Substructure Cathodic Protection in Ontario: Field Trials 1982 to 1986

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In 1981, the Ontario Ministry of Transportation and Communications initiated a research program aimed at developing an effective method of repair for bridge substructures. Cathodic protection was identified as the most promising repair method available, and the emphasis of the program was placed on field testing. Eleven experimental systems, at two sites, were designed, installed, and monitored over the period 1982 to 1986. The effectiveness of the corrosion protection offered to the embedded steel, the cost and ease of installation, and the durability of the components were evaluated for each system. Anode materials used included conductive paints, conductive polymer, carbon fibers, zinc ribbon anodes and flame-sprayed zinc, and anode meshes of conductive polymer and of titanium. Updated in this paper is information on the Burlington Bay Skyway test site given in earlier publications and also described are installations at the Leslie Street test site. Installation of the first permanent substructure cathodic protection system covering one complete pier of the Burlington Bay Skyway, carried out under contract in 1986, is also discussed.

In 1981, the Ontario Ministry of Transportation and Communications initiated a research program to develop an effective method for the permanent repair of bridge substructures. Cathodic protection, in combination with rehabilitation of deteriorated concrete, was selected as the most promising repair method for use, based largely on its successful use on bridge decks and the fact that it was the only repair method that would stop active corrosion. The major focus of the substructure program, carried out between 1982 and 1986, was the design, installation, and evaluation of 11 small-scale experimental systems on in-service structures.

The first four systems were installed on piers of the Burlington Bay Skyway in 1982. In 1983, four more experimental systems were installed on additional piers at the same site. Work began at the Leslie Street test site in 1984, when two installations were completed, and another system was added in 1985. The first permanent substructure cathodic protection system, covering one complete pier at the Burlington Skyway, was completed in 1986.

This paper updates information included in earlier publications, and emphasizes the durability and performance of the several systems evaluated. It also describes how the experience with the experimental systems influenced the selection and design of the permanent installation.

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BURLINGTON BAY SKYWAY TEST SITE

A summary of the main features of each of the eight experimental systems at this site is given in Table 1. Systems 1 to 4 were installed in 1982 and Systems 5 to 8 in 1983. The design, installation, and performance of the systems up to July 1984 have been described in detail in previous publications *(1, 2, 3)*. This section summarizes the most important findings from these installations and describes their performance until they ceased to operate, or until 1986, when those systems still operating were shut down because of extensive repairs being made to the bridge superstructure.

The main conclusion from the work at this site was that cathodic protection of bridge substructure components is feasible, using impressed current systems. The seven impressed current systems operated at current densities in the range of 10 to 15 mA/m^2 of concrete surface. Current pickup probes embedded at the level of the reinforcing steel indicated that better distribution of current was achieved in those systems with a mesh anode, or a continuous coating, than in those systems with discrete anodes. These probes also indicated that there was little spread of protective current to steel beyond the limits of the protection system. There was insufficient current output from the galvanic system to provide adequate protection to the embedded steel. Despite the effectiveness of several systems in stopping corrosion, there were concerns with the durability of many of the system components from the outset. The durability performance of the systems is discussed in greater detail in the following sections.

Systems with a Shotcrete Overcoat (Systems 1, 3, 4, 5, and 7)

As noted in the previous publications, debonding of the shotcrete from the underlying concrete proved to be a problem in all of the impressed current systems with shotcrete overcoats. In all cases, areas of debonding increased with time as the systems operated. Alligator cracking developed over the shotcrete surface. In Figure 1, the extent of debonding detected by sounding System 5 three years after installation is illustrated. When this system was sounded one month after installation, only one very small delamination was present. Figure 2, showing large pieces of shotcrete removed intact from System 3 in 1985, illustrates the lack of bond with the base concrete.

Systems 1 and 3, which had relatively poor current distribution, experienced substantial increases in anode-to-rebar resistance with time because of the breakdown of the connection

TABLE 1 SUMMARY OF ANODE SYSTEMS USED AT BURLINGTON TEST SITE

System	Primary Anodes	Secondary Anodes	Overcoat
1	Conductive polymer rods placed vertically at 450-mm spacing	–	Conventional shotcrete
2	Conductive polymer rods in three horizontal rings at 1.2-m spacing	Conductive paint 1	–
3	Conductive polymer rods Two on E and W faces, one on N and S faces	Carbon fiber N and E faces, pitch-based S and W faces, PAN-based	Conventional shotcrete
4[a]	Zinc ribbon placed vertically at 150-mm spacing	–	Shotcrete with added NaCl
5	Conductive polymer anode mesh	–	Conventional shotcrete
6	Conductive polymer rods—N and W faces Graphite rods—S and E faces	Conductive paint 2	Latex paint E and W faces
7	Conductive polymer rods—S and E faces Conductive polymer cast-in-situ—N and W faces	Carbon fiber, PAN-based	Conventional shotcrete
8	Platinized niobium wire embedded in conductive paste	Conductive paint 3	Latex paint and tie coat N face Latex paint E and W faces

[a]System 4 is a galvanic system; all others are impressed current systems.

FIGURE 1 System 5: The shaded area indicates the extent of debonding of the shotcrete overcoat 3½ yr after installation.

FIGURE 2 System 3: Removal of the shotcrete overcoat in 1985 is shown. The lack of bond between shotcrete and underlying concrete is indicated by the large piece of shotcrete removed intact. The carbon fiber secondary anode is visible.

between the lead wire and the anode. These connections were particularly vulnerable to corrosion, and repair was not practical as the connections were embedded in the shotcrete overcoat. An attempt was made to avoid the problem the following year in Systems 6 and 7, by using commercial, precast, polymer anodes that had the connection embedded within the anode. However, cracking of the anode material allowed moisture to penetrate to the connection and corrosion to occur. It was concluded that it would be most advantageous to maintain the anode-to-lead-wire connection outside the shotcrete in a junction box, where it would be accessible.

Systems 5 and 7, with conductive polymer mesh and carbon fiber mesh systems, respectively, continued to operate long after the extent of shotcrete debonding became unacceptable. Cores removed from System 5 indicated that the anode material remained in good condition.

The debonding that developed in the impressed current systems did not occur in the galvanic system (System 4), where current density was approximately one tenth that of the impressed current systems. To determine if the debonding of the shotcrete was directly related to current density, the north and east faces of System 4 were connected to a rectifier and powered at approximately double the current density of the impressed current systems. No delaminations were present on those faces at the time power was first applied. After 7 months of operation, six separate areas of debonding totalling less than 2 m^2 were present on the two faces. The south and west faces continued to operate as a galvanic system and no debonding

occurred during the same period. Because of extensive repairs to the bridge superstructure, it was necessary to interrupt the power supply in the spring of 1986, and therefore it was not possible to continue applying power to the north and east faces in order to provide more conclusive results. Although the experience with System 4 would indicate that current flow has contributed to debonding, it is interesting to note that in Systems 1, 3, and 7, where discrete primary anodes were employed, the areas of delamination did not appear to correspond to the position of the anodes, which is where they might have been anticipated because of higher current densities occurring near the anodes.

In view of the uncertainty surrounding the cause of the debonding, together with the relatively high unit costs for small quantities of shotcrete and concern for its appearance, a decision was made in 1983 to concentrate future efforts on testing of systems using exposed anodes or thin mortar coatings rather than anodes that required a shotcrete overcoat.

Conductive Paint Systems (Systems 2, 6, and 8)

By mid 1986, paint had been almost entirely removed from the surfaces of Systems 2 and 8 by weathering, to the extent that both systems had effectively failed. The extent of the degradation of System 8, three years after installation, is shown in Figure 3. The materials were not sufficiently durable to withstand the harsh climate and the exposure to salt-laden run-off, which are typical of the Ontario highway environment.

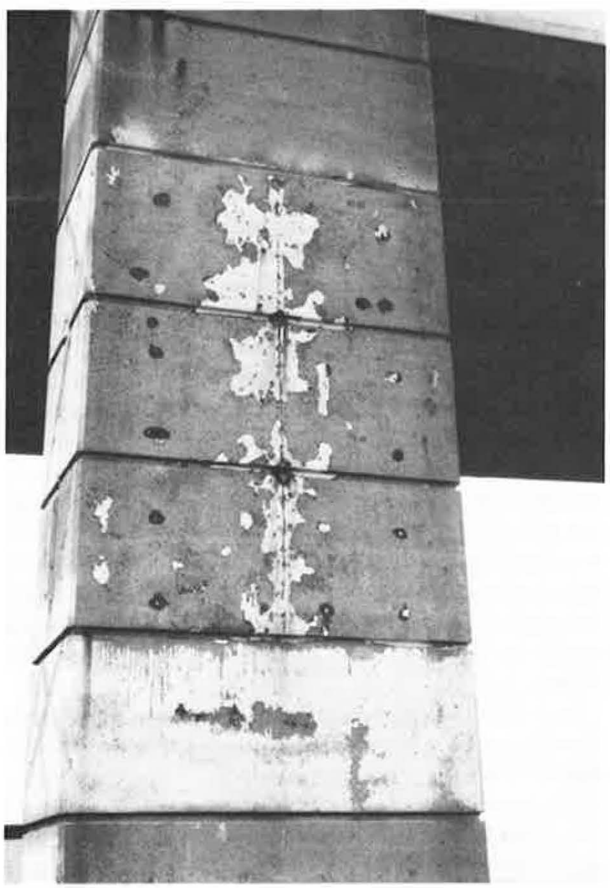

FIGURE 3 System 8: Three years after installation, almost all traces of the conductive paint anode with its white latex overcoat have been removed by weathering.

Based on the promising performance of the paint used in System 6 after 2 years of exposure, it was selected for further field testing. When powered by graphite primary anodes, this system presented obvious advantages in terms of its relatively low cost, ease of installation, and accessibility of components for repair. Three years after installation it displayed some minor damage as scattered flaking of the paint occurred in areas both with and without protective overcoats.

Other Findings

An important aspect of the early work at Burlington was the appreciation gained for the practical problems encountered in substructure protection, in terms of materials selection and handling, installation, and the monitoring of operating systems. When work was initiated at the site, the marketplace had little to offer in terms of packaged anode systems suitable for bridge substructure installations or instrumentation for corrosion measurements. Many of the products in the eight systems were installed before their introduction to the marketplace and thus the installation and operating characteristics provided valuable experience for both the manufacturer and the Ministry. From the Ministry's point of view, the work at the Burlington Bay Skyway test site also provided a basis for the judgment used to assess other new systems and materials as they became available.

The wide range of instrumentation used at Burlington to determine the effectiveness of the several systems, which has been described elsewhere *(4)*, was not repeated in subsequent installations. Consequently, an important product of the installations in 1982 and 1983 was the identification of instrumentation that was suitable for evaluating other systems. Permanently embedded carbon reference cells and rebar pickup probes have proven to be an economical and reliable means of assessing the effectiveness of cathodic protection systems. Information from these can be augmented by periodic surface potential surveys, where appropriate. The long-term monitoring of system operating characteristics such as voltage, current, and anode-to-ground resistance provides a data base from which normal system behavior can be defined, enabling deviations from the norm to be detected and corrected.

Finally, the work at the Burlington test site provided the impetus and confidence to progress toward the goal of full-scale, permanent installations of cathodic protection on bridge substructures through contracts awarded by conventional competitive-bidding procedures.

LESLIE STREET TEST SITE

The major disadvantage of the Burlington Bay Skyway test site was that the massive piers of the structure were not typical of most of Ontario's highway bridges. This fact, combined with the difficult access to the site during the period 1984 to 1985 resulting from the twinning of the facility, led to the development of a second test site at Leslie Street.

The site, which is shown in Figure 4, consists of several bridges carrying a freeway over a major urban, arterial road-

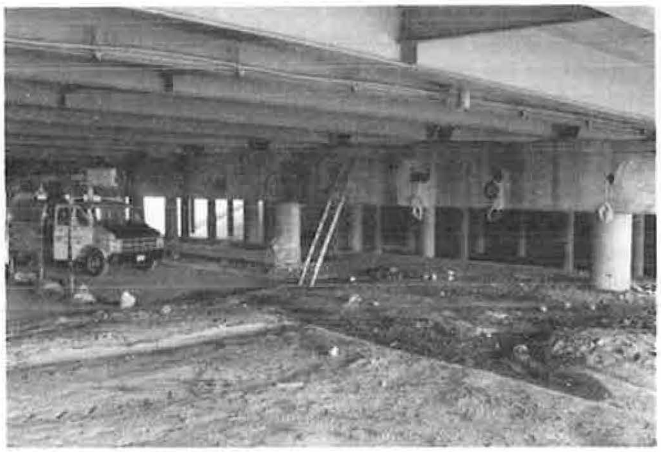

FIGURE 4 Leslie Street test site: One of the pier bents is shown, with instrumentation in place, before application of the conductive paint overcoat.

way. It was selected because the spirally reinforced columns and cap beams making up the pier bents are representative of many in Ontario, and access was convenient. In contrast to the Burlington site, the piers were sheltered from weathering. Like those at Burlington, however, they were subjected to surface run-off through leaking deck joints and exhibited active corrosion potentials and corrosion-induced damage.

Two conductive coating systems, a conductive paint and flame-sprayed zinc, were installed on pier bents 160 m^2 and 110 m^2, respectively, at the Leslie Street site in 1984. A proprietary mesh anode system was installed in 1985. Details of these installations and their performance are given in the following sections.

1984 Installations

Before the installation of either system, the pier bents were repaired using conventional concrete patching procedures. After curing the patches, the entire surface of the pier bents was sandblasted. Any exposed metal was removed or insulated by coating with epoxy.

The conductive paint used was the same as System 6 at Burlington and was chosen on the basis of its good performance since its installation in 1983. By 1984 the product was available commercially. The conductive paint was applied by brush and roller to achieve an average thickness of approximately 0.30 mm. Power was supplied to the paint through widely-spaced graphite primary anodes mounted on the concrete surface.

The flame-sprayed zinc anode was selected for testing on the basis of favorable reports from the California Department of Transportation, which had used this metallizing technique for cathodic protection of a bridge pier in 1983 *(5)*. The zinc was applied by using standard commercial metallizing equipment, and eight passes of the spray gun were necessary to obtain a thickness of approximately 0.20 mm over all surfaces of the pier. Although the zinc was relatively inexpensive, the application process was labor intensive and slow, both because of the physical limitations of the site, and the delivery rate of the equipment used. Scaffolding was required and the low headroom restricted movement. Power was supplied to the zinc anode by connection of lead wires to steel plates anchored on the concrete surface, and coated by the zinc.

When the systems were activated in the fall of 1984, the very low circuit resistance indicated that short circuits were occurring between the zinc anode and the underlying steel. Locating the points of contact between the two proved difficult. A pachometer was useful in locating a number of tie wires just beneath the surface, but removal of these did not increase the low resistance between anode and ground. A current was supplied to the system and a thermographic camera was used to scan the surface for indications of hot spots where current passed from anode to steel through a very small contact area. This was, however, also unsuccessful. By dividing the bent into progressively smaller zones (by cutting through the continuous zinc coating), it was determined that the shorts were confined to the columns of the bent that had scattered, deep bugholes. These bugholes brought the anode into close proximity with the steel (typically tie wires or localized areas of shallow cover). This steel was not recognized as potentially troublesome in the original pachometer survey because the cover from the concrete surface, as opposed to the bottom of the bughole, was adequate. It is interesting that this problem did not arise with the conductive paint, which did not penetrate to the bottom of the bugholes.

The zinc was removed from the columns by sandblasting, and the remaining portion of the anode was powered in the normal way. The experience indicated that it would have been better to install the system by dividing the bent into several zones so that problem areas could have been identified more easily. It also indicated that it might be worthwhile to investigate the feasibility of spraying the entire component with a thin coat of relatively high resistance material (e.g., portland cement mortar) before applying the anode.

Once the initial problems were overcome, the zinc system performed well, with good current distribution and polarization of the steel. The zinc anode is well bonded to the concrete and there has been no visual evidence of consumption of the zinc at the power supply points or elsewhere. The resistance between the surface anode and ground has increased very slightly with time, and experiences only minor fluctuation in response to changes in temperature. Except for a slight white staining of areas that are frequently wetted, there has been no change in color, and the dull gray appearance of the pier bent means that the cathodic protection installation is very unobtrusive. The major disadvantage was the tedious application process. Additional data on long-term performance is required to determine whether the selection of 0.20 mm coating thickness is the optimum.

The conductive paint anode began to show visible deterioration within a few months of installation as small areas of paint debonded from the concrete. Initially the areas of deterioration did not appear to be directly related to the exposure conditions or the chloride content of the concrete. In view of the experience at Burlington it was decided to investigate whether current density was contributing to the damage. Accordingly, the system was divided into two zones. One zone was operated at a slightly increased current density while the other zone was switched off. During the next year of operation in this config-

uration, the deterioration continued to increase with no significant difference between the two zones, indicating that current density was not the major factor in the debonding. However, as time passed, the paint in those areas subject to the greatest amount of leakage and weathering deteriorated more rapidly, as illustrated in Figure 5. It is not clear whether the initial debonding of the paint and the long-term deterioration are interrelated, or result from different mechanisms.

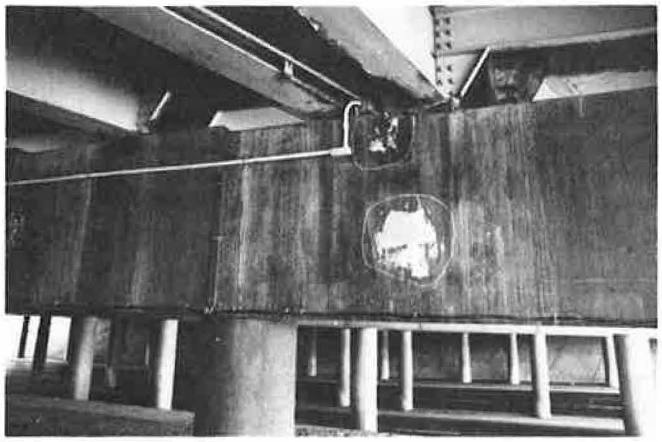

FIGURE 5 Leslie Street test site: Deterioration of the condition of the conductive paint anode in June 1985 is shown (approximately 10 months after installation). Surface areas subject to leakage from the deck above are visibly stained.

It has not been possible to identify any differences in material composition or method of application between the paints used at the Leslie Street and the Burlington sites. The marked difference in performance appears to be due to different moisture conditions in the concrete environment, and this aspect is the subject of further investigation. In view of the unsatisfactory performance of the paint at Leslie Street, criteria for site selection and the condition of the concrete at the time of application of the paint need to be developed before proceeding with further installations.

Both systems installed at the Leslie Street site continue to operate and are monitored seasonally.

1985 Installation

In 1985, a total of 8 m^2 of a new proprietary anode material was installed on two columns at the Leslie Street site. The anode consisted of an expanded mesh of titanium and mixed metal oxides. The mesh was attached to the column using plastic anchors and covered with a 5-mm thickness of a commercially available, acrylic-modified cementitious mortar. The mortar was applied by low pressure spray. The anode was selected for installation because the close mesh spacing was expected to result in good current distribution; the redundancy of current paths was a desirable feature and it was the only mesh anode available that did not require a shotcrete overcoat because the anode is thin and is mounted close to the current surface. The anode and overcoat were easy to install and the appearance of the completed installation was satisfactory.

One of the columns was powered, and the other column, which was identical to the powered column, served as a control to assist in identifying current-related effects. Control sections were not constructed at Burlington or at Leslie Street in 1984, with the result that modifications to the experimental design had to be made to try and identify the causes of debonding of the shotcrete and the conductive paint. The construction of unpowered control sections is strongly recommended in any experimental program similar to the one described here.

After 18 months of operation, no debonding of the overcoat material had occurred on either the powered or unpowered columns. Adequate protection to the reinforcing steel was found to be provided at current densities less than 10 mA/m^2 of concrete surface. However, the operating voltage increased fivefold during the 18-month period because of a gradual increase in the resistance between the anode and the reinforcing steel. This increase in resistance did not occur in the control section. If the circuit resistance continues to increase, this may jeopardize the long-term performance of the system, although the performance to date has been satisfactory. Monitoring of the system's operative characteristics will continue. It should be noted that the increase in resistance would not be as significant in a larger installation as in this small one, as the initial anode-to-ground resistance in a large system would be much lower.

BURLINGTON BAY SKYWAY PERMANENT INSTALLATION

In the fall of 1986, the first substructure cathodic protection contract in Ontario was completed. The contract consisted of cathodically protecting the entire 330 m^2 surface of a pier bent of the Burlington Bay Skyway. The site was chosen because major rehabilitation of all the piers of the structure will be undertaken in the near future. It was recognized that the experience gained in a pilot contract would be useful in selecting the method of rehabilitation, preparing contract documents, and establishing reliable costs. The design was carried out in-house, contract documents were prepared, and the work was competitively bid by contractors experienced in bridge repairs but not in the installation of cathodic protection.

All delaminated concrete was removed, shotcrete was used to repair the pier, and all the concrete surfaces were sandblasted before applying the cathodic protection. The particular system chosen was the same as that installed at the Leslie Street site in 1985. The decision was based on the ease of installation and the good operating characteristics of the anode material. The overcoat material was also the same as that used at Leslie Street.

The mesh anode was anchored in place with insulating fasteners. Figure 6 shows a roll of anode material being attached to the concrete surface. The anode material, which was designed for a lower current density than that installed the previous year, was flexible and tended to curl and stretch at the edges. This meant additional anchors were required to secure the anode tightly against the concrete, and the thickness of the overcoat was increased to cover the mesh. Both these items increased the cost of the installation considerably.

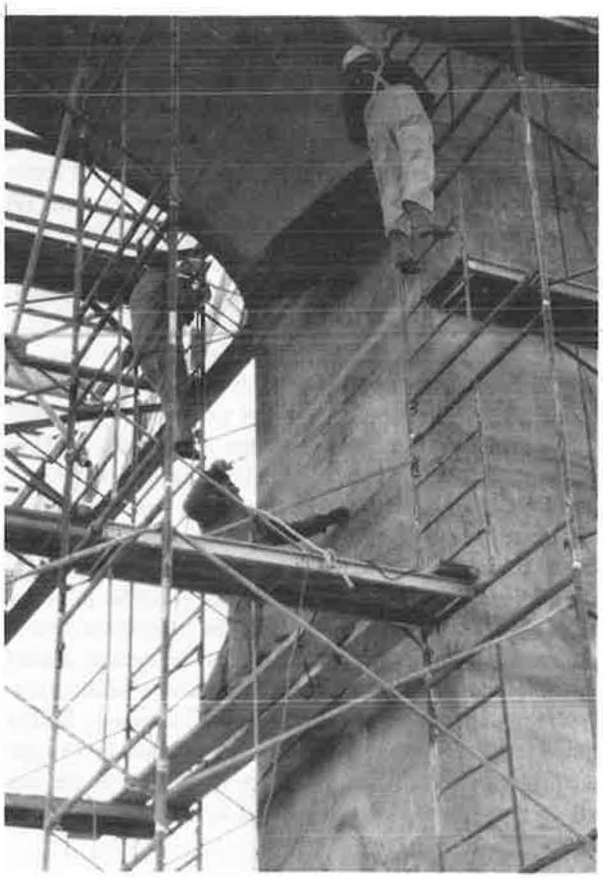

FIGURE 6 Pier S16, Burlington Bay Skyway: Attachment of the anode mesh (supplied in rolls 1.2 m wide x 61 m long) to the concrete surface.

Following the experience gained in the experimental installations, the system was designed so that the current supply wires and the connections to the anodes were outside the concrete. The wires were protected by polyvinyl chloride (PVC) conduit and the connections were made in junction boxes. Embedded instrumentation consisted of carbon reference cells with one cell for approximately each 18 m^2 of concrete surface. The rectifier specified was capable of constant current or voltage output, or could be programmed to maintain a constant potential on one of the reference cells. The system was divided into 10 anode zones, providing the capacity to control current flow to various areas of the structure. The completed installation is shown in Figure 7.

Quality control checks during construction included verification of the proper functioning of reference cells as they were placed, determination of the continuity of the reinforcing steel by connection to a number of locations on the rebar network, and monitoring of the resistance between anode and ground as the overcoat was placed to ensure that the two were not inadvertently shorted.

The total cost of the work (including repairs to the concrete, installation of the cathodic protection system and instrumentation, and provision of power to the system) was (Canadian) \$441.00/m^2 of concrete surface area. Repairs alone accounted for \$168/m^2, with \$273/m^2 associated with application of the cathodic protection system. A breakdown of costs is given in

FIGURE 7 Pier S16, Burlington Bay Skyway: The pier is shown after installation of the anode system and overcoat. Surface-mounted conduit carried current supply wires to the anode.

Table 2. Concrete repair costs were high because of the large amount of deteriorated concrete that had to be removed from the soffit and replaced. It should be noted that costs associated with access to the surface of the structure are included in the figures shown. Because of the 12 m height of the pier bent, the cost of access was considerable, as scaffolding had to be erected around the pier and remained in place until all surface work was completed. As the costs reported for this work cannot be considered typical because of the large amount of concrete removal and the difficulty of access, it must be recognized that the unit costs for substructure repairs will be several times the cost of similar repairs on bridge decks.

In addition to the difficulties associated with the flexible anode mesh, other difficulties encountered during construction were underestimation of the amount of concrete to be removed, and the cold weather experienced during application of the overcoat. The amount of overhead repair work necessitated a change from the formed patches specified, to shotcrete. This experience emphasizes the need for a thorough condition survey of a structure before repair, even though such a survey might be difficult and expensive.

The cold weather in the late fall necessitated construction and heating of a plastic enclosure around the pier to maintain a

TABLE 2 COSTS ASSOCIATED WITH INSTALLATION OF CATHODIC PROTECTION ON PIER S16, BURLINGTON BAY SKYWAY

Items	Cost (Can.) (\$/m)^2
Concrete removal	104
Shotcrete repairs	64
Surface preparation	20
Embedded electrical hardware	44
Anode materials and hardware	59
Anode installation	44
Overcoat	49
Power supply	42
Housing and heating	15
Total	441

temperature of at least 10°C during application and curing of the overcoat. This did not appear to affect the quality of the overcoat material adversely, and it was found to be well bonded to the concrete when sounded after application.

On the positive side, the contract specifications prepared were found to be workable and with minor modifications will form the basis for preparing a standard specification for future substructure contracts. Guidelines for monitoring and controlling the system will also be prepared, as a companion to the existing guide for monitoring of bridge deck cathodic protection systems provided to the Ministry's electrical inspectors.

The system was activated in early 1987. The installation is being used as a pilot project to evaluate the feasibility of using remote monitoring, via telephone, to supplement and possibly replace routine on-site monitoring. The initial anode-to-rebar resistance for the system of approximately one ohm provides assurance that, should there be an increase similar to that which occurred in the same system at Leslie Street, the resistance would still be relatively low and the system would continue to operate within the capacity of the power source.

CONCLUDING REMARKS

Summarized in this paper are the sequence of research activities and the experience gained through the installation of 11 experimental installations and 1 permanent installation of cathodic protection as they relate to achieving the primary goal of the research program of developing methods for the repair of bridge substructure components. A secondary overall goal of the Ministry is to execute the work by concrete rehabilitation contractors, though not necessarily specialists in cathodic protection, under competitive bidding procedures.

The initial work at the Burlington Bay Skyway test site succeeded in demonstrating the feasibility of using impressed current cathodic protection for substructure repair. It also identified desirable attributes of cathodic protection systems and suitable instrumentation, and provided the impetus for further testing. This testing was undertaken at the Leslie Street test site and led to the identification of better systems and the refinement of design procedures, with the result that it was possible to undertake the major repair contract in 1986. This contract demonstrated the feasibility of administering a contract for substructure cathodic protection with a non-specialist contractor and without serious problems in contract preparation, award, or quality assurance. As a result of the field trials during the period 1982 to 1986, further contracts for substructure cathodic protection can now be undertaken.

An important aspect of the work has been the identification of the high cost of substructure repair. The overwhelming effort required to deal with bridge deck repairs has overshadowed the need to address problems associated with substructure deterioration. However, it is known that many jurisdictions face serious problems. Not only is substructure repair technically more challenging than deck repair, because replacement is rarely an option, but there is a greater challenge to ensure that the funding that will be required for substructure repairs over the next two decades will be available when it is needed.

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