GARDEN CITY SKYWAY SUBSTRUCTURE REHABILITATION

Issam ElKhatib, P.Eng., Dennis Baxter, P.Eng.
Totten Sims Hubicki Associates, Canada

Abstract

The rehabilitation history of the Garden City Skyway Bridge indicates that, since original construction (1963), partial rehabilitation of the superstructure has been carried out on several occasions, with full rehabilitation of the deck in early 2002. However, there has been no major rehabilitation work undertaken for the substructure. Previous condition survey records (1997 and 1998) indicate that the overall condition of piers vary from acceptable to poor with the majority of the piers being in fair to poor condition. This increased deterioration of bridge components, especially those of the bridge substructure, warranted immediate attention to undertake remedial repairs to restore the structural integrity for the protection of the public. Since there are a wide range of conventional repair and rehabilitation methods available, the most suitable for the subject project were selected: Patching, Concrete Jacketing, Pinning of Delaminated Concrete, Advanced Pile Encapsulation, Shotcreting, Cathodic Protection and Chloride Extraction

1. Introduction

The Garden City Skyway Bridge (GCS) is located along the Queen Elizabeth Way in the City of St. Catharines and consists of forty-eight spans for a total length of 2,200 m. The superstructure consists of steel box and I-girders with concrete deck and the substructure consists of rigid frame solid and hollow piers, ranging in height from 5.9 m near the abutments to 34.1 m supporting the main span over the Welland Canal. The west piers are labeled from W30 down to W1 and the east piers from E1 to E17. The rehabilitation of the superstructure has been carried out on several occasions, with full rehabilitation of the deck in early 2002. However, there has been no major rehabilitation work undertaken for the substructure. Previous inspections indicate that the overall condition of the piers vary from acceptable to poor with the majority of the piers being in fair to poor condition. Due to chloride contamination through the open deck joints and deterioration of sealed deck joints over the years, significant deterioration (scaling, delaminations, spalls and cracks) of the bearing seats, pier caps and pier columns has occurred.

Figure 1: Garden City Skyway

Due to the extent of deterioration and chloride impregnation, a variety of rehabilitation techniques were employed to minimize cost while ensuring durable, long-lasting repairs. The repair treatments considered included concrete patch repairs, patching with passive cathodic protection, concrete jacketing and jacketing with cathodic protection, as well as shotcreting, pinning of delaminations, electrochemical chloride extraction and pier cap strengthening. The selection of the repair for each component was based on the level of deterioration of individual substructure components and a life cycle cost analysis.

2. Scope of work and methodology

After the Condition Survey was carried out identifying all areas of concrete defects and deterioration including areas of spalls and delaminations, the findings and observations were compared and analysed with the findings of the 1997 and 1998 Condition Survey Reports. In addition, a comparative statement of propagation of deterioration since previous inspections was prepared. In preparing the most suitable rehabilitation strategy and repair methods, informal value engineering sessions were internally conducted to evaluate the chosen methods from cost, durability, construction and maintenance perspective (life-cycle analysis). Also, industry experts in the field of concrete restoration were consulted.

The repair and rehabilitation of the GCS bridge substructure components involves replacement of deteriorated/lost concrete with the most suitable material and addressing any deficiencies in structural capacity due to deterioration. The technical consideration in the selection of the rehabilitation method alternative(s) was based on merits and shortcomings of options. The following methodology relevant to the tasks undertaken was adopted:

- Data Collection and Review
- Field Inspections and Condition Surveys
- Comparative and Deterioration Curves
- Structural Evaluations in accordance with CHBDC
- Construction Sequencing Stability Analysis
- Seismic Perspective - Bearings and Bearing Seats
- Quantities for Removals
- Corrosion Protection: Concrete Removal and Corrosion Protective Remedies such as Chloride extraction and Cathodic Protection
- Life-Cycle Cost Analysis & Cost Estimates
- Bearing Assessment

3. Summary of findings of condition surveys

The results of the Condition Survey that included inspection for surface deterioration such as cracks, delaminations, honeycombing and spalls illustrate that the substructure components vary in condition from acceptable to poor. Some of the major findings of this study are as follows:

3.1 Concrete members

Chloride Content - During the life of the bridge until the major deck rehabilitation, expansion joints were provided over almost all of the pier caps. Leakage through the joints was an ongoing concern. High chlorides are also evident in the columns that are within splash zones of adjacent roadways. The detailed substructure condition surveys completed in 1997 and 1998 indicate that the depth of chloride penetration extends beyond the 1st layer of reinforcing steel in many locations tested. The extent of chloride infiltration was summarized by extent and depth for each major pier component for assessment.

3.2 Steel girder members

At a number of locations the paint coatings on the steel girders have peeled and/or flaked off. This is due to the drain downspout outlet locations and leakage through deteriorated expansion joints. To permit assessment of full recoating versus overcoating alternatives, pull-off tests of the existing coatings were undertaken to confirm the adhesion of the paint coatings between layers and to the native steel. These tests indicated that the paint coatings were generally bonded to the native steel, however, bonding between coats was quite variable.

3.3 Rocker bearings / bearing seats

The existing bearings consist of rocker bearings at expansion joint locations, except at the abutments, where the rockers have been replaced with elastomeric pads. The rocker bearings were typically observed to be in fair to good condition. Some of the bearings, which are in fair condition, exhibit minor pitting corrosion. Significant debris was observed on the pier caps and in the bearing mating surfaces. The measured rotations of the bearings generally did not match the design rotations. This may be due to misalignment of the superstructure and substructure components at the time of construction, or the bearings may not have recovered completely from rotations undergone during previous temperature changes.

With the exception of the east abutment bearing seat, the width of the bearing seats generally conforms to the seismic requirements of CHBDC. The deviation of the required bearing seat width from the required was very small and modification of the bearing seat width was not considered necessary at this time. The condition, position and seismic findings of the bearings, as well as condition of the bearing pedestals, for each pier were summarized for individual evaluation of repair needs.

4. Summary of findings of structural evaluation

Detailed structural analysis was carried out to evaluate the structural capacity of the columns and the pier caps. Two-dimensional computer models of respective segments of the bridge were developed in the computer analysis program “S-Frame” for analysis. Logical spreadsheet-based programs were also developed to carryout member resistance checks and interaction diagrams developed in accordance with CHBDC. The structural evaluation of the existing condition of the GCS Bridge substructure concluded that substructure components possessed sufficient capacities (but with very small reserve capacity) to resist all current loading conditions and no strengthening was required; however, construction sequencing/staging to limit the removals and prevent undesired and unacceptable overstresses were developed.

5. Rehabilitation design

5.1 Rehabilitation design strategy

As part of the Verification Engineering process, meetings were conducted with suppliers, MTO officials and senior structural engineers at TSH and it was concluded that the alternatives were to be evaluated from the following essential perspectives:

- Constructability
- Specialized construction needs
- Environmental impacts
- Service life to next major rehabilitation
- Traffic considerations
- Case studies of similar applications on previous projects
- Life Cycle Cost Analysis

5.2 Rehabilitation design repair alternatives

There are a wide range of conventional repair and rehabilitation methods available, which may be suitable for the subject project. New advanced repair methods were also investigated. The rehabilitation design repair alternatives are:

- Alternative 1, Patching
- Alternative 2, Concrete Jacketing
- Alternative 3, Pinning of Delaminated Concrete
- Alternative 4, Advanced Pile Encapsulation
- Alternative 5, Shotcreting
- Alternative 6, Cathodic Protection
- Alternative 7, Chloride Extraction

In addition to the above, passive cathodic protection systems were considered in conjunction with Alternative 1, Patching. Preliminary cost estimates for the applicable alternatives for each pier were generated. The cost estimates included all works associated with the piers, including bearing and coating rehabilitation. The following is a detailed assessment of the various rehabilitation alternatives presented in this Paper:

Alternative 1: Patching

Alternative 1 consists of repair of concrete substructure components by forming and pumping of concrete patches. This alternative has an anticipated service life ranging between 10 to 20 years depending on exposure to future chlorides. The service life can be extended to minimum of 25 years by the introduction of passive cathodic protection systems (see alternative 6 for description). Patching has been considered for piers with deterioration not exceeding 30% of the surface area. The following construction staging was incorporated into the detail design of patch repairs:

- Removal beyond the mid-point of the main reinforcing steel bars (45M) in the pier cap soffit was restricted to removal of unsound concrete only. In addition, removal along the length of the cap was staged to maintain stresses in the pier cap within tolerable limits. In areas of restricted removal, steel mesh reinforcing and anchorage inserts were provided to improve patch adhesion in the absence of placing concrete around the reinforcing steel bars.
- Similarly, removals from the vertical faces of the pier cap were restricted to one face at a time to prevent loss of shear capacity.
- Removals from pier columns were also staged to maintain the structural integrity during construction.
- Depth of removals was limited to 200 mm without on-site assessment by the Engineer.
- To limit shrinkage cracking of the concrete, the linear shrinkage requirements were restricted beyond the standard MTO limits.

Additionally, patching without removal of high corrosion potential concrete does not provide a suitable service life unless combined with cathodic protection. For piers in which the patching method has been considered, the life-cycle costing indicates that it is the lowest cost alternative, generally in combination with passive cathodic protection. Concrete sealers have been included for areas subject to continued chloride exposure.

Figure 2: Typical spalls on pier cap of pier W11

Figure 3: Typical spalls on south column of pier W17

Alternative 2: Concrete jacketing

Alternative 2 consists of repair of concrete substructure components by full jacketing or resurfacing. The service life of this alternative for jacketing of the concrete substructure components is anticipated to be 15 to 25 years depending on exposure to future chlorides and whether all high corrosion potential concrete is removed during the repair. The use of passive cathodic protection systems is not considered necessary for this alternative because the full jacketing does not induce the localized severe cathodic reaction which can be associated with localized concrete patches. Jacketing has been considered for piers with deterioration and/or high corrosion potential concrete exceeding 30% of the surface area. The proposed jacketing thickness was 100 mm with a grid of 10M reinforcing steel bars and 15M dowels. Restrictions for removals and staging and concrete shrinkage specifications were implemented as noted under concrete patches.

In this alternative, formwork must be designed for the forces generated by the placement of the concrete, particularly if super plasticizers are used. For piers in which patching is not suitable, the life-cycle costing indicates that jacketing is the lowest cost alternative. Concrete sealers have been included for areas subject to continued chloride exposure.

Alternative 3: Pinning of delaminated concrete
This method of repairing delaminated concrete areas was developed based on methods of repairing cracks in concrete by pneumatically injecting epoxy grout to seal and restore existing concrete. The delaminated area of concrete is pinned using pins located properly on the surface at specific points, then a bonding agent is applied between the loose and sound concrete, and finally epoxy grout is injected to ensure an integral new repaired surface. A major disadvantage of this alternative is that it will not prevent and stop the extensive chloride contamination and corrosion that might have caused the delaminations in the deteriorated area. This repair method was examined, but is not considered to meet the minimum requirement of 15 year service life without further repairs and subsequently was not carried forward.

Alternative 4: Advanced pile encapsulation (APE)
This method of repair also takes advantage of Fiber-Reinforced Polymer (FRP) technology. It involves wrapping the concrete component with prefabricated Glass Fiber-Reinforced Polymer (G-FRP) jackets which are marine grade laminates of glass woven roving and mat, impregnated with a clear, UV light-stabilized, polyester resin. The jackets are translucent to allow the progression of grout inside the jackets to be monitored from outside the jackets. The jackets are precisely moulded to conform to the structure being encapsulated and come complete with grout injection ports and integral overlapping seams. APE method reduces the amount of removals significantly and does not require loose or unsound concrete to be removed and can be wrapped on existing concrete reducing the removals significantly. However, the main disadvantage is that it does not eliminate the cause of the deterioration (chloride contamination and corrosion). This repair method was examined but not carried forward, due to lack of studies and project history and anticipated failure to meet the minimum requirement of 15 year service life without further repairs.

Alternative 5: Shotcreting
Alternative 5 consists of repair of concrete substructure components by application of silica fume concrete. Shotcreting has been considered for piers with deterioration not exceeding 30% of the surface area. The service life of this alternative for patching of the concrete substructure components is anticipated to be 15 to 25 years depending on exposure to future chlorides and whether all high corrosion potential concrete is removed

during the repair. The long-term durability of this rehabilitation method is also highly influenced by the experience and care of the applicator. Based on the above, shotcrete repairs are considered to provide similar results to the form and pump concrete patching alternative, with additional environmental concerns, higher disposal needs and the requirement of specialist applicators. A cost comparison of form and pumping concrete versus shotcreting for this structure indicated that form and pumping was more economical. In the absence of any significant advantages over form and pump patch repairs, the shotcrete alternative was not carried forward.

Alternative 6: Cathodic protection

Cathodic protection systems are broken down into two basic types, namely impressed current (active cathodic protection) and sacrificial anodes (passive cathodic protection). Cathodic protection has been considered for piers with large areas of high corrosion potential. Impressed current systems have been in use for many years with diverse results. Early cathodic protection systems tended to fail because of maintenance/monitoring issues. This system requires jacketing or encasement with embedded anode mesh and has been considered for substructure components requiring jacketing. The ongoing maintenance and monitoring requirements of impressed current cathodic protection systems are a significant concern when compared with other alternatives.

Three systems were assessed for the passive cathodic protection system, as follows:

- Galvanic anodes;
- Thermally sprayed galvanic coatings; and
- Zinc hydrogel anode system.

Galvanic anode systems consist of embedding sacrificial anodes in concrete patches. Previous case studies of MTO rehabilitation contracts using galvanic anodes indicate that these systems have had poor performance without the anticipated cathodic protection being realized in the concrete immediately adjacent to the repair areas. The thermally sprayed galvanic coatings are placed directly on the concrete surface throughout the structure component in conjunction with patch repair with connection to reinforcing steel at localized locations (one connection per 100 m^2 of surface area). The zinc hydrogel anode system is similar, but the zinc anode materials are adhered to the concrete surface with a hydrogel adhesive. The main advantages of the passive cathodic protection system over the impressed current system is the simplicity of the installation, limited number of components and limited requirements for specialist contractors (mainly for confirming conductivity and suitable attachment of the cathodic protection system to the reinforcing steel). This system is considered to be suitable for substructure components undergoing patch repairs and will require the presence of moisture to provide the overall conductivity of the system. The absence of moisture in some areas may affect the performance; however, the absence of moisture will also limit the additional deterioration that may be experienced in the future. The service life of patching and jacketing repairs is considered to be extended by about 20% with the addition of cathodic protection systems. For piers in which this method has been considered, the life-cycle costing indicates that it is typically more economical when evaluated against patching only and sometimes economical when evaluated against jacketing, dependent to a great degree on the extent of high corrosion potential concrete versus the extent of deteriorated concrete.

Alternative 7: Chloride extraction

This alternative consists of inducing a low voltage DC electric field between a temporary external anode and the reinforcing steel within the concrete to extract the existing chloride ions from the concrete matrix. If chlorides have penetrated into the concrete beyond the level of the reinforcing steel, they will not be removed by this process and will remain in place. The concrete immediately beyond the rebar will be pacified. Jacketing the concrete and the recent modification of the deck articulation with elimination of expansion joints and placement of sealed joints in other locations will reduce the ingress of moisture into the concrete. When the process is complete, the system is removed, leaving the reinforcing steel in a chloride free, non-corrosive environment. The benefit of removing the chloride ions electrochemically is that contaminated concrete which is still structurally sound would not require removal and will remain in place after the application of the chloride removal process.

Environmental protection requirements are much higher with this system because of the need to desalinate all waste water produced by the operation. The amount of waste water is considerable because of the need to maintain a moisture barrier between the chloride extraction equipment and the concrete surface, and the significant time periods in which the chloride extraction process is active. This system has only been considered in substructure components with areas of high corrosion potential greater than 30 %. This repair methodology has been used in a limited number of applications using current techniques, and therefore, the long-term results are unknown.

Based on the above, chloride extraction repairs are considered to provide similar results to cathodic protection alternative, at a similar initial construction cost to induced current. Because of the similar construction cost to induced current cathodic protection systems, chloride extraction was considered in the financial evaluation of alternatives and impressed current cathodic protection was not

6. Cost estimates and life-cycle cost analysis

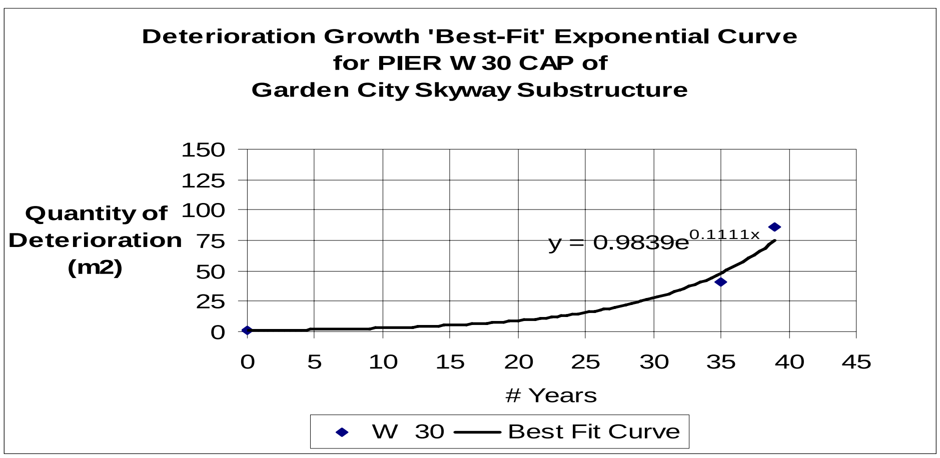
The cost of rehabilitation work of Garden City Skyway Substructure was determined based on the repair program selected for each pier, as follows:

1- Unit rates are developed based on MTO’s Computer Costing System, HiCo. These rates were adjusted to reflect the site characteristics (i.e. high level piers).
2- Volumes of deterioration for the specific type of repair and for the specific pier component are then determined and multiplied by the rates from (1). These volumes

are calculated by increasing the actual measured areas of deterioration by 15% using an average removal thickness of 165 mm and an additional 100 mm thickness for jacketing.

3- Life Cycle Cost Analysis was performed to determine the most economical alternative.

Standard MTO policy of removal quantity extrapolation is to increase the anticipated concrete removals for rehabilitation by approximately 10% per year. Because of the significant cost implications of quantity overruns, a more elaborate system for determining repair quantities was developed. Two methods were investigated. First method is simply a linear extrapolation based on the number of years since original construction. Method 2, which was adopted, involves determining the most appropriate deterioration extrapolation curve for each pier. These curves were developed using EXCEL program using the 'Trend Line' approach or 'Best Fit' curve for the given deterioration quantities. These curves were developed for each major component of each individual pier and calculated anticipated deterioration projected over a 5 year period. Two contracts for the rehabilitation of the GCS piers have been completed to date with very good correlation of anticipated and actual repairs using this methodology.



7. Recommendations

Based on the field investigations, structural and rehabilitation evaluations, rehabilitation strategies or a combination of them was recommended for each of the pier and abutments for a total construction cost of **$30 Million**. The restoration will be undertaken over a period of approximately 5 years. Two contracts involving rehabilitation of 17 piers for a construction cost of $10 Million have been completed to date.