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FINAL REPORT

Project Title: S28: Review of Performance of Concrete Pipe Culverts (Year 1 - 2017/18)

ARRB Project No: PRG17022

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SUMMARY

A desktop study undertaken by TMR during a review of the specification MRTS25 *Steel Reinforced Precast Concrete Pipes* found that many reinforced concrete pipes in service on the TMR network have developed longitudinal cracking. This indicates that the pipes may be being overloading either during construction or when in service. There may also be latent issues associated with the design, manufacture or installation of concrete pipe culverts. The concern is that the development of longitudinal cracking may lead to in-service pipes not achieving their intended design lives or requiring significant maintenance funding allocations. Consequently, there is a need to determine the causes of longitudinal cracking and other defects so that remedial actions can be implemented if necessary.

The aim of this project was to investigate the condition of the concrete pipe culvert network and determine typical types, magnitudes and causes of existing defects with a focus on longitudinal cracking. This was achieved through a staged investigation which included the following:

- a review of overall culvert structure condition
- a review of 80P concrete pipe component condition
- a review of historical defect development
- a review of detailed inspection records
- a set of case studies focussing on key findings from the condition reviews.

The review of overall structure condition found that 5% of the culvert network can be considered as being in a defective condition state of 3 and 4 (CS3/4) if only precast concrete pipe components are considered when calculating condition state. Of the culvert network, 23% had no Level 2 (L2) inspection data recorded in the TMR Bridge Information System (BIS). These structures were excluded from the review of structure and component condition.

The review of pipe component condition found that there were some districts and decades of component construction which showed increased longitudinal cracking incidence. These variations in longitudinal cracking incidence were investigated in further detail through a set of case studies. Longitudinal cracking was found to be less common in CS3/4 rated components compared to spalling and joint defects. The review of historical defect development showed that there was no discernible temporal trend associated with the time taken for defects to develop in 80P components which trigger CS3/4 ratings. The review of L2 inspection records found that there were some instances where more severe defect ratings would be appropriate but, in general, condition ratings were appropriate. No evidence was found of district-specific inspection practices which could explain trends in longitudinal cracking incidence.

The case studies found that there were some potential causes for variations in the prevalence of longitudinal cracking between decades of construction associated with past updates and introduction of specifications relating to design, manufacture and installation of precast concrete pipes. Investigation of these potential causes was hindered by the fact that many culverts either do not have any design drawings recorded in the BIS, or do not have information relating to specifications recorded on the drawings that are

available. Some structures did have relevant information recorded, but there were not enough such structures to allow any patterns to be established or definitive conclusions to be made. No data was available to investigate potential district-specific variations in defect prevalence. A selection of design drawings was reviewed, and some issues were identified relating to missing information. It was found that the TMR culvert standard drawing has not been updated since 2003, and references outdated specifications for construction loading.

It is recommended that culvert design drawings are checked by E&T Structures prior to approval, and that key culvert details including pipe class, year of construction, depth of fill and relevant design/manufacture/installation specifications are recorded on drawings and entered into BIS. Data management practices within the TMR bridge asset management process should be strengthened to ensure that all culvert drawings are retained and entered into BIS. A record should be kept in BIS of all design drawings provided for a structure to ensure that all supplied drawings are accounted for in case the drawings themselves cannot be found. It is also recommended that the culvert standard drawing SD1359 is updated to reference the most recent specifications.

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1 INTRODUCTION

1.1 Background

A desktop study undertaken during a review of MRTS25 *Steel Reinforced Precast Concrete Pipes* found that many in-service reinforced pipes have developed longitudinal cracking, indicating the possibility that the mechanism causing the cracking is overloading either during construction or in service. In addition, many of the older in-service pipes have displayed signs of concrete spalling resulting in exposed reinforcement. The concern with these findings is that reinforced concrete pipes may not achieve the intended design life and will require significant maintenance funding allocations. There is therefore a need to establish the causes of the observed defects in order to identify corrective measures for new works and to update current specification documentation.

1.2 Aim and Objectives

The overall aim of this project was to investigate the condition of the concrete pipe culvert network to determine the types, magnitude and underlying causes of defects observed and make recommendations to improve the future longevity of the concrete pipe culvert network. The investigation primarily focused on the issue of longitudinal cracking and its prevalence in relation to other observed defects.

This was achieved through the following approaches:

1. Conduct a network-wide investigation of Level 2 (L2) component inspection data from the TMR Bridge Information System (BIS) to determine the extent and nature of the defects observable in the current system and use data analysis techniques to determine potential correlations and root causes.
2. Use the findings of the network-wide investigation to target a selection of specific case studies to further analyse and develop a better understanding of the root causes surrounding key defect issues in the network, exploring the potential issues around construction specifications, design specifications, construction quality and installation techniques.
3. Use the findings of objectives 1 and 2 to make recommendations to improve current understanding of the capacity and longevity of the concrete pipe culvert network.

1.3 Scope

This study was limited to major (having diameters greater than or equal to than 1.8 m) steel-reinforced circular precast concrete pipes only, as per the aims and objectives above.

The study did **not consider**:

- other components of the culvert such as head walls, wingwalls, aprons etc.
- minor culverts
- current in situ soil conditions
- fibre-reinforced concrete pipes
- box culverts
- the current design discrepancies between MRTS25, AS 5100 and the pipe code AS 4058.

1.4 Outline

This report details the methodologies and findings of each stage of the investigation. It is structured as follows:

- Section 2 details the methodologies for each of the stages of the investigation and gives an overview of the processes utilised during each stage.
- Section 3 presents key observations and findings from investigation of pipe culvert condition at a structure and component level. It includes key observations on the prevalence of longitudinal cracking and other defects at a component level. This section presents the key findings relating to longitudinal cracking and is the basis for the majority of further investigation presented in following sections.
- Section 4 presents key observations and findings from the investigation of trends in historic L2 inspection records at a structure and component level. Potential trends in deterioration were investigated to determine if the deterioration of culvert components can be shown to be exclusively time-dependent based on the available dataset.
- Section 5 presents key observations and findings from the investigation of a selection of detailed L2 inspection reports and comparison to TMR guidelines. L2 inspection reports were investigated to determine whether there were any anomalies in inspection practices.
- Section 6 presents case studies focussing on potential causes for longitudinal cracking defects relating to historic changes in design/manufacture/installation specifications and quality/availability of design drawings and records.
- Section 7 provides conclusions and recommendations based on the observations and findings of the investigations detailed in the report.

Appendix A provides the full dataset from the investigation of pipe culvert condition (Section 3). Appendix B and Appendix C provide the full dataset for the structure and component level historical analysis, respectively (Section 4). Appendix D provides detailed data from the review of L2 inspection records (Section 5).

An explanation of some of the terms used throughout the report is provided in Table 1.1. The names and office locations of the TMR districts associated with the district IDs used in data analysis tables are provided in Table 1.2.

Table 1.1: Definition of common terms

Term	Definition
Major/minor culverts	For concrete pipe culverts, a culvert is considered to be major if it has at least one barrel (cell) with diameter ≥ 1.8 m. Culverts not satisfying this are considered minor and have not been considered in this study.
80P	Component code for precast concrete pipes as specified by the SIM.
CS	Condition State: The CS of component defects and structures is assessed by inspectors during Level 2 inspections. As subjective ratings, CS1 is good ('as new'), CS2 is fair, CS3 is poor, and CS4 is very poor. CS5 is the worst rating possible (unsafe: immediate closure of structure), but it is not applied to components and is not considered in this study.
CS1/2; CS3/4	Condition State 1/2; Condition State 3/4. See CS.
L2; L2 inspection	Level 2 inspection: structure inspections carried out to determine the condition of structures as a whole and the condition of individual structural components.
Defective	A term used to refer to culverts rated as CS3/4. See CS.
BIS	Bridge Information System: database of information relating to structures maintained by TMR.

Table 1.2: TMR district details

District ID	District name	Office location
401	Central West	Barcaldine
402	Darling Downs	Toowoomba
403	Far North	Cairns
404	Fitzroy	Rockhampton
405	Mackay/Whitsunday	Mackay
406	Metropolitan	Brisbane
407	North Coast	Maroochydore
408	Northern	Townsville
409	North West	Cloncurry
410	South Coast	Nerang
411	South West	Roma
412	Wide Bay Burnett	Bundaberg

2 METHODOLOGY

2.1 Background

TMR has provided the dataset from the BIS database relevant to the precast concrete pipe structures installed on the network. The database includes the inventory information, component condition ratings and overall condition rating data associated with L2 inspection records logged in the BIS. The following points have formed the focus for the review of BIS database records:

- Review the data for completeness, accuracy and relevance.
- Identify and report the current condition of the network.
- Classify/code instances of defects using the L2 comments field in the BIS to quantify the instances of different defect types.
- Compare the prevalence of longitudinal cracking on the TMR concrete pipe network with that of other common defects.
- Identify correlations, potential root causes and potential interactions associated with particular defect types, (i.e. correlations between factors such as fill height, various forms of cracking, spalling, environment, region, construction age etc.).
- Determine typical deterioration times for concrete pipe components and identify correlations between deterioration time and longitudinal cracking/spalling.

Additionally, TMR has provided a selection of L2 inspection reports for complete concrete pipe culvert structures which include detailed data on defects and condition ratings for concrete pipes. These have been reviewed for consistency with the TMR manuals recommended practice and to identify issues with defect identification and Condition State (CS) assessment. Potential links between inspection practices and high instances of reported longitudinal cracking have been investigated.

Historic design and construction specifications used by TMR for concrete pipe installation have been reviewed with the aim of determining if any links can be drawn between the content of specifications and the condition of the network. Specifically, any potential links between time-specific variations in defect prevalence and specification update/release dates have been investigated.

A selection of culvert design drawings has been supplied and have been reviewed for possible defect causes and consistency with TMR specifications.

2.2 Network-wide Pipe Data Analysis

2.2.1 Data Supplied and Amalgamation

TMR has provided two data files with information extracted from the BIS:

- Pipe concrete culverts 24082017.xlsx; provided on 24 August 2017
  - included: structure ID, historical component CS, pipe structure component inspection report comments, span and deck information which includes construction data, depth of fill, surfacing type
  - missing: overall CS ratings; L2 inspection comments.
- Pipe concrete culverts 25092017.xlsx; provided on 25 September 2017
  - included: as per original file plus overall conditions state ratings for the latest inspection and L2 inspection comments and an additional 28 structures that were missing L2 component information in the original file were added to the dataset

— missing: span and deck information, historic overall CS ratings (only the most current overall CS was provided); 133 structures identified in the span data were missing L2 data.

These source documents were generated by querying BIS with the following filters:

- structure-level data: open-to-traffic major concrete pipe culverts
- inspection-level data: 80P components.

The two files were amalgamated during the analysis process to capture and use all the information provided.

Through the amalgamation process it was found that:

- The structure ID information in the ‘span’ and ‘deck’ tabs of 24082017.xlsx were consistent in terms of unique IDs. The span tab was used as the definitive.
- There were a number of structure IDs in the span tab that were missing from the overall condition rating data and component condition rating dataset.

There were a number of structures that were found to have missing information. Using the structure IDs from the deck tab, these included:

- There were 133 structures found to not have L2 component condition information or overall condition information. These structures were excluded from the overall structure CS analysis and the component CS analysis.
- There were 144 structures found without overall condition information. These structures were excluded from the overall structure CS analysis.
- Of the 144 structures without overall condition information, 11 were found to have L2 component condition information. These structures have been included in the component CS analysis but have been excluded from the overall structure CS analysis.
- There were 5 structures found to have overall condition information but no component condition information. These structures have been excluded from the overall structure CS analysis and the component CS analysis.

All structures in these over-lapping groups have been investigated and all gaps are legitimate, being due to:

- recent transition of culverts from minor to major, triggering the need for new inspections
- new structures
- draft inspections
- third party management (e.g. Transurban)
- non-precast concrete pipes
- updates that occurred between 24 August and 25 September 2017.

The final dataset used for the analyses in this report is accurate in terms of condition ratings and existing structures/components as of 25 September 2017.

A number of issues were found during the data amalgamation process including:

- inspection frequency: the recommended maximum interval for L2 inspection is five years, but longer intervals are common
- quality of the defect identification and reporting

- consistency in recording
- incorrect codes.

2.2.2 Overall CS Network Analysis

Analysis of the overall CS data was undertaken to summarise the data and address the following questions:

- What is the current distribution of overall CS across all concrete pipe culverts in the network?
- Are the overall CS governed by the concrete pipes themselves or other components of the pipe culvert structure? That is, are there any differences between the CS of the pipe component and the overall condition rate?
- Are there any patterns that emerge when compartmentalising the overall CS data into districts, exposure class, decade of construction and depth of fill?

The overall condition ratings provided from the BIS are based on the entire structure including components other than the precast concrete pipes (80P components). This study is focussed on precast concrete pipe components. In order to determine the impact of 80P component condition on the condition of structures, the overall condition rating needs to be recalculated using only the precast concrete pipe components of a structure. The 25% rule provided by the *Structures Inspection Manual* (Part 3, Section 3.7.3.3) (if more than 25% of the structure component is in CS3 or CS4 all the structure shall be classified respectively) has been applied (Queensland Department of Transport and Main Roads 2016). Condition ratings for 80P components are applied per lineal metre, and the following example is provided to illustrate how the 25% rule is applied:

- A component with a span length of 20 m has 10 m rated in CS2 and 10 m rated in CS3.
- For this hypothetical component, more than 25% of the component span is rated as CS3, so the CS of the structure based on the 80P component would be CS3.
- Where multiple 80P components exist in a structure, the structure CS based on 80P components is determined using the component in worst condition based on the application of the 25% rule.
- Where no 80P components that meet the > 25% CS3/4 criteria exist for a structure, the CS based on 80P components is made CS1/2.

The process outlined above allows the overall CS for the 80P pipe components to be understood thus providing a level of appreciation of the magnitude of the problem at a structure level. Also, by comparing the calculated overall CS due to the pipe components to the overall CS provided in the BIS due to all components in a structure, an understanding of whether issues are related to pipe components or other components can be developed. The results of the overall CS network analysis can be found in Section 3.1.

2.2.3 Component Defect Network Analysis

The primary data on component-level culvert defects was accessed in the Excel worksheet ‘Inspections 25.09.17 Defects’. Data on each structure’s construction date and depth of fill was obtained from the structure and deck worksheets, which are described in Section 2.2.1.

Records were checked individually and only the most current inspection record was used in the analysis. Where the most recent record was incomplete and did not contain information on all component groups, data from the next most recent complete inspection record was retained for the relevant component groups. A number of duplicate component records which were identical to other records were detected during the check of records and were subsequently removed from the analysis.

Key statistics relating to the spread of components between the districts, decades of construction, exposure class and depth of fill were generated from the filtered record set within Excel and are recorded in Section 3.2.1. Key statistics relating to the spread of defects relative to each condition state and the presence of defects in each district were also generated and are presented in Section 3.2.2.

The L2 inspection comments field associated with each 80P component record was used as the basis to code the different types of defects. Each record was reviewed individually, and any component defects were catalogued using the defect categories in Table 2.1. The typical positioning of transverse and longitudinal cracks is shown in Figure 2.1 and Figure 2.2.

Table 2.1: Coded defect category

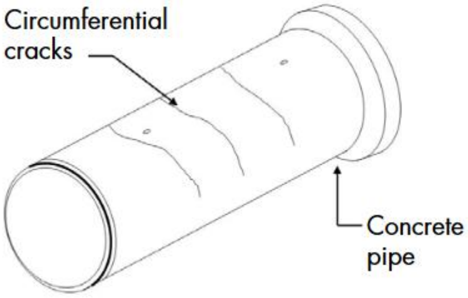
Coded defect category
Longitudinal cracking*
Transverse cracking
Shrinkage cracking
Nondescript cracking
Repaired cracking
Possible crack repair**
Any type of cracking
Spalling
Settlement
Misaligned joints
Waterway
Abrasion
No defect/comment

Notes:

*In some cases where defect descriptions did not provide conclusive detail regarding crack orientation, ARRB exercised judgement as to the likely defect detail. Comments which indicated cracking 'along' or 'across' or 'full length of structure' were noted as longitudinal cracking. In general, cracks described as 'severe', 'major' or 'moderate' were considered longitudinal cracks. Cracks in 'roof', 'wall' or 'soffit' were maintained as longitudinal. Cracks described as 'minor' that were not noted as horizontal were generally reclassified as nondescript. Longitudinal/horizontal shrinkage cracks were classified as shrinkage cracks only. Cracks described as longitudinal/horizontal but not transverse were reclassified as longitudinal only.

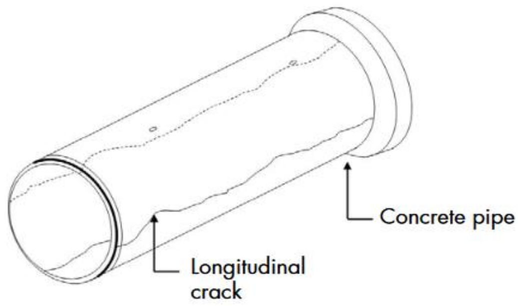
**This is noted/coded when earlier reported cracking is not noted in later inspection records for the same structure/component.

Figure 2.1: Transverse cracking (also known as circumferential cracking)



Source: Al-Saleem & Langdon (2014).

Figure 2.2: Longitudinal cracking



Source: Concrete Pipe Association of Australasia (2008).

Tables and charts were produced which showed the relationships between defects (longitudinal cracking, transverse cracking, shrinkage cracking and spalling) and parameters including district, construction date, depth of fill and exposure class. The tables generated were studied and any noteworthy statistics and observations were synthesised and recorded for further investigation.

Condition ratings are applied to 80P components on a lineal metre basis. For the component analysis, the CS of each component was taken as the worst CS that had been applied to each component regardless of what proportion of the component was rated in each CS.

The investigation of longitudinal cracking in 80P components is the primary focus of this study, and the discovery of notable relationships between longitudinal cracking defects and key parameters has formed the focal point of the network defect analysis findings which are presented in Section 3.2.3. A summary of key findings related to other defects is also presented in Section 3.2.4, but these findings have generally not been investigated further as a part of this study. The full set of data obtained from the network defect analysis is provided as charts and tables in Appendix A.

2.3 Historical Analyses

2.3.1 Structure-level Analysis

The methodology documented in Section 2.2.2 explains how structures were rated overall using precast pipe components (80P) only. This was used as a basis to identify all the structure IDs with current overall CS3 and CS4 ratings. These structures were then historically analysed using past L2 inspection records in the BIS. The overall CS was calculated for each historic record and where possible the defect causing the structure to be classified in the associated CS was noted. The results are provided in Section 4.1.

2.3.2 Component-level Analysis

The overall purpose of the component-level historical analysis is to investigate trends in deterioration time at a component level. Deterioration trends for longitudinal cracking, spalling and all defects are calculated and compared to the lifespans of components which have not yet deteriorated. Ultimately the historical analysis seeks to determine whether the deterioration and development of defects in 80P components can be considered to be time-dependent, i.e. whether the presence of defects correlates with the age of components.

Deterioration time is defined here as the time that a component takes to reach CS3/4 from its construction date. Deterioration time has been measured from the construction date of the component to the first inspection date which places the component in CS3/4.

The components included in the deterioration time analysis met the following criteria:

- Are an original component – i.e. were installed when the structure as a whole was installed and have the ‘O’ modification code.
- Have been inspected more than once.
- Have at least one inspection record where the component was placed in CS3/4.
- Have an initial inspection record which places the component in CS1/2.

L2 inspection records are only available from the early 2000s, but the oldest components analysed were constructed in the 1950s. In order to produce reasonable estimates of deterioration time, components are only considered if the first inspection places the component in CS1/2. It is assumed that the component in question was not in a CS3/4 state at any time prior to the first inspection, and that the inspection record placing the structure into CS3/4 after the first inspection is the first instance of the structure entering CS3/4 by current inspection standards. Components which were placed into CS3/4 at the first inspection date have not been considered since it is impossible to tell how long the component was in a CS3/4 state prior to the first inspection. Components which have only been inspected once have been excluded for similar reasons relating to the uncertainty of when the component reached CS3/4.

Original components excluded from the initial deterioration time analysis due to the reasons outlined in the previous paragraph have been graphed separately in order to highlight their potential impact on deterioration time and illustrate the fact that the components initially analysed are not wholly representative of the entire population of components.

The excluded components graphed for comparison include:

- original components which were placed in CS3/4 at the first BIS recorded inspection
- original components which have never entered CS3/4.

Only components which are identified as original have been considered due to the lack of consistent construction date data for components which are marked as modifications. It is assumed that components marked as modifications would have a construction date different to that of the original structure. The results of the analysis are provided in Section 4.2.

2.4 L2 Inspection Record Review

TMR has provided a selection of complete L2 inspection records for various culvert structures. The records were selected by TMR based on the presence of keywords relating to longitudinal cracking including ‘moderate’, ‘severe’, and ‘full length’. Where a structure has undergone multiple inspections, record sets have been provided for each inspection. Each record set includes a structure condition inspection report, a defective components report, and a photo and sketches record.

The aim of the L2 inspection record review is to review the appropriateness of the CS ratings given to 80P components in each report. The appropriateness of ratings for components other than 80Ps has not been reviewed. Appendix D of the *Structures Inspection Manual* (Queensland Department of Transport and Main Roads 2016) provides specific guidelines on the rating of 80P components. Part 2 of the manual provides detailed descriptions of the typical defects which may be present in concrete.

The 80P component ratings have been reviewed based on the content of the comments recorded in the condition and defect reports and the photos provided with each record. The rating given to each component has been compared to what is recommended by Appendix D and Part 2 of the *Structures Inspection Manual* (Queensland Department of Transport and Main Roads 2016). The content of inspection reports has also been reviewed at a district level in order to investigate possible connections between inspection practices and the incidence of defects. Defect observations made during the network-level pipe data analysis have been compared to the content of reports sourced from relevant districts. Ultimately, the inspection records review seeks to determine whether any of the observed high/low rates of longitudinal cracking and other defects observed during the network defect analysis can be explained by inspection practices. The L2 inspection record review can be found in Section 5.

2.5 Case Studies

The case studies section of the report seeks to investigate and, if possible, verify potential explanations to the key findings of the network defect analysis and historical CS analysis. The case studies are located in Section 6.

The key constituents of the case studies are:

- investigation of current and superseded design, manufacture and installation specifications for precast pipes
- investigation of current and superseded TMR standard drawings for precast pipe installation
- investigation of specific structure design, manufacture and installation records where available
- review of culvert data management practices at TMR.

TMR has provided a summary of updates and changes to concrete pipe design, manufacture and installation specifications which details changes to design-life requirements, water absorption limits, sampling frequencies, loading requirements (vehicles, construction loads, design loads), environment cover requirements, load classes and pipe marking. Current and superseded versions of the TMR specifications MRTS03 *Drainage, Retaining Structures and Protective Treatments* for installation of drainage components and MRTS25 *Steel Reinforced Precast Concrete Pipes* for manufacture of reinforced concrete pipes have been obtained from the TMR website. The history of the Australian standards AS/NZS 3725 *Design for Installation of Buried Concrete Pipes* and AS/NZS 4058 *Precast Concrete Pipes (Pressure and Non-pressure)* has also been assessed.

The content of specifications and changes made at each specification update have been investigated for links to temporal variations in the prevalence of longitudinal cracking. TMR has also provided the most recent standard drawing for culvert installation, as well as superseded versions dating back to 1992. These have been reviewed for potential defect causations.

TMR has accessed the BIS and the Geospatial Information Management System (GIMS) in order to extract data for 20 unique culvert structures. The structures selected were constructed after 1993 and had some length of structure rated in CS3/4. A culvert construction year limit of 1993 was imposed due the fact that older structures are less likely to have available design and construction records. Information provided by the BIS was used to assist in the location of design drawings and records within GIMS for the selected set of structures. In many cases it was found that culverts either do not have associated design drawings or can only be seen in high-level drawings for certain road sections. Where drawings existed, culvert parameters including number of spans, size, and design loading/pipe class were confirmed if possible. A selection of the sourced culvert drawings was provided for review. These drawings have been reviewed for consistency with TMR guidelines and potential causes for culvert deterioration have been investigated.

3 ANALYSIS OF NETWORK-WIDE PIPE CULVERT DATA

3.1 Overall CS Analysis

As per the methodology, the following parameters were considered for the overall CS analysis:

- year of construction
- condition rating of the pipe component
- overall condition rating of the structure
- exposure class of the structure
- location (district).

3.1.1 Key Findings

- A total of 449 culverts were considered. This figure excludes the 144 structures identified as having no overall CS information, and the 5 structures identified as having overall CS information but no component condition information (Section 2.2.1). Two duplicate structure records were identified in the 449 total, but these have not been removed as they do not significantly impact on the analysis (IDs 42622 and 43067 had 2 records each).
- A third of all existing culverts were constructed in the 1970 and 1980s (Table 3.1).
- Districts 401, 409 and 411 have significantly small culvert populations of 4, 0 and 5 structures with overall CS information respectively. There are 3 structures in district 409, but none of these structures have overall CS information (Table 3.1).
- Of the structures considered, 10.1% are in CS3/4 overall. This drops to 7.5% when only considering the pipe components themselves (that is, ignoring headwalls etc.).
- This number of structures on the network which can be considered as being in CS3/4 based on the condition of the 80P components only is fairly small at 34 structures. This indicates that the network is in overall good condition, and that defects existing in 80P components are not often considered serious enough to warrant rating the entire structure in CS3/4.
- Most of the structures rated CS3 and CS4 are more than 30-years old.
- By decade of construction, the 1970s had the highest proportion of overall defective structures (CS3/4) at 15%.
- Environmental class is not a significant variable in overall CS3/4 ratings.
- A strict interpretation of the *Structures Inspection Manual* (SIM) 25% rule (Queensland Department of Transport and Main Roads 2016) would reclassify 12 CS2 structures as CS3 and 6 CS3 structures as CS4.

3.1.2 Distribution and Age Profiles

Table 3.1 provides a breakdown of the distribution of culverts among the districts and the construction age. It shows that more than a third of the culverts were built between 1970 and 1990 (163 structures), while the number of culverts built in recent decades is fairly consistent at around 60–70 structures per year. Furthermore, districts 401, 409 and 411 have a very small number of culverts with CS data.

Table 3.1: Pipe culvert district location vs. decade of construction

District ID	Decade of construction								Total
	1950	1960	1970	1980	1990	2000	2010	No date	
401		1	1	1	1				4
402	3	2	10	4	2	2	1		24
403	8	5	3	5	3	7			31
404	3	5	16	13	10	4	8		59
405		6	7	15	3	6	3		40
406	1	6	11	11	5	7	5		46
407	2	10	7	10	14	6	27	1	77
408		1	12	6	4	7			30
409									0
410	10	5	7	6	11	13	1		53
411						2	3		5
412	4	16	13	5	9	10	23		80
Total	**31**	**57**	**87**	**76**	**62**	**64**	**71**	**1**	**449**

3.1.3 Overall Condition Rating

In general, the majority of the network is in good condition. Figure 3.1 presents the distribution of the condition rating of the structures with overall L2 inspection data. It shows that 90% are in CS1 and CS2, 10% in CS3, and less than 1% are in CS4.

Similarly, Figure 3.2 shows the distribution of overall condition rating using the precast concrete pipe components only. Still the predominant CS is CS2 (63% of the structures), followed by CS1 (30%), CS3 (6%) and CS4 (approximately 1%).

Figure 3.1: Overall structure CS as reported by BIS (449 structures)

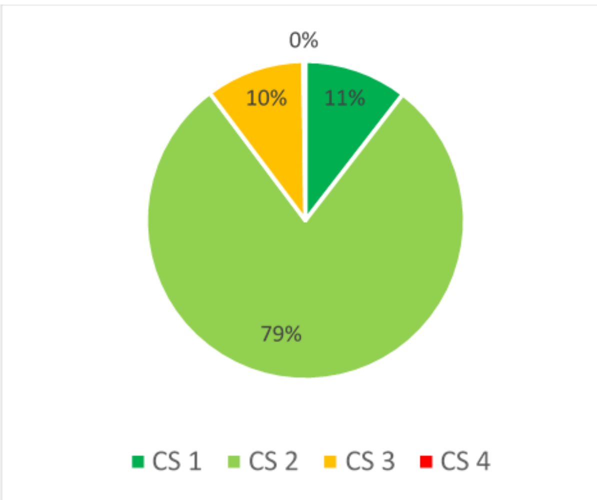


Figure 3.2: Overall CS based on 80P components only (449 structures)

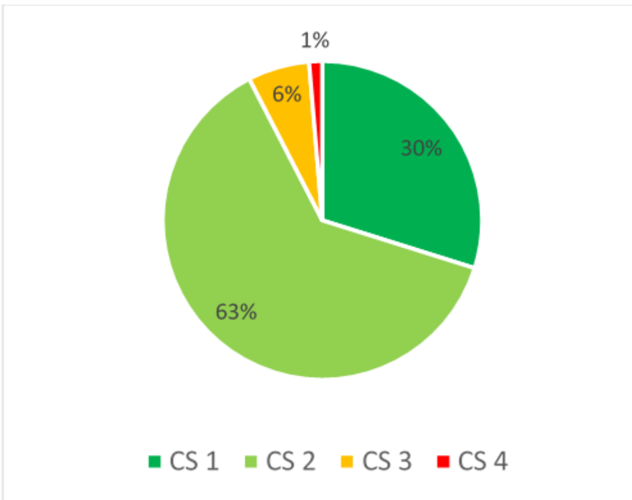


Figure 3.3 shows the differences between the component CS based on precast pipe components only and the overall CS using all components.

Table 3.2 presents this correlation between component condition rating and overall condition rating. There were six structures where the highest condition rating of its components is CS4 while they were overall rated CS3. This contradicts the current guidelines in the *Structures Inspection Manual* (Part 3, Section 3.7.3.3), which requires that if 25% or more of a principal structural component is rated CS3 or CS4, the overall structure shall be rated in CS3 or CS4, respectively.

Figure 3.3: Overall structure CS as reported by BIS vs. overall CS based on 80P components only

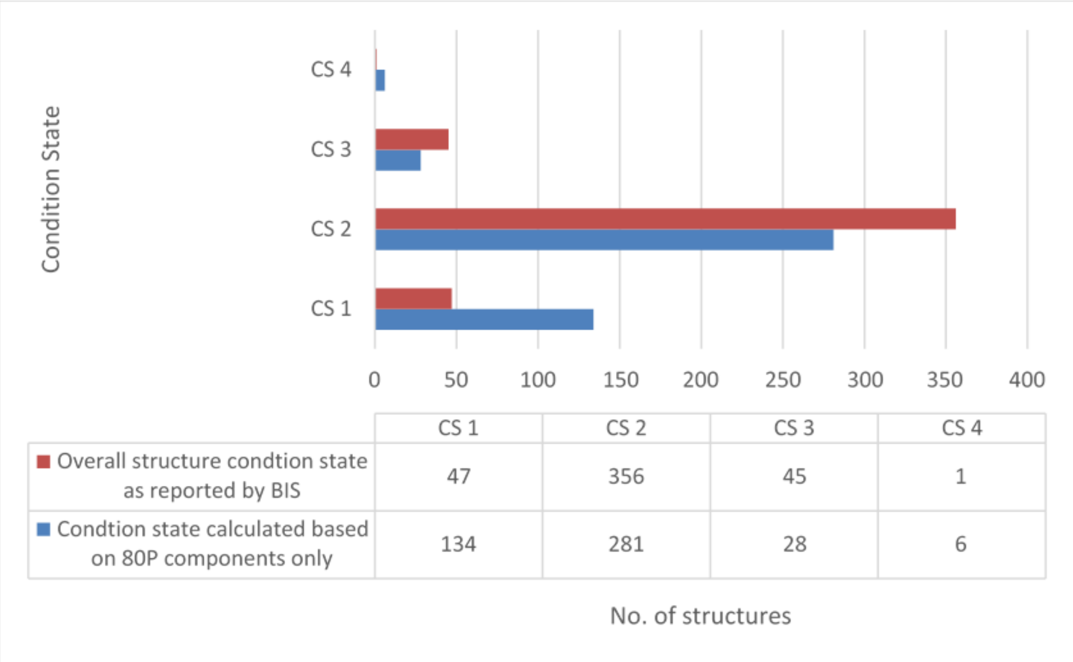


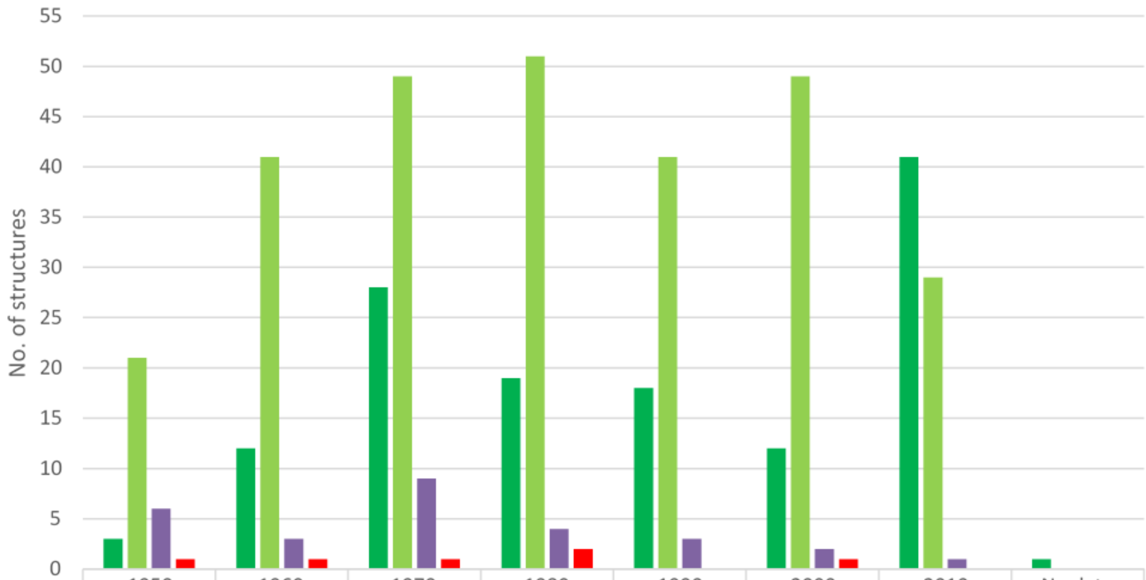
Table 3.2: Overall structure CS as reported by BIS vs. overall CS based on 80P components only

	Overall structure CS				Total number	Total %
Overall CS based on 80P components only	CS1	CS2	CS3	CS4		
CS1	47	83	4	0	134	30%
CS2	0	259	21	1	281	63%
CS3	0	14	14	0	28	6%
CS4	0	0	6	0	6	1%
Total number	47	356	45	1	449	100%
Total percentage	11%	79%	10%	0%	100%	

3.1.4 Overall CS vs. Structure Age

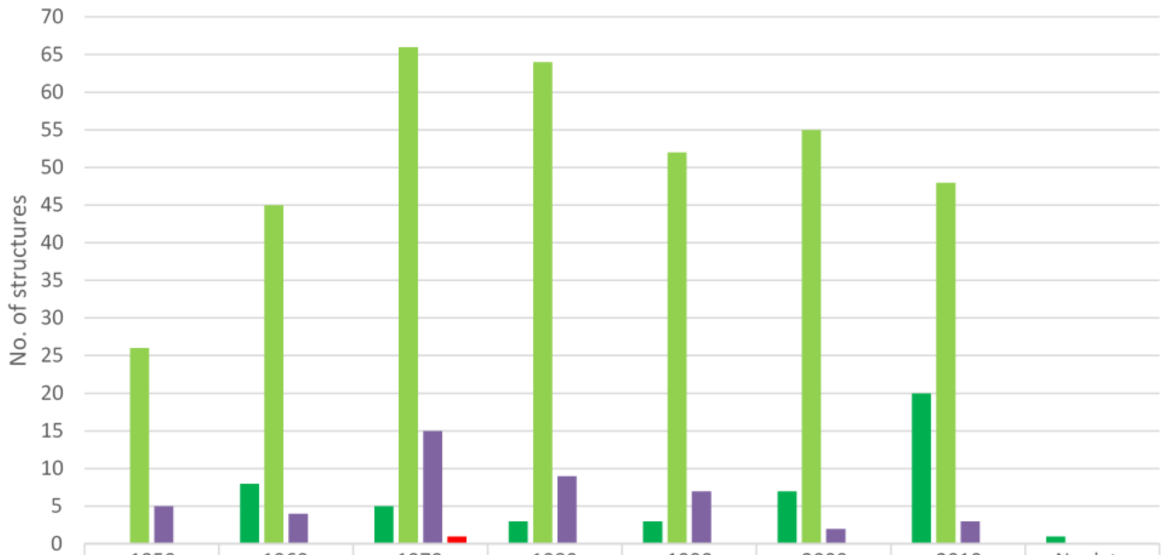
Figure 3.4 plots the distribution of overall CS of the structure considering 80P components only against age of the culverts. Figure 3.5 plots the overall CS of structures provided by the BIS (which is based on all components) against age.

Figure 3.4: Overall CS based on 80P components only vs. decade of construction



	1950	1960	1970	1980	1990	2000	2010	No date
CS 1	3	12	28	19	18	12	41	1
CS 2	21	41	49	51	41	49	29	
CS 3	6	3	9	4	3	2	1	
CS 4	1	1	1	2		1		

Figure 3.5: Overall structure CS (all components) as reported in BIS vs. decade of construction



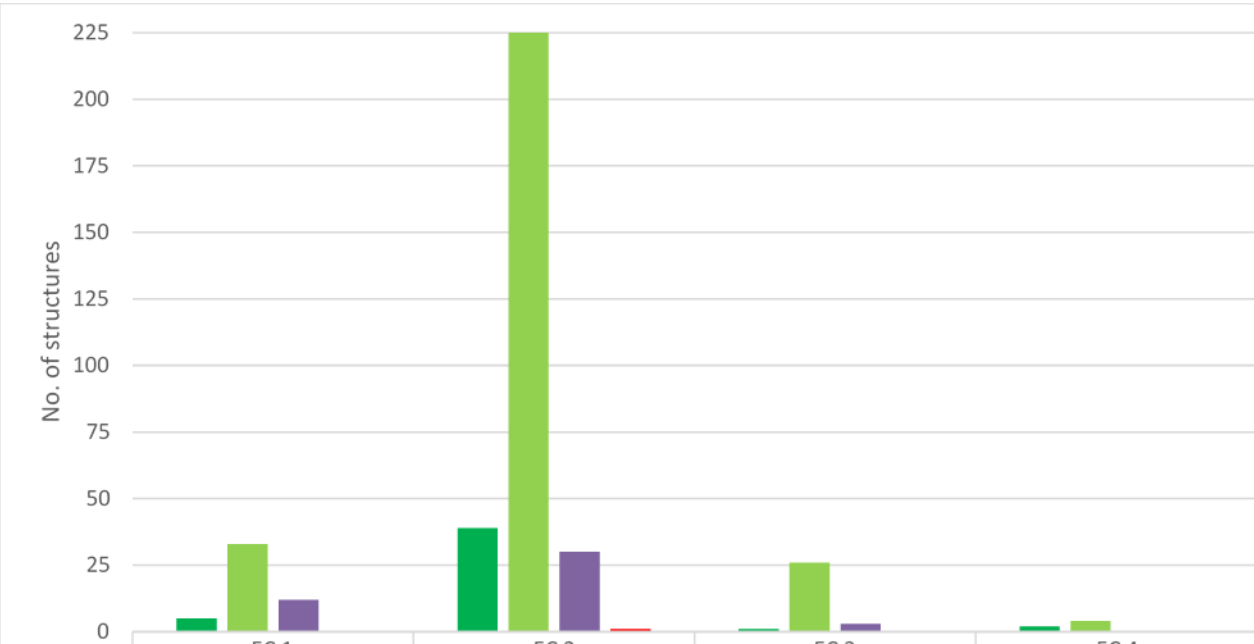
	1950	1960	1970	1980	1990	2000	2010	No date
CS 1		8	5	3	3	7	20	1
CS 2	26	45	66	64	52	55	48	
CS 3	5	4	15	9	7	2	3	
CS 4			1					

3.1.5 Exposure Class

An analysis of the environment exposure class against the overall condition rating of the structure considering 80P components only found that there was no structure in CS3/4 for exposure class 4. Additionally, Figure 3.6 shows that most of the structures are reported as being in exposure class 2. It was speculated that exposure class 3 and 4 may have only been used for recently constructed pipes, but Figure 3.7 shows that there is an even temporal spread of structures in exposure class 3. For exposure class 4 however, four out of the six structures in the class have been constructed since 2010, which supports the possibility that exposure class 4 alone may have only recently come into use.

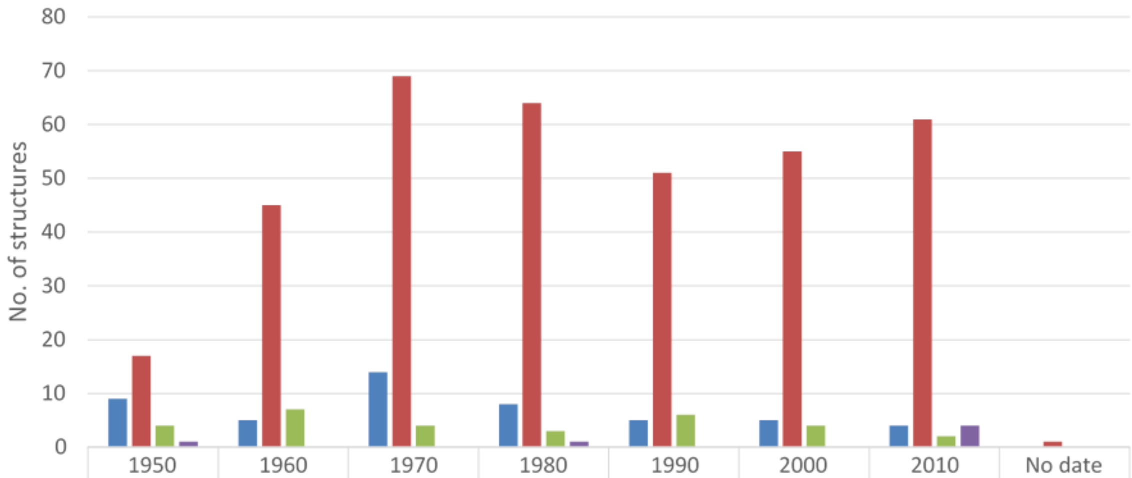
The system of three exposure (environment) conditions defined by MRTS25 *Steel Reinforced Precast Concrete Pipes* differs from the exposure classification system used by the BIS which has four possible exposure conditions. Currently, the exposure condition determined for a pipe using MRTS25 must be converted to correspond to a BIS exposure condition rating. It is unclear whether this has occurred in all situations, which may have contributed to the high proportion of pipes entered under exposure class 2 in the BIS.

Figure 3.6: Overall structure CS as reported in BIS vs. environmental exposure class



	EC 1	EC 2	EC 3	EC 4
CS 1	5	39	1	2
CS 2	33	293	26	4
CS 3	12	30	3	
CS 4		1		

Figure 3.7: Environmental exposure class vs. decade of construction



	1950	1960	1970	1980	1990	2000	2010	No date
EC 1	9	5	14	8	5	5	4	
EC 2	17	45	69	64	51	55	61	1
EC 3	4	7	4	3	6	4	2	
EC 4	1			1			4	

Environment Exposure class

3.2 Component-level Defect Analysis

The analyses detailed in this section have been conducted as outlined in the methodology (Section 2.2.3). Key component statistics are presented in Section 3.2.1 which allow statistical observations to be made for the prevalence of defects. A summary of defects found in the components considered is presented in Section 3.2.2.

A total of 458 structures have been considered for the component-level defect analysis. This figure includes 11 structures that were found to have component CS data but no overall structure CS data. The two duplicate records identified in Section 3.1.1 have been excluded from the total and the 5 structures which had overall structure CS data, but no component CS data, have also been excluded. These 458 structures correspond to a total of 1472 80P components (spans), or roughly 38 km of pipe.

3.2.1 Key Statistics

- Single-span structures are the most common (125 structures), followed by structures with 2 (95 structures) and 3 span components (93 structures). There is a total of 35 structures with greater than 6 and up to 15 span components per structure (Figure 3.8).
- The number of components ranges widely between districts from 211 in district 410 to 0 in district 409 (due to no component data) (Table 3.3). District 409 has been excluded from further component data tables presented in Section 3.
- The number of components rated in CS3/4 also varies widely between districts from 0 in districts 401, 409 and 411 to 63 in districts 407 and 410 (Table 3.6).
- Component population by decade of construction is fairly consistent with a high point during the 1970s and 80s (Table 3.3).
- The average age of components is fairly consistent across most districts with the outlier being district 411 which has a small recently constructed population (Figure 3.9).

- Of the components considered, 55% (813) have no data for the depth of fill (Table 3.9); 34% (500) of the components considered have fill depths from 0 to 2 m.

Figure 3.8: Number of 80P components (spans) per structure

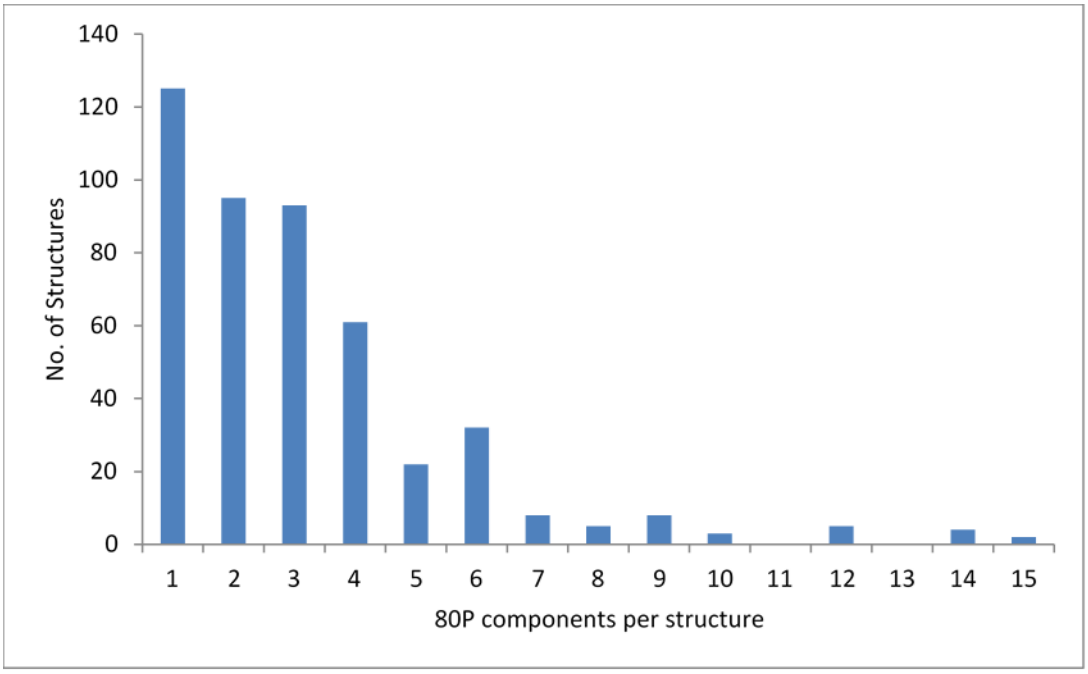
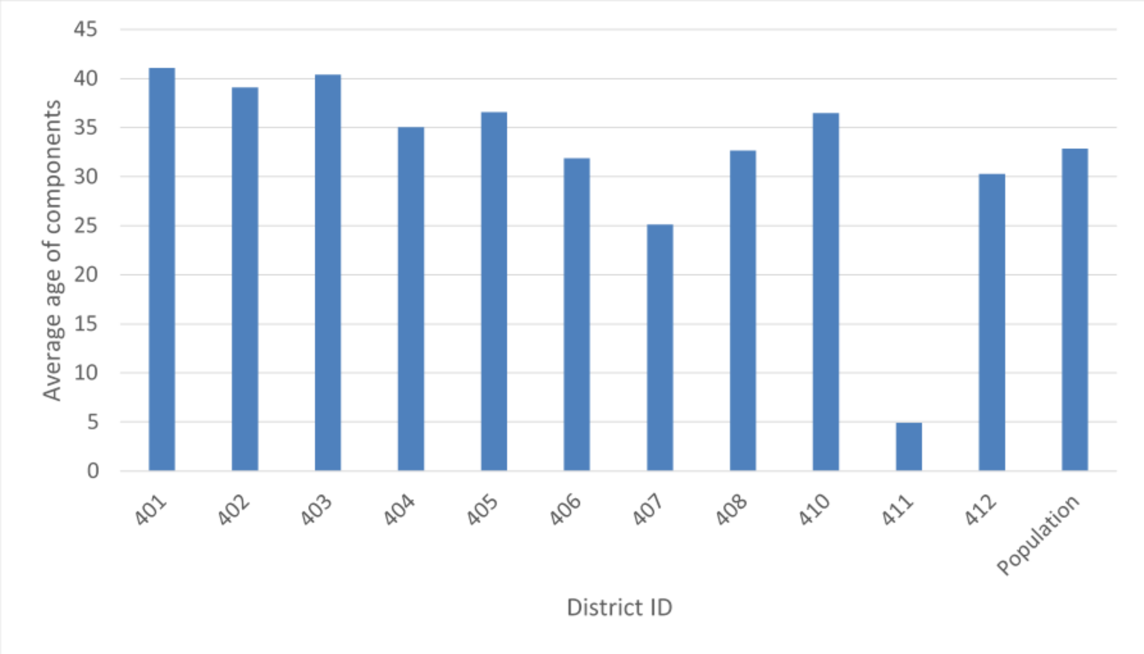


Table 3.3: District vs. construction decade – all considered 80P components

District ID	Decade of construction								Total
	1950	1960	1970	1980	1990	2000	2010	No date	
401		5	3	3	1				**12**
402	10	4	27	20	9	5	2		**77**
403	20	12	7	16	6	22			**83**
404	15	24	58	47	42	11	12		**209**
405	3	29	43	60	6	15	4		**160**
406	1	38	43	54	23	23	23		**205**
407	3	24	19	23	37	11	54	2	**173**
408		9	38	30	16	26			**119**
409									**0**
410	37	29	32	43	29	40	1		**211**
411						2	36		**38**
412	8	49	29	10	25	23	41		**185**
Total	**97**	**223**	**299**	**306**	**194**	**178**	**173**	**2**	**1472**

Figure 3.9: Average age of components vs. district



3.2.2 *Summary of Defect Types*

Table 3.4 summarises the typical types of defects with regard to the component condition rating.

Key findings include:

- The most common defects in CS3/4 rated components are:
  - joint defects (present in 58% of cases)
  - spalling (present in 41% of cases)
  - cracks (present 41% of cases).
- Longitudinal cracking is more common than transverse cracking. This is due in part to the methodological decision detailed in the footnotes of Table 2.1. Longitudinal cracking is present in 26.9% of all CS3/4 components, while transverse cracking is present in 16.1%.

Table 3.4: Instances of defects vs. CS

Condition rating	Longitudinal cracking	Transverse cracking	Shrinkage cracking	Nondescript cracking	Cracks*	Spalling	Settled/ misaligned	Joint defects	Waterway defects	Abrasion	Others	No defects or no comments	Total**	As a % of all components
CS1	4	2	1	2	7	2		7	3		2	399	416	28.3
CS2	76	52	23	34	182	77	78	216	113	13	33	250	759	51.4
CS3	64	30	3	13	102	89	27	135	24	11	15		227	15.4
CS4	16	18	3	5	38	35	18	39	8		4		70	4.8
Total all CS	160	100	30	54	329	203	123	397	148	24	54	649	1472	100
Total CS3/4	80	48	6	18	140	124	45	174	32	11	19	0	297	20.0

*The cracks defect encompasses all types of cracking including longitudinal, transverse, shrinkage and nondescript cracking.

**Some structures exhibit more than one form of cracking/defect. Rows do not add up to the value in the total column.

Table 3.5: Instances of defects in components rated in any CS vs. district

District ID	Longitudinal cracking	Transverse cracking	Shrinkage cracking	Nondescript cracking	Cracks*	Spalling	Settled/ misaligned	Joint defects	Waterway defects	Abrasion	Others	No defects or no comments	Total**	As a % of all components
401									5			7	12	1
402	3	1	15	1	17	8	4	13	6			45	77	5
403	11			5	16	6	2	4	6	4	13	43	83	6
404	6				6	9	1	27	5		6	168	209	14
405	18	2		12	32	21	1	7	12		8	93	160	11
406	25	6	3	12	42	37	63	90	30	8	12	40	205	14
407	12	3			14	10	9	55	26	2	2	93	173	12
408	11	1	1	9	22	5	3	12	15	6	1	71	119	8
409													0	0
410	59	5	10	9	76	79	25	75	33	4	11	29	211	15
411	1				1	1		5	1			30	38	3
412	14	82	1	6	103	27	15	109	9		1	30	185	13
Total all CS	160	100	30	54	329	203	123	397	148	24	54	653	1472	100

*The cracks defect encompasses all types of cracking including longitudinal, transverse, shrinkage and nondescript cracking.

**Some structures exhibit more than one form of cracking/defect. Rows do not add up to the value in the total column.

Table 3.6: Instances of defects in components rated in CS3/4 vs. district

District ID	Longitudinal cracking	Transverse cracking	Shrinkage cracking	Nondescript cracking	Cracks*	Spalling	Settled/ misaligned	Joint defects	Waterway defects	Abrasion	Others	No defects or no comments	Total**	As a % of all CS3/4 components
401													0	0
402	3		3	1	5	3	4	10	4				14	5
403	8			1	9	3	1		1	2	3		13	4
404	1				1	8	1	7			2		16	5
405	5	2		1	8	11		1	1		6		18	6
406	15	5		4	21	15	14	34	4	3	1		50	17
407	8	3			10	9	6	53	18	2	1		63	21
408	4	1		5	10	2		6	1	3	1		13	4
409													0	0
410	31	3	3	5	36	49	11	30	2	1	5		63	21
411													0	0
412	5	34		1	40	24	8	33	1				47	16
Total CS3/4	80	48	6	18	140	124	45	174	32	11	19	0	297	100

* The cracks defect encompasses all types of cracking including longitudinal, transverse, shrinkage and nondescript cracking.

**Some structures exhibit more than one form of cracking/defect. Rows do not add up to the value in the total column.

3.2.3 Analysis of Longitudinal Cracking

This section details the key findings made from the comparisons of longitudinal cracking data at a component level with location (district), age (construction decade), exposure class and depth of fill. The key findings are summarised with recommendations for further investigation. Some of the key findings made in this section are investigated further in Section 6. More comprehensive statistics relating to longitudinal cracking can be found in Appendix A.1. The investigation has been conducted as per the methodology outlined in Section 2.2.3.

Key findings:

- Overall, longitudinal cracking is present in 10.8% of all components considered, and CS3/4 components with longitudinal cracking constitute 5.4% of components considered.
- District 410 has by far the greatest number and percentage of reported longitudinally cracked components of any district for all CS at 27.2% of components considered for the district (Table 3.7; Figure 3.10). The reason has not been narrowed down but contributing factors could include: age, design and construction specifications, or supplier/manufacturer and/or installation parameters. Inspection records should also be checked for consistency with the inspection manual. The average age of components in district 410 is 37 years, which is greater than the population average of 33 years (Figure 3.9), but since there are several other districts with similar average component ages no definitive correlation between the older component age and the prevalence of defects can be made.
- Conversely, districts 401, 404 and 411 have significantly lower instances of CS3/4 longitudinal cracking defects of between 0 and 0.5% of the components considered for each district (Table 3.7; Figure 3.10). A likely cause for the low instances of cracking in districts 401 and 411 is the fact that there are very few reported culverts in the districts (Table 3.1). This is not the case in district 404 however, and the low prevalence of cracking warrants investigation to determine why, and if there can be any lessons learnt. Importantly, inspection records should also be checked for consistency with the inspection manual. It is possible that the low number of defects is due to pipes with defects being replaced, but Table 3.3 shows that the majority of components in district 404 were constructed from the 1970s to the 1990s, which makes replacement of old pipes an unlikely cause in this case.
- Grouping components by decade of construction shows significant variation but no discernible trend other than a weak increase in cracking with age which is expected (Table 3.8; Figure 3.11).
- Of the components installed since 2000, 10% exhibit longitudinal cracking. Additionally, 3.7% of components installed since 2000 are in CS3/4 and exhibit longitudinal cracking (Table 3.8; Figure 3.11). Any significant cracking in components installed in the 2000s can be considered to be premature and this warrants further investigation.

Analysing exposure class and depth of fill, it was found that the majority of culverts are classified as exposure class 2 (~80% overall), which means that exposure class is not clearly correlated to defect trends. Depth of fill was also found to be poorly correlated to defect trends, with 58% of the network having no depth of fill data, and the remainder of the network being clustered around 0–2 m of fill. Refer to Appendix A.1 for further details.

Table 3.7: Proportions of longitudinally cracked 80P components vs. district – all CS

District ID	No. of longitudinal cracked components	As a proportion of all components in the district	No. longitudinally cracked components (CS3/4)	CS3/4 as a proportion of all components in the district	Total components in a district
401		0.0%		0.0%	12
402	3	3.8%	3	3.8%	77
403	11	13.3%	8	9.6%	83
404	6	2.9%	1	0.5%	209
405	18	11.3%	5	3.1%	160
406	25	12.2%	15	7.3%	205
407	12	6.9%	8	4.6%	173
408	11	9.2%	4	3.4%	119
410	59	28.0%	31	14.7%	211
411	1	2.6%		0.0%	38
412	14	7.5%	5	2.7%	185
Totals	**160**	**10.8% of 1472 components overall**	**80**	**5.4% of 1472 components overall**	**1472**

Figure 3.10: Longitudinally cracked 80P components in each district rated in any CS and rated in CS3/4 only as proportions of all components considered for each district

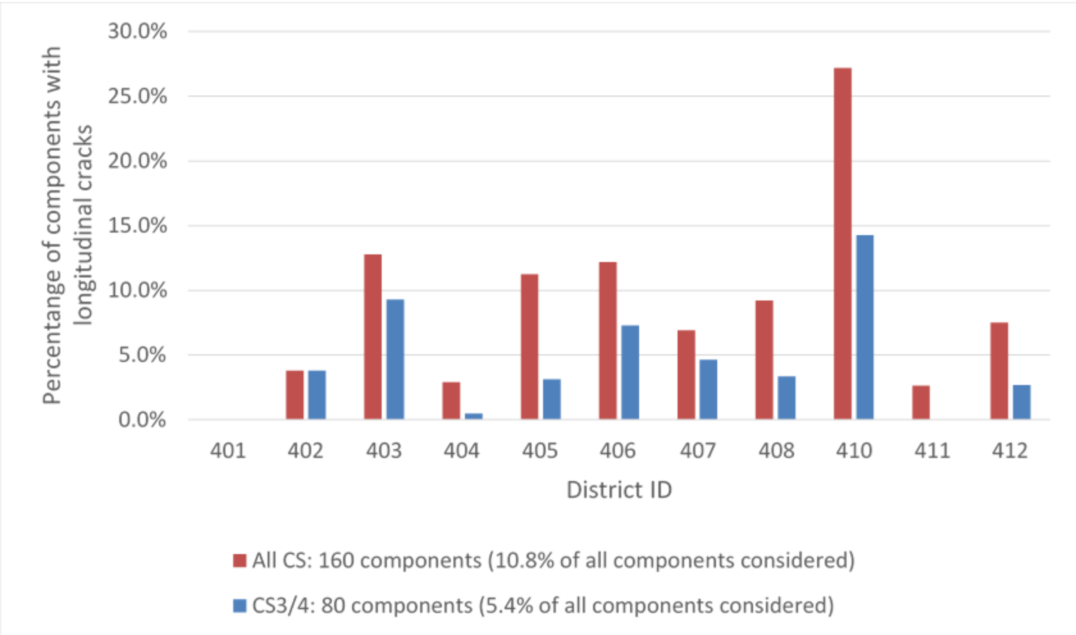
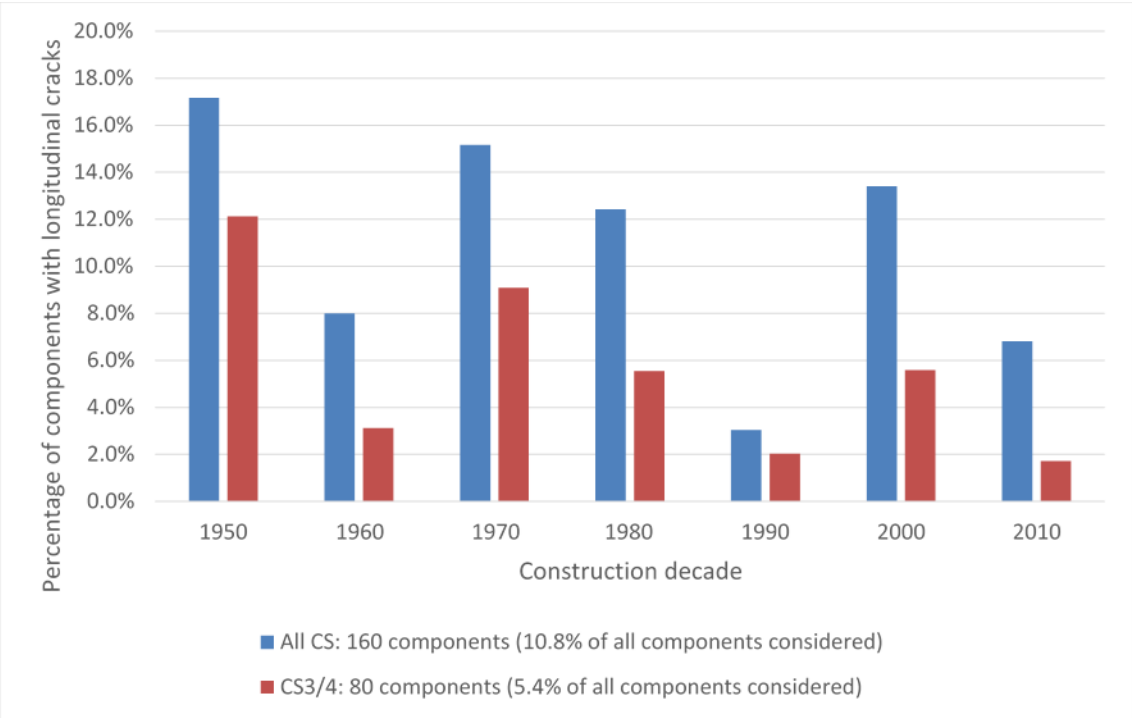


Table 3.8: Proportions of longitudinally cracked components vs. construction decade – all CS

Construction decade	No. of longitudinally cracked components	As a proportion of all components in a decade	No. of longitudinally cracked components (CS3/4)	CS3/4 as a proportion of all components in a decade	Total components constructed in a decade
1950	17	17.2%	12	12.4%	97
1960	18	8.0%	7	3.1%	223
1970	45	15.2%	27	9.0%	299
1980	38	12.4%	17	5.6%	306
1990	6	3.0%	4	2.1%	194
2000	24	13.4%	10	5.6%	178
2010	12	6.8%	3	1.7%	173
Totals	**160**	**10.8% of 1470 components overall**	**80**	**5.4% of 1470 components overall**	**1470***

*Two components with no construction date omitted.

Figure 3.11: Longitudinally cracked 80P components constructed in each decade rated in any CS and rated in CS3/4 only as proportions of all components considered for each decade



3.2.4 Other Defects

While not the primary focus of this study, analysis of transverse cracking, spalling, shrinkage cracking and all cracking (encompassing all crack types) has been carried out in addition to the analysis of longitudinal cracking. As for the longitudinal cracking analysis, comparisons were made for component location (district), age (construction decade), exposure class and depth of fill. The full datasets and comprehensive observations can be found in Appendix A.2, Appendix A.3,

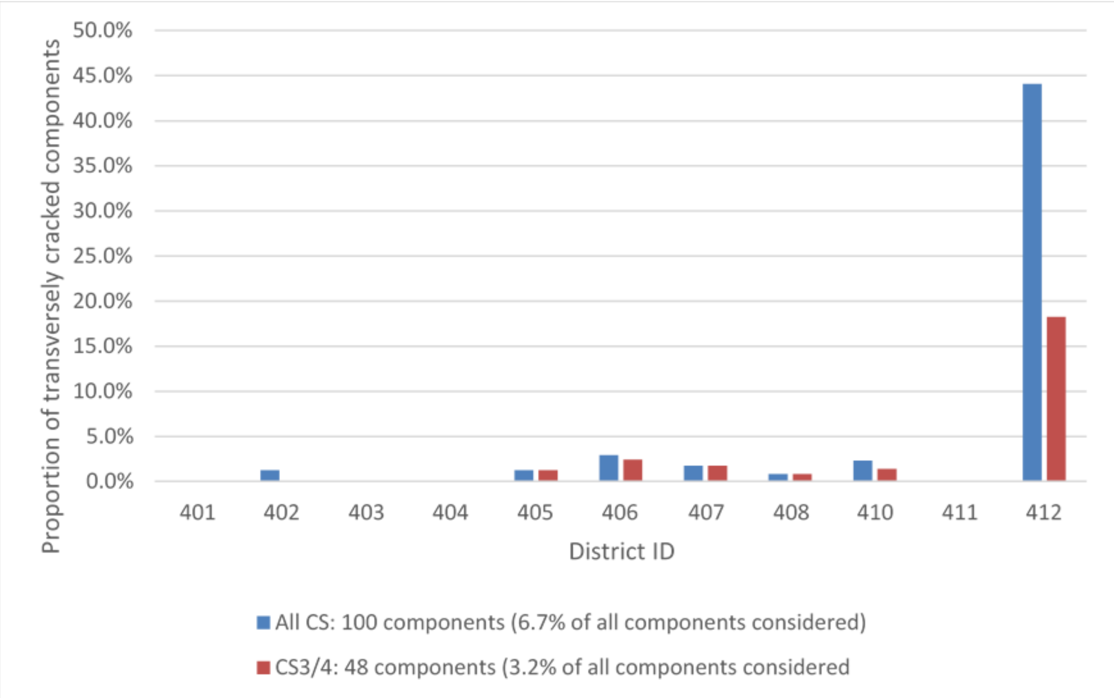
Appendix A.4, and Appendix A.5. It has been noted where there are potential correlations between the prevalence of longitudinal cracking and other defects.

The key findings from the analysis of other defects include:

Transverse cracking

- District 412 stands apart with a large number of components in CS3/4 with transverse cracking (18.4% of all components in the district) (Figure 3.12). Transverse cracking does not generally impact the structural integrity of a pipe but can become an issue if a crack widens enough to allow backfill to enter the pipe and leave voids (Al-Saleem & Langdon 2014). Transverse cracks are commonly caused by unevenness/poor compaction of bedding, loads during construction and settlement of pipes (Al-Saleem & Langdon 2014). Investigation showed that 65% of the components in CS3/4 with transverse cracking in district 412 were installed from 1960 to 1980. These components are known to have been designed for lower loads than what is currently specified (Queensland Department of Transport and Main Roads 2015b), but there are many components in this age range which have not developed transverse cracking. If viable, construction and installation practices for concrete pipes in district 412 should be investigated to determine if there are any underlying issues. Inspection records should also be checked for consistency with the inspection manual.

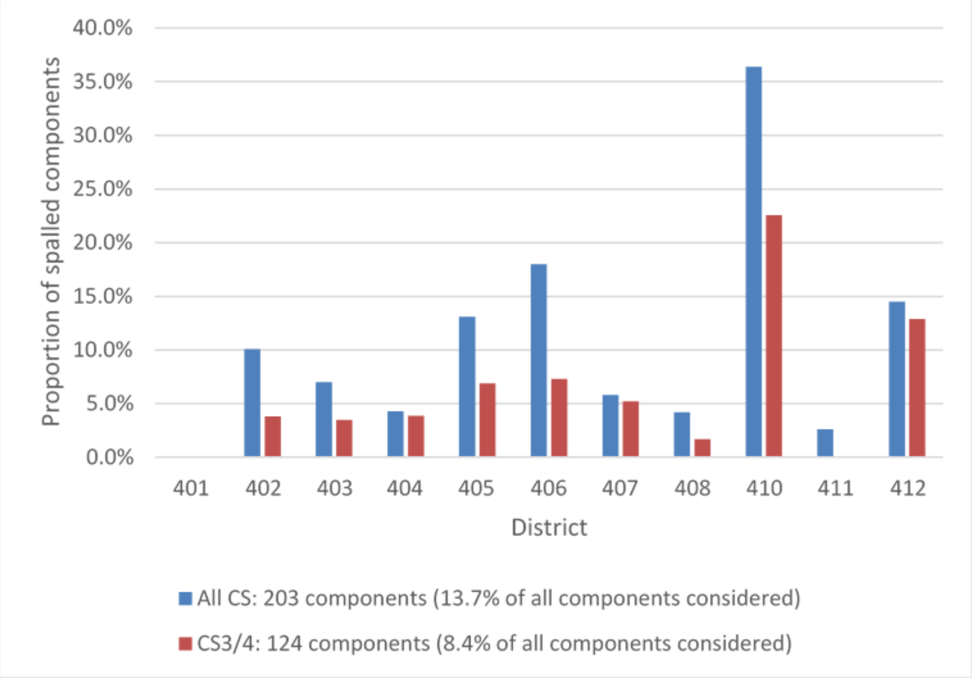
Figure 3.12: Transversely cracked 80P components in each district rated in any CS and rated in CS3/4 only as proportions of all components considered for each district



Spalling

- District 410 has by far the highest proportion of spalled components; 23.2% of components in the district are rated in CS3/4 and reported as being spalled (Figure 3.13; Table A 20; Table A 21).
- The high rates of spalling in district 410 seem to correlate with the reported high rates of longitudinal cracking for the district (28.0% of all considered components in the district are longitudinally cracked). Further investigation showed that 10% of all components considered for the district are both spalled and longitudinally cracked.

Figure 3.13: Spalled 80P components in each district rated in any CS and rated in CS3/4 only as proportions of all components considered for the district



Shrinkage cracking

- Reporting and identification of cracks as shrinkage cracks is isolated to a few districts with wide variations in rates of occurrence. District 402 reports 19.5% of considered components as having shrinkage cracks (Table A 29; Figure A 7).

All cracking

- The all cracking category captures all forms of reported cracking, including longitudinal, transverse, shrinkage and nondescript cracks. If the word 'crack' was included in the L2 comment field for a component it has been included in the data considered for this section.
- Considering all cracking, rates by district vary considerably from 55% of considered components (district 412) to 3% (district 404) (Table A 34; Table A 35; Figure A 9).
- In district 407, only 15.9% of 63 considered components in CS3/4 are reported as having any form of cracking. This compares to the overall rate of 41%. There may be value in investigation to determine why other defects are more prevalent than cracking in this district (Table A 35). Table 3.6 shows that joint defects are the most prevalent defect reported for CS3/4 components in district 407, present in 53 components (84% of CS3/4 components in the district). District 407 has the largest of number of CS3/4 joint defects of any district, which may warrant investigation.
- In district 402, 36% of components in CS3/4 are cracked compared to an overall 47% (Table A 34). This could indicate that cracked components are successfully being treated to prevent further deterioration. Table 3.4 shows a marked decrease in the proportion of cracked pipes in higher CS.
- There is a spike in the proportion of cracked pipe components with 2–3 m of fill (41% vs.an overall 22%) (Table 3.9). This is mostly due to transverse cracking (see also Table A 17).

Table 3.9: Proportions of components with any form of cracking vs. depth of fill – all CS

Depth of fill (m)	No. of cracked components	As a proportion of all components in district	No. of cracked components (CS3/4)	CS3/4 as a proportion of all components in district	Total components with a certain depth of fill
No data	171	21.0%	83	10.2%	813
0–1	76	22.7%	22	6.6%	335
1–2	42	25.5%	15	9.1%	165
2–3	23	41.1%	14	25.0%	56
3–4	7	24.1%	2	6.9%	29
4–5	1	4.8%		0.0%	21
5–6		0.0%		0.0%	12
6–7	1	11.1%		0.0%	9
7–8	2	18.2%		0.0%	11
8–9	4	100.0%	2	50.0%	4
9–10	2	11.8%	2	11.8%	17
Totals	**329**	**22.2% of 1472 components overall**	**140**	**9.4% of 1472 components overall**	**1472**

4 ANALYSIS OF DETERIORATION OVER TIME

4.1 Structure-level Analysis

As per the methodology, a review was completed of structure CS history for the structures which were rated in CS3/4 based on 80P components (Table 3.2). Where available, the CS and defects noted in the most recent inspection and those prior have been determined from the structure-level data and recorded in Table B 1. The historical CS and defects present in structures have been reviewed for structures which have been inspected more than once and were placed in CS1/2 at the first inspection. The detailed dataset is provided in Appendix B.

Key observations include:

- Many structures do not appear to have historical L2 inspection records other than for the most recent inspection. This means that the dataset for deterioration over time is much smaller than that for current defects and CS. In all, 28 structures which had been inspected more than once and had at least one CS3/4 rating based on 80P components were considered for the analysis in this section.
- Two structures (IDs 4836 and 31537) have been in CS4 for more than 15 years. This warrants investigation to:
  - determine whether repairs have been taking place
  - determine what, if any management plans are in place for these structures
  - determine whether the reported defects are severe enough to warrant a CS4 rating (investigation of inspection practices and rating guidelines).
- In all, there were 10 structures in the 28-structure dataset that progressed from a CS1/2 state to a CS3/4 state based on the 80P components (see Section 2.2.2 for explanation of 80P component condition rating methodology).
- Cracking was the most common defect observed in structures which progressed from a CS1/2 state to a CS3/4 state based on the 80P components, with a total of 4 structures showing this pattern. Longitudinal cracking was identified for 2 out of these 4 structures.
- In the majority of cases, there were common defects present from one inspection to the next when CS worsened. Two exceptions to this were structures that had no defects recorded for the first inspection. There were no cases where there wasn't at least one common defect between the CS1/2 inspection and the CS3/4 inspection for structures that had some defect recorded for both inspections.
- There were 6 structures which were in CS3/4 and had not been inspected within the last 5 years. This highlights a potential L2 inspection shortfall, and there may be value in conducting a review of inspection scheduling to ensure that at-risk structures (rated in CS3/4) are inspected regularly.

4.2 Component-level Analysis

The overall purpose of this section is to investigate trends in deterioration time at a component level. Deterioration time is defined here as the time that a component takes to reach CS 3/4 from its construction date. Deterioration time has been measured from the construction date of the component to the first inspection date which places the component in CS 3/4. Key findings are presented and discussed with supporting graphs. Further detailed charts are provided in Appendix C.2. The full dataset used for the analysis of components with at least one CS1/2 inspection before a CS3/4 rating was given is provided in Appendix C.

Only original components were used for the analysis, as reliable construction date data for modifications was not available. Removing non-original components from the dataset used for the component-level defect analysis (Section 3.2) left a total of 1287 components. A further 2 components with no completion date data and 1 which had the first inspection date before the completion date were excluded to leave 1284 components considered for the analysis.

Key findings:

- The observations made in this section generally show that the development of defects that trigger CS3/4 ratings of 80P components is not exclusively time dependent. Deterioration times of components which have reached CS3/4 are evenly distributed across the lifespan of the component network and, as there is also an even distribution of non-deteriorated components in greater numbers across each 5-year time interval investigated, it can be concluded that the deterioration times of the components which have already deteriorated cannot be reliably applied as predictors for all components (Figure 4.1).
- Newer culverts on the network should have expected design lives of 100 years, while culverts constructed prior to 1976 likely have an expected design life of 50 years (Queensland Department of Transport and Main Roads 2015b). Site histories are not available, so it is impossible to tell whether newer pipes are original constructions or structures which were installed to replace deteriorated structures. Without information on all structures which have deteriorated it is hard to make any accurate predictions of structure lifespan. Nonetheless, Figure 4.1 shows that a majority of components (components in CS1/2) are on track to achieve their design life at the time of data capture.
- There are 41 components which deteriorated to a CS3/4 condition in 5 years or less after construction (Figure 4.1). This is an unexpected result, as pipes designed for a 100-year service life should not deteriorate in such a short period of time. Thirteen of the most recently deteriorated of these components are located in district 407, were installed after 2010 and have joint-separation issues. This may be due to either construction/design practices, or inspection practices. Both of these possibilities should be investigated, and the root cause should be rectified if possible. In order to determine if defects are caused by construction, handover inspections are essential and need to be recorded in BIS. Ensuring this information is captured is an important recommendation from this study.

Observations for all defects:

- Eight of the components in the 15–20-year bracket are from the same structure, which highlights how one structure in overall poor condition can skew the results for deterioration time at a component level (Figure 4.1).
- The times for components to reach CS3/4 are evenly spread across the decades, and there is not an obvious trend of higher numbers of CS3/4 components with longer deterioration times (components with at least 1 inspection before CS3/4 rating as shown in Figure 4.1).

Longitudinal cracking observations:

- There are 39 components which meet the criteria for analysis outlined in the methodology and are identified as longitudinally cracked at the first CS3/4 inspection (Figure 4.2).
- There is a fairly even spread of deterioration times across the longitudinally cracked components analysed, with 1-3 components typically reaching CS3/4 after each increasing 5-year interval of deterioration time (Figure 4.2).

Spalling observations:

- There are 52 components which are spalled and meet the criteria for analysis.

- The data for spalled components is more varied compared to the data for longitudinally cracked components and the data for all defects. Three of the five records for the 60–65-year interval are for the same structure (Figure 4.3). A deterioration time of 35–45 years is the most prevalent for spalling defects, with 17 out of 52 components reaching CS3/4 after this amount of time (Figure 4.3).

Excluded component observations:

It must be recognised that the deterioration times for components shown in Figure 4.1, Figure 4.2 and Figure 4.3 have not been formulated using the entire population of components. There are three times as many components which have not entered CS3/4 during their lifetime (933 components) compared to those that have (351 components) (Figure 4.1).

Figure 4.1 shows that for any given time interval, there are significantly more components which have not deteriorated (remaining in CS1/2) than have deteriorated. This discrepancy between the numbers of deteriorated and non-deteriorated components becomes lesser for time intervals greater than 50 years, indicating that older components are generally more likely to have entered CS3/4. It must be noted however that the time intervals greater than 50 years generally contain less components than the shorter time intervals, which contributes to the reduction in discrepancy between the numbers of deteriorated and non-deteriorated components. Taking into account the components which have not deteriorated in each time interval, it can be predicted that the true population-wide average deterioration time would be significantly longer than what is shown by analysis of the components which have already deteriorated. It is also a fact that components which have critically deteriorated in the past are likely to have been replaced and are consequently not included in the analysis. It is impossible to predict what impact these components would have on deterioration time estimates without access to records of failed and replaced components.

The initial analysis excluded components which were rated in CS3/4 at the first inspection (‘components placed in CS3/4 at first inspection’ in Figure 4.1). It is impossible to determine the exact deterioration times of these components, but it is possible that the deterioration times are shorter than that shown by the set analysed and shown by ‘components with at least 1 inspection before CS3/4 rating’. In particular, there are 41 components which have deteriorated in 5 years or less since construction (Figure 4.1).

Figure 4.1: Comparison of component deterioration times to continuing lifespan of non-deteriorated components

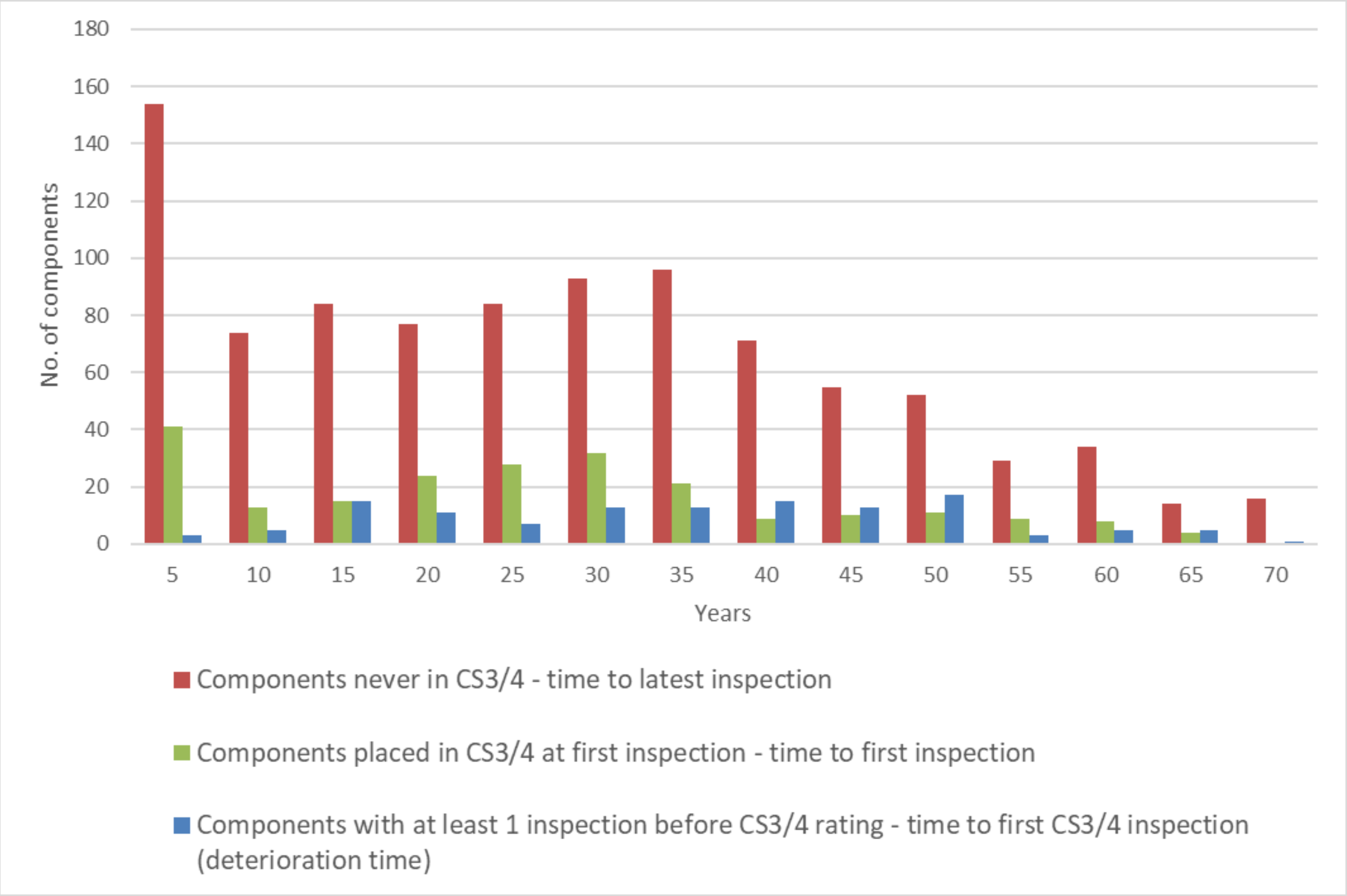


Figure 4.2: Time to CS3/4 for longitudinally cracked components

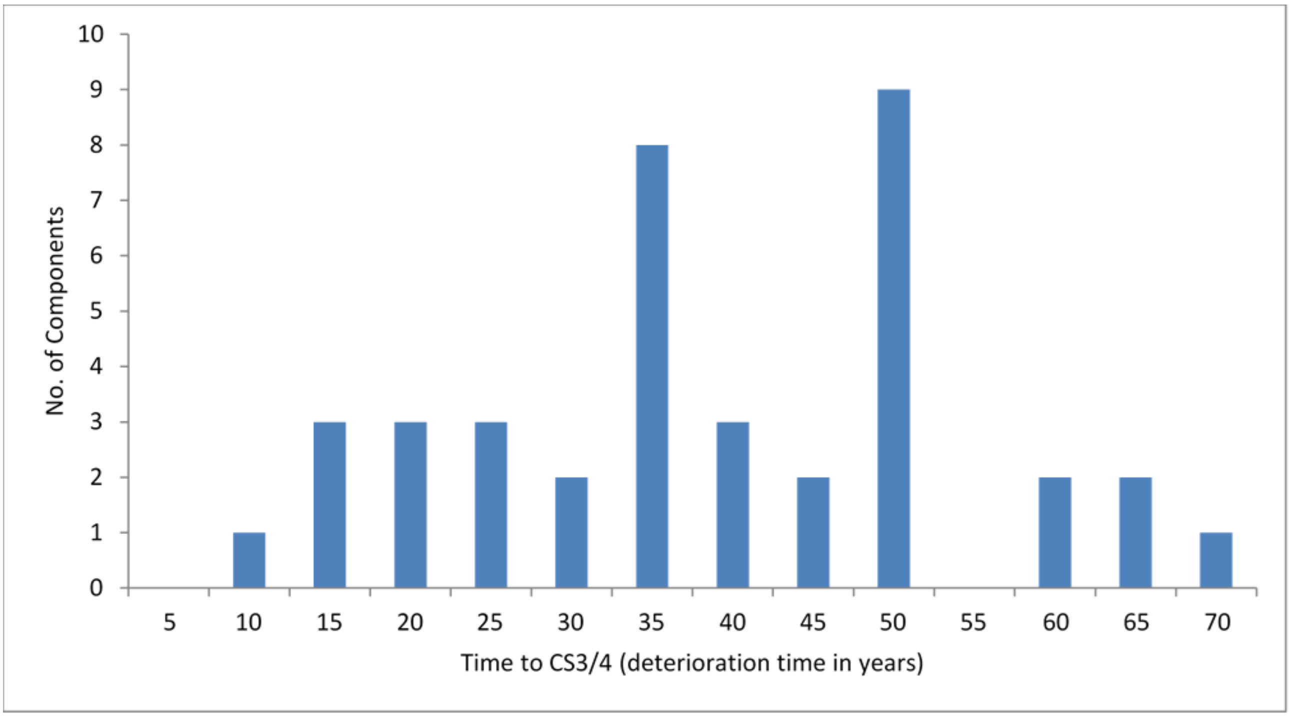
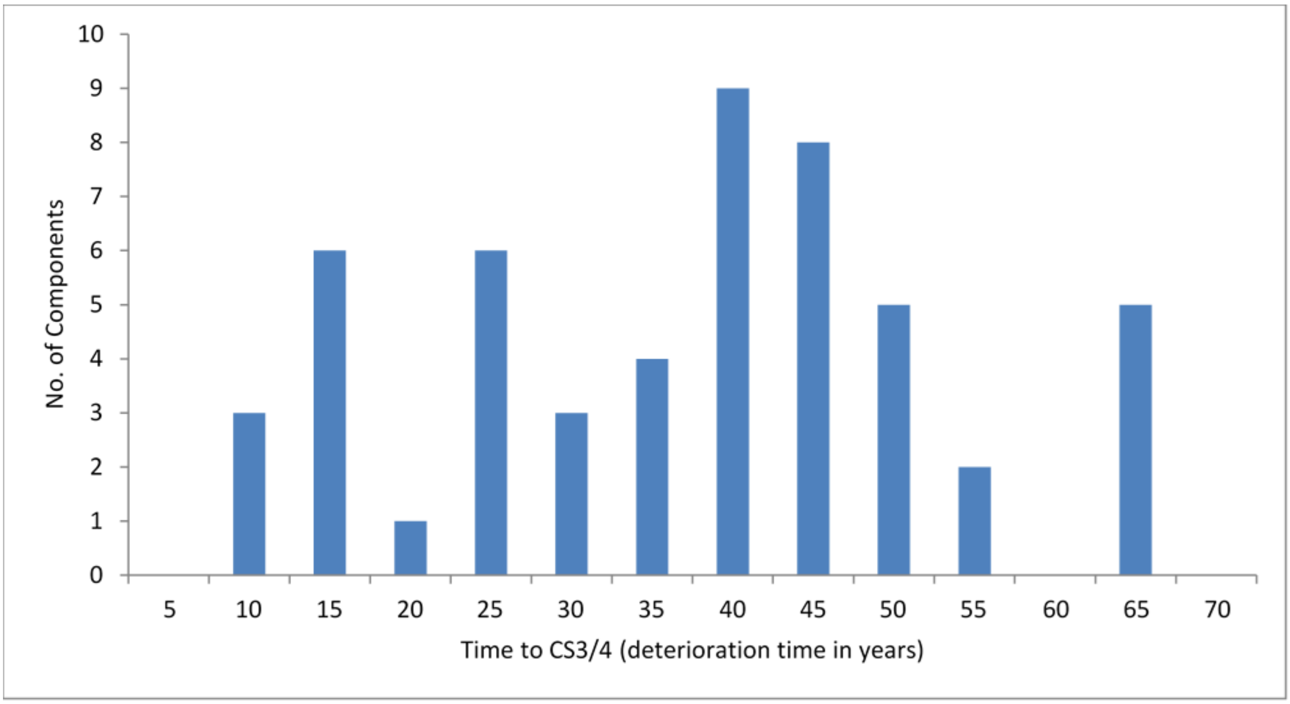


Figure 4.3: Time to CS3/4 for spalled components



4.2.1 Policy Changes

The September 2016 update to the 80P rating guidelines (detailed in Section 5) may have changed how inspectors assess existing structures. This may have in turn led to changes in CS ratings that are linked to the change in policy rather than actual deterioration of components. There are 28 components with a prior CS1/2 rating which entered CS3/4 for the first time after September 2016. There are 36 components which were given a CS4 rating in an inspection after September 2016. Detailed investigation of the history of these components may allow conclusions to be made regarding inspection practices, but no indications of CS changes due to policy changes were found during the review of L2 inspection records, detailed in Section 5. It is uncertain whether further investigation would allow better conclusions to be made.

5 REVIEW OF L2 INSPECTION RECORDS

5.1 Background

As per the methodology in Section 2.4, TMR has provided 23 complete L2 inspection records from 12 culvert structures. The records were selected by TMR based on the presence of keywords relating to longitudinal cracking including 'moderate', 'severe', and 'full length'. Where a structure has undergone multiple inspections, record sets have been provided for each inspection. Each record set includes a structure condition inspection report, a defective components report, and a photo & sketches record.

One objective of this section was to review the appropriateness of the CS ratings given to defects existing for the 80P components in each report. The appropriateness of ratings for defects in components other than 80P has not been reviewed. Ratings have been reviewed based on the content of the comments recorded in the condition and defect reports and the photos provided with each record. The rating given to each defect has been compared to what is recommended by Appendix D and Part 2 of the *Structures Inspection Manual* (Queensland Department of Transport and Main Roads 2016). Appendix D of the manual provides specific guidelines on the rating of defects in concrete pipe culverts (component 80P). Part 2 of the manual provides detailed descriptions of the typical defects which may be present in concrete. A summary table of the L2 records reviewed and findings made is provided as Table D 1 in Appendix D (of this report).

5.2 Discussion

The majority of the provided records show ratings that are reasonable and adhere to the TMR structure inspection guidelines. There are four records which have been assessed as showing a potentially unsuitable condition rating of a pipe component. All of the records flagged reported cracking defects. In all cases, the defect in question was given a CS3 rating, while the comments and photos indicated that a CS4 rating may be more appropriate based on the guidance of the TMR inspection manual. Two of the records flagged relate to longitudinal cracking, while the remaining two relate to vertical (transverse) cracking.

No cases of incorrectly labelled defects or cases where a lower condition rating would be appropriate have been observed. Instead, all findings have identified situations where a higher condition rating may be warranted. Situations where a defect is given a lower rating than is warranted may lead to delays in repair which in turn can lead to worsening of defects. Longitudinal cracking in particular may worsen over time if it is due to mechanisms such as overloading or reinforcement corrosion.

District 410 was identified as having a high proportion of CS3/4 longitudinal cracking during the network-wide review of BIS data. Six inspection reports from district 410 were investigated as a part of the L2 inspection record review. The majority of the reports investigated were found to give ratings to defects that were either appropriate or potentially not high enough. There was one structure that was a potential exception to this, but insufficient photo evidence was available to make any definitive conclusion regarding the condition rating or defects present in the structure. No reports were supplied for structures from the districts that were identified as having low proportions of longitudinally cracked components, so no investigation of any potential issues was carried out. It should be noted that the inspection reports reviewed were chosen based on the presence of defects and were not intended be representative of regions, meaning that the review of region-specific practices was somewhat limited based on the records supplied.

There were several records which did not include clear photos of key defects, which hindered the review of defect identification to a degree. Clear and relevant photos are a key part of structure inspections and if any issues with inspection photos happen to be found, it is important that steps be taken to investigate and rectify them if possible.

The *Standard Component CS Guidelines* (Appendix D of the *Structures Inspection Manual*) does not specify a threshold crack width for a component to be placed in CS4. Threshold crack widths of 0.3 mm (normal conditions) and 0.15 mm (aggressive conditions) are provided for CS3. Part 2 of the manual specifies a CS4 threshold crack width of 0.6 mm. The omission of a CS4 threshold crack width in Appendix D of the manual allows inspectors judgement to play a larger part in the decision to rate components in CS4. This is generally appropriate, as a CS4 rating should only be given to components which require immediate attention. However, to ensure that inspectors and reviewing engineers are aware of the general guidelines for concrete condition rating, it may be appropriate that a reference back to Part 2 of the manual should be included in the Appendix D rating guidelines or additional text added for the rating of 80P components to provide clarity to inspectors.

There have been several updates to the TMR structure inspection guidelines since the introduction of the *Bridge Inspection Manual* (BIM) in 2000 (Queensland Department of Transport and Main Roads 2000). Updates to the BIM were conducted in 2004, 2012 and 2016. In 2016, the BIM was relabelled as the *Structures Inspection Manual* (SIM). A number of updates were made to the 80P component-specific condition rating guidelines during the 2016 transition to the SIM. These included:

- No updates to the CS1 and CS2 guidelines.
- The first sentence of the CS3 guideline section was amended to read: ‘Moderate cracking, spalling or delaminated areas due to non-structural mechanisms, such as corrosion of reinforcement or ASR, may be present, having a minor effect on strength and serviceability of the pipe.’ Prior to the 2016 update, the guideline did not identify that the defects were to be due to non-structural mechanisms.
- A crack width guide was added to the CS3 rating guidelines, based on the general crack width guide for concrete included in Part 2 of the manual. Previously, no crack width guide was provided in the component-specific Appendix D of the manual.
- The text ‘There may be loss of section of reinforcement due to corrosion greater than 20% (and the resultant cracking and spalling this may cause)’ was added to the CS4 guideline.

These changes may have impacted on how 80P components are assessed. Essentially, these changes mean that the CS ratings given during inspections prior to 2016 are not necessarily comparable to the rating that would be given if the current guidelines were used for assessment. This may account for some of the discrepancies between the ratings assigned to components and the recommended ratings discussed in this section. The omission of crack width from the 80P component CS3 rating guidelines prior to 2016 may have led to underestimation of the severity of cracks if the general concrete cracking guidelines (Part 2 of the manual) were not referred to. There is however a degree of subjectivity involved in inspection, and it is hard to make a definitive call on whether or not a condition rating is appropriate without knowledge of a certain component’s defect history and the location of cracking defects. Reviewing of inspection reports post-inspection is an important process which allows for discussion around the condition rating process and strengthens the quality of condition ratings.

6 CASE STUDIES

6.1 Background

The aim of this section is to investigate key observations made during the network defect analysis relating to the prevalence of longitudinal cracking and other defects throughout the network.

As per the methodology in Section 2.5, this section includes:

- investigation of current and superseded design, manufacture and installation specifications for precast pipes
- investigation of current and superseded TMR standard drawings for precast pipe installation
- investigation of specific structure design, manufacture and installation records where available
- review of culvert data management practices at TMR.

Issues encountered during the investigations have been noted and are presented along with the findings.

6.2 Investigation and Findings

6.2.1 Construction Date/Culvert Age Investigation

The earliest TMR standard drawing for culvert installation was released in September 1992, which covered field installation of concrete pipes, corrugated steel pipes and box culverts. No culvert design records have been able to be sourced for culverts constructed prior to the release of the standard drawing, and it is assumed that culverts constructed during the 1970s are likely to have been constructed to AS CA33 *Code of recommended Practice for Concrete Pipe Laying Design* which was also current during the 1960s and 1980s. This means that the high prevalence of longitudinal cracking observed in culverts constructed during the 1970s (Section 3.2.3) cannot be linked to changes in design or construction specifications. The introduction of AS CA33 in 1962 may have some link to the lower incidence of longitudinal cracking observed for components installed in the 1960s, but without access to design drawings and records from this era this connection cannot be verified. The earliest available design drawings supplied by TMR are from the 1990s.

The *Road Drainage Manual* (Queensland Department of Transport and Main Roads 2015b) advises that precast and cast in-situ culverts installed prior to 1976 were designed for significantly lighter loads than are specified by the current AS 5100 standards which have been followed by TMR since 2004. These pre-1976 structures were also typically designed for a 50-year design life. This means that culverts constructed during the 1960s and 1950s have now exceeded that design life. Longitudinal cracking in these components is not unexpected, as it is possible that these structures are being overloaded. Of greater interest is the high proportions of components (~80%) installed during the 1950s–1960s which are reported as being in CS1/2. As previously noted there are no available design records or drawings from this era which means that this good performance cannot be investigated. If traffic statistics are available for routes on which these structures are located, it may be valuable to determine what loadings these structures are currently subjected to for comparison with the expected strength of the structures. If structures are to be replaced, there may be also be value in proof load/destructive testing of the structures prior to decommissioning. Destructive testing of decommissioned structures which have CS3/4 longitudinal cracking and other defects may also be of value to enhance understanding of the structural impact of defects which are considered to be severe.

The Australian standard AS 3725 *Loads on Buried Concrete Pipes* was introduced in 1989 and provided a revision of AS CA33. The introduction of this revision may explain the time history drop in the prevalence of longitudinal cracking which can be observed in pipes installed during the 1990s compared to the 1980s and decades prior. AS 3725 provided updated design rules which allowed for a simplified treatment of rail and road traffic loadings. Railway loadings were previously not accounted for by AS CA33. The name of the standard was changed and a specific focus on the calculation of working loads on buried pipes and test loads was introduced. The update also introduced metric units (the units used by AS CA33 were imperial). The fact that there are no design drawings available for culverts constructed during the 1980s and 1990s makes it hard to verify the impact of AS 3725, but the TMR standard drawing for culvert installation (SD 1359) introduced in 1992 references AS 3725 which means that the standard was in use during the 1990s.

The network defect analysis revealed that there was a significantly higher incidence of longitudinal cracking in components constructed in the 2000s compared to components constructed in the 1990s. Changes to the TMR culvert standard drawing implemented between 1992 and 2003 have been reviewed to check for any potential causes, but no changes have been found that could individually explain the increase in cracking defects. The main changes to SD1359 between 1992 and 2003 are summarised below:

- 1996 update:
  - the threshold point for the change in required foundation bedding depth from 100 mm to 150 mm was altered from a pipe diameter of 1500 mm to a pipe diameter of 1350 mm
  - trench wall compaction requirements were added
  - added note that minimum depth of overlay zone may include pavement.
- 2000 update:
  - corrected reference to AS 3725, 1996 version referred in error to AS 3275.
- 2002 update:
  - reference to MRS11.03 for construction loads added
  - added location of top of embankment to drawings.
- 2003 update:
  - no update to concrete pipe section of standard.

The TMR specification MRTS03 *Drainage, Retaining Structures and Protective Treatments* which applies to the supply of drainage structures and other structures for roadworks was first released in 2009. MRTS03 provides detailed information on material quality requirements, geometric tolerances and requirements for installation for culverts and other drainage structures. The adoption of this document may have some link to the drop in longitudinal cracking observed in culverts constructed during the 2010s compared to those constructed during the 2000s. TMR has advised that there are some existing issues with MRTS03 related to its comprehensiveness and usability, but full investigation of these issues is beyond the scope of this report.

In 2007, the TMR specification MRS11.25 (later revised as MRTS25 *Steel Reinforced Precast Concrete Pipes*) was updated to make all cracking defects as defined by AS/NZS 4058 which occur during pipe manufacture unacceptable. The update meant that the only acceptable cracks are shrinkage or other hairline cracks. Previously, cracks with a width greater than the test crack width (dependent on cover as defined by AS/NZS 4058) and less than 0.5 mm in width measured at a depth of 3 mm were acceptable. This may have led to pipes with cracking defects being accepted for installation. Later, these accepted cracks may have developed into more serious defects. There may be value in checking whether CS3/4 pipe components with longitudinal cracking were cracked during manufacture, but this would only be possible if there were detailed construction records available with relevant information. If an inspection was conducted at handover, it would be possible to see if any cracks were present after construction, but it is fairly likely that it would be unknown whether cracks developed during construction or during manufacture. Nonetheless, it is very important that handover inspections are conducted and recorded in BIS, so that any defects induced by manufacture or installation are picked up and can be distinguished from defects which occur during service. TMR advised that currently handover inspections are not conducted by RoadTek, and subsequently are not entered into BIS since the inspectors do not have access to it. Potential solutions to this issue include allowing non-RoadTek inspectors some access to data entry facilities, interfacing with inspectors conducting handover inspections to capture the data, or having RoadTek conduct handover inspections.

AS 5100 *Bridge Design* was introduced and adopted by TMR for design load provision in 2004. A significant portion (70%) of the CS3/4 longitudinally cracked components installed during the 2000s were installed prior to 2004, meaning that they were installed to less stringent design loads, which in turn makes the structures more susceptible to overloading. This may explain the drop in longitudinal cracking defects observed in components installed in the 2010s compared to those installed in the 2000s, but it does not account for the low proportion of cracked components observed for the 1990s.

6.2.2 District Investigation

District 410 was identified during the network defect analysis as having a relatively high proportion of CS3/4 longitudinally cracked components. Further investigation of the data revealed that 45% (98 of the components in the district were constructed prior to 1980. Furthermore, 65% of the longitudinally cracked components rated in CS3/4 in the district were constructed prior to 1980. As discussed in the previous section, components constructed prior to 1976 are known to have been designed based on relatively light design loads and are approaching the end of their typical 50-year design lives. It can be concluded that the typical age of the components in district 410 has some impact on the high prevalence of longitudinal cracking defects.

No evidence has been found of district-specific application of manufacture, design or construction specifications that could impact on defect prevalence. The lack of drawings for specific structures makes it impossible to identify patterns in the adoption of specifications.

Investigation of the potential impact of district-specific inspection practices on rates of longitudinal cracking and other defects has been carried out and is detailed in Section 5.

6.2.3 Investigation of Design Drawings for Specific Culverts

TMR ran a search of the BIS and GIMS databases and extracted available drawings and design records for a selection of culverts. The structures that drawings were provided for were structure IDs 43931, 32597 and 27626. A longitudinal section was provided for culvert 43931, a set of cross-sections was provided for culvert 32597, and a longitudinal section was provided for culvert 27626.

Key findings:

- All 80P components of culvert 43931 were rated in CS4 due to severe longitudinal cracking less than two years after its construction in 2009. Considering that severe defects were detected during an inspection not long after construction, it is possible that the defects developed during construction. The design longitudinal section for this structure referenced SD1359 for installation, which has not been updated since 2003, and does not reference the most current specification for construction loading (MRTS03). SD1359 references

MRS11.03, which has not been current since 2009, but it is possible that copies of the old standard remain in use.

- The culvert 43931 longitudinal section was not fully set out in accordance with the *Drafting and Design Presentation Standards* manual (Queensland Department of Transport and Main Roads 2015a). No details for grade, flow velocity or capacity are provided in the drawing, but it is unknown whether this is indicative of any design or construction issues.
- The drainage cross-section provided for culvert 32597 was found to be laid out in accordance with the manual. The cross-sections do not provide information on culvert design specifications, but this level of detail is not required in cross-sections by the TMR drafting manual. It is recommended that the manual is amended to require the inclusion of pipe design specifications and pipe class on at least one drawing for all future culvert structures. Installed culverts should ideally have a detailed longitudinal section which includes design specification details. This drawing should be entered into GIMS and linked to its respective culvert in BIS.
- The longitudinal section provided for culvert 27626 was found to be in accordance with the manual. There are spalling issues associated with a gas pipe entering the structure, but the longitudinal section does not show that the gas pipe impacts on the section of pipe in question. It is unknown whether any more detailed design was done to accommodate for services.
- As no further drawings are provided for culvert 27626, issues around data retention and lack of detail on available drawings are highlighted. It is recommended that data management practices be strengthened to ensure that all design drawings are entered into GIMS and linked to their respective culverts in BIS. A record of what design drawings were provided for a culvert should also be kept in case the drawings themselves go missing.

6.3 Discussion

During the search of the BIS and GIMS databases, a number of issues came to light relating to the availability of various types of data for the selected culvert structures. Specifically:

- No drawings could be retrieved and positively identified for 14 out of the 20 culverts studied. The issue of missing drawings extends to even the most recently constructed culverts.
- No data is recorded in BIS for design load or pipe class. Data on design load/pipe class was only able to be retrieved from available drawings in GIMS, and where no detailed drawings were available, no data on design load/pipe class could be accessed.
- Some BIS entries for culverts are flagged as having drawings in GIMS, but the linked drawings did not correspond to the correct culvert.
- Searching for culvert drawings in GIMS required using the Tdist, and Road ID fields from BIS was problematic for identifying individual culverts since Tdists did not match up and often multiple culverts were included on each drawing. Even when the BIS entry had a linked drawing, this page could have multiple culverts (without BIS IDs to differentiate them).

In some cases, there are drawings that show the existence of culvert structures, but no drawings relating to the culvert's installation proper. Drawings which show the existence of culverts are typically associated with other works taking place on the site in the vicinity of the culvert.

The lack of design records, drawings and crucial data such as fill height and pipe class for such a large proportion of culverts makes the task of determining causes for deterioration very difficult. Where the data exists, causes can be speculated, but since a large proportion of the culvert population does not have data it is hard to establish trends and make strong conclusions.

In particular, the lack of design records and drawings makes it impossible to tell exactly which specifications a certain component was designed, manufactured or installed to. This in turn makes it very difficult to verify theories which relate changes in specifications to temporal changes in defect prevalence. Additionally, the lack of records makes it impracticable to determine whether any practices have been in place at a district level which have contributed to variations in the incidence of defects. The lack of records and drawings for a high proportion of structures highlights issues with data management. It is recommended that asset management practices be strengthened to ensure that construction records and drawings are maintained and entered into the BIS.

Missing pipe class data can be attributed in part to the fact that the TMR standard drawing for concrete pipe construction (SD1359) has not been updated since 2003 and does not reference pipe load class. The standard drawing also does not provide information on the most recent update to the construction loadings which is outlined by MRTS25 *Steel Reinforced Precast Concrete Pipes.* MRTS25 also includes some changes to superimposed live loading specifications which override those outlined by AS/NZS 3725, the standard referenced by SD1359. The standard drawing SD1359 should be updated to reference MRTS25. It is also recommended that when a culvert has been installed with reference to SD1359, it is recorded in BIS.

Often the date recorded in BIS or GIMS is the date that the culvert data was entered into the system, and not the actual date that culvert construction finished. Additionally, there is often no data recorded for construction date of culvert widenings and other modifications even when new 80P components were added to a structure. This should be rectified so that an accurate construction date is recorded for all new culvert components included in future construction.

It was found that while the importance of considering construction load during design and construction is mentioned in the *Road Drainage Manual*, there is no provision of calculation methods, or references to relevant specifications relating to construction load (Queensland Department of Transport and Main Roads 2015b). It is unknown whether this is having an impact on the installation of culverts, but the manual is the primary reference document for individuals involved in the provision of drainage infrastructure. Consequently, the manual should be updated to include guidance on the determination of construction load, or reference specifications which provide the relevant guidance.

7 CONCULSIONS AND RECOMMENDATIONS

This report details the findings of an investigation into the condition of the TMR major concrete pipe culvert network (80P components). Culvert condition and the prevalence of longitudinal cracking and other defects has been investigated on a structure and component level using L2 inspection data sourced from TMR's BIS. Potential temporal trends in component deterioration (time to reach CS3/4 by TMR definitions) have been investigated through review of historic L2 inspection records, and a selection of detailed L2 inspection reports has been reviewed for any issues of concern. Also, historic specifications and design drawings have been reviewed to check for any potential causes of trends identified during the component-level investigation of CS and defect prevalence.

7.1 Conclusions

It was found that longitudinally cracked components rated in CS3/4 constituted 5.4% of all components considered, which was lower than the incidence of CS3/4 components with spalling and joint defect issues. The incidence of longitudinal cracking and other defects was compared to the parameters of district, decade of construction, exposure class and depth of fill. Notably high incidences of CS3/4 longitudinal cracking were found for components installed in district 410, and the 1950s and 1970s were found to be the decades of construction with the highest incidences of longitudinal cracking which may be linked to shorter design lives associated with culverts constructed prior to 1976. Additionally, 10% of all considered components installed since the year 2000 are reported to be longitudinally cracked, which may be leading to premature deterioration.

District 404 was found to have a significantly lower incidence of longitudinal cracking while having the third-largest component population of any district. Exposure class and depth of fill were found to be poor indicators of defect trends for all forms of defects. Of all the components considered, 55% were found to have no data for depth of fill, and 34% had fill depths ranging from 0 to 2 m. Considering other defects, district 412 was found to have by far the highest prevalence of CS3/4 transverse cracking with 18.3% of CS3/4 components transversely cracked. Spalled components were most prevalent in district 410, and there was a low proportion of components with any form of CS3/4 cracking in district 407. Components with 2–3 m of fill showed a spike in the proportion of cracking, which was mostly due to transverse cracking.

The investigation of historic L2 inspection records found that in general there are no discernible trends associated with the time that it takes a component to deteriorate from a CS1/2 condition to a CS3/4 condition. Deterioration times were spread evenly across the full lifespan of the network. There were 41 components which had deteriorated in five years or less, but since no data from handover inspections was available it was impossible to determine whether the components were in poor condition after construction or whether the deterioration occurred during service. The review of L2 inspection records also found that there are 6 structures which are in CS3/4 and have not been inspected in the last five years, which highlights a potential shortfall in L2 inspection frequency. The review of L2 inspection reports found that based on the TMR guidelines, in some cases a CS4 rating would have been more appropriate for a defect rated as CS3. This was the case in 4 out of 22 reports reviewed. No definitive evidence of district-specific inspection practices affecting the number of components in CS3/4 was found during the review.

The review of historic specifications found some potential causes for temporal variances in the incidence of longitudinal cracking, but there was insufficient evidence available in the form of design records or drawings to be able to make any definitive conclusions. Particularly, the elevated rate of longitudinal cracking in components installed since the year 2000 could not be definitively linked to changes in specifications. Investigation of the BIS and GIMS found that many culvert structures did not have design drawings or records available, and that many structures did not have data on specifications used, depth of fill or pipe class. Additionally, many culvert modifications such as extensions or widenings do not have a recorded construction date and handover inspections are not recorded in the BIS.

Review of the provided culvert design drawings found that in general, the drawings were compliant with the TMR guidelines but did not always provide all relevant information. The TMR standard drawing for culvert pipe installation (SD1359) was reviewed and it was found that it did not reference the most current TMR specifications for design and manufacture of 80P components.

7.2 Primary Recommendations

A number of recommendations are made based on consultation with TMR, and the findings of the case studies:

- It is recommended that drawings for major culverts are checked by E&T Structures prior to approval to ensure that all relevant information is provided. Key data to be included in drawings includes pipe class, exposure classification, depth of fill, design load, assumed construction loads and information on the specifications that the pipe(s) are to be constructed to.
- Data management processes should be strengthened to ensure that all new culvert design drawings are entered into BIS and GIMS.
- The TMR standard drawing should be updated to reference the most recent TMR and Australian standards for pipe construction, including the updated provisions for construction load.
- The *Road Drainage Manual* should be updated to reference current specifications for the determination of construction load.
- It is recommended that handover inspections are conducted after the conclusion of construction for all new major culverts, and the handover inspection details are entered into the BIS. A solution should be worked out so that either data from non-RoadTek inspections can be entered into the BIS, or RoadTek inspectors can conduct handover inspections. Culvert details should be checked and approved by E&T Structures prior to their entry into the BIS to ensure that the data is of an acceptable standard.

7.3 Secondary Recommendations

The recommendations outlined in this section are not intended to be taken as required work in the context of the current study, but there may be value in additional investigation if further work is to be done in related areas, including:

- Several district-level variations in defect prevalence were observed which could be investigated by discussing design, construction and/or inspection practices with local staff in the districts. This approach may not yield any significant results as it is dependent on the turnover of staff in each district and whether they were involved in the installation of any of the culverts in question. There may also be value in reviewing inspection reports from each district. The defect variations in question are:
  - high numbers of CS3 joint defects present in 80P components installed during the last decade in district 407
  - high incidence of transverse cracking in 80P components constructed in district 412
  - low prevalence of longitudinal cracking in 80P components constructed in district 404. The aim of investigating this would be to determine whether any lessons can be learnt and applied to culvert design and construction in other districts.
- The spike in cracking for components with 2–3 m of fill could be investigated further through a review of construction practices or design records.

- There may be some value in reviewing inspection scheduling to determine the reasons for the six structures overdue for L2 inspections identified during the structure-level historical analysis. It is possible that inspections have been conducted in the time between the sampling of the dataset and the publication of this report.

REFERENCES

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Queensland Department of Transport and Main Roads

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APPENDIX A NETWORK DEFECT ANALYSIS

A.1 Longitudinal Cracking

This appendix provides detailed analytical data relating to the network-level analysis of longitudinal cracking defects.

Data is tabulated as follows:

1. Count of longitudinally cracked components in each CS by district (Table A 1)
2. Longitudinally cracked components as a proportion of total components by district (Table A 2 and Figure A 1)
3. Defective (CS3/4) longitudinally cracked components as a proportion of total defective (CS3/4) components by district (Table A 3)
4. Longitudinally cracked components as a proportion of total components by decade of construction (Table A 4 and Figure A 2)
5. Defective (CS3/4) longitudinally cracked components as a proportion of total defective (CS3/4) components by decade of construction (Table A 5)
6. Longitudinally cracked components as a proportion of total components by exposure class (Table A 6)
7. Defective (CS3/4) longitudinally cracked components as a proportion of total defective (CS3/4) components by exposure class (Table A 7)
8. Longitudinally cracked components as a proportion of total components by depth of fill (Table A 8)
9. Defective (CS3/4) longitudinally cracked components as a proportion of total defective (CS3/4) components by depth of fill (Table A 9).

Table A 1: Condition state of longitudinally cracked components vs. district

District ID	CS1	CS2	CS3	CS4	Total longitudinally cracked components
401					
402			2	1	3
403		3	8		11
404		5		1	6
405	2	11	4	1	18
406		10	12	3	25
407	1	3	8		12
408		7	3	1	11
410		28	23	8	59
411		1			1
412	1	8	4	1	14
Totals	**4**	**76**	**64***	**16***	**160**

* Of the 80 components in CS3/4 there are 50 unique structure IDs.

Table A 2: Proportions of longitudinally cracked 80P components vs. district – all CS

District ID	No. of longitudinally cracked components	As a proportion of all components in the district	No. of longitudinally cracked components (CS3/4)	CS3/4 as a proportion of all components in the district	Total components
401		0.0%		0.0%	12
402	3	3.8%	3	3.8%	77
403	11	13.3%	8	9.6%	83
404	6	2.9%	1	0.5%	209
405	18	11.3%	5	3.1%	160
406	25	12.2%	15	7.3%	205
407	12	6.9%	8	4.6%	173
408	11	9.2%	4	3.4%	119
410	59	28.0%	31	14.7%	211
411	1	2.6%		0.0%	38
412	14	7.5%	5	2.7%	185
Totals	**160**	**10.8% of 1472 components overall**	**80**	**5.4% of 1472 components overall**	**1472**

Table A 3: Proportions of longitudinally cracked components in CS3/4 vs. district

District ID	No. of longitudinally cracked components (CS3/4)	As a proportion of all components in CS3/4 in the district	Total components in CS3/4 in the district
401	0	0.0%	0
402	3	21.4%	14
403	8	61.5%	13
404	1	6.3%	16
405	5	27.8%	18
406	15	30.0%	50
407	8	12.7%	63
408	4	30.8%	13
410	31	49.2%	63
411	0	0.0%	0
412	5	10.6%	47
Totals	**80**	**26.9% of 297 components in CS3/4**	**297**

Figure A 1: Longitudinally cracked 80P components in each district rated in any CS and rated in CS3/4 only as proportions of all components considered for each district

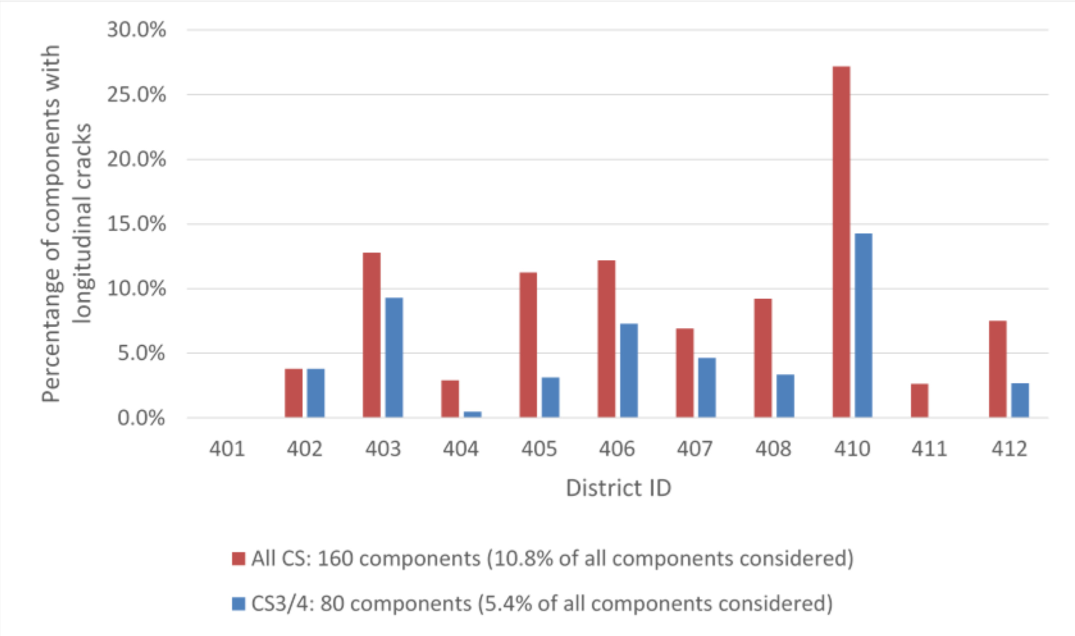

Table A 4: Proportions of longitudinally cracked components vs. construction decade – all CS

Construction decade	No. of longitudinally cracked components	As a proportion of all components in a decade	No. of longitudinally cracked components (CS3/4)	CS3/4 as a proportion of all components in a decade	Total components constructed in a decade
1950	17	17.2%	12	12.4%	97
1960	18	8.0%	7	3.1%	223
1970	45	15.2%	27	9.0%	299
1980	38	12.4%	17	5.6%	306
1990	6	3.0%	4	2.1%	194
2000	24	13.4%	10	5.6%	178
2010	12	6.8%	3	1.7%	173
Totals	**160**	**10.8% of 1470 components overall**	**80**	**5.4% of 1470 components overall**	**1470***

*Two components with no construction date omitted.

Table A 5: Proportions of longitudinally cracked components in CS3/4 vs. construction decade

Construction decade	No. of longitudinally cracked components (CS3/4)	As a proportion of all components in CS3/4 for a decade	Total components in CS3/4 for a decade
1950	12	50.0%	24
1960	7	18.4%	38
1970	27	33.3%	81

Construction decade	No. of longitudinally cracked components (CS3/4)	As a proportion of all components in CS3/4 for a decade	Total components in CS3/4 for a decade
1980	17	31.5%	54
1990	4	9.3%	43
2000	10	31.3%	32
2010	3	12.0%	25
Totals	**80**	**26.9% of 297 components in CS3/4**	**297**

Figure A 2: Longitudinally cracked 80P components constructed in each decade rated in any CS and rated in CS3/4 only as proportions of all components considered for each decade

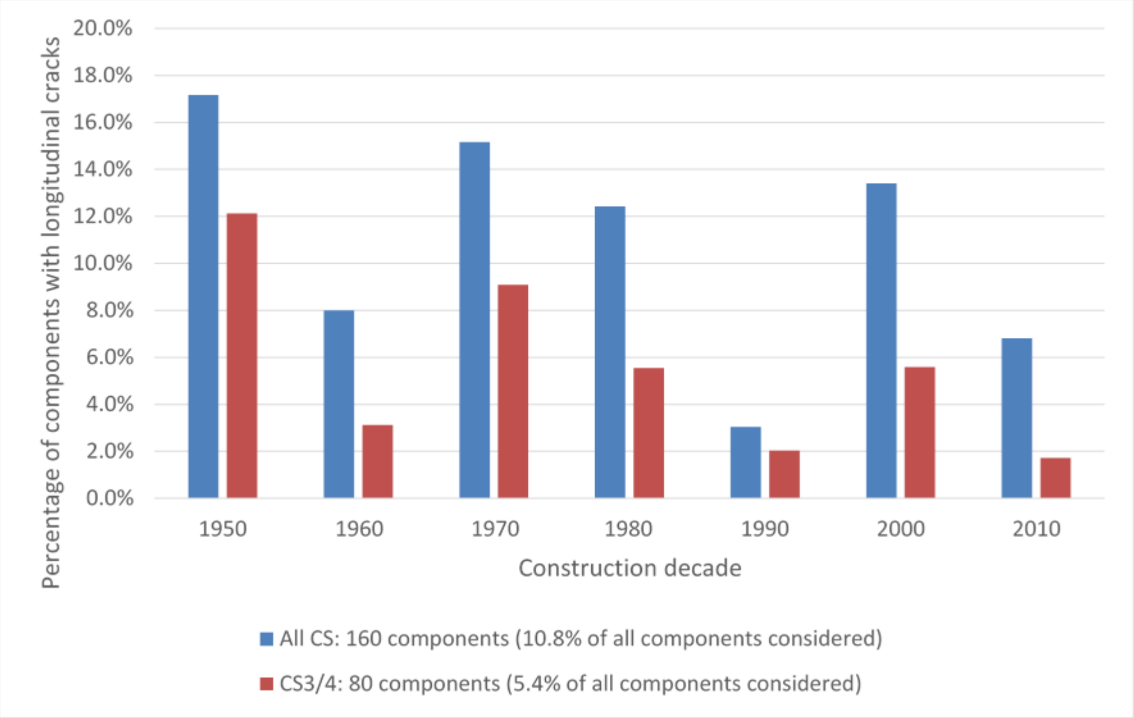

Table A 6: Proportions of longitudinally cracked components vs. exposure class – all CS

Exposure class	No. of longitudinally cracked components	As a proportion of all components in an exposure class	No. of longitudinally cracked components (CS3/4)	CS3/4 as a proportion of all components in an exposure class	Total components in an exposure class
1	28	16.2%	18	10.4%	173
2	125	10.6%	56	4.8%	1172
3	7	6.6%	6	5.7%	106
4	0	0.0%	0	0.0%	21
Totals	**160**	**10.8% of 1472 components overall**	**80**	**5.4% of 1472 components overall**	**1472**

Table A 7: Proportions of longitudinally cracked components in CS3/4 vs. exposure class

Exposure class	No. of longitudinally cracked components (CS3/4)	As a proportion of all components in CS3/4 for an exposure class	Total components in CS3/4 for an exposure class
1	18	47.4%	38
2	56	22.4%	250
3	6	66.7%	9
4	0	0.0%	0
Totals	**80**	**26.9% of 297 components in CS3/4**	**297**

Table A 8: Proportions of longitudinally cracked components vs. depth of fill – all CS

Depth of fill (m)	No. of longitudinally cracked components	As a proportion of all components with a certain fill depth	No. of longitudinally cracked components (CS3/4)	CS3/4 as a proportion of all components with a certain depth of fill	Total components with a certain depth of fill
No data	101	12.4%	52	6.4%	813
0–1	34	10.1%	14	4.2%	335
1–2	12	7.3%	5	3.0%	165
2–3	6	10.7%	5	8.9%	56
3–4		0.0%		0.0%	29
4–5	1	4.8%		0.0%	21
5–6		0.0%		0.0%	12
6–7	1	11.1%		0.0%	9
7–8	1	9.1%		0.0%	11
8–9	2	50.0%	2	50.0%	4
9–10	2	11.8%	2	11.8%	17
Totals	**160**	**10.8% of 1472 components overall**	**80**	**5.4% of 1472 components overall**	**1472**

Table A 9: Proportions of longitudinally cracked components in CS3/4 vs. depth of fill

Depth of fill (m)	No. of longitudinally cracked components in CS3/4	As a proportion of all components with a certain fill depth in CS3/4	Total components in CS3/4 with a certain depth of fill
No data	52	26.4%	197
0–1	14	33.3%	42
1–2	5	17.2%	29
2–3	5	33.3%	15
3–4		0.0%	4
4–5		0.0%	0
5–6		0.0%	0
6–7		0.0%	2

Depth of fill (m)	No. of longitudinally cracked components in CS3/4	As a proportion of all components with a certain fill depth in CS3/4	Total components in CS3/4 with a certain depth of fill
7–8		0.0%	
8–9	2	33.3%	6
9–10	2	100.0%	2
Totals	**80**	**26.9% of 297 components in CS3/4**	**297**

A.2 Transverse Cracking

This section details transverse cracking against location, age, exposure class and depth of fill of culvert components.

Data is tabulated as follows:

1. Count of transversely cracked components in each CS by district (Table A 10)
2. Transversely cracked components as a proportion of total components by district (Table A 11 and Figure A 3)
3. Defective (CS3/4) transversely cracked components as a proportion of total defective (CS3/4) components by district (Table A 12)
4. Transversely cracked components as a proportion of total components by decade of construction (Table A 13 and Figure A 4)
5. Defective (CS3/4) transversely cracked components as a proportion of total defective (CS3/4) components by decade of construction (Table A 14)
6. Transversely cracked components as a proportion of total components by exposure class (Table A 15)
7. Defective (CS3/4) transversely cracked components as a proportion of total defective (CS3/4) components by exposure class (Table A 16)
8. Transversely cracked components as a proportion of total components by depth of fill (Table A 17)
9. Defective (CS3/4) transversely cracked components as a proportion of total defective (CS3/4) components by depth of fill (Table A 18).

Table A 10: Condition state of transversely cracked components vs. district

District ID	CS1	CS2	CS3	CS4	Total transversely cracked components
401					
402		1			1
403					
404					
405			2		2
406		1	2	3	6
407			3		3
408				1	1
410		2	1	2	5

District ID	CS1	CS2	CS3	CS4	Total transversely cracked components
411					
412		48	22	12	82
Totals		**52**	**30***	**18***	**100**

* Of the 48 components in CS3/4 there are 36 unique structure IDs.

Table A 11: Proportions of transversely cracked components vs. district – all CS

District ID	No. of transversely cracked components	As a proportion of all components in district	No. of transversely cracked components (CS3/4)	CS3/4 as a proportion of all components in district	Total components in district
401		0.0%		0.0%	12
402	1	1.3%		0.0%	77
403		0.0%		0.0%	83
404		0.0%		0.0%	209
405	2	1.3%	2	1.3%	160
406	6	2.9%	5	2.4%	205
407	3	1.7%	3	1.7%	173
408	1	0.8%	1	0.8%	119
410	5	2.4%	3	1.4%	211
411		0.0%		0.0%	38
412	82	44.3%	34	18.4%	185
Totals	**100**	**6.7% of 1472 components overall**	**48**	**3.2% of 1472 components overall**	**1472**

Table A 12: Proportions of transversely cracked components in CS3/4 vs. district

District ID	No. of transversely cracked components	As a proportion of all components in CS3/4 in district	Total components in CS3/4 in district
401		0.0%	
402		13.3%	14
403		38.5%	13
404		6.3%	16
405	2	33.3%	18
406	5	22.9%	50
407	3	10.8%	63
408	1	23.1%	13
410	3	39.2%	63
411		0.0%	
412	34	77.1%	47

District ID	No. of transversely cracked components	As a proportion of all components in CS3/4 in district	Total components in CS3/4 in district
Totals	**48**	**16.2% of 297 components in CS3/4**	**297**

Figure A 3: Transversely cracked 80P components in each district rated in any CS and rated in CS3/4 only as proportions of all components considered for each district

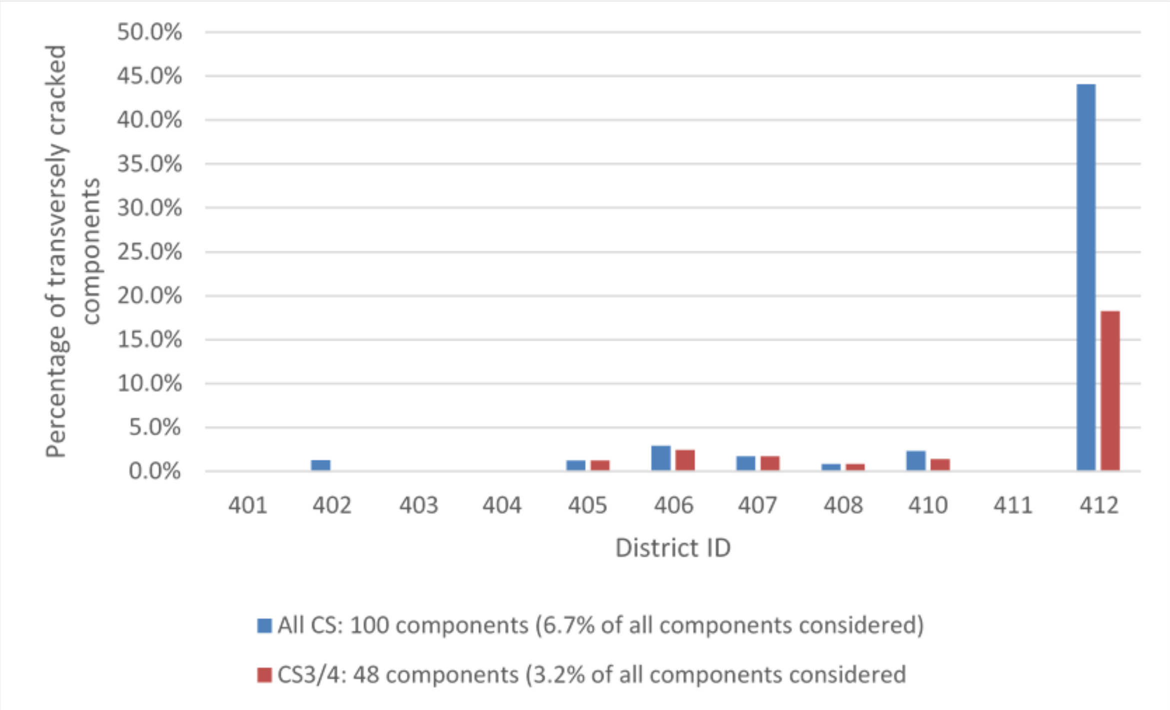

Table A 13: Proportions of transversely cracked components vs. construction decade – all CS

Construction decade	No. of transversely cracked components	As a proportion of all components	No. of transversely cracked components (CS3/4)	CS3/4 as a proportion of all components in a decade	Total components constructed in a decade
1950	5	5.2%	3	3.1%	97
1960	25	11.2%	15	6.7%	223
1970	24	8.0%	14	4.7%	299
1980	13	4.2%	6	2.0%	306
1990	21	10.8%	4	2.1%	194
2000	7	3.9%	3	1.7%	178
2010	5	2.9%	3	1.7%	173
Totals	**100**	**6.7% of 1470 components overall**	**48**	**3.2% of 1470 components overall**	**1470***

*Two components with no construction date omitted.

Table A 14: Proportions of transversely cracked components in CS3/4 vs. construction decade

Construction decade	No. of transversely cracked components – CS3/4	As a proportion of all components in CS3/4 for a decade	Total components in CS3/4 for a decade
1950	3	12.5%	24
1960	15	39.5%	38
1970	14	17.3%	81
1980	6	11.1%	54
1990	4	9.3%	43
2000	3	9.4%	32
2010	3	12.0%	25
Totals	**48**	**16.2%**	**297**

Figure A 4: Transversely cracked components constructed in each decade rated in any CS and rated in CS3/4 only as proportions of all components considered for each decade

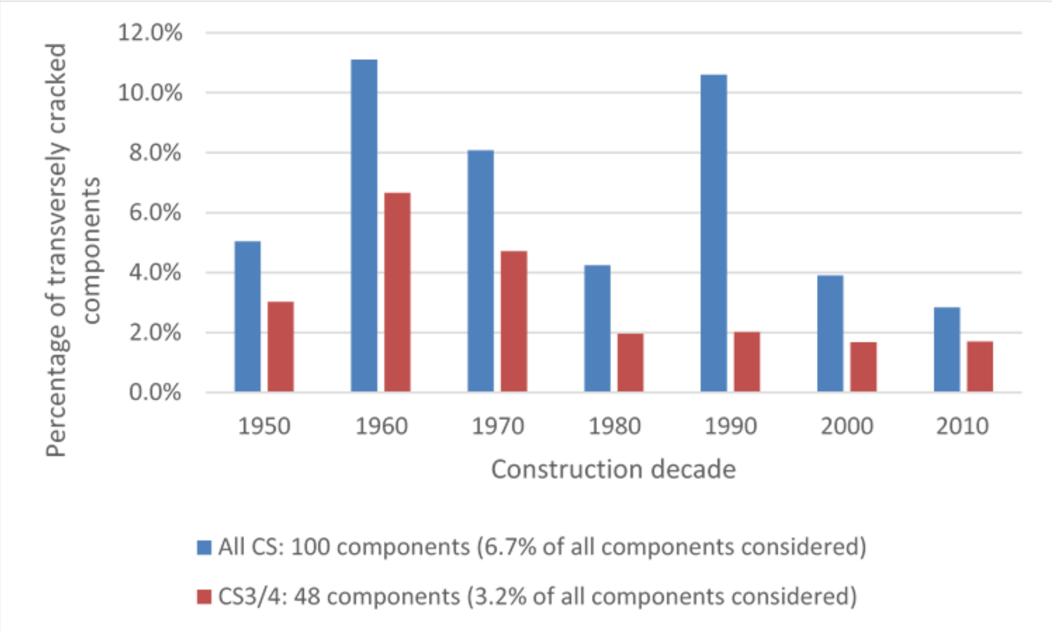

Table A 15: Proportions of transversely cracked components vs. exposure class – all condition states

Exposure code	No. of transversely cracked components in exposure class	As a proportion of all components in an exposure class	No. of transversely cracked components (CS3/4)	CS3/4 as a proportion of all components in an exposure class	Total components in an exposure class
1	1	0.6%	1	0.6%	173
2	97	8.3%	46	3.9%	1172
3	2	1.9%	1	0.9%	106
4		0.0%		0.0%	21
Totals	**100**	**6.7% of 1472 components overall**	**48**	**3.2% of 1472 components overall**	**1472**

Table A 16: Proportions of transversely cracked components in CS3/4 vs. exposure class

Exposure code	No. of transversely cracked components (CS3/4)	As a proportion of all components in CS3/4 in an exposure class	Total components in CS3/4 in an exposure class
1	1	2.6%	38
2	46	18.4%	250
3	1	11.1%	9
4		0.0%	0
Totals	**48**	**16.2% of 297 components in CS3/4**	**297**

Table A 17: Proportions of transversely cracked components vs. depth of fill – all condition states

Depth of fill (m)	No. of transversely cracked components	As a proportion of all components with a certain depth of fill	No. of transversely cracked components (CS3/4)	CS3/4 as a proportion of all components with a certain depth of fill	Total components with a certain depth of fill
No data	39	4.8%	20	2.5%	813
0–1	21	6.3%	6	1.8%	335
1–2	18	10.9%	10	6.1%	165
2–3	15	26.8%	9	16.1%	56
3–4	6	20.7%	2	6.9%	29
4–5		0.0%		0.0%	21
5–6		0.0%		0.0%	12
6–7		0.0%		0.0%	9
7–8		0.0%		0.0%	11
8–9		0.0%		0.0%	4
9–10	1	5.9%	1	5.9%	17
Totals	**100**	**6.7% of 1472 components overall**	**48**	**3.2% of 1472 components overall**	**1472**

Table A 18: Proportions of transversely cracked components in CS3/4

Depth of fill (m)	No. of transversely cracked components (CS3/4)	As a proportion of all components in CS3/4 with a certain depth of fill	Total components in CS3/4 with a certain depth of fill
No data	20	10.2%	197
0–1	6	14.3%	42
1–2	10	34.5%	29
2–3	9	60.0%	15
3–4	2	50.0%	4
4–5		0.0%	
5–6		0.0%	
6–7		0.0%	2
7–8		0.0%	
8–9		0.0%	6

Depth of fill (m)	No. of transversely cracked components (CS3/4)	As a proportion of all components in CS3/4 with a certain depth of fill	Total components in CS3/4 with a certain depth of fill
9–10	1	50.0%	2
Totals	48	16.2% of 297 components in CS3/4	297

A.3 Spalling

This section details spalling data compared to location, age, exposure class and depth of fill.

Data is tabulated as follows:

1. Count of spalled components in each CS by district (Table A 19)
2. Spalled components as a proportion of total components by district (Table A 20 and Figure A 5)
3. Defective (CS3/4) spalled components as a proportion of total defective (CS3/4) components by district (Table A 21)
4. Spalled components as a proportion of total components by decade of construction (Table A 22 and Figure A 6)
5. Defective (CS3/4) spalled components as a proportion of total defective (CS3/4) components by decade of construction (Table A 23)
6. Spalled components as a proportion of total components by exposure class (Table A 24)
7. Defective (CS3/4) spalled components as a proportion of total defective (CS3/4) components by exposure class (Table A 25)
8. Spalled components as a proportion of total components by depth of fill (Table A 26)
9. Defective (CS3/4) spalled components as a proportion of total defective (CS3/4) components by depth of fill (Table A 27).

Table A 19: Condition state of spalled components vs. district

District ID	CS1	CS2	CS3	CS4	Total spalled components
401					
402		5	2	1	8
403		3	2	1	6
404		1	2	6	9
405	1	9	8	3	21
406	1	21	14	1	37
407		1	9		10
408		3	2		5
410		30	34	15	79
411		1			1
412		3	16	8	27
Totals	**2**	**77**	**89***	**35***	**203**

*Of the 124 components in CS3/4 there are 76 unique structure IDs.

Table A 20: Proportions of spalled components vs. district – all condition states

District ID	No. of spalled components	As a proportion of all components in district	No. of spalled components (CS3/4)	CS3/4 as a proportion of all components in district	Total components in district
401		0.0%		0.0%	12
402	8	10.4%	3	3.9%	77
403	6	7.2%	3	3.6%	83
404	9	4.3%	8	3.8%	209
405	21	13.1%	11	6.9%	160
406	37	18.0%	15	7.3%	205
407	10	5.8%	9	5.2%	173
408	5	4.2%	2	1.7%	119
410	79	37.4%	49	23.2%	211
411	1	2.6%		0.0%	38
412	27	14.6%	24	13.0%	185
Totals	**203**	**13.7% of 1472 components overall**	**124**	**8.4% of 1472 components overall**	**1472**

Table A 21: Proportions of spalled components in CS3/4 vs. district

District ID	No. of spalled components in CS3/4	As a proportion of all components in CS3/4 in district	Total components in CS3/4 in district
401		0.0%	
402	3	21.4%	14
403	3	23.1%	13
404	8	50.0%	16
405	11	61.1%	18
406	15	30.0%	50
407	9	14.3%	63
408	2	15.4%	13
410	49	77.8%	63
411		0.0%	
412	24	51.1%	47
Totals	**124**	**41.8% of 297 components in CS3/4**	**297**

Figure A 5: Spalled 80P components in each district rated in any CS and rated in CS3/4 only as proportions of all components considered in each district

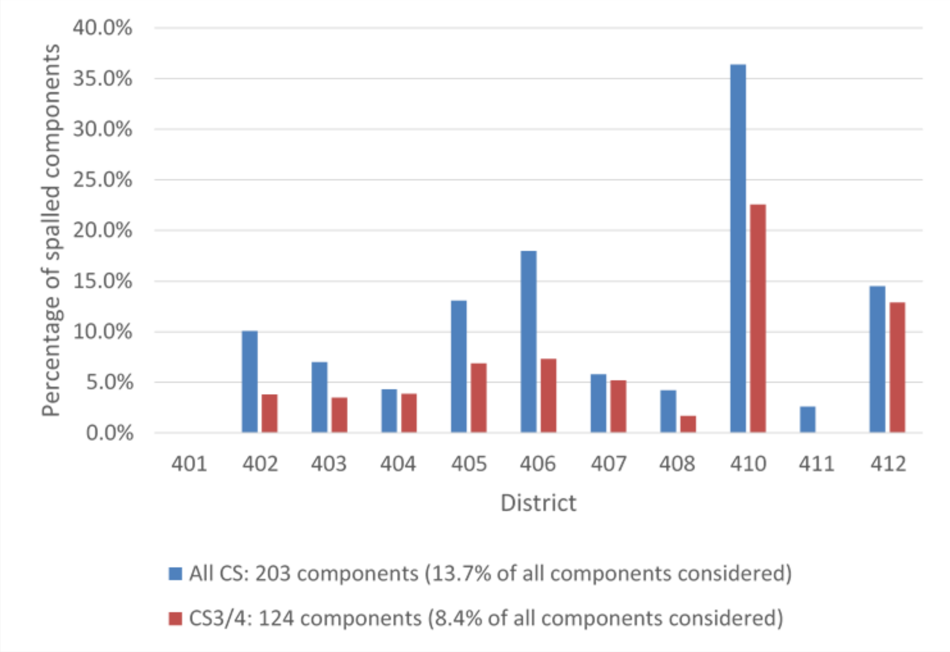

Table A 22: Proportions of spalled components vs. construction decade – all CS

Construction decade	No. of spalled components	As a proportion of all components constructed in decade	No. of spalled components (CS3/4)	CS3/4 as a proportion of all components constructed in a decade	Total components constructed in decade
1950	10	10.3%	8	8.2%	97
1960	31	13.9%	23	10.3%	223
1970	55	18.4%	34	11.4%	299
1980	45	14.7%	26	8.5%	306
1990	26	13.4%	17	8.8%	194
2000	30	16.9%	14	7.9%	178
2010	6	3.5%	2	1.2%	173
Totals	**203**	**13.7% of 1470 components overall**	**124**	**8.4% of 1470 components overall**	**1470***

*Two components with no construction date omitted.

Table A 23: Proportions of spalled components in CS3/4 vs. construction decade

Construction decade	No. of spalled components (CS3/4)	As a proportion of all components in CS3/4 in a decade	Total components in CS3/4 in a decade
1950	8	33.3%	24
1960	23	60.5%	38
1970	34	42.0%	81

1980	26	48.1%	54
1990	17	39.5%	43
2000	14	43.8%	32
2010	2	8.0%	25
Totals	**124**	**41.8% of 297 components in CS3/4**	**297**

Figure A 6: Spalled 80P components constructed in each decade rated in any CS and rated in CS3/4 only as proportions of all components constructed in each decade

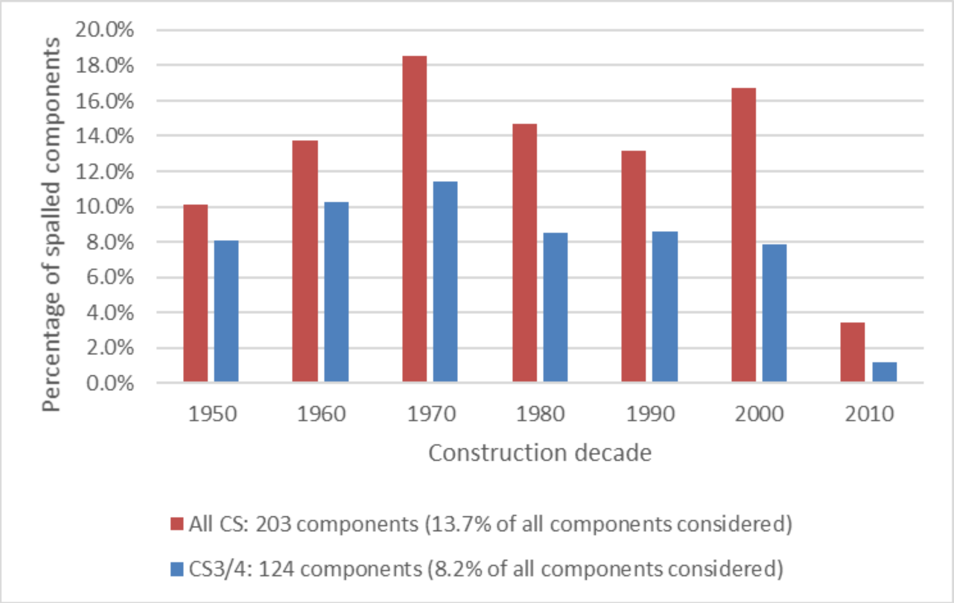

Table A 24: Proportions of spalled components vs. exposure class – all CS

Exposure code	No. of spalled components	As a proportion of all components in an exposure class	No. of spalled components (CS3/4)	CS3/4 as a proportion of all components in an exposure class	Total components in an exposure class
1	10	5.8%	5	2.9%	173
2	182	15.5%	117	10.0%	1172
3	10	9.4%	4	3.8%	106
4	1	4.8%	0	0.0%	21
Totals	**203**	**13.7% of 1472 components overall**	**124**	**8.4% of 1472 components overall**	**1472**

Table A 25: Proportions of spalled components in CS3/4 vs. exposure class

Exposure code	No. of spalled components	As a proportion of all components in CS3/4 in an exposure class	Total components in CS3/4 in an exposure class
1	5	21.1%	38
2	117	44.8%	250
3	4	44.4%	9

Exposure code	No. of spalled components	As a proportion of all components in CS3/4 in an exposure class	Total components in CS3/4 in an exposure class
4		0.0%	
Totals	**124**	**41.8% of 297 components in CS3/4**	**297**

Table A 26: Proportions of spalled components vs. depth of fill – all CS

Depth of fill (m)	No. of spalled components	As a proportion of all components with a certain depth of fill	No. of spalled components (CS3/4)	CS3/4 as a proportion of all components with a certain depth of fill	Total components with a certain depth of fill
No data	115	14.0%	75	9.2%	813
0–1	30	8.9%	14	4.2%	335
1–2	30	18.2%	20	12.1%	165
2–3	12	21.4%	9	16.1%	56
3–4	3	10.3%	2	6.9%	29
4–5		0.0%		0.0%	21
5–6		0.0%		0.0%	12
6–7		0.0%		0.0%	9
7–8		0.0%		0.0%	11
8–9		72.2%		100.0%	4
9–10	13	0.0%	4	0.0%	17
Totals	**203**	**13.7% of 1472 components overall**	**124**	**8.4% of 1472 components overall**	**1472**

Table A 27: Proportions of spalled components in CS3/4 vs. depth of fill

Depth of fill (m)	No. of spalled components	As a proportion of all components in CS3/4 with a certain depth of fill	Total components in CS3/4 with a certain depth of fill
No data	75	38.1%	197
0–1	14	33.3%	42
1–2	20	69.0%	29
2–3	9	60.0%	15
3–4	2	50.0%	4
4–5		0.0%	
5–6		0.0%	
6–7		0.0%	2
7–8		0.0%	
8–9		0.0%	2
9–10	4	66.7%	6
Totals	**124**	**41.8% of 297 components in CS3/4**	**297**

A.4 Shrinkage Cracks

This section details reported shrinkage cracking, which occurs during construction and typically does not impact on the condition of components unless it is of a significant width.

Data is tabulated as follows:

1. Count of shrinkage cracked components in each CS by district (Table A 28 and Figure A 7)
2. Shrinkage cracked components as a proportion of total components by district (Table A 29)
3. Shrinkage cracked components as a proportion of total components by decade of construction (Table A 30 and Figure A 8)
4. Shrinkage cracked components as a proportion of total components by exposure class (Table A 31)
5. Shrinkage cracked components as a proportion of total components by depth of fill (Table A 32).

Table A 28: Condition state of shrinkage cracked components vs. district

District ID	CS1	CS2	CS3	CS4	Total shrinkage cracked components
401					
402		12	2	1	15
403					
404					
405					
406		3			3
407					
408		1			1
410		7	1	2	10
411					
412	1				
Totals	1	23	3*	3*	30

*Of the 6 components in CS3/4 there are 5 unique structure IDs.

Table A 29: Proportions of shrinkage cracked components vs. district – all CS

District ID	No. of shrinkage cracked components	As a proportion of all components in district	No. of shrinkage cracked components in CS3/4	CS3/4 as a proportion of all components in district	Total components in district
401	0	0.0%	0	0.0%	12
402	15	19.5%	3	3.9%	77
403	0	0.0%	0	0.0%	83
404	0	0.0%	0	0.0%	209
405	0	0.0%	0	0.0%	160
406	3	1.5%	0	0.0%	205
407	0	0.0%	0	0.0%	173

District ID	No. of shrinkage cracked components	As a proportion of all components in district	No. of shrinkage cracked components in CS3/4	CS3/4 as a proportion of all components in district	Total components in district
408	1	0.8%	0	0.0%	119
410	10	4.7%	3	1.4%	211
411	0	0.0%	0	0.0%	38
412	1	0.5%	0	0.0%	185
Totals	**30**	**2.0% of 1472 components overall**	**6**	**0.4% of 1472 components overall**	**1472**

Figure A 7: Shrinkage cracked 80P components in each district as proportions of all components considered in each district

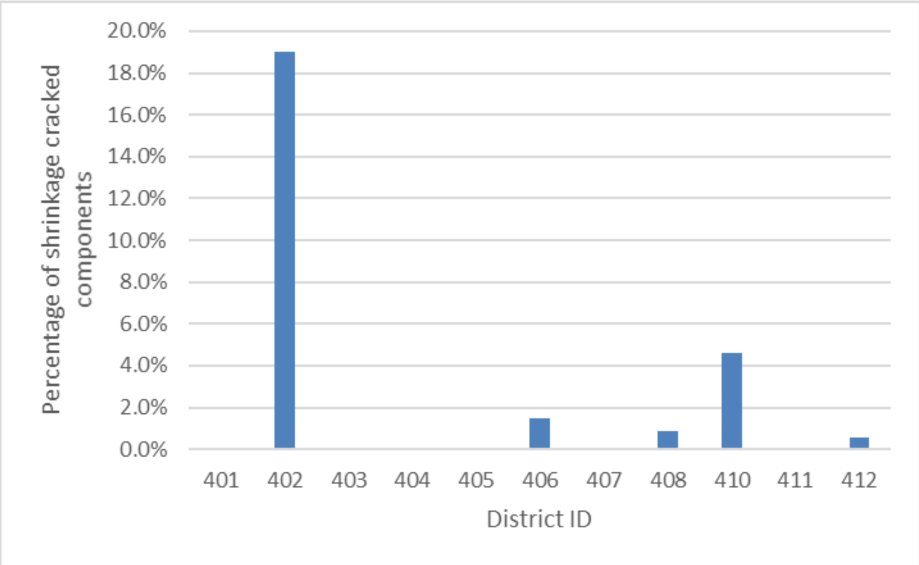

Table A 30: Proportions of shrinkage cracked components vs. construction decade – all CS

Construction decade	No. of shrinkage cracked components	As a proportion of all components constructed in decade	No. of shrinkage cracked components (CS3/4)	CS3/4 as a proportion of all components in a decade	Total components constructed in decade
1950	8	8.2%	2	2.1%	97
1960	1	0.4%		0.0%	223
1970	5	1.7%	1	0.3%	299
1980	5	1.6%	2	0.7%	306
1990	3	1.5%		0.0%	194
2000	7	3.9%	1	0.6%	178
2010	1	0.6%		0.0%	173
Totals	**30**	**2.0% of 1470 components overall**	**6**	**0.4% of 1470 components overall**	**1470***

*Two components with no construction date omitted.

Figure A 8: Shrinkage cracked 80P components constructed in each decade as proportions of all considered components constructed in each decade

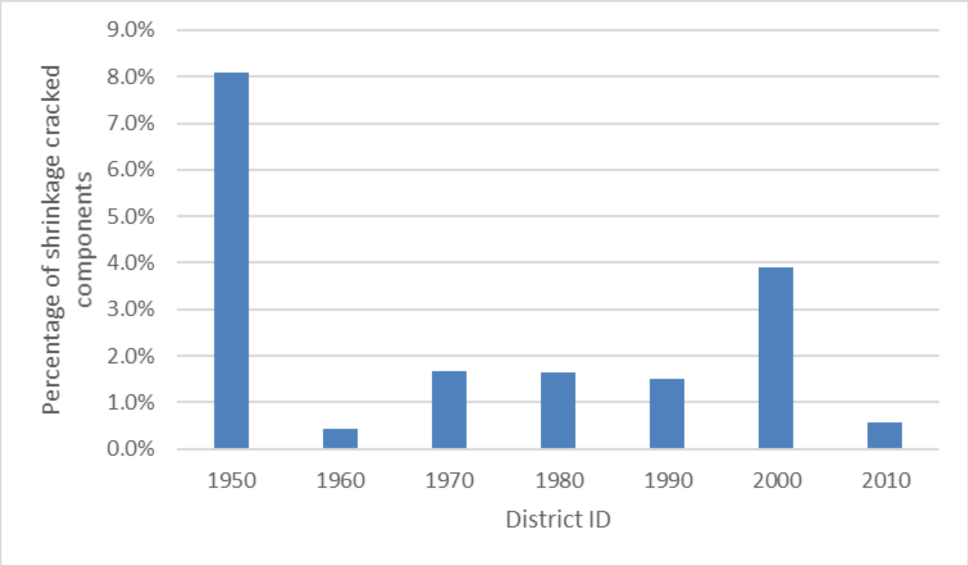

Table A 31: Proportions of shrinkage cracked components vs. exposure class – all CS

Exposure code	No. of shrinkage cracked components	As a proportion of all components in an exposure class	No. of shrinkage cracked components (CS3/4)	CS3/4 as a proportion of all components	Total components in an exposure class
1	5	2.9%	1	0.6%	173
2	22	1.9%	5	0.4%	1172
3	3	2.8%		0.0%	106
4		0.0%		0.0%	21
Totals	**30**	**2.0% of 1472 components**	**6**	**0.4% of 1472 components**	**1472**

Table A 32: Proportions of shrinkage cracked components vs. depth of fill – all CS

Depth of fill (m)	No. of shrinkage cracked components	As a proportion of all components	No. of shrinkage cracked components (CS3/4)	CS3/4 as a proportion of all components	Total components with a certain depth of fill
No data	11	1.4%	1	0.1%	813
0–1	16	4.8%	3	0.9%	335
1–2	2	1.2%	2	1.2%	165
2–3		0.0%		0.0%	56
3–4		0.0%		0.0%	29
4–5		0.0%		0.0%	21
5–6		0.0%		0.0%	12
6–7		0.0%		0.0%	9
7–8		0.0%		0.0%	11
8–9		0.0%		0.0%	4

Depth of fill (m)	No. of shrinkage cracked components	As a proportion of all components	No. of shrinkage cracked components (CS3/4)	CS3/4 as a proportion of all components	Total components with a certain depth of fill
9–10	1	5.9%		0.0%	17
Grand Total	**30**	**2.0% of 1472 components overall**	**6**	**0.4% of 1472 components overall**	**1472**

A.5 All Cracking

This section captures all reported cracking, including longitudinal, transverse, shrinkage and nondescript cracking.

Data is tabulated as follows:

1. Count of cracked components in each CS by district (Table A 33)
2. Cracked components as a proportion of total components by district (Table A 34 and Figure A 9)
3. Defective (CS3/4) cracked components as a proportion of total defective (CS3/4) components by district (Table A 35)
4. Cracked components as a proportion of total components by decade of construction (Table A 36 and Figure A 10)
5. Defective (CS3/4) cracked components as a proportion of total defective (CS3/4) components by decade of construction (Table A 37)
6. Cracked components as a proportion of total components by exposure class (Table A 38)
7. Defective (CS3/4) cracked components as a proportion of total defective (CS3/4) components by exposure class (Table A 39)
8. Cracked components as a proportion of total components by depth of fill (Table A 40)
9. Defective (CS3/4) cracked components as a proportion of total defective (CS3/4) components by depth of fill (Table A 41).

Table A 33: Condition state of all cracked components vs. district

District ID	CS1	CS2	CS3	CS4	Total cracked components
401					
402		12	3	2	17
403		7	9		16
404		5		1	6
405	3	21	7	1	32
406		21	15	6	42
407	1	3	10		14
408		12	7	3	22
410		40	25	11	76
411		1			1
412	3	60	26	14	103
Totals	**7**	**182**	**102***	**38***	**329**

*Of the 140 components in CS3/4, there are 87 unique structure IDs.

Table A 34: Proportions of components with any form of cracking vs. district – all CS

District ID	No. of cracked components	As a proportion of all components in district	No. of cracked components (CS3/4)	CS3/4 as proportion of all components in district	Total components in district
401		0.0%		0.0%	12
402	17	22.1%	5	6.5%	77
403	16	19.3%	9	10.8%	83
404	6	2.9%	1	0.5%	209
405	32	20.0%	8	5.0%	160
406	42	20.5%	21	10.2%	205
407	14	8.1%	10	5.8%	173
408	22	18.5%	10	8.4%	119
410	76	36.0%	36	17.1%	211
411	1	2.6%		0.0%	38
412	103	55.7%	40	21.6%	185
Totals	**329**	**22.2% of 1472 components overall**	**140**	**9.4% of 1472 components overall**	**1472**

Table A 35: Proportions of components with any form of cracking in CS3/4 vs. district

District ID	No. of cracked components (CS3/4)	As a proportion of all components in CS3/4 in a district	Total components in CS3/4 in district
401			
402	5	35.7%	14
403	9	69.2%	13
404	1	6.3%	16
405	8	44.4%	18
406	21	42.0%	50
407	10	15.9%	63
408	10	76.9%	13
410	36	57.1%	63
411		0.0%	
412	40	85.1%	47
Totals	**140**	**47.1% of 297 components in CS3/4**	**297**

Figure A 9: Cracked 80P components in each district rated in any CS and rated in CS3/4 only as proportions of all components considered for the district

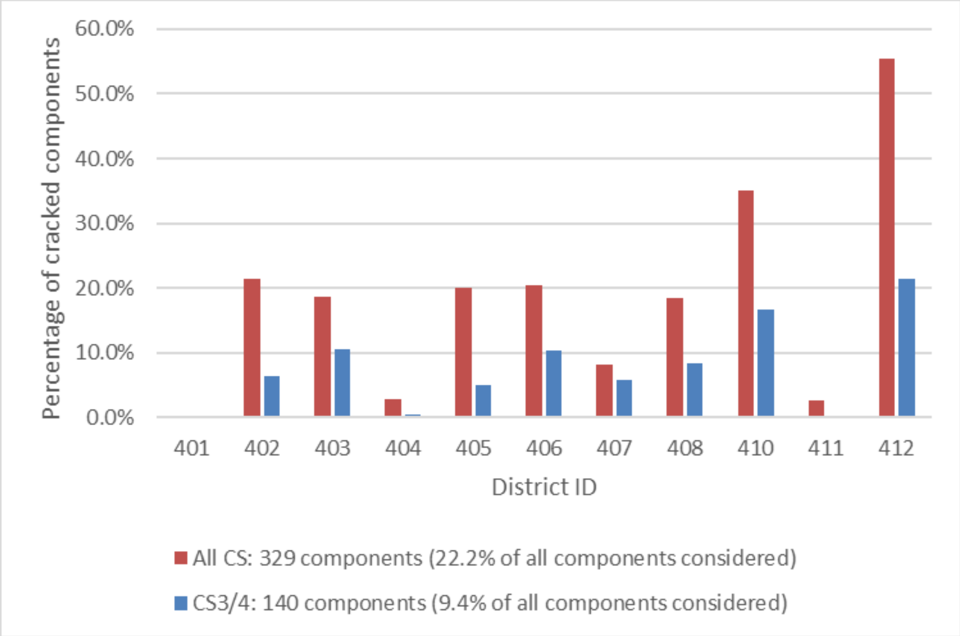

Table A 36: Proportions of components with any form of cracking vs. construction decade – all CS

Construction decade	No. of cracked components	As a proportion of all components constructed in decade	No. of cracked components (CS3/4)	CS3/4 as a proportion of all components	Total components constructed in decade
1950	32	33.0%	16	16.5%	97
1960	48	21.5%	21	9.4%	223
1970	90	30.1%	49	16.4%	299
1980	66	21.6%	26	8.5%	306
1990	36	18.6%	10	5.2%	194
2000	38	21.3%	12	6.7%	178
2010	19	11.0%	6	3.5%	173
Totals	**329**	**22.2% of 1470 components overall**	**140**	**9.5% of 1470 components overall**	**1470***

*Two components with no construction date omitted.

Table A 37: Proportions of components with any form of cracking in CS3/4 vs. construction decade

Construction decade	No. of cracked components	As a proportion of all components in CS3/4 constructed in a decade	Total components in CS3/4 constructed in decade
1950	16	66.7%	24
1960	21	55.3%	38
1970	49	60.5%	81
1980	26	48.1%	54
1990	10	23.3%	43

2000	12	37.5%	32
2010	6	24.0%	25
Totals	**140**	**47.1% of 297 components in CS3/4**	**297**

Figure A 10: Cracked 80P components constructed in each decade rated in any CS and rated in CS3/4 only as proportions of all components considered for a decade

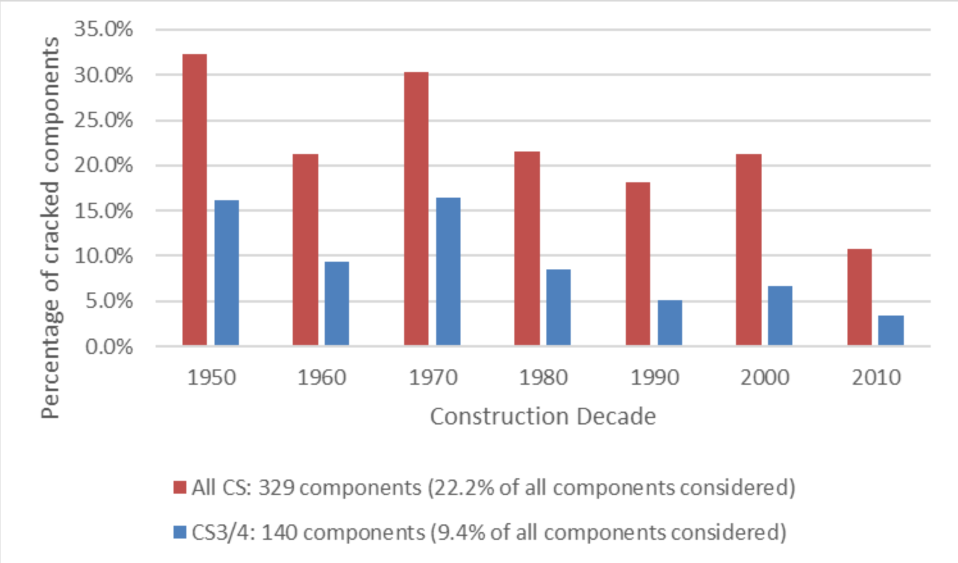

Table A 38: Proportions of components with any form of cracking vs. exposure class – all CS

Exposure code	No. of cracked components	As a proportion of all components	No. of cracked components (CS3/4)	CS3/4 as a proportion of all components	Total components in an exposure class
1	43	24.9%	24	13.9%	173
2	272	23.2%	108	9.2%	1172
3	14	13.2%	8	7.5%	106
4		0.0%		0.0%	21
Totals	**329**	**22.2% of 1472 components overall**	**140**	**9.4% of 1472 components overall**	**1472**

Table A 39: Proportions of components with any form of cracking in CS3/4 only vs. exposure class

Exposure code	No. of cracked components (CS3/4)	As a proportion of all components in CS3/4	Total components in CS3/4 in an exposure class
1	24	63.2%	38
2	108	43.2%	250
3	8	88.9%	9
4			
Totals	**140**	**47.1% of 297 components in CS3/4**	**297**

Table A 40: Proportions of components with any form of cracking vs. depth of fill – all CS

Depth of fill (m)	No. of cracked components	As a proportion of all components	No. of cracked components (CS3/4)	CS3/4 as a proportion of all components	Total components with a certain depth of fill
No data	171	21.0%	83	10.2%	813
0–1	76	22.7%	22	6.6%	335
1–2	42	25.5%	15	9.1%	165
2–3	23	41.1%	14	25.0%	56
3–4	7	24.1%	2	6.9%	29
4–5	1	4.8%		0.0%	21
5–6		0.0%		0.0%	12
6–7	1	11.1%		0.0%	9
7–8	2	18.2%		0.0%	11
8–9	4	100.0%	2	50.0%	4
9–10	2	11.8%	2	11.8%	17
Totals	**329**	**22.2% of 1472 components overall**	**140**	**9.4% of 1472 components overall**	**1472**

Table A 41: Proportions of components with any form of cracking in CS3/4 only vs. depth of fill

Depth of fill (m)	No. of cracked components (CS3/4)	As a proportion of all components in CS3/4	Total components in CS3/4 with a certain depth of fill
No data	83	42.1%	197
0–1	22	52.4%	42
1–2	15	51.7%	29
2–3	14	93.3%	15
3–4	2	50.0%	4
4–5			
5–6			
6–7			2
7–8			
8–9	2	100.0%	2
9–10	2	33.3%	6
Totals	**140**	**47.1% of all components in CS3/4**	**297**

APPENDIX B STRUCTURE-LEVEL HISTORICAL ANALYSIS

Table B 1 presents the CS and defects noted in the most recent and previous inspections for structures rated in CS3/4 based on 80P components. It shows the progression, or otherwise, of individual defect descriptions.

Highlighted structures indicate where at the time of data capture (25/9/2017) an L2 inspection had not been carried out in the five years prior. Inspections may have been carried out in the time between the sampling of the dataset and the publishing of this report.

Table B 1: Historic progressions of overall CS deterioration for precast pipe culverts (80P components only) with current CS3/4 defects

Structures in CS3 based on 80P components				
No.	**Structure ID**	**Date**	**CS**	**Defect identification**
1	2368	25-Jul-17	3	1. Horizontal cracking. 2. Minor pipe separation. 3. Grout loss between units. 4. Leaching at joints.
2	4363	29-Nov-01	1	1. Minor spalling around lifting holes. 2. Concrete collar deteriorated at bottom. 3. Reinforcement mesh noted at the bottom of pipe 4.
		11-Oct-06	1	No comment provided.
		7-Dec-11	2	1. Edge spalling at unit's joint. 2. 20% reinforcement loss noted at entrance of span 2 edge spall. 3. Spalling at lifting holes.
		16-Mar-16	3	1. Spalling with exposed reinforcement.
3	11209	27-Sep-01	3	1. Noted severe cracks. 2. Exposed reinforcement at the base.
		23-Jul-08	3	1. Noted severe cracks.
4	16273	21-Nov-01	2	1. Joint deterioration.
		30-Aug-07	2	1. Joint deterioration. 2. Minor cracking.
		7-May-17	3	This was identified because of widening deterioration (1 m in CS3 over total 3.6 m length): 1. Horizontal cracks. 2. Minor spalling noted.
5	18582	17-Aug-17	3	1. Pipe separation with grout loss. 2. Backfill visible with voids. 3. Exposed corrosive reinforcement. 4. Leaching at joint. 5. Noted settlement at span 2.

6	23415	30-Oct-02	1	1. Minor crack.
		15-Nov-07	2	1. Minor cracking at top and along the invert.
		28-Mar-17	3	1. Severe cracking. 2. Separation between units with deteriorated grout joint. 3. Minor spalling.
7	24635	24-Jan-02	1	No comment provided.
		14-Jun-07	3	1. Large sag in the alignment. 2. Water accumulated.
		11-Aug-10	3	1. Large sag in the alignment. 2. Water accumulated. 3. Blocked outlet.
8	25119	27-Nov-01	3	1. Separation of units at joint. 2. Heavy leaching. 3. Rust stains.
		30-Jan-03	3	1. Separation of units at joint. 2. Heavy leaching. 3. Deviation in line of pipes.
		24-Jul-08	No data	1. Unable to access structure.
9	25163	15-Aug-17	3	1. Exposed corrosive reinforcement. 2. Pipe’s unit separation at joints with loss of grout. 3. Spalling. 4. Settlement noted.
10	25500	16-Jun-02	2	No comment provided.
		16-Oct-03	3	1. Settlement and misalignment (drop 30 mm).
		21-May-04	2	No comment provided.
		13-May-09	2	No comment provided.
		23-Mar-17	3	1. Gap between units. 2. Void at top behind unit. 3. Minor longitudinal crack/shrinkage.
11	25635	24-Jul-17	3	1. Moderate transverse cracking. 2. Separation between units. 3. Loss of grout at joints. 4. Leaching at joint.
12	26004	24-Jun-02	1	1. Exposed reinforcement. 2. Pipe joint broken.
		6-Jul-05	2	1. Spalling with exposed corroded reinforcement. 2. Crack at the base.
		14-Mar-08	2	1. Hairline-to-minor cracking.
		27-Apr-17	3	1. Spalling with exposed corroded reinforcement. 2. Cracking and spalling noted at joints. 3. Heavy leaching at joints. 4. Minor transverse cracking.

13	26014	2-Jul-02	1	1. Horizontal cracks.
		10-Jun-04	1	1. Minor cracking. 2. Water leaching.
		23-Jun-09	3	1. Severe horizontal cracking. 2. Separation gap between units.
		3-May-17	3	1. Severe transverse cracking. 2. Separation gap between units. 3. Settlement noted. 4. Spalling with exposed reinforcement at joints.
14	27460	22-May-03	2	1. Moisture leaching through joints. 2. Differential settlement.
		8-Dec-08	3	1. Separated gap between units. Backfill starting to escape. 2. Differential settlement.
15	34333	14-Mar-08	2	1. Minor cracking. 2. Moderate build-up of silt though cell.
		27-Apr-17	3	1. Spalling with exposed reinforcement. 2. Minor transverse cracking. 3. Moderate vertical cracking. 4. Initial stage of spalling at joints.
16	38941	26-May-10	3	1. Moderate to severe horizontal cracking.
17	39800	2-May-17	3	Missing information for span 1. 1. Severe longitudinal cracking. 2. Minor horizontal/longitudinal cracking. 3. Drummy section. 4. Spalling with exposed reinforcement. 5. Moisture hold.
18	39816	21-Sep-17	3	1. Loss of grout between units. 2. Backfill escaping between joints. 3. Spalling with exposed reinforcement. 4. Minor horizontal cracking.
19	39830	21-Sep-17	3	1. Loss of grout between units. 2. Backfill escaping between joints. 3. Minor cracking.
20	42625	5-Aug-10	1	1. Loss of grout between units. 2. Minor cracking.
		29-Jun-17	3	1. Separation gap between units.
21	42641	27-Jul-10	3	1. Spalling with exposed reinforcement. 2. Minor-to-severe horizontal cracking. 3. Loss of grout between units. 4. Separation gap between units.
		22-Jun-17	3	1. Minor-to-severe horizontal/vertical cracking. 2. Spalling with exposed reinforcement. 3. Small lifting lug holes. 4. Joint deterioration.

22	42964	31-May-10	3	1. Exposed reinforcement at bottom of units due to loss of cover (wear off). 2. Spall with exposed reinforcement.

Structures in CS4 based on 80P components

No.	Structure ID	Date	CS	Defect identification
1	4836	14-Nov-01	4	1. Spalling with exposed reinforcement. 2. Invert silted.
		31-Jul-03	4	1. Spall with exposed reinforcement. 2. Severe crack.
		17-Jul-06	4	1. Spall with exposed reinforcement.
		15-Jul-09	4	1. Spall with exposed reinforcement. 2. Rotation of widening. 3. Joint fill loss.
2	19204	11-Nov-10	2	1. Spalling with exposed reinforcement. 2. Moderate cracks.
		5-Nov-15	4	1. Spalling with exposed reinforcement. 2. Severe cracks along the spans.
3	27858	5-Nov-02	3	1. Cracks noted. 2. Soil movement.
		9-Jun-04	1	No comment provided.
		23-May-09	2	No comment provided.
		2-May-17	4	1. Severe separation gap between units. 2. Void noted with loss of backfill. Crack noted at the road wearing surface. 3. Minor spalling. 4. Minor silt build-up.
4	31547	21-Jan-04	4	1. Severe cracks along the barrel length. 2. Vertical misalignment. 3. Separation gap between units.
		21-May-07	3	1. Minor-to-severe cracking along barrel length. 2. Rust stain noted.
		27-Apr-10	4	1. Minor-to-severe cracking along barrel length.
		27-Apr-17	4	1. Minor-to-severe longitudinal cracking.
5	41459	6-May-17	4	1. Severe spalling with exposed reinforcement. 2. 50% silt build-up.
6	52561	26-Jul-17	4	1. Severe transverse cracks. 2. Joint deterioration and separation. 3. Minor settlement. 4. Leaching at joints.

APPENDIX C COMPONENT-LEVEL HISTORICAL ANALYSIS

This appendix contains the dataset used for the investigation of component-level deterioration presented in Section 4.2.

C.1 First CS3/4 Record for Original Components with Earlier CS1/2 Records: All Defects

Structure ID	Comp. group no.	Construction date	Inspection date	CS	Time to CS (years)	L2 comment (provided unedited from BIS)
33127	1	18-Dec-2003	27-Oct-09	CS3	5	Pc2-out of alignment 15 mm at top & photo 3. Pc1-6 joint gaps of up to 38 mm & photo 4.
33127	2	18-Dec-2003	27-Oct-09	CS3	5	Pc1-6-Joint gaps up to 46 mm (PC3) & photo 6. Pc3 & 4 & 5 out of alignment up to 18 mm (PC5) & photo 5.
33127	3	18-Dec-2003	27-Oct-09	CS3	5	Pc1-6 have joint gaps of up to 39 mm (Pc1). Pc5- out of alignment 14 mm.
18662	3	05-Nov-1999	22-Jul-09	CS3	9	Cells 2& 3 & 8 have Minor Spalling with Steel Exposed at Top at E1. Steel requires cleaning& coating & patching.
18662	4	05-Nov-1999	22-Jul-09	CS3	9	PC 8 has Minor Spalling with Steel Exposed at Top of E1& requires cleaning& coating & patching.
25884	1	02-Apr-2002	4-May-12	CS3	10	Misaligned on PC2 up to 40 mm @ top& photo 3. PC10 & PC11 soil intrusion on face 2& photo 4.
41456	3	27-Apr-2006	8-Jun-16	CS4	10	#010 - PC2 - large crack where area is going to fall out (approx 0.5 m2). #011 - PC8 - large drummy area to repair (approx 1 m2).
41456	4	27-Apr-2006	8-Jun-16	CS3	10	#012 - PC8 - drummy section to repair - approx 0.5 m2. #013 - PC6 - spall / reo to repair - approx 0.5 m2.
25230	1	18-Jan-2002	29-Oct-13	CS3	11	13x Cells at 1950 mm. Cell 13 Has crack to 5 mm on E2 of Wall 1 - (Photo 004) - Requires sealing - Also on cell 13 - spall with steel exposed at E2 - base (Photo 005) - Requires steel cleared & coated & spall patched. Unit 11& 12 & 13 have H/L to 0.1 mm shrinkage cracks at top of Wall 2 & Roof No mortar between Units (Photo 007).
31937	6	01-Jan-2000	7-Jul-11	CS3	11	Joints between units have been sealed with Plywood& plywood is now rotting. Cell 6 consists of 12X2.4 m long units& 1700 internal diameter. #022&023&024
23242	1	08-Dec-2000	18-Nov-15	CS3	14	10x Pre Cast PC Units 2100 mm in diam. 4.8 LinM CS3 Due to Moderate Settlement at E1 / Outlet of PC Units 1 & 2 (Photo 006 & 007)& Settlement has Caused Spalling with Steel Exposed in Ends of PC Units 1& 2 & 3 Join (Photo 008& 009& 010& 011 & 012)& No signs of Loss of Backfill between PC Units& Minor Settlement visible in LHS of CW above - Settlement requires Monitoring& Spalling with Steel Exposed requires Cleaning Coating & Patching. H/L to 0.3mm Cracks appearing at Various locations throughout Bases & Tops of PC Units 3& 4& 5& 6& 7& 8 & 9 (Photo 013 & 014) - Monitor.

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23967	1	26-Sep-2000	1-Dec-14	CS3	14	33x 2450mm Diameter RCP. 0.1 LinM CS3 Due to Unit 31 having Spall with steel exposed in Base (Photo 007) - requires Cleaning& Coating & Patching. Unit 32 has spall in E2 Wall 500mm up from base No steel exposed - Monitor. No Grout Seal between Units at Joins possibly allowing Backfill to Escape (Photo 005 & 006) - Seal requires Installing between All Units.
23967	2	26-Sep-2000	1-Dec-14	CS3	14	0.1 LinM CS3 Due to PC unit 32 having Spall with steel exposed at E1 join refer (Photo 007) - requires Cleaning& Coating & Patching. PC unit 33 has Spalling in roof at E1 join& No steel Exposed - Monitor. No Grout Seal between Units at Joins possibly allowing Backfill to Escape (Photo 012) - Seal requires Installing between All Units.
23967	3	26-Sep-2000	1-Dec-14	CS3	14	0.2 LinM CS3 Due to PC Unit 20 having spall with steel exposed in roof & Unit 32 having spall with steel exposed in E1 Wall refer (Photo 007) - Both require Cleaning& Coating & Patching. No Grout Seal between Units at Joins possibly allowing Backfill to Escape (Photo 009& 010 & 011) - Seal requires Installing between All Units.
24407	1	26-Sep-2000	1-Dec-14	CS3	14	12 x 1950mm RCP Units refer (Photo 001). 0.1 Linm CS3 Due to Spalling with Steel Exposed in PC3 at E2 (Photo 003 & 004) - Steel requires Cleaing& Coating & Patching. Grout Seal Missing between All PC Units at Joins& Joins between Various Units have Roots Growing through Gap (Photo 005) & signs of Silt leeching through Gap (Photo 002) - Grout Seal requires Installing.
32597	8	31-May-1998	25-Oct-12	CS4	14	PC2-Cracking to 2.1mm in top along E1 edge (possibly from construction). (repair with cement grout)
23596	2	17-Jan-2000	4-Feb-15	CS3	15	0.1 LinM CS3 Due to Spalling with Steel Exposed around Lifting Hole in Top of Unit 10 (Photo 004) - requires Cleaning& Coating & Patching. H/L to 0.3mm Cracks in Roof of Various PC Units (Photo 003) - Monitor. Grout Seal at Join Missing between All PC Units& possibly allowing Backfill to Escape (Photo 005) - Seal requires Installing between All PC Units.
27452	1	01-May-1989	28-Apr-05	CS3	15	O/S1/PC& consists of 16 x 1800 Rcp's with 15 to 25mm gaps in all pipe joints not grouted& [photo 6]. View looking through cell showing join of 1800mm pipe to 1740mm pipe& (Photo005).
27452	2	01-May-1989	28-Apr-05	CS3	15	Simular condition to O/S1/PC.
27452	3	01-May-1989	28-Apr-05	CS3	15	Simular condition to O/S1/PC.
27452	4	01-May-1989	28-Apr-05	CS3	15	Simular condition to O/S1/PC.
9035	3	25-Jul-1989	19-Sep-07	CS3	18	UNIT 4 0.4MM CRACKING UNIT 5 0.7MM CRACKING
26014	2	30-Jun-1990	23-Jun-09	CS3	18	PC1-Cs3&Horizontal cracking to CW 0.6mm in roof& photo 6 PC3-Cs3&horizontal cracking to CW 0.6mm in roof. photo 7 PC5-Cs3&separation gap width to 32mm.
27460	1	01-Feb-1990	8-Dec-08	CS3	18	Units 6 and 7 have separated and dropped (Approx 15-20mm).(Monitor)#006 #007

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27460	2	01-Feb-1990	8-Dec-08	CS3	18	Units 6 and 7 have separated and dropped (Approx 15-20mm) (Monitor)#008 #009
27460	3	01-Feb-1990	8-Dec-08	CS3	18	Units 6 and 7 have separated and dropped (Approx 20-30mm) and fill has started to come through separation (Monitor)#010 #011
27460	4	01-Feb-1990	8-Dec-08	CS3	18	Units 6 and 7 have separated and dropped (Approx 15-20mm).(Monitor)#012 #013
27460	5	01-Feb-1990	8-Dec-08	CS3	18	Units 6 and 7 have separated and dropped (Approx 15-20mm) (Monitor)#014
27460	6	01-Feb-1990	8-Dec-08	CS3	18	Units 1 and 2-/-6 and 7 have separated and dropped (Approx 20-30mm) and fill has started to come through separation. Unit 7 has a previous repair which is starting to crack and spall again.(Monitor)#015
27460	7	01-Feb-1990	8-Dec-08	CS3	18	Units 6 and 7 have separated and dropped (Approx 20-30mm) and fill has started to come through separation (Monitor)#016
27460	8	01-Feb-1990	8-Dec-08	CS3	18	Units 6 and 7 have separated and dropped (Approx 15-20mm) (Monitor)
23457	3	06-Oct-1989	2-Jun-10	CS4	20	PC1- horizontal cracking to Cw 0.2mm. PC2- vertical crack E1 to 2mm & horizontal to 0.3mm. PC3- PC12- horizontal cracking to Cw 0.1mm.
19242	1	28-Feb-1994	28-Aug-17	CS3	23	*5 x Units @ 1800mm Diameter -RA bolted to top of Unit 5 & into HW to prevent movement of PC`s (Photo 009) *CS3 *Unit 1 has 3 x minor spalls with steel exposed at E1(Photo 004) -requires steel cleaned & coated & spalls patched *CS4 *Gaps between all Units range from 25mm to 50mm (Photo`s 005 & 006 & 007) -gaps require filling with cement grout *Unit 5 has severe cracks & spalling with steel exposed at E1 of roof (Photo 008) -requires 2 x Lin M of cracks sealed & steel cleaned & coated & spalls patched
19242	2	28-Feb-1994	28-Aug-17	CS4	23	*CS4 *Gap to 87mm between Units 4 & 5 with minor loss of backfill through gap (Photo 010) -requires cement grout to fill gap *Minor spall with steel exposed at E1 of Unit 1 (Photo 011) -requires steel; cleaned & coated & spall patched -Maintenance backlog created -RA bolted to top of Unit 5 & into HW to prevent movement of PC`s (refer to Photo 009)
19242	3	28-Feb-1994	28-Aug-17	CS4	23	*CS3 *E1 of Unit 1 has moderate spall with steel exposed (Photo 013) -requires steel cut away & spall patched *CS4 *Gap to 57mm between Units 4 & 5 with void to 100mm deep above PC (Photo 014) -requires gap & void filled with cement grout *Minor crack to 0.3mm along top of Leg 1 in Unit 5 (Photo 015) -marked for future inspections -RA bolted to top of Unit 5 & into HW to prevent movement of PC`s (Photo 009)

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19242	4	28-Feb-1994	28-Aug-17	CS4	23	*Gap to 60mm between Units 1 & 2 with void to 100mm deep above PC (Photo 016) -& gap to 82mm between Units 4 & 5 (Photo 017) with void to 160mm above PC (Photo 018) -requires gaps & voids filled with cement grout & RA bolted to top of Unit 5 & into HW to prevent further movement -No RA on top (refer to Photo 012)
21793	2	30-Jun-1985	16-Nov-10	CS3	25	PC6-CS3& large spalled area E1 side 1. Photo 7. PC1& PC2 and PC6 horizontal cracking to CW 0.35mm. Gaps at joins up to 24mm.
32602	2	01-Jan-1989	9-Apr-14	CS3	25	*CS3* * Unit 8 has Spall with steel exposed at E1 of Roof (Photo 010) -requires steel cleaned & coated & spall patched *Unit 11 has spall lwith steel exposed at E1 of base (Photo 011) -requires steel cleaned & coated & spall patched *Grout missing & large gap between Units 13 & 14 (Photo 012) -requires grouting. *CS2* *Unit 14 has H/L to 0.1mm cracks on Wall 2 (Photo 013) -marked & dated for future Inspections
34345	3	01-Jan-1985	15-Jan-10	CS3	25	p.c unit 8 spalling at base with reo exposed #&
24489	2	08-Oct-1986	18-Sep-13	CS3	26	Spall with exposed reo in PC1 (13_05). Minor crack in PC1. Large spall with exposed reo on side 1 of PC1 (13_06).
26003	1	30-Jun-1979	7-Jul-05	CS3	26	regrout all joints
26017	3	01-Dec-1979	7-Feb-08	CS3	28	unit 4 cs3 2mm cracking at base 2.1mm cracking at top.. units 5-8 cs2
27554	1	01-May-1980	6-Oct-08	CS3	28	Water washing through pipe and starting to deteriorating the grout in various joins. Monitor for further deterioration.
27554	2	01-May-1980	6-Oct-08	CS3	28	Water washing to bottom of Pipe and starting to deteriorate grout in joins of various units allowing water to penetrate through.(#008)
27554	3	01-May-1980	6-Oct-08	CS3	28	Water washing to bottom of Pipe and starting to deteriorate grout in joins of various units allowing water to penetrate through.
27554	5	01-May-1980	6-Oct-08	CS3	28	Water washing to bottom of Pipe and starting to deteriorate grout in joins of various units allowing water to penetrate through.
33048	2	01-Jan-1982	9-Feb-10	CS3	28	Minor spalling in unit1 on RH end. Unit 13 repair failing and moisture seeping through.Concrete over pour below failing repair.#019.
22883	1	17-Nov-1972	17-Apr-03	CS3	30	Severe cracking PC1 cw15mm at Abutment 1 side. Grout with high build mortar.
25500	1	30-Jun-1973	16-Oct-03	CS3	30	The pipes have droped out of alignment by about 30 mm with gaps between units of over 40 mm. This should be monitored.
25500	2	30-Jun-1973	16-Oct-03	CS3	30	The pipes have droped out of alignment by about 30 mm with gaps between units of over 40 mm. This should be monitored.

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32604	3	14-Apr-1978	18-Dec-08	CS4	30	Minor moisture leakage with slight misalignment at joins in units& all joins have been mortored. Severe spalling in soffits of units 11& and 12 at join& all reo exposed and bent and severely rusted#010&#011& #012
22885	5	17-Nov-1972	18-May-04	CS3	31	Exposed reinforcing in invert. Pipe 5. Photo 14. Repair.
41670	1	01-Jul-1985	6-May-17	CS3	31	Unit 1- E1-1.0mm crack outside edge in mortar repair. Photo#005 Monitor
41670	2	01-Jul-1985	6-May-17	CS4	31	Unit 1-E1-minor spall exposed reo& no loss to reo. Unit 7-E2-moderate spall exposed reo&100% loss of section. 900mm x 150mm x 150mm. Photo #006 Cs4 Replace reinforcing Cleaning and Priming Reinforcement Reinstate repair area with concrete
18628	2	01-Jan-1977	17-Jul-09	CS3	32	PC1 & PC2 are Seperating due to a Tree Root at Base (Photo 003). PC3 & PC4 have Cracking in Base requiring Sealing. Also Grout is Missing between All PC's & requires Replacing. All Cells have Ripples in Base caused from Steel bring to Close to Surface (Monitor)
18628	5	01-Jan-1977	17-Jul-09	CS3	32	PC3& PC4 & PC7 have Spalling with Steel Exposed in Base at E1. PC2 E2 in Roof also has Spalling with Steel Exposed. All requires cleaning& coating & patching. PC5 has Moderate Cracking to 3mm Full length of Base requiring Sealing. Also Grout is Missing between All PC's & requires Replacing. PC5 & PC6 have Minor Cracks in Roof which have been Marked & Dated for Future Reference.
18628	6	01-Jan-1977	17-Jul-09	CS3	32	PC3 E2& PC5 E1 & E2& PC6 E1 & MS All have Spalling with Steel Exposed in Bases requiring cleaning& coating & patching. PC5 has Crack to 3mm Full Length of Base requiring Sealing. Also Grout is Missing between All PC's & requires Replacing. PC5 (Photo 010)
32612	1	31-Dec-1984	25-Sep-17	CS3	32	- Pipe 4 side 1 has a 0.3mm horizontal crack& Ph 00003& recommend sealing with a cement grout& approximately 3 Lin/m.
25676	1	31-May-1972	4-Apr-06	CS3	33	Cell 9 settled (photo 1)
16278	1	01-Oct-1971	30-Sep-07	CS3	35	UNIT 3& 4 HAVE 0.6MM & 0.4MM CRACKING RESPECTIVELY& OTHERS HAVE MINOR CRACKING
22862	1	27-Jul-1973	29-May-09	CS4	35	Unit 3 has 0.9mm cracking in soffit& # 3 and 1mm cracking in base& # 2.
26013	2	01-Apr-1982	8-Jun-17	CS3	35	Minor spalling with exposed reo on Unit 5 Face 2 - 100mm x 20mm. Minor spalling with exposed reo on Unit 5 Face 2 at E2 - 600mm x 160mm. Photo #006. Minor spalling with exposed reo on Unit 6 Face 2 E1 - 200mm x 90mm. Photo #007. Monitor all spalls at this stage. Minor water over floor.
27577	1	01-Aug-1973	16-May-09	CS3	35	Unit 8 has a moderate crack 0.6mm in pipe soffit about 600mm long.#004 Sketch #001 Some grout loss between units may be due to Minor misalignments of unit.

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27577	2	01-Aug-1973	16-May-09	CS4	35	Severe crack in pipe soffit unit 8 up to 1mm.#009&#010 Sketch #001 Some grout loss between units may be due to Minor misalignments of unit. Minor spalling to lift holes in various units.
34333	1	30-Dec-1980	27-Apr-17	CS3	36	PC3& 4 & 8 -Cs3& areas of spalling /exposed reo at joints E2& photos 4-6 . (treat steel/ repair with nonocrete) All remaining have cracking & starting to spall at joints& photo 7 indicative. Minor transverse cracking in PC4& 5 & 6 <0.1mm.
34333	2	30-Dec-1980	27-Apr-17	CS3	36	PC4& 5 & 8 -Cs3& areas of spalling /exposed reo at joints& photos 9-11 . (treat steel/ repair with nonocrete)PC8 -has 2 vertical cracks to Cw 0.5mm& photo 13 All remaining have cracking & starting to spall at joints& photo 12 indicative.
12831	1	20-May-1966	20-Jan-04	CS3	37	There is some cracking around one of the joints with some signs of soil and rust leaching out of the joint. This can be seen in Photo 5.
26017	1	01-Dec-1979	3-May-17	CS3	37	Transverse cracking in PC1 - Cw 0.8mm - PC4 - cracking to 1.0mm & spalling & exposed reo at joint E2 - PC6 - Cracking to 0.7mm . photo 7-10. (seal with chemical grout/ treat steel/repair with nanocrete) PC2& 5 & 7 -Minor transverse cracking to Cw <0.3mm.
26017	2	01-Dec-1979	3-May-17	CS3	37	Transverse cracking in PC1 - Cw 0.6mm - PC7 - Cw 0.8mm - PC8 - Cw 0.7mm . photo 11-13. PC5 - minor transverse cracking to Cw 0.2mm and spalling at joint E2& photo 14. (seal with chemical grout/ treat steel/repair with nanocrete)
32609	1	29-Mar-1976	8-Apr-14	CS3	38	Length of Span has been changed since previous Inspections -Dates stamped into PC`s confirm New length - 1964 dated in S2 Unit 8. *Unit 1 has spall with steel exposed at E1 base (Photo 008)-requires steel cleaned & coated & spall patched *Unit 1 also has rust stains leaching through on Wall 2 due to lack of cover over steel (Photo 009) *Unit 2 has spalls with steel exposed on Wall 2 (Photo 010)-requires steel cleaned & coated & spalls patched *Unit 6 has spalls with steel exposed at E2 base (Photo 011)-requires steel cleaned & coated & spalls patched *Unit 9 has spall with steel exposed at E2 base (Photo 012)-requires steel cleaned & coated & spall patched
32609	2	29-Mar-1976	8-Apr-14	CS3	38	*Unit 2 has spall with steel exposed at E2 of Wall 2 (Photo 022) -requires steel cleaned & coated & spalls patched *Unit 4 has spall with steel exposed at E1 of Wall 2 (Photo 023) -requires steel cleaned & coated & spall patched *Unit 5 has failing patch on Wall 1 with Spalling & exposed steel (Photo 024) -requires steel cleaned & coated & spalls patched *Unit 5 also has steel close to surface along base due to lack of cover (Photo 025) *Unit 9 has spall with steel exposed at E2 of Wall 2 (Photo 026) -requires steel cleaned & coated & spall patched *Date on Unit 8 roof-- 1964 (Photo 051)

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32609	3	29-Mar-1976	8-Apr-14	CS3	38	Unit 2 has spalling with steel exposed at lower section on Wall 2 due to lack of cover (Photo 034)-requires steel cleaned & coated & spall patched
32609	4	29-Mar-1976	8-Apr-14	CS3	38	*CS3* * UNit 3 has spall with steel exposed on Wall 2 (Photo 041) -requires steel cleaned & coated & spalls patched *Unit 4 has Spall with steel exposed at E1 of Wall 1 (Photo 042) -requires steel cleaned & coated & spalls patched *Unit 5 has spall with steel exposed at E1 base (Photo 043) -requires steel cleaned & coated & spall patched * Unit 8 has spall with steel exposed at E1 of Wall 1 (Photo 044) & Spall with steel exposed at E1 of Wall 2 (Photo 045) -requires steel cleaned & coated & spalls patched *Unit 9 has spall with steel exposed at E1 of Roof (Photo 046) & Spall with steel exposed at E2 of Wall 2 (Photo 047) -requires steel cleaned & coated & spalls patched *CS2* *Moisture leaking between Units 1 & 2 in Roof (Photo 040)
31934	2	01-Jan-1970	15-Jun-09	CS3	39	0.5 - 0.6mm horizontal crack& full length of unit 3& adjacent to drainage pipe entry point. #011&012
33982	4	01-Apr-1970	25-Mar-10	CS4	39	* Small Voids are appearing mid way up the pipe at joins 5 & 6 inside the concrete pipe with some breakage of concrete (Photo 006& 007& 008& 009& 010& 011). The Back fill behind the Pipe appears to be stable with only minor loss& Voids require filling with grout & pipe patched. * Cell 1 has some minor cracks appearing on A2 side of the pipe (Photo004) (Monitor). * Each cell have gaps appearing between the pipe joins any where from 25mm to 40mm in the lower invert & 15mm to 25mm in the top section of the pipe due to poor placement during Construction the alignment of the Pipe is still Sound (Photo 005). * Maintenances to the Gaps in the lower invert require filling with grout to stop water under mining the pipe.
4363	1	01-Jan-1971	7-Dec-11	CS3	40	Edge spalling at unit joins #002& spalling on bottom of units 4+6 due to lack of cover <10mm #003. Spalling in top of unit 2 (CS3) around lifting hole& reinforcement deteriorated approx. 20% #004& L400mm x 500mm W x D15mm.
4363	2	01-Jan-1971	7-Dec-11	CS3	40	Edge spalling at unit joins. Minor spall in top of unit 1 around lifting point. Edge spall bottom E1 of unit 7 (CS3) with reinforcement loss of approx. 20% W 300mm x L 1200mm x D 40mm #009. Spalling at E2/unit 7 in floor L 900mm x W 50mm x D 20mm #010.
4836	2	23-Jul-1963	31-Jul-03	CS4	40	Pipe 1 has a 1mm crack in wall see photo 9. Pipe 4 has a 0.6mm crack in wall see photo 8.
24339	4	31-Dec-1976	16-May-17	CS3	40	PC5 - transverse cracking Cw 0.4mm. photo 5. (monitor) PC1 -minor tranverse cracking to Cw 0.1mm. Minor separation at joints and loose grout& photo 6 & 9 indicative.
22885	6	17-Nov-1972	26-May-14	CS3	41	UNIT 2 SPALLING AND EXPOSED REO 400MM X 50MM PH011 AND MINOR WATER WEAR (O)

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23373	1	01-Jan-1968	15-Jul-09	CS3	41	Cell 4 has 2 Sections of Spalling in Base both with Steel Exposed (Photo 002 & 003). Cell 6 also has Spalling with Steel Exposed. All require Steel Cleaned & Coated with Protective Coating & Patched. Also there is No Grout Sealant between All Cells& requires Grouting& Refer to (Photo 002& 003& 005 006 & 007).
23373	2	01-Jan-1968	15-Jul-09	CS3	41	Cell 1 has Cracks appearing on Both Wall up to 0.5mm marked & dated for monitoring. Cell 2& Cell 3 & Cell 6 have Spalling with Steel Exposed in Base. All require Steel Cleaned& Coated & Patched. Cell 2 (Photo 005) & Cell 3 (Photo 006). There is No Grout Sealant between Joins in All Cells& All require Grouting& Refer to (Photo 002& 003& 005 006 & 007).
23373	3	01-Jan-1968	15-Jul-09	CS3	41	Cell 2& Cell 3 & Cell 6 have Spalling with Steel Exposed in Base. Cell 2 (Photo 007). Cell 5 has Spalling with Steel Exposed at Base (Photo 008) & on LH Wall (Photo 009). All Spalling requires Cleaning& Coating & Patching. Also there is No Grout Sealant between Joins in All Cells& All require Grouting& Refer to (Photo 002& 003& 005 006 & 007).
23373	4	01-Jan-1968	15-Jul-09	CS3	41	Cell 1 LHS Base & Cell 8 RHS Base have Minor Spalling with Steel Exposed. Requires Cleaning& Coating & Patching. Also there is No Grout Sealant between Joins in All Cells& All require Grouting& Refer to (Photo 002& 003& 005 006 & 007).
24360	2	26-Aug-1975	30-May-17	CS3	41	PC3 -has 500mm2 area of spalling/exposed in base E1& photo 7 (repair with nanocrete) PC1- had some repairs to spalling E2 leg 1 & photo 8 (needs further repair) Leaching at all joints& photo 6 & 10. indicative.
24360	3	26-Aug-1975	30-May-17	CS3	41	PC3 -has 500mm2 area of spalling/exposed in base E1& photo 9 (repair with nanocrete) Leaching at all joints& photo 6 & 10. indicative
24360	4	26-Aug-1975	30-May-17	CS3	41	PC1& 2 & 4 -has 500mm2 area of spalling/exposed in base E1& photos 12 -14 (repair with nanocrete) PC2& 5& 8 & 9 - minor trnsverse cracking to Cw 0.15mm. photo 11 indicative. Leaching at all joints& photo 6 & 10. indicative
33407	1	01-Jan-1968	8-Jul-09	CS4	41	Unit 1 has sever vertial cracking of 1.0mm 3/4 of PC . Refer to sketch 1. Minor loss of grout missing between various units with no scouring evident. Horizontal HL cracking evident in various units.
33407	3	01-Jan-1968	8-Jul-09	CS3	41	Moderate horizontal crack of 0.4mm in unit 2 leg 2. Minor horizontal cracks through various units. Minor loss of grout missing between various units with no scouring evident.
25676	2	31-May-1972	28-Mar-17	CS4	44	50mm separation between units 2-3 loss of fill evident void behind units. refer to photo #005 - lay tingling& seal gap between culvert elements& reinstate fill.
27565	1	01-Jul-1962	4-Feb-09	CS3	46	25 to 50mm seperation at join in pipes with backfill visible between O/S1/PC& and WR1/S1/PC.#006.
27565	2	01-Jul-1962	4-Feb-09	CS3	46	25 to 50mm seperation at join in pipes with backfill visible between O/S2/PC& and WR1/S2/PC #010

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27565	3	01-Jul-1962	4-Feb-09	CS3	46	Up to 40mm seperation at join in pipes with backfill visible between O/S3/PC& and WR1/S3/PC.#013. Seperation requires grouting with a approved grout.
17826	1	01-Jan-1956	19-Mar-03	CS3	47	UNIT 4 (RHS) 1mm CRACK AT TOP OF PIPE.
17826	2	01-Jan-1956	19-Mar-03	CS3	47	UNITS 2&3&4 HAVE 0.2 CRACK IN TOP HALF OF PIPES.
23323	1	29-Mar-1962	26-May-10	CS3	48	Horizontal cracking PC1 & PC3 to Cw 0.2mm& 500 long. PC4 cracking to Cw 0.4mm and PC5 to 0.3mm. (All in top A2 side). Photo 4.
23323	2	29-Mar-1962	26-May-10	CS4	48	PC2-Cs2&Horizontal cracking to Cw 0.1mm. PC3-Cs4&cracking to Cw 0.7mm at top A2 side.Photo 3. PC4-Cs2& cracking to Cw 0.1mm and PC5 to 0.2mm at top A2 side.
26018	1	30-Dec-1960	23-Jun-09	CS3	48	PC5-Cs3&lifting to 25mm & separating at joint gap 42mm&photo 4. PC1 & 3&horizontal cracking to CW 0.3mm&photo 3.
26018	2	30-Dec-1960	23-Jun-09	CS3	48	PC5-Cs3&horizontal cracking to CW 0.3mm & separating at joint to gap width 39mm at top&photo 5.
22778	5	09-Feb-1968	3-May-17	CS3	49	#007 - PC1 and PC2 impact damage (montior).
22783	1	09-Feb-1968	3-May-17	CS3	49	#004 shows minor spalled section with exposed reo (reinstate 300mm2 section) #005 shows approx 100mm seperation between WL1 & O. (monitor for change) *Fabric behind pipes still intact preventing loss of material.
23409	1	31-Dec-1967	23-Mar-17	CS4	49	PC2-7 -Minor transverse cracking to Cw 0.2mm.photo 6 PC7- Cs3& area of spalling/exposed reo at top& photo 5 . (treat steel/repair with nanocrete)
23409	3	31-Dec-1967	23-Mar-17	CS4	49	Minor transverse cracking rhs in PC1& 2& 3& 5 & 6 to Cw 0.2mm& photo 6 typical. PC6 - spalling in invert on very end E2 -some corrosion stains visible& photo 7.(repair with nanocrete)
23409	4	31-Dec-1967	23-Mar-17	CS3	49	PC1 - has transverse cracking lhs to Cw 0.6mm. photo 8. (monitor) PC6 -Cs3 &cracking in invert to 1mm and spalling on E1& photo 9. (repair with nanocrete) All have transverse cracking to Cw 0.3mm.
23415	1	31-Dec-1967	28-Mar-17	CS3	49	PC1 -minor cracking at top rhs to Cw 0.4mm. PC2 & 3 - cracking along invert to 1.5mm& photos 6 & 7.(monitor/repair with cement/chemical grout)
24816	1	31-Dec-1961	31-Mar-11	CS4	49	PC6 - horizontal crack in leg 2 at bottom to 2mm minor horizontal cracking in PC2 - PC7. Spalling& exposed reo at joints PC5& 6 and 8. Minor separation of PC throughout. Photos 8& 9 and 10.(seal cracks & gaps with cement grout)
24816	2	31-Dec-1961	31-Mar-11	CS4	49	38mm separation & 20mm settlement between PC1 and PC2. Spalling at joints PC2 and PC6& minor separation of PC's to 25mm& minor horizontal cracking in PC3& 4 and 5. Photos 11 and 12.
1260	5	01-Jan-1961	22-Aug-13	CS3	52	Water seepage between PC1 & 2 & Photo 10. (grout gap)
3195	1	01-Jan-1961	28-Nov-16	CS3	55	Some joins spalling ph77 & 78& Fix- reinstate .5m2 of concrete mortar at joins with programmed maintenance prior to next inspection.

Structure ID	Comp. group no.	Construction date	Inspection date	CS	Time to CS (years)	L2 comment (provided unedited from BIS)
24819	1	31-Dec-1961	6-Apr-17	CS3	55	PC2 -Cs3& spalling & exposed reo at joints both ends& photo 5 & 6.(treat steel/repair with nanocrete) PC3& 4 & 5 -fine transverse cracking to Cw 0.1mm& photo 7. Minor joint separation and loss of grout at all joints.
33558	1	01-Jan-1961	10-Jul-17	CS3	56	10mm gap in all joins ph03& Fix- fill all gaps with concrete mortar with programmed maintenance prior to next inspection.
33558	2	01-Jan-1961	10-Jul-17	CS3	56	10mm gap in all joins ph07& Fix- fill all gaps with concrete mortar with programmed maintenance prior to next inspection.
24635	1	01-Jan-1950	14-Jun-07	CS3	57	Pipe holding water. Also large sag in alignment. refer to photo #7_07.
11209	2	01-Jan-1950	23-Jul-08	CS3	58	As per Span 1
11209	4	01-Jan-1950	23-Jul-08	CS3	58	As per Span 1
1432	4	01-Jan-1950	26-Jun-13	CS4	63	1 LinM CS4 Due to Spall in Base of PC10 at E1 allowing Backfill to Escape leaving Void behind PC (Photo 005 & 006) - Spall requires Patching & Sealing & Void Backfilled. Grout Joints between PC Units finshes half way up sides of PC leaving Gap at Top & Existing Grout showing signs of Decay& Wear &/or have Sections Missing - Joints require Replacing to Prevent Scouring of Earth behind PC units.. Due to Water Level Bases of PC Units & Joints could Not be Fully Inspected & require Monitoring.
1431	1	01-Jan-1950	10-Jun-15	CS4	65	1800 RCP (Photo 006). 0.2 LinM CS4 Due to Severe Cracking to 1mm in Top of PC8 at E2 & Spalling with Steel Exposed in Top of PC9 at E1 (Photo 009& 010 & 011) - Crack requires Sealing & Spalling with Steel Exposed require Cleanning& Coating & Patching. Mortar Joints between PC Units have Broken away Exposing Bacfill (Photo 012) - Joints require Replacing to Prevent Scouring behind PC Units. H/L to 0.3mm Shrinkage Cracks in Tops & Sides of Various PC Units throughout (Photo 008) - Monitor.
1431	2	01-Jan-1950	10-Jun-15	CS4	65	0.5 LinM CS4 Due to Spalling & Missing Seal with Void behind PC1 were Backfill has Escaped (Photo 022 & 023) & Spalling with Steel Exposed on Side of PC Unit (Photo 021) - Void requires Backfilling& Seal & Spall Patched & Spaaling with Steel Exposed requires Cleaning & Coating. Mortar Joints between PC Units have Broken away Exposing Bacfill refer (Photo 012) - Joints require Replacing to Prevent Scouring behind PC Units. Minor Shrinkage Cracks in PC4 refer (Photo 008) - Monitor.
1431	4	01-Jan-1950	10-Jun-15	CS4	65	0.2 LinM CS4 Due to Spalling at Base of PC Exposing Void upto 250mm Deep behind PC1 at E1 (Photo 017 & 018) - Void requires Backfilling & Spall Sealed. Mortar Joints between PC Units have Broken away Exposing Bacfill (Photo 015 & 016) - Joints require Replacing to Prevent Scouring behind PC Units. Join between Original & Widening PC Units has bee Sealed with Plastic Mesh Sacks at Top (Photo 014) & No signs of Loss of Backfill - Rubberised Sealant requires Installing.

Structure ID	Comp. group no.	Construction date	Inspection date	CS	Time to CS (years)	L2 comment (provided unedited from BIS)
34706	1	01-Jan-1950	20-Jan-15	CS4	65	*CS4* *Unit 5 has severe cracks to 3mm along base (Photo 009) *Unit 6 has severe cracks to 3mm along base (Photo 010) -Both Units require cleaning & thin layer of ACROM (Polyeurathane) to seal cracks *CS3* *Unit 2 has moderate cracks to 0.6mm along base (Photo 008) *Unit 7 has moderate cracks to 0.6mm along base (Photo 011) -both require cracks sealed *Unit 9 has minor spall with steel exposed at base (Photo 012) -requires steel cleaned & coated & spall patched *Pipes were not installed level during construction (Photo 013) Grout is missing from between Units (Photo`s 014 & 015) -requires new grout between Units *CS2* *Unit 1 has H/L to 0.1mm cracks along Wall 1(Photo 006) & along Wall 2 (Photo 007)-cracks are marked & dated for future Inspections
33722	1	01-Jan-1950	24-Aug-17	CS3	67	*CS3 *U/1 Leg 2 has longitudinal cracks to 0.4mm (Photo 011) -Monitor *U/1 Leg 1 has cracks to 0.2mm (Photo 010) *Unit 2 is half length Unit

C.2 Deterioration Time

Figure C 1: Time to CS3/4 for components with any type of defect

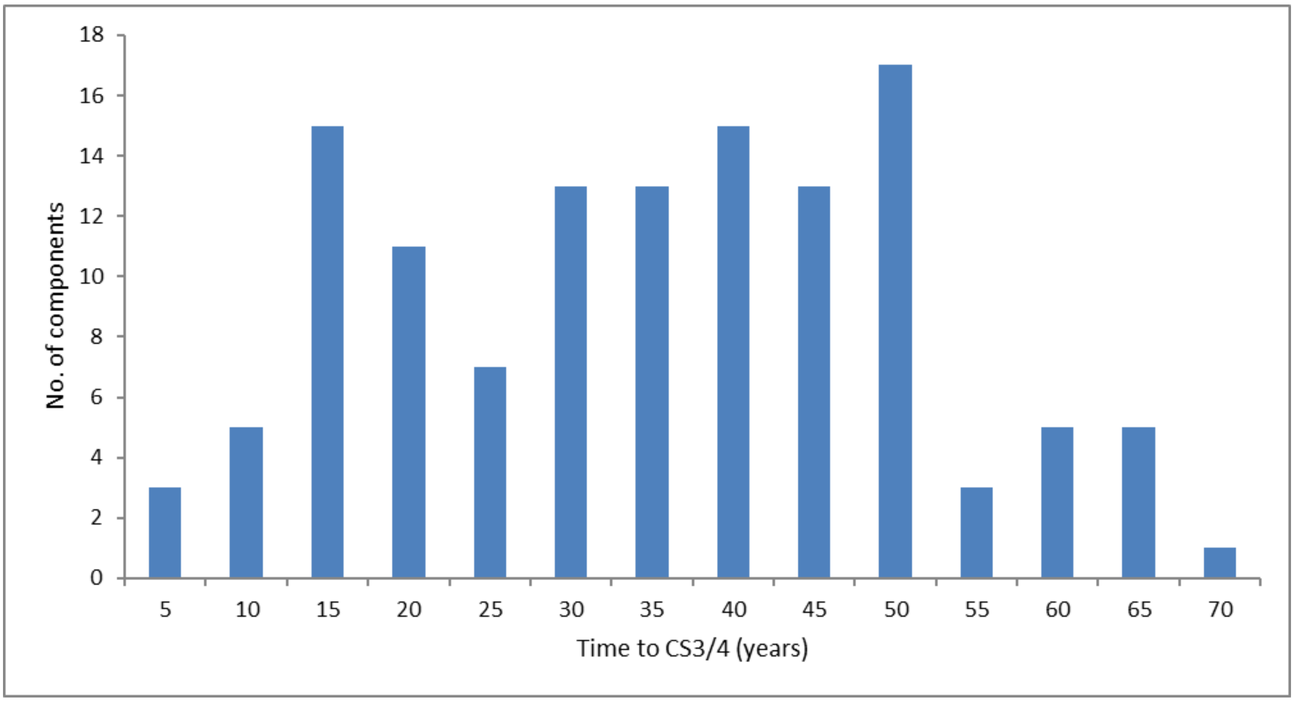


Figure C 2: Time from construction to most recent inspection – components which have never entered CS3/4

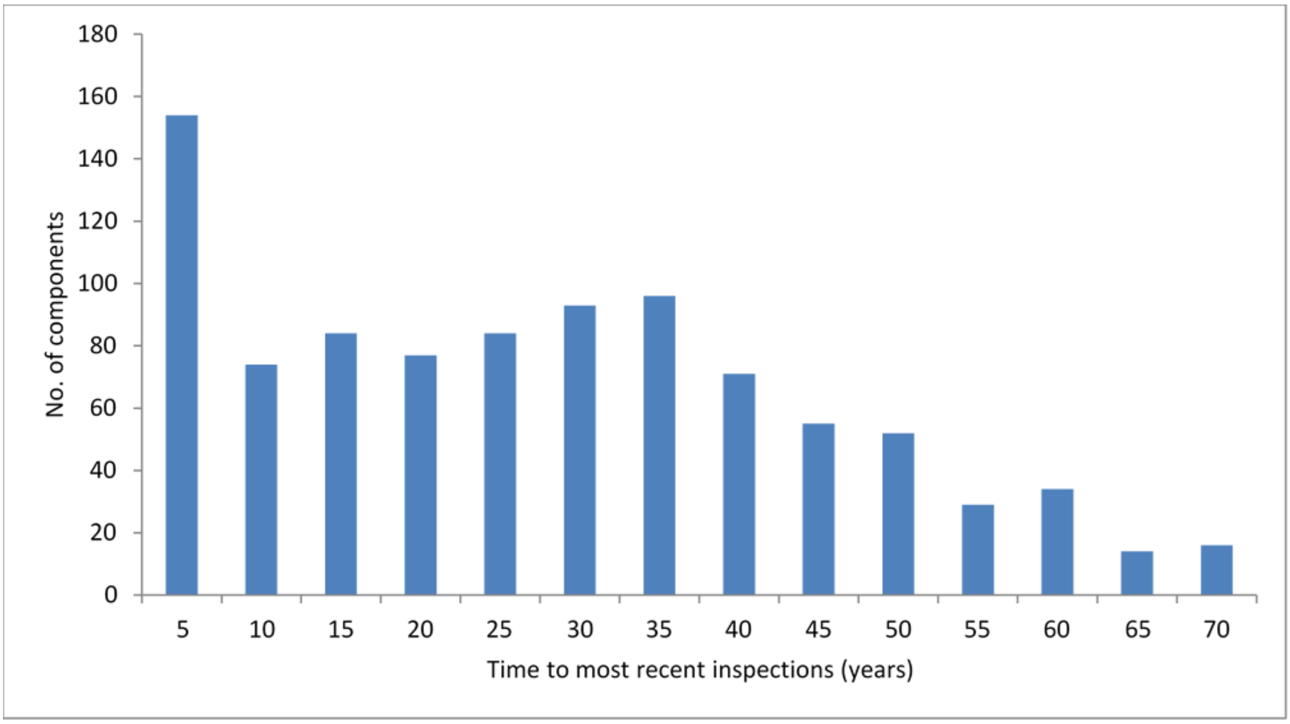
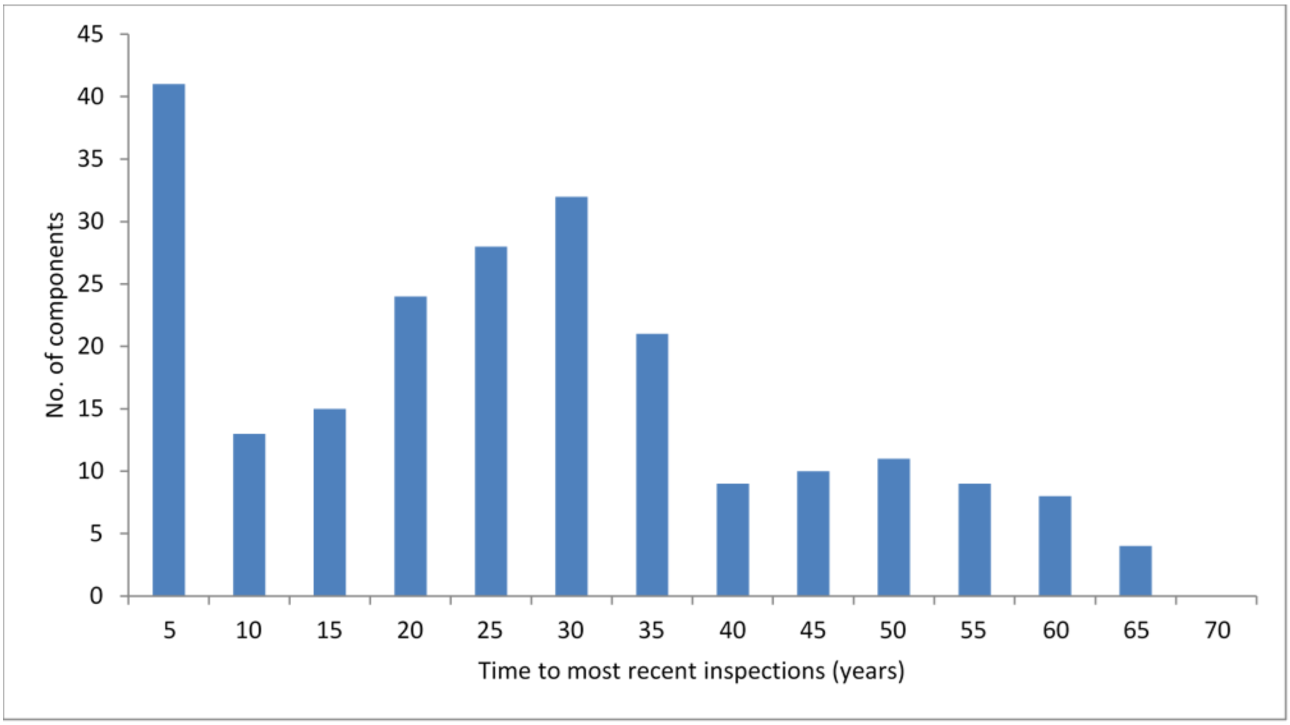


Figure C 3: Time from construction to first inspection for components which were placed in CS3/4 at the first inspection



APPENDIX D L2 INSPECTION RECORD REVIEW

This appendix contains the summary table of L2 inspection reports reviewed in Section 5 and provides detailed observations and findings pertaining to the review. In the summary table, the 'current rating' is based on the worst defect rating applied to any defect existing in the considered 80P component.

Table D 1: Review of L2 inspection records

Structure ID	District ID	Inspection date	Component group	Current rating	Suggested rating	Comment
1432	410	26-JUN-2013	S4	CS4		No issues with rating, CS4 spall is allowing fill to escape.
17826	405	28-AUG-2017	S1	CS2		0.1 mm longitudinal crack, possible rust staining around crack but appearance is likely due to other factors (photo #004).
18628	410	17-JUL-2009	S4	CS3	CS4	5 mm longitudinal crack full length of base should be CS4 based on SIM.
			S6	CS3	CS4	3 mm longitudinal crack full length of base should be CS4 based on SIM.
		25-OCT-2004	S1	CS3		Severe cracking reported, some photo evidence provided but further photos would be helpful.
19204	410	05-NOV-2015	S1	CS4		CS3 rated spall could be rated as CS4, component has been rated CS4 due to cracking.
		11-NOV-2010	All	CS3		Spalling defects are at joints with minimal exposed steel. CS3 rating is appropriate.
23967	410	01-DEC-2014	S1	CS3		No issues with ratings. Spalling defect is hard to make out in photo (#006).
27421	406	04-OCT-2017	S1	CS4		No issues with ratings, silt build-up prevents defect identification. Can assume previously identified cracking defects are still present.
		11-FEB-2008	S1	CS3		No images included, condition ratings given are mostly reasonable based on comments.
31654	406	15-NOV-2013	S2	CS4		No issue with ratings. Component is given CS3 rating in defective components report, likely a typing error.
			S3	CS3	CS4	2 mm crack should place component in CS4 based on SIM (photo #014).
		17-DEC-2008	S2	CS4		No issue with rating.
			S3	CS3	CS4	1 mm crack should be CS4 based on SIM (photo #018).
32597	404	27-AUG-2017	All	CS2		Only defects are in headwall/wingwall.
		25-OCT-2012	All	CS4/CS2		No issues with ratings.
32977	407	28-JUN-2017	All	CS2		All CS4 defects in headwall/apron. Gaps between cells are 10–25 mm wide. No loss of fill or retaining water reported so assume CS2 rating of PC units is appropriate.
		21-OCT-2008	All	CS4		No cracking defects. No photos provided but ratings appear to be reasonable based on comments.
34706	410	09-SEP-2017	S1	CS4		Unclear photos (#004, #006), hard to make out longitudinal cracking defects reported as severe. Photos which do show clear cracks also show markings of H/L and 0.1 mm (photo #005, #007).
		20-JAN-2015	S1	CS4		No issues with ratings.

Structure ID	District ID	Inspection date	Component group	Current rating	Suggested rating	Comment
39920	410	25-NOV-2015	S1	CS3	CS4	0.2 mm to 1.0 mm cracks are reported. Photos #010, #011 show the cracks are longitudinal and located in the soffit of the PC units.
		04-FEB-2015	S1	CS4		No issues with ratings.
		18-JUL-2013	S1	CS4		Overall fair rating. Some cracks are identified as 'shrinkage' cracks but are up to 1.0 mm in width (photos #009, #013, #014). CS4 longitudinal crack is in base.
43931	406	13-FEB-2013	All	CS4/CS3/CS2		No issues with ratings. Repairs noted for defects flagged in 2011 inspection.
		29-SEP-2011	All	CS4		No issues with ratings based on review of comments. Three PDFs which show cracking and defects in several components have not been provided. The structure is a confined space, so photos of cracks were likely not practical. It should be noted that the cracking defects have been flagged less than two years after construction.