.3	0.1
17	1.0	1.5	36	11.3	1.0
18	2.5	1.4	37	10.5	2.5
19	23.0	2.5	38	9.0	5.0



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

Figure 1: Voltage Gradient Test Locations and Test Apparatus

Discussion on Electrical Continuity

Northwest Corrosion Engineering was asked to provide commentary on the status of electrical continuity and specifically installing a bonding conductor between each of the breakwater supports (eleven supports for the North Breakwater and seventy-nine supports for the East Breakwater). As previously discussed, each support unit (consisting of an H-pile and pipe batter pile) was not made to be intentionally electrically continuous with its adjacent support units. Thus, a total of two galvanic anodes were installed on each unit, one on the moorage side and one on the seaside. These anodes are providing corrosion protection to the submerged surfaces of the H-pile/pipe batter pile unit to which they are attached. However, given the low driving voltage of the anodes and because there is not a dedicated path for electron flow, protective current from the anodes will not discharge to adjacent structures. Furthermore, because the anode material provides a lower resistance to earth than the carbon steel support units, any stray current picked up by the carbon steel will discharge off of the anode, preserving the carbon steel but shortening the life of the anodes. It was noted by the diving crew during the installation of the anodes that there appeared to be a larger amount of ‘anode activity’ on the new anodes than what they were accustomed to seeing. In speaking with the diving foreman (Erik with Global Diving), this anode activity was likely the accumulation of aluminum oxide on the surface of the anode. Aluminum oxide deposits on the surface of the anode during the corrosion process, suggesting a higher than normal discharge of anode current which could be a result of the initial polarization process or the presence of stray current.

Discharge of anode current occurs when it is connected to a more noble (less active) material such as carbon steel, resulting in corrosion protection of the streel structure. If the carbon steel surface area is much larger than the anode surface area, an increase in anode current output and subsequent accumulation of aluminum oxide will occur on the anode surface. Stray current can also cause this type of condition with the effects being more pronounced and over a much shorter time period. The specific locations of these ‘active anodes’ were not provided; however, it is recommended to perform a dive inspection within one year to catalog the condition of each anode. If accelerated loss of anode material is noted, then additional stray current investigation should be completed.

From a corrosion control standpoint, installing a bonding jumper between each H-pile/pipe batter pile unit would result in the submerged surfaces of the carbon steel support structures to be at a consistent voltage level. The bonding jumper would provide a path for electron flow such that anode current could flow to adjacent H-pile/pipe batter pile structures which would decrease that anodes life. If stray current is an issue, having the support structures electrically isolated from each other would result in accelerated loss of anode material at the specific support structure experiencing stray current corrosion which would be observed during dive inspections. Additional provisions could then be put in place to correct the effects of the stray current. Provisions would include increasing the size of the affected pile/anode or eliminating the stray current source.

CONCLUSIONS

The following conclusions are based upon the results of the March 2022 and March 2023 testing:

1. The installation of the aluminum anodes is providing adequate corrosion protection to the individual H-pile/pipe batter pile units.
2. The metallic support structures were not made to be intentionally electrically continuous. Previous testing showed that several adjacent pile segments are electrically isolated from each other.
3. Using the cell-to-cell measurement procedure, there were no significant voltage gradients measured at the 38 tested locations within the marina at time of our evaluation. These results would be different if there was a source of stray current at the time of our testing.

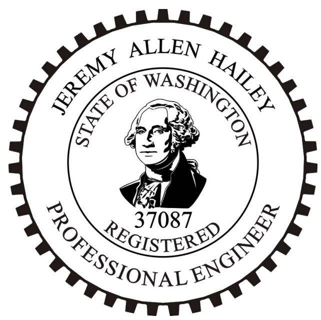
4. Based upon the significant amount of observed corrosion, particularly at the North Breakwater, it is likely that stray AC and/or DC electrical currents have occurred in the past and will occur in the future. Stray currents can be generated through a faulty ground or by other nearby impressed current cathodic protection sources.

RECOMMENDATIONS

1. Conduct a dive inspection of the anodes after approximately one year of operation. The inspection should consist of a visual examination of the piles as well as measuring the dimensions of representative anodes. Dimensions of the anodes in varying degree of consumption will allow for a determination of remaining useful life.
2. Apply a protective coating to the pile members in the tidal and splash zone. Anodes are only effective in a continuous electrolyte and during low tides, the exposed steel will not receive cathodic protection current.

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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