# Inspection of the Substructure of the Chesapeake Bay Bridge-Tunnel Above and Below the Waterline

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The Chesapeake Bay Bridge-Tunnel, completed in 1964, was 24 years old when Wilbur Smith Associates, BTML Division, supplied engineering services as part of an in-depth, above-and-below water inspection of the substructure for the Chesapeake Bay Bridge-Tunnel District. As part of this inspection, a visual inspection of all substructure elements was conducted. A total of 60 bents were selected for a hands-on inspection. From these bents, 10 piles were selected for an in-depth evaluation. The 24-year-old substructure of the Chesapeake Bay Bridge-Tunnel was in fair condition. The splash zone and below-water portions of the piles were in good condition because of the protection provided by excessive marine growth. The above-water portions of the piles were found to be in generally fair condition. Almost all piles had hairline cracks; some piles had open cracks that allowed the ingress of corrosive agents. The prestressing strands were in good condition with no section loss. Corrosion generally began as the surface of the pile crack increased beyond ¼ in. Chloride ion presence in the concrete at the level of prestressing strand was almost negligible. The corrosion potential readings correlated with the rating of the crack tested. Caps were found to be in good condition with only isolated signs of deterioration. The report to the Chesapeake Bay Bridge-Tunnel District made the following recommendations: cracks open less than 1/16 in. need only be monitored; cracks open 1/16 to ¼ in. should be sealed by epoxy injection to prevent corrosion initiation; and piles with cracks open more than ¼ in. should be rehabilitated using a structural jacket or replaced.

The Chesapeake Bay Bridge-Tunnel facility, completed in 1964, was 24 years old when Wilbur Smith Associates, BTML Division, supplied engineering expertise, beginning in July 1988, as part of an inspection of the substructure of the facility above and below the waterline for the Chesapeake Bay Bridge-Tunnel District. Besides Wilbur Smith Associates, Crofton Diving Corporation of Portsmouth, Virginia, the prime contractor, supplied boats, divers, and access equipment, and Tidewater Construction Corporation of Newport News, Virginia, the original builder, supplied construction expertise. This ongoing project was originally scheduled for completion in early 1990. Its inspection procedures, inspection findings, and recommended repair-rehabilitation alternatives are described here. The Chesapeake Bay Bridge-Tunnel crosses the mouth of the Chesapeake Bay, which exposes the facility to a number of adverse conditions, including the full force of ocean storms and rough seas that they produce. The salinity of the water is roughly that of sea water. Tidal currents in the area are strong, averaging 3 knots and, under a worst-case scenario, would exceed 6 knots because of the hydraulic constriction caused by the substructure units. In addition, some of the largest vessels in the world use the Hampton Road ports and have struck the facility on occasion.

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The Chesapeake Bay Bridge-Tunnel is the longest facility of its type in the world. The facility, which is 17.6 mi in length, consists of 830 three-pile bents as shown in Figure 1, 18 two-column reinforced concrete piers, and 8 abutments that support a series of 75-ft, precast, prestressed-concrete girders, various steel girder spans, and a through-truss. The facility incorporates four man-made islands, providing access to two tunnels and one natural island.

Most of the substructure units consist of three piles supporting a cap. Piles are hollow, 5-in.-thick prestressed concrete cylinders, 54 in. in diameter. They were precast in 16-ft-long sections that were posttensioned together, grouted, then driven into the bay bottom. The piles were then filled with sand to approximately 4 ft below the bottom of the cap. Cylinders have either 12 or 16 prestressing strands, depending on the height of the bent above the point of fixity used in the design, and are laterally reinforced with No. 2 spirals that are not in direct contact with the prestressing strands.

The caps for these bents are precast, mild, reinforced concrete and set on top of the piles. They were cast with a protruding, reinforcing-steel cage that was inserted into each pile. The caps have 9-in.-diameter holes over each pile that allowed concrete to be placed inside the remaining hollow 4-ft sections of piling.

## FINDINGS OF THE CURSORY ABOVE-WATER INSPECTION

The field work for this project was divided into four tasks: cursory and in-depth inspections both above and below the waterline. The cursory above-water inspection was quickly performed to summarize the general condition of the structure.

The first of the four tasks was to photograph and sketch both sides of each substructure unit. The sketches included a list of all deficiencies identified and an estimate of the quantities involved. An example of the data collected is shown in Figure 2.

Before the start of the inspection, guidelines were developed for assessing the condition of the substructure. These guidelines rated three types of deterioration found on the substructure—cracks, scaling, and impact damage—on a

**FIGURE 1 General view of facility.**

numerical scale based on the National Bridge Inspection Standards (NBIS). Rating guidelines are presented in Table 1. The cap and the three piles were rated separately. The condition with the lowest rating controlled the overall rating of that member. The conditions were defined as follows:

| *Scaling* | *Characteristic* |
|---|---|
| None | No loss of surface mortar. |
| Minor | Slight loss of surface mortar. |
| Moderate | Aggregates exposed. |
| Advanced | Up to 1-in.-deep loss of section. |
| Severe | Steel exposed, greater than 1-in. loss of section; structural integrity appears OK. |
| Serious | Structural integrity questionable. |

| *Impact Damage* | *Characteristic* |
|---|---|
| None | No visible damage. |
| Minor | Surface scrapes or scars. |
| Moderate | Up to 3-in.-deep scrape or steel exposed. |
| Severe | Greater than 3-in.-deep scrape or steel damage; structural integrity appears OK. |
| Serious | Greater than 3-in.-deep scrape or steel damage; structural integrity questionable. |

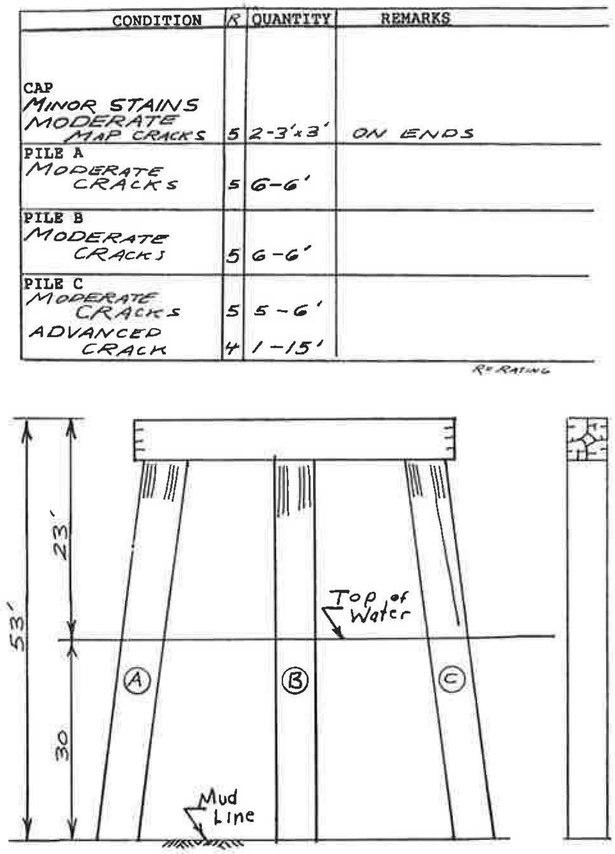


**FIGURE 2 Data sheet.**

| *Cracks* | *Characteristic* |
|---|---|
| Minor | Visible hairline cracks. |
| Moderate | Cracks open $\frac{1}{16}$ in. or less, or hairline cracks with rust stains or efflorescence. |
| Advanced | Cracks open $\frac{1}{16}$ to $\frac{1}{4}$ in. |
| Severe | Cracks open $\frac{1}{4}$ to $\frac{1}{2}$ in. and structural integrity appears OK. |
| Serious | Cracks open 2 in. or more or structural integrity appears questionable, or both. |

TABLE 1 RATING GUIDELINES

| NBIS RATING | CONDITION | TYPE PROBLEM: SCALING | IMPACT DAMAGE | CRACKS |
|---|---|---|---|---|
| 9 | NEW | | | |
| 8 | GOOD | NONE | NONE | NONE |
| 7 | | MINOR | NONE | NONE |
| 6 | FAIR | MINOR | NONE | MINOR |
| 5 | | MODERATE | MINOR | MODERATE |
| 4 | POOR | ADVANCED | MODERATE | ADVANCED |
| 3 | | SEVERE | SEVERE | SEVERE |
| 2 | SERIOUS | SERIOUS | SERIOUS | SERIOUS |
| 1 | CLOSED | -- | -- | -- |
| 0 | -- | -- | -- | -- |

In this rating system, the condition rated and the quantities involved have been separated. For example, moderate cracks are determined by their width and whether corrosion is apparent. The length and number of cracks are considered separately. The purpose of this system is to provide a means of grouping the condition categories. On a facility of the size of the Chesapeake Bay Bridge-Tunnel, this system is helpful in evaluating the magnitude of problems and planning a maintenance strategy.

### Caps

The caps were found to be in good condition. As shown in Figure 3, open deck expansion joints wet the surfaces of the caps resulting in minor discoloration caused by moss, lichen, road oil, and light efflorescence. Many cap ends exhibited minor map cracks. Figure 3 also shows a cap with extensive map cracks.

### Piles

The piles were in generally fair condition, typically having minor and moderate cracks over the prestressing strands around the uppermost 4 to 6 ft of each pile. Figure 4 shows this condition. Some piles had open cracks and some had minor scaling of the concrete surface, which would be expected of 25-year-old concrete.

Many piles in Trestle A have received impact damage. This damage is the result of a barge that came loose from its moorings in a storm and was driven against the exterior piles of the facility. The barge struck the facility repeatedly for a length of 2 mi, causing much damage.

A similar incident involved another vessel, which came loose from its moorings and destroyed four substructure units and five spans before drifting out to sea.

## FINDINGS OF THE IN-DEPTH, ABOVE-WATER INSPECTION

In-depth test procedures were administered to determine the detailed condition of selected piles to draw conclusions for all piles and to develop recommended remedial actions. For these tests, 60 bents were selected for hands-on, above-water inspections, which consisted of sounding all concrete surfaces with a hammer and visually assessing all deficiencies at close range. During the course of these studies, 10 piles were selected for an in-depth inspection. This inspection consisted of four steps:

1. Locating all prestressing strands and the spiral reinforcing-steel cage in the vicinity of the test site,
2. Drilling the concrete surface with a rotary impact hammer to expose the prestressing strand for a visual assessment of the remaining cross-sectional area,
3. Collecting dust samples for determination of chloride content from a location adjacent to the exposed strand near the concrete surface and at a depth equal to that of the prestressing strand, and
4. Conducting a corrosion potential survey of an area adjacent to the exposed strand.

FIGURE 3 Cap with map cracking.

FIGURE 4 Pile with typical cracks.

The 10 piles were selected to study damage associated with various condition categories. A pyramid-shaped design test group was selected, as shown in Figure 5, so that a spectrum of cracks would be investigated with emphasis placed on cracks with lower ratings.

All piles tested came from approximately the same location in Trestle A, Bents 30 to 42, except for one bent located in the surf zone and another bent located closer to the center of the bay. The test piles were grouped in this manner so that as many independent variables as possible could be held constant for the test group.

### Remaining Cross-Sectional Area

The results of the visual assessment of the remaining cross-sectional area of the prestressing strand show that only three

| RATING DESCRIPTION | | | | |
|---|---|---|---|---|
| 7 NO CRACK | 1 | | | |
| 5 MODERATE CRACK | 2 | 3 | | |
| 4 ADVANCED CRACK | 4 | 5 | 6 | |
| 3 SEVERE CRACK | 7 | 8 | 9 | 10 |

**FIGURE 5 Test group design.**

test locations show any sign of corrosion (see Figure 6). Of these, two had minor corrosion and the other had heavy corrosion.

By grouping the test scores according to crack severity (crack rating), averages can be generated for each rating category. The result is that prestressing strands with no associated cracks, moderate cracks, advanced cracks, and severe cracks (rated 7, 5, 4, and 3, respectively), have an average percent remaining steel area of 100, 100, 99.7, and 85 percent, respectively. If the 50 percent datum value is discarded, the average value for severe cracks changes from 85 to 96.7 percent. A graph of these averages is shown in Figure 7. The plot is exponential, as might be expected.

A function describing the empirical data that were collected is

$$A = 100 \text{ for } R > 5, \text{ and} \tag{1}$$

$$= -1.4(4.5 - R)^2 + 100 \text{ for } R < 5 \tag{2}$$

where $A$ is the area of remaining steel (in percent) and $R$ is the rating of the crack severity. This function indicates that

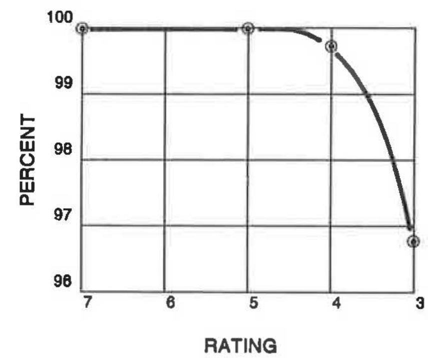


**FIGURE 7 Remaining steel area.**

corrosion initiates halfway between a rating of 4 and 5 and progresses at a rate of 1.4 percent per rating-decrease squared.

**Corrosion Potential**

Data collected from the corrosion potential survey are shown in Figure 8. The values shown are the absolute maximum readings for each pile tested. Averages were taken of the data in each crack severity category, as previously discussed. The averages are −0.17, −0.41, −0.42, −0.50 for strands with no associated cracks, moderate cracks, advanced cracks, and severe cracks, respectively. If the datum value of −0.35 is discarded, the average of −0.50 changes to −0.54. A plot of this data is shown in Figure 9. A straight line has been plotted between the first and last average values, −0.17 and −0.54. This line falls close to the two intermediate average values. The graph has been extended to the left to show that the line plotted passes close to the origin of the graph, i.e., a rating of 9, which is defined as "new condition" under the NBIS guidelines, would have a corresponding corrosion potential reading of near zero.

The function that describes the line thus plotted is

$$P = 0.09(9 - R) + 0.02 \tag{3}$$

where $P$ is the potential for corrosion in volts. This equation

| RATING DESCRIPTION | | | | |
|---|---|---|---|---|
| 7 NO CRACK | 100 | | | |
| 5 MODERATE CRACK | 100 | 100 | | |
| 4 ADVANCED CRACK | 100 | 100 | 99 | |
| 3 SEVERE CRACK | 90 | 50 | 100 | 100 |

**FIGURE 6 Remaining steel area (percent).**

| RATING DESCRIPTION | | | | |
|---|---|---|---|---|
| 7 NO CRACK | -0.17 | | | |
| 5 MODERATE CRACK | -0.30 | -0.51 | | |
| 4 ADVANCED CRACK | -0.41 | -0.47 | -0.38 | |
| 3 SEVERE CRACK | -0.54 | -0.35 | -0.51 | -0.58 |

**FIGURE 8 Corrosion potential (volts).**

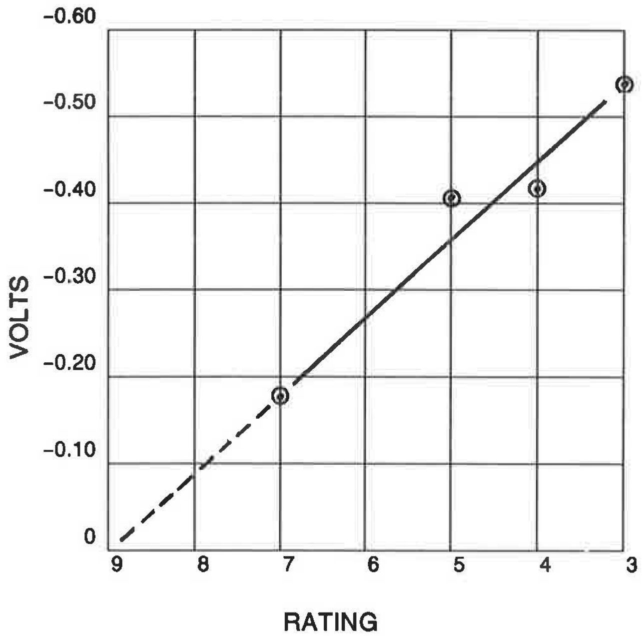


**FIGURE 9 Corrosion potential.**

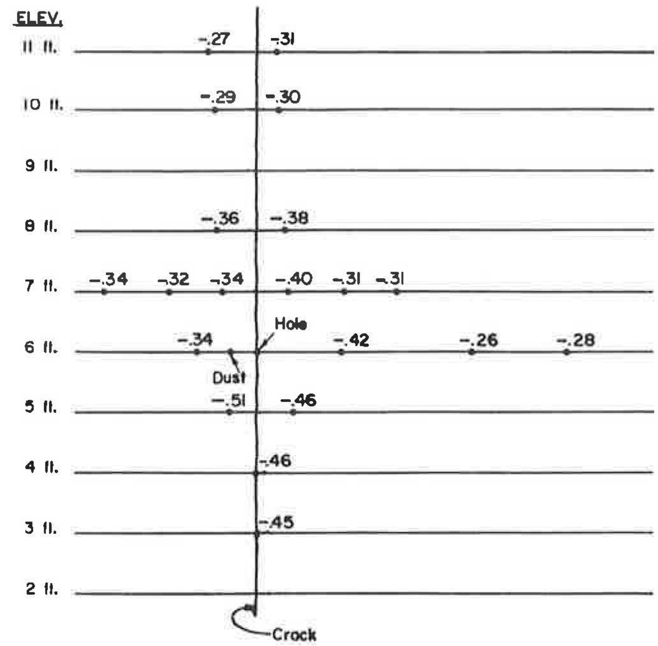


**FIGURE 10 Potential readings.**

reveals that the potential for corrosion increases at a rate of −0.09 volt per rating decrease.

Half-cell corrosion potential readings correlated with the rating of the crack tested. The prestressing strand with no associated crack had a low potential for corrosion, the moderate and advanced cracks tested had a moderate potential, and the severe cracks had a high potential for corrosion. The categories for corrosion potential are based on FHWA guidelines for bridge decks, which use the values of −0.35 and −0.50 volt as breakpoints to separate low, moderate, and high potential readings.

In addition to the maximum values, readings were also taken on the pile surface in the vicinity of the test site. The widest point along the crack with the lowest rating on any given pile was selected. The readings showed that the location of the absolute maximum value for corrosion potential was about 1 ft below the location chosen from a visual inspection of the surface.

The additional potential readings have been mapped. A typical map is shown in Figure 10. The information reveals that (a) potential readings are greatest in the vicinity of the test site, (b) potential reading values decrease with distance above and below the test site, and (c) no trend exists to predict reading horizontally around the pile, as might be expected, because strands are electrically insulated.

### Chloride Penetration Near the Concrete Surface

Figure 11 shows the data that resulted from the chemical analysis of dust samples, which shows a fair amount of scatter. Averages have been plotted in Figure 12. A correlation exists, however, between the crack severity and level of associated chloride ion content. After extensive data manipulation, the plot shown in the graph was developed. This plot passes to the right of the origin of the graph indicating that, near a

| RATING DESCRIPTION | | | | |
|---|---|---|---|---|
| 7 NO CRACK | 2.0 | | | |
| 5 MODERATE CRACK | 0.8 | 2.0 | | |
| 4 ADVANCED CRACK | 3.1 | 7.4 | 4.7 | |
| 3 SEVERE CRACK | 2.3 | 4.7 | 4.3 | 5.5 |

**FIGURE 11 Chloride content near surface (lb/yd$^3$).**

rating of 8 (good condition), the chloride concentration should be near zero. This offset implies that chloride intrusion is not immediate. The equation that describes the plot is

$$[Cl] = 0.9(9 - R) - 0.8 \quad (4)$$

where [Cl] is the chloride content near the concrete surface, in pounds per cubic yard.

Equation 4 indicates that the concentration of chloride ions increases at a rate of 0.9 lb/yd$^3$ per rating decrease.

The chloride ion content measured near the concrete surface was in the contaminated range for cracks rated 6 or less on the basis of the FHWA breakpoint of 2 lb/yd$^3$ for plain reinforced concrete bridge decks. It has been previously recommended that for prestressed-concrete beams, ". . . permissible water soluble chloride ion content . . . not exceed 0.10 percent by weight of portland cement" (*1*). This amount translates into a value of approximately 4 lb/yd$^3$.

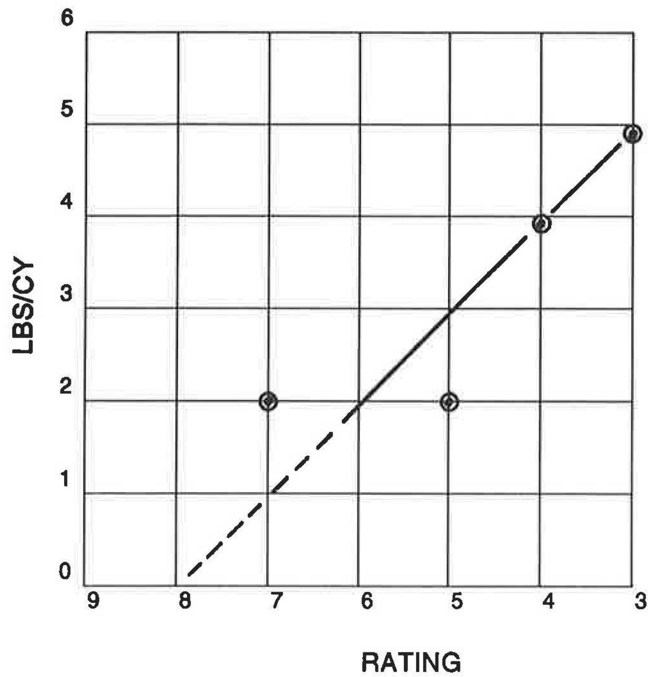


**FIGURE 12 Chloride content near surface.**

**Chloride Content at the Level of the Prestressing Strands**

Data from the chloride ion analysis of the dust samples collected at the level of the prestressing strand are shown in Figure 13. These data show that all values except one are extremely low. These values are, in fact, near the threshold of detection and are well below the level at which the concrete is considered contaminated with chlorides.

## FINDINGS OF THE BELOW-WATER CURSORY AND IN-DEPTH INSPECTIONS

Almost all of the pilings were in good condition below the waterline with only occasional minor and moderate cracking,

| RATING DESCRIPTION | | | | |
|---|---|---|---|---|
| 7 NO CRACK | <0.4 | | | |
| 5 MODERATE CRACK | 0.4 | 0.4 | | |
| 4 ADVANCED CRACK | 0.8 | 0.8 | 2.3 | |
| 3 SEVERE CRACK | 0.4 | <0.4 | 0.4 | 0.4 |

**FIGURE 13 Chloride content at depth of strand.**

in part because the piles were encrusted with heavy biological fouling up to 3-ft thick as shown in Figure 14. This biological fouling consists of barnacles, oysters, mussels, and coral. Figure 15 shows an underwater inspector cleaning a pile. Bands 1 ft high were cleaned around the circumference of the piles to look for damage. These bands were located at the waterline, mudline, and at two intermediate points. Typical underwater cracks can be seen in Figure 16.

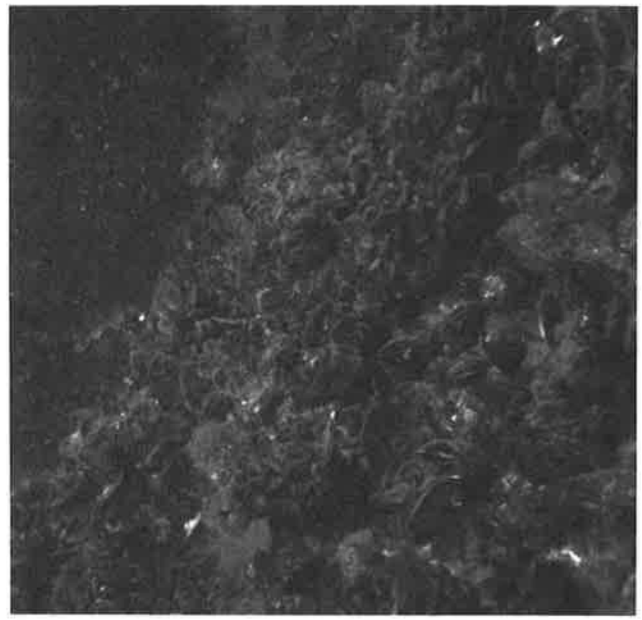

**FIGURE 14 Pile surface before scraping.**

**FIGURE 15 Underwater inspector cleaning pile.**

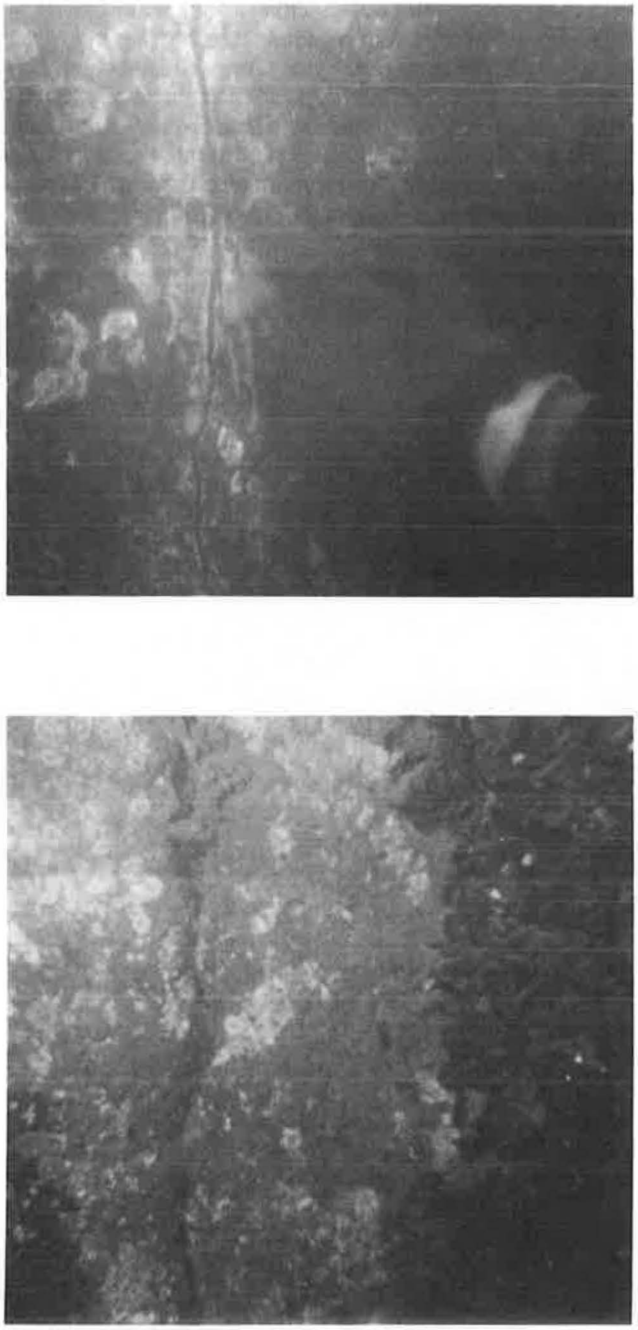

FIGURE 16 Two views of underwater cracks.

The bay bottom in the vicinity of each bent is overlaid with oyster beds—a process in which oysters, growing on the side of the pile, die and deposit their shells on the bottom, forming a mantle on which new oysters grow. This deposit protects the piles from abrasion by drifting sand.

A hydrographic survey was run parallel and perpendicular to the facility and showed the formation of a scour pocket beneath the approach trestle near one of the man-made islands. As shown in Figure 17, the scour pocket approaches 30 ft in depth and has compromised the structural integrity of the piling. This compromise occurs when scour lowers the bay bottom locally either to an elevation below the point of fixity

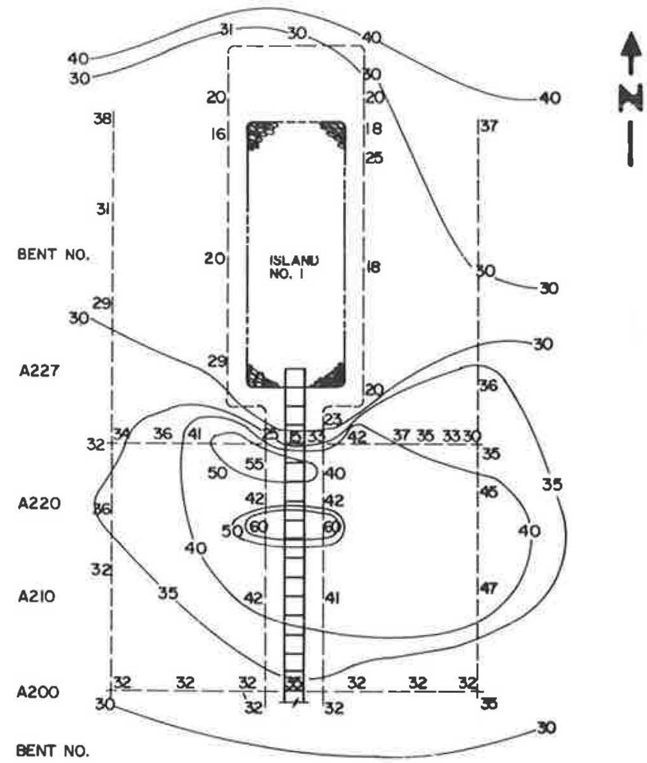


FIGURE 17 Contour map of first island vicinity (not to scale).

assumed in the design or to an elevation near the pile tip elevation.

## CONCLUSION

The Chesapeake Bay Bridge-Tunnel is in fair condition after 25 years of service in a marine environment.

The bent caps are wetted by rainwater because of the open deck slab expansion joints, which have been left open to help drainage. This wetting has resulted in moderate staining of the pier caps and in light efflorescence of the concrete surface by allowing aggressive agents to enter through the top of the cap, percolate through the concrete matrix, and leave through the bottom and side faces of the cap. This process weakens the concrete paste by removing soluble compounds. Future bridge projects should not allow open joints to continually wet the pier cap with salt-laden spray, contaminated rainwater, and road oils.

The results of the in-depth testing of the piles indicate that even though the potential for corrosion exists, chlorides have not penetrated the concrete cover to the level of the prestressing strands. Further, strands that are exposed in open cracks are not corroding, except for those exposed in the largest of the cracks. Chlorides do not penetrate the concrete cover because of the extremely dense concrete of strength 5,000 psi, which was cast in a spinning cylinder. In addition, strands exposed in open cracks may not have corroded because the vertical orientation of the crack allows water and corrosive agents to drain quickly. Therefore, the cracks are not the result of the expansive nature of corrosion byproducts. At and below the waterline, corrosion has not occurred because of the protection provided by the heavy marine growth. This protection also extends to the adjacent bay bottom area and guards the pile at the bottom line from abrasion of drifting sands. Future bridge projects using these piles should place an emphasis on protecting the above-water portions of the concrete surfaces.

The scour pocket, which exists near one of the four man-made islands, is the result of tidal currents that must now flow around the islands. This pocket has formed on the trestle side of each island because the piles create a restriction that increases the flow velocity. In addition, this side of the island is not extensively overlaid with riprap for the tunnel tube cover. This scour pocket has compromised the structural integrity of the piles in the vicinity by increasing the unsupported length. It has either attained depths below the point of fixity assumed in the design of the pile or attained depths near the pile tip elevation. Future bridge projects under similar conditions should try to minimize any obstacles to tidal flow.

## RECOMMENDATIONS

Although the joints on this type of superstructure are left open to increase drainage and neoprene bearing pads are provided, it is recommended that open bridge deck expansion joints not be used on a bridge subjected to large amounts of salt spray. Once the joints are sealed, a maintenance program should be established to ensure that the joints remain watertight.

Minor and moderate cracks require no remedial action at this time, because active corrosion is not the cause of cracking. However, it is recommended that these cracks be monitored during future inspection for any signs of progressive deterioration.

It is also recommended that advanced cracks be sealed by epoxy injection, because corrosion has yet to initiate. Such repair work is in progress.

It is recommended that piles with severe and serious cracks be replaced or rehabilitated with structural jackets. A structural jacket uses shear connectors embedded in the existing pile to transfer the pile load to the jacket for the length of the pile weakened by the crack. Corrosion has already initiated and the structural integrity of a 5-in. concrete shell has been compromised by these cracks.

Finally, it is recommended that the scour pocket that has formed near the man-made island be filled with riprap. This riprap should take the shape of a cone centered around the piles and slope away from each bent. This remedial work is now in progress.

## REFERENCE

1. D. Stark. *Determination of Permissible Chloride Levels in Prestressed Concrete*. Technical Report 3, Prestressed Concrete Institute, Chicago, Ill., June 1983.

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