Decision Criteria for the Rehabilitation of Concrete Bridge Decks

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A systematic approach to bridge-deck rehabilitation is presented. Bridge-deck rehabilitation is consuming an increasing proportion of the resources of highway agencies. The nature and extent of deterioration are highly variable so that there is neither a single problem nor a single solution. The requirements for a condition survey are described. The performance of concrete overlays, waterproofing membranes, and cathodic protection applied to existing structures is assessed from field studies and the literature. Decision criteria that can be used to identify the most appropriate method of rehabilitation for any particular structure are given.

An increasing emphasis is being placed on the maintenance and rehabilitation of bridges. Now that fewer changes are being made in the highway network, many structures that were once replaced as part of improvements in highway alignment must be kept in service. Deterioration is especially serious in bridge decks in areas of North America where deicing chemicals are used in winter maintenance operations. The salt penetrates the concrete and initiates corrosion of the steel reinforcement. This in turn causes cracking and rupturing of the concrete and spalling of the concrete surface. In addition, some older bridge decks, built to lower standards of quality than modern structures and constructed without the benefit of efficient waterproofing systems and air entrainment, suffer a more deep-seated distress as the concrete progressively disintegrates from the surface downward under freeze-thaw action.

A major consideration that complicates the development of a policy for bridge-deck rehabilitation is the variability in the condition of the structural concrete, the reinforcing steel, and, more recently, the prestressing systems in structures und he jurisdiction of a single authority. Such variability is inevitable because the condition of the deck slab is affected by many factors, the most important of which are age, the standards in use at the time of construction, the quality of the materials and workmanship, the type of design, and the service environment. Since it is clear that no single problem of bridge-deck durability exists, it is also apparent that there is no single solution for the rehabilitation of all concrete deck slabs. What is needed is a systematic approach that includes the identification of the deterioration on a particular structure and the development of decision criteria that will lead to the selection of the most cost-effective solution for that structure.

CONDITION SURVEYS

A condition survey of a bridge deck may be required for either of two reasons: (a) to establish repair priorities on a statewide scale or (b) to provide details of the nature and extent of concrete deterioration needed for design and execution of the restoration work. The work required to determine repair priorities can be described as a general survey, and the more comprehensive inspection prior to the design of the restoration work is called a detailed condition survey.

The objective of the general survey is to obtain an overall rating of the deck slab so that, where necessary, it can be programmed for future restoration. Deck slabs that have an exposed concrete surface can be rated relatively straightforwardly, and measurements of concrete cover, half-cell potentials of the reinforcing bars, areas of temporary patches and delaminations, and the presence of significant cracks and scaled areas on a sample area of the concrete surface provide adequate information in most cases.

The presence of an asphalt wearing surface on a bridge deck, which is the case with the majority of structures in Ontario, makes it difficult to determine the overall condition of the concrete slab. Some asphalt-covered deck slabs date back to the 1920s, and their condition is highly variable (1). When deterioration is more advanced, it is sometimes obvious from a visual examination of the deck, and the rehabilitation work can be programmed without a general survey. In most cases, however, it will be necessary to take core samples and remove small sections of the asphalt overlay to determine the condition of the concrete.

Some general criteria can also be established that will assist in determining whether deterioration is likely and whether a general survey of the structure is required. The age of the structure is a key indicator of its condition. Cracking and repairs to the asphalt or leakage, wet spots, or cracks on the underside of the deck slab are useful clues to the condition of the concrete in the deck. Severe deterioration of exposed areas, such as sidewalks, curbs, and handrail posts, may also indicate deterioration in the deck slab.

Detailed condition surveys are carried out when the structure has been programmed for rehabilitation and it is necessary to select the method of repair and prepare the contract documents. Although guidelines and the general scope of the survey can be prepared in advance, the details of the work must be determined by the engineer on site. Existing information on the condition of the deck slab is considered, and additional information is obtained as the work proceeds. For example, if it is clear that the deck must be replaced, as in the case of an older deck that exhibits widespread cracking as the result of alkali-aggregate reactivity, then little or no testing is required. If it is not clear whether the deck slab can be effectively rehabilitated or must be replaced, a very detailed survey may be needed.

In the detailed survey, as in the general survey, asphalt-covered decks are more difficult to evaluate than decks with an exposed concrete surface, and consequently the cost of the detailed survey will be greater and the reliability of the data lower.

In most cases, the detailed condition survey will include the following:

1. If there is a bituminous overlay, its condition and its thickness are determined and significant cracks in the wearing surface are recorded.
2. If there is a waterproofing membrane, its condition is appraised and it is identified by type.
3. Patched and open spalled areas, delaminated concrete, scaled areas, and significant cracks on exposed concrete deck surfaces are recorded and measured.
4. Concrete cover to the top layer of reinforcing steel is surveyed. On asphalt-covered decks, cover can only be measured where sections of

the asphalt overlay are removed.

5. The corrosion activity of the top layer of reinforcing steel is determined by measuring half-cell potentials. Holes are drilled through the bituminous overlay to the deck surface to ensure a good electrical contact.

6. The general condition of the concrete slab is determined by coring and removing sections of asphalt overlay.

7. Tests are performed on concrete core samples to determine chloride content, air void system, and, occasionally, compressive strength.

8. The underside of the deck slab is inspected, and deteriorated concrete, wet areas, efflorescence, significant cracks, corrosion spalling, and other defects are identified.

9. Deck drains are inspected, and their condition, position, and adequacy are determined.

10. Curbs, sidewalks, barrier walls, handrails, and other components of the structure above the riding surface are inspected.

11. The condition, type, and measurement of expansion and fixed-joint assemblies and special features needed for future reconstruction are identified.

12. Other parts of the structure that should be repaired as part of the contract for rehabilitation of the deck are identified.

13. A comprehensive report is produced that documents in detail the condition of the deck slab and its components. The report contains plans, core logs, photographs, tables, and test data.

The test methods, the number of samples required, and the sequence of operations are discussed in detail elsewhere (2).

OPTIONS FOR REPAIR

Many methods of bridge-deck rehabilitation have been proposed and investigated. This paper discusses the application of the three methods of rehabilitation that are currently used in Ontario when major rehabilitation of either an exposed-concrete or asphalt-covered deck slab is required. These three methods are (a) patching, followed by waterproofing and paving; (b) application of a concrete overlay; and (c) cathodic protection. Temporary repairs such as local patching or epoxy injection are not discussed.

It is not our intention to describe in detail the construction procedures involved in each method, since these are well documented elsewhere (2-4). However, the essential processes of each method can be described as follows:

1. The patching, waterproofing, and paving method consists of saw-cutting around areas of delaminated and spalled concrete, removing all unsound concrete, patching [usually with portland cement concrete (PCC)], and applying a waterproofing membrane, a protective layer, and a bituminous wearing course. There are many waterproofing systems available, but those that have proved most satisfactory all require application of a protection board and bituminous concrete (5).

2. In the placing of a concrete overlay, the entire deck surface is scarified, all delaminated and unsound concrete is removed, and a bonding layer is applied. This is followed by an overlay, which may consist of high-quality conventional PCC or a latex-modified concrete.

3. The type of cathodic protection system used in Ontario (4) is installed by placing concrete patches in exactly the same manner as if the deck were to be waterproofed, placing anodes in the deck surface, and applying an electrically conductive bituminous mixture and a conventional bituminous wearing course. Power in the form of a low-voltage direct current is supplied to the anodes from an alternating-current rectifier.

When the basic problem on a bridge deck is corrosion of the reinforcing bars and shallow surface spalling, one of the most difficult decisions to make is how much concrete must be removed as part of the repair contract. The chloride ion concentration in most bridge decks that are in need of repair exceeds the threshold value sufficiently to initiate corrosion of the reinforcing steel. The threshold value is commonly accepted to be 0.15 percent of the soluble chloride by mass of cement content of the concrete (6). Under these circumstances, unless cathodic protection is to be applied, the only way to ensure that corrosion does not continue is to remove all concrete that contains chlorides in excess of the threshold value and then prevent further applications of deicing salts from gaining access to the reinforcing steel (7,8). Most of the chloride-contaminated concrete is, however, usually physically sound, so that its removal is not only tedious but also very expensive, almost as expensive as replacing the deck. Deck replacement (except when it is required for structural reasons) or the removal of all chloride-contaminated concrete is beyond the financial capability of most highway authorities. Consequently, many authorities believe that it is more economical not to remove chloride-contaminated concrete that is otherwise sound and to accept the resulting uncertainty about the future life of the deck slab. This practice, which is referred to as "experimental cost-effective reconstruction", is common in both the United States (9) and Canada (3).

PERFORMANCE OF REHABILITATION METHODS

The effect of waterproofing or of a concrete overlay on the continuing corrosion activity in a bridge deck is not well documented, yet the ability to predict the future life of the deck slab is an essential ingredient in the technical and financial analysis that must be undertaken to select the most appropriate repair method. Data on which to base investment decisions are lacking, not only because major deck rehabilitation is a relatively new phenomenon but also because many methods have only been in use for a few years and satisfactory tools for measuring the performance of rehabilitation techniques have generally not been available. The use of the half-cell method of measuring the corrosion activity of the reinforcing steel in a concrete bridge deck was first reported in 1973 (10) and formalized as a standard test method in 1977 (11). Only recently have highway agencies initiated systematic surveys to document the condition of decks before repair and to monitor their performance after repair. Few results have yet been published because of the number of years required to establish meaningful trends.

Concrete Overlays

The first low-slump concrete overlay in Ontario was placed in May 1976 and has been monitored regularly. The results of the annual half-cell surveys are shown in Figure 1. The results are presented in the form of cumulative frequency distribution curves, a convenient method of

Figure 1. Corrosion potentials at Interchange 4, Ontario 401.

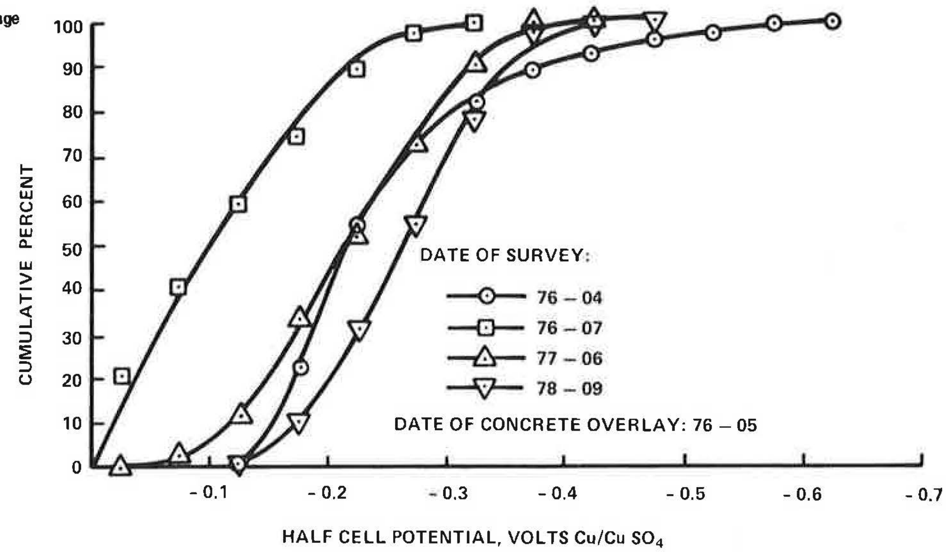
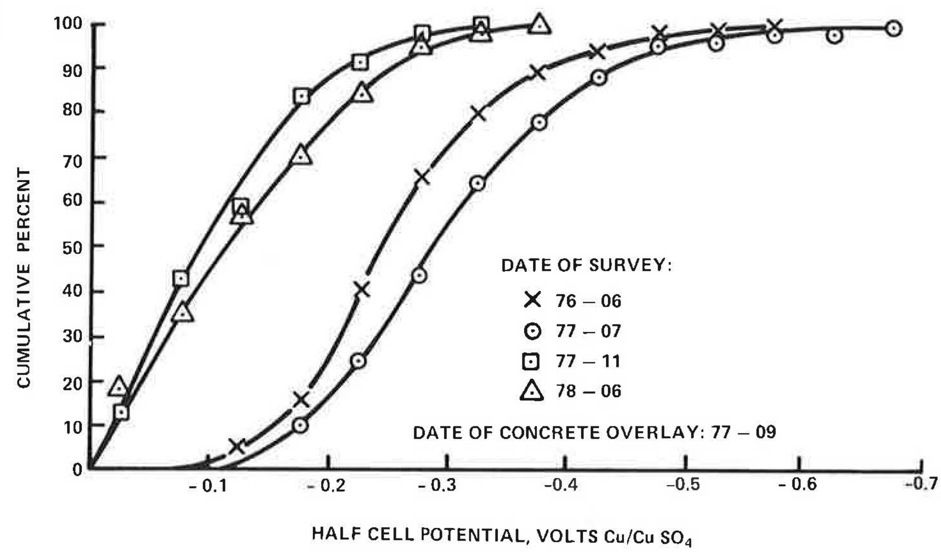


Figure 2. Corrosion potentials at Englehart River Bridge, Ontario 66.



observing changes in corrosion activity between surveys. A shift of the curve to the left indicates a reduction in corrosion activity, and a shift to the right indicates the opposite.

The significant reduction in corrosion activity immediately after application of a concrete overlay has been reported elsewhere (3). This occurs because concrete is removed from around the bars that exhibit the greatest corrosion activity. Delaminations are usually associated with a half-cell potential of more (negative) than -0.50 V and, in the course of removing delaminated concrete, it is often necessary to remove the concrete from around the exposed bars. When the concrete overlay is placed, these exposed bars are covered by the mortar bonding grout and are surrounded by chloride-free concrete so that corrosion activity is suppressed in these areas. Later measurements have shown that the initial reduction in corrosion activity has not been sustained and the overall level of activity has gradually increased.

Although Figure 1 shows the curve for the 1978 survey to be to the right of the curve representing the original deck survey, the area of the deck that exhibits active corrosion (more negative than -0.35 V) is less than it was before the overlay was applied, and the highest potential recorded is much less.

The results of half-cell surveys on a badly deteriorated deck to which a low-slump concrete overlay was applied in 1977 are shown in Figure 2. Two surveys made prior to overlay are shown, and the measurements demonstrate the significant increase in corrosion activity that occurred between 1976 and 1977. Figure 2, like Figure 1, shows a sharp reduction in corrosion activity after construction of the overlay, but in Figure 2 the increase in corrosion in the second year is only slight. Because the deck represented in Figure 2 was considerably more deteriorated than that represented in Figure 1, a greater portion of the reinforcing steel was surrounded by new concrete, and this may account for the slower rate of increase in corrosion activity.

Other decks that have been given either a low-slump or a latex-modified concrete overlay have been monitored and found to exhibit trends similar to those shown in Figures 1 and 2, which can be considered to represent the range of the conditions recorded. Other authorities have reported a similar initial reduction in corrosion activity beneath low-slump concrete overlays (12,13) and latex-modified concrete overlays (14,15), but this has not always been the case. On some structures, corrosion activity has continued (16) or increased (12) after placement of a latex-modified concrete overlay. The wider variation in the results for latex-modified concrete overlays probably results from the fact that the deck must be wet down before the latex-modified bonding grout is applied. Rapid rust formation takes place when exposed reinforcing bars, which have been sandblasted, are wet down, and this may mask the overall change in the corrosion activity of the reinforcing steel.

Although half-cell potentials are a valid measure of the presence of corrosion activity in a bridge deck, they do not indicate the rate of corrosion, which is determined primarily by the availability of oxygen and moisture at the cathode and the structure and formation of the corrosion products at the anode. It is possible to have a high reading for corrosion potential but a very low rate of corrosion so that physical distress may not occur for many years. In the same way, rapid corrosion rates may be associated with lower, but active, potential readings. Corrosion potentials are thus a useful indication of performance, but the deciding factor will always be actual service life in the field.

Concrete overlays have been used for as long as 15 years in many jurisdictions, including British Columbia (17), and by several state highway departments. A report published by the Iowa State Highway Commission in 1974 (18) indicated good performance of such overlays, which were then from one to nine years old, despite relatively high chloride levels in the concrete in the original deck slab. A more recent study (19) reports the investigation of the condition of the same bridge decks five years after the original investigation. The latest study included a delamination survey and the measurement of corrosion potentials, which were not part of the original survey. The results show that the majority of the decks exhibited delaminations and that most of these were just below the bond line between the overlay and the original deck concrete. Despite the presence of the delaminations, no surface distress was observed and the performance of overlays on chloride-contaminated decks was considered adequate. It should be noted that the overlays were constructed to specifications that required thinner overlays and the removal of less concrete than existing specifications.

A survey of 149 latex-modified concrete overlays in Ohio, West Virginia, Michigan, and Kentucky (14), some of which were more than 15 years old, found that, despite local debonding and cracking, performance was generally satisfactory. Consequently, the trends in the corrosion potentials shown in Figure 1, and the performance of overlays in Iowa and elsewhere, give a better indication of the economic life of a concrete overlay applied to a chloride-contaminated deck than has previously been possible and suggest that 15-20 years is probably a realistic period.

Patching, Waterproofing, and Paving

Data on the effect of repairing a chloride-contaminated deck by patching, waterproofing, and paving are even less available than data on concrete overlays. In Ontario, systematic before-and-after surveys have not been made, but in 1978 a study was undertaken to determine the effect of waterproofing on the corrosion activity in a deck slab. Where half-cell readings had been taken on deck slabs that had subsequently been waterproofed, potentials were measured at the same grid points by drilling through the waterproofing to ensure an electrical contact with the deck surface. For most structures, only part of a deck was included in the original survey, in which case only the same part of the structure was included in the 1978 survey.

The most reliable data were available from two structures that were built in 1959 and 1960 with a bituminous concrete surface but without a waterproofing layer. The concrete decks were exposed in 1975 and resurfaced with a hot-applied rubberized-asphalt waterproofing membrane, a protection board, and 75 mm (3 in) of hot mix as part of the same resurfacing contract. Half-cell measurements, cover, and areas of delamination were recorded on both decks when they were exposed in 1975. The half-cell data, together with those from the 1978 survey, are shown for each structure in Figures 3 and 4.

When the Nith River bridge (Figure 3) was examined in 1975, extensive areas of delamination were recorded. These were associated with areas of inadequate cover to the reinforcing steel. The cover varied between 20 and 60 mm (0.75 and 2.375 in) and averaged 35 mm (1.38 in). Delaminated concrete was removed, and concrete patches were placed in the spalled and delaminated areas. The deck on the Canadian Pacific Railway (CPR) structure (Figure 4) was in good condition in 1975 and free from delamination. The cover varied between two isolated readings of 25 mm (1 in) and a high of 70 mm (2.75 in) and averaged 55 mm (2.2 in).

Of the seven cores taken in 1978 from the Nith River bridge, five were taken at grid points included in the 1975 survey. The half-cell measurements at the time of the two surveys ($Cu/CuSO_4$ half-cell) and the condition of the cores are given below (NR = not recorded):

Core No.	Half-Cell Potential (V) 1975	Half-Cell Potential (V) 1978	Core Delaminated
1	-0.49	-0.50	No
2	NR	-0.56	Yes
3	-0.29	-0.30	No
4	-0.37	-0.54	Yes
5	-0.23	-0.23	No
6	-0.42	-0.55	Yes
7	NR	-0.54	No

Of the five cores taken where the potential was -0.50 V or greater, three were found to be delaminated. Although it is possible that not all delaminated areas were removed at the time of repair in 1975, this is unlikely, and the half-cell measurements taken at the locations of cores 4 and 6 in 1975 suggest that the delaminations were not present when the waterproofing was applied. Figure 3 also shows that there has been an increase in overall corrosion activity in the deck between waterproofing and examination three years later.

The opposite effect has occurred on the CPR structure, in which there has been a reduction in corrosion activity since the deck was waterproofed.

An attempt was made to compare the effectiveness of the waterproof membrane on the two decks by using resistivity measurements (20). The resistivity on both decks was low, but this is thought to be the result of moisture in the bituminous concrete shorting the electrical circuit to the reinforcing steel by way of the deck drains. In selected locations on both decks, the waterproofing was examined by removing the bituminous concrete. In all cases, it was found to be well bonded to both the deck and the protection board, of uniform thickness, and in good condition. The reason for

Figure 3. Corrosion potentials at Nith River Bridge, Ontario 401.

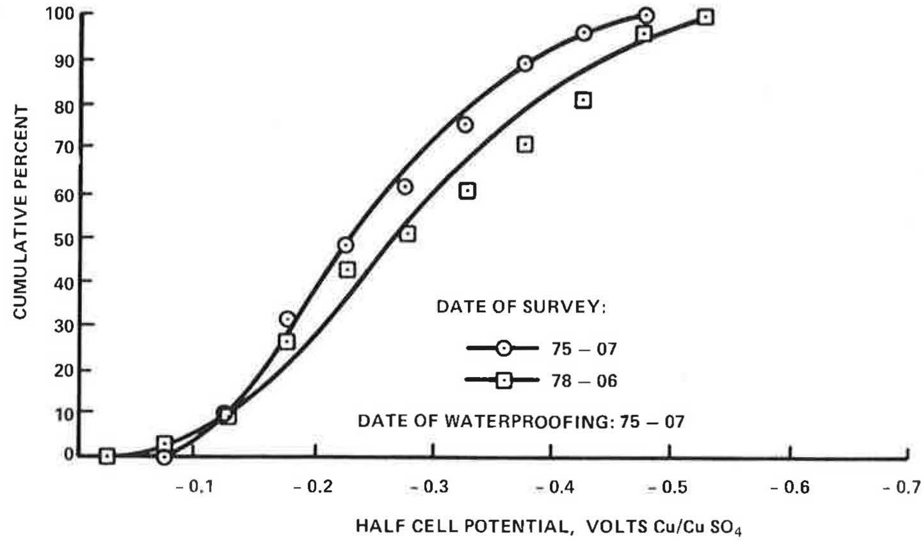
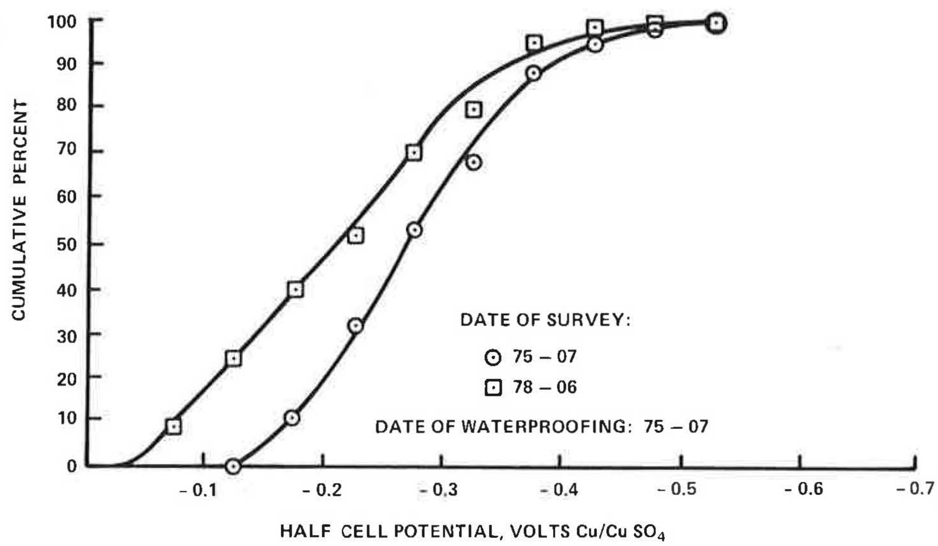


Figure 4. Corrosion potentials at CPR overhead, Ontario 401.



the difference in the performance of the waterproofing membranes is not clear.

Wide variations in the performance of waterproofing membranes applied to chloride-contaminated decks have been the common denominator in other bridge-deck surveys. A survey of 74 structures was undertaken in Ontario in 1974 to evaluate the effectiveness of waterproofing membranes (21), and measurements were made of both electrical resistivity and half-cell potentials. Thirty-seven of the structures tested, including some of the 17 structures that were new at the time of waterproofing, exhibited active corrosion potentials. There was no correlation between resistivity and corrosion measurements so that high resistivity readings, which indicate good membrane performance, were often associated with high potential measurements.

A similar lack of correlation between resistivity and corrosion was found in a survey of 44 decks in New York State (22). All of the decks were waterproofed after being in service for a number of years. Forty percent of the decks indicated active corrosion over more than 25 percent of the deck area. When half-cell measurements were made on the same deck over a number of years, the number of readings in excess of -0.35 V fluctuated widely from year to year. With few exceptions, the percentage of readings that indicated active corrosion increased with time.

Work in California has shown that repairing delaminations before waterproofing will reduce the percentage of active corrosion potentials in a deck but that corrosion activity will continue at other locations in a chloride-contaminated deck (23). Other surveys in the United States have reported both a reduction in corrosion activity (12) and renewed spalling (24) beneath membranes applied to decks that were previously exposed to deicing salts.

In many ways, the results of the surveys on waterproofed decks are confusing, and the effect of waterproofing on the future service life of the deck slab is unpredictable. Spalls and delaminations have occurred within three years of waterproofing a chloride-contaminated deck. Given the variability in membrane performance, it would seem prudent to seek other methods of rehabilitating such decks until such time as the effect of the waterproofing is better understood.

Cathodic Protection

Cathodic protection differs from the application of a waterproofing membrane or a concrete overlay in that it actively prevents continued corrosion of the reinforcing steel. The low-voltage direct current that is applied over the deck surface by way of the conductive mixture polarizes the reinforcing steel so that corroding anodes on the steel are prevented from discharging ions and become current-receiving cathodes. The effectiveness of the cathodic protection in arresting the corrosion of the reinforcing steel has been demonstrated by embedding corrosometer probes in the deck slab (4).

The first installation of cathodic protection on a bridge deck in Ontario took place in 1974 (25). Only half the deck was protected because the method was considered experimental. The remaining half received a dense bituminous concrete overlay and served as the control for the experiment. All spalls on both sides of the deck were patched with concrete, and the delaminated areas were injected with epoxy.

The bituminous concrete was removed in 1977 so that the concrete deck slab could be examined and a cathodic protection system applied to the entire deck. Many delaminations were located on the unprotected side of the deck. Delaminations were also located on the protected side of the deck, although closer examination showed that these could be divided into two categories--those that had occurred in areas previously injected with epoxy and those that were adjacent to the centerline of the deck. The epoxy used to inject the delaminated areas in 1974 was a dielectric material that prevented the flow of current to the reinforcing steel beneath the injected areas so that further corrosion took place. The delaminations adjacent to the centerline were part of much larger delaminations on the unprotected north side, and the extension of the delaminations into the south side was thought to be the result of corrosion activity in the unprotected side (27).

The examination of the deck surface confirmed the effectiveness of cathodic protection in arresting corrosion in a deck slab but also resulted in a change in repair practices. These now require the removal of all delaminated areas and the placing of concrete patches prior to the application of cathodic protection. Newer installations have also included the recessing of the electrical hardware and the use of a conductive mixture with good stability characteristics (26).

FACTORS THAT AFFECT SELECTION OF A REPAIR METHOD

The selection of the most appropriate method of repair for any particular structure is determined not only by the technical considerations that have already been discussed but also by a number of other factors, some of which are economic and others purely practical. Although the purpose of this paper is to present a systematic approach to bridge-deck rehabilitation, repairs to the deck cannot be separated from an evaluation of the condition and load-carrying capacity of the remainder of the structure. If the structure as a whole is found to be functionally obsolete when current criteria for width, clearances, alignment, and load limits are applied, or if deficiencies are noted in other components of the structure that will limit its service life, then the rehabilitation strategy must be compatible with the life of the structure as a whole. Methods of conducting an economic analysis to determine the costs and benefits of replacing or repairing a structure and repair priorities between structures have been published (28-30), but the usefulness of such an analysis is limited by the accuracy with which the cost and the life expectancy of the various rehabilitation schemes can be predicted.

The factors that affect the selection of the repair method and the priority of repair can be summarized as follows:

1. The location of the structure and its importance in the highway network;
2. The volume of traffic at the site and the impact of lane closures on traffic flow;
3. The type, size, and geometry of the structure;
4. The nature of the deterioration;
5. The extent of the deterioration;
6. The anticipated service life of the structure;
7. The load-carrying capacity of the structure;
8. The cost of repairs and the availability of funds;
9. The future reconstruction program; and
10. Local experience and contractor expertise.

The importance of a structure is determined by traffic volumes at the site and the availability of alternate routes. Consequently, some freeway structures warrant a greater priority for repairs and a higher standard of maintenance than could be justified for other structures in the highway network. Traffic volumes also affect the choice of the method of repair in that they determine the number of lanes that can be closed at any one time and in some cases may dictate the selection of a rehabilitation scheme that is expedient rather than the one that is the most technically desirable. Greater priority must also be given to the repair of structures in which the deck is part of the main structural member, as in the case of thick-slab structures and some box-and-tee-girder bridges. The size of the structure affects the economics of the various rehabilitation strategies, and unusual deck geometry may eliminate some repair methods. For example, structures with changing superelevation, large skews, or sharp tapers may exclude the use of finishing machines that have transverse oscillating screeds such as those used in placing low-slump concrete overlays. Latex-modified concrete overlays are difficult to place on steep grades and crossfalls, and waterproofing membranes should not be used on grades in excess of 4 percent or in areas that are subject to rapid vehicle acceleration, braking, or turning movements. Cathodic protection cannot be used unless electric power can be supplied to the site, although experimental solar-powered installations are being developed.

The nature and extent of the deterioration have a very significant effect on the selection of the repair method. On severely deteriorated decks, the patching required prior to the installation of a waterproofing membrane or cathodic protection becomes a major item in the repair contract and, when the deterioration has resulted from inadequate cover, the cover is still inadequate after patching. Conversely, concrete overlays are well suited for use on badly deteriorated decks because the areas of concrete removal do not require perimeter saw-cutting and the concrete is replaced in the course of applying the concrete overlay. Furthermore, the concrete overlay acts as a structural component of the deck and, where the load-carrying capacity of the structure is a factor, the additional load from the bituminous overlays used with waterproofing and cathodic protection may be unacceptable. Active cracks in the deck slab

Table 1. Relative merits of rehabilitation methods.

Rehabilitation Method	Advantages	Disadvantages
Concrete overlay (low-slump or latex-modified concrete)	Structural component of deck slab; relatively impermeable; relatively long service life; well suited to repair of badly spalled or scaled decks; many qualified contractors	Not suited to decks with complex geometry; cannot bridge moving cracks; difficult to provide adequate texture on low-slump concrete surface; may not stop active corrosion
Waterproofing membrane with bituminous concrete wearing course	Bridge cracks with small amounts of movement; relatively impermeable; provides good riding surface; applicable to any deck geometry; many qualified contractors	Performance highly variable; will not stop active corrosion; service life limited by wearing course; nonstructural component of deck slab; not suitable for grades greater than 4 percent
Cathodic protection	Stops active corrosion; can be used on decks with moving cracks; provides good riding surface; applicable to any deck geometry	Presence of wearing course will accelerate deterioration of marginal quality concrete; nonstructural component of the deck slab; periodic monitoring of performance required; wearing course requires periodic replacement; specialized contractor and inspection required; electrical power source required

Table 2. Decision matrix indicating which repair methods are excluded for which repair criteria.

Criterion	Concrete Overlay	Waterproofing Membrane and Paving	Cathodic Protection
Delamination and spalls that exceed 5 percent of the deck area		No	No
Corrosion potentials greater than -0.35 V over more than 20 percent of the deck area		No	
Active cracks in the deck slab	No		
Remaining life of structure < 10 years	No		No
Concrete not properly air entrained			No
Complex deck geometry; skew exceeding 50°, curvature exceeding 10°, or changing superelevation	No[a]		
Limited load capacity of structure or span-to-thickness ratio of deck slab > 15		No	No
Electrical power unavailable			No
Epoxy injection repairs previously performed and will not be removed			No

[a]Restriction applies only to finishing machines whose axis of screed is transverse to the axis of the roadway.

generally preclude the use of concrete overlays because they are susceptible to reflection cracking, which may limit their service life. The quality of the concrete in the deck slab must also be evaluated and, where the use of cathodic protection is contemplated, the air-void system needs to be measured by using the linear traverse or point-count method to ensure that the concrete will remain durable after application of the cathodic protection system. The bituminous overlay is permeable, increases the severity of the service environment of the deck slab by increasing the degree of saturation of the concrete, and, where the deck surface is previously exposed concrete, increases the number of freeze-thaw cycles. The relative advantages and disadvantages of the various rehabilitation schemes are summarized in Table 1 (2).

The future reconstruction program also affects the time at which repairs are undertaken. It may be more economical to include a structure that does not warrant immediate rehabilitation but is located in close proximity to other structures to be repaired than to award a separate contract at a later date, especially if no other work is planned in that area for several years. Local experience is also an important factor in selecting the repair method. For example, some authorities have reported good success with waterproofing membranes (31), and others have replaced membranes within three years of installation (32). Consideration should also be given to the expertise of local contractors and the available construction equipment.

The discussion above has dealt with the technical and practical considerations involved in selecting the method of bridge deck rehabilitation but has made no mention of costs. Costs have always been of paramount importance but vary so widely that it is difficult to generalize about them. Actual costs for concrete overlays in Ontario have ranged from \$55 to \$160/m^2 (\$5-\$15/ft^2) of deck area. These costs include all of the work associated with the application of the concrete overlay, such as deck preparation, modification of deck drains and joints, paving of bridge approaches, and traffic protection. Costs for cathodic protection, expressed on the same basis, have ranged from \$85 to \$145/m^2 (\$8-\$13.50/ft^2). The costs for patching, waterproofing, and paving depend heavily on the amount of patching required but tend to be somewhat lower than the costs of either a concrete overlay or cathodic protection (33). The costs for all three repair methods vary not only with such obvious items as the size and location of the structures involved but also with less tangible factors such as scheduling, other types of work included in the contract, and the overall volume of the construction work (2). To be meaningful, a cost analysis of the various technically feasible repair schemes must be made for each repair contract.

SELECTION OF THE REPAIR METHOD

Having completed the survey of the condition of the bridge deck, the engineer must use the survey results to select the most appropriate method of repair for that particular structure. A method used in Ontario has been to quantify the information summarized in Table 1 and to express it in the form of a decision matrix, as in Table 2. This method has proved very useful when the other factors discussed previously have been kept in mind. The criteria used in constructing Table 2 are based on experience in Ontario to date but are subject to change as more information on performance, costs, and construction experience becomes available.

It should be noted that the decision matrix is constructed so that, by elimination, it leads to the identification of the rehabilitation scheme that is least objectionable rather than the one that is most suitable. This is not accidental; it is an acknowledgment of the fact that there is rarely an ideal solution and that the method of repair will always be a compromise between what is technically feasible and what is economically feasible.

In some cases, the matrix may exclude all of the methods of repair--as, for example, in the case of a deck with active cracks and with spalls and delamination over more than 5 percent of the deck area. In this case, it is useful to work through the matrix again and, on the basis of engineering judgment and cost estimates, to examine the implications of violating each criterion in turn. In the example quoted, the choice may well be between paying the high cost of patching the deck before the application of cathodic protection or accepting the risk of limited service as the result of cracking in a concrete overlay. In extreme cases, deck replacement may be the most economical solution. A possible alternative may be to combine more than one system. In the case cited above, for example, instead of patching the deck it may be possible to extend the service life of the deck by applying a concrete overlay and then either waterproofing and paving or applying cathodic protection.

CONCLUSIONS

Rehabilitating a bridge deck is both complex and challenging. Decisions often have to be made on the basis of inadequate performance data and in the face of serious operational and financial constraints. Sophisticated methods of analysis are not sufficient. Sound engineering judgment, an appreciation of all of the factors involved, and a systematic approach are the key elements in identifying the most appropriate method of rehabilitating any particular structure. Arbitrary selection of a repair method, often without visiting the structure, can no longer be tolerated. The condition and performance of structures are so highly variable that an individually engineered solution is required for every structure. This can only be done by completing a detailed condition survey and assessing the implications of the condition of the structure with regard to the cost of repairs and the future performance of the bridge deck for the various alternative rehabilitation methods.

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Publication of this paper sponsored by Committee on Corrosion.

Successful Application of Cathodic Protection to a Concrete Bridge Deck

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The effectiveness of the cathodic protection treatment of an Ontario concrete bridge deck after three years of service is evaluated. The Duffins Creek bridge was the first Ontario deck to be repaired and treated with cathodic protection. Half of the deck was treated, and the other half was left untreated. Corrosometer probes were placed in the treated half of the deck. These probes showed that cathodic protection was preventing further corrosion. After three years, the deck was stripped and the protected and unprotected sides were compared. It was found that the treated side had much less corrosion than the untreated side. It also became apparent that corrosion had occurred below the rebars, where the epoxy injection technique had been used for repairs. The most current Ontario system of cathodic protection has now been applied to the entire deck.

The Duffins Creek bridge, located on Ontario 7, 8 km east of Ontario 48, was the first of two Ontario bridges to be treated with cathodic protection. The bridge is 28 m long and 11 m wide and was built in 1967. Its concrete deck was left exposed. In 1974, the deck rebars were corroding, and this was causing serious spalling and delaminations to occur in the deck, especially along the centerline. The deck was surveyed for corrosion by using a copper/copper sulfate ($Cu/CuSO_4$) half-cell (1). It was found that potentials in excess of -0.35 V existed in a good portion of the deck, which indicated an active state of corrosion. The original corrosion voltage survey is discussed elsewhere (2,3).

The delaminations in the deck were repaired by using an epoxy injection, and the spalls were patched with concrete. Since at that time cathodic protection was still an experimental method, it was used only on the eastbound lane. The westbound lane was left unprotected for comparison. It was covered with dense asphaltic concrete to match the level of the protected eastbound lane.

A full description of the original method used for applying cathodic potection to the Duffins Creek bridge is given elsewhere (2,3). In this method, a series of Duriron anodes were applied to the deck and attached to it with epoxy cement. The connecting wires were run along the deck to the curb, from the curb to the end of the deck, then down through a hole to the control panel. Graphite anodes were also used in order to compare their behavior and stability with those of the Duriron anodes. The entire deck surface was covered with an electrically conductive mixture of coke breeze and asphalt cement. The mixture was then compacted in the usual manner to a thickness of 5.0 cm and covered with 3.8 cm of surface mix, designated HL-1, which distributed the electric power evenly across the deck. Experiments showed that three electrodes down the center of the deck were sufficient to give an even distribution of power in the mix. Electrical resistance probes buried in the deck showed that corrosion stopped as soon as the power was applied.

The deck was under constant current control rather than the constant potential control applied to later decks. The system worked very well and required only two adjustments per year. The reason for this was that during the summer the concrete deck was drier than in the winter and its resistance changed. If the current was set to produce a polarized potential of, say, 1.0 V during the summer, this would produce a lower potential during the winter when the deck resistance was lower because of absorption of deicing salt solutions. In this case, an adjustment would have to be made.

The bridge deck was protected by this system for three years. During the second year, however, several fine random cracks appeared in the asphalt surfacing on the protected half of the bridge while the unprotected half remained uncracked. It was believed that the cracks developed as a result of water saturation in the conductive layer. This conductive layer was 80 percent by weight coke breeze and 20 percent by weight asphalt cement. Although this mix had excellent conductive properties (resistivity = 0.0148 Ω·m), it was low