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CORROSION CONDITION EVALUATION OF PILES, BENT CAPS, AND THE UNDERSIDE OF DECK OVERHANGS ON BRIDGE NO. 154371 IN PINELLAS COUNTY

FINAL REPORT
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Executive Summary

Bridge No. 154371 is located on San Martin Boulevard over Riviera Bay in St. Petersburg, Florida. The bridge consists of five spans and was constructed in 1962. Mr. Tom Menke with the Engineering and Technical Support Division of Pinellas County requested a corrosion condition evaluation to be performed on piles, bent caps, and the underside of the deck overhangs.

At the time that the corrosion condition evaluation was conducted in November 2011, the bridge had been exposed to an extremely aggressive corrosive environment for 49 years. Principal findings from the corrosion condition evaluation and the recommendations made for repair and corrosion control are provided below. The recommendations are made from a corrosion viewpoint only and are based on the assumption that the remaining service life of the bridge and an economic analysis will warrant long-term rehabilitation measures. The recommendations also consider the fact that the service life of standard patch repairs, necessitated by reinforcing steel corrosion, without cathodic protection is typically only three to five years. To ensure that structural engineering issues are adequately addressed, the recommendations should be reviewed and evaluated by a Bridge Structural Engineer when considering rehabilitation alternatives. Also, during the rehabilitation work, any severely deteriorated reinforcing steel should be repaired as directed by a Bridge Structural Engineer and determination of the need to incorporate new structural reinforcing steel into the repairs should be made by a Bridge Structural Engineer.

Piles

Work was limited to portions of the piles that are exposed above the water line. Continuously submerged portions of piles were not included since any damage there would not typically be caused by corrosion of reinforcing steel. In addition, Pile 5-3 was not included in the scope of work since it was unique in that it has a conventional jacket and because it was already known that the jacket was badly deteriorated.

The piles are in good condition at this time. Some of the piles have small spalled areas that are believed to have been caused by impacts from marine vessels. There are also patched areas that appear to be the result of lift hooks and impacts from marine vessels. No cracks, corrosion staining, or other spalls were found on any of the piles. The original concrete comprising the piles is well consolidated, dense, has a typical amount of small entrapped air voids, and the average concrete cover over prestressed strands in the piles is considered typical based on the age of the piles.

Although the pile concrete is currently in good condition, corrosion has initiated on the pile reinforcing steel. Prestressed strands that were exposed in cored holes exhibited minor corrosion up to 4' above the marine growth line (MGL) and the chloride content at the reinforcing steel depth is well above the corrosion threshold, particularly on portions

of the piles close to the water line. In addition, corrosion potential measurements indicated that active corrosion is occurring up to 1.5' above the MGL on the piles.

In summary, the pile concrete is currently in good condition, but widespread corrosion of the reinforcing steel is occurring in areas that do not yet exhibit concrete damage. Corrosion induced concrete damage will undoubtedly occur on the piles and will continue to worsen with time unless a corrosion protection system is installed. Also, the future combined cost of concrete repairs and corrosion control measures will be greater than the cost of taking corrosion control measures alone now. Therefore, a proactive approach to rehabilitating the piles will be more cost effective depending on the anticipated remaining service life of the bridge. Consequently, it is recommended that consideration be given to installing non-structural sacrificial cathodic protection jackets and bulk zinc anodes on all of the piles. The existing conventional jacket on Pile 5-3 should also be completely removed.

The scope of work did not include investigation of continuously submerged portions of piles; however, installation of bulk zinc anodes should be sufficient to address any ongoing reinforcing steel corrosion in this region. Submerged portions of piles should be investigated if there are any structural concerns under water.

Bent Caps

The bent caps typically have cracks and existing repairs, including crack repairs and patched areas, at various locations. A portion of one of the patched areas on the bent cap that was evaluated is delaminated and there is corrosion staining on one of the cracks on that bent cap. The original concrete comprising the bent caps is well consolidated, dense, and has a typical amount of small entrapped air voids, although the average concrete cover over the reinforcing steel is less than desirable from a corrosion prevention point of view. The repair concrete used on the bent cap that was evaluated has larger entrapped air voids relative to the original concrete and these may be indicative of inadequate consolidation.

Reinforcing steel that was exposed in cored holes in original and repair concrete had a minor to moderate degree of corrosion. The chloride content at the reinforcing steel depth in the original concrete is several times greater than the corrosion threshold, but chlorides have not yet permeated to the reinforcing steel depth in the repair concrete. In spite of the fact that corrosion is known to be occurring in at least some areas on the bent cap that was investigated, corrosion potential measurements indicated that active corrosion was not occurring at the time that the measurements were taken. Considering the known corrosion condition of the bent caps, it is suspected that the measurements were influenced by a lack of moisture in the concrete at the time that the measurements were taken and that corrosion becomes active when sufficient moisture is present.

Based on the existing amount of concrete damage on the bent caps, the extent of past repairs that have been made, and the chloride content of the concrete, reinforcing steel corrosion has been occurring for some time. Also, reinforcing steel corrosion is currently

occurring in areas that do not yet exhibit concrete damage and in areas that have been repaired. If corrosion protection is not implemented, the extent of corrosion and related concrete damage on the bent caps will become more widespread in the future. It is recommended that all existing repair concrete and all damaged original concrete be removed. These areas should then be repaired in accordance with standard concrete repair procedures. For corrosion control purposes, it is recommended that a metalized zinc cathodic protection system be installed on all exposed surfaces on all of the bent caps. During the rehabilitation design phase, special consideration will be needed to address the limited working space available (i.e. 5.5" to 6.5") between Bent Caps 1 and 6 and the corresponding abutments.

Deck Overhangs

There are cracks, delaminations, minor spalling, and some repaired areas on the underside of the overhangs. The cracks typically have corrosion staining and run longitudinally. Some of the cracks on the underside and vertical faces of the overhangs have been repaired by epoxy injection and at least some of these repairs have failed. There is a delamination on each of the two sections of deck overhang that were evaluated. The delamination on the underside of the east deck overhang encompassed a portion of several cracks. The delamination on the underside of the west deck overhang encompassed a portion of one crack and was immediately adjacent to a patched area.

In terms of crack length, width, and frequency, the cracking on the east overhang is worse than on the west overhang and some of the cracks on the east overhang extend the full length of the spans. In addition to corrosion staining along cracks, there is a significant amount of other corrosion staining on the overhangs that appears to have resulted from corroding steel chairs and/or form nails used during construction. Also, some of the corrosion staining on the underside of the overhangs originates from cracks on the outside vertical face where the corrosion staining has migrated down the vertical face and onto the underside surface.

The original concrete comprising the deck overhangs is well consolidated, dense, and has a typical amount of small entrapped air voids, but the average concrete cover over the reinforcing steel is less than desirable from a corrosion prevention point of view. The repair concrete that was used on one of the deck overhang sections that was evaluated has larger entrapped air voids relative to the original concrete and these may be indicative of inadequate consolidation.

The degree of corrosion on reinforcing steel bars that were exposed in cored holes in original and repair concrete ranged from minor to severe and the chloride content at the reinforcing steel depth in all areas that were tested is above the corrosion threshold. Also, corrosion potential measurements on original concrete indicated that active corrosion is occurring in 22% of the east deck overhang area that was evaluated and 89% of the west deck overhang area that was evaluated and concrete resistivity measurements indicated a high probability that the concrete will allow corrosion current to flow. In addition, 75% of the corrosion potential measurements in areas with repair concrete on the west deck

overhang (there are no patched areas on the section of the east deck overhang that was evaluated), indicated that active corrosion is occurring. A few corrosion potential measurements were taken on cracks in original and repair concrete on the west deck overhang and all of them indicated that active corrosion is occurring.

Reinforcing steel corrosion on the deck overhangs is widespread and is in an advanced state. In addition, corrosion activity is currently occurring in areas that do not yet exhibit concrete damage and in areas that have been repaired. Without effective corrosion protection, the extent of corrosion and related concrete damage on the deck overhangs will become more widespread in the future. It is recommended that all existing repair concrete, existing crack repair material, and all damaged original concrete be removed on both the west and east overhangs. These areas and all areas with corrosion staining due to steel chairs and form nails should then be repaired in accordance with standard concrete repair procedures. For corrosion control purposes, it is recommended that a metalized zinc cathodic protection system be installed on the underside and outside vertical face of the entire length of both overhangs. The existing pipe attached along the west edge of the bridge will have to be temporarily removed to facilitate the rehabilitation work.

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I. INTRODUCTION

Bridge No. 154371 is located on San Martin Boulevard over Riviera Bay in St. Petersburg, Florida. The bridge consists of five spans and was constructed in 1962. Mr. Tom Menke with the Engineering and Technical Support Division of Pinellas County requested a corrosion condition evaluation to be performed on piles and the underside of the deck overhangs. After reviewing the November 10, 2009, routine bridge inspection report, it was decided to also evaluate the bent caps. Pertinent information from that inspection report is summarized below.

> Piles: All 30 of the prestressed concrete piles have a Condition State rating of 2. However, one of the piles (Pile 5-3) has a severely damaged conventional jacket that was constructed with epoxy-coated rebar.
>
> Bent Caps: There are six bent caps. The Abutment 1 Cap has two cracks, Cap 4 has a delamination, and previously reported delaminations and cracks on Cap 6 were repaired.
>
> Underside of Deck Overhangs: There are delaminations and cracks with corrosion staining and minor spalling with no exposed steel on the underside of the overhangs. There are also some repaired areas. Based on the original bridge plans and photographs provided by Mr. Menke, the top surface of the deck has an asphalt overlay, the portion of the deck between the overhangs is comprised of precast prestressed deck panels with conventionally reinforced concrete on top of the deck panels, and the overhangs are comprised of cast-in-place conventionally reinforced concrete.

In November 2011, a comprehensive corrosion condition evaluation was conducted on the piles, bent caps, and the underside of the deck overhangs and the findings are reported herein.

II. SCOPE OF WORK

The corrosion condition evaluation was conducted by Concorr Florida, Inc. under contract with the FDOT State Materials Office (FDOT-SMO). The scope of work for the corrosion condition evaluation is described below. With respect to the piles, work was limited to portions of the piles that are exposed above the water line. Continuously submerged portions of piles were not included since any damage there would not typically be caused by corrosion of reinforcing steel. In addition, Pile 5-3 was not included in the scope of work since it was unique in that it has a conventional jacket and because it was already known that the jacket was badly deteriorated.

1. Conduct a cursory visual survey on the piles, bent caps, and underside of the deck overhangs. Based on the observations made during the cursory visual survey, select the following components for additional evaluation:

- Three piles. If possible, select one pile with no visible concrete damage and two piles with concrete damage.

- One bent cap with concrete damage.

- Two deck overhangs; one on the west side and one on the east side of the bridge extending the full length of a span. The selected overhangs should have concrete damage and previous repairs.

2. Conduct detailed visual and sounding surveys on each of the selected components.

3. Perform the testing and sampling described below on each of the selected components.

   - Obtain non-destructive concrete cover measurements, corrosion potential measurements, and concrete resistivity measurements.

   - Obtain an overall total of fourteen 2 in. diameter cores in areas of solid concrete for chloride content analysis. Specific locations are as follows:

     - One core over a prestressed strand 6" above the marine growth line (MGL) on each selected pile.

     - One core over a prestressed strand 4' above the MGL on each selected pile.

     - One core over a horizontal bar and one core over a vertical bar in original concrete on the cap.

     - One core over a horizontal bar and one core over a vertical bar in a repaired area on the cap (if there are no repairs on the selected cap, take these cores in a repaired area on Cap 6).

     - One core in original concrete and one core in a repaired area on each selected overhang.

   Drill all cores to the depth of the reinforcing steel. Measure the concrete cover at each core location and document the visual condition of the reinforcing steel. Patch all cores holes after all testing is completed.

4. To determine the environmental classification at the bridge location, collect a water sample for laboratory analyses.

III. VISUAL AND SOUNDING SURVEY FINDINGS

A general visual inspection was conducted to identify concrete damage on the piles, bent caps, and the underside of the deck overhangs. The observations made are summarized below.

All of the piles visually appear in overall good condition except for Pile 5-3 which has a conventional jacket and was excluded from the scope of work. On some of the piles there are small spalled areas that are believed to have been caused by impacts from marine vessels (see Figure 1). There are also patched areas that are believed to be the result of lift hooks and impacts from marine vessels. Typical examples of the patched areas are shown in Figure 2. Some of the patches that appear to be over lift hooks were made with grout and others were made with epoxy. Also, a few of the piles have some minor scaling above the MGL (see Figure 3). No cracks, corrosion staining, or other spalls were found on any of the piles.

Figure 1. Typical spalled area on a pile that is believed to have been caused by an impact from a marine vessel.

Figure 2. Typical patched areas on piles that are believed to be the result of lift hooks (left photograph) and impacts from marine vessels (right photograph).

Figure 3. Typical scaling above the MGL on piles.

The bent caps typically have cracks and existing repaired areas at various locations (see Figure 4) and Bent Cap 4 has the most cracking and previous repairs relative to the other bent caps.

Figure 4. Typical repaired areas on bent caps.

The underside of the deck overhangs typically has longitudinal cracks with corrosion staining and efflorescence. In terms of crack length, width, and frequency, the cracking on the east overhang is worse than on the west overhang, probably due to the most aggressive Bay exposure on that side. Some of the cracks on the east overhang run the full length of the spans. In addition, the east overhang in Span 3 is in the overall worst condition and the extent of damage in the other spans generally decreases with increasing distance from the center of the bridge. The longitudinal cracks in the east and west overhangs are typically located between 2" to 4" from the outside edge of the overhangs (many of these cracks continue longitudinally onto the outside vertical face of the overhangs) and along the center of the overhangs. On the east overhang, there are also longitudinal cracks located 4" to 6" from the deck panels. Some of the cracks on the underside and vertical faces of the overhangs have been repaired by epoxy injection. In addition to corrosion staining along cracks, there is a significant amount of other corrosion staining on both the east and west overhangs that is believed to have resulted from corroding steel chairs and/or form nails used during construction. Corrosion staining from exposed steel chairs and/or form nails is more extensive on the west overhang than it is on the east overhang. Also, some of the corrosion staining on the underside of the overhangs originates from cracks on the outside vertical face where the corrosion staining has migrated down the vertical face and onto the underside surface. Typical examples of cracking, corrosion staining, and epoxy injection crack repairs on the overhangs are shown in Figure 5.

The components selected for comprehensive testing and sampling are listed in Table 1. Due to the general good visual condition of the piles, the three piles shown in Table 1 were randomly selected based on their location in order to provide a representative sampling of the piles throughout the bridge. Bent Cap 4 was chosen because it had the most cracking and previous repairs relative to the other bent caps. The deck overhang areas shown in Table 1 were selected because they exhibited typical conditions based on the cursory visual survey.

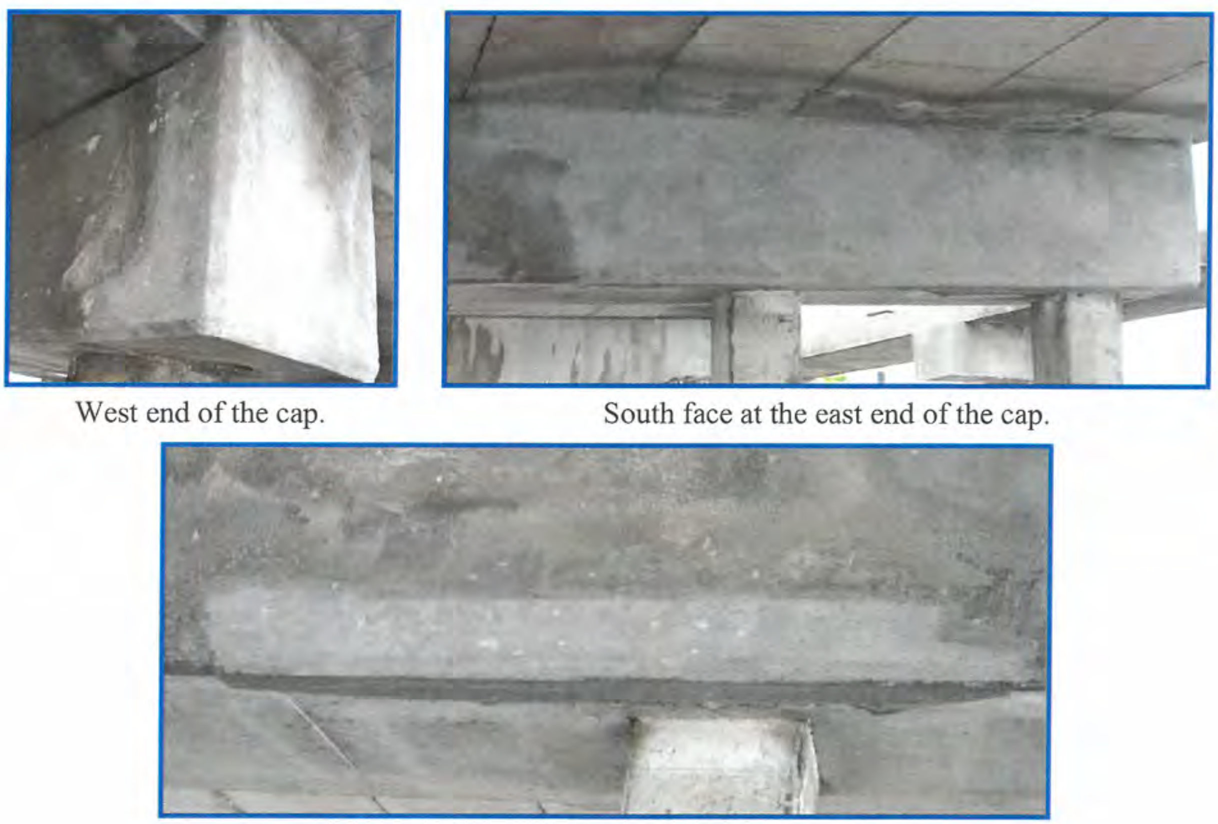
Table 1. Components selected for comprehensive testing and sampling.

Component
Pile 1-5
Pile 3-3
Pile 5-1
Bent Cap 4
East Deck Overhang, Span 2
West Deck Overhang, Span 3

Figure 5. Typical examples of cracking, corrosion staining, and epoxy injection crack repairs on the overhangs.

Thorough visual and sounding surveys were conducted on each of the components shown in Table 1. Each of the three piles was surveyed from the MGL up to the bent cap, all side and end surfaces and the bottom surface over the entire length of Bent Cap 4 were surveyed, and the entire length of the underside of each selected deck overhang was surveyed. The findings are described below.

Two of the piles had light scaling near the MGL. No other damage was found on the piles. On Bent Cap 4 there were three large repaired areas with a total surface area of approximately 58 ft^2 (about 26% of the total area surveyed on the bent cap). These repairs are shown in Figure 6. About 3 ft^2 of one of the repaired areas on the bottom surface was delaminated and there was a 3" deep void within the delaminated area (see Figure 7). There were also five cracks from 5 mils to 40 mils wide on the north face. One of these cracks continued onto the bottom surface and there was corrosion staining on that portion of the crack (see Figure 8). On the east face there were multiple cracks from 2 mils to 16 mils wide along with three small spalled areas and three small epoxy patch areas (the epoxy in one of these areas was covered with grout). Figure 9 shows an overall view of the east face of the bent cap.



West end of the cap.

South face at the east end of the cap.

South face at the center of the cap.

Figure 6. Three large repaired areas on Bent Cap 4.

Figure 7. Delaminated repair area (shown with black crosshatch markings) with a 3" deep void on the bottom surface of Bent Cap 4.

Figure 8. Corrosion staining on a crack on the bottom surface of Bent Cap 4.

Figure 9. East face of Bent Cap 4 with multiple cracks, three small spalled areas, and three small patched areas.

On the underside of the east deck overhang in Span 2 there were multiple corrosion induced longitudinal cracks with corrosion staining and efflorescence (see Figure 10). The width of the cracks ranged from 6 mils to 125 mils. Some of the cracks had been repaired by epoxy injection and the repairs have failed as shown in Figure 11. The longitudinal cracks were located near the outside edge of the overhang, along the center of the overhang, and adjacent to the deck panel. There was also a 3 ft^2 delamination that encompassed a portion of several of the cracks (see Figure 12). In addition, there was corrosion staining in one area that appeared to be caused by a steel chair or form nail and there were two epoxy repair areas on the vertical face of the overhang.

Figure 10. Longitudinal cracks with corrosion staining on the east deck overhang in Span 2.

Figure 11. Typical failed epoxy injection crack repairs on the east deck overhang in Span 2.

Figure 12. Cracked and delaminated area (shown with black crosshatch markings) on the east deck overhang in Span 2.

On the underside of the west deck overhang in Span 3 there were several relatively short longitudinal cracks with some corrosion staining and efflorescence (see Figure 13). The width of the cracks ranged from 10 mils to 30 mils. The cracks were all located near the outside edge of the overhang and two of the cracks continued onto the outside vertical face. There was also a 1.7 ft^2 delamination that encompassed a portion of one of the cracks (see Figure 14). The delamination extended onto the outside vertical surface and was immediately adjacent to a 14 ft^2 repaired area at the south end of the overhang. The repair area extended across the entire width of the overhang and continued onto the outside vertical surface. In addition, there was corrosion staining in several areas on the overhang that appeared to be caused by steel chairs or form nails (see Figure 15).

Figure 13. Longitudinal cracks with corrosion staining and efflorescence on the west deck overhang in Span 3.

Figure 14. Cracked and delaminated area (shown with black crosshatch markings) immediately adjacent to a repaired area on the west deck overhang in Span 3.

Figure 15. Typical areas with corrosion staining caused by steel chairs or form nails on the west deck overhang in Span 3.

IV. ENVIRONMENTAL CLASSIFICATION

A water sample was collected to determine the environmental classification at the bridge location (i.e. to characterize the corrosive properties of the water). Laboratory analyses were performed by FDOT-SMO. Chloride content, sulfate content, resistivity, and pH measurements of the sample are shown in Table 2. Based on the test results and parameters provided in the FDOT Structures Design Guidelines, the corrosion classification for the bridge is "Extremely Aggressive".

Table 2. Results of laboratory testing of a water sample.

Chloride Content, ppm	Sulfate Content, ppm	Resistivity, ohm-cm	pH
12,196	1,246	28	7.68

V. CORROSION TESTING AND ANALYSIS

Concrete Cover Measurements

Concrete cover measurements were obtained on each of the components listed in Table 1. Test data are shown in Table 3. The average concrete cover over prestressed strands in the piles ranged from 2.36" to 2.80" which is considered typical based on the age of the piles. The average concrete cover over vertical bars in the bent cap was 1.6" and this was less than the average concrete cover over horizontal bars. The average concrete cover over the transverse bars in the deck overhangs ranged from 1.40" to 1.82". The amount of concrete cover on bridge components in marine environments is critical with respect to prolonging the onset of reinforcing steel corrosion and the measurements made on the bent cap and deck overhangs are less than desirable for this purpose.

Table 3. Concrete cover measurements.

Component	Reinforcing Steel	Concrete Cover, in.	
		Average	Range
Pile 1-5	Prestressed Strands	2.36	2.08 to 2.60
Pile 3-3	Prestressed Strands	2.80	2.35 to 3.24
Pile 5-1	Prestressed Strands	2.65	2.09 to 3.18
Bent Cap 4	Horizontal Bars	2.56	1.95 to 3.24
	Vertical Bars	1.60	1.15 to 2.06
East Deck Overhang, Span 2	Transverse Bars	1.40	0.50 to 2.00
	Longitudinal Bar *	1.31	N/A
West Deck Overhang, Span 3	Transverse Bars	1.82	1.70 to 1.93

* One measurement only.

Concrete Core Sampling

A total of 14 two inch diameter cores were taken in sound concrete areas at the locations described in the scope of work. All of the cores were drilled to the depth of the reinforcing steel. Details related to each core along with the condition of the reinforcing steel exposed at each location are shown in Table 4. All cored holes were patched with a cementitious grout containing pea gravel after all testing was completed.

Table 4. Core sampling and condition of reinforcing steel.

Core No.	Component	Core Location	Concrete Type	Steel Type	Steel Condition	Photographs
1	Pile 1-5	4' Above MGL	Sound Original	Prestressed Strand	Minor corrosion.	
2		6" Above MGL	Sound Original	Prestressed Strand	Minor corrosion.	
3	Pile 3-3	4' Above MGL	Sound Original	Prestressed Strand	Minor corrosion.	
4		6" Above MGL	Sound Original	Prestressed Strand	Minor corrosion.	

Table 4 (continued). Core sampling and condition of reinforcing steel.

Core No.	Component	Core Location	Concrete Condition	Steel Type	Steel Condition	Photographs
5	Pile 5-1	4' Above MGL	Sound Original	Prestressed Strand	Minor corrosion.	
6		6" Above MGL	Sound Original	Prestressed Strand	Minor corrosion.	

Table 4 (continued). Core sampling and condition of reinforcing steel.

Core No.	Component	Core Location	Concrete Condition	Steel Type	Steel Condition	Photographs
7	Bent Cap 4	4" Above Bottom	Sound Repair	Horizontal Bar	Minor to moderate corrosion.	
8		8" Above Bottom	Sound Repair	Vertical Bar	Minor to moderate corrosion.	
9		3" Above Bottom	Sound Original	Horizontal Bar	Minor to moderate corrosion.	
10		6" Above Bottom	Sound Original	Vertical Bar	Minor to moderate corrosion.	

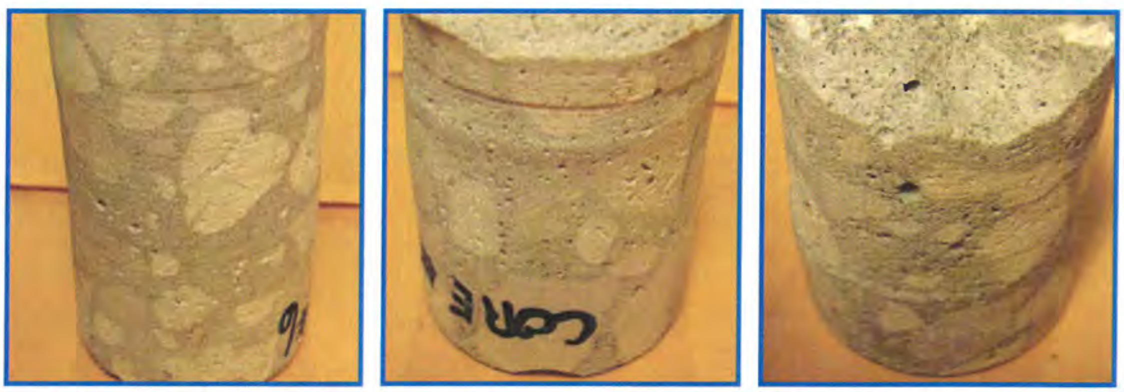
Table 4 (continued). Core sampling and condition of reinforcing steel.

Core No.	Component	Core Location	Concrete Condition	Steel Type	Steel Condition	Photographs
11	East Deck Overhang, Span 2	14" From End of Span & 3" From Outside Edge	Sound Original	Longitudina l & Transverse Bar	Moderate to severe corrosion.	
12 *		10' From End of Span & 16" From Outside Edge	Sound Repair	Transverse Bar	Moderate to severe corrosion.	
13	West Deck Overhang, Span 3	51" From End of Span & 14" From Outside Edge	Sound Repair	Transverse Bar	Minor to moderate corrosion.	
14		66" From End of Span & 20" From Outside Edge	Sound Original	Transverse Bar	Moderate corrosion.	

* This core was taken in Span 3 because there were no repaired areas in Span 2.

Prestressed strands exhibited minor corrosion in all of the piles at 6" and 4' above the MGL. Horizontal and vertical bars located in the bottom portion of the bent cap all had a minor to moderate degree of corrosion in original and repair concrete. Reinforcing steel bars in the east deck overhang were moderately to severely corroded in original and repair concrete. The extent of corrosion on reinforcing steel bars in the west deck overhang was somewhat less than that in the east deck overhang. The difference in the degree of corrosion on the west overhang relative to the east overhang corresponds with visual observations of the amount of concrete damage on the two overhangs.

Based on the visual appearance of the core samples obtained, the original concrete comprising the piles, bent caps, and deck overhangs is well consolidated, dense, and has a typical amount of small entrapped air voids (see Figure 16). As shown in Figure 17, the repair concrete used on Bent Cap 4 and the deck overhangs has larger entrapped air voids relative to the respective original concrete. In addition, some of the voids in the repair concretes are quite large and may be indicative of inadequate consolidation, particularly in the repair concrete used on the deck overhangs.



Original pile concrete. Original bent cap concrete. Original overhang concrete.

Figure 16. Condition of original pile, bent cap, and deck overhang concrete.

Bent Cap 4 repair concrete. Overhang repair concrete (apparently trowel applied).

Figure 17. Condition of repair concrete on Bent Cap 4 and deck overhangs.

Concrete Chloride Content Analysis

Chloride content analysis of the core samples was performed by FDOT-SMO in accordance with the procedures defined in Florida Method 5-516 and assuming a concrete unit weight of 3,800 lb/yd^3. Since the chloride content in cracked, delaminated, and/or spalled areas is expected to be higher than in sound concrete, all concrete core samples were intentionally taken in areas with no visible concrete damage and no delaminations in order to assess the probability of corrosion damage occurring in these areas in the future.

Chloride content analyses results at various depths in the core samples are shown in Table 5. Samples were extracted at or near the reinforcing steel depth in all of the cores. For some of the cores, samples were also obtained at 0.5" intervals in order to develop chloride content profiles versus depth. It is generally recognized that a total chloride content of about 1.2 lb/yd^3 (pcy) of concrete is sufficient to initiate corrosion of reinforcing steel, although other variables, such as oxygen and moisture availability and concrete quality can significantly affect this threshold.

The test results shown in Table 5 can be summarized as follows:

- The chloride content at the reinforcing steel depth in the piles is well above the corrosion threshold, particularly on portions of the piles close to the water line.
- The chloride content at the reinforcing steel depth in original concrete on the bent cap is several times greater than the corrosion threshold, but chlorides have not yet permeated to the reinforcing steel depth in the repair concrete.
- The chloride content at the reinforcing steel depth in original and repair concrete on the deck overhangs is above the corrosion threshold in all areas that were tested.

Corrosion Potential Measurements

Corrosion potential measurements were taken using a copper-copper sulfate reference electrode (CSE) in areas of solid concrete on each of the components shown in Table 1. Most of the measurements were intentionally taken in areas with no visible concrete damage and no delaminations in order to assess the probability of corrosion damage occurring in these areas in the future. Also, on the deck overhangs, a few measurements were taken in delaminated areas and on a crack.

Although corrosion potential measurements can be affected by the moisture content of the concrete and other factors that exist at the time measurements are taken, ASTM C876, "Standard Test Method for Half-Cell Potentials of Uncoated Reinforcing Steel in Concrete," states the following:

Table 5. Chloride content analysis of concrete core samples.

Core No.	Component	Core Location	Concrete Type	Steel Depth, in.	Sample Depth, in.	Chloride Content, pcy
1	Pile 1-5	4' Above MGL	Sound Original	2.50	2.0 - 2.5	0.14
2		6" Above MGL	Sound Original	2.13	1.6 - 2.1	12.30
3	Pile 3-3	4' Above MGL	Sound Original	3.19	0.0 - 0.5 0.5 - 1.0 1.0 - 1.5 1.5 - 2.0 2.0 - 2.5 2.5 - 3.0	4.96 8.54 4.63 1.80 0.61 0.19
4		6" Above MGL	Sound Original	2.50	2.0 - 2.5	16.60
5	Pile 5-1	4' Above MGL	Sound Original	2.19	1.7 - 2.2	2.06
6		6" Above MGL	Sound Original	3.13	0.0 - 0.5 0.5 - 1.0 1.0 - 1.5 1.5 - 2.0 2.0 - 2.5 2.5 - 3.1	23.93 22.94 15.99 12.48 10.11 7.81

(Shaded) Equals or exceeds typical corrosion threshold of 1.2 lb/yd^3.

Table 5 (continued). Chloride content analysis of concrete core samples.

Core No.	Component	Core Location	Concrete Type	Steel Depth, in.	Sample Depth, in.	Chloride Content, pcy
7	Bent Cap 4	4" Above Bottom	Sound Repair	3.19	0.0 - 0.5	0.56
					0.5 - 1.0	0.15
					1.0 - 1.5	0.17
					1.5 - 2.0	0.16
					2.0 - 2.5	0.19
					2.5 - 3.0	0.19
					3.0 - 3.5	0.26
8		8" Above Bottom	Sound Repair	2.06	1.6 - 2.1	0.31
9		3" Above Bottom	Sound Original	2.00	0.0 - 0.5	4.48
					0.5 - 1.0	4.43
					1.0 - 1.5	6.45
					1.5 - 2.0	4.35
10		6" Above Bottom	Sound Original	1.25	0.75 - 1.25	6.34
11	East Deck Overhang, Span 2	14" From End of Span & 3" From Outside Edge	Sound Original	0.50	0.0 - 0.5	3.04
12 *		10' From End of Span & 16" From Outside Edge	Sound Repair	1.50	0.0 - 0.5	1.28
					0.5 - 1.0	0.81
					1.0 - 1.5	1.41
13	West Deck Overhang, Span 3	51" From End of Span & 14" From Outside Edge	Sound Repair	1.75	1.25 - 1.75	4.48
14		66" From End of Span & 20" From Outside Edge	Sound Original	1.88	0.0 - 0.5	7.33
					0.5 - 1.0	10.03
					1.0 - 1.5	8.68
					1.5 - 1.9	8.67

*This core was taken in Span 3 because there were no repaired areas in Span 2.

(shaded) Equals or exceeds typical corrosion threshold of 1.2 lb/yd^3.

- Corrosion potentials more negative than –350 mV CSE indicate that there is a greater than 90% probability that active corrosion is occurring within the tested area.
- If corrosion potentials are between –200 and –350 mV CSE, corrosion activity is uncertain.
- Measurements less negative than –200 mV CSE indicate with a greater than 90% probability that active corrosion is not occurring within the tested area (i.e. the reinforcing steel is in a passive state).

Corrosion potential measurements on piles were taken at a 6" spacing starting at the MGL and extending up to the bent cap. On the bent cap, measurements were taken at a 6" spacing along horizontal and vertical bars. Measurements on the underside of the deck overhangs were taken on a 1' grid throughout the length and width of each overhang. Test data are shown in Table 6 and a summary of pertinent findings is provided below.

- There is a high probability that active corrosion is occurring up to 1.5' above the MGL on the piles. Also, a significant number of measurements from 1.5' to 3' above the MGL were in the uncertain range with respect to corrosion activity.

- No measurements indicative of active corrosion were obtained in original concrete or repair concrete on the bent cap. However, a few of the measurements in repair concrete were in the uncertain range with respect to corrosion activity.

- On the east deck overhang, 14% of the measurements indicate a high probability that the reinforcing steel is in a passive state, 64% of the measurements were in the uncertain range with respect to corrosion activity, and 22% of the measurements indicate a high probability that active corrosion is occurring. Also, two of the measurements were taken in a delaminated area and both of these were in the uncertain range with respect to corrosion activity.

- In areas with original concrete on the west deck overhang, 11% of the measurements were in the uncertain range with respect to corrosion activity and 89% of the measurements indicate a high probability that active corrosion is occurring. Also, two of the measurements were taken in a delaminated area and three measurements were taken on a crack. One of the measurements in delaminated concrete was in the uncertain range with respect to corrosion activity and the other measurement indicates a high probability that active corrosion is occurring. All three of the measurements on a crack indicate a high probability that active corrosion is occurring.

- In areas with repair concrete on the west deck overhang, 25% of the measurements were in the uncertain range with respect to corrosion activity and 75% of the measurements indicate a high probability that active corrosion is occurring. Also, three of the measurements were taken on a crack and all of them indicate a high probability that active corrosion is occurring.

Table 6. Corrosion potential measurements.

Distance, ft. *	Corrosion Potentials, mV CSE					
	Pile 1-5		Pile 3-3		Pile 5-1	
	North Face	East Face	West Face	South Face	East Face	West Face
8.0	-227	19				
7.5	-143	79	-188	-105		
7.0	-80	137	-93	-25	-129	-177
6.5	-69	129	-74	12	-111	-164
6.0	-75	47	-63	-10	-94	-16
5.5	-60	104	-83	-31	-67	40
5.0	-207	68	-105	38	-52	30
4.5	-143	34	-137	42	-90	-4
4.0	**	8	**	-93	**	-36
3.5	-160	3	-207	-118	-195	-70
3.0	-209	-1	-247	-166	-217	-110
2.5	-233	-72	-285	-218	-254	-167
2.0	-272	-185	-341	-262	-256	-205
1.5	-321	-206	-402	-361	-304	-301
1.0	-459	-327	-404	-459	-389	-402
0.5	-520	**	-462	**	-433	**
0.0	-527	-466	-555	-641	-502	-557

Notes:

* Above the MGL. ** Core location.

Measurements were taken along prestressed strands.

No corrosion activity.

Corrosion activity is uncertain.

Active corrosion.

Table 6 (continued). Corrosion potential measurements.

Location *	Corrosion Potentials, mV CSE											
	Bent Cap 4				East Deck Overhang, Span 2				West Deck Overhang, Span 3, Concrete Type			
	Repair Concrete	Original Concrete	Repair Concrete	Original Concrete	Original Concrete				Original			Repair
1	-111	-116	-77	-144	-148	-244	-239	-197	-384	-367	-378	-250
2	-245	-132	-157	-136	-293	-366	-407	-354	-480	-303	-294	-485
3	-203	-161	-144	-89	-296	-278	-323	-292	-430	-346	-407	-473
4	-85	**	-103	-38	-255	-265	-233	-271	-388	-383	-345	-483
5	-56	-103	-79	-21	-215	-205	-305	-284	-476	-385	-406	-236
6	-135	-77	-214	-3	-354	-387	-399	-383	-540	-531	-375	-399
7	-140	-43			-339	-288	-283	-298	-584	-515	-445	-405
8	-159	-41			-217	-223	-270	-240	**-334**	**-394**	-438	-360
9	-180	-42			-313	-327	-282	-251	-396	-383	-399	-280
10	-112	-40			-413	-393	-373	-395	-503	-385	-528	-419
11	-170	-43			-278	-248	-310	-329	-583	-585	-587	-425
12	-158	-39			-235	-262	-175	-129	-499	-435	-472	-463
13	-150	-32			-299	-260	-240	-257	-421	-364	-375	-278
14	-153	-20			-367	-360	-373		-508	-451	-429	-467
15	**				-250	-290	-297		-572	-454	-517	-425
16	-155				-235	-145	-177		-506	-438	-424	-397
17	-138				-275	-302	-300		-407	-369	-320	-299
18	-103				-365	**-348**	**-349**		-478	-481	-410	-454
19	-31				-285	-256	-299		-483	-480	-407	-439
20	-48				-219	-211	-281		-415	-432	-347	-432
21	-17				-272	-247	-265		-451	-361	-350	
22	-12				-387	-368	-367		-449	-494	-375	
23	-56				-163	-120	-264		-370	-527		
24	-40				-140	-115	-162		-375	-524		
25	-31				-317	-186	-354		-440	-415		
26	34				-352	-258	-226		-290	-535		
27	40				-201	-292	-171		-415	-589		
28	14				-243	-373	-208		-440	-497		
29	14				-218	-177	-412		-435	-425		

Notes:
Bold readings were in a delaminated area. Red readings were on a crack.
* Bent Cap 4 - first two columns of data - 6" interval along a horizontal bar located 3" to 4" up from the bottom, next two columns of data - 6" interval along vertical bars with Location 1 at the bottom of the cap. Deck Overhangs - 1' interval throughout length and width of the overhangs.
** Core location.

No corrosion activity.
Corrosion activity is uncertain.
Active corrosion.

Concrete Resistivity Measurements

Resistivity measurements were taken in sound concrete on each of the components shown in Table 1 in order to determine the ability of the concrete to allow corrosion current to flow. Results of these measurements indicate the concrete electrical resistance to a depth of approximately 2 to 2.5 inches. Corrosion criteria suggest that concrete resistivity measurements of about 12 kohm-cm or less indicate a very high probability that the concrete will allow corrosion current (DC) to flow through the concrete (electrolyte) onto the surface of the steel, thereby facilitating corrosion development. At higher resistivity values, the probability of corrosion proportionally decreases.

On the piles, concrete resistivity measurements were taken at a 1' spacing starting at the MGL and extending up to the bent cap. On the bent cap, measurements were taken near the bottom, center, and top of a vertical face. Measurements on the underside of the deck overhangs were taken at random locations. Test data are shown in Table 7 and are summarized below.

- In spite of the fact that corrosion is known to be occurring in at least some areas on the piles and bent cap that were investigated, only one measurement on the piles and one measurement on the bent cap (on repair concrete) indicates a high probability that the concrete will allow corrosion current to flow. It is suspected that the outer concrete surface may have been too dry at the time that the measurements were taken and, consequently, the test data do not accurately reflect actual conditions when the moisture content of the concrete is higher.
- All of the measurements on the deck overhangs, including one measurement in repair concrete, indicate a high probability that the concrete will allow corrosion current to flow.

VI. DISCUSSION

At the time that the corrosion condition evaluation was conducted, the bridge had been exposed to an extremely aggressive corrosive environment for 49 years. Principal findings from this study are discussed below.

Piles

The piles are in good condition at this time. Some of the piles have small spalled areas that are believed to have been caused by impacts from marine vessels. There are also patched areas that appear to be the result of lift hooks and impacts from marine vessels. No cracks, corrosion staining, or other spalls were found on any of the piles, although one of the piles has an existing conventional jacket that is badly deteriorated. Also, the original concrete comprising the piles is well consolidated, dense, has a typical amount of small entrapped air voids, and the average concrete cover over prestressed strands in the piles is considered typical based on the age of the piles.

Table 7. Concrete resistivity measurements.

Distance, ft. *	Concrete Resistivity, kohm-cm					
	Pile 1-5		Pile 3-3		Pile 5-1	
	North Face	East Face	West	South	East	West
8.0	50	73	371	473		
7.0	104	171	369	432	213	216
6.0	153	119	389	265	158	252
5.0	208	352	310	154	169	205
4.0	191	207	231	188	163	231
3.0	164	201	163	120	102	287
2.0	132	231	178	79	77	345
1.0	150	134	54	42	45	124
0.0	90	77	52	87	11	43

Location **	Concrete Resistivity, kohm-cm			
	Bent Cap 4		East Deck	West Deck
	Repair Concrete	Original Concrete	Overhang, Span 2	Overhang, Span 3
1	16	86	15	7
2	71	503	7	3
3	89	86	5	4 ***

Notes:

* Above the MGL line on piles.

** Locations 1, 2, and 3 on Bent Cap 4 are on a vertical face 3" from the bottom, in the center, and 3" below the top respectively. Locations 1, 2, and 3 on the deck overhangs are at random locations.

*** Repair concrete.

Although the pile concrete visually appears in good condition, measurements and testing indicates that corrosion has initiated on the piles reinforcing steel. Prestressed strands that were exposed in cored holes exhibited minor corrosion up to 4' above the MGL and the chloride content at the reinforcing steel depth is well above the corrosion threshold, particularly on portions of the piles close to the water line. In addition, corrosion potential measurements indicated that active corrosion is occurring up to 1.5' above the MGL on the piles.

In summary, the pile concrete is currently in good condition, but widespread corrosion of the reinforcing steel is occurring in areas that do not yet exhibit concrete damage. Corrosion induced concrete damage will undoubtedly occur on the piles and will continue to worsen with time unless a corrosion protection system is installed due to the very high chloride content observed.

Bent Caps

The bent caps typically have cracks and existing repairs, including crack repairs and patched areas, at various locations. A portion of one of the patched areas on the bent cap that was evaluated is delaminated and there is corrosion staining on one of the cracks on that bent cap. The original concrete comprising the bent caps is well consolidated, dense, and has a typical amount of small entrapped air voids, although the average concrete cover over the reinforcing steel is less than desirable from a corrosion prevention point of view. The repair concrete used on the bent cap that was evaluated has larger entrapped air voids relative to the original concrete and these may be indicative of inadequate consolidation.

Reinforcing steel that was exposed in cored holes in original and repair concrete had a minor to moderate degree of corrosion. The chloride content at the reinforcing steel depth in the original concrete is several times greater than the corrosion threshold, but chlorides have not yet permeated to the reinforcing steel depth in the repair concrete. In spite of the fact that corrosion is known to be occurring in at least some areas on the bent cap that was investigated, corrosion potential measurements indicated that active corrosion was not occurring at the time that the measurements were taken. Considering the known corrosion condition of the bent caps, it is suspected that the measurements were influenced by a lack of moisture in the concrete at the time that the measurements were taken and that corrosion becomes active when sufficient moisture is present.

Based on the existing amount of concrete damage on the bent caps, the extent of past repairs that have been made, and the chloride content of the concrete, reinforcing steel corrosion has been occurring for some time. Also, reinforcing steel corrosion is currently occurring in areas that do not yet exhibit concrete damage and in areas that have been repaired. If corrosion protection is not implemented, the extent of corrosion and related concrete damage on the bent caps will become more widespread in the future.

Deck Overhangs

There are cracks, delaminations, minor spalling, and some repaired areas on the underside of the overhangs. The cracks typically have corrosion staining and run

longitudinally. Some of the cracks on the underside and vertical faces of the overhangs have been repaired by epoxy injection and at least some of these repairs have failed. There is a delamination on each of the two sections of deck overhang that were evaluated. The delamination on the underside of the east deck overhang encompassed a portion of several cracks. The delamination on the underside of the west deck overhang encompassed a portion of one crack and was immediately adjacent to a patched area.

In terms of crack length, width, and frequency, the cracking on the east overhang is worse than on the west overhang (probably due to most aggressive exposure to the Bay) and some of the cracks on the east overhang extend the full length of the spans. In addition to corrosion staining along cracks, there is a significant amount of other corrosion staining on the overhangs that appears to have resulted from corroding steel chairs and/or form nails used during construction. Also, some of the corrosion staining on the underside of the overhangs originates from cracks on the outside vertical face where the corrosion staining has migrated down the vertical face and onto the underside surface.

The original concrete comprising the deck overhangs is well consolidated, dense, and has a typical amount of small entrapped air voids, but the average concrete cover over the reinforcing steel is less than desirable from a corrosion prevention point of view. The repair concrete that was used on one of the deck overhang sections that was evaluated has larger entrapped air voids relative to the original concrete and these may be indicative of inadequate consolidation.

The degree of corrosion on reinforcing steel bars that were exposed in cored holes in original and repair concrete ranged from minor to severe and the chloride content at the reinforcing steel depth in all areas that were tested is above the corrosion threshold. Also, corrosion potential measurements on original concrete indicated that active corrosion is occurring in 22% of the east deck overhang area that was evaluated and 89% of the west deck overhang area that was evaluated and concrete resistivity measurements indicated a high probability that the concrete will allow corrosion current to flow. In addition, 75% of the corrosion potential measurements in areas with repair concrete on the west deck overhang (there are no patched areas on the section of the east deck overhang that was evaluated), indicated that active corrosion is occurring. A few corrosion potential measurements were taken on cracks in original and repair concrete on the west deck overhang and all of them indicated that active corrosion is occurring.

Reinforcing steel corrosion on the deck overhangs is widespread and is in an advanced state. In addition, corrosion activity is currently occurring in areas that do not yet exhibit concrete damage and in areas that have been repaired. Without effective corrosion protection, the extent of corrosion and related concrete damage on the deck overhangs will become more widespread in the future.

VII. RECOMMENDATIONS

The recommendations provided below are made from a corrosion viewpoint only and are based on the assumption that the remaining service life of the bridge and an economic analysis will warrant long-term rehabilitation measures. The recommendations also consider the fact that the service life of standard patch repairs in chloride contaminated concrete, necessitated by reinforcing steel corrosion, without cathodic protection is typically only three to five years. To ensure that structural engineering issues are adequately addressed, these recommendations should be reviewed and evaluated by a Bridge Structural Engineer when considering rehabilitation alternatives.

Piles

If corrosion protection measures are not implemented, reinforcing steel corrosion will continue and related concrete damage will occur and will continue to worsen with time. Also, the future combined cost of concrete repairs and corrosion control measures will be greater than the cost of taking corrosion control measures alone now. Therefore, a proactive approach to rehabilitating the piles will be more cost effective depending on the anticipated remaining service life of the bridge. Consequently, consideration should be given to installing non-structural sacrificial cathodic protection jackets and bulk zinc anodes on all of the piles. This is not considered an immediate necessity, but for long term service, it will be necessary. The jackets should extend from 2' below the mean low water elevation up to at least 4' above the MGL. The existing conventional jacket on Pile 5-3 should also be completely removed and replaced with cathodic protection.

The scope of work did not include investigation of continuously submerged portions of piles, however, installation of bulk zinc anodes should be sufficient to address any ongoing reinforcing steel corrosion in this region. Submerged portions of piles should be investigated if there are any structural concerns under water.

Bent Caps

Remove all existing repair concrete and all damaged original concrete and repair these areas in accordance with standard concrete repair procedures. Install a metalized zinc cathodic protection system on all exposed surfaces on all of the bent caps.

During the rehabilitation work, any severely deteriorated reinforcing steel should be repaired as directed by a Bridge Structural Engineer and determination of the need to incorporate new structural reinforcing steel into the repairs should be made by a Bridge Structural Engineer. Also, during the rehabilitation design phase, special consideration will be needed to address the limited working space available (i.e. 5.5" to 6.5") between Bent Caps 1 and 6 and the corresponding abutments (see Figure 18).

Figure 18. Limited available working space between Bent Caps 1 (left photograph) and 6 (right photograph) and the abutments.

Deck Overhangs

Remove and replace all existing patch concrete, existing crack repair material, and all damaged (cracked or delaminated) original concrete on both the west and east overhangs. Repair these areas and all areas with corrosion staining due to steel chairs and form nails in accordance with standard concrete repair procedures. Following, install a metalized zinc cathodic protection system on the underside and outside vertical face of the entire length of both overhangs. The metalizing would then need to be re-applied at 10 – 12 year intervals.

During the rehabilitation work, any severely deteriorated reinforcing steel should be repaired as directed by a Bridge Structural Engineer and determination of the need to incorporate new structural reinforcing steel into the repairs should be made by a Bridge Structural Engineer. Also, the existing pipe attached along the west edge of the bridge will have to be temporarily removed to facilitate the rehabilitation work.

Consideration form the long term financial aspect should also be given to a full depth replacement of the overhangs as an alternative to the above.