MOUNTAIN-PLAINS CONSORTIUM

MPC 20-415 | S. Pei, N. Wehbe, H. Liu and J. Paul

Evaluation of Cost Effectiveness, Performance, and Selection Criteria for Concrete Structures

MOUNTAIN-PLAINS CONSORTIUM REGION 8

A University Transportation Center sponsored by the U.S. Department of Transportation serving the Mountain-Plains Region. Consortium members:

Colorado State University
North Dakota State University
South Dakota State University
University of Colorado Denver
University of Denver
University of Utah
Utah State University
University of Wyoming

Evaluation of Cost Effectiveness, Performance, and Selection Criteria for Concrete Structures

Shiling Pei
Associate Professor
Colorado School of Mines
Golden, CO 80401
Email: spei@mines.edu

Nadim I. Wehbe
Professor and Department Head
Department of Civil and Environmental Engineering
South Dakota State University
Brooking, SD 57007
Phone: (605) 688-5427
Email: nadim.wehbe@sdstate.edu

Hongyan Liu
Teaching Associate Professor
Colorado School of Mines
Golden, CO 80401
Email: hyliu@mines.edu

Jordan Paul
Graduate Research Assistant
Department of Civil and Environmental Engineering
South Dakota State University
Brooking, SD 57007

June 2020

Acknowledgments

The authors would like to acknowledge the financial support of the Mountain-Plains Consortium (MPC) for funding this study through project MPC-351.

Disclaimer

ABSTRACT

A study was conducted to develop recommendations for short span concrete structure type selection based on analyses of existing structure costs and performance data from South Dakota roadway systems. Through a combination of data sources, including the PONTIS database, local owner and inspector surveys, past project bidding costs, and typical bridge plan estimations, costs of commonly used short span concrete structure type alternatives were compared. The expected service life of these structures was also estimated based on inspection rating data. The data collection effort in this project indicated a lack of cost data in the current bridge and culvert database. With limited cost data, the most commonly adopted structure alternatives for short span concrete structures at different span requirements were compared based on average annual cost, which was obtained based on unit cost distribution and expected service life. Based on the comparison, recommendations were made to conduct selection of short span concrete structures. The current practice in construction, maintenance, and management of short span concrete structures was summarized in this study. Recommendations were also made on improving cost data collection, building performance monitoring, and implementing additional protection measures for precast concrete structures. A four-step procedure to determine short span structure type selection is proposed at the end of the report.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

EXECUTIVE SUMMARY

This report is part of SDDOT Research Project SD2010-02, "Evaluation of Cost Effectiveness, Performance, and Selection Criteria for Concrete Structures." A comprehensive investigation of current practices for selection, design, construction, and maintenance of short span bridges and box culverts in South Dakota was conducted in order to develop guidelines for short span concrete structure alternative selection based on long-term cost effectiveness. The study was conducted through query of the PONTIS database and specially designed surveys to bridge owners, engineers, inspectors, and precast manufacturers. The scope of this study was originally focused on simply supported bridges and culverts, and was later expanded to include multi-span concrete slab bridges and prestressed girders with cast-in-place (CIP) decks. The performance of these structures was quantified in this study through a component rating in the PONTIS database. Qualitative information on structure performance was also obtained through customized surveys with county superintendents, engineers, inspectors, and precast manufacturers. The most challenging component of this study was the collection of cost data. Due to the lack of cost-related data on existing structures in the PONTIS system, the cost data in this study were obtained from historical bid letting abstracts and electronic records kept by SDDOT. This study included about 2,400 short span concrete bridges and 1,200 concrete culverts; only 325 culverts and 167 bridges have cost data. Because of the lack of cost data for certain bridge types, bidding cost estimation was also conducted later in this project for selected representative bridges based on construction plans.

After obtaining the cost and performance data, statistical analyses were conducted to identify controlling factors for structure cost and performance. Concrete structures were divided into different categories based on their span and structure type. Regression analysis was conducted to estimate the service life of these structures based on structure ratings. Then an average annual cost statistic was derived for each category and used as the criteria for cost effectiveness comparison. A total of five different structure alternatives were considered in the analysis, namely CIP culvert, precast culvert, CIP slab bridge, prestressed Tee bridge, and prestressed I girder bridge with CIP deck. These structure types represented the most commonly used structure types in South Dakota for short span applications. Based on the analysis results and existing practices in South Dakota, recommendations on structure type selection were developed. Other recommendations for future practice and management were also proposed, including the use of improved joint detail on precast elements, better cost data management, and monitoring of relatively new structures. These recommendations should be implemented or investigated further in the future.

It was concluded that precast concrete culvert is a cost-effective option for structures shorter than 30 feet if the hydrological condition allows. A CIP concrete slab bridge is a good option for longer multi-span applications because it eliminates the problematic joints. Prestressed Tee bridges have consistent performance and cost-effectiveness over all span requirements over 30 feet. The newly adopted construction method using precast I girders with CIP bridge deck shows superior performance and cost effectiveness at mid-to-long span applications when compared with prestressed Tee. However, both the I-girders with CIP deck and precast culverts have quite a short history and track record in South Dakota. Their performance should be monitored closely in the future to verify their cost-effectiveness.

The following recommendations were made:

- A more integrated project cost management system at the state and local level should be developed. This will potentially benefit future research effort and management because much more emphasis has been put on life-cycle cost effectiveness of the infrastructure systems.
- The PONTIS system should be configured so the information about replaced structures can be retrieved. Currently, the new structure will assume the same structure number of the old structure and overwrite important information. An archive for replaced structures will be extremely valuable to similar studies if the cause of replacement can be recorded.

- Most of the performance issues on precast concrete structures are related to joint performances. Thus, it is recommended that extra quality control measures be developed to monitor the construction process to make sure the joints were installed correctly. Also, special design details such as moisture barrier membranes can be studied in the future to evaluate potential benefits.
- Although it is difficult to compare the benefit of different structural alternatives thoroughly with limited data, precast concrete culvert is a cost-effective option for short span applications. For longer spans, prestress I girder with CIP deck construction is an alternative that may be recommended. However, due to the lack of track record history for these newer structure types, their performance should be closely studied and monitored in the future.
- Although special maintenance and repair activities may have to be conducted in particular cases, short span concrete structures are typically very robust and do not require constant care over their service life. There is no significant shortcoming in current management and maintenance practices for these structures in South Dakota.
- Include in the SDDOT PONTIS database a customized entry for bidding price of the new and replacement bridges and culverts.
- In addition to the current component rating in PONTIS, develop a new joint rating category for precast element joint performance.
- With its current increasing popularity and relatively short track record on performance, a future study should be designed to investigate long-term performance of precast culvert systems used in South Dakota.

For future new and replacement projects, selection of short span concrete structure types in South Dakota can be conducted based on required span length, initial bidding cost, and expected service life estimated in this study. However, due to the lack of cost data, project-specific characteristics, and uncertainty in long-term performance of a couple of relatively new alternatives, the report did not provide a universal solution but proposed a four-step procedure in type selection as implementation.

1. INTRODUCTION

1.1 Project Description

State and local governments must address the ongoing need for replacement of bridges and box culverts. Especially on local road systems, a significant portion of structures have exceeded their expected life and have become structurally deficient or functionally obsolete. The structure type used in replacements should be cost effective considering the life-cycle cost of the structure.

Cast-in-place and precast concrete structures are both viable alternatives for short span structure replacements. Selection of the most appropriate alternative for a given situation depends on many factors, including needed hydraulic capacity, floodplain restrictions, structure length, number of spans, traffic loading, road surface type, materials availability, and estimated construction time and cost. Cast-in-place structures generally offer excellent performance but may involve longer construction duration and more complex on-site work. Challenges in ensuring reliable delivery of materials and an adequate supply of qualified labor at remote construction sites can increase risk and elevate bid prices. In contrast, precast structures can offer production yard quality control and quicker on-site construction, but problems with joint-related performance are occasionally reported.

Although agencies often base selection of structure type on initial cost, which can be estimated from construction bid prices, more robust decisions require consideration of life-cycle costs, including maintenance. Inadequate maintenance can reduce the life of both types of structures, although the effects may show in different areas. For example, precast beams have construction joints and often lack edge drains, allowing deicing chemicals and moisture to migrate underneath the superstructure. Cast-in-place concrete can be subject to surface cracking that allows penetration of deicers and moisture to weaken the concrete over time. Both structure types experience similar problems at abutments and where moisture tends to pool.

To enable local and state transportation agencies to invest their limited funding most effectively, research is needed to provide guidance for selection of precast and cast-in-place concrete bridges and box culverts in South Dakota and for design, construction, and maintenance practices that prolong the life of both structure types.

1.2 Objectives

Four main objectives were addressed in this study. Following is a description of those objectives.

- Describe current practices for selection, design, construction, and maintenance of concrete bridges and box culverts in South Dakota. A comprehensive investigation of current practices for selection, design, construction, and maintenance of short span bridges and box culverts in South Dakota was conducted through a combination of PONTIS database search and individual survey/interview with bridge owners, designers, personnel who conduct biennial bridge inspections, and precast companies. The information was systematically gathered with emphasis on the structure's observed performance and long-term cost-effectiveness of using different structure types. This seemingly simply task turned out to be very challenging due to the lack of records either at the state or the local level. A significant amount of efforts and attempts were made to gather as much usable data as possible. The lack of data led to adjustment of the proposed research plan, which was discussed in detail in this report.
- Analyze the performance and cost-effectiveness of in-service concrete bridges and box culverts over the range of site conditions prevalent in South Dakota. Statistical analysis on the available cost and performance data for different structure types and site conditions was conducted to

identify the factors that significantly impact performance and cost-effectiveness. All available cost data were normalized and compared between different structure groups. The performance of different structure types was also compared through the sufficiency rating data available. The impact of structure type (pre-cast vs. cast-in-place) to performance and cost-effectiveness was evaluated. Based on the current practice on management and maintenance of these short span concrete structures, the cost effectiveness for different structure categories was estimated using average annual cost over the estimated service life of the structures.

- Provide guidance for selection of concrete structure type on state and local roads in South Dakota. Based on limited cost data from existing projects, the long-term cost benefit analysis was introduced in this study to provide a guideline for selection among commonly encountered concrete structure types. Based on the span requirement of the project, the owner can select, based on the analysis result, a recommended structure type that would potentially achieve good long-term cost savings.
- Recommend changes to the design, construction, and maintenance of pre-cast and cast-in-place structures that will improve their performance or cost-effectiveness. Based on the analysis results and existing practices in South Dakota, recommendations on selection and management of short span concrete structures in South Dakota were proposed. The recommendations include improving bridge inventory management with integrated cost information, the need for improving joint detail and quality on precast elements, structure type selection considering long-term cost effectiveness, and monitoring of the long-term performance of emerging structure types. These recommendations should be implemented or investigated further in the future.

1.3 Scope

The research covered in this report included collection and analysis of the cost and performance data for existing short span concrete structures on the South Dakota roadway system, which include both the state-owned structures and locally owned structures. Originally, the scope of the study only included simply supported concrete bridges and different types of culverts, with a single span less than 100 ft. It was later adjusted based on the recommendation of the Technical Panel to also include simply supported multi-span bridges with cast-in-place concrete decks. The inventory of the bridges was then increased to include bridges longer than 100 ft.

All short span bridge and culvert data in the South Dakota PONTIS system was queried for use in this project. However, the PONTIS database does not have any cost or maintenance related information. Bidding records stored by South Dakota DOT were included in this project's data collection, which includes both the hard-copy bidding records for projects before 1995 and electronically stored cost records for newer projects. Most of these records kept by SDDOT only represent state owned structures. The information on locally owned bridges and culverts was gathered through a survey of county superintendents.

The long-term performance of existing concrete structures was investigated through a survey of owners, inspectors, and designers. A field trip to a representative bridge and culvert was conducted to record performance problems in detail.

2. LITERATURE REVIEW

2.1 Introduction

As the main objective of this study is to develop recommendations for concrete structure type selection based on long-term life-cycle cost, the literature review for this study was conducted in order to identify the state-of-the-art understanding on life-cycle cost analysis and long-term performance issues of short span concrete structures. The following sections summarized findings from the literature review focused on three main areas: (1) long-term performance and existing problems of short span concrete structures, including bridges and culverts; (2) life-cycle cost (LCC) analysis for bridge structures; and (3) experiences and recommendations from existing studies on measures to improve life-cycle performance of concrete structures.

2.2 Performance of Short Span Concrete Structures

Short span concrete structures defined for this study mainly include single span (or multiple simply supported span) bridges and culverts. These types of structures represent a major portion of total bridge inventory on local road systems in South Dakota (see Chapter 6 for details). As these structures were not traditionally viewed as critical structures from a research standpoint, the existing literature that focuses on life-cycle performance of these relatively small structures is limited. There has been no prior literature that addressed South Dakota's situation on these short span structures directly. The following are some of the studies that include information that can be of reference value to this study.

Fabian C. Hadipriono et al. (1988) did a study on service life performance of concrete culverts in Ohio. Through on-site surveys of close to 400 concrete pipe culverts installed, the study concluded that the expected life of these structures is about 63 to 89 years. The authors used linear regression analysis to develop empirical equations for life expectancy, but the correlation was shown to be weak between speculated dependent variables (subjective 0-5 rating) and independent variables, including age, slope, geometry, etc. The R-square values for all of the models presented are below 0.6. Although the target structure for this study was not directly applicable to the current study (not pipe culvert), it is one of a few that took an approach similar to this study, using surveyed data to construct a regression model for the life-span of the structure. Also, the expected life-span for pipe culvert may be of some reference value to other culverts. It indicated that concrete culverts are typically quite robust structures once they are designed and constructed correctly, and can last a relatively long time. The correlation between culvert rating and independent variables such as age is not very high.

Masada et al. (2007) recently conducted a survey on culvert structures in Ohio (not just for pipe culverts) and conducted risk assessment analysis using a new refined 0-9 scale rating system. In 2003, the ODOT implemented a new culvert management program and provided funding to inspect 25 representative culvert sites that resulted in this study. Regression analysis (linear) was conducted with a limited amount of data (25 sites). In addition to factors typically included in regression analysis of the rating such as age and geometry, the study also included ADT, water pH value, and flow abrasiveness. The study concluded that age, water pH value, and flow abrasiveness contribute to gradual deterioration, but other factors, such as ADT, flow velocity, sulfate concentration, and soil cover, are not statistically significant. Similar to the Fabian study in 1988, the regression model R-square values are below 0.6. Another interesting result from this study is the observed performance issues with surveyed culverts, including backfill infiltration through joint opening of precast elements, and longitudinal cracks at the crown.

For long-term performance of short span bridges, the existing literature often focused on specific details or construction methods. For example, Issa et al. (1995) examined the performance of joint performance of full depth bridge deck concrete panels for bridge construction. Although this system is typically used in longer span bridges and steel-concrete systems, the study pointed out an important fact that, besides deterioration of precast concrete system itself, joint detailing is one of the major issues for long-term performance problems in precast concrete bridge components. The study covered most of the states that had implemented this precast system and summarized performance issues and recommendations. One recommendation that can be applied to the direction of short span precast structures is the use of a waterproofing membrane system, which is a measure adopted by all DOTs for full depth deck systems.

Smith et al. (2011) reported a problem related to longitudinal joints on decked precast prestressed concrete bridges, which is also observed in some simply supported local bridges in South Dakota using double tee elements. This study used finite element numerical modeling to evaluate the effectiveness of inter-girder connectors in limiting differential movement between girders under live loads. The study proposed to use a nonlinear spring element for modeling of inter-girder connectors for future studies. This study provided little information that is directly applicable for current research, but it highlighted the universal problem of precast element differential movement and its potential impact to long-term structure performance.

Ehlen (1997) conducted a study on life-cycle costs of new construction materials for highway structures. An overall methodology was developed and used in an example to compare the cost of FRP composite bridge deck systems to traditional deck systems. The results indicated that no matter what type of material was used, the initial construction cost will typically dominate the life-cycle cost.

Cook and Bloomquist (2002) conducted a research project for FDOT on the performance of precast box culverts. The study included detailed surveys to a number of DOTs within the nation and also on many site survey inspections. The study reported practices and common problems on precast box culverts and concluded they are generally very reliable. With only a short track record period (about 20 years at the time of the study), the most predominate problem is only associated with joints, which can be improved through better quality control during construction or improved design. The survey results indicated the main reason for using precast culverts is construction time savings and lower costs. Some states require the end components to be cast-in-place, while some states already moved to precast wing wall and headwall options. Based on the surveys, all states require some form of rubber preformed mastic joint filler between each culvert section and a filter fabric covering each joint to prevent earth infiltration into the culvert. A few states also require a waterproofing membrane to prevent water from entering into the culvert through the joints. In some states, longitudinal mechanical ties were actually required to ensure that the sections do not separate. Overall, the report concluded that there has not been any major failure or defect in current precast culvert practices; and the system is a good alternative for the traditional cast-in-place option. Waterproof membrane detail was recommended at the end of the report as an option for higher performance.

This study also surveyed South Dakota’s experience in using precast culverts. It was shown that the use of precast box culverts started in the 1980s. This option is almost always adopted when skewness and special inlet/outlet constraint is not a problem. Mechanical joint ties were required between sections; and drainage fabric was required along the joint to prevent soil infiltration. South Dakota surveys indicated that the problems in construction typically related to poor quality of concrete and dimensional control, which can be minimized with rigorous plant inspections. Due to some incidents of erosion at ends, South Dakota recommended that inlet and outlet cutoff walls be specified on all drainage crossing type precast box culverts. South Dakota has had a very long and very good history with cast-in-place box culverts with only limited problems in joints. An added number of connections in precast culverts had raised concerns with the widespread use of this system. But the system has not been implemented long enough to reveal all possible problems.

The availability of performance and cost data for bridge and culvert structures is also a critical issue for the proposed study. Currently, in all state DOTs, bridge and culvert inventory is typically managed using a computerized database such as the PONTIS system recommended by AASHTO. Chase and Ghasem (2006) reviewed the evolution of U.S. bridge management systems dating back to the creation of the National Bridge Inspection Program (NBIP) in 1970. The study described the limitation of the NBI database and mentioned the effort of some DOTs to include more detailed and objective information about bridges using PONTIS. Nonetheless, the study indicated that the current levels of detail on bridge performance and cost data in typical database systems are not adequate to conduct or calibrate a comprehensive life-cycle cost analysis (LCCA). However, the study also pointed out that the applications of the LCCA to bridge projects are likely to grow in the future; and the accuracy of such applications will largely depend on the availability and quality of relevant data.

2.3 Life-cycle Cost Analysis Methods

LCCA has been used primarily as a research tool for highway bridge structures in recent years. Many studies were focused on developing either a generalized framework or structure-specific applications. Assumptions and empirical models were used in most of the studies in this category without comprehensive verification due to the lack of life-cycle data. Although this study does not intend to conduct detailed LCCA for a specific design, several studies listed below provided examples of techniques and challenges in conducting a rigorous LCCA.

So et al. (2009) developed an integrated life-cycle cost management strategy for concrete bridges that considers corrosion related service life, performance-based management goals, cost-effectiveness of management options, and an integrated LCCA model. The study highlighted the importance of service life prediction and condition limit state definition used in assessing service life. The proposed framework was applied to a bridge in a marine environment. Monte Carlo simulation was adopted in the prediction of the bridge service life.

Thoft-Christensen (2007) discussed interesting statistics on user costs of several major U.S. bridges and highlighted the importance of these data to life-cycle cost-benefit analysis. The study concluded that life-cycle cost analysis was used in limited real applications mainly due to a misunderstanding among engineers and policymakers on its benefit. Insufficient data on bridge conditions, on deterioration of bridges, and on user costs also contribute to the sparse applications of such analyses. The study also touched on the difference between conducting LCCA for an individual structure and LCCA for an entire network inventory. The paper cited another study by Koch et al. (2001) showing that indirect user costs related to traffic delays and lost productivity to be more than 10 times the direct maintenance and repair costs.

Enright and Frangopol (1999) used a Bayesian updating technique to combine the information from inspection and engineering judgment. The proposed method can be helpful when reasonable assessment has to be made with a very limited amount of objective data. In this study, the influence of inspection updating on time-variant bridge reliability is illustrated for an existing reinforced concrete bridge and was shown to be realistic.

Kong and Frangopol (2003) used a modified event tree analysis to compute the probability of maintenance application over a given time horizon and the expected life-cycle maintenance cost of deteriorating structures. The method is reported to be more computationally efficient and simpler than direct integration of probabilistic functions or Monte Carlo simulation. With a simulated numerical testing of two different maintenance strategies applied to a large stock of about 1,500 bridges in the United Kingdom, the study concluded that preventive maintenance is more economical than relying on major maintenance activity planned over a long period of time.

Panesar and Churchill (2010) studied practical application of LCCA through case studies of precast culverts using ground granulated blast furnace slag in concrete mix. The study was unique for using CO2 production and absorption as one of the life-cycle performance gauges of the construction method and design. One of the conclusions that can be referenced in this study is that the capital cost and the discount rate have a much greater impact on the present cost than the maintenance cost in LCCA. The maintenance cost for yearly inspections and subsequent repairs, although continuous throughout the service life of the culvert, are quite small compared with the capital cost of the culvert itself.

From all the existing literature reviewed in this study related to LCCA, it is concluded that the current LCCA methods are still in the stage of framework development. There has not been any notable practical implementation of LCCA on short span concrete structures. Since it is a relatively new concept, it is very hard to find a bridge performance or cost database suitable for full calibration and verification of LCCA.

2.4 Performance Problems and Remedies

Because short span concrete structures are typically not considered to be critical, there are not many devoted studies on these structures, with the exception of several precast culvert studies mentioned earlier. The defects on these short span concrete structures were mostly gradual and related to concrete deterioration and leaking joints. Although these defects can be repaired through sealing and patching, short span structures typically do not have high priority when it comes to maintenance and repair. Due to the lack of resources and funding, such defects were often unattended until the entire structure needed to be replaced. However, following literature highlighted common long-term performance problems in concrete structures and possible practical remedies for prevention and restoration. This information is potentially useful for developing repair plans or for improving the design of newly installed structures.

Suwito and Xi (2008) presented detailed theoretical models for predicting the chloride invasion process for concrete specimens with a focus on microscopic behavior. The model was used to evaluate the time needed for concrete to develop micro-cracks due to the rust expansion of reinforcing steel. The examples in the study showed a very short time frame for initial cracks to develop. However, in applications where micro-cracks are not critical for structure functionality, the predicted service life from this type of chemical diffusion-based model is not directly applicable.

A topic more relevant to concrete bridge and culvert service life is the method used in crack repair. Tsiatas and Robinson (2002) examined a total of six different materials for repairing existing cracks on concrete, including cementitious systems, epoxy-based systems, and methacrylate products. Following the manufacturer's recommended approach, each product was used to repair concrete cracks with different widths and then subjected to a freeze-thaw cycle. Specimens repaired with the cementitious system were unable to resist any significant amount of fatigue-loading cycles. But the repair with epoxy and methacrylate products performed satisfactorily.

An NCHRP report (report 558) summarized some useful information related to the service life of bridge superstructures under corrosion damage. The topics covered included the inspection and evaluation method, modeling of service life, and repair strategy. As a manual, the report did not go into a detailed description of individual models or methods. One interesting point raised by the report is that the repairing of damaged sections may introduce a corrosion cell due to the new patched concrete's chemical makeup. The report also recommended certain measures for corrosion control based on the concentration of chloride ions at the steel level (indicated by SI), as shown in Figure 2.1. Lower SI value indicates more intense level of chloride ions close to steel. When extensive corrosion damage has been infected on the element, the report suggests replacement of the damaged component with a new element incorporating corrosion control measures.

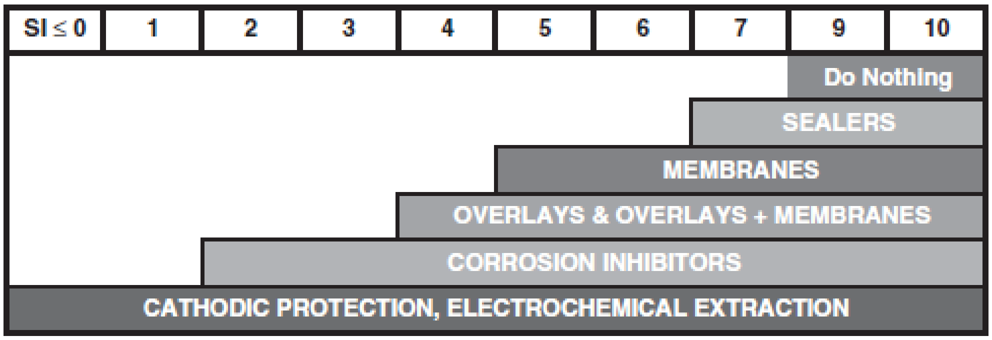

Figure 2.1 Corrosion control measures suggested by NCHRP558

Konda et al. (2007) developed a new steel-concrete hybrid precast system for short span bridges on low volume roads. The design utilized a multi-span arch-shaped cross section for an integrated beam-in-slab configuration, with the advantage of low cost and local availability. This system is constructed by Black Hawk County local forces in Iowa and brought substantial savings. Laboratory and on-site testing helped verify the structural performance of the system. Although it is a little too early to tell if the system will perform satisfactorily in the long term, it serves as a reminder that developing new and easy to implement systems is always an option for enhancing life-cycle cost performance on low-volume roads.

Hyman (2005) reviewed a list of rehabilitation measures for concrete corrosion defects, which are a major source of problems in Florida, on different components of a bridge. The measures covered in this study include full depth deck repair, pile jackets, cathodic protection, carbon fiber reinforced polymer bonding, and external post-tensioning. This study also reviewed typical crack repairing practices with high early strength concrete. As for erosion to culvert, the guniting procedure was recommended, which is essentially air pressure sprayed sand, water, and cement mix on the deteriorating surface of culverts. However, dewatering of the culvert will be needed if the portion to be repaired was below the water level. Finally, the study summarized the experience in extending concrete service life under corrosion, including increased cover, denser concrete, splash zone requirements, corrosion resistant reinforcing, and improved tendon protection. Although it is unlikely the techniques covered in this study will be frequently used on low-volume road short span structures, the experiences and recommendations should be taken into consideration when repair is needed.

Two NCHRP synthesis reports (reports 220 and 425) summarized the application of waterproofing membranes for concrete bridge decks in recent decades (report 220 reviews the practice before 1995, and report 425 updated the results until 2012). The reports summarized survey results from the state DOTs about the use of membrane systems on bridge decks, described lab and field testing and evaluation techniques, and provided design and selection criteria used for this detail. The membrane system generally has good performance and typically lasts over 15 years. The main defects of the membrane system are debonding and moisture penetration. The report cited the cost comparison conducted by Hearn and Xi (2007) for bridge deck systems and concluded that the deck with the membrane can reach superior cost-effectiveness due to extended service life expectancy compared with unprotected systems.

3. PERFORMANCE AND COST DATA COLLECTION

This chapter described the rationale and approaches used in this study to collect data for cost-effectiveness assessment of short span concrete bridges and culverts in South Dakota. The original research plan was targeted at collecting three categories of data shown in Table 3.1. Performance data can be used to develop a cost-effectiveness index and be later used as dependent variables in statistical and regression analysis. Passive and active control data covered the potential factors that will affect the performance of the structures. Data collection was conducted through a variety of avenues, including the South Dakota DOT maintained PONTIS bridge management database, customized surveys to the engineers and bridge owners, hard copy bidding records from the 1980s, and field surveys of structure defects. Data collection consists of a major portion of research efforts in this project. The collection process and summary of the results from each collection source are described in the sections below.

Table 3.1 Proposed Data Collection Category

Performance Data	Passive Control Data	Active Control Data
1. Bidding price 2. Period of construction 3. Inspection/maintenance cost 4. Repair/rehabilitation cost 5. Down time for maintenance 6. Down time for repair 7. Rating assigned to the structure and components 8. Specific problems affect functionality	9. Location 10. Years in service 11. Distance to construction material site (precast facility if precast) 12. Span requirement 13. ADT	14. Structural type 15. Design code implementation 16. Special features in design 17. Deicing schedule and procedure 18. Inspection/maintenance schedule

3.1 Concrete Structure Performance Data from PONTIS System

3.1.1 PONTIS System at South Dakota

Since its first release in 1995 by AASHTO, PONTIS is continuing to gain ground with widespread adoption among state DOTs. The system is compatible with National Bridge Inventory (NBI) inspection and data, while enabling detailed element level inspections. The program also provides a certain level of flexibility, such as letting each DOT define its customized data entry. At SDDOT, the PONTIS system was managed by the bridge design office. The database consists of all bridges and culverts in the state for all ownership. The database includes critical information, such as location, geometry, structural type, and NBI and component ratings from each inspection cycle. With the help of the bridge design office, all data that are available in PONTIS and related to the three categories listed in Table 3.1 were extracted for short span bridges and culverts. It was discovered there is certain information needed for this study that is lacking from PONTIS records, such as structure costs, which will be discussed later. Initially, the scope of the query was limited by following criteria:

1) Concrete bridge and culverts that were constructed after 1980
2) Bridges should be simply-supported with spans less than 100 feet

This initial query scope was decided during the initial panel meeting with the intension to 1) include as many data points as possible and 2) include only the structures that cost data can be retrieved from. Later in the project, it was discovered that additional query needs to be conducted to help estimate the expected service life of these structures.

3.1.2 Data Obtained from PONTIS System

Based on the initial query criteria, a total of 534 short span bridges and 594 culverts were listed from all structures in South Dakota. Most of these structures were owned and managed by the county, as shown in Figure 3.1.

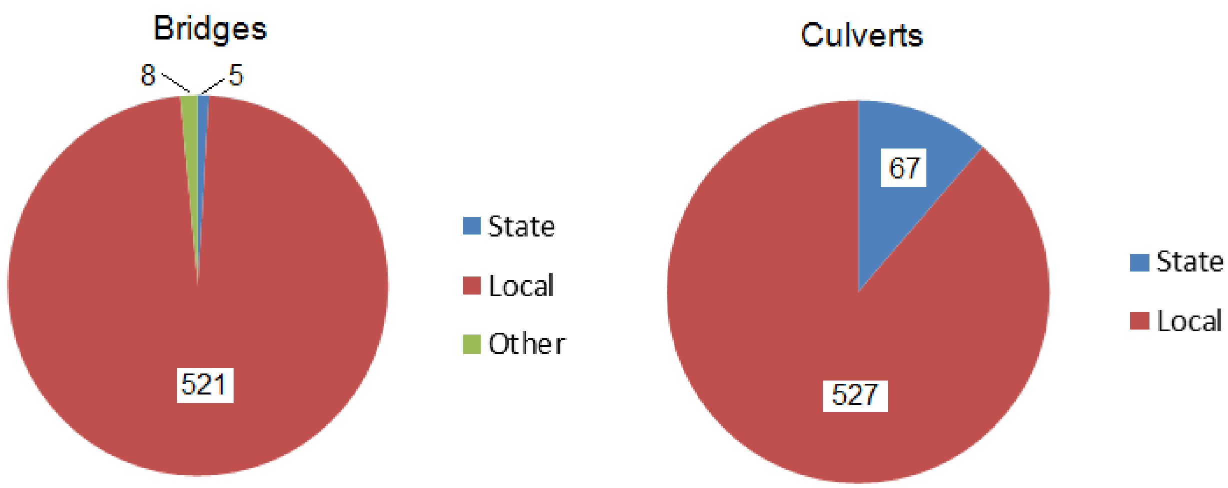

Figure 3.1 Composition of structure ownership

There is a rich category of information attached to each structure in the PONTIS database; the following data entries were requested during the query for this study:

Bridges: bridge id, owner, facility (the road the bridge belongs to), feature of intersect (the road or river the bridge crosses), location (latitude and longitude), material, design (structure type), year built, year reconstructed (replacement or major repair), structure length (structure may include multiple spans), span length, date of inspection, inspection ratings (including approach, superstructure, deck, substructure, and overall sufficiency ratings).

Culverts: Structure ID, owner, facility (the road the bridge belongs to), feature of intersect (the waterway culvert crosses), location (latitude and longitude), material, design (structure type), element key, year built, year reconstructed (replacement or major repair), structure length (structure may include multiple cells), culvert dimensions (width and length), date of inspection, inspection ratings (including approach, culvert, and overall sufficiency ratings).

The PONTIS database provided critical information within the planned data collection categories but was not able to satisfy all data needs for this project. The fulfillment of each data category after PONTIS query was listed below with a description about the problems associated with the data:

Passive control data

Location: Completed through PONTIS query, latitude and longitude of the structure were obtained through the query; the information of the road, which the structure carries, is also obtained.

Years in service: This information can be calculated based on year-built data in PONTIS. However, it was found that in the case of a bridge replacement, the same structure ID of the old structure was used for the new structure. Thus, certain information about the previous bridge was overwritten and lost. However, these overwritten/lost data are valuable for performing life-cycle cost analysis on bridges and culverts.

This was not possible in this study, but there might be a way to incorporate this data entry in PONTIS for future replacements.

Distance to construction material site: Not available. In theory, the distance between building and material site can be calculated based on bridge location. However, there is no record available in PONTIS about construction details. It is not possible to track the supplier for concrete batch or precast elements.

Span requirement: Completed through PONTIS query.

ADT: Completed through PONTIS query.

Active control data

Structural type: For initial query, the focus was to distinguish structures using precast elements and structures using cast-in-place construction method. This information is completed in PONTIS database.

Design code implementation: The code information is not directly available from PONTIS. However, the applicability of major code provisions can be tracked based on the year-built information of these structures. Based on information provided by the SDDOT bridge design office, the AASHTO LRFD Bridge Design Specifications were adopted by SDDOT in 2008. Prior to that, the AASHTO Standard Specifications for Highway Bridges were in effect in South Dakota. The bridge structures selected in this study were built after 1980. Only minor changes occurred in the Standard Specifications between 1980 and the 16th Edition (last edition) as related to the design of bridges and culverts similar to those included in this study. A manual check was conducted by the research team on design provisions related to concrete bridge and culvert structures in different versions of the AASHTO codes. There is no significant change in design practice for all structures included in the analysis.

Special features in design: Special design details or other features are not directly available from PONTIS. Gathering of this information was attempted later in surveys to local officials and manufacturers (will be discussed later). There is no significant change of details identified these short span structures.

Deicing procedure and schedule: This information is not available in PONTIS. According to SDDOT, the deicing operation was organized on an as-needed basis depending on the weather. There is no systematic record for the work done on these bridges. Questions about deicing procedures or related problems were included in the survey to local bridge owners. But quantitative data for deicing procedure and schedule were not retrievable in this study.

Inspection and maintenance schedule: Based the inspection date records in PONTIS, short span concrete structures will fall into a two- or four-year inspection cycle, depending on the structure ADT, condition, and age. Specific schedule is not available for maintenance, as such activities are minimal and only arranged on an as-needed basis. According to the surveys conducted later in this project, these short span structures were not maintained on a regular basis. When they become inadequate, they will often be replaced instead of being repaired.

Performance data

Most of the needed performance data related to life-cycle costs of short span concrete structures are not available in PONTIS. However, PONTIS does provide component and overall ratings for structures based on each inspection.

Bidding price: Not available in PONTIS.

Period of construction: No records kept in PONTIS.

Inspection/maintenance cost: This information is not available. Maintenance cost was not applicable to most of these short span structures. Inspection costs can be assumed based on inspection frequency. However, either of these cost types was believed to contribute significantly to life-cycle costs.

Repair/rehabilitation cost: No records kept in PONTIS and may not be applicable in most cases.

Down time for maintenance: No records kept in PONTIS and may not be applicable in most cases.

Down time for repair: No records kept in PONTIS and may not be applicable in most cases.

Rating assigned to the structure and components: Data collection on structure ratings was completed through PONTIS query.

Specific problems affect functionality: PONTIS system does not keep general records for specific problems. This information was retrieved later through surveys to inspectors and county superintendents and site visits, which will be discussed in detail later.

3.1.3 PONTIS Data Deficiency

As a tool primarily developed for bridge inventory management, PONTIS system contains a wide range of useful information that can help with decision making at the state and local level. However, based on the experiences of conducting PONTIS query in this study for cost effectiveness assessment, several improvements need to be made on the data collection strategy for PONTIS in South Dakota in order to make essential data available for life-cycle cost estimation.

First, it will be beneficial to keep the history of the structure replacement at a given site, instead of overwriting previous structure information with the new one. For example, there is a group of culvert structures put in after year 2000 to replace earlier built culverts from the 1940s. Such replacements provided a great opportunity to gain data on the full life-cycle performance and trends on the replaced structures. However, because the new structure uses the same structure ID as the old structure, the information of the replaced structure is not available once PONTIS updates.

Second, there are no cost data in the current PONTIS database. As most of the decisions at the state and local level were made based on safety and costs, it is reasonable and beneficial to start developing cost related data categories in the PONTIS database. Currently, the performance indicators in PONTIS only include inspection ratings, which are important because they directly indicate the safety of the structure. The other major component of building performance, life-cycle cost, or related data that can be used to derive life-cycle cost, should be incorporated in the PONTIS data collection. For the current study, the cost data were gathered from other sources provided by DOT.

3.2 Structure Cost Data

Life-cycle costs for bridge structure can be divided into initial construction cost and maintenance costs until the end of the bridge service life. As mentioned earlier, the maintenance cost component does not usually exist for short span concrete structures due to the nature of management of operation for such structures in South Dakota. The main factor that affects life-cycle cost effectiveness of these structures is the initial construction costs. As most of the projects were built by a contractor, the winning bidding cost for each project is the true cost induced in the construction. Thus, the winning bidding price was used in this study as the initial cost of the structure. All bidding price data used in this study were provided by

South Dakota DOT. Cost data for some of the locally owned structures were not retrievable because DOT does not keep all bidding records on local roads. Based on the initial query scope, among all 534 bridges included in the study, bidding prices for 167 bridges were retrieved. Among 594 culverts, bidding prices for 325 culverts were obtained.

3.2.1 Cost Data Before 1995

South Dakota DOT kept bidding records for a large portion of the bridge and culvert projects constructed before 1995. All of these records are in hand-written hard copies and scanned into PDF files for electronic storage. Figure 3.2 showed a sample of the bidding records.

SOUTH DAKOTA DEPARTMENT OF TRANSPORTATION ABSTRACT OF BIDS RECEIVED December 10 19 80 LETTING SHEET 1 OF 1 ITEM NO. 2

PROJECT NO. BRO 8015(2) FAS Bridge Replacement TYPE OF WORK Structure LENGTH MILES None

COUNTY Codington over Willow Cr. SE side of Watertown. CONTRACT TIME on or before 8-1-81

	ITEMS	UNIT	APPROX. QUANTITY	Engineer's Estimate		D.W. Proehl Const. Co. Sioux Falls, S.Dak.		Jerke Const. Co. Sioux Falls, S.Dak.	
001	MOBILIZATION	L.S.	1.000	6000.0000	6,000.00	3000.0000	3,000.00	3000.0000	3,000.00
002	INCIDENTAL WORK	L.S.	1.000	4000.0000	4,000.00	3000.0000	3,000.00	3000.0000	3,000.00
003	STRUCTURAL STEEL	L.S.	1.000	4000.0000	4,000.00	4000.0000	4,000.00	2500.0000	2,500.00
004	TRAFFIC CONTROL	UNIT	500.000	6.0000	3,000.00	5.0000	2,500.00	4.0000	2,000.00
005	UNCLASSIFIED EXCAVATION	CUYD	2497.000	1.0000	2,497.00	1.0000	2,497.00	3.0000	7,491.00
006	STRUCTURE EXCAVATION, BRIDGE	CUYD	83.700	25.0000	2,092.50	20.0000	1,674.00	20.0000	1,674.00
007	SPECIAL STEEL RAILING	L.F.	137.300	35.0000	4,805.50	35.0000	4,805.50	30.0000	4,119.00
008	60" PRE-STR CONCRETE CHANNEL	EACH	8.000	3800.0000	30,400.00	3500.0000	28,000.00	3500.0000	28,000.00
009	PRESTR CONCRETE PLANK (4X22)	L.F.	1364.000	15.0000	20,460.00	16.0000	21,824.00	16.0000	21,824.00
010	FURN STEEL PILES HP10X42	L.F.	580.000	14.0000	8,120.00	15.0000	8,700.00	13.0000	7,540.00
011	DRIVE STEEL PILES HP10X42	L.F.	580.000	3.0000	1,740.00	2.0000	1,160.00	2.0000	1,160.00
012	FURN ST TEST PILES HP10X42	L.F.	126.000	15.0000	1,890.00	18.0000	2,268.00	14.0000	1,764.00
013	DRIVE ST TEST PILES HP10X42	L.F.	126.000	4.0000	504.00	2.0000	252.00	3.0000	378.00
014	FURNISH ST WNG PILES HP10X42	L.F.	420.000	14.0000	5,880.00	15.0000	6,300.00	13.0000	5,460.00
015	DRIVE ST WNG PILES HP10X42	L.F.	420.000	3.0000	1,260.00	2.0000	840.00	2.0000	840.00
016	FURN STEEL PILES HP12X53	L.F.	228.000	19.0000	4,332.00	21.0000	4,788.00	30.0000	6,840.00
017	DRIVE STEEL PILES HP12X53	L.F.	228.000	4.0000	912.00	2.0000	456.00	2.0000	456.00
018	BANK PROTECTION GABIONS	CUYD	16.000	120.0000	1,920.00	100.0000	1,600.00	100.0000	1,600.00
019	MBE DEVELOPMENT	L.S.	1.000	1200.0000	1,200.00	1200.0000	1,200.00	1200.0000	1,200.00
	TOTAL BID				105,013.00		98,864.50		100,846.00
020	GROSS RECEIPTS EXCISE TAX	L.S.	1.000	1575.2000	1,575.20	1482.9700	1,482.97	1512.6900	1,512.69
	TOTAL OR GROSS SUM BID				106,588.20		100,347.47		102,358.69

	ITEMS	UNIT	APPROX. QUANTITY	Hollaway Const. Co., Inc. Mitchell, S.D.		Graves Const. Co., Inc. Melvin, IA		Dave Gustafson & Co., Inc. Sioux Falls, S.D.	
001	MOBILIZATION	L.S.	1.000	5000.0000	5,000.00	3000.0000	3,000.00	5000.0000	5,000.00
002	INCIDENTAL WORK	L.S.	1.000	3000.0000	3,000.00	4000.0000	4,000.00	6000.0000	6,000.00
003	STRUCTURAL STEEL	L.S.	1.000	3000.0000	3,000.00	4277.5000	4,277.50	2700.0000	2,700.00
004	TRAFFIC CONTROL	UNIT	500.000	4.0000	2,000.00	6.0000	3,000.00	7.0000	3,500.00
005	UNCLASSIFIED EXCAVATION	CUYD	2497.000	1.2000	2,996.40	2.0000	4,994.00	2.2500	5,618.25
006	STRUCTURE EXCAVATION, BRIDGE	CUYD	83.700	9.8000	820.26	15.0000	1,255.50	20.0000	1,674.00
007	SPECIAL STEEL RAILING	L.F.	137.300	42.4000	5,821.52	45.0000	6,178.50	40.0000	5,492.00
008	60" PRE-STR CONCRETE CHANNEL	EACH	8.000	3625.0000	29,000.00	3500.0000	28,000.00	3800.0000	30,400.00
009	PRESTR CONCRETE PLANK (4X22)	L.F.	1364.000	16.9000	23,051.60	17.0000	23,188.00	17.0000	23,188.00
010	FURN STEEL PILES HP10X42	L.F.	580.000	13.4000	7,772.00	13.0000	7,540.00	11.5000	6,670.00
011	DRIVE STEEL PILES HP10X42	L.F.	580.000	3.0000	1,740.00	2.0000	1,160.00	3.1500	1,827.00
012	FURN ST TEST PILES HP10X42	L.F.	126.000	14.0000	1,764.00	15.0000	1,890.00	11.5000	1,449.00
013	DRIVE ST TEST PILES HP10X42	L.F.	126.000	3.0000	378.00	3.0000	378.00	6.0000	756.00
014	FURNISH ST WNG PILES HP10X42	L.F.	420.000	13.4000	5,628.00	13.0000	5,460.00	11.5000	4,830.00
015	DRIVE ST WNG PILES HP10X42	L.F.	420.000	3.0000	1,260.00	2.0000	840.00	3.1500	1,323.00
016	FURN STEEL PILES HP12X53	L.F.	228.000	29.4500	6,714.60	35.0000	7,980.00	27.0000	6,156.00
017	DRIVE STEEL PILES HP12X53	L.F.	228.000	3.0000	684.00	3.0000	684.00	9.0000	2,052.00
018	BANK PROTECTION GABIONS	CUYD	16.000	193.0000	3,088.00	90.0000	1,440.00	135.0000	2,160.00
019	MBE DEVELOPMENT	L.S.	1.000	1200.0000	1,200.00	1200.0000	1,200.00	1200.0000	1,200.00
	TOTAL BID				104,918.38		106,465.50		111,995.25
020	GROSS RECEIPTS EXCISE TAX	L.S.	1.000	1573.7800	1,573.78	1596.9800	1,596.98	1679.9300	1,679.93
	TOTAL OR GROSS SUM BID				106,492.16		108,062.48		113,675.18

I CERTIFY THAT THIS IS A TRUE TABULATION OF BIDS RECEIVED [illegible] ADM. ENGR. TYPE CODE X081

Figure 3.2 Example records for bidding record abstract

It can be seen that the bidding record listed the project structure ID, location, cost items, estimated quantity of the work, and three estimates from design engineers and all the bidding companies. All costs occurred during the construction project is included in the record, including construction of the structure itself, traffic control, and mobilization of the work force. The total cost accurately reflected the owner's expense in completing the project. In this study, all bidding abstracts from 1980 to 1995 at DOT were manually reviewed. The company with the lowest total cost was assumed to be the final cost, as there is no record on the abstract indicating the winning bid. The costs obtained were linked back to the structures list from PONTIS based on structure ID. As shown in Figure 3.2, the vast majority of the short span concrete bridges were locally owned, so the cost data from bidding records are not complete.

3.2.2 Cost Data After 1995

The South Dakota DOT bridge design office helped to provide the cost information for bridge and culvert projects from 1996 and 2010, which is stored electronically by DOT. Both new construction and rehabilitation projects were included in the database. However, the data provided by DOT include all projects conducted during this period. Thus, a matching process was conducted manually to assign costs to short span structures. Only two rehabilitation projects for short span structures were found, which verified the comment from the survey (discussed later) that there is virtually no repair work for these short span structures. The difference between the electronically available data and the bidding cost is that the electronic cost data only consist of structurally related costs. The other costs, such as traffic control and mobilization, are not included and not available. Thus, the cost data are not the true costs of the construction project. A simplified adjustment was conducted (discussed in 6.2.3) to estimate this part of additional costs in this study based on the available data from before 1995.

3.2.3 Process Cost Data

Because the ultimate objective of this study is to compare structure type costs, the cost data for each structure must be processed to provide an equivalent comparable basis. The cost data obtained were recorded at the year of construction and must be brought up to current value while considering inflation. The size of the structure must then be taken into account as a larger structure will cost more but not necessarily have low cost effectiveness. Figure 3.3 illustrates the procedure adopted in this study to obtain a normalized unit cost for all structures.

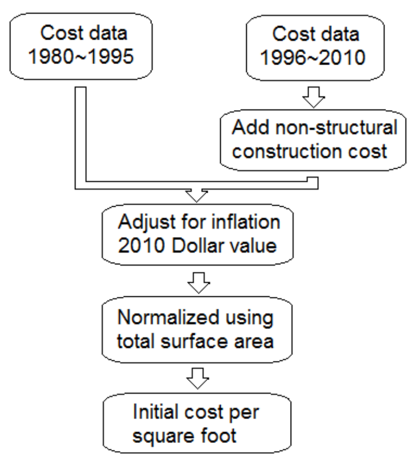

Figure 3.3 Procedure adopted to process the cost data

Adjustment for non-structural cost (for structures after 1995)

The adjustment for non-structural cost was only needed for projects after 1995. Because the actual data are not available, a factor was derived using the cost category listed in the projects before 1996. Twenty projects were randomly selected from the bidding abstract to obtain the ratio between total bidding cost and non-structural cost (including mobilization, incidental work, and traffic control). The distribution of the non-structural to total cost ratio is shown in Figure 3.4. The mean value of the obtained ratio was calculated to be 10.1%. Thus, a ratio of 10% was used to adjust the costs after 1996 to obtain the total project cost (by dividing the costs by 0.9). Although the non-structural cost was treated in a very simplistic way, it provided reasonable contingency and a level ground for cost-effectiveness comparison for projects from two different time periods.

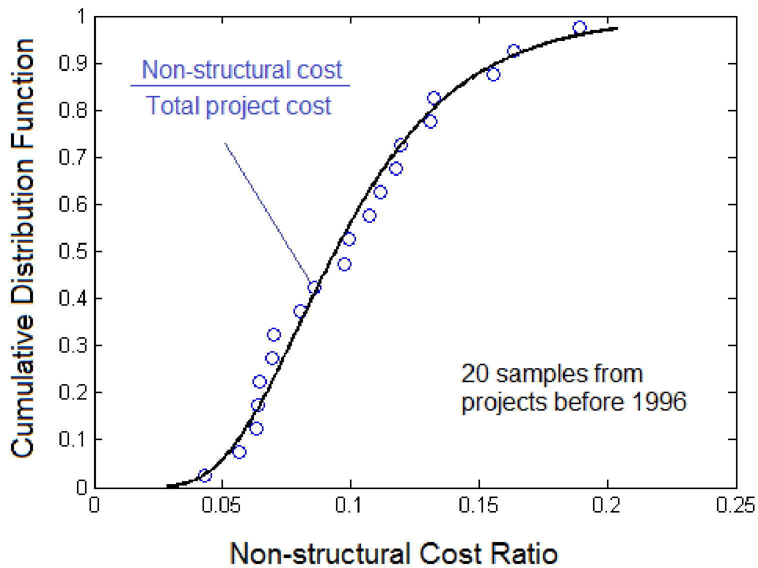

Figure 3.4 The ratio of non-structural to total project cost

Adjustment for inflation

The cost data were adjusted for inflation based on the year built. All costs in this study were converted to 2010 dollar value using the inflation rates listed in Table 3.2. Figuring inflation, $1.00 in 1980 is worth about $3.00 in 2010.

Table 3.2 Inflation rate for converting construction costs*

Year	989	988	987	986	985	984	983	982	1981	1980
Inflation	.8%	.1%	.7%	.9%	.5%	.3%	.2%	.2%	10.4%	13.6%
Year	999	998	997	996	995	994	993	992	1991	1990
Inflation	.2%	.6%	.3%	.9%	.8%	.6%	.0%	.0%	4.3%	5.4%
Year	009	008	007	006	005	004	003	002	2001	2000
Inflation	0.3%	.8%	.9%	.2%	.4%	.7%	.3%	.6%	2.8%	3.4%

* Historical inflation rates calculated based on average of monthly inflation rate data from http://inflationdata.com

Normalized by surface area

In order to compare the cost effectiveness of short span structures of different sizes, the converted total project present (2010) costs were divided by the surface area of the structure to generate the unit cost per square foot. The structure dimensions were obtained from the PONTIS system or GIS database of South Dakota (deck area is an entry of the database and can be used directly).

3.3 Data Collection through Surveys

Although most of the data related to design and rating of bridge and culvert structures are obtained from PONTIS, additional information was needed for this study, including owner preference and experiences, observed deficiencies, additional cost data, and potential improvement measures to increase service life. Customized surveys were designed for different interest groups in short span concrete structure construction and maintenance. The interviewees included county superintendents, bridge inspectors, and precast manufactures.

3.3.1 County Superintendent Surveys

The county superintendent survey was designed to identify the current practice, understand the needs and decision-making strategy of the owner, maintenance operation, and common defects experienced in the past. The county superintendents were first contacted by phone; the survey question list (See Appendix A) was then mailed to them to be filled out. The completed surveys were mailed back to researchers. Two attempts were made to contact superintendents who failed to complete the form. The response rate from the survey is below average: 21 out of 66 counties completed the survey. The results from the responses are summarized here.

It appears a little more than half of the counties (14/21) keep bidding costs of projects conducted. Of the 14 counties with the record, only six confirmed the availability of the cost data for research use. Thus, the research team decided not to retrieve these data since the amount of data obtained will not likely impact the final results significantly. About the same proportion of counties (16/21) also kept repair and maintenance records; but it is not clear if the records were on short span bridges and culverts or not. When asked about commonly encountered defects, nine counties did not report any problem, while others mentioned separation of elements along the joints, erosion, and rusting of culverts. This survey did not reveal any special details or design provisions that are worth adopting. Cut-off walls on large culverts were recommended by Hand County.

For future bridge projects, the overwhelmingly popular choice is precast girders. The reason for choosing these over cast-in-place structures is mainly time and cost saving. Only one survey preferred steel girder with cast-in-place deck because of previous experience. The same trend persists with new culvert construction. Some counties make more use of steel (metal) culverts than concrete. It is very apparent from the survey that the driving factor in local construction decision making is price, time, and ease of construction. When it comes to deciding on replacement of bridges and culverts, most superintendents depend on engineer or inspector recommendations.

The scanned copies of the superintendent surveys were available electronically with this report. These survey results reflected the owners experience and opinion toward different structural options. A summary of superintendent survey responses was organized in tables in Appendix B.

3.3.2 Bridge Inspector Surveys

The intention of conducting bridge inspector surveys was to gather information on common defects that may significantly reduce structure service life. The list of inspector contact information was obtained through a county superintendent survey. The inspectors were contacted before sending the survey questions (see Appendix A). The response rate for the inspector survey was very good. All 11 identified inspectors responded to the survey. The following paragraph summarizes the information gathered through this process. The detailed response from each inspector is available electronically with this report.

All inspectors reported the most commonly encountered defects in concrete bridges are spalling of concrete and corrosion of the exposed steel. The joint area of the precast elements is a high-risk region for corrosion. One inspector mentioned scour is a problem more critical than structural deficiency. Better quality control during construction is a commonly suggested remedy by inspectors for such defects. The response also indicated that deicing and chemical substances aggravated the problem. Replacement is often the only realistic option when deterioration is extensive. When the inspectors were asked about preference of CIP and precast systems, about one-third of the inspectors preferred CIP due to less chance for defects. The other inspectors either felt the two systems perform similarly or were unable to make a decision due to the lack of CIP bridges now in the inventory.

For concrete culverts, the inspectors suggested the problematic areas were mainly at joints for precast elements. The spalling and deterioration were observed along the water line or below the water. Culverts constructed in recent years were typically free of problems. Leaking joints were observed due to low quality control for construction. In general, notable defects only occur when the age of the culvert is more than 30-40 years old. The inspectors suggest the best way to reduce these defects is increasing the quality of both manufacturing and installation. All inspectors were responsible to provide recommendations to the owners for repair and replacement. The decision was typically based on the severity of the problem reflected in the PONTIS rating. The preference between CIP and precast culvert is not clear. Some inspectors prefer CIP culvert due to its good track record. Many felt the culverts typically perform very well as long as they are under 50 years. The performance of precast culverts was hard to gauge due to the short period in service and lack of solid data for long-term performances. The inspectors typically also serve as the engineering consultant at the county level for bridge and culvert design. It was indicated that when hydraulic condition allows, the local officials will prefer culverts over bridges for short span structures due to cost and time saving.

Detailed responses from the inspectors were listed in Appendix B for reference.

3.3.3 Precast Manufacturer Surveys

Phone interview surveys were conducted with two precast manufacturers in South Dakota, Gage Brothers in Sioux Falls and Cretex West in Rapid City. The interview questions were focused on special design detail changes or improvements for precast concrete elements. A questionnaire was prepared and sent to the two major precast concrete fabricators in South Dakota mentioned above. A copy of the questionnaire form is attached in Appendix A. Of the two precasters, only Cretex West fabricates prestressed double tees, prestressed bulb tees, and precast culvert units for short-span bridges and box culverts used on county roads in South Dakota. A brief summary of the survey results is listed below.

Precast Bridge Girders

The standard units produced for use in short-span bridges are precast prestressed double tee bridge decks (up to 70’ in length), precast prestressed bulb tee bridge decks (up to 99’ in length), and precast prestressed I-girders (up to 140’ in length). The most commonly used units by the counties are double-tee bridge decks in 23” or 30” depths and 3’-10” width, and bulb tee bridge decks in 6.0’, 6.5’, or 8.0’ widths.

Cost estimates for fabrication, transportation, and erection were provided by the pre-caster. The FOB cost of the above units (fall 2011 prices) ranged between $115/lf for the 23” deep double tee to $270/lf for the 8.0’ wide bulb tee.

The pre-caster reported serviceability issues in existing bridges, such as corrosion and concrete spalling, especially in the exterior deck of older units. However, bridges made with deck units manufactured in recent years were reported to have required little maintenance, presumably as a result of implementing some design/detailing changes. Changes to double-tee structures were implemented as of 1988 and beyond. The changes include the addition of end diaphragms, installation of bearing pads and dowel pins at the abutments and bents, use of galvanized bolts for the rail post connections in the exterior deck units, and use of higher strength concrete. The design live loads changed from HS20 to HL93 when SDDOT adopted the AASHTO LRFD Bridge Design Specifications in lieu of the Standard Specifications for

Highway Bridges. The pre-caster does have any suggest changes for future bridges other than those listed.

Precast Box Culverts

Precast box culverts are produced in single cell and double cell units. The sizes range from 6' x 3' to 14' x 14' for single cell units and from 7' x 3' to 14' x 14' for double cell units. No cost estimate for fabrication of box culverts was provided. This may be due to the significant difference in the unit price of different size units. The pre-caster was not aware of any serviceability issues or design concerns related to precast box culverts. However, the only change implemented was the use of fractured ledge rock aggregates (limestone and quartzite) instead of river rock in the concrete mix.

3.4 Field Survey of Bridge and Culverts

The survey of superintendents and inspectors revealed some typical defects on short span concrete structures. Two sites near Sioux Falls were selected based on inspector recommendations for field survey of defects. On October 7, 2011, the PIs conducted inspection of a double-tee bridge and a cast-in-place box culvert at selected sites to observe some of the deficiencies that had been reported in the inspectors' survey.

3.4.1 Double Tee Concrete Bridge near Sioux Falls

A single span (57'-0") prestressed concrete double-tee bridge is located approximately 0.2 miles north of Maple Street on Marion Road in Sioux Falls. The original structure was built in 1930 and was reconstructed in 1981. These double tees have deteriorated to the point where we have suggested that this structure should be inspected annually. The structure number is #50-170-188. However, this bridge is not included in the initial data collection scope since it was constructed in the 1930s (PONTIS system will recognize the structure as built in 1930 and reconstructed in 1981). The reconstruction simply replaced the original bridge with precast double tees. The deterioration in this bridge is a good example of a short span concrete structure service life cut short due to leaking joints. The double tees are connected during construction only at selected locations with steel plates, which have accumulated a significant amount of rust from moisture and chemicals as shown in Figure 3.5. One possible reason for the severe deterioration along the girder longitudinal joints may be the relative movement of individual girders under live load. This can be seen from the bridge overlay asphalt deck, which has the same crack pattern at the joint location (see Figure 0.5). This deficiency may be addressed by either a new precast detail to increase bridge lateral integrity or by application of a moisture barrier membrane system.

Figure3.5 Leaking joints and spalling of concrete

3.4.2 Cast-in-Place Concrete Culvert

The inspected box culvert was Structure #50-03-180 on the north side of Sioux Falls, located on the approach of Benson Road and SD 155. The culvert was a cast-in-place construction. It was built in 2000 and consists of twin 10' x 5' barrels. It crosses a concrete-lined drainage ditch and it carries local traffic from the main road to storage facilities.

The inspection revealed that the culvert walls, floor, and ceiling were in excellent condition with no apparent deficiencies. However, several cracks were noted in the wing walls at both ends of the culvert. Cracks were also observed in the concrete that extends from the wing walls and frames around the culvert's inlet and outlet. The cracks appear to be temperature and shrinkage cracks since they extend throughout the wall thickness. Figure 3.6 shows the culvert and the cracking in the wing walls. The observation revealed excellent performance of CIP culvert, especially when the time in service is short. This confirms the survey feedback received from inspectors about concrete culverts.

Twin Barrel Box Culvert

Cracking in the Wing Walls

Crack through the Wall Thickness

Cracking between the Culvert Wall and the Wing Wall Extension

Figure 3.6 Culvert cracks observed near wing wall extension

3.5 Initial Statistical Analysis of the Existing Cost Data

With the cost and structural rating obtained, preliminary analyses were conducted to identify possible trends in order to guide the modeling effort. The techniques utilized in the preliminary analyses were not meant to be complicated as the purpose is only to provide a big picture of the data. The first attempt is to plot performance indicators and control factors against each other in order to observe apparent trends. The performance indicators included construction price and current sufficiency rating. The plots for bridges and culverts are listed in the following figures.

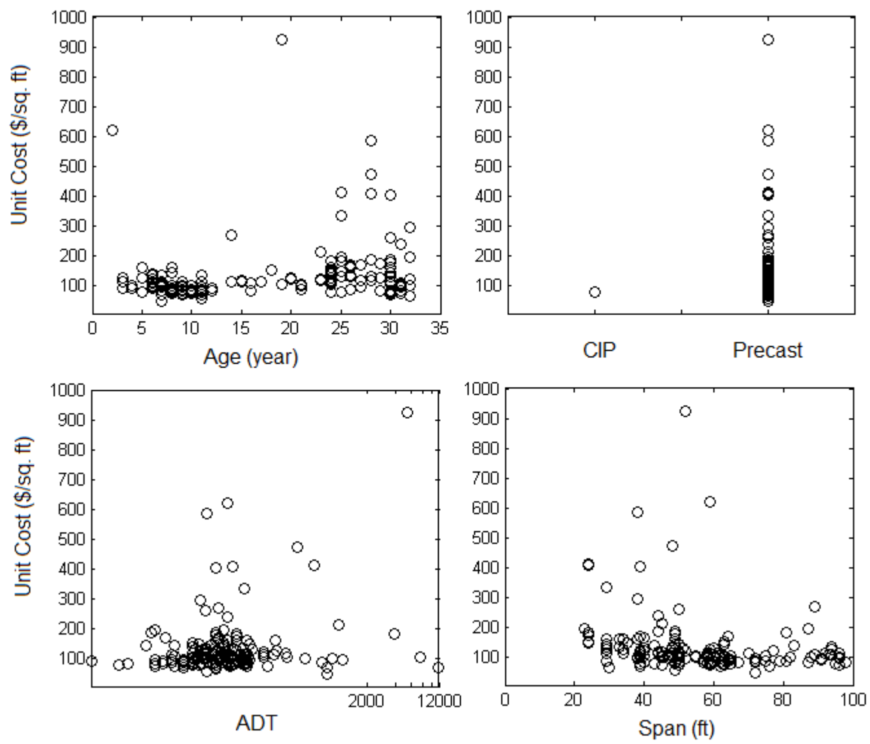

Figure 3.7 Correlation between control variables and unit cost (2010 value) for short span concrete bridges

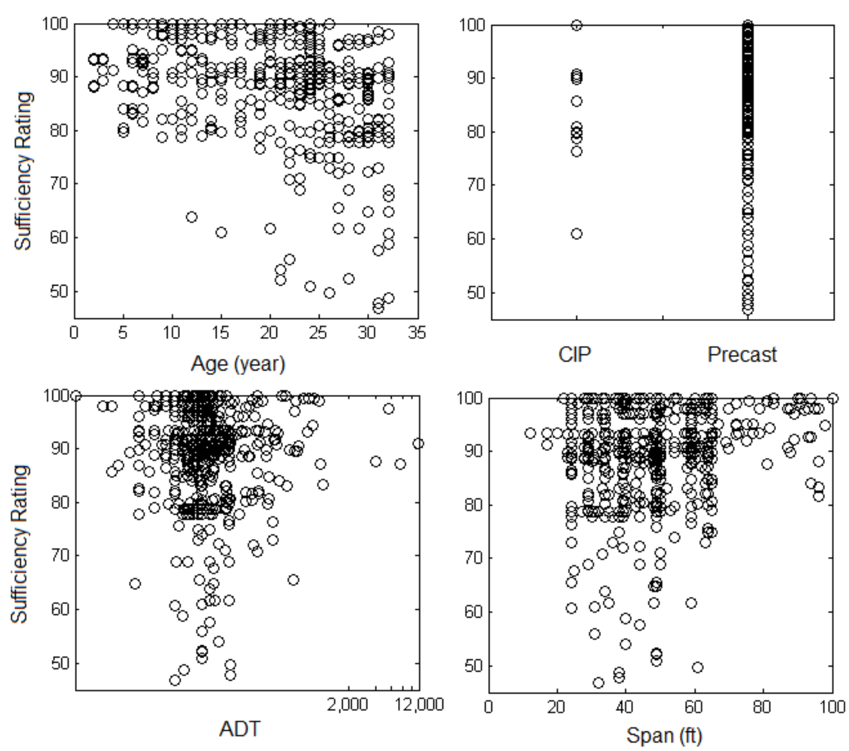

Figure 3.8 Correlation between control variables and current sufficiency rating for short span concrete bridges

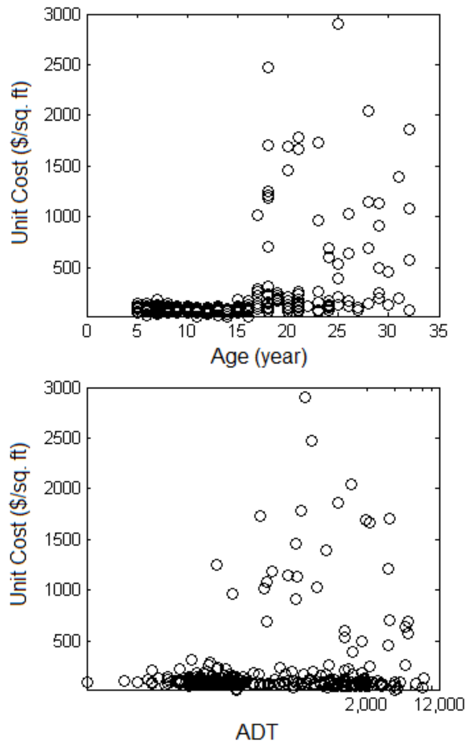

Figure 3.9 Correlation between control variables and unit cost (2010 value) for concrete culverts

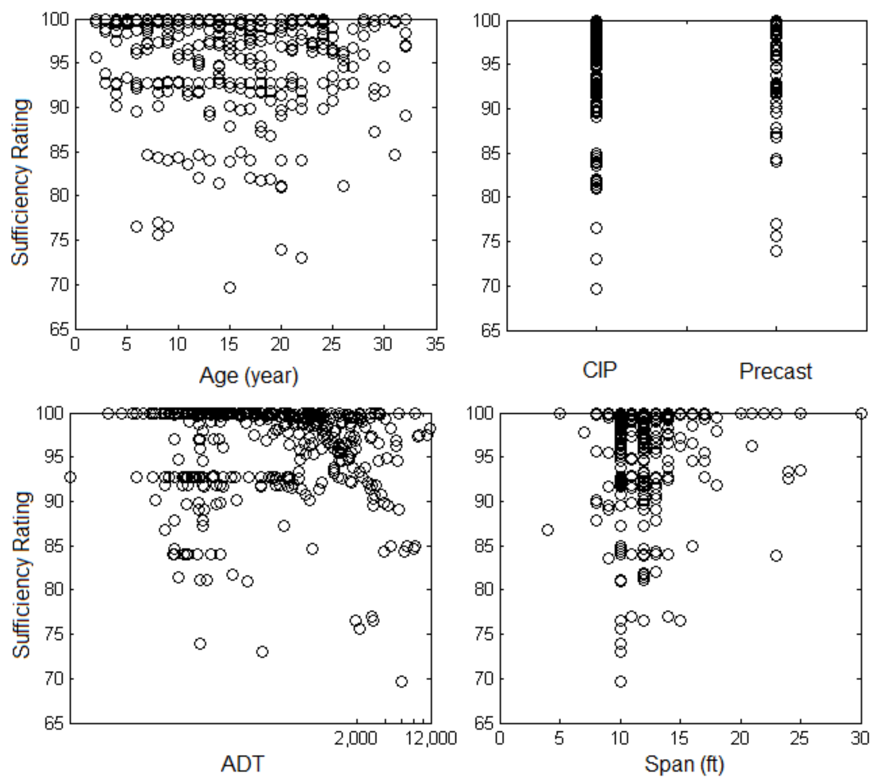

Figure 3.10 Correlation between control variables and current sufficiency rating for concrete culverts

As the correlation between the variables plotted in Figure 3.7 through Figure 3.10 was not apparent through visual inspection, it was necessary to conduct statistical analysis to see if each control factor really affects cost and rating performance. This analysis was done through traditional ANOVA (analysis of variance). The dependent variables were sufficiency rating and unit cost; the independent variables considered included year in service, type selection (CIP vs. precast), ADT, and span. The resulted ANOVA statistics are listed in Table 3.3 through Table 3.6.

Table 3.3 Culvert Sufficiency Rating ANOVA

Source	Sum Sq.	Dof	Mean Sq	F	Prob>F
Age	173.1	1	173.054	6.43	0.0115
Span	71.7	1	71.695	2.67	0.103
ADT	146.3	1	146.278	5.44	0.02
Type	0.6	1	0.552	0.02	0.886

Table 3.4 Bridge Sufficiency Rating ANOVA

Source	Sum Sq.	Dof	Mean Sq	F	Prob>F
Age	5824.9	1	5824.87	66.98	0
Span	2.7	1	2.69	0.03	0.8604
ADT	12.9	1	12.94	0.15	0.6998
Type	695.2	1	695.25	7.99	0.0049

If one uses 0.05 as the significance threshold, age, ADT, and structure type have some impact on structure sufficiency level. The results are different for bridge and culvert structures. Keeping in mind that the number of CIP bridges in South Dakota is very limited, the accuracy of this test might not be very high. As expected, the analysis did confirm that the age of the building has a significant impact on structure sufficiency rating.

Table 3.5 Culvert Cost ANOVA

Source	Sum Sq.	Dof	Mean Sq	F	Prob>F
Age	19070882	1	19070882	53.05	0
Span	474507.9	1	474507.9	1.32	0.2515
ADT	695354.2	1	695354.2	1.93	0.1653
Type	87872.5	1	87872.5	0.24	0.6214

Table 3.6 Bridge Cost ANOVA

Source	Sum Sq.	Dof	Mean Sq	F	Prob>F
Age	73294.5	1	73294.5	6.89	0.0095
Span	686	1	686	0.06	0.7998
ADT	8184.1	1	8184.1	0.77	0.3817
Type	8744.8	1	8744.8	0.82	0.3659

It can be seen from ANOVA for unit cost that age of construction has a consistently significant impact on the cost. However, the issue of lacking cost data is even more severe in a cost analysis case. In fact, there is only one data point for the bidding price of CIP bridges. The expected strong correlation between control factors and construction cost does not exist. When the independent variable is not significant based on ANOVA, the regression using these variables will not produce very useful results. This observation provided the justification for changing the original research plan outlined in the proposal.

3.6 Summary of Cost and Performance Data Collected

There are two major conclusions based on the assessment of available data obtained through PONTIS query and various surveys. First, composition and status of current short span bridges and culverts inventory in South Dakota is not suitable for conducting statistical inference on type selection between precast and cast-in-place methods. The number of short span cast-in-place bridges in South Dakota is very limited and does not provide the level of confidence suitable to directly assist decision making. And most precast culverts in South Dakota were constructed less than 40 years ago and do not generate enough experience on the performance and long-term cost of such structures. These situations were also reflected in the owner and inspector survey results. Second, there is no consistent source of cost data for existing current bridges and culverts owned by local counties and the state. The amount of retrievable data in PONTIS or other format is limited, making it hard to assess cost-effectiveness for these structures. The initial bidding costs were organized in different format. True cost to the owner is not recorded with structural costs. The rehabilitation costs were recorded only for projects after 1995.

Preliminary statistical significance analysis did not identify any consistently strong correlation between initially planned independent variables to cost performance. The age of the structure is a factor that affected cost even after converted to current values, but this is a passive control factor that is not very useful in developing type selection strategies for future projects. On the other hand, the owner and engineer surveys suggested that the current practice in type selection between CIP and precast format is initial-price driven (construction time directly translates to overall cost of the project). The long-term performance of these structures has only a limited impact on decision making and often relies on existing experiences (one survey indicated that a bad experience with a particular CIP culvert project affected type selection for culverts on future projects within that county).

Based on survey and interview results, the life-cycle cost structure for these short span structures is relatively simple compared with larger structures that require frequent maintenance. Most structures will be constructed and then inspected on a two- or four-year schedule. There is typically no repair or maintenance work until they are scheduled for replacement based on inspector’s or engineer’s recommendation. As a result, the only cost for most of these structures is the initial construction, thus the assessment of structure cost effectiveness becomes quite simple. The structure type that can provide the longest service life with the least amount of initial investment will be the preferred option from a long-term cost effectiveness standpoint. Any design improvements that can extend the service life of the structure while maintaining or reducing construction cost will be beneficial to structure cost effectiveness.

Although the county survey indicated there are repair cost data for work conducted on county-owned structures, it is not clear if these works were conducted on the short span structures of interest. Also, less than 10% of the counties confirmed the availability of cost data, so it is doubtful the added data will be representative of maintenance practices for these short span structures in the state. This issue was discussed during a technical panel meeting in 2012, and the researchers decided not to pursue this data collection at the local level based on panel suggestions.

Based on these findings, a change of research plan was proposed by the researchers and discussed during the Tech Panel meeting in May 2012. It is recommended that construction plans for typical design configurations be analyzed to develop a benchmark cost estimate for each type. Then the estimated costs will be combined with existing cost data within these categories to generate distribution of the unit cost for each type selection. This cost information will be combined with the estimated service life of the structure (obtained from regression analysis of structural ratings for all structure types) to generate life-cycle cost effectiveness for different structure types.

4. ANALYSIS OF ALTERNATIVE COST EFFECTIVENESS

This chapter describes the additional analysis conducted in this study in order to obtain cost effectiveness of different short span concrete structure options. After the examination of existing cost and performance data, the researchers felt a change in research plan was needed to produce reasonable results because the availability of cost data does not support the development of a type selection procedure based on regression analysis. This conclusion was reported to the Tech Panel during a meeting in 2012. A new research plan was developed based on feedback from the panel, which involves a new query criteria for PONTIS database to retrieve more data, and a more detailed focus on comparison of commonly used structural types (instead of just looking at CIP and precast option). A special type of construction consisting of precast I girders with CIP deck was requested by the Tech Panel to be included in the comparison. Since the cost effectiveness of short span concrete structures is primarily determined by initial construction cost and service life, the Tech Panel suggested expanding the scope of the data collection on structures built before 1980 so that long-term performance over 30 years can be established. These changes resulted in a new query of the PONTIS system with following criteria:

- Concrete structure
- Bridge or culvert
- Total structure length <200 feet
- In South Dakota

This updated query included all concrete short span structures with a total length structure less than 200 feet in the SD PONTIS database, which also includes multiple-span precast girder bridges with CIP deck. Although the cost data for most of these bridges are not available, this comprehensive query will provide critical information on long-term performance through rating of these structures over 90 years.

4.1 Long-Term Structural Performance of Bridge Alternatives

4.1.1 Queried Representative Structure Types

The queried structures include 1,223 culverts and 2,400 bridges dating back to the early 1900s. Based on Tech Panel recommendations and PONTIS design categories, six main construction alternatives for bridges and culverts were identified. The breakdown of these types was listed below, with the total number of structures in each type in the parentheses.

Culvert has two types:

- Cast-in-place culvert (989)
- Precast culvert (234)

  Bridge has four types:
- Concrete slab bridges (1261): Almost all of these structures are CIP reinforced concrete systems. They are also continuous bridges if they have multiple spans.
- Prestress tees (753): These bridges are simply supported without CIP deck.
- Prestress I-girders with CIP deck (100): This type is specially mentioned in the Tech Panel meeting as it is a relatively new construction practice that was believed to have better performance than other precast bridges.
- Reinforced concrete channel (286): These bridges are built with precast concrete channels. The member is not prestressed, does not have CIP deck system, and is simply supported.

The composition of different structure types in the new query is shown in Figure 4.1. Based on the recommendation of the Tech Panel, the bridge performance comparison for the newly queried data was conducted using individual component ratings, including deck rating and super-structure rating. Sufficiency rating is not used here because, overall, it does not necessarily reflect structural deficiency problems of interest to this study. For culvert structure, the comparison was conducted using the culvert rating. The results presented here are the CURRENT ratings of the bridge and culverts from the inspections conducted most close to current date. It is most likely all these ratings are from inspections after 2008.

There are other performance measures available in PONTIS, including a health index calculated based on component rating value. However, an overall performance index that does not differentiate specific problems was not preferred in this study. The health index was found to be strongly correlated to sufficiency rating and was not used in this study.

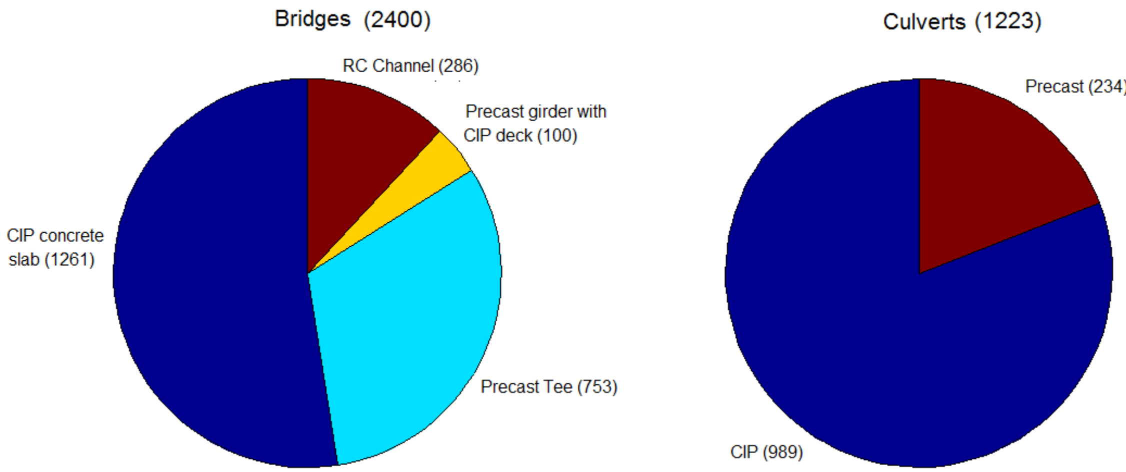

Figure 4.1 Types of Transverse Contraction Joints Considered in the Study

4.1.2 Performance Assessment over Time (Bridges)

Since bridges and culverts are quite different in their performance at the component level (culverts do not have deck or superstructure rating). The comparison of their performance was done separately. The following plots (Figure 4.2 and Figure 4.3) compared the deck rating and super-structure rating of all bridge types. Note that the component rating is a number between 0 and 9, with the higher number indicating better condition.

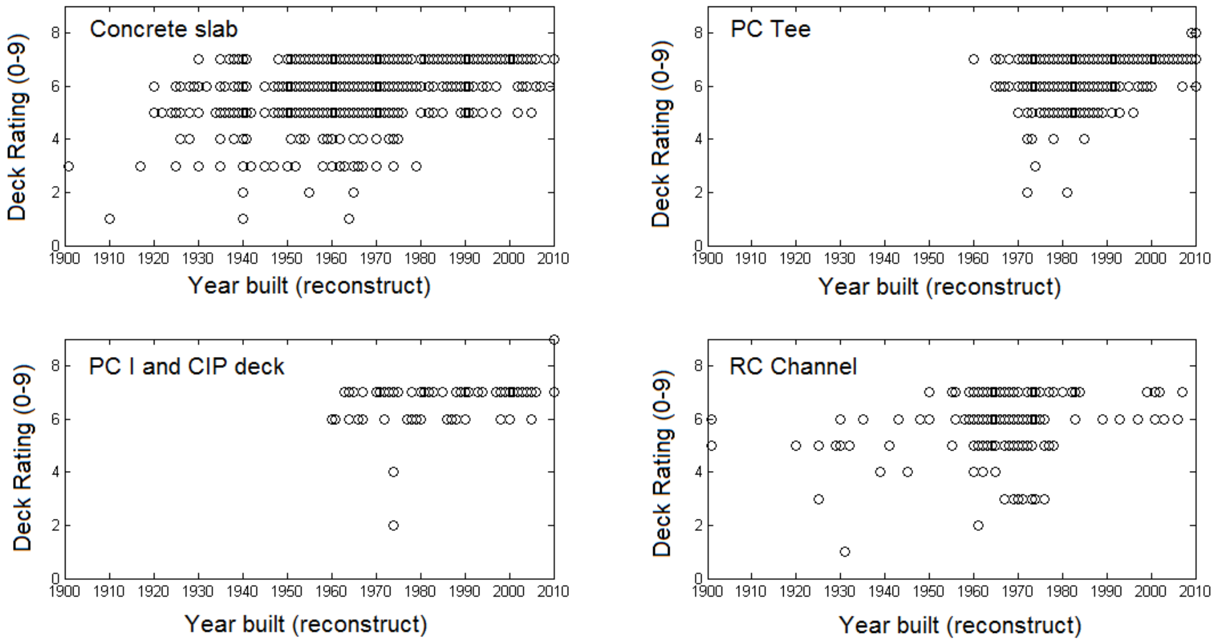

Figure 4.2 Bridge deck rating comparison breakdown

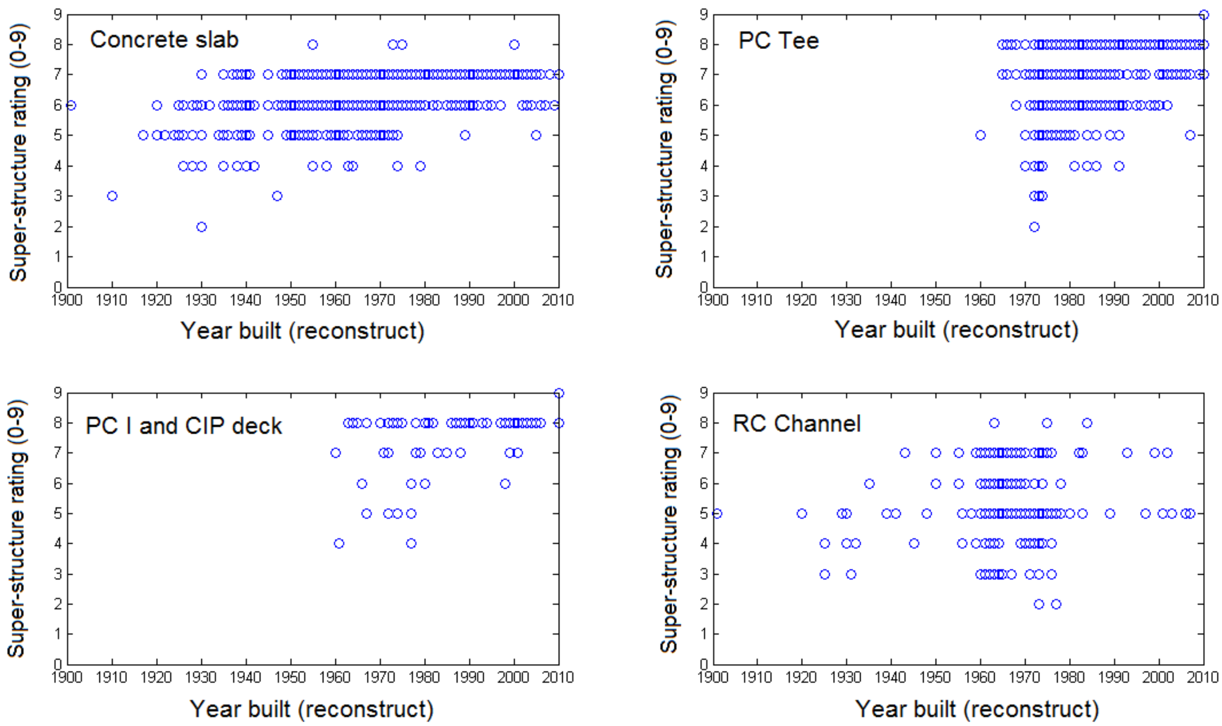

Figure 4.3 Bridge super-structure rating comparison breakdown

From these plots, the trends of structural components rating over time can be observed. In addition, the popularity of particular construction types in a given period can also be estimated. One can see that concrete slab bridge type has been quite frequently used since the 1920s; and a gradual trend for rating deteriorating over time can be clearly seen. Prestress tee and I girders were not in existence until after the 1960s, among which I girders with CIP deck showed very good resilience over time. RC channel bridge type was once popular from the 1960s to 1980s but was not adopted frequently in recent years, possibly because of the low rating from those 30- to 40-year-old structures. It is very clear that structure age has a significant impact on the rating. Statistical analysis will be conducted in later sections to establish the relationship between structure age and component ratings. In this section, the first question to be answered is if one bridge type performs better than others in the long term.

One interesting observation from the trends of structure rating is a sudden rating drop after a certain age. If similar plots were constructed with a sufficiency rating (Figure 4.4), it is more apparent that for structures built after 1990, there is barely any deterioration (most bridges rate above 80%). For structures before 1990, a drastic drop in rating was observed for all bridge types. Recall that the rating is conducted by bridge inspectors in a subjective manner. As a result, there might be some level of subjectivity in the rating judgment (e.g., if a bridge is more than 20 years old, the inspector might be more critical during inspection because he or she is "expecting" some defects).

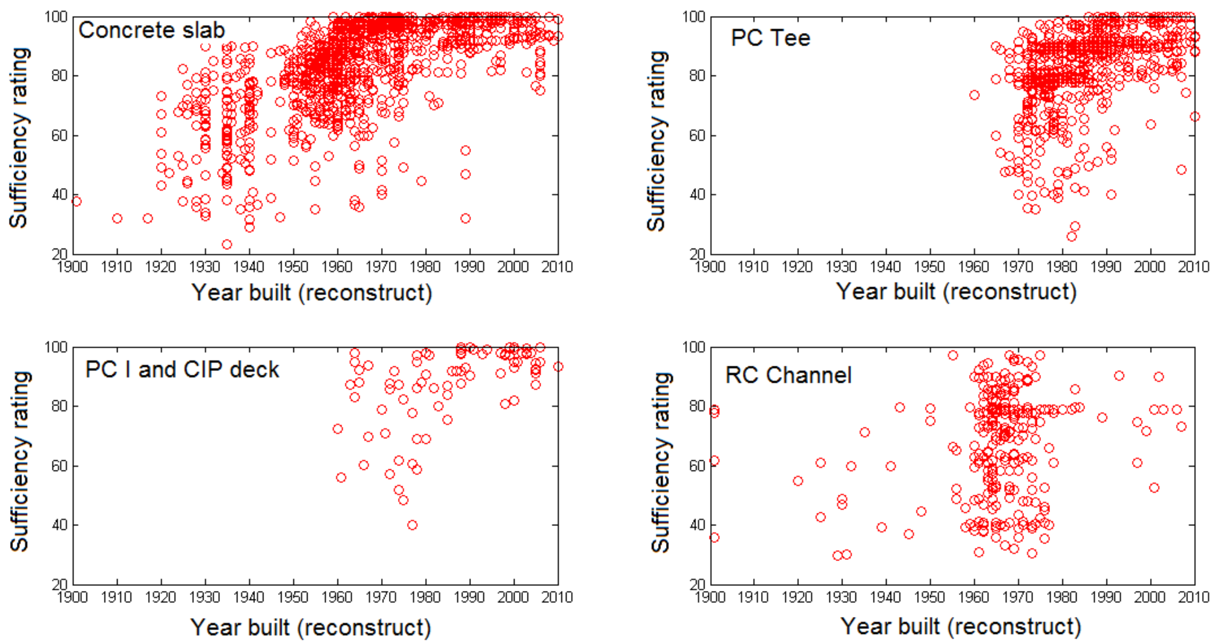

Figure 4.4 Bridge sufficiency rating comparison breakdown

In order to answer the question about relative comparison of the performance, ANOVA was conducted between different types. A comparison using all structures within a type is not reasonable because some bridge types (e.g., prestress members) are not available before 1960. There will be little meaning to compare the rating of concrete slab bridges constructed before 1960 with some of the newer types. Due to this consideration and also the issue of potential subjectivity in rating, comparison of bridges in two equivalent "duration groups" were developed to identify the more preferable type in the same time horizon.

Group 1: All bridges constructed after 1990

This is a "new structure" category. ANOVA for this sample pool will reveal if the performance of different bridge types is statistically different in short-term performance of the bridge deck and super-structure rating. In other words, the comparison is focused on learning if there will be a difference in 20 years for different bridge types.

Group 2: All bridges constructed between 1960 and 1990

This is an "old structure" category. ANOVA for this sample pool will reveal if the performance of different bridge types is statistically different in long-term performance of the bridge deck and super-structure rating. In other words, the comparison is focused on finding out if there will be a difference in 50 years for different bridge types.

It is not feasible to evaluate bridge alternative performance over 50 years based on historical data, because some of the bridge types did not have such a long history in South Dakota.

The comparison between these groups was conducted with ANOVA, which is basically a statistical test used to accept or reject a hypothesis that the mean values of two or more sample groups are equal. When ANOVA P>F statistics is below a threshold (5% is typically used), it is felt to be confident that the two groups have different mean values (Reject H_0 Hypothesis). However, ANOVA does not directly indicate if this difference is of any significance to engineering applications. For example, if one structure type has a sufficiency rating average score of 88%, and the other one has an average score of 90%, when enough data from these two types are obtained and put through ANOVA, eventually the result will show that these two types have different mean values based on statistic testing. But whether an engineer will consider this two-point difference to be significant in an engineering application will need further analysis, such as considering the cost. In other words, the "statistical significance" used with ANOVA simply refers to the level of confidence to say that the average rating values from two or more structure types are different. Thus, the rating distributions from different bridge types are also shown below with box plots in order to indicate their engineering significance. The comparison results are discussed in the following section.

Group 1 result

One important issue raised by the Tech Panel is the performance of Prestress I-girder with CIP deck. The Tech Panel is interested in its comparison with other alternatives. To answer this question, ANOVA was performed only between each of the type combinations, and the results are listed in Table 4.1. The box plot of the sample data distributions are shown in Figure 4.5. Although only samples after 1990 were used, the size of the sample pool (sample pool size marked on box plots) is reasonable. Note in the box plot, the borders of the box represent 25% and 75% percentile values, the red line indicates median. With most samples being integer numbers, the box can collapse into a single line for some types. If one looks at the average rating from four groups (calculated from all data points from each type, marked on Figure 1.5), the RC channel type definitely underperforms when compared with other types.

Table 4.1 ANOVA results between two types for bridge (short term)

Deck rating: Individual ANOVA comparison results		
Comparison group	Is one better than the other?	Pr>F compared to 5%
PI+CIP deck vs. Concrete slab	No difference	6.85%
PI+CIP deck vs. Prestress Tee	No difference	84.2%
PI+CIP deck vs. RC channel	PI+CIP deck is better	0.5%
Prestress Tee vs. Concrete slab	PT is better	0.3%
Super-structure rating: Individual ANOVA comparison results		
Comparison group	Is one better than the other?	Pr>F compared to 5%
PI+CIP deck vs. Concrete slab	PI+CIP deck is better	1.3e-36%
PI+CIP deck vs. Prestress Tee	No difference	5.19%
PI+CIP deck vs. RC channel	PI+CIP deck is better	4.5e-15%
Prestress Tee vs. Concrete slab	PT is better	6.1e-37%

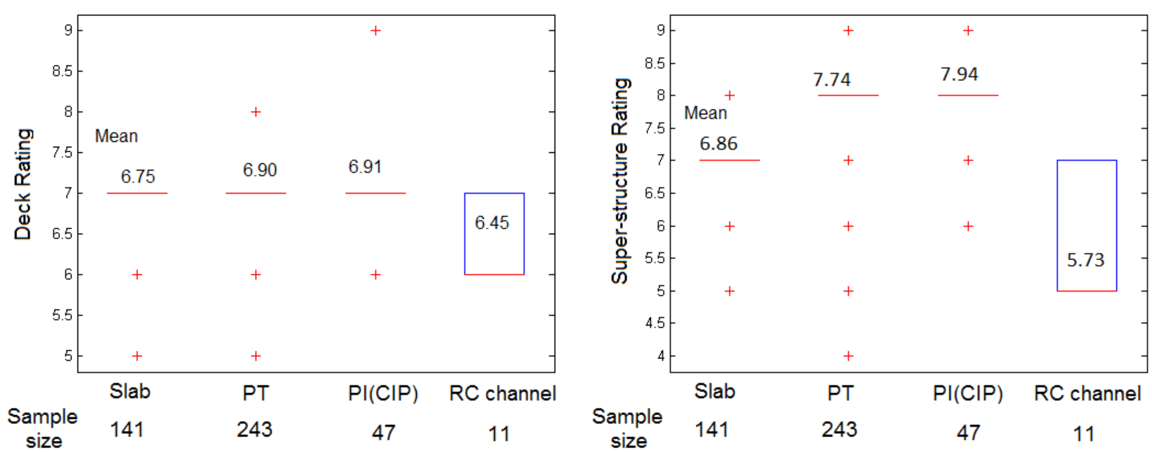

Figure 4.5 Group 1 comparison between bridge types

Group 2 result

A similar analysis procedure was applied to Group 2 bridge samples. The ANOVA results are summarized in Table 4.2 and the box plots are shown in Figure 4.6. In the long term, Prestress tee and Prestress I with CIP deck outperform the other two options.

Table 4.2 ANOVA results between two types for bridge (long term)

Deck rating: Individual ANOVA comparison results		
Comparison group	Is one better than the other?	Pr>F compared to 5%
PI+CIP deck vs. Concrete slab	PI+CIP deck is better	0.24%
PI+CIP deck vs. Prestress Tee	No difference	15.9%
PI+CIP deck vs. RC channel	PI+CIP deck is better	0.29%
Prestress Tee vs. Concrete slab	PT is better	4.2e-4%
Super-structure rating: Individual ANOVA comparison results		
Comparison group	Is one better than the other?	Pr>F compared to 5%
PI+CIP deck vs. Concrete slab	PI+CIP deck is better	7e-15%
PI+CIP deck vs. Prestress Tee	PI+CIP deck is better	5%
PI+CIP deck vs. RC channel	PI+CIP deck is better	1.5e-17%
Prestress Tee vs. Concrete slab	PT is better	2.6e-18%

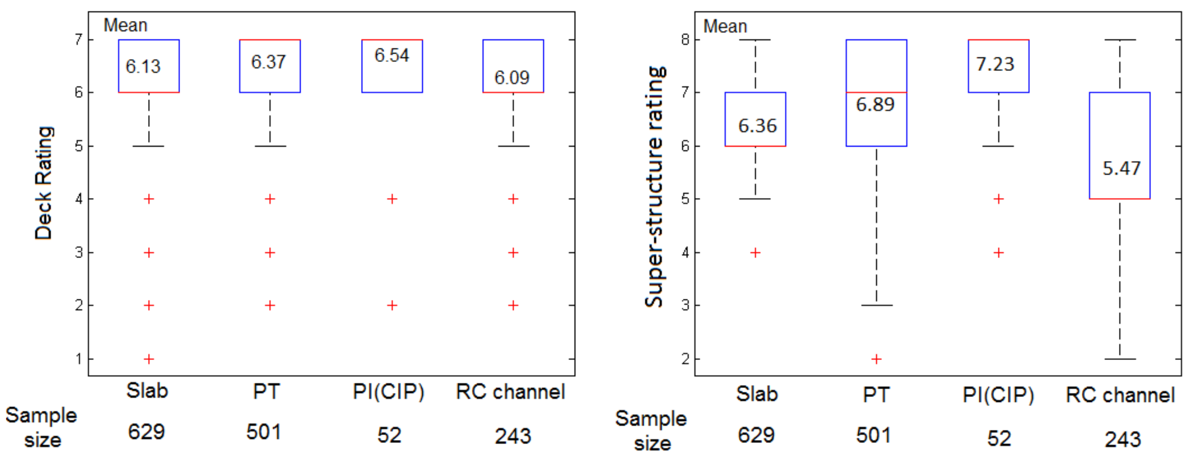

Figure 4.6 Group 2 comparison between bridge types

4.1.3 Performance Assessment Over Time (Culverts)

Figure 4.7 shows the culvert rating and sufficiency rating breakdown for two types and for each construction year. The data seem to indicate what has been brought up by inspectors: PRC culvert has too short of a track record to show any significant performance problems. The joint problem was mentioned by many inspectors, but this emphasis may be because it is the only problem this structure has so far. This problem does not seem to drag down the rating of the precast culvert structure. A separate joint performance rating might be introduced in PONTIS for culvert structures in the future.

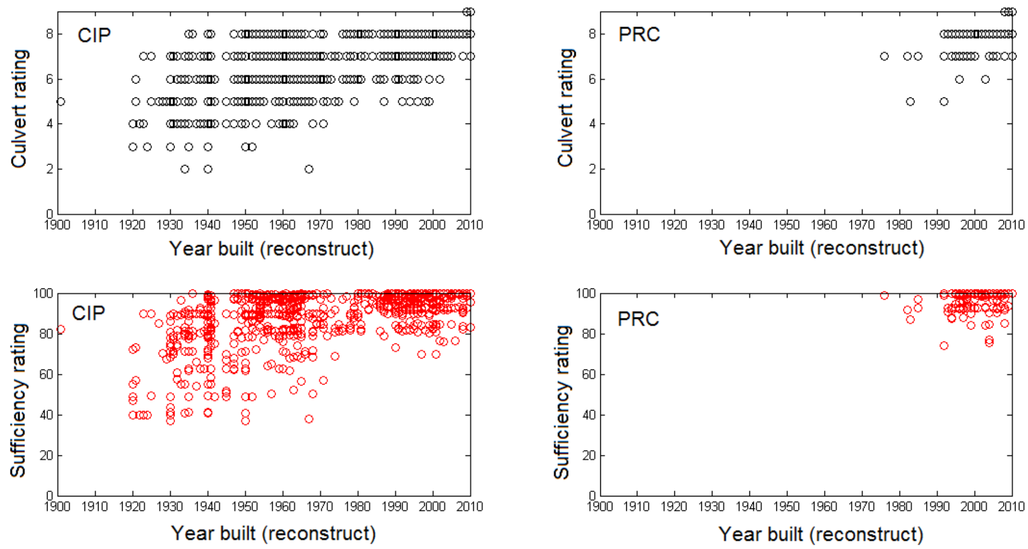

Figure 4.7 Culvert rating comparison breakdown

Similar analysis procedures were conducted for culvert structures, including the ANOVA and box plots (Figure 4.8). However, the culvert structures were quite different from bridges. Almost all precast culverts were constructed after 1990. Thus, there was just one duration group for comparison. Also, there are only two types (CIP and precast) within culverts. The precast culverts and CIP culverts constructed after 1990 were included in this analysis. The rest of the earlier CIP culverts were excluded from the comparison. These historical rating data were used to develop estimation of service life in later sections.

The ANOVA for culvert rating data after 1990 (576 samples, 348 CIP, 228 PRC) indicates significance between two types (ANOVA with sufficiency rating has P>F: 0.3%; ANOVA with culvert rating has P>F: 0.2%). Surprisingly, based on the mean values, PRC seems to be getting better average ratings even with joint problems. Out of curiosity, ANOVA was also conducted for very new culverts (using only samples constructed after 2000, less than 10 years of age). This analysis showed that type is not significant (Pr>F: 9.9%), i.e., the performance is the same.

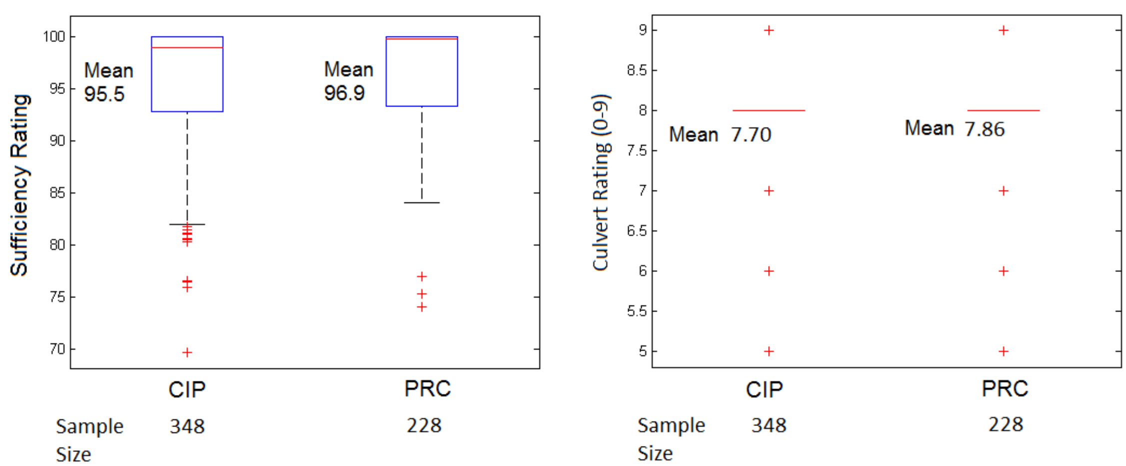

Figure 4.8 Culvert sufficiency rating box plot

4.1.4 Performance Summary

A summary of observations on the analysis conducted on the existing performance data was presented in this section. This part of the analysis focused on structure performance instead of cost, because the cost data for structures from before 1980 were not collected. The cost comparison for these different categories limited to after 1980 will be presented in later sections.

For the bridge types considered, RC channel type performs worst in both the short term and long term based on deck rating and super-structure rating assessment. Thus, it is not recommended to use this type of structure in the future. In fact, the use of this bridge type was once popular but has been fading out from construction practices in recent years. Considering performance of bridge deck, prestress I-girder with CIP deck is better than concrete slab configuration but is equivalent to prestress tee. When looking at performance of bridge superstructure, prestress I-girder with CIP deck is equivalent to prestress tee in the short term. In the long term, prestress I-girder with CIP deck is better than all other options. Concrete slab bridge has the lowest performance in both the long and short term.

Comparing precast and CIP culverts, the performance seems to be equivalent in the short term (10 years). Although the issue with joints seemed to be a major problem based on inspector survey, it does not affect the rating assigned to these culverts. The statistical analysis indicated that precast culverts have better ratings than CIP culverts in 20 years of service life.

4.2 Cost Estimation for Typical Design Alternatives

Due to the nature of construction and maintenance practice for short span concrete structures, two factors were deemed to be critical in assessing their cost effectiveness. The first is the initial construction cost, which can be represented by the winning bidding price. The second factor is the service life of the structure before it has to be replaced. Because there is essentially no repair or maintenance activity conducted for these structures, the structure type that will produce the least average cost over its service life will be the most cost-effective one. In order to help develop a guideline for type selection, all possible structure type options for a given short span concrete project were explored; the initial cost for each design option was calculated and combined with existing cost data to develop empirical distribution for each option. Later these cost distributions will be combined with service life distributions to generate cost-effectiveness statistics for decision making.

Initial construction cost was grouped for design options for various span length ranges. For each span length, we can potentially have three alternatives for bridges and two alternatives for culverts. Bridge types can be CIP concrete slab bridge, prestress tee bridge, and prestress I-girder with CIP deck bridge. The RC channel option is not considered here due to its poor performance and diminishing trend in SD construction practice. For culverts, the options are simply CIP culvert and precast culvert.

In order to obtain cost estimation for structures that do not have cost records, one bridge structure from each category was selected and its construction plan was requested from DOT. Based on the construction plan, project cost estimation was conducted by a graduate student under the supervision of an experienced local contractor. The intention of the estimation was to provide at least a basis for cost estimation for each category. However, the construction plan of some of the bridge groups cannot be retrieved. In the end, costs for representative structures from most of the categories were obtained (see Appendix D for a summary of estimated costs for these representative structures).

As shown in Table 4.3 and Table 4.4, a total of 27 categories were established in this study as the potential structure alternative selection. The distribution of existing structures within the category based on PONTIS data is also listed in the table. The number in parentheses is the number of structures in each category that have cost data (including cost estimates based on bridge plan). Apparently, the lack of cost data makes it impossible to compare cost effectiveness between certain categories, such as CIP slab bridge and other bridge types.

Table 4.3 Number of culverts in each subcategory (culverts have cost data)

Structure span	CIP culvert	Precast culvert
<30 ft	612 (127)	187 (76)
30~50 ft	335 (88)	39 (13)
>50 ft	42 (18)	8 (3)

Table 4.4 Number of bridges in each subcategory (bridges have cost data)

Structure span	CIP slab	Prestress Tee	Prestress I & CIP deck
<30 ft	44 (0)	55 (7)	2 (0)
30~50 ft	125 (1)	326 (37)	30 (3)
50~70 ft	125 (1)	200 (36)	13 (6)
70~90 ft	153 (1)	59 (13)	20 (12)
90~110 ft	244 (1)	59 (14)	16 (9)
110~150 ft	378 (1)	40 (9)	6 (1)
>150 ft	192 (1)	14 (9)	13 (5)

These estimated values were used as mean of the cost distribution for each category if no historical data were available. When there are historical cost data within the category, the estimated cost was simply counted as an additional sample. The distribution parameters of unit cost for each category were obtained based on least-square fit of the cost data using a lognormal distribution model. Figure 4.9 and Figure 4.10 show the fitted distribution of the cost data for selected categories. Table 4.5 and Table 4.6 list the parameters for each cost distribution, together with the mean value calculated based on the fitted parameter. The overall average initial unit costs for all categories are listed in Table 4.7.

Table 4.5 Lognormal fitted parameters for culvert costs

Structure span	CIP culvert			Precast culvert		
	sigma	mu	Mean	sigma	mu	Mean
<30 ft	0.93	4.95	216.94	0.35	4.40	86.45
30~50 ft	0.33	4.56	100.92	0.13	4.51	91.97
>50 ft	0.75	4.62	134.62	0.18	4.21	68.45

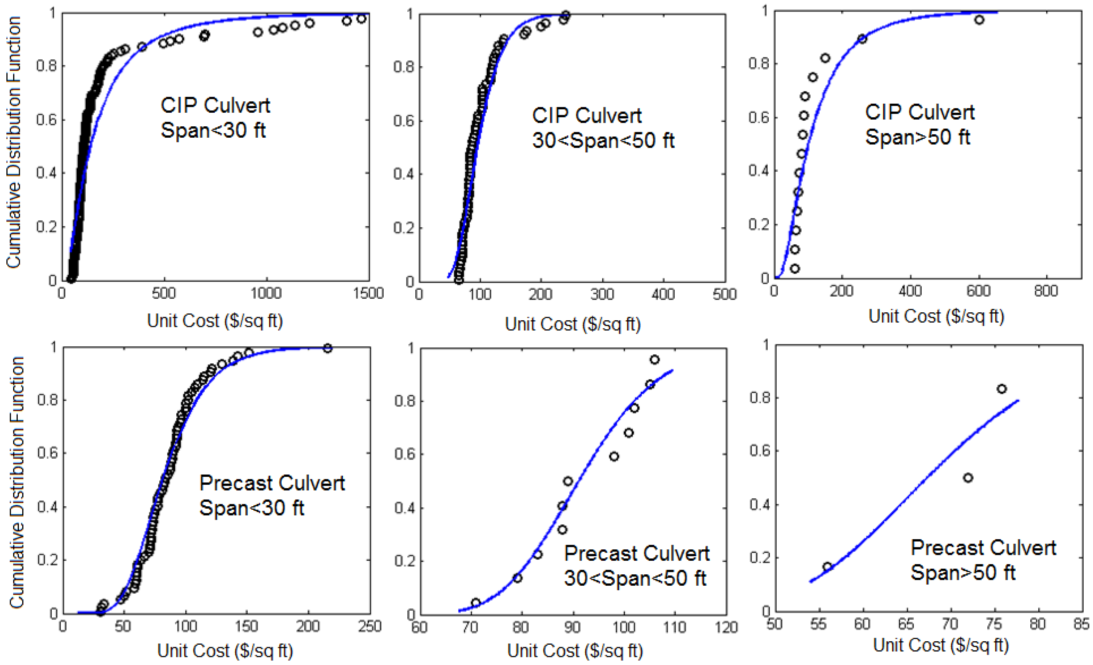

Figure 4.9 Culvert cost data and fitted lognormal distribution curves

Table 4.6 Lognormal fitted parameters for bridge costs

Structure span	CIP slab			Prestress Tee			Prestress I & CIP deck		
	sigma	mu	Mean	sigma	mu	Mean	sigma	mu	Mean
<30 ft	N/A	N/A	N/A	0.71	5.25	245.17	N/A	N/A	N/A
30~50 ft	N/A	N/A	242.69	0.42	4.94	151.96	0.30	4.71	115.89
50~70 ft	N/A	N/A	136.61	0.24	4.59	101.12	1.02	5.11	277.48
70~90 ft	N/A	N/A	162.66	0.31	4.75	121.03	0.30	4.69	113.73
90~110 ft	N/A	N/A	134.02	0.17	4.54	95.38	0.80	4.88	181.59
110~150 ft	N/A	N/A	165.06	0.14	4.69	110.29	N/A	N/A	110.00
>150 ft	N/A	N/A	129.90	0.19	4.59	100.72	0.31	4.82	129.93

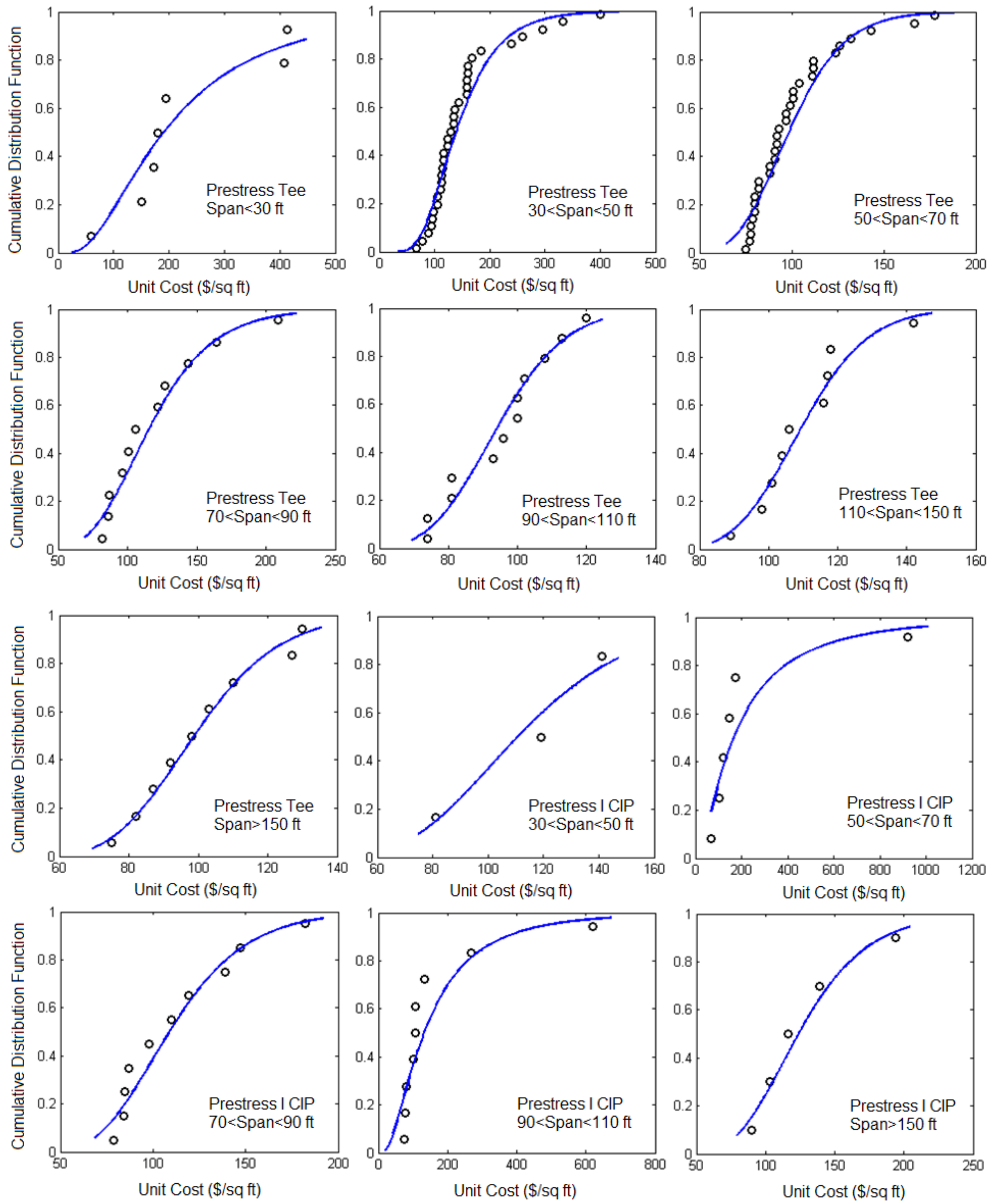

Figure 4.10 Bridge cost data and fitted lognormal distribution curves

Table 4.7 Average unit cost for different structure alternatives (initial cost)

Span	Culverts		Bridges		
	CIP	Precast	CIP slab	Prestress Tee	Prestress I with CIP deck
<30 ft	216.94	86.45	N/A	245.17	N/A
30~50 ft	100.92	91.97	242.69	151.96	115.89
50~70 ft	134.62	68.45	136.61	101.12	277.48
70~90 ft			162.66	121.03	113.73
90~110 ft			134.02	95.38	181.59
110~150 ft			165.06	110.29	110.00
>150 ft			129.90	100.72	129.93

4.3 Expected Life Span Based on PONTIS Data

With the unit cost distribution for each category, the life-cycle cost effectiveness of a given category can be obtained by dividing the initial cost by the expected service life of the structure. Because the replacement records are not retrievable through the current PONTIS system, there is no actual service life data for existing structures. The county superintendent survey revealed that the replacement of a bridge or culvert was planned when the deterioration of the structure became extensive based on structure rating during inspection. Thus, the expected life of these short span structures can be estimated based the change of their rating over time. Various regression analyses were conducted in this section to develop expected service life for different structure type categories.

4.3.1 Life Span Estimation with Selected Rating Thresholds

A new structure's rating keeps decreasing over time if no retrofit is performed; this is the case for these short span concrete structures. Based on superintendent survey responses, short span concrete structures typically do not have high priority when planning for replacement and repair. The PONTIS database indicated there are still significant numbers of such structures (especially bridges) in service with structure ratings less or equal to 4 on a 0 to 9 scale. It is not clear at which rating level a structure will be replaced, because there are other factors that affect the decision-making process, such as availability of funding, other non-structural performance (e.g., hydraulics), and schedules of nearby projects. In this study, replacement of bridges was assumed to be controlled by superstructure rating. Although deck rating was also investigated in earlier sections, it is assumed that when the superstructure rating is satisfactory, a low deck rating will only result in deck repair or replacement, instead of removing the entire bridge. For culvert structures, culvert rating is used as the indicator for replacement. The possibility of using an "overall" indicator, such as sufficiency index or health index, was discussed during the Tech Panel meeting. It was concluded through discussion that these general indices can be affected by defects not related to type selection (such as substructure problems related to hydraulics) and should not be used in this study.

In this study, the threshold for the structure rating for replacement is set to be 4 on a 0 to 9 scale. Based on the PONTIS record, about 3.4% of all concrete bridges and about 5.9% of all culverts in service have a superstructure or culvert rating equal to or less than 4. This ratio is felt to be reasonable for replacement in a practical environment. First, the rating and age data from all major structure types were used to conduct generalized regression analysis for an empirical prediction equation of rating given structure age as input. It is reasonable to assume that the deterioration of concrete structures and structure age does not follow a linear relationship, because a structure with defects is more susceptible to further deterioration. Thus, an exponential decaying relationship, shown in Equation 1.1, was assumed.

$$R = 10 - exp\,(a + b\frac{T}{100})$$ Equation 1.1

Where R is the rating of the structure; T is the age of structure in years; *a* and *b* are regression coefficients. Based on this regression model, the results from the analysis are presented in Figure 4.11 and Table 4.8

Table 4.8 Expected service life regression and estimation

CIP culvert			Precast culvert			Service life based on threshold rating=4		
a	b	service life	a	b	service life			
0.6691	0.9752	115.1	0.5636	1.9102	64.3			
CIP slab Bridge			Prestress Tee bridge			Prestress I & CIP deck bridge		
a	b	service life	a	b	service life	a	b	service life
1.0804	0.457	155.7	0.7713	0.7155	142.6	0.6269	0.8074	144.3

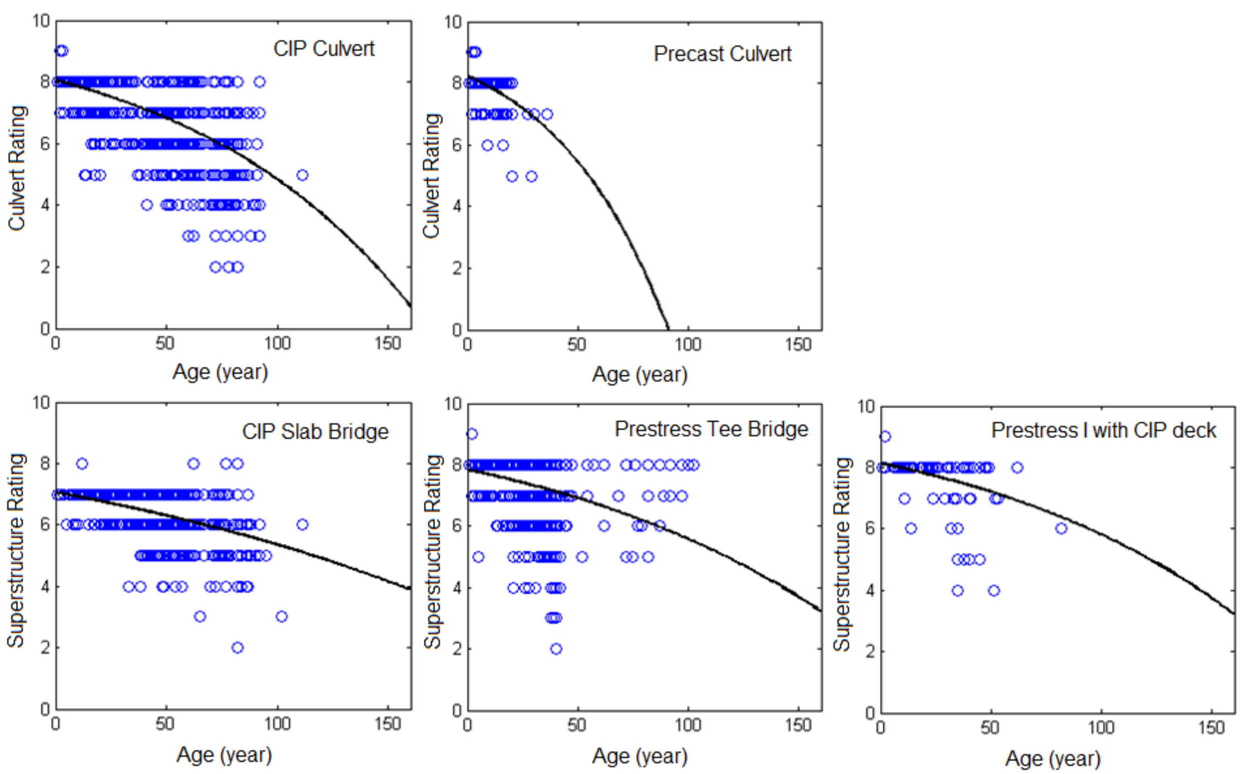

Figure 4.11 Regression analysis on structure rating for service life prediction

4.3.2 Life Span for Different Structure Types

The regression analysis was conducted using the all of the bridge or culvert data within the five most commonly used construction types. As the structures were further broken down into different span categories, it was possible that the regression results for different span lengths would be different. Although the regression within some of the sub-categories may not be reliable since there are limited data points, it became necessary for this regression analysis be done to these sub-categories to thoroughly examine their performance. The same regression formula (Equation 1.1) was applied in this section for span sub-categories outlined in this chapter, and the regression results are listed in Table 4.9 and Table 4.10. The regression results were also plotted in Figure 4.12 through Figure 4.15. When the number of data points within one category is too low to be reasonable, the regression results were not adopted, and the regressions from the overall structural type were used.

Table 4.9 Subcategory service life prediction for culverts

Culverts	CIP culvert			Precast culvert		
	a	b	service life	a	b	service life
<30 ft	0.664	0.9864	114.3	0.5841	1.7161	70.4
30-50 ft	0.6746	0.9531	117.2	0.4766	2.8641	45.9
>50 ft	0.6575	1.1383	99.6	0.6152	1.3655	86.2

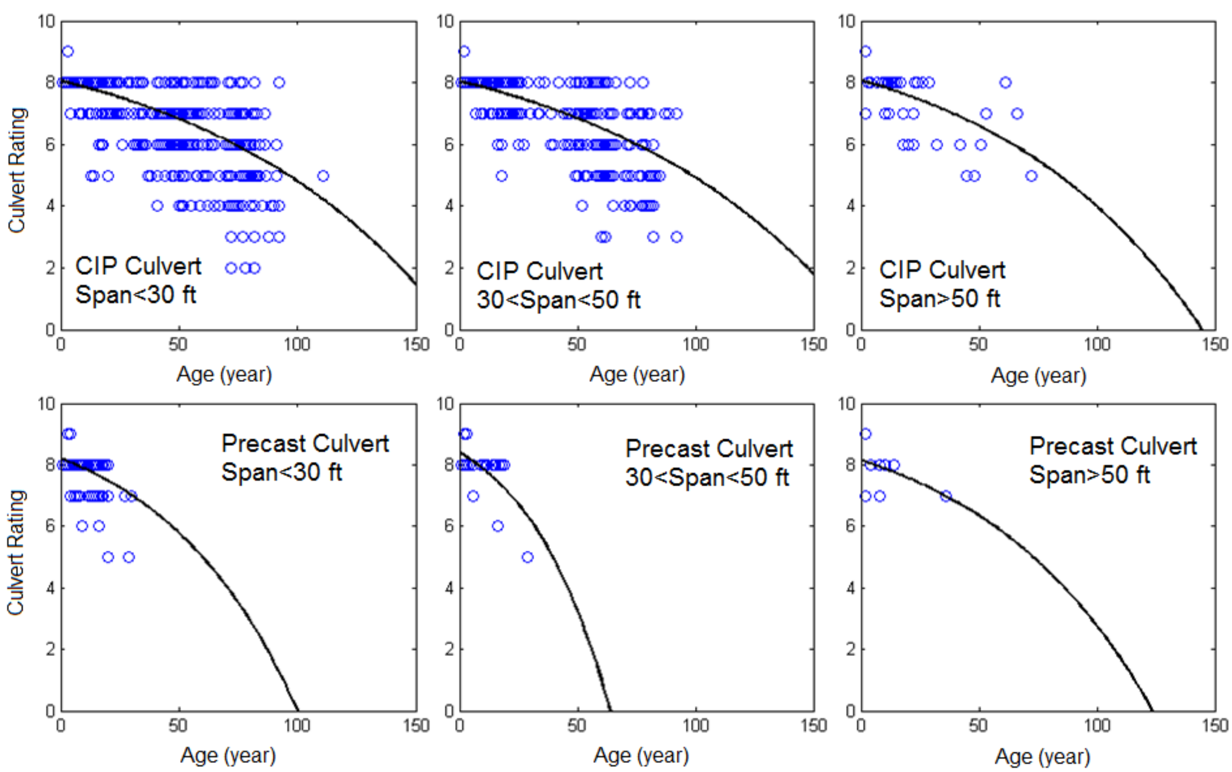

Figure 4.12 Regression analysis on structure rating for service life prediction (culverts)

Table 4.10 Subcategory service life prediction for bridges

Bridges	CIP slab Bridge			Prestress Tee bridge			Prestress I & CIP deck bridge		
	a	b	service life	a	b	service life	a	b	service life
<30 ft	0.8613	0.7525	123.6	0.9111	0.0398	2212.7	0.36	2.7766	51.6
30~50 ft	1.1117	0.4134	164.5	0.8404	0.4875	195.2	0.6693	0.7113	157.8
50~70 ft	1.1343	0.3695	177.9	0.6792	0.8341	133.4	0.6321	0.8376	138.5
70~90 ft	1.0717	0.4748	151.7	0.7895	0.943	106.3	0.7378	-0.06	-1771.4*
90~110 ft	1.042	0.537	139.6	0.6357	1.3412	86.2	0.6397	0.2467	467.0
110~150 ft	1.0654	0.491	147.9	0.5728	1.8347	66.4	0.6659	0.7748	145.3
>150 ft	1.1591	0.2753	229.8	0.8327	1.2165	78.8	0.5893	1.0508	114.4

* unrealistic regression resulting from lack of data; this should not be used.

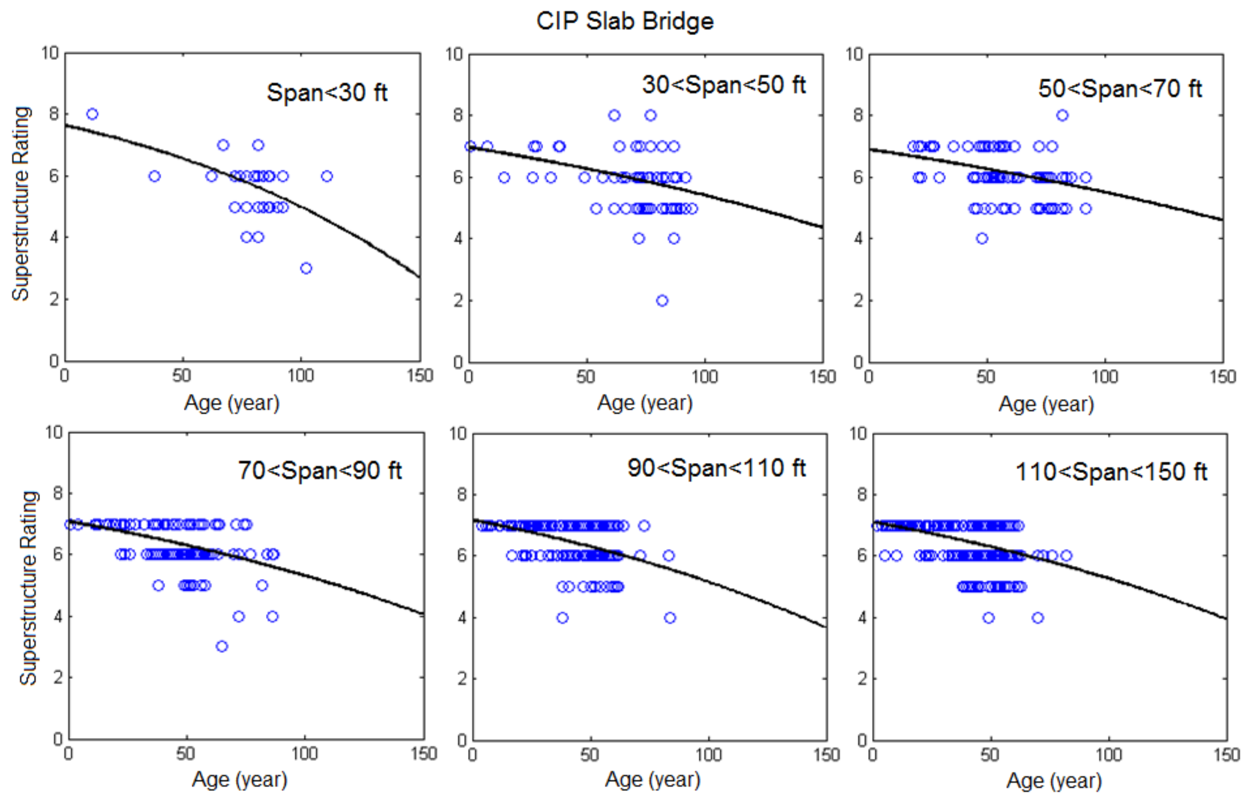

Figure 4.13 Regression analysis on structure rating for service life prediction (CIP slab bridge)

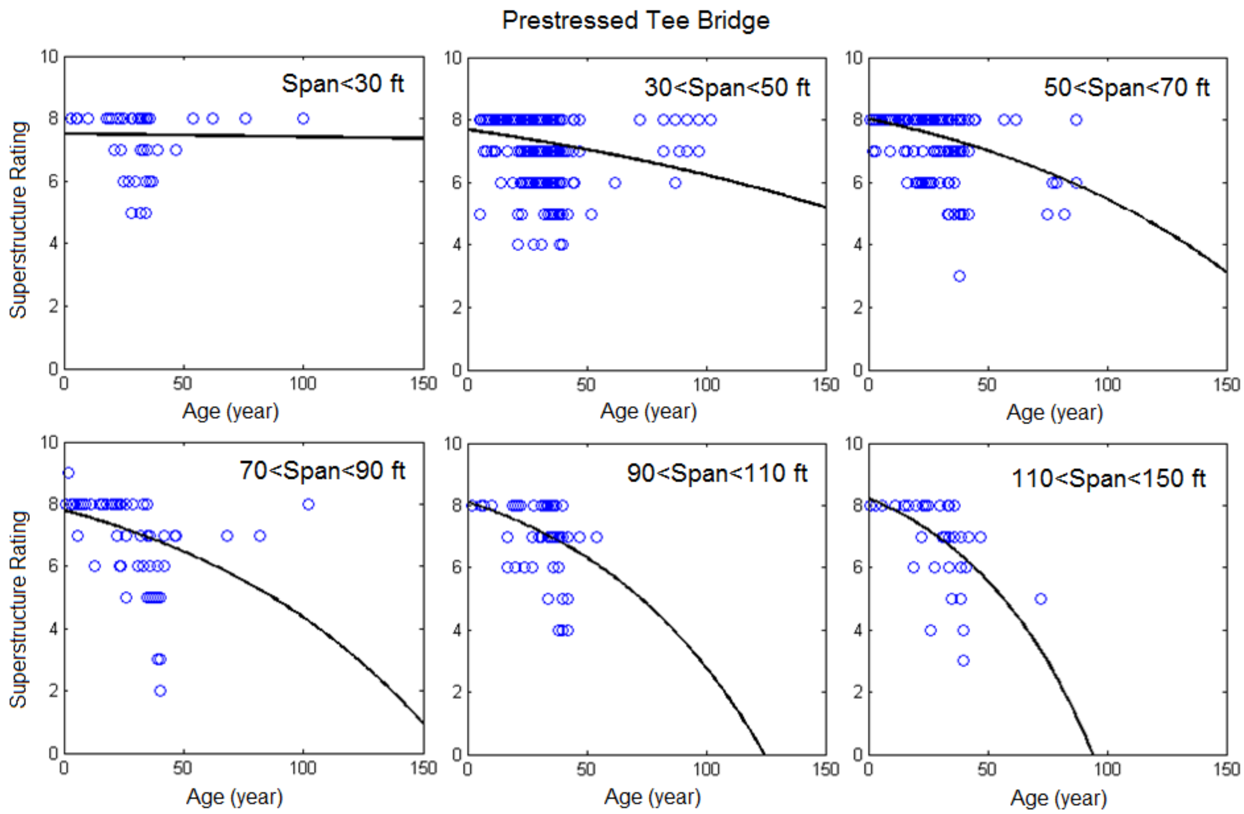

Figure 4.14 Regression analysis on structure rating for service life prediction (prestressed tee bridge)

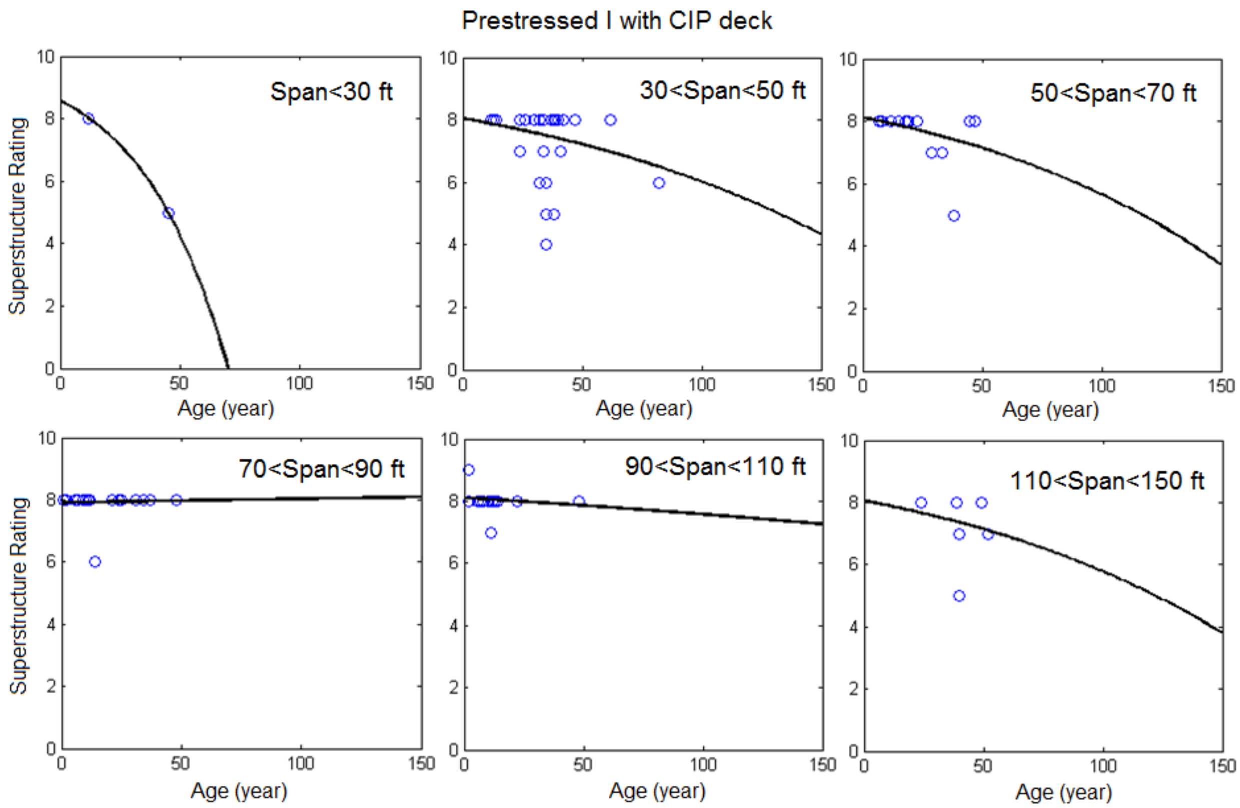

Figure 4.15 Regression analysis on structure rating for service life prediction (prestressed I and CIP deck bridge)

It can be seen from the plots and service life projections listed in the tables that not all regression analyses yield reasonable results. Due to the lack of data, or lack of trends in a limited amount of data, some results from the regression (see Table 4.10) should not be adopted. When this situation arises, the expected service life for the sub-category should be taken from the regression analysis for the entire category, i.e., from Table 4.8. A simple rule was used to combine regression results from global and sub-category analyses. If the sub-category has more than 10 data points, and the regression produces a lower service life, the result from the sub-category analysis was used as the final service life estimation. Otherwise, the result from global regression analysis for the structure type was used. This rule was based on the assumption that the performance of the same structure type with different spans can be different. And this effect is taken into account only if there are enough data to support it. The final service life was taken as the smaller between different analyses so that the result is conservative. Based on this rule, the final expected life span for each sub-category is listed in Table 4.11.

Table 4.11 Estimated service life for subcategories (year)

Span	Culverts		Bridges		
	CIP	Precast	CIP slab	Prestress Tee	Prestress I with CIP deck
<30 ft	114.3	64.3	123.6	142.6	144.3
30~50 ft	115.1	45.9	155.7	142.6	144.3
50~70 ft	99.6	64.3	155.7	133.4	138.5
70~90 ft			151.7	106.3	144.3
90~110 ft			139.6	86.2	144.3
110~150 ft			147.9	66.4	144.3
>150 ft			151.7	78.8	114.4

4.4 Alternative Selection Guideline Based on Cost Effectiveness

Based on construction cost distribution and estimated service life, the average annual cost of different alternatives for short span concrete structures can be calculated. In this study, the mean value of unit structure cost from Table 4.7 was divided by the estimated service life listed in Table 4.11. The final annual costs of the alternatives are listed in Table 4.12. The alternative that produces the best cost-effectiveness was marked with a shaded cell.

Table 4.12 Estimated annual unit cost ($/sq. ft/year)

Span	Culverts		Bridges		
	CIP	Precast	CIP slab	Prestress Tee	Prestress I with CIP deck
<30 ft	1.90	1.34	N/A	1.72	N/A
30~50 ft	0.88	2.00	1.56	1.07	0.80
50~70 ft	1.35	1.06	0.88	0.76	2.00
70~90 ft			1.07	1.14	0.79
90~110 ft			0.96	1.11	1.26
110~150 ft			1.12	1.66	0.76
>150 ft			0.86	1.28	1.14

Keep in mind that the results presented in the table are based on historical performance data only. With the lack of quality data explained earlier in this report, this result represents only a limited knowledge base (especially for some new structure types) and should be interpreted as an average and relative comparison. The specific numerical values resulting from these analyses should be used with caution. The conditions of individual projects may vary greatly, and non-structural factors affecting the projects can be the dominant factor for decision making. Thus, the authors felt it was not appropriate to develop any comprehensive structure type selection procedure solely based on the currently available data and analysis. The tool that targeted such a premise will be misleading with the current quantity and quality of cost data kept at their current stage. Because of this, the decision-making tool originally proposed was not developed as a result of this study.

Based on limited performance and cost data, it can be seen that for a required span length less than 30 feet, precast concrete culverts should be used if allowed by hydrological conditions. For longer span structures, prestress I girder with CIP deck was quite favorable for certain span ranges. A prestressed tee bridge often falls in the middle of cost effectiveness and performs quite consistently. A CIP concrete slab bridge has a good track record from the past and can be beneficial at longer spans due to its integrity. The selection of bridge or culvert alternatives can use the average annual cost in Table 1.12 as a reference, while considering other restraints such as material availability and hydrology. As an alternative, the selection of the structure type can be based on cost estimation for different alternatives for the site condition given, with the consideration of expected service life listed for each category in Table 4.11. The alternative that has the lowest average cost over its life-cycle should be selected.

5. SUMMARY, CONCLUSIONS, RECOMMENDATIONS, AND IMPLEMENTATION

5.1 Summary

A comprehensive investigation of current practices for selection, design, construction, and maintenance of short span bridges and box culverts in South Dakota was conducted in order to develop guidelines for short span concrete structure alternative selection based on long-term cost effectiveness. The study was conducted through query of PONTIS database and customized surveys to bridge owners, engineers, inspectors, and precast manufacturers. Cost data collection becomes the most challenging part of this study due to the lack of cost-related data on existing structures. Originally, the scope of the study only included simply supported concrete bridges and different types of culverts, with a single span less than 100 feet. It was later adjusted based on the recommendation of the Technical Panel to also include simply supported multi-span bridges with cast-in-place concrete decks. The inventory of the bridges was then increased to include bridges longer than 100 feet. Because of the lack of cost data for certain bridge types, bidding cost estimation was conducted later in this project for selected bridges based on construction plans.

After obtaining the cost and performance data, statistical analyses were conducted to identify controlling factors for structure cost and performance. Concrete structures were divided into different categories based on their span and structure type. Regression analysis was conducted to estimate the service life of these structures based on structure ratings. Then an average annual cost statistic was derived for each category and used as the criteria for cost effectiveness comparison. Five different structure alternatives were considered in the analysis, representing the most common structure types used in South Dakota for short span applications. Based on the analysis results and existing practices in South Dakota, recommendations on structure type selection were proposed, including the direct use of average annual cost derived in this study and combining the estimated actual cost for each alternatives and estimated service life. Other recommendations for future practice and management were also proposed, including use of improved joint detail on precast elements, better cost data management, and monitoring of relatively new structures. These recommendations should be implemented or investigated further in the future.

5.2 Conclusions

Based on the collection and analysis of cost and performance data for short span concrete structures in this study, some conclusions can be drawn regarding current practices in design, construction, and maintenance of these structures in South Dakota. This study also revealed availability of useable data for life-cycle cost analysis of these structures, and their estimated long-term cost effectiveness.

Most of the short span concrete structures are owned by local counties and also managed at the local level. The management practices and preferences on these structures vary over the state. But they are generally considered to be robust and low maintenance. There have not been significant problems or defects due to design observed on these structures. Most of the issues were related to normal aging. No routine maintenance activity is implemented for these structures except the routine inspection at a two- or four-year cycle. There are not very good records on the performance and cost-related data for these types of structures. When selecting structural alternatives to be constructed, the local owner often will consider construction time and price. The long-term performance or cost effectiveness were not considered. Many local agencies do not keep well documented records for maintenance activities or cost of these structures.

Among all the initially selected factors that might affect the performance or cost of short span structures, the only factor that showed a consistent significance is the age and structure type. Other factors, such as ADT, span requirement, and location, do not seem to affect sufficiency rating or cost. This conclusion may not be applicable for larger bridges on high traffic volume roads. One performance problem constantly reported by both local owners and inspectors is the deterioration of precast element joints. The old-fashioned CIP construction was favored by a number of owners and inspectors because of the lack of joints.

The cost data for bridge and culvert structures in South Dakota are not centrally organized, which makes it very challenging to collect needed data for this study. The PONTIS system provides excellent information on design and structural characteristics of bridges and culverts, but lacks cost and maintenance related information. As future management objectives lean more toward cost-related measures, incorporating such a capacity for the PONTIS system will be extremely beneficial.

The analysis of cost and service life for short span concrete structures revealed relative cost effectiveness for different span categories. It was concluded that precast concrete culvert is a cost-effective option for structures less than 30 feet, if the hydrological condition allows culverts to be put in place. The CIP concrete slab bridge is a good option for longer multi-span application because it eliminates the problematic joints. Prestress tee bridges have consistent performance and cost-effectiveness over all span requirements. The newly adopted construction method using precast I girders with CIP bridge decks shows superior performance and cost effectiveness at mid- to long-span applications when compared with prestress tee. However, both the I-girder with CIP deck and precast culvert have quite a short history and track record in South Dakota. Their performance should be monitored closely in the future as an ongoing process.

Finally, the quantity and quality of cost-related data available to this study were not felt to be suitable for a comprehensive life-cycle cost analysis. As a result, the decision on type selection for short span concrete structures should be based on multiple factors in practice instead of only on annual average costs estimated in this study.

5.3 Recommendations

Based on the results of this study, the following recommendations are made:

- A more integrated project cost management system at the state and local level should be developed. This will potentially benefit future research efforts and management because more and more emphasis has been put on life-cycle cost effectiveness of the infrastructure systems.
- The PONTIS system should be configured so that the information about replaced structures can be retrieved. Currently, the new structure will assume the same structure number of the old structure and overwrite important information. An archive for replaced structures will be extremely valuable to similar studies if the rating and cause of replacement can be recorded.
- Most of the performance issues on precast concrete structures are related to joint performances. Thus, it is recommended that extra quality control measures be developed to monitor the construction process to make sure the joints were installed correctly. Also, special design details, such as moisture barrier membranes, can be studied in detail for future implementation.
- Although it is difficult to compare the benefit of different structural alternatives thoroughly with limited data, precast concrete culvert is a cost and money saving option for short span applications. For longer spans, prestress I girder with CIP deck construction is an alternative that may be recommended. However, due to the lack of a track record history for these newer structure types, their performance should be closely studied and monitored in the future.
- Although special maintenance and repair activities may have to be conducted in particular cases, short span concrete structures are typically simple and robust. They do not require constant care

over their service life. There is no significant shortcoming in current management and maintenance practices for these structures in South Dakota

- Include in the SDDOT PONTIS database a customized entry for bidding price of the new and replacement bridges and culverts.
- In addition to current component rating in PONTIS, develop a new rating category for precast element joint performance.
- With its current increasing popularity and relatively short track record on performance, a future study should be designed to investigate long-term performance of precast culvert system used in South Dakota.

5.4 Implementation

Due to the complicated nature of particular project constraints, it is not possible to develop universal recommendations on the "best" solution for every future project. With limited information gathered and analyzed in this study, the following four-step procedure may be followed in the short span concrete structure type selection process to identify the option with best cost-effectiveness in the long term:

1. **Preliminary selection:** It is recommended that at least two alternatives be considered for any new or replacement project. One of the alternatives should be the structure options highlighted in Table 1.12 (shaded) for the span requirement. However, if the hydraulic and site condition does not allow the highlighted type to be selected, the project engineer's recommendation should be followed.
2. **Initial cost analysis:** The design of both alternatives from step 1 should be developed. The engineer should develop cost estimation based on the design for each alternative. Given that most short span structures follow a routine and standard design, this step is not supposed to dramatically increase the engineering effort. The benefit of having a more long-term cost-effective system is expected to offset the additional engineering costs.
3. **Annual cost estimation:** The cost estimation from step 2 should be divided by expected service life for the structures in Table 1.11 to come up with the annual cost estimate. This step can be performed based on unit area cost or total project cost, whichever is deemed more relevant by the owner and engineer.
4. **Final decision:** If the annual cost comparison from step 3 is within a certain threshold (10% can be used; the arbitrary number can be decided by the owner), both alternatives should be presented for bid by the contractors. The final decision should be made after evaluating the final bidding costs. Otherwise, the option with lower annual cost should be the final selection that is to be put out for bidding.

6. REFERENCES

Chase, S. and Ghasemi, H. (2009). "Implications of the long-term bridge performance program for life-cycle costing in the United States." *Structure and Infrastructure Engineering*, Vol.5, No.1, pp 3-10

Cook, R., and Bloomquist, D. (2002). "Evaluation of precast box culvert systems." Florida Department of Transportation, Report number BC354 RPWO #47–Part 1

Ehlen, M. (1997). "Life-cycle costs of new construction materials." *Journal of Infrastructure Systems* Vol 3 No. 4 pp 129-133

Enright, M., and Frangopol, D. (1999). "Condition prediction of deteriorating concrete bridges using bayesian updating." *Journal of Structural Engineering*, Vol.125, No. 10, pp 1118-1125

Hadipriono F., Larew R., and Lee O. (1988). "Service life assessment of concrete pipe culverts." *Journal of Transportation Engineering*, Vol.114, No.2, pp 209-220

Hearn, G., and Y., Xi (2007). "Service Life and Cost Comparisons for Four Types of CD Bridge Decks, Report No. CDOT-2007-2." Final Report, Colorado Department of Transportation, Denver CO.

Hyman, A. (2005). "Inspection, repair and rehabilitation of concrete structures due to corrosion." *Int. J. Materials and Product Technology*, Vol 23 No.3/4 pp 309-337

Issa, M., Yousif, A., Issa, M.A., Kaspar, I., and Khayyat, S. (1995). "Field performance of full depth precast concrete panels in bridge deck reconstruction." *PCI Journal* Vol.40, No.3, pp 82-108

Kong, J., and Frangopol, D. (2003). "Evaluation of Expected Life-Cycle Maintenance Cost of Deteriorating Structures." *Journal of Structural Engineering*, Vol. 129, No. 5, pp 682-691

Konda, T., Klaiber, W., Wipf, T., and Schoellen, T. (2007). "Precast Modified Beam-in-Slab Bridge System an Alternative Replacement for Low-Volume Roads." *Transportation Research Record: Journal of the Transportation Research Board*, No. 1989, Vol. 1, pp. 335–346.

Kock, H., Brongers, M., Thompson, N., Virmani, Y., and Payer, J. (2001). "Corrosion Cost and Preventive Strategies in the United States, Report R315-01." CC Technologies Laboratories, Dublin, OH. and NACE Int., Houston, TX.

Manning, D.G. (1995). "NCHRP synthesis of highway practice 220: Waterproofing membranes for concrete bridge decks." TRB Washington, D.C.

Masada, T., Sargand, S., Tarawneh, B., Mitchell, G., and Gruver, D. (2007). "Inspection and Risk Assessment of Concrete Culverts under Ohio's Highways." *Journal of Performance of Constructed Facilities*, Vol.21, No.3.

Panesar, D., and Churchill, C. (2010). "Structure and Infrastructure Engineering: Maintenance, Management, Life-Cycle Design and Performance." *Structure and Infrastructure Engineering* Vol.9, No.3, pp 201–213

Russell, H. (2012). "NCHRP SYNTHESIS 425 Waterproofing Membranes for Concrete Bridge Decks." TRB Washington, D.C.

Smith, M., Li, Y. and Bulleit, W.M. (2011). “A method for evaluation of longitudinal joint connections of decked precast concrete girder bridges.” *Structural Engineering and Mechanics*, Vol.40 No.3 pp 297-313

So, K., Cheung, M., and Zhang, E. (2009). “Life-cycle cost management of concrete bridges.” *Bridge Engineering* 162 Issue BE3 pp 103-117

Sohanghpurwala, A. (2006). “Manual on Service Life of Corrosion-Damaged Reinforced Concrete Bridge Superstructure Elements.” NCHRP Report 558 TRB Washington, D.C.

Suwito, C., and Xi, Y. (2008). “Structure and Infrastructure Engineering: Maintenance, Management, Life-Cycle Design and Performance.” *Structure and Infrastructure Engineering*, Vol.4, No.3, pp 177 – 192

Thoft-Christensen, P. (2009). “Life-cycle cost-benefit (LCCB) analysis of bridges from a user and social point of view.” *Structure and Infrastructure Engineering*, Vol.5, No.1, pp 49 – 57

Tsiatas, G., and Robinson, J. (2002). “Durability Evaluation of Concrete Crack Repair Systems.” *Transportation Research Record* 1795 pp 82-87

APPENDIX A: SURVEY QUESTIONS

Three sets of customized survey questions were developed in this study in order to gather the information about performance, cost, and practice of short span concrete bridges and culverts in South Dakota. The survey questions were listed in this appendix.

A.1 Inspector Survey

Short Span Bridge and Culvert Survey

South Dakota State University

Please provide the following information
Name:________________________________
Company:________________________________
Contact information (Email preferred):_____________________________

The objective of this survey is to collect data for a SD DOT sponsored research project on cost-effectiveness of short span concrete bridge and culvert design/construction options. We are looking into the performance of **short span simply-supported concrete bridges and concrete culvert structures** in South Dakota in order to compare the cost of two construction methods: cast-in-place construction and precast construction. The purpose of the project is to provide references and recommendations for type selection of short span structures. In order to carry out the analysis, we need to identify commonly observed deficiencies for existing **short span concrete bridges and culverts** in the State. So we would like to obtain your opinions and observations on these structures during the inspection.

We really appreciate if you could provide inputs on following questions and get back to us within a week. You may:

- Fill out the survey and mail it back to us at "Nadim Wehbe, Civil and Environmental Engineering, South Dakota State University, Brookings SD 57007"
- Fill out the survey in word and email it back to suellen.lhy@gmail.com
- If you prefer us to conduct this survey by phone, please let us know through email of a good time to contact you. Please send your email to Zachary Gutzmer at: Zachary.Gutzmer@sdstate.edu.

We appreciate your time for this survey and look forward to hearing back from you. If you have any questions about this survey, please feel free to contact us at 605-688-4999 (Zachary Gutzmer), 605-688-4291 (Nadim Wehbe), or 605-688-6526 (Shiling Pei).

Survey questions

1. How many years have you been doing inspection on bridge and culvert structures?

2. In which South Dakota counties do you conduct inspection?

3. Please list some commonly observed deficiencies in concrete bridges (simply-supported, span<100ft) during your inspection.

4. Could you please comment on the cause and possible remedy for some of the deficiencies listed in (3)?

5. From your inspection experience, which structural type exhibits better structural performance (less deficiencies) for short span bridges: Cast-in-place or Precast? Please specify if there is not a very clear distinction.

6. Please list some commonly observed deficiencies in concrete culverts during your inspection.

7. Could you please comment on the cause and possible remedy for some of the deficiencies listed in (6)?

8. Are you responsible for making recommendations (repair or replacement) to the owner based on the inspection results? If so, what criteria do you use?

9. From your inspection experience, which structural type exhibits better structural performance (less deficiencies) for culverts: Cast-in-place or Precast? Please specify if there is not a very clear distinction.

10. Are there any other comments you would like to share about the performance of short-span concrete structures from your inspection experiences? Are there any recurring performance deficiencies or other maintenance issues that might be related to specific design detailing?

A.2 Superintendent Survey

Short Span Bridge and Culvert Survey

South Dakota State University

Please kindly provide the following information
Name:__________________________________
County:__________________________________
Contact information (Email preferred):_______________________________

The objective of this survey is to collect data for a SD DOT sponsored research project on cost-effectiveness of short span concrete bridge and culvert design/construction options. We are looking into the initial and long-term cost related to **short span simply-supported concrete bridges and concrete culvert structures** in South Dakota in order to compare the cost of two construction methods: cast-in-place construction and precast construction. The purpose of the project is to provide references and recommendations for type selection of short span structures. In order to carry out the analysis, we need to collect any cost and performance related data that we can find for existing bridges and culverts in the State. The initial cost and maintenance information in South Dakota Dot central office is not very complete especially for county owned structures. So we would like to obtain available data on these structures through your help.

We really appreciate if you could provide inputs on following questions and get back to us within 2 weeks. You may:

- Fill out the survey and mail it back to us at “Nadim Wehbe, Civil and Environmental Engineering, South Dakota State University, Brookings SD 57007”
- If you prefer us to conduct this survey by phone, please let us know through email of a good time to contact you. Please send your email to Zachary Gutzmer at: Zachary.Gutzmer@sdstate.edu.

We appreciate your time for this survey and look forward to hearing back from you. If you have any questions about this survey, please feel free to contact us at 605-688-4999 (Zachary Gutzmer), 605-688-4291 (Nadim Wehbe), or 605-688-6526 (Shiling Pei).

Survey questions

1. Does your county keep any record for the construction or bidding price for existing Bridge and Culvert projects in your county?

   If Yes: Could we use these cost data in this study?
   If No: Do you know where we can find this information?

2. Does your county keep any record on maintenance or repair work done to Bridges and Culverts in your county?

   If Yes: What information is in these records? Do these records have cost or price for the work done?
   If No: Do you know where we can find this information?

3. Are there any commonly occurring problems or deficiencies related to concrete bridges and culverts that caught your attention in your county?

   If Yes: what is the problem?
   Is the problem associated to a particular structural type? Such as pre-cast and cast-in-place?

4. Have your county ever adopted any special design and construction details for concrete bridges and culverts to address deficiencies or to improve performance?

   If Yes: Could you provide some details on it?

5. What is the version of the design specification used for your county for bridge and culvert structures? Do you recall any major code changes applied to your county's structures after 1980?

6. Does your county perform winter maintenance activities, including deicing, on your bridge and culvert structures?

   If Yes: Is there a record of the deicing activities done? Could you describe briefly what method is used? Is there any major change in the deicing practices (procedure, material, technique, etc.) after 1980?

7. Could you please provide contact information of the crew or person who oversees the bridge and culvert inspection in your county?

8. Could you please provide contact information of the crew or person who oversees the bridge and culvert design in your county?

9. Could you please provide contact information of the crew or person who oversees the bridge and culvert maintenance operation in your county?

10. For your county's future projects on simply-supported short span bridges, what material and method will you more likely to use?

- Pre-cast concrete
- Cast-in-Place concrete
- Steel
- Timber
- Other

Could you comment on why you will favor that choice?

11. For your county's future project on Culverts, what material and method will you more likely to use?

- Pre-cast concrete
- Cast-in-Place concrete

Could you comment on why you will favor that choice?

12. What criteria will you typically use to decide if a bridge or culvert should be repaired or replaced?

13. Do you have any other information that might help us in this research project?

14. Please provide your email for possible follow up questions in the future.

A.3 Precast Manufacturer Survey (Phone Interview Questions)

Culverts and Short Span Bridges Pre-casters Survey

South Dakota State University

Please provide the following information
Name:________________________________
Company:________________________________
Contact information (Email preferred):_____________________________

The objective of this survey is to collect data for a SD DOT sponsored research project on cost-effectiveness of short span concrete bridge and culvert design/construction options. We are looking into the performance of **short span simply-supported concrete bridges and concrete culvert structures** in South Dakota in order to compare the cost of two construction methods: cast-in-place construction and precast construction. The purpose of the project is to provide references and recommendations for type selection of short span structures. In order to carry out the analysis, we need to identify commonly observed deficiencies for existing **short span concrete bridges and culverts** in the State. So we would like to obtain your opinions and observations on these structures during the inspection.

We really appreciate if you could provide inputs on following questions and get back to us within 2 weeks. You may fill out the survey and email us an electronic copy at nadim.wehbe@sdstate.edu or mail it back to us at "Nadim Wehbe, Civil and Environmental Engineering, South Dakota State University, Brookings SD 57007".

We appreciate your time for this survey and look forward to hearing back from you. If you have any questions about this survey, please feel free to contact us at 605-688-4291 (Nadim Wehbe), or 605-688-6526 (Shiling Pei).

Survey Questions

Short Span Bridges

1. Do you produce precast elements for short-span simply supported bridge superstructures?

   Yes ______ No ______

   If your answer is "No", please move to Part B of this survey.

2. Please list the precast bridge superstructure products that are fabricated at your facility.

3. Can you provide us with a catalog for those products? If "Yes", could you send us a copy to the address shown on the cover page of this survey?

4. Which product(s) is most commonly used by South Dakota counties for short span bridges?

5. Please provide the FOB cost estimate for the products listed under (4).

6. Please provide the transportation cost estimate per mile (or in any other form) for the products listed under (4).

7. Can you add any information regarding the construction cost of such elements?

8. Are you aware of serviceability issues related to those elements (corrosion, spalling, cracking, etc.) that require frequent maintenance? If yes, please list the serviceability issues.

9. Have you implemented any design/detailing changes over the years to address certain serviceability issues and/or improve the performance of such elements? If yes, please list those changes.

10. Do you propose any design/detailing changes to improve the serviceability and performance of currently produced elements? If yes, please list your proposed changes.

11. Please provide a chronological list of the design codes that have been used to design those elements. Please indicate major changes in the requirements of subsequent codes whenever applicable.

Precast Culverts

1. Do you produce precast culverts?

   Yes ______ No ______

   If your answer is "No", you may stop at this point in the survey.

2. Please list the precast culvert unit sizes and configurations that are fabricated at your facility.

3. Can you provide us with a catalog for those units? If "Yes", could you send us a copy to the address shown on the cover page of this survey?

4. Which units are most commonly used by South Dakota counties?

5. Please provide the FOB cost estimate for the products listed under (4).

6. Please provide the transportation cost estimate per mile (or in any other form) for the products listed under (4).

7. Can you add any information regarding the construction cost of such elements?

8. Are you aware of serviceability issues related to those elements (corrosion, spalling, cracking, etc.) that require frequent maintenance? If yes, please list the serviceability issues.

9. Have you implemented any design/detailing changes over the years to address certain serviceability issues and/or improve the performance of such elements? If yes, please list those changes.

10. Do you propose any design/detailing changes to improve the serviceability and performance of currently produced elements? If yes, please list your proposed changes.

11. Please provide a chronological list of the design codes that have been used to design those elements. Please indicate major changes in the requirements of subsequent codes whenever applicable.

APPENDIX B: SURVEY RESULTS

B.1 Inspector Survey feedback

Survey responses from 11 bridge (culvert) inspectors are summarized in this section. Each table contains the responses from one inspector.

Table B-1: Inspector survey results

Survey question	Responses
Name	Jay Larson
Company	Mitchell region-SDOT
Experience (year)	9+
Structure inspected	state structure only, no simply supported, no precast bridges
Counties	Aurora, Bon Homme, Brule, Buffalo, Charles Mix, Clay, Davison, Douglas, Gregory, Hanson, Hutchinson, Jerauld, Lake, Lyman, McCook, Miner, Minnehaha, Moody, Sanborn, Turner, & Yankton
Problem for bridges	cracking, spalling, delamination
Causes of bridge problem	poor construction, age, wear, chemical
CIP vs. Precast, which one is better for bridge?	don't know
Problem for culverts	cracking, spalling, delamination
Cause of culvert problem	poor construction, age, wear, chemical
Do you provide recommendation for repair and replacement?	yes
Criteria for replacement recommendation	degree of problem, if a similar problem is scheduled for repair nearby
CIP vs. Precast, which one is better for culvert?	no major difference, all good if less than 50 years
Other Comments	none
Contact	N/A

Table B-2: Inspector survey results (Cont.)

Survey question	Responses
Name	Don Hammond
Company	Brosz Engineering
Experience (year)	18
Structure inspected	N/A
Counties	N/A
Problem for bridges	scour and hydraulic more than structural, minor cracking but not problem, bridges from WPA days are still sound
Causes of bridge problem	substructure may need repair due to wear, route and sale cracks
CIP vs. Precast, which one is better for bridge?	CIP, fewer areas for problems
Problem for culverts	hydraulics, joints of precast box spalling
Cause of culvert problem	age and chemical
Do you provide recommendation for repair and replacement?	yes
Criteria for replacement recommendation	experience, critical, ADT, Orientation, etc.
CIP vs. Precast, which one is better for culvert?	CIP, good track record, precast does not have a long history to tell
Other Comments	all viable, sometime stream characteristics decide
Contact	jonh@broszeng.com

Table B-3: Inspector survey results (Cont.)

Survey question	Responses
Name	Randy Sauter
Company	Rapid city region -SDDOT
Experience (year)	30+
Structure inspected	N/A
Counties	Harding, Perkins, Butte, Meade, Lawrence, Pennington, Custer, Fall River, Shannon, Ziebach
Problem for bridges	spalling and crack on slab, delamination , spalling on girders (minor)
Causes of bridge problem	better structural design, epoxy chip seal cracks, better quality control, detailing
CIP vs. Precast, which one is better for bridge?	CIP is better, bridge Precast and CIP deck is good
Problem for culverts	cracks, joint leak, joint not good
Cause of culvert problem	wear, T&S, construction and fabrication quality, improve structural design
Do you provide recommendation for repair and replacement?	yes
Criteria for replacement recommendation	methods, cost
CIP vs. Precast, which one is better for culvert?	CIP
Other Comments	N/A
Contact	randy.sauter@state.sd.us

Table B-4: Inspector survey results (Cont.)

Survey question	Responses
Name	Paul Nelson
Company	SDDOT
Experience (year)	14
Structure inspected	all bridge are precast deck
Counties	Corson, Campbell, McPherson, Walworth, Potter, Dewey, Ziebach, Stanley, Haakon, Hughes, Sully, Hyde, Lyman, Jones, Jackson, Gregory, Tripp, Todd, Mellette, Bennett & Shannon
Problem for bridges	corrosion of re-steel in stem of double T, sub structure due to weld deficiencies
Causes of bridge problem	lack of inspection during construction
CIP vs. Precast, which one is better for bridge?	don't know
Problem for culverts	CIP with shallow reinforcement, precast is misalignment and joints, both has debris problem
Cause of culvert problem	better inspection, better detailing
Do you provide recommendation for repair and replacement?	yes
Criteria for replacement recommendation	safety, usage, aesthetic
CIP vs. Precast, which one is better for culvert?	precast better quality but more hydraulic problem,
Other Comments	N/A
Contact	paul.nelson@state.sd.us

Table B-5: Inspector survey results (Cont.)

Survey question	Responses
Name	Mark Junker
Company	Aason Engineering
Experience (year)	8
Structure inspected	N/A
Counties	Codington, Deuel, Grant, and Lake Counties, Watertown and parks
Problem for bridges	erosion at bridge ends, railing damage, chipped beam, rebar corrosion, cracking, spalling, joint separation,
Causes of bridge problem	gaps in abutments, connection, collision, chemical, insufficient erosion protection
CIP vs. Precast, which one is better for bridge?	both OK
Problem for culverts	channel erosion, wing wall erosion, settlement at ends, deterioration of rebar and concrete for CIP
Cause of culvert problem	poor backfill, age, poor cover
Do you provide recommendation for repair and replacement?	yes
Criteria for replacement recommendation	safety, age, serviceability, resources
CIP vs. Precast, which one is better for culvert?	both OK
Other Comments	favor culvert over bridge if hydraulic allows, precast DT with CIP deck is good option
Contact	mjunker@iw.net 605-882-2371

Table B-6: Inspector survey results (Cont.)

Survey question	Responses
Name	Dan Johnson
Company	Johnson Engineering
Experience (year)	6
Structure inspected	N/A
Counties	Gregory, Yankton, Bon Homme, Clay, Union, Turner, Douglas, Hutchinson, and the City of Yankton
Problem for bridges	spalling , poor drainage on deck and joints, chloride contamination, map cracking
Causes of bridge problem	better quality control, less salt, design details
CIP vs. Precast, which one is better for bridge?	no distinction
Problem for culverts	spalling, not much deficiency
Cause of culvert problem	construction and manufacturing
Do you provide recommendation for repair and replacement?	yes
Criteria for replacement recommendation	NBI, Core Elements System, ratings
CIP vs. Precast, which one is better for culvert?	no clear distinction
Other Comments	no typical bad design flaws for short span structures
Contact	dkjjec@iw.net

Table B-7: Inspector survey results (Cont.)

Survey question	Responses
Name	Todd Hertel
Company	SDDOT
Experience (year)	15
Structure inspected	N/A
Counties	Aberdeen Region (NE South Dakota),McPherson, Brown, Marshall, Roberts, Edmunds, Faulk, Spink, Day, Grant, Codington, Clark, Hyde, Hand, Beadle, Kingsbury, Brookings, and Deuel
Problem for bridges	deck deterioration, spalling and cracking, abutment walls
Causes of bridge problem	limit deicing, ensure good drainage for deck, epoxy the cracks, ensure clear steel cover
CIP vs. Precast, which one is better for bridge?	CIP, precast has some issues
Problem for culverts	settlement, joint separation and deterioration, spalling due to lack of cover
Cause of culvert problem	quality material and construction process, cover joints before backfill
Do you provide recommendation for repair and replacement?	yes
Criteria for replacement recommendation	safety, cost analysis on cost vs life, budget
CIP vs. Precast, which one is better for culvert?	CIP better, custom for site, but precast is quick to construct
Other Comments	skew angle should be minimized, ensure clear cover and proper cure
Contact	todd.hertel@state.sd.us

Table B-8: Inspector survey results (Cont.)

Survey question	Responses
Name	Tami Jansma
Company	Clark Engineering
Experience (year)	4
Structure inspected	N/A
Counties	N/A
Problem for bridges	crack on deck, spalling on abutment, open joints, spalling around drain, and rail post connection, exposed rebar
Causes of bridge problem	better construction control
CIP vs. Precast, which one is better for bridge?	CIP has less deficiencies, precast is less expensive
Problem for culverts	spalling along waterline, vertical cracks, leaking joints
Cause of culvert problem	construction and maintenance quality
Do you provide recommendation for repair and replacement?	yes
Criteria for replacement recommendation	PONTIS score, element rating
CIP vs. Precast, which one is better for culvert?	precast cheap and better quality
Other Comments	N/A
Contact	tjansma@clark-eng.com

Table B-9: Inspector survey results (Cont.)

Survey question	Responses
Name	Carey Bretsch
Company	CDI
Experience (year)	16
Structure inspected	N/A
Counties	Davison and Moody although I have provided inspections in Grant, Hamlin, Kingsbury, Brookings, Pennington, Codington and Deuel Counties
Problem for bridges	abutment back wall and wing wall constant source of problem, some historical problem on precast members
Causes of bridge problem	only economical solution was replacement
CIP vs. Precast, which one is better for bridge?	both OK, but joint for precast culvert not good
Problem for culverts	age, cracks common but does not always mean problem
Cause of culvert problem	replacement is the only remedy
Do you provide recommendation for repair and replacement?	yes
Criteria for replacement recommendation	AASHTO bridge inspection manual, engineering judgment
CIP vs. Precast, which one is better for culvert?	no distinction, but precast is for fast construction, skewed condition sometimes require CIP
Other Comments	favor culvert over bridge, precast is often recommended because of the time of construction
Contact	cbretsch@civildes.com

Table B-10: Inspector survey results (Cont.)

Survey question	Responses
Name	Peter S. Johnson
Company	Johnson Engineering Co
Experience (year)	34
Structure inspected	N/A
Counties	Union, Clay, Yankton, Bon Homme, Charles Mix, Douglas, Hutchinson, and Turner
Problem for bridges	Timber substructure rot, crack on DT stem due to welding, DT stem inadequate rebar cover lead to spalling, Corrosion of steel pile
Causes of bridge problem	Replace timber substructure, welding down DT practice stopped 20 years ago, manufacturing process inspection not on County work, but these DT are not used for new bridges anymore
CIP vs. Precast, which one is better for bridge?	Not enough CIP for conclusion, most dated back to WPA days
Problem for culverts	serious scaling and deterioration at bottom, Full height cracks at Joint between Barrel and Wing, no problem if less than 30-40 years old
Cause of culvert problem	Problem only in 50+ year structures
Do you provide recommendation for repair and replacement?	Yes
Criteria for replacement recommendation	engineering judgment
CIP vs. Precast, which one is better for culvert?	both OK, but prefer CIP due to joints in precast, large precast culverts are new and problems not shown yet
Other Comments	Highway superintendents like box culvert over bridge due to cost, time to install, and no bridge rails
Contact	psjjec@iw.net

Table B-11: Inspector survey results (Cont.)

Survey question	Responses
Name	Doug Wessel
Company	Banner Associates
Experience (year)	15
Structure inspected	N/A
Counties	Brookings
Problem for bridges	Only a few old CIP, but in good shape. Cracks, Spalling at end of precast units and steel plate embedment, problem with Timber abutments
Causes of bridge problem	Manufacture quality control
CIP vs. Precast, which one is better for bridge?	don't know since CIP so few
Problem for culverts	CIP: wing wall diagonal crack, vertical cracks in parapets, on exterior walls. Precast: Brookings only has a few, all pretty new
Cause of culvert problem	CIP wing wall cracks already addressed by SDDOT specifying additional bars
Do you provide recommendation for repair and replacement?	Yes
Criteria for replacement recommendation	Safety, Load rating, sufficiency rating, life expectancy
CIP vs. Precast, which one is better for culvert?	don't know due to limited amount of data
Other Comments	N/A
Contact	dougw@bannerassociates.com

B.2 County Superintendent Survey feedback

Survey results from county superintendents are summarized in this section. The original survey responses were also compiled in PDF format and available electronically with this report. The feedbacks from responsive counties were grouped and listed in the tables following the summary below.

Out of the 21 counties responding to the survey, 14 counties keep some kind of bidding price records and seven counties do not keep cost records. Among the 14 counties that have cost records, only six responded that the data are available for researchers. When it comes to repair and maintenance related data, only 16 counties have repair and maintenance records. These data were recorded in various formats (e.g., special computer program, hard copy timecard records, bid file, cost record journal, etc.) and is hard to utilize. There are five counties that could not locate such records. Most of these records include information such as dates of the work, labor and materials, equipment, and sometimes costs. Ten counties responded that they do not conduct winter deicing maintenance at the local level. For counties that conducted deicing, most of them use salt and sand mix, and there is no major change in deicing practice over the last couple of decades that they are aware of.

As for the performance of short span concrete structures, most of the concern was focused on separation of joints of precast elements. The age of structure and erosion associated with aging is also a common concern. In addition, hydraulic issues, such as scour, plug of culverts, were deemed to be more common than structural performance problems for these short span structures. Most of the counties use inspection reports from the inspector and engineers to decide if the structure should be replaced. On scheduling the replacement, the structures were prioritized based on sufficiency rating, age, traffic counts, and costs.

For new short span bridge construction (including replacements), 18 out of 21 counties favor precast girder bridges, with one county specifically favoring precast girder with CIP deck. Two counties prefer steel bridges, and one prefers CIP bridges. The reason for choosing precast is due to savings on money and time. The county that favors CIP simply views it as a better built system with higher quality.

For new culvert construction and replacement, 14 out of 21 counties chose precast culvert. Three counties favor steel culvert and one county likes CIP. Two responses indicated they do not have a preference. And one county seldom uses culverts. The reason for choosing a precast culvert is similar to the reason for precast bridge construction, simply for time and money savings.

Table B-12: Owner responses on data availability

County	Survey completed by	Bidding records kept?	Bidding cost available?	Repair record kept?	Repair cost available?
Lawrence County	Dick Birk	Y	N/A	Y	N/A
Edmunds County	Lenny Chrich	Y	N/A	Y	N/A
Mellette County	Leon V. Huber	N	N/A	N	N
Douglas County	Scot Jegethoff	Y	N/A	Y	Y
Corson County	Benny Zoe Schell	Y	N	Y	Y
Hand County	Ron Blachfond	Y	Y	Y	N/A
Hutchinson County	John Hazen	Y	Y	Y	N/A
Custer County	Gary Woodford	N	N/A	N	N/A
Buffalo County	Ken Wolff	N	N/A	N	N/A
Deuel County	Jamie Hintz	Y	N/A	Y	N/A
Hyde County	Mike Cowan	Y	N/A	Y	N/A
Miner County	Ron Krempges	Y	N/A	Y	N/A
Clark County	John Howardson	N	N/A	N	N/A
Jackson County	N/A	N	N/A	Y	Y
Grant County	Kerwin Schultz	Y	N/A	Y	N/A
Todd County	Norman Rolet	N	N/A	N	N/A
McCook County	Michael Kreutzfeldt	Y	Y	Y	Y
Sanborn County	Lee Goergen	N	N/A	Y	N/A
Brown County	Jan Weismantel	Y	Y	Y	N/A
Clay County	N/A	Y	Y	Y	Y
Brookings County	Larry Jensen	Y	Y	Y	N/A

Table B-13: Owner responses on current practices

County	Common performance issues	Special design details	Major change in design requirements	Conduct Deicing?	Record kept?
Lawrence County	None	None	No	Y	N/A
Edmunds County	None	None	No	N	N/A
Mellette County	None	None	N/A	N	N/A
Douglas County	None	None	No	N	N/A
Corson County	None	None	No	N	N/A
Hand County	short sections of concrete pipe were used with no ties or joint sealing causing separation	specified cut off walls on the last culvert	No	Y	N
Hutchinson County	age of the structures	None	No	Y	N
Custer County	None	None	No	N	N/A
Buffalo County	precast member separation at joints	None	No	N	N/A
Deuel County	Old concrete culverts are separating and joints cause cave-ins. Heavy silting adds to this problem by keeping drainages saturated. Several bridges with wood abutments are failing because of rod and absence of proper anchors down the pilings. With steel culvers, deterioration is an on-going problem.	flared ends on culverts, large rip-rap on inlet and outlet sides, and pour cement in the rip-rap in areas with high flash flood tendencies	No	Y	N
Hyde County	Erosion	None	No	Y	N/A
Miner County	Box culverts can plug up with trash, trees + debris.	None	No	Y	N
Clark County	Columns deterioration, scour beneath structure	N/A	No	N	N/A
Jackson County	None	None	No	N	N/A
Grant County	some of the culverts that have been in place for a long time the ends drop off as they are not tied together otherwise concrete has performed well.	None	No	N	N/A
Todd County	N/A	N/A	No	N/A	N/A
McCook County	Scour issue	None	No	Y	N

Sanborn County	None	None	No	N	N/A
Brown County	concrete culverts separating / Culverts rusting / washing out	None	No	Y	N
Clay County	trash in the inlets + settling of approaches	None	No	Y	N
Brookings County	head walls, metal rusting	None	No	Y	N

Table B-14: Owner responses on future preference

County	Future bridge option	Future Culvert option	When to replace
Lawrence County	Pre-cast concrete, because of the logging traffic and construction traffic	Pre-cast durable, long life expected	Bridge inspection data from Interstate Engineering
Edmunds County	Pre-cast concrete	Pre-cast concrete	leave it up to contracted Engineers Clark
Mellette County	Steel culvers, simplest for s to install	Use Steel	Rusted out culverts, washed out culverts
Douglas County	We use pre-cast deck and timbers because it is faster & costs less	Pre-cast concrete, easier to install and faster	Bridge inspection done by the state. We inspect the culvers ourselves.
Corson County	Pre-cast concrete, very good product	Pre-cast concrete, same as above answer	Bridge report from state
Hand County	Pre-cast concrete and Steel. Cost is a factor. Ease of installation. Less downtime on roads	Pre-cast concrete, less downtime on roads	age, safety sufficiency rating
Hutchinson County	Pre-cast concrete and steel. Pre-cast, because of the speed in which they can be put in. steel, because of the cost	Pre-cast concrete. I think pre-cast is as good, time saving. A bad experience with a cast-in-place box culvert. Project took forever and the county received no compensation.	the extent of the deterioration of the structure and its age
Custer County	Pre-cast concrete. Engineering choice	Pre-cast concrete. Time factor	Engineering recommendation
Buffalo County	Pre-cast concrete	metal culverts only	workout
Deuel County	Pre-cast concrete and cast-in-place concrete, whichever is cheaper, and what is recommended by Engineers	We use all steel on our culvert projects and replacements because of price and time of installation.	traffic counts, cost, heavy loads (elevator or gravel pit used)
Hyde County	Pre-cast concrete. Many of our bridges will be replaced with large pre-cast concrete box culverts.	Pre-cast concrete. Looks like less time of road closed.	Broz Engineering Bridge Inspection, Phone 605-224-1123
Miner County	Pre-cast concrete. Speed of construction, simplicity	Cast-in-Place concrete. No change of seams pulling apart to allow water to undermine.	Engineers 2 year bridge inspection report and our own visual inspections.
Clark County	Pre-cast concrete	Pre-cast concrete	Bridge inspection reports
Jackson County	cast-in-place concrete and steel.	none	state DOT report

County	Future bridge option	Future Culvert option	When to replace
Grant County	Pre-cast concrete. Faster	Pre-cast concrete. We use almost no concrete culverts.	sufficiency and ton rating. Depends on what part of the structure Is failing. Location
Todd County	Pre-cast concrete	Pre-cast concrete	Bridge inspection results
McCook County	Steel, strictly a short term money decision	Pre-cast	safety, FO/SD, type of traffic, traffic volume
Sanborn County	Pre-cast concrete, not much maintenance	Pre-cast concrete, Faster completion	inspection reports
Brown County	Pre-cast concrete, Hallaway Const. does our replacements	Pre-cast concrete, we normally use steel – very rarely pre-cast	ratings, usage, inspection information
Clay County	20 Pre-cast concrete, usually faster + cheaper	if we are using Fed Funds it would be cast-in-place, if we are using County Funds probably Pre-cast	Bridge inspections for our bridges, but other culverts could be county inspections visual
Brookings County	Pre-cast concrete, availability + time frame	Pre-cast concrete, depending on applications , time	sufficiency rating

APPENDIX C: RAW AND PROCESSED COST DATA

This section summarizes all of the cost data used in this project. The raw data were the original costs obtained from DOT. The processed data were the final cost data corresponding to 2010 dollar value and normalized by the structure surface area of the structure. These data were also available electronically in Excel format as part of this report.

Table C-1: Existing cost data for bridges

Structure ID	Year Built	Raw Cost ($)	2010 Cost ($)	Normalized Cost ($/sq ft)
34258090	1980	58,972	177,432	64
10096374	1980	131,526	395,729	98
3338220	1980	48,711	146,560	119
10250375	1980	528,887	1,591,296	194
23436060	1980	135,302	407,090	295
7073140	1981	145,609	385,734	75
41100087	1981	94,206	249,562	81
6240179	1981	83,315	220,712	81
52732343	1981	160,927	426,314	92
12591390	1981	122,260	323,879	100
41025020	1981	97,627	258,625	101
7103073	1981	161,503	427,839	104
55151250	1981	49,721	131,716	106
42110112	1981	115,416	305,750	239
31024230	1982	29,763	71,450	66
2223090	1982	98,983	237,620	74
34147090	1982	43,646	104,778	77
30207170	1982	51,658	124,010	81
14109030	1982	169,143	406,047	101
3268030	1982	67,165	161,236	105
20110028	1982	42,829	102,816	111
25180148	1982	72,386	173,772	130
10496106	1982	191,047	458,630	142
24204160	1982	70,599	169,480	158
47671247	1982	101,260	243,087	178
48200168	1982	121,183	290,912	186
27095260	1982	161,428	387,527	259
52759479	1982	179,489	430,882	400
7331380	1983	54,926	124,203	80
55101180	1983	51,377	116,179	123
22200028	1983	51,030	115,393	173
38050042	1984	215,243	471,552	117

Structure ID	Year Built	Raw Cost ($)	2010 Cost ($)	Normalized Cost ($/sq ft)
47644200	1984	275,523	603,612	130
22240175	1984	102,112	223,705	184
55220404	1984	144,219	315,953	408
68119196	1984	536,228	1,174,763	470
27461331	1984	282,117	618,058	586
6190136	1985	78,472	164,825	93
31059020	1985	68,061	142,958	117
28260478	1985	98,647	207,201	167
47220463	1986	119,148	241,691	87
7001410	1986	155,226	314,876	127
49173170	1986	61,442	124,636	135
63167210	1986	120,818	245,080	159
12260029	1986	173,638	352,225	164
12496260	1986	143,860	291,820	167
6131170	1987	122,309	243,465	76
10111380	1987	329,904	656,698	127
52990352	1987	149,136	296,867	147
39243190	1987	59,943	119,321	179
22151140	1987	65,428	130,240	195
32395080	1987	154,868	308,277	333
52239394	1987	178,636	355,589	413
42207240	1988	80,866	155,284	75
63140177	1988	163,356	313,686	102
28351480	1988	246,367	473,090	103
47498462	1988	571,525	1,097,479	103
24390289	1988	159,894	307,038	106
25190145	1988	231,648	444,826	110
53018532	1988	245,078	470,614	118
20112020	1988	69,299	133,073	124
25311100	1988	182,732	350,894	139
3200266	1988	68,224	131,009	141
15242145	1988	115,204	221,223	144
16240136	1988	151,048	290,052	144
15286200	1988	60,221	115,640	151
22220089	1988	77,238	148,318	160
41093081	1988	331,701	636,953	182
7173440	1989	259,953	479,628	116
39070129	1989	126,374	233,167	121
52480282	1989	408,067	752,908	209
47713218	1991	243,140	406,045	87

Structure ID	**Year Built**	**Raw Cost ($)**	**2010 Cost ($)**	**Normalized Cost ($/sq ft)**
63224190	1991	309,990	517,686	98
53460065	1991	102,147	170,586	101
24360143	1992	233,778	374,493	120
26023120	1992	213,558	342,102	122
29161168	1992	142,764	228,695	124
19358167	1993	137,677	214,063	104
41156169	1993	1,752,172	2,724,305	922
53020353	1994	209,487	316,362	149
7080295	1995	136,523	221,030	112
15220161	1996	104,952	165,279	80
15157010	1996	177,771	279,955	106
40061230	1997	110,045	168,366	114
40060228	1997	112,031	171,405	116
49172160	1998	77,823	116,345	113
12497270	1998	189,344	283,068	267
47150555	2000	124,941	179,996	79
14108213	2000	556,885	802,275	90
27017120	2001	55,672	77,584	53
27261187	2001	56,643	78,937	67
63156200	2001	102,940	143,456	79
62080243	2001	176,597	246,103	79
5033125	2001	140,053	195,176	84
14120022	2001	142,987	199,265	86
6130158	2001	92,215	128,510	92
6220081	2001	123,930	172,707	111
6132160	2001	86,111	120,003	134
53290015	2002	170,737	231,383	74
28349484	2002	158,922	215,372	76
14060067	2002	77,986	105,687	77
28328500	2002	153,756	208,371	80
47607150	2002	158,268	214,485	85
62147500	2002	83,537	113,210	96
64018140	2002	208,446	282,487	100
41080037	2003	126,926	169,325	68
54100224	2003	96,562	128,818	73
26300064	2003	128,761	171,773	82
41063178	2003	200,775	267,842	87
25305020	2003	83,805	111,799	95
62351250	2003	85,780	114,434	98
31040054	2003	178,804	238,532	110

Structure ID	Year Built	Raw Cost ($)	2010 Cost ($)	Normalized Cost ($/sq ft)
33288030	2003	450,823	601,417	110
3320251	2004	104,245	135,977	71
3020015	2004	113,880	148,545	78
26030087	2004	119,584	155,986	80
23477105	2004	376,607	491,247	82
53303592	2004	127,674	166,538	84
23434020	2004	98,803	128,879	88
26030103	2004	125,946	164,284	91
25280136	2004	142,030	185,264	97
3323250	2004	209,147	272,812	143
23425220	2004	142,364	185,700	158
29290133	2005	82,444	104,736	45
52450290	2005	313,176	397,857	69
14120055	2005	96,168	122,171	82
49094110	2005	114,113	144,969	82
14021100	2005	107,190	136,174	92
5198180	2005	244,473	310,577	98
16571070	2005	195,466	248,319	100
6180078	2005	152,112	193,242	101
52433330	2005	458,463	582,429	102
43095190	2005	228,910	290,806	107
44093060	2005	129,871	164,988	113
12416344	2005	304,783	387,195	133
3002030	2006	136,891	168,201	88
43200199	2006	243,866	299,644	89
18163085	2006	281,732	346,171	93
15230166	2006	181,245	222,700	96
15283230	2006	235,126	288,905	96
6150111	2006	139,260	171,112	97
14060058	2006	256,983	315,761	108
7011350	2006	265,873	326,684	108
62072071	2006	286,183	351,640	113
26327050	2006	239,394	294,149	119
52978340	2006	143,069	175,792	132
58061080	2006	147,239	180,916	137
6318098	2007	124,212	147,837	78
10395403	2007	359,112	427,414	123
54299120	2007	138,651	165,022	161
26260067	2008	148,414	171,741	88
26031030	2008	120,955	139,966	99

Structure ID	Year Built	Raw Cost ($)	2010 Cost ($)	Normalized Cost ($/sq ft)
17226094	2009	159,126	177,315	91
23427180	2009	178,031	198,381	112
23349180	2009	171,443	191,040	126
15202190	2010	374,257	1,090,594	619

Table C-2: Existing cost data for culverts

Structure ID	Year Built	Raw Cost ($)	2010 Cost ($)	Normalized Cost ($/sq ft)
14074050	1980	85,530	257,340	83
42146140	1980	575,639	1,731,961	574
11074020	1980	933,541	2,808,801	1,082
46108230	1980	1,304,604	3,925,242	1,856
48371255	1981	269,560	714,094	201
28410472	1981	1,211,414	3,209,174	1,392
52925490	1981	141,747	375,504	7,942
47210515	1982	67,470	161,968	130
24293026	1982	799,537	1,919,379	452
53161290	1983	202,586	458,107	199
14061000	1983	207,606	469,460	244
40022130	1983	452,844	1,024,016	496
10341100	1983	629,192	1,422,791	916
52833552	1983	1,782,042	4,029,731	1,130
64089010	1984	77,834	170,518	139
12079000	1984	499,364	1,094,001	695
48020274	1984	745,870	1,634,044	1,141
34070205	1984	1,679,252	3,678,887	2,046
29135148	1985	78,042	163,923	82
15190137	1985	45,275	95,096	100
43120038	1986	94,863	192,431	117
65302100	1986	158,020	320,544	122
49098130	1986	298,901	606,322	171
41172149	1986	2,322,428	4,711,056	635
23330217	1986	1,202,661	2,439,602	1,034
39005080	1987	99,886	198,831	126
17320064	1987	171,517	341,417	204
42100109	1987	419,520	835,086	392
17332067	1987	445,224	886,253	529
47759141	1987	2,954,120	5,880,401	2,900
40200082	1988	46,115	88,553	74

Structure ID	Year Built	Raw Cost ($)	2010 Cost ($)	Normalized Cost ($/sq ft)
17338072	1988	144,286	277,068	110
17330064	1988	280,102	537,871	119
50327180	1988	222,270	426,817	137
45050039	1988	138,737	266,412	175
26180020	1988	802,672	1,541,343	176
62028270	1988	1,932,853	3,711,590	601
68079202	1988	2,787,612	5,352,955	691
17161088	1988	3,732,372	7,167,143	3,633
22230178	1989	45,039	83,099	61
6260176	1989	92,783	171,189	75
17363066	1989	1,030,398	1,901,144	150
50139210	1989	682,377	1,259,024	258
15070042	1989	43,584	80,415	957
58002330	1989	2,601,188	4,799,343	1,730
59402306	1990	169,307	297,989	122
42027070	1991	59,324	99,072	67
15180022	1991	77,053	128,678	82
15200052	1991	51,500	86,005	100
34300222	1991	122,530	204,626	117
24188247	1991	146,582	244,793	142
31061100	1991	376,666	629,036	179
24200253	1991	251,161	419,442	188
48020205	1991	305,388	510,001	229
65240188	1991	209,751	350,285	267
29180166	1991	3,125,435	5,219,502	1,671
16562082	1991	1,845,609	3,082,182	1,782
27476330	1992	128,763	206,267	70
39052010	1992	61,849	99,077	96
20213121	1992	87,304	139,853	99
55143300	1992	70,889	113,559	109
58007330	1992	113,256	181,426	129
17328015	1992	132,657	212,505	164
54307080	1992	176,533	282,790	206
23380002	1992	1,978,653	3,169,633	1,463
17234172	1992	5,508,413	8,824,007	1,686
46305166	1993	224,483	349,030	169
49097070	1993	119,525	185,839	179
40080132	1993	108,519	168,727	195
69181173	1993	255,941	397,941	225
50230165	1993	963,898	1,498,684	244

Structure ID	Year Built	Raw Cost ($)	2010 Cost ($)	Normalized Cost ($/sq ft)
10254300	1994	96,739	146,092	61
22212040	1994	69,839	105,469	92
55070126	1994	91,220	137,757	96
42111210	1994	88,724	133,988	103
49167127	1994	95,791	144,661	139
47560198	1994	149,545	225,838	152
28337150	1994	153,699	232,112	216
33380121	1994	207,848	313,887	239
61350076	1994	223,507	337,534	311
12230077	1994	1,260,568	1,903,675	700
53150289	1994	2,059,550	3,110,276	1,187
20100157	1994	1,668,923	2,520,362	1,210
52391328	1994	1,260,568	1,903,675	1,244
52469278	1994	3,878,244	5,856,818	1,704
69360425	1994	2,834,109	4,279,994	2,474
33112125	1995	148,656	240,674	95
30291210	1995	123,488	199,927	118
30100188	1995	123,128	199,343	141
33170107	1995	135,347	219,127	220
41204277	1995	323,203	523,265	220
8084042	1995	465,579	753,771	256
19040180	1995	179,167	290,071	291
60190070	1995	1,399,327	2,265,505	1,011
50002210	1995	4,489,298	7,268,157	4,395
52224439	1996	50,137	78,956	18
6278160	1996	98,132	154,539	62
30298299	1996	194,326	306,026	69
50178170	1996	465,936	733,758	73
45380164	1996	92,308	145,367	74
45380183	1996	150,229	236,581	79
6246160	1996	169,026	266,183	81
6139100	1996	105,790	166,599	88
30216260	1996	166,922	262,870	88
14075063	1996	102,098	160,784	88
18140094	1996	261,937	412,500	93
30184258	1996	276,089	434,786	101
50174222	1996	803,621	1,265,546	129
55160216	1996	105,432	166,035	167
40083127	1997	65,664	100,464	50
21174030	1997	110,693	169,358	57

Structure ID	Year Built	Raw Cost ($)	2010 Cost ($)	Normalized Cost ($/sq ft)
26194059	1997	106,623	163,131	57
55070190	1997	119,307	182,537	60
42225281	1997	58,017	88,765	70
40077128	1997	139,769	213,843	71
55074190	1997	107,709	164,792	72
6220143	1997	61,871	94,661	79
42225271	1997	111,209	170,147	84
26183047	1997	116,157	177,717	86
15200083	1997	62,532	95,672	96
26222069	1997	245,398	375,453	104
14110020	1997	77,731	118,927	109
49181190	1997	78,889	120,698	122
27168174	1997	181,477	277,656	184
52221445	1998	34,621	51,758	10
52226438	1998	47,063	70,359	17
44152210	1998	88,498	132,304	43
44119210	1998	91,268	136,445	45
52221447	1998	307,467	459,661	61
22148002	1998	74,694	111,667	61
41161038	1998	243,488	364,013	64
60310074	1998	473,411	707,747	72
24257097	1998	77,829	116,354	72
28032309	1998	95,985	143,497	81
42120117	1998	85,820	128,300	82
40199210	1998	80,553	120,426	84
15250061	1998	60,968	91,147	84
52232439	1998	229,307	342,813	88
52231439	1998	301,844	451,255	90
12230039	1998	155,194	232,014	91
41231144	1999	46,250	68,087	31
41174149	1999	72,891	107,306	32
41198147	1999	97,575	143,644	33
26270068	1999	98,755	145,381	71
42050169	1999	107,491	158,242	75
63140043	1999	84,719	124,718	76
42150027	1999	168,185	247,592	80
15190019	1999	100,198	147,506	80
47560162	1999	85,532	125,915	96
47720153	1999	80,515	118,529	100
47504100	1999	86,813	127,801	102

Structure ID	Year Built	Raw Cost ($)	2010 Cost ($)	Normalized Cost ($/sq ft)
2200038	1999	139,340	205,128	103
9142081	1999	302,965	446,007	113
65180063	1999	70,307	103,502	115
40130138	2000	153,746	221,494	43
50180166	2000	242,906	349,942	50
47050311	2000	67,358	97,039	64
7180387	2000	89,671	129,184	65
24200232	2000	75,759	109,142	66
34060005	2000	134,446	193,689	70
34060050	2000	110,411	159,063	72
24200222	2000	128,382	184,953	74
16537330	2000	89,144	128,425	77
34060107	2000	90,614	130,543	79
34060119	2000	95,201	137,151	83
24382200	2000	92,390	133,101	83
26243190	2000	88,420	127,382	87
5138210	2000	301,505	434,362	89
20213111	2000	78,586	113,215	92
29230017	2000	61,095	88,016	93
47147513	2000	127,181	183,223	102
24377200	2000	81,320	117,153	106
34060091	2000	150,823	217,283	109
47040395	2001	30,457	42,444	18
50176175	2001	120,460	167,871	57
62110259	2001	205,519	286,409	57
54306130	2001	98,425	137,164	60
54307130	2001	98,425	137,164	60
35062427	2001	126,939	176,900	61
40170096	2001	69,607	97,003	65
49010071	2001	84,019	117,088	70
44015030	2001	100,887	140,595	71
26310183	2001	80,838	112,655	72
35097434	2001	91,788	127,915	75
26210043	2001	72,194	100,609	76
18149096	2001	345,031	480,831	82
49166120	2001	90,417	126,004	84
7340297	2001	75,728	105,534	89
43025323	2001	368,630	513,718	103
52500279	2002	117,562	159,320	56
10237366	2002	177,702	240,822	57

Structure ID	Year Built	Raw Cost ($)	2010 Cost ($)	Normalized Cost ($/sq ft)
41187214	2002	130,666	177,079	59
6171100	2002	89,301	121,021	60
42059220	2002	52,984	71,804	66
41156177	2002	160,821	217,945	68
30160021	2002	95,480	129,395	71
30160045	2002	113,189	153,394	77
30160122	2002	182,911	247,882	83
20013210	2002	116,652	158,087	84
29153155	2002	97,267	131,817	88
14090065	2002	70,614	95,696	89
18040213	2002	94,960	128,690	90
49097170	2002	115,674	156,762	93
59057280	2002	188,276	255,152	93
30160111	2002	357,732	484,799	98
56069060	2002	127,935	173,378	102
30160150	2002	505,322	684,814	103
30157242	2002	233,542	316,497	104
24405201	2002	116,615	158,037	105
30160181	2002	373,262	505,846	115
30160203	2002	266,368	360,983	117
15093077	2003	79,744	106,382	59
57434419	2003	149,637	199,622	59
6181010	2003	140,300	187,166	69
6203202	2003	200,204	267,081	70
57433421	2003	133,707	178,371	71
54170087	2003	108,005	144,083	73
48020162	2003	201,026	268,177	73
54170077	2003	119,308	159,162	74
49231050	2003	156,567	208,867	75
54170102	2003	133,429	178,000	77
50050083	2003	142,976	190,736	80
12092020	2003	81,542	108,781	81
43020135	2003	304,631	406,391	85
40236040	2003	72,442	96,641	88
43024183	2003	569,910	760,284	88
22240144	2003	66,289	88,432	89
44003000	2003	118,800	158,484	89
20010295	2003	88,836	118,511	90
43021169	2003	571,648	762,603	97
49125230	2003	82,536	110,107	97

Structure ID	Year Built	Raw Cost ($)	2010 Cost ($)	Normalized Cost ($/sq ft)
51080187	2003	167,699	223,718	98
40127127	2003	100,890	134,592	99
40131131	2003	87,500	116,729	101
32091120	2003	84,153	112,264	108
40132131	2003	98,873	131,901	110
27482325	2003	162,741	217,103	121
47170612	2003	231,944	309,423	122
17377209	2004	160,686	209,599	52
17382180	2004	414,273	540,379	55
17377212	2004	419,758	547,534	56
48440241	2004	109,570	142,923	64
40046210	2004	94,386	123,117	70
64091020	2004	60,028	78,301	70
10429196	2004	72,811	94,975	79
2007220	2004	107,265	139,917	79
6151070	2004	116,519	151,988	80
14108010	2004	125,307	163,451	83
64076040	2004	71,706	93,534	84
50280106	2004	123,935	161,661	85
47192610	2004	207,924	271,217	86
53349240	2004	80,698	105,263	87
34040012	2004	121,187	158,077	93
47060301	2004	75,150	98,026	94
27030252	2004	70,842	92,407	98
20056220	2004	71,367	93,091	98
14060014	2004	75,271	98,184	101
32110308	2004	97,230	126,827	105
34252118	2004	153,930	200,787	109
53210139	2004	76,046	99,195	114
19030032	2004	88,734	115,745	117
14066030	2004	103,557	135,080	117
55060173	2004	148,445	193,632	120
55020044	2004	93,522	121,990	142
17309046	2005	111,333	141,437	43
47033449	2005	150,457	191,140	47
17302039	2005	76,397	97,054	60
17304045	2005	85,395	108,485	60
69002640	2005	149,738	190,226	60
40065240	2005	110,662	140,585	66
50284100	2005	90,014	114,353	69

Structure ID	Year Built	Raw Cost ($)	2010 Cost ($)	Normalized Cost ($/sq ft)
44137040	2005	116,386	147,856	70
43160265	2005	92,823	117,922	71
8245060	2005	98,558	125,208	77
5248180	2005	101,373	128,784	80
51039170	2005	163,306	207,463	80
6160057	2005	123,075	156,354	82
6220113	2005	114,634	145,631	83
47110335	2005	70,528	89,598	84
12394244	2005	120,645	153,267	85
12389243	2005	121,597	154,476	93
29300034	2005	135,118	171,653	95
51020159	2005	132,786	168,691	95
26210006	2005	102,538	130,264	97
26363170	2005	80,797	102,644	100
49094200	2005	150,957	191,775	104
44130037	2005	106,361	135,121	120
27230339	2005	126,249	160,386	124
60468130	2005	125,979	160,043	133
55140372	2005	120,518	153,106	184
18090209	2006	40,036	49,193	24
24356012	2006	608,318	747,454	59
60172240	2006	117,822	144,771	82
28200416	2006	81,356	99,964	83
52719310	2006	89,477	109,942	86
7079480	2006	143,501	176,323	88
49000078	2006	121,662	149,489	91
29270104	2006	70,769	86,955	105
26250040	2006	154,258	189,540	107
6105110	2006	79,192	97,305	113
64020218	2006	137,096	168,453	116
32482340	2006	128,168	157,483	120
55070169	2006	155,459	191,016	139
19062090	2006	105,058	129,087	142
19060089	2006	107,045	131,529	144
19066090	2006	107,045	131,529	144
2180167	2007	109,546	130,381	58
64038147	2007	195,062	232,162	59
64056150	2007	96,738	115,137	70
50131230	2007	113,767	135,405	86
6220079	2007	96,940	115,378	102

Structure ID	Year Built	Raw Cost ($)	2010 Cost ($)	Normalized Cost ($/sq ft)
33059013	2007	427,159	508,403	118
60129235	2007	347,234	413,277	122
16310313	2007	177,001	210,666	142

APPENDIX D: COST ESTIMATION OF REPRESENTATIVE STRUCTURES

The cost of typical bridge and culvert types with selected span length was estimated based on the construction plan of the projects provided by DOT. The cost estimation was conducted by a graduate student under the supervision of an experienced local contractor. The cost estimated is believed to be an accurate reflection of the current cost for the structures selected based on the work required in the construction plans. The detailed breakdown of the cost for each structure was available electronically as part of this report.

Table D-1: Price estimation for representative bridges

Structure ID	Total length	Year of build	structure type	Estimated Cost ($)
52318312	25	1958	Prestress Tee	22622
63210057	36	2004	CIP slab	262104
41159165	63.999	1993	CIP slab	474719
53048010	60	2011	Prestress Tee	496687
53303592	64	2004	Prestress I and CIP deck	363559
57169389	83.323	2011	CIP slab	496767
49050026	77	2011	Prestress Tee	311336
14000103	80	2010	Prestress I and CIP deck	453347
23466090	102.75	2008	CIP slab	477371
47510237	100	2010	Prestress Tee	349084
36480091	145.42	2008	CIP slab	1024212
53381506	150	1998	Prestress I and CIP deck	672842
17367246	186	2004	CIP slab	934241
10395403	187	2007	Prestress Tee	401119
33288030	190	2003	Prestress I and CIP deck	662228

Table D-2: Price estimation for representative culverts

Structure ID	Total length	Year of build	culvert length	structure type	Estimated Cost ($)
14068010	22.583	2011	44	CIP	135367
10100213	20.667	2011	60	Precast	150519
64038040	44.67	2010	48	CIP	257037
51095150	35.75	2009	80	Precast	304975
30160111	57.201	2002	90.125	CIP	463198
17382180	55.416	2004	186	Precast	781219