University of Southern Queensland

Faculty of Health, Engineering & Sciences

Investigation of Culvert Failures During Extreme Flood Events

A dissertation submitted by

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Abstract

Culverts are vital pieces of road infrastructure which offer a cost-effective solution for providing road or rail crossings across natural creeks and drainage channels. This makes culverts vulnerable to damage or complete failure when discharges close to or greater than their operating capacity occur during extreme flood events. A culverts resilience to failure can be imperative in the immediate aftermath of such an event to allow effective disaster recovery to take place. Furthermore, long term social and financial consequences can result from subsequent road closures and repair works where extensive damage to road networks occur.

While some design guidelines do provide effective advice on improving the resilience of culverts subjected to extreme flood events, it is evident that this knowledge is not adopted in standard practice within many jurisdictions across Australia.

This project has identified the common failure mechanisms experienced by culverts during extreme flood events through data collected from a field investigation of damaged culverts in the Lake Hume region. Information from this field investigation has then been used to guide a numerical investigation aimed at identifying the main vulnerabilities of culverts in extreme flood scenarios and how these vulnerabilities can theoretically be overcome.

Based on observations from the field and numerical investigations, range of potential protection measures have been explored which would have the effect of increasing a culverts resilience to failure during an extreme flood event. Finally, a number of recommendations for improving the resilience of culverts subjected to extreme flood events have been proposed as well as potential avenues for future research in this field.

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I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

Philip Stahl

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Nomenclature

Symbol	Description	Units
c	Cohesion	Pa
D	Pipe diameter	m
d_{50}	Minimum rock size	mm
E	Modulus of elasticity	Pa
e	Void ratio	Dimensionless
g	Gravity constant	9.81 m/s^2
H	Height of road embankment	m
h	Height of material	m
K0	Horizontal stress ratio	Dimensionless
L	Length of rock protection	m
P	Hydrostatic pressure	Pa
S_0	Bed slope	Dimensionless
y	Depth of water	m
Δ	Displacement	m
ϵ	Strain	Dimensionless
ν	Poisson's ratio	Dimensionless
ρ	Density	kg/m^3
σ	Normal stress	Pa
τ	Shear strength	Pa
τ_b	Bed shear stress	Pa
$\emptyset$	Angle of internal friction	°

Glossary

CFD	Computational fluid dynamics
CMP	Corrugated metal pipe
FCR	Fine crushed rock
FEM	Finite element model
RCP	Reinforced concrete pipe
USDA	United States Department of Agriculture

Chapter 1

Introduction

A culvert is a hydraulic structure which allows water to pass underneath a roadway, railway, other structures or embankments without affecting their functionality. Culverts typically consist of a pipe or square section known as a box culvert overlayed with soil with the roadway or other structure built on top of the soil layer.

Culverts can have a single or multiple pipe or box sections placed side-by-side depending on its requirements. An example of a small culvert is a single small diameter pipe placed within a table drain to allow a driveway to be built over the drain such as the one shown in figure 1.1 below. Larger culverts are often used extensively in rural areas for creek and major drain crossings instead of elevated bridges due to their effectiveness and lower costs of construction and replacement (Cahoon, Baker & Carson 2002 p. 197).

Figure 1.1: A small driveway culvert.

Figure 1.2: A larger box culvert supporting a roadway (Dream Civil 2022).

Typically, culverts are designed to withstand a certain sized flood event and expected to overtop if this event is met or exceeded. A culvert can also overtop in smaller flood events if the flow through the culvert is blocked or severely restricted by trapped debris. When a culvert overtops, it is expected that it will cause major damage or complete failure of the structure and often requires extensive repairs or complete replacement of the overlaying roadway or railway.

If a culvert is damaged during a flood event as a result of a blockage or severe restriction of flow, the overall damage from the event is generally isolated to that culvert and the cost of repair work is manageable. However, when an extreme flood event occurs, it is common for multiple culverts within a network to sustain serious damage or fail completely. When this occurs, the overall cost of repairs as a result from the flood event can be massive and much more time is required to restore the road or rail networks to a safe operational condition.

An example of this is the major flood events which occurred in 2011 and 2013 in the Lockyer Valley region of southeast Queensland in which around 58% of floodways and culverts were damaged (Wahalathantri et al. 2016, p. 1).

Hudson et al. (2012) defines resilience as the ability to maintain functionality and return to normal following a harmful event. The need for infrastructure to be resilient when subjected to extreme natural events, particularly road infrastructure, has been well documented globally in many research papers.

It is widely accepted that road infrastructure plays an important role in modern society but is also highly vulnerable to a range of natural hazards. Thus, damage or destruction of road infrastructure can cause major disruptions and negative socioeconomic impacts (Argyroudis et al. 2019; Gajanayake et al. 2016).

It is argued that critical road infrastructure is not only an integral public asset for the day-to-day functionality of society but also crucial for disaster response and recovery following natural disasters such as extreme flood events (Oh et. al. 2010). Therefore, if the road infrastructure becomes badly damaged or destroyed during a natural disaster, the ability for authorities and members of the public to respond effectively to the disaster is hindered.

The resilience of this infrastructure can play a crucial role in evacuations or lifesaving efforts and this fact alone helps justify the need to develop more resilience in critical road infrastructure such as culverts to withstand the forces experienced during extreme flood events and to understand what factors can be employed to create more resilient structures.

1.1 Idea Initiation

The idea for this project came following heavy rainfall events across the east coast of Australia between November 2021 and January 2023 due to the effects of the La Nina climate pattern at the time. The increased rainfall led to various widespread flash flooding events throughout Queensland, New South Wales and Victoria.

These events devasted road infrastructure throughout these states resulting in time consuming and costly repairs for rural councils, many of which were already struggling to maintain their road infrastructure at an acceptable level prior to the additional damage caused by flooding. In particular, natural water crossings where culverts and floodways are located were some of the most susceptible areas to damage due to the concentration of runoff flow in these locations.

This initiated the idea of developing a better understanding of the vulnerability of culverts and what can potentially be done to increase their resilience during these extreme events.

The aim of this research is thus to investigate the main failure mechanisms of culverts and attempt to accurately simulate their behaviour during extreme flood events to observe which parts of the structure pose the highest levels of vulnerability.

1.2 Aims and Objectives

The aim of this project is to generate a better understanding of how major culverts can be better protected or reinforced in a cost-effective manner to improve their resilience during major or extreme flood events. The aim of this project can be broken into four main objectives being:

1. Identify the most common failure mechanisms for culverts based on recent flood events in northeast Victoria and identify similarities in geometry and mate rials used.

2. Develop a finite element model in Strand 7 of a culvert based on the identified similarities in geometry and materials.

3. Apply flood loadings to the model and simulate a range of scenarios to identify vulnerabilities and potential solutions to increase the resilience of culverts.

4. Provide recommendations on how to best increase the resilience of culverts based on results from the finite element modelling and field investigation.

1.3 Project Scope and Outline

The initial stage of this project is concerned with identifying and analysing existing literature relevant to the project topic. The purpose of this is to develop an understanding of research already completed in this field and identify gaps in existing literature to help develop clear aims for this project.

The literature review also provides an opportunity to become familiar with methodologies used in previous research to help determine a suitable methodology to be adopted for this project.

It also allows an opportunity to understand the various design standards and guidelines commonly used in Australia for culvert design and evaluate their current requirements for culvert protection.

A field investigation has then been completed to analyse damaged or failed culverts around the Lake Hume area to understand the most common failure mechanisms for culverts subjected to extreme flood events. A number of damaged culverts were inspected personally and measurements of main geometries and material properties were also documented.

This data has then been used to develop a base model of a 'typical' culvert using the finite element package Strand7. The base model has then been fully developed into a functional model by experimentally determining the required model extents, boundary restraints and mesh size.

The fully developed culvert model has then been used as part of a numerical investigation to identify vulnerabilities of culverts in an extreme flood scenario and determine potential solutions for increasing their resilience to common failure mechanisms identified in the field investigation.

A number of limitations have been discussed at the beginning of chapter 5 regarding the use of Strand7 for this type of analysis. Due to these limitations, the numerical investigation has taken an empirical approach where the general concepts have been analysed.

Thus, the loading applied during the numerical investigation is intended to represent loading expected during an extreme flood event and does not consider other loads or loading combinations typically considered in the design of culverts.

Therefore, this project has not attempted to yield exact values which could be considered in the design process of similar culverts. Instead, a number of recommendations have been made based on the general behaviour of the model observed in the numerical investigation.

Chapter 2

Literature Review

An abundance of literature exists which is concerned with the hydraulic and structural design of hydraulic structures as well as the effects of extreme natural events on critical civil infrastructure. Hence, this literature review focusses on the most relevant and recent research associated with this project topic and may not include all literature broadly related to the topic area.

It focusses on research recently conducted by academics at the University of Southern Queensland (UniSQ) on floodway design, studies related to the failure mechanisms of culverts, current design guidelines and standards for culvert design in Australia as well as hydraulic and mechanical loading theory relevant to culvert design and flood events.

2.1 UniSQ Floodways Research

Following the 2011 and 2013 extreme flood events in southeast Queensland, a group of academics from UniSQ conducted a 6 and a half year research program aimed at enhancing the resilience of critical road infrastructure in Australia (Setunge et al. 2017, p. 6). The research produced several papers which mainly focussed on floodways but broadly included bridges and culverts as well.

The first stage of the program focussed on collecting data from a case study area (Lockyer Valley Regional Council), understanding the main failure mechanisms of floodways and developing vulnerability models for critical infrastructure.

It was found that around 58% of floodways in the case study area were damaged following the flood events and most of the damage was a result of debris impact loads (Lokuge et al. 2014, p. 85). It was also noted that at the time a national standard for floodway design did not exist and the guidelines available in various jurisdictions do not consider debris impact loads as part of the design.

A parallel study used the case study data to undertake a vulnerability assessment of damaged floodways using a proposed damage index method. The purpose of this study was to develop a comparative tool to measure the cost of repair against the cost of full replacement for damaged road infrastructure and then prioritise repair and reconstruction activities (Wahalathantri et al. 2016).

The second stage of the research program was concerned with optimising maintenance and strengthening techniques to create more resilient floodway structures. Lokuge et al. (2019) used the research conducted in the first stage of the program as a basis for identifying the most vulnerable floodway designs. A three-dimensional finite element model was also developed using Strand7, shown in figure 2.1 below, to analyse the structural loads acting on different floodway types in various flooding scenarios.

This research was furthered by Greene et al. in 2020 to create design charts for the structural design of floodways considering the worst-case loading scenario. A design method was then developed to integrate the structural design charts with current hydraulic design methods to ensure adequate structural resilience during extreme flood events.

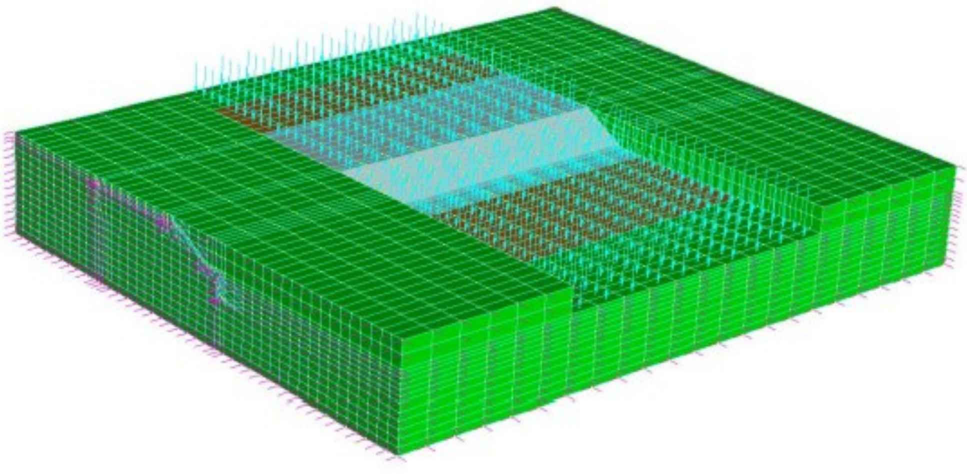

Figure 2.1 Strand7 model of a Type 2 floodway (Greene et al. 2018).

Other relevant research conducted by UniSQ academics includes Wahalathantri et al. (2018) who investigated the issue of limited information availability in rural areas for completing adequate hydraulic analyses of floodways and culverts. The paper also identified a potential link between floodway failures and the duration and intensity of a flood.

Another study completed by Tran et al. (2022) investigated the application of a Markov model for tracking and predicting the structural deterioration of culvert networks using visual inspection data from a case study area. The case study data revealed that the culverts using reinforced concrete pipes were more susceptible to severe deterioration from random damage events such as floods or debris impact than reinforced concrete box culverts.

2.2 Culvert Failure Mechanisms

Cahoon, Baker & Carson (2002) have identified a range of culvert failure mechanisms with the most relevant being:

- Sedimentation or debris collection in the culvert causing blockage or flow restriction which could lead to premature overtopping of the culvert.

- Corrosion or abrasion from sediment/debris which can degrade the structural integrity of the culvert leading to failure. This is mainly relevant for culverts using corrugated metal pipe (CMP) or older reinforced concrete pipes or boxes (see figure 2.2).

- Mechanical damage to culvert structure from vehicles, debris impact or poorly executed maintenance activities. More common for smaller, exposed culverts (see figure 2.3).

- Settlement can change the slope of the culvert altering its hydraulic behaviour which can lead to other failures. Settlement of the culvert can also cause severe damage to an overlying roadway.

Figure 2.2 A CMP culvert with corrosion damage (Haghani & Yang 2016).

Figure 2.3: Mechanical damage on an exposed driveway culvert.

- Separation at joints of prefabricated culvert sections which can cause water infiltrate into surrounding fill material or overlying road base. This can be hard to detect and has the potential to cause major damage to the overall culvert structure and roadway.

- Piping which occurs when water seeps between the pipe and soil material creating voids. This leads to instability of the culvert structure and can cause damage to an overlaying road surface (see figure 2.4). Piping usually occurs due to inadequate end treatments on the upstream side or poor compaction of soil around the culvert.

Figure 2.4: Road settlement due to piping (Piratla, Jin & Yazdekhasti 2019).

- Erosion of embankments on the upstream or downstream side of the culvert due to inadequate armouring or poor design/construction. Piping or overtopping typically causes erosion on the downstream side of the embankment (see figure 2.5).

Figure 2.5: Embankment erosion on the downstream side of a culvert.

2.2.1 Scouring

There have also been several recent studies completed involving numerical modelling of scouring around culvert outlets to predict the maximum scour depth for a particular culvert and the location it occurs. Severe scouring can lead to the failure of culverts if it undermines the foundations of the outfall structure (National Roads Authority 2015), an example of this can been seen in figure 2.6.

A UniSQ dissertation completed by Stainwall (2016) used computational fluid dynamics to identify critical areas where scouring is likely to occur as well as the effect of the scour depth on the overall structure.

Figure 2.6: Severe scouring at a culvert outlet.

The ability of numerical methods to predict scour depth and location in unsteady flow has also been investigated by Ahmed et al. (2021).

2.2.2 Embankment Failure

The failure of culvert embankments due to overtopping in extreme flood events has also been documented by several research papers. An investigation into highway infrastructure damage following major flooding along the Missouri River floodplain in 1993 found that the culverts which had overtopped suffered substantial damage or complete failure.

This included erosion of the downstream embankment and road shoulder, undermining of the outlet structure and road pavement and in extreme cases caused an embankment breach and complete washout of the culvert structure (Parola 1998, p. 69).
Similar failure mechanisms were also documented by Gassman et al. (2017) following a 1 in 1000-year rainfall event in South Carolina in 2015.

The studies were aimed at collecting observational data to be used for further research and highlighted the extent that this failure mechanism is observed during an extreme flood event. Figure 2.7 below illustrates this failure mechanism occurring during a flood event.

Figure 2.7: Progressive failure of an overtopping culvert (Vermont Local Roads 2012).

The vulnerability of older culvert embankments utilising poor quality fill material has been analysed by Heyerdahl et al. (2013) after prolonged rainfall caused extensive damage to railway networks in Southern Norway. Most of the failed culvert embankments had been constructed between 1850 and 1950 using poor material making them highly susceptible to failure during a flood event.

Another study found that geotechnical weaknesses in a culvert embankment structure can lead to internal erosion processes resulting from seepage through the embankment during a flood event (Polemio & Lollino 2011, p. 3395). Similar to the piping mechanisms mentioned earlier, this erosion process can quickly degrade the stability of the embankment causing localised or complete failure. These two studies show that there is a need to understand the geotechnical factors associated with culvert embankments in order to thoroughly understand this failure mechanism.

2.3 Culvert Protection

Many of the discussed failure mechanisms can be controlled without the need for novel solutions. For example, the failure mechanisms common for CMP culverts can be eliminated by using reinforced concrete pipe instead.

Mechanical damage can be avoided by providing adequate protection for exposed culvert ends and taking care when conducting maintenance activities. Settlement, separation of joints and structural collapse can also be avoided through proper design and construction methods.

2.3.1 Outlet Protection

There has been a limited amount of research regarding protection measures specifically for culvert outlets where damage or failure of culverts frequently originate during major flooding. Most of the existing literature in this area was published decades ago with little advancement in modern research.

Simons, Stevens & Watts (1970) details a series of concrete and rock riprapped basin designs which function as energy dissipating structures at culvert outlets. The purpose of these basins is to minimise the maintenance activities required when excessive scouring occurs at the culvert outlet. The research presented four basin designs with varying degrees of effectiveness and construction costs.

Experiments were also conducted around a similar time by U.S. army engineers which were aimed at determining the effectiveness of rock riprap protection against scour and erosion at culvert outlets. Fletcher & Grace (1972) focussed on finding methods of estimating the extent of scour and erosion downstream of culvert outlets. Their research also investigated methods of controlling the phenomena using riprap, preformed scour holes and expansions.

A similar study by Bohan (1970) focussed specifically on using riprap as a protection measure and a series of destructive tests were performed. These tests helped provide an understanding of what stone sizes and blanket configurations are most effective at preventing scour and erosion at culvert outlets. An example of riprap protection at a culvert outlet is provided in figure 2.8.

Another study on the performance of riprap protection was conducted by Abt & Johnson (1991) which was used to determine an optimal riprap design for flows overtopping embankments rather than controlling scour at culvert outlets.


Figure 2.8: Riprap Protection at a culvert outlet (Wikipedia 2022).

2.3.2 Embankment Protection

The protection of embankments against erosion and breaching has received a large amount of attention from researchers and thus an abundance of literature exists in this topic area.

Most of this research relates to overtopping dam embankments, levees and road embankments but most of the concepts can be made applicable to culvert embankments. Research by Powledge et al. found that erosion of embankments during overtopping flows is a complex, multivariable problem but can be controlled to an extent with vegetative systems or artificial surface reinforcement (Powledge et al. 1989a, p. 1054; Powledge et al. 1989b p. 1073).

These include grass vegetation, geotextiles, soil cement, roller compacted concrete, concrete blocks, rock filled wire baskets and riprap. Their research also found that embankments made of well compacted cohesive soil are much more resistant to erosion than those constructed of non-cohesive soils and erosion is reduced in submerged areas such as where tailwater is present.

A similar study was conducted by Gilbert & Miller (1991) which resulted in similar conclusions to the study completed by Powledge et al.

A more recent parametric study was completed by Nasrin (2013) which focussed on investigating the properties of vetiver grass to determine its suitability for the application of erosion control of embankments in Bangladesh.

More recent studies on embankment overtopping protection systems for dams have been completed by Chanson (2015) and Hepler, Crookston & Crowder (2018). Chanson (2015) determined that several techniques were suitable for embankment overtopping protection systems including concrete protection systems, timber cribs, sheet piles, riprap, gabions, reinforced earth, minimum energy loss weirs, stepped spillways and precast concrete blocks.

Finally, Hepler, Crookston & Crowder (2018) describes the successful performance of roller-compacted concrete protection and articulating concrete block protection on embankment dams and earthen spillways in the United States.

2.4 Australian Design Standards and Guidelines

2.4.1 Australian Standards

Due to the absence of a specific Australian standard for the design of culverts, design loads, load combinations and other design considerations applied to culverts are usually adopted from the Australian standards for bridge design being AS 5100.1:2017, AS 5100.2:2017 and AS 5100.3:2017. The structural aspects for precast reinforced concrete box culverts are detailed in AS 1597.1:2010 and AS 1597:2013 however, these standards do not provide design guidance for the operation of culverts.

2.4.2 Austroads

In Australia, the main design guide for culverts is chapter 3 from part 5B of Austroads Guide to Road Design (Austroads 2013). This provides a range of details for the design of culverts including their optimal locations, hydraulic design, structural design, operating conditions and end treatments.

Culvert Protection

In regard to the design of protection for culverts, section 3.13 of Austroads (2013) states that outlet protection is required in situations where:

- Outlet velocity exceeds the scour velocity of the bed or bank material.
- An unprotected channel bend exists within a short distance of the culvert outlet.
- The outlet channel and banks are actively eroding.
- If an erodible channel bank exists less than 10 to 13 times the pipe diameter downstream of the outlet and this bank is in line with the outlet jet (i.e. likely to be eroded by the outlet jet), the bank should be adequately protected to control any undesirable damage as a result of the outlet jetting.

The minimum size of rocks used for outlet protection and the required length of the rock apron for a single pipe outlet can be determined from figures 2.9 with figure 2.10 detailing the geometry of the rock apron.

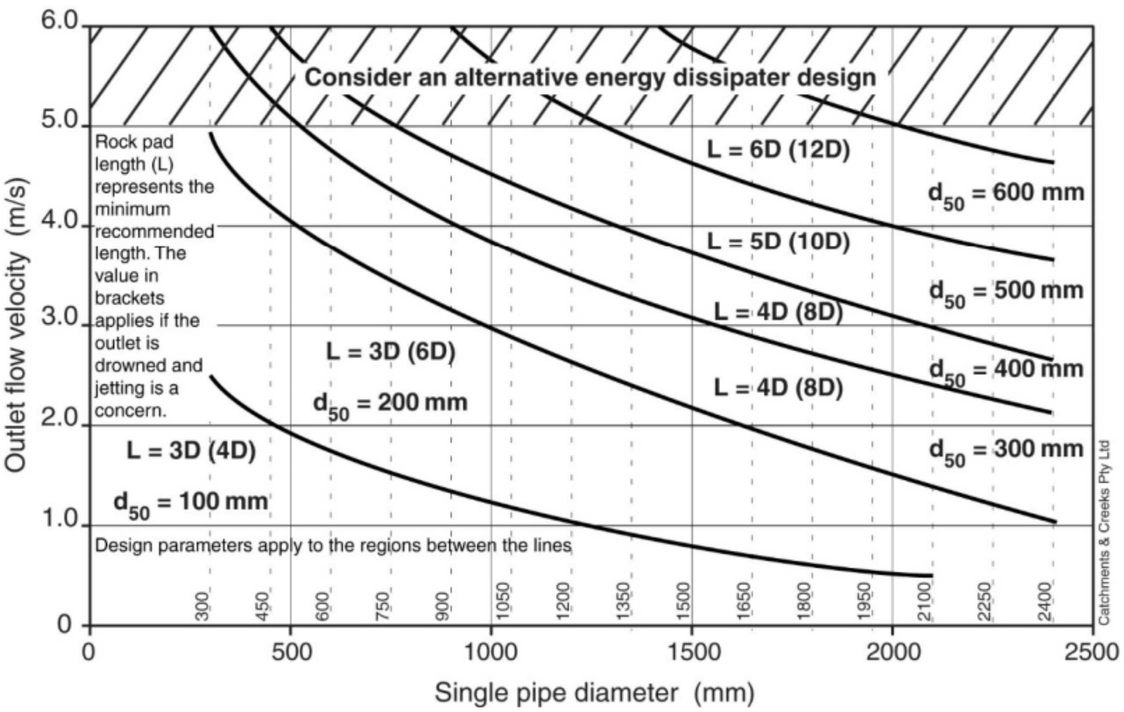

Figure 2.9: Rock size and apron length for a single pipe outlet (Austroads 2013).

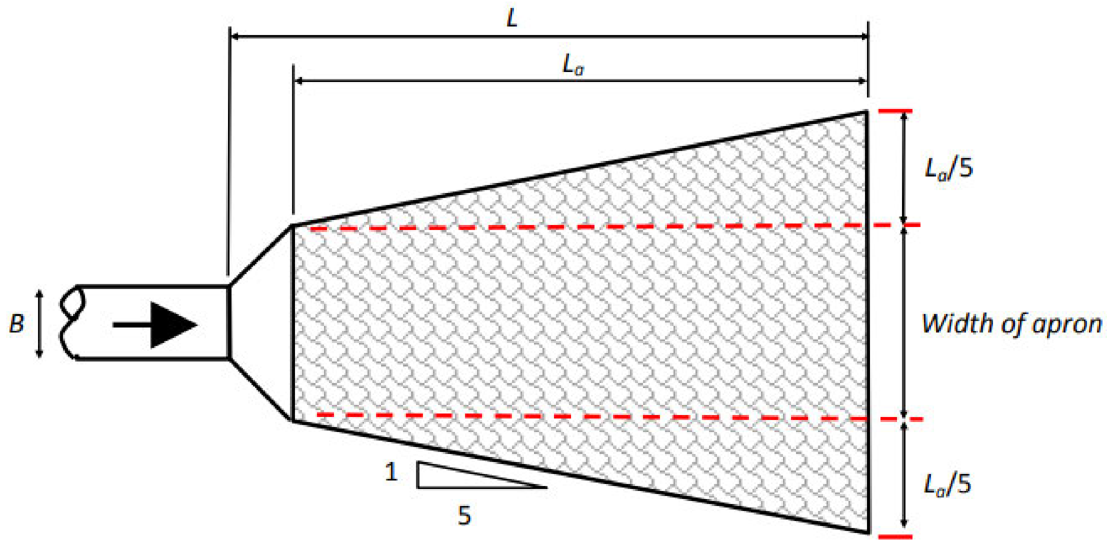

Figure 2.10: Rock apron geometry for a single pipe outlet (Austroads 2013).

In addition to outlet protection, section 3.14 provides some details on the use of culvert end treatments such as wingwalls, cut-off walls and erosion control measures which may be required to perform one or more of the following functions:

- Prevent fill from encroaching on the culvert opening.
- Prevent erosion of the fill and adjacent channel.
- Prevent undermining of culvert ends.
- Help anchor the structure to the ground.
- Inhibit seepage and piping through the bedding and backfill.
- Meet traffic safety requirements.
- Improve the appearance of large culverts.
- Resist hydraulic uplift forces on corrugated metal pipe culverts.

- Strengthen the ends of large flexible culverts, especially those with mitred or skewed ends.

Floodway Batter Protection

Section 4.5 of Austroads (2013) details a range of protection measures for the downstream batters of floodways which could possibly be adapted for culverts as downstream embankment protection. In summary, the batter protections detailed include:

- Grassed batters. This is considered as minimum protection for batters and its effectiveness depends on the type of grass used and quality of grass cover.

- Concrete protection. This is commonly used and typically performs well (see figure 2.11).

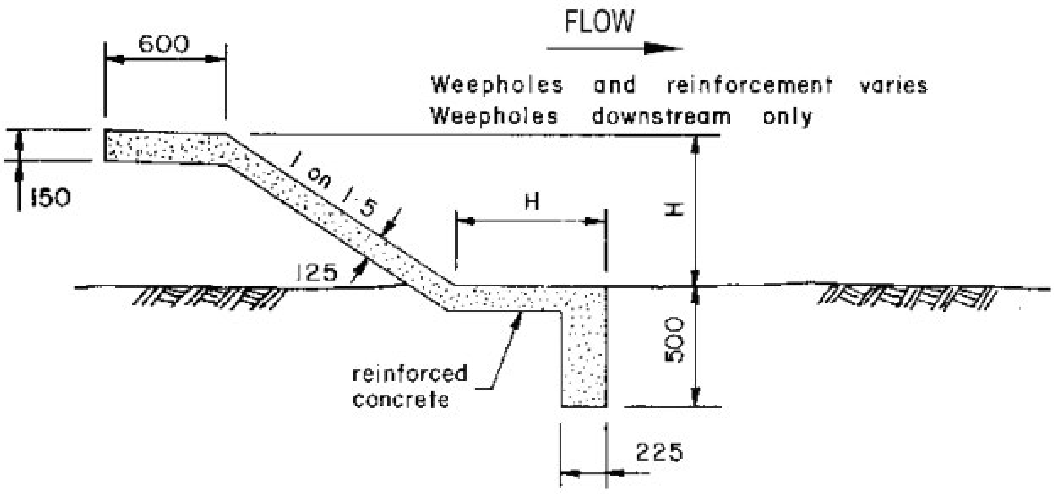

Figure 2.11: Type 1 concrete protection for floodway batters (Austroads 2013).

- Rock mattress protection.

- Bitumen seal protection.

- Dumped rock (riprap) protection.

2.4.3 State Authorities

Some state authorities have also published their own guidelines which either supersede or supplement part 5B of Austroads Guide to Road Design.

Queensland Department of Transport and Main Roads

Queensland's department of Transport and Main Roads has produced its own Road Drainage Manual (Queensland Government 2019) that supersedes certain parts of part 5B of Austroads Guide to Road Design including sections 3.13 and 3.14. It states that for sections 3.13 and 3.14, the following amendments must be considered:

1. In all types of culvert outlets, protection of the stream bed would normally be provided by the department's standard apron treatment as shown on Standard Drawings 1240, 1250 and 1260 (TMR). Typically, the distance of protection required, measured from the outlet of the culvert, is 1.5D metres where 'D' is the diameter of a pipe or the height of a box culvert.

2. Wingwalls, in conjunction with the apron and cut-off wall, protect the integrity of the embankment from erosion/scour caused by stormwater flows. The length of the wingwall (W1 & W2 as per Standard Drawings 1240, 1250, 1260, 1304, and 1305 (TMR)) is calculated based on the slope of the batter – the flatter the batter slope, the longer the wingwall needs to be. The wings should extend to at least the interface between the batter slope and the natural slope. For further detail on calculating wingwall lengths, refer to Appendix 9D.

   Should shorter wingwalls be proposed (that is, some of the embankment is ex posed to inlet/ outlet flow), it is recommended that there be a requirement to mitigate any possible Chapter 9: Culvert Design Road Drainage Manual, Transport and Main Roads, September 2019 28 erosion/scour of the exposed em bankment via works with a similar durability/design life as normal wingwalls (typically 50 years).

3. Use of pre-cast end/headwalls must comply with the department's Standard Drawing 1243 and Technical Note TN27 – Guidelines for Design of Precast Culvert and Pipe Headwalls. NB: For concrete pipe culverts there is to be no step between the culvert invert level and the adjacent apron level. This requires the depth of the recess in the precast end unit to match the thickness of the concrete pipe.

In addition to these amendments, the Road Drainage Manual (Queensland Government 2019) also includes section 9.21 which details considerations for downstream slope protection to improve the resilience of culverts subjected to extreme events. It states that downstream slope protection should meet the following criteria for culverts with an embankment height greater than 500mm and flood immunity less than 2% AEP:

- Maximum slope of downstream batter is 1 (vertical) to 3 (horizontal).
- All shoulders shall be sealed.
- All headwalls must be permanently physically attached to the culvert even after scour.
- The headwall, apron and cut-off wall shall be integral.
- Minimum depth of cut-off wall of 450 mm.
- Use of pre-cast end/headwalls must comply with the department's Standard Drawing 1243 and Technical Note TN27 – Guidelines for Design of Precast Culvert and Pipe Headwalls. Precast ends to culverts must have cut-off walls.
- The downstream embankment face adjacent to a culvert shall be protected with either grouted rock, reinforced concrete or wire mattress (except where protecting sand or non-cohesive material). Note that where wire mattresses are proposed for the protection of non-cohesive embankment materials, proper filter protection, such as geotextile, shall be designed and installed behind the wire mattresses.

- All downstream batter protection shall extend to at least the toe of the batter and tie into a cut-off wall of at least 450 mm in depth Chapter 9: Culvert Design Road Drainage Manual, Transport and Main Roads, September 2019 31.

- For culverts with a drop less than 2 metres, vegetation may be used if it remains lush and thick for the entire year (typically coastal areas).

- For culverts, batter protection on the downstream side of the road embankment shall extend along the carriageway past the culvert (in both directions) for a distance twice the height of the road embankment or channel width (whichever is the greater).

Main Roads Western Australia

Main Roads Western Australia (Main Roads Western Australia 2020) has produced a supplement to the Austroads guide which contains some additional considerations for culvert designs in Western Australia but mainly adopts the information provided in the Austroads guide.

It states that outlet protection should be provided in accordance with part 5B of Austroads Guide to Road Design but does not need to be provided for minor culverts where serious scour problems are unlikely to occur.

Other States

Many other design manuals and guidelines from various jurisdictions and independent sources also exist which give detailed information on the design aspects of culverts.

Other state authorities such as VicRoads and Roads and Maritime Services (RMS) provide standard drawings and documents relating to the design and construction of culverts within those states. However, they do provide a prescribed document which supplements or supersedes part 5B of Austroads Guide to Road Design which is universally considered as the primary guideline to follow for any aspect regarding road design.

2.5 Summary and Research Justification

While the common failure mechanisms of culverts are well understood, culvert damage and failure still occur widely, particularly following extreme flood events. Though methods for protecting culvert embankments do exist, there is an absence in recent research concerning the effectiveness of modern techniques.

A range of literature does exist which describes various protection measures adopted for dam and levee embankments to avoid breaching during overtopping events however, these have not been specifically applied to culverts in most cases. Only the Road Drainage Manual developed by Queensland's Department of Transport and Main Roads provides guidance on how the resilience of culverts can be improved through protection of the downstream embankment.

The aim of this research project directly responds to the need for more resilient road infrastructure by providing an improved understanding of how the resilience of culvert structures subjected to extreme flood events can be enhanced. The reality of climate change means there is a high likelihood that design flows for a particular sized flood event will increase over time meaning many culverts will become undersized when compared to the flood event they were originally designed to withstand.

This effect is further compounded by an ever-increasing population resulting in the expansion of urban areas which will generally increase the design discharge for a particular catchment area. It would not be practical to simply increase the size of culverts impacted by an increased design discharge and thus making them more resilient to failure could be a potential solution to this problem.

Chapter 3

Methodology

3.1 Overview

The project specification available in Appendix A outlines the main steps taken to complete this project. The initial part of the project was concerned with identifying the most commonly occurring failure mechanisms for culverts by studying damaged culverts in the Lake Hume area and other major culvert failures in northeast Victoria.

Where possible, damaged culverts have been further investigated to better understand the mechanics of the failure mechanisms observed. Measurements were also taken of the main geometries and the materials used were identified.

This information has then been used to develop a finite element model which represents a 'typical' culvert structure observed in the area. Once developed, hydrostatic loading representing an extreme flood is applied to model and material properties are adjusted to identify the most vulnerable parts of the culvert structure and compare the results to the failure mechanisms observed in the field.

The final part of the project involved simulating a range of practical solutions that could make the structure less vulnerable to the failure mechanisms identified in the first stage of the project. This research focussed solely on major culverts providing road access across naturally formed channels as these can be critical 'weak points' along roadways when extreme flooding occurs.

3.2 Field Investigation

To determine the most common failure mechanisms for major culverts in extreme flood events, a number of culverts around the Lake Hume area in Victoria were visually inspected for damage resulting from extreme rain events which occurred during January 2022. Where damage to a culvert was observed, the type and extent of the damage was documented and photographed, measurements of the main geometries were noted and soil samples of the embankment fill used were taken.

Additionally, two other culverts which sustained substantial damage were also analysed to understand the mechanics of the failure mechanisms involved. These were not able to be inspected in person due to accessibility issues however, sufficient information and photos were available to understand each failure mechanism.

3.2.1 Key Parameters

The main parameters and geometries for each culvert which was visually inspected as part of the field investigation were documented which included:

- Culvert type and size (box culvert, corrugated metal pipe, reinforced concrete pipe).
- Embankment height above the obvert of the culvert.
- Approximate length of the culvert.
- Material used for the embankment.
- Any evidence of protection mechanisms such as headwalls or rock protection.

All physical measurements were made using a measuring tape meaning some desired parameters, such as the slope of embankments, were not possible to obtain with any degree of accuracy.

Though the method used for measuring reduces the accuracy of results for this exercise (except for measurements of pipe diameters), this has little meaningful implications for the overall project as the purpose of the measurements are only to inform the geometry and proportions of the finite element model, not to create an accurate representation of a single existing culvert.

3.2.2 Soil Samples

A sample of the material used for each culvert's embankment was also collected to understand the soil types commonly used for embankment fill in the area and to estimate their material properties. For each sample, a simple classification test was performed to approximate the ratios of sand, silt and clay in the soil so that its physical properties could be estimated using published data. Although in-situ soil tests would be more ideal and provide better results, access to the required equipment was not possible for this project.

The process for the soil classification testing involved the following main steps:

1. Any clumps in the soil were broken down and any substantial pieces of gravel or rock were removed and set aside.

2. A clear bottle was filled almost halfway with the soil and filled to approximately 80% full with water.

3. The bottle was then shaken thoroughly to ensure the soil and water mixed completely before being placed on a level bench to rest for 48 hours.

4. After 48 hours, the soil completely settles into layers with the bottom layer containing sand and gravel particles, followed by a layer of silt and final layer of clay on top.

5. The height of each layer was then measured with a ruler to determine the approximate ratio of sand, silt and clay in each soil.

The information collected has then been sorted and analysed to identify similarities in soil types to then be used in the development of the finite element model.

3.3 Model Development

The finite element modelling has been completed using the Australian developed software package, Strand7. The finite element method involves simplifying a complicated problem into a finite number of discrete elements to approximate a solution which approaches the true solution as the number of discrete elements increases (Zienkiewicz et al. 2005, p. 1). The method is widely used in many engineering and scientific applications.

The model development for this project follows a similar methodology to that used in the UniSQ floodways research to develop the Strand7 floodway model discussed in the literature review.

3.3.1 Modelling Techniques

The modelling process used to develop the model in Strand7 is as follows:

1. Nodes are firstly created in the x-y plane to represent the cross-sectional geometry of the culvert structure and are then connected by plate elements representing different materials. The plate elements are then extruded along the z axis to create 3-dimensional brick elements. In cases where elements in the geometry are not perpendicular, such as the creation of embankments, it is simpler to connect nodes directly with brick elements and omit the use of plate elements.

2. Brick elements are then subdivided into smaller elements to create a mesh of desired size. During this process, it is imperative to ensure that elements are subdivided in a manner which does not result in discontinuities in the mesh. Discontinuities occur when neighbouring element are subdivided unequally resulting in nodes not aligning along a common axis (see figure 3.1). This causes instability in the model and will result in incorrect outputs from the software.

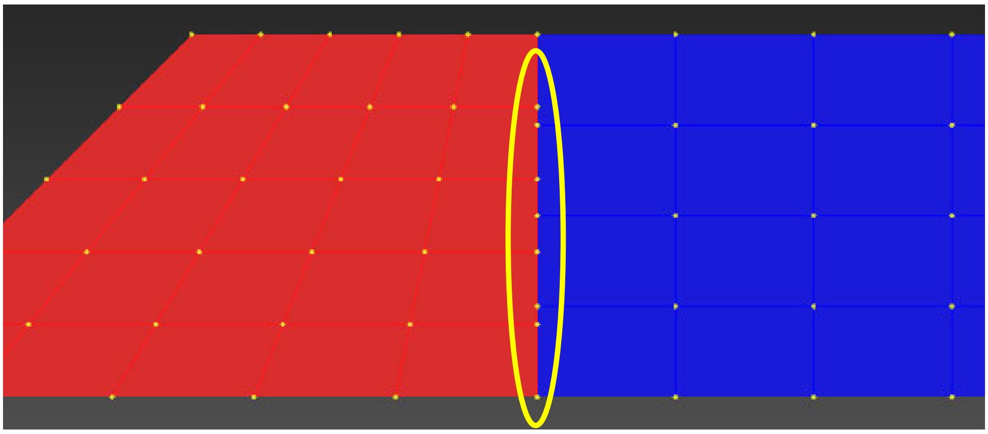
Figure 3.1: Discontinuity of mesh between brick elements.

3. Once the mesh has been created, material properties are assigned to all the brick element types. Strand7 has a comprehensive inbuilt library of material properties for a range of commonly used structural materials like steel, concrete and timber. Other less common materials such as soils require the material parameters to be manually input into the software.

4. Appropriate boundary conditions are then assigned to external nodes to ensure the model is restrained in a way which best simulates a real-world case. The extent of adjoining soil in the model needs to be determined experimentally to ensure the restraints applied to the nodes do not over-stiffen the model and produce inaccuracies in the results.

5. The desired loading pattern is then applied to the relevant elements in the model under a particular load case. A secondary load case is then created to define the magnitude and direction of gravity acting on the model. Finally, the global freedom case for the model is also defined.

6. The final step in developing the finite element model involves using the built in soil in-situ stress tool which uses the defined freedom and gravity load case to assign in-situ stresses to soil elements. These need to be defined for a non-linear analysis to ensure there is no vertical displacement in the mesh when the gravity load is applied to model (Strand7 2023a).

Prior to the full culvert model being developed, a simple verification model is created which represents a section of the final model. This model is created to verify outputs from the software but to also develop the modelling process described above and eliminate any errors that appear during the process.

3.3.2 Strand7 Solvers

Linear Static

Strand7 has a number of different solvers available for a wide range of finite element problems. The most commonly used solver is the linear static solver which applies two main assumptions:

- The applied loading is static (i.e. it's magnitude and direction do not change with time) (Strand7 2023b).

- The deformation of elements in the model is linearly proportional to the applied loading (Strand7 2023b).

These assumptions have little effect on most modelling problems in Strand7 utilising linearly behaving materials such as steel and standard geometries. Where materials are used which do not respond linearly to loading such as soils, or where nonlinear geometries are used, the non-linear static solver needs to be used to achieve realistic outputs.

Nonlinear Static

The non-linear static solver is used for problems where a linear analysis is not valid due non linearity in the model. The nonlinear static solver still assumes static loading conditions however, according to Strand7 (2023b), the non-linear static solver is able to account for three types of non-linearity being:

- Nonlinear geometry where structural stiffness can change as the model deforms resulting in further displacement being unproportional to the applied load.

- Nonlinear materials which do not deform proportionally to the applied loading.

- Boundary nonlinearity which occurs when the stiffness of contacting elements is affected by the load between them resulting in displacement being unproportional to the applied load.

The non-linear solver uses an iterative process to numerically solve the problem and relies on the results from each iteration to converge before being able to provide a solution. Non-convergence can occur where a physically impossible scenario is presented to the software or nonlinearity is too extreme for the solution algorithm to deal with. Where significant non-linearity exists in a model, loading can be applied incrementally by the solver to help achieve converging results.

Due to the inclusion of soil materials in the modelling for this project, the non-linear static solver will be used develop the culvert model and analyse the final model under flood loading.

3.3.3 Soil Models and Interpreting Failure

Strand7 has five soil material models available to be used for analysis, including a Mohr-Coulomb soil model which is commonly used for geotechnical problems and will be used to define soil materials for this project.

The Mohr Coulomb failure law is given by:

$$\tau = \sigma \tan \emptyset + c$$

Where:

τ = Shear strength (Pa);

σ = Normal Stress (Pa);

$\emptyset$ = Friction angle (°)

c = Cohesion (Pa)

This defines the failure envelope for a particular soil and as can be seen from the equation above, is governed by the applied stress, the cohesion of the soil and the internal friction angle. This failure envelope is represented graphically in figure 3.2 below.

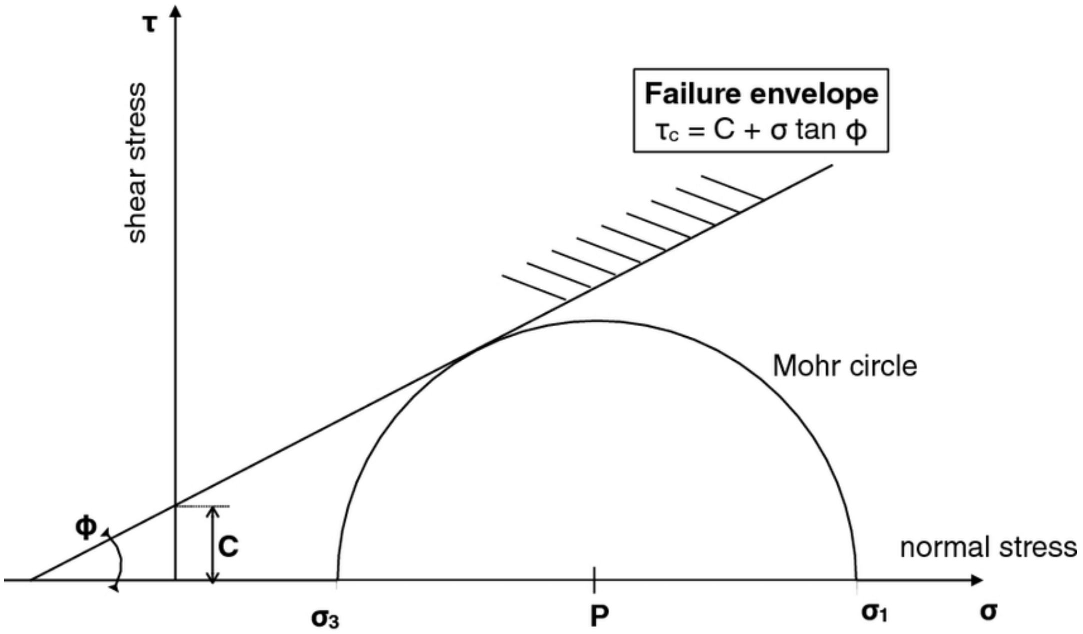

Figure 3.2: Mohr-Coulomb yield criterion (Hestroffer et. al. 2019).

When a model is solved in Strand7 using the non-linear static solver, the program uses this theorem to identify regions of soil which have yielded or failed by assigning a yield index value to each soil element. If the value is greater than zero, the element has yielded, if the value is less than zero it has not yielded and if the value is exactly zero it is at the yield threshold.

3.4 Numerical Investigation

Once the Strand7 model has been fully developed it will be analysed in a number of scenarios based on the most common failure mechanisms identified in chapter 4. Because of this, the exact methodology of the numerical investigation will be dependent on the outcomes of the field investigation. The model will then be manipulated to better understand the characteristics of the identified failure mechanism and support recommendations on how similar culverts can be made more resilient in these scenarios.

3.4.1 Flood Scenarios

The developed model will be analysed with the applied flood loading to identify potential vulnerable areas. Material and loading conditions will then be altered systematically to analyse the critical failure mechanism identified in the field investigation. Once the failure mechanisms have been analysed, the focus will shift to how the failure mechanisms can be controlled through changes to geometry and material properties in the model.

3.4.2 Improving Resilience

Based on results from both the field investigation and the numerical investigation, a range of potential options will be explored which would have the effect of improving the resilience of similar culverts subjected to extreme flood events.

Chapter 4

Field Investigation

Although the typical failure mechanisms for various types of culverts have already been identified in the literature review, this project does not have the scope to investigate practical solutions to mitigate all of these types of failures. Furthermore, effective methods to protect culverts from some of these failure mechanisms are already well understood.

Therefore, a field investigation has been undertaken to document failure mechanisms observed across the Lake Hume area to identify which failure mode is most prevalent and poses the largest risk of major damage to road infrastructure.

This area experienced extreme rain events during January 2022 producing flooding estimated to be above the 100-year average recurrence interval for the region causing extensive damage to road infrastructure. This was compounded by subsequent heavy rain events during the Spring months of 2022 which caused further flooding and damage to already saturated catchments.

4.1 Major Failures

A small number of major culvert failures did occur around the Lake Hume area due to excessive rainfall and flooding during various major events in 2022. Most of these culverts were not able to be thoroughly investigated as part of this project.

This was due to either being active construction sites during the course of the field investigation for this project, or due to repairs having already been completed by the time this project commenced.

One of the most notable of these failures occurred near Rutherglen, Victoria, where an entire section of the roadway and embankment was washed away due to a complete blockage of the culvert (see figure 4.1).

Figure 4.1: Culvert failure near Rutherglen, Victoria (Indigo Shire Council 2022).

The culvert followed a similar failure mechanism to that shown in figure 2.7 where the restriction caused by the culvert caused water to build up on the upstream side creating a damming effect.

Over time and due to the hydrostatic pressure on the embankment and additional pressure induced by the flow of water upstream of the culvert, water progressively seeped into the upstream side of the embankment.

This increased the plasticity of the soil causing the embankment and roadway to begin failing progressively from the upstream side (see figure 4.2) until the pressure induced by the upstream floodwater was able to wash the remainder of the embankment away. This caused the culvert itself to become completely dislodged and resulted in a large, impassable chasm being created in the roadway.

Figure 4.2: Culvert failure near Rutherglen, Victoria (Indigo Shire Council 2022).

Another culvert in the township of Bethanga was badly damaged during a heavy storm where the hydraulic capacity of the culvert was exceeded and water overtopped the roadway. This event caused significant erosion damage to the downstream side of the embankment (see figure 4.3).

Figure 4.3: A major culvert failure in Bethanga, Victoria.

The roadway surface above the culvert had also become undulated following the event due to uneven settlement in various spots. This suggested that water had seeped into the embankment from the upstream side during the event and some of the soil had begun to shift due to increased plasticity.

In conjunction with the significant erosion on the downstream side, this suggests that the culvert had come close to completely failing in a similar manner to the culvert near Rutherglen.

There were four other culverts around the Lake Hume area which sustained notably major damage during these flood events resulting in the affected roadway either being closed completely or reduced down to a single lane operation.

One of these culverts had already been completely repaired at the time of this project while the other three had been blocked off as construction sites. The three culverts all had significant erosion damage on the downstream side of the embankment however, it was not possible to determine whether this was caused by severe scouring at the outlet or water overtopping the culverts.

4.2 Culvert Inspections

A total of 5 culverts were physically inspected as part of the parametric study with damage to the culverts ranging from minor to severe. The location of each culvert is shown on the map in figure 4.4 below.

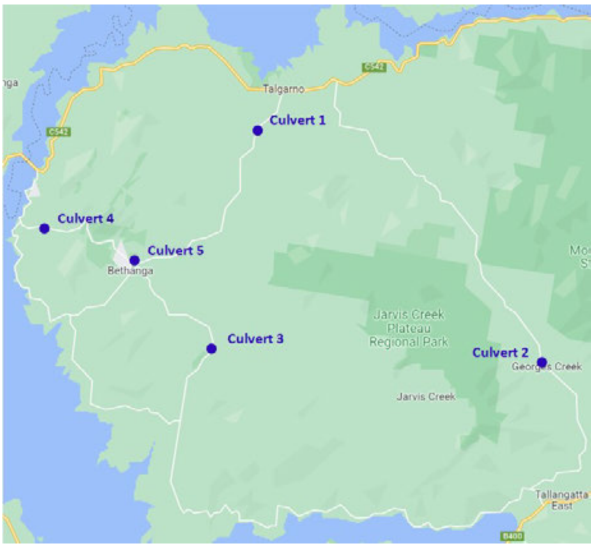

Figure 4.4: Locations of damaged culverts investigated in the Lake Hume area.

Most of the damage observed occurred during an extreme rainfall event which impacted the region in January 2022 which caused a number of major culverts overtop.

Whilst some culverts were able to mostly withstand the forces associated with the extreme rainfall, others were damaged extensively requiring urgent repairs to ensure the safety of the roadway above.

4.2.1 Culvert 1

The first culvert was of a substantial size and consisted of two 1200 mm reinforced concrete pipes (RCPs) providing road access across a small, natural creek. This culvert showed signs of minor erosion damage at the top of the embankment on both the upstream and downstream sides (figure 4.5) which suggested that flood waters had overtopped it during the major flood event.

Figure 4.5: Damage to a culvert on the upstream (left) and downstream (right) side.

It appeared that some rock protection had been installed on the upstream side however, most of the rocks had dislodged and no longer provided adequate protection to the embankment.

Though no immediate repair work seemed necessary to ensure safe operation of the road, a similar flood event in the future would likely cause more extensive damage to the embankment requiring significant repairs due to the existing erosion and damage to the rock protection.

4.2.2 Culvert 2

The 2nd culvert was relatively small and consisted of a single 750 mm RCP providing road access across a small creek. The upstream side of the culvert was undamaged however, the downstream side had suffered severe erosion damage most likely from heavy scouring at the culvert outlet during the flood event and may have been exacerbated by water overtopping the roadway (figure 4.6).

Figure 4.6: Scouring damage to a culvert on the downstream side.

The scouring was severe enough to completely erode the downstream embankment up to the edge of the road pavement creating a major hazard for road users. The culvert itself had also been undermined causing significant stresses on the pipe resulting in a length of the RCP separating completely.

It appeared that additional scouring was also still occurring where water exiting the culvert at the separation of the pipe (figure 4.6). This was further undermining the culvert still in place and compromising the integrity of the roadway. There was also no evidence of any protection measures on either the upstream or downstream side of the embankment.

The roadway already had some potholes forming above the damaged culvert suggesting that moisture had infiltrated the embankment or the roadway was starting to deflect due to the undermining of the culvert.

The culvert required urgent repairs to ensure the safety of road users and further undermining of the undamaged part of the culvert could cause the culvert to fail entirely. If a similar flood event were to occur prior to the culvert being repaired, it would be likely that the culvert and roadway would fail completely making it impassable.

4.2.3 Culvert 3

The 3rd culvert was relatively large and consisted of a single 2000 mm diameter CMP providing road access across a large natural channel approximately 10 m wide with steep side slopes. Some minor erosion damage was visible on the downstream side at the top of the embankment (figure 4.7) suggesting that the culvert may have been overtopped during the major rainfall event.

Figure 4.7: Minor damage to a CMP culvert on the downstream side.

There was rock protection present on the downstream side of the however, some rocks had become dislodged near the top of the embankment where the erosion had occurred. The upstream side was undamaged and did not appear to have any rock protection.

It also appeared that some minor scouring had occurred at the culvert outlet removing supportive material at the downstream end of the culvert causing its shape to deform.

The bottom of the CMP also appeared to show signs of corrosion damage.

Although the erosion at the top of the embankment was not immediately affecting the safety of the roadway, the scouring at the outlet could have the potential to undermine the culvert and cause further damage to the CMP if left unrepaired. A similar rainfall event in the future could also have the potential cause severe damage to the embankment and roadway requiring major repairs.

4.2.4 Culvert 4

The 4th culvert was of a substantial size and consisted of a single 1500 mm RCP providing road access across a small creek. This culvert showed signs of moderate erosion damage on the downstream side with the upstream side remaining mostly undamaged due to the presence of a stone headwall though the headwall itself had received some minor damage (figure 4.8).

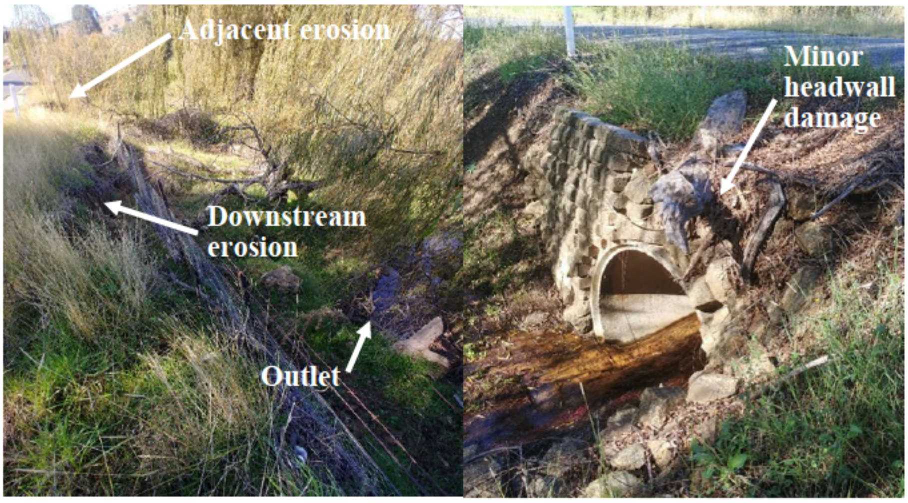

Figure 4.8: Culvert 4 downstream (left) and upstream (right).

The most extensive damage to the embankment occurred adjacent to the culvert outlet where a large section of the embankment had eroded away (figure 4.9), likely due to flood water overtopping the roadway.

Though damage to the downstream embankment was extensive, it is likely that further damage would only occur if the culvert were to be overtopped again in a similar event. This would have the potential to cause damage to the roadway and effect road users however due to the length of the culvert, complete failure would be unlikely.

Figure 4.9: Erosion damage adjacent to culvert 4 outlet.

4.2.5 Culvert 5

The 5th culvert was relatively small and consisted of a 450 mm RCP and a 900 mm RCP providing road access across a small creek. The upstream side of the culvert was completely undamaged due to the presence of a concrete headwall however, the downstream side (figure 4.10) suffered substantial erosion to the embankment.

Figure 4.10: Culvert 5 upstream (left) and downstream (right).

A concrete block appearing to provide protection to the downstream side of the embankment had also been completely dislodged.

In its damaged state, a similar event would likely cause further erosion and potentially cause damage the roadway itself.

4.2.6 Measured parameters

A summary of key parameters measured in the field for each culvert is given in table 4.1.

Table 4.1: Summary of key parameters.

Culvert	Material	Diameter (mm)	Length (m)	Fill above obvert (m)
1	RCP	2 x 1200	8	1.8
2	RCP	750	7	0.6
3	CMP	2000	8	0.8
4	RCP	1500	10	0.9
5	RCP	450 & 900	8	1.1

A number of soil samples were collected from the embankment of each culvert to conduct the soil classification testing shown in figures 4.11 and 4.12.

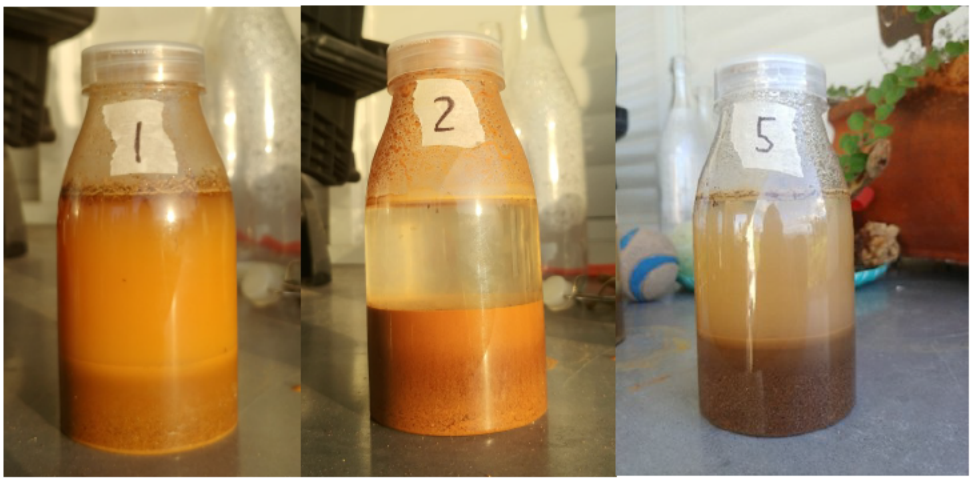

Figure 4.11: Soil test for culvert 1 (left), culvert 2 (middle) and culvert 3 (right).

Figure 4.12: Soil test for culvert 4 (left) and culvert 5 (right).

Note that the number on number on each test represents a sample number and the number of the culvert it has been sampled from.

The proportions of sand, silt and clay were physically measured from each test and is summarised in table 4.2.

Table 4.2: Summary of soil proportions.

Culvert	% Sand	% Silt	% Clay
1	70	15	15
2	50	40	10
3	70	15	15
4	60	5	35
5	75	5	20

4.3 Investigation Summary

The field investigation proved a valuable exercise for gaining a better understanding of the common failure mechanisms and extent of damaged culverts in the Lake Hume area, further reinforcing the need for more resilient structures.

A number of other damaged culverts were identified during the investigation but excluded from this report due to the observed failure mechanism being largely attributed to:

- Significant under sizing of the culvert considering the cross section of the upstream channel and height of the roadway embankment.

- The age of the culvert.

These were excluded as they would likely cause a significant skew in the results from the field investigation and do not represent what most would consider a 'typical' culvert.

4.3.1 Failure mechanisms

The field investigation found damage consistent with a number of failure mechanisms, with the most common being:

- Failure of the downstream embankment

- Failure of the upstream embankment

- Scouring at the culvert outlet

Failure of the downstream embankment was the most prevalent failure mechanism and will become the focus for the remainder of this project due to limited previous research on this mechanism.

Though scouring at the outlet is also a very common failure mechanism, this has already been extensively researched by a number of studies as has been highlighted in section 2.2.1 of the literature review.

Failure of the upstream embankment will also be considered in the remainder of this study as both failure mechanisms occur under similar conditions (during extreme floods with overtopping flows) and potential protection measures against both mechanisms are similar.

Both the upstream and downstream failure will be investigated in the numerical model based on the overall loading on the culvert structure during an overtopping flood event. This is due to limitations of the software not being able to model the mechanics involved in erosion and the effect of 3-dimensional flow.

4.3.2 Model Parameters

The initial model parameters have been determined by averaging the measured geometries and soil proportions from the culverts in the field investigation. Although all the culverts measured had pipes, it was decided that a box culvert would be used in the finite element model. This was due to known complexities involved in developing a model and obtaining accurate solutions for components with circular sections in Strand7.

Instead, the average cross-sectional area for each culvert has been used to select a suitable box culvert based on the collected data. Using nominal sizes provided in product catalogues from Civilmart (2023) shown in figure 4.13, the box culvert with a cross-sectional area closest to the average of 1.68 m2 is the 1.5 m x 1.2 m section which has a cross-sectional area of 1.8 m2.

To slightly simplify the geometry for the model development process, the average height of fill above the obvert has been rounded to the nearest 0.05 m and the width of the embankment from shoulder to shoulder has been rounded to the nearest 1 m.

Culvert Fill height = 0 - 2m Length = 2440 mm			
Inner Span A	Inner Leg B	Mass (tons)	Order Code
1500	600	3.1	CV-156F
1500	900	3.6	CV-159F
1500	1200	3.8	CV-1512F
1500	1500	4.5	CV-1515F
1800	600	3.5	CV-186F
1800	900	3.9	CV-189F
1800	1200	4.1	CV-1812F
1800	1500	4.8	CV-1815F
1800	1800	5.6	CV-1818F
2100	600	3.9	CV-216F
2100	900	4.3	CV-219F
2100	1200	4.7	CV-2112F
2100	1500	5.5	CV-2115F
2100	1800	6.2	CV-2118F
2100	2100	6.7	CV-2121F
2400	600	4.5	CV-246F
2400	900	4.9	CV-249F
2400	1200	5.4	CV-2412F
2400	1500	6.5	CV-2415F
2400	1800	7	CV-2418F
2400	2100	7.8	CV-2421F
2400	2400	9.3	CV-2424F

Culvert Fill height = 0 - 2m Length = 2440 mm			
Inner Span A	Inner Leg B	Mass (tons)	Order Code
2700	600	5.3	CV-276F
2700	900	5.8	CV-279F
2700	1200	6.2	CV-2712F
2700	1500	6.9	CV-2715F
2700	1800	7.8	CV-2718F
2700	2100	8.3	CV-2721F
2700	2400	9.8	CV-2724F
2700	2700	10.3	CV-2727F
3000	600	6.0	CV-306F
3000	900	6.5	CV-309F
3000	1200	6.8	CV-3012F
3000	1500	7.7	CV-3015F
3000	1800	8.2	CV-3018F
3000	2100	9.1	CV-3021F
3000	2400	10.5	CV-3024F
3000	2700	11.2	CV-3027F
3000	3000	11.7	CV-3030F
3300	900	7.6	CV-339F
3300	1200	8.1	CV-3312F
3300	1500	8.7	CV-3315F
3300	1800	9.2	CV-3318F
3300	2100	10.0	CV-3321F
3300	2400	11.5	CV-3324F
3300	2700	12.0	CV-3327F
3300	3000	12.6	CV-3330F

Culvert Fill height = 0 - 2m Length = 2440 mm			
Inner Span A	Inner Leg B	Mass (tons)	Order Code
3600	900	8.5	CV-369F
3600	1200	9.0	CV-3612F
3600	1500	9.6	CV-3615F
3600	1800	10.4	CV-3618F
3600	2100	10.9	CV-3621F
3600	2400	12.3	CV-3624F
3600	2700	13.1	CV-3627F
3600	3000	13.6	CV-3630F
3600	3300	17.0	CV-3633F
4200	900	10.5	CV-429F
4200	1200	11.0	CV-4212F
4200	1500	11.8	CV-4215F
4200	1800	12.6	CV-4218F
4200	2100	13.2	CV-4221F
4200	2400	14.7	CV-4224F
4200	2700	15.2	CV-4227F
4200	3000	17.0	CV-4230F
4200	3600	19.6	CV-4236F

NOTE: Dimensions are nominal, Weights shown are estimates.

Figure 4.13: Box culvert sizes available from Civilmart (2023).

Table 4.3 contains the final key geometrical parameters which will be used to develop the full culvert model.

Table 4.3: Initial parameters for model development.

Type	Internal Dimensions (mm)	Length (m)	Fill above obvert (m)
Concrete box culvert	1500 x 1200	8	1.05

The average proportions of sand, silt and clay in the soil materials for each culvert have been used to classify the type of soil most commonly used as fill material for the embankments using the United States Department of Agriculture (USDA) soil classification triangle in figure 4.14.

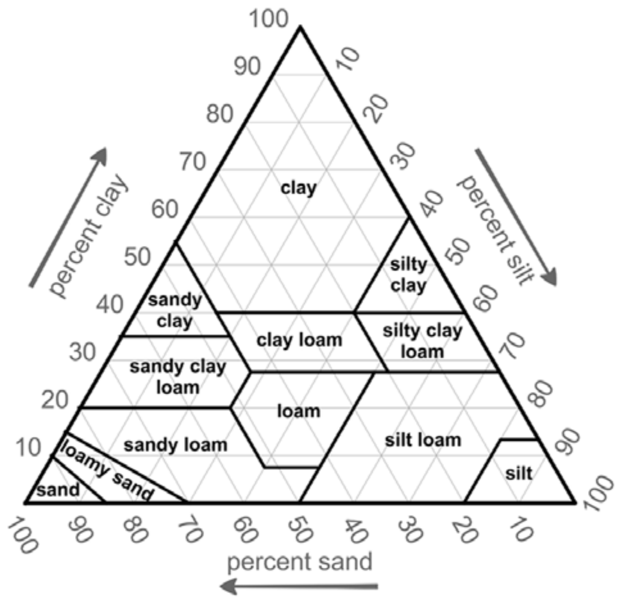

Figure 4.14: USDA soil classification triangle (Lebauer 2011).

Based on the classification triangle and average soil proportions from section 4.2.6, material properties for the embankment in the culvert model will be chosen to represent either sandy loam or sandy clay loam.

Chapter 5

Model Development

5.1 Limitations

Strand7 was used for this finite element analysis due to the availability of support and expertise in using the program within UniSQ itself. Although it is very capable of completing soil analysis problems, it is not necessarily the ideal software to perform a flood analysis of culverts and their embankments.

There are two main limitations to consider when using Strand7 for this type of analysis:

1. Simplified geometry: Because the model is being built manually within the software (i.e. defining nodes, extruding plates and subdividing bricks), the complexity of the model development greatly increases with the introduction of non-square geometries. This refers to using shapes which are not completely square or rectangular such as circles, large triangles or trapezoids.

   It is for this reason that a box culvert has been chosen and the only non-square geometry in the model will be trapezoidal elements representing the embankments and chamfering in the top corners of the box culvert. The crossfall of the roadway and adjoining embankments representing a natural channel have both been omitted from the model and their absence is expected to have little effect on the results of the numerical analysis.

2. Simplified loading: In Strand7, it is only possible to apply pressure loads to the model which are either perpendicular to a surface (normal stresses) or parallel to a surface (shear stresses). The program does not have the capability to apply and analyse the three-dimensional loading expected from a complex water flow regime during a flood event. Therefore, the loading applied to the model will remain two-dimensional representing the principle forces expected from an extreme flood event.

5.2 Verification Model

In order to develop a solid understanding of the modelling techniques required and to verify that the outputs from the software were logical, a simple verification model was created. The model represents a small section of the overall culvert model and includes a 1.8 m x 4 m section of the top of the box culvert as well as the overlying soil and roadway. The development of a verification model serves two main purposes:

- To become familiar with the required modelling techniques and nonlinear solver.
- To verify the outputs from the software are logical and identify and eliminate errors from the modelling process as they arise.

Both of these objectives were much easier achieved with a simplified model rather than the more complex augmented model.

5.2.1 Geometry, Materials and Restraints

The geometry of the verification model is a simple rectangular prism divided into three layers representing the top wall of the box culvert, a layer of soil representing the fill material for the embankment and a layer of fine crushed rock (FCR) representing the roadway (see figure 5.1).

The geometry and relevant properties of the materials used for the verification model are summarised in table 5.1. Further information on the materials used is available in section 5.3.2.

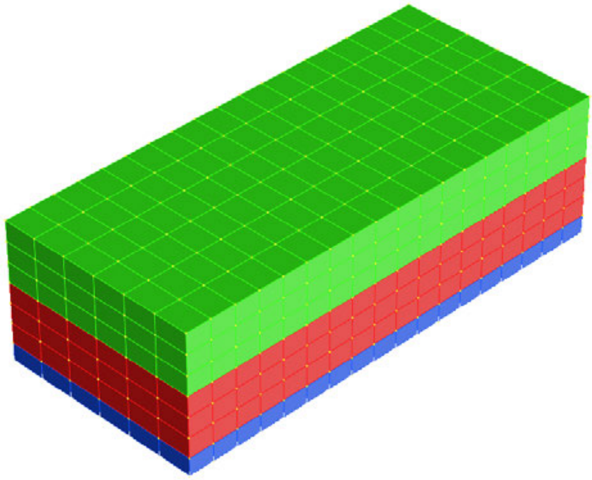

Figure 5.1: Verification model in Strand7.

Table 5.1: Material properties for the verification model.

Layer	Colour	Width (m)	Length (m)	Depth (mm)	E (MPa)
Concrete		1.8	4	150	30,100
Soil Fill		1.8	4	525	30
FCR		1.8	4	525	150

In order to verify the vertical displacement of the verification model, all nodes on the base of the model have been restrained against translation in the x, y and z axis.

Although these restraints will not be in the same location in the full model (i.e. the underside of the top wall of the culvert will not have any restraints applied in the full model), this does not have any meaningful implications for the verification process.

5.2.2 Load Application and Strand7 Solvers

A single vertical load of 5 kPa was applied the top of the verification model which represents a hydrostatic loading induced by a depth of water of 0.51 m, a depth considered extreme but not unreasonable for an overtopping flow in certain scenarios. The verification model has been solved using both the linear and nonlinear static solvers within Strand7, the characteristics of both of which have been explained in section 3.2.2.

The purpose of this is mainly to verify that the outputs from the nonlinear static solver are valid and comparable to both hand calculations and the outputs from the linear static solver.

In order for the nonlinear static solver to work correctly, the in-situ stresses for Mohr-Coulomb defined soils must be calculated. This is completed using a tool built into the software and has produced the in-situ stresses shown in figure 5.2 below.

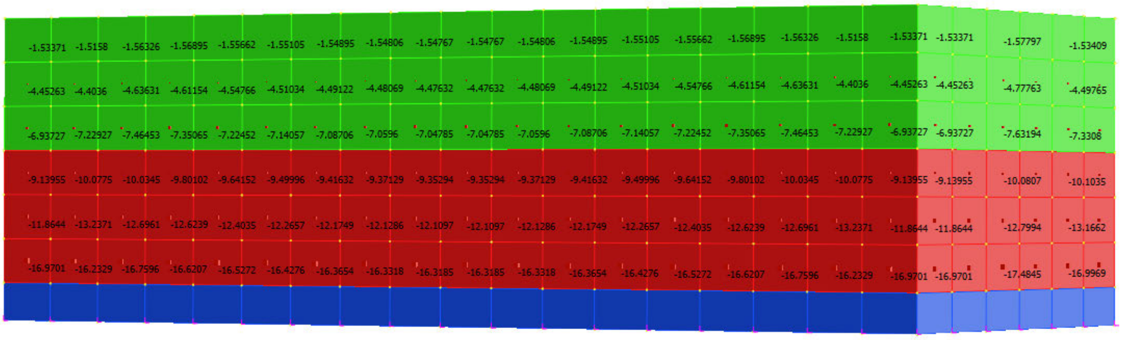

Figure 5.2: Verification model in situ stresses.

As can be seen from figure 5.2, the magnitude of the in-situ stress increases proportionally with the depth of soil material as would be expected since the soil towards the bottom of the model has more weight above it.

5.2.3 Mesh Refinement and Vertical Displacement

In order to verify the outputs calculated by both the linear and nonlinear static solvers, the total vertical displacement of the model under the applied loading was compared between the two solvers and verified against hand calculations. The hand calculations have been made based on a variation of Hooke's law which states:

$$\sigma = E \times \epsilon$$

Where:

σ = Stress (Pa)

E = Elastic modulus (Pa)

ϵ = Strain (dimensionless)

Using this relationship and knowing that:

$$\Delta = \epsilon \times h$$

Where:

Δ = Displacement (mm)

ϵ = Strain (dimensionless)

h = Thickness of material (mm)

The following equation for the vertical deflection of each layer can be derived:

$$\Delta = \frac{\sigma}{E} \times h$$

By applying both equations to each layer in the verification model and summing the results, the expected total vertical displacement can be calculated:

Layer 1 – Concrete: $\Delta = \frac{\sigma}{E} \times h = \frac{5}{3.01 \times 10^7} \times 150 = 2.49 \times 10^{-5}$ mm

Layer 2 – Soil Fill: $\Delta = \frac{\sigma}{E} \times h = \frac{5}{3 \times 10^4} \times 525 = 0.0875$ mm

Layer 3 – FCR: $\Delta = \frac{\sigma}{E} \times h = \frac{5}{1.5 \times 10^5} \times 525 = 0.0175$ mm

Total vertical displacement $= 2.49 \times 10^{-5} + 0.0875 + 0.0175 = 0.105$ mm

The effect of different mesh sizes has also been tested during the verification process. As mentioned in section 3.2.1, a finer mesh size should result in a more accurate solution but will also increase the solution time depending on the processing power of the computer used.

A course, medium and fine mesh were tested for the verification model to demonstrate the effect of mesh size and further verify the outputs of the program. A summary of the three mesh sizes is shown in table 5.2.

Table 5.2: Summary of mesh sizes for the verification model.

Mesh Size	Course	Medium	Fine
Total Nodes	390	2,250	15,827
Total Bricks	240	1,728	13,824

The total vertical displacement for the three mesh sizes calculated by each solver is summarised in table 5.3 below including the difference to the hand calculation in percentage.

From the results of the vertical displacement verification, it can be concluded that:

Table 5.3: Summary of vertical displacements for the three mesh sizes.

Solver	Linear Static		Nonlinear Static	
Mesh Size	Displacement (mm)	% Different	Displacement (mm)	% Different
Coarse	0.0950	9.55	0.1120	6.64
Medium	0.0959	8.97	0.1100	4.74
Fine	0.0964	8.69	0.1094	4.17

- The non-linear static solver better predicts
- The finer mesh sizes produce results closer to expected solutions.
- Discrepancies that do exist between the hand calculations and Strand7 outputs are likely due to the simplified nature of the hand calculations only taking into account the elastic modulus of the material.

5.2.4 Contact Elements

Contact elements are used to define the interaction between different materials in the model such as where the soil from the embankment contacts the concrete box culvert.

The effect of using contact elements in Strand7 was tested in a similar project completed by Greene (2018). He reported that using contact elements significantly increased the complexity of the modelling process and showed that results obtained when using contact elements compared to not using contact elements were very similar.

Due to the findings from that project, the use of contact elements has been omitted from the modelling process for this investigation.

5.3 Culvert Model

5.3.1 Geometry

The general geometry of the culvert and embankment has been adapted from the results of the field investigation and summarised in section 4.3. Although the slope of the embankments were not physically measured during the investigation, all were considered to be very steep and it was estimated that a slope of 1 in 1 or 100% would be reasonable for the model.

Similarly, the length of the embankment either side of the culvert was not able to be measured and varied greatly from culvert to culvert. For the purpose of the model development, the embankment extends 4 m either side of the culvert giving a total embankment length of 9.8 m.

Using all these parameters, the base geometry for the culvert model is provided in figure 5.3 and figure 5.4 with coordinates marking the key vertices of the geometry.

A road base depth of 0.525 m was chosen as this helped maintain a consistent mesh between various mesh sizes and represents a reasonable depth of pavement.

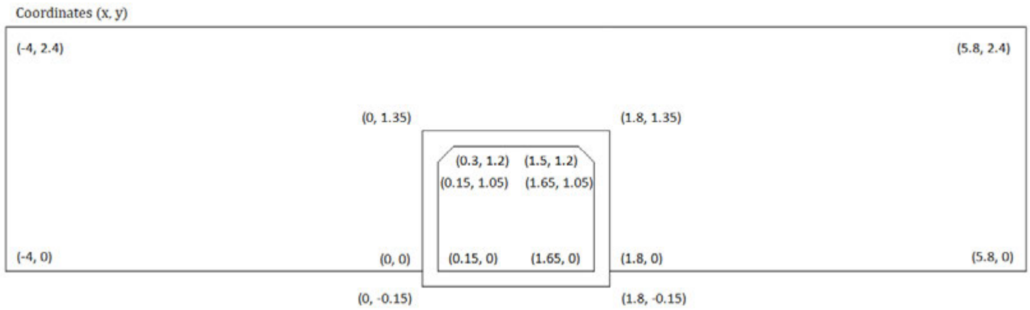

Figure 5.3: Culvert model geometry in the xy plane.

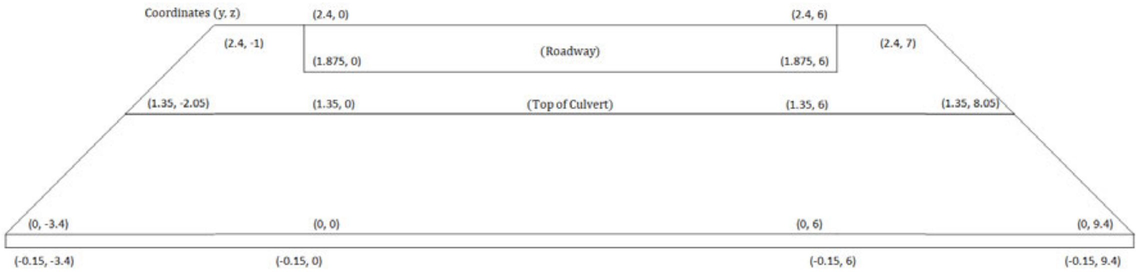

Figure 5.4: Culvert model geometry in the yz plane.

Note that the following geometrical features were omitted from the model due to their addition having negligible effect on the results of the analysis whilst adding significant complexities to the model development process:

- Crossfall of the roadway.
- Bed slope of the culvert or channel bed.
- Approach and departure grades of the roadway.
- Asphalt sealing on the roadway.
- Adjoining embankments representing a trapezoidal channel, a common channel cross-section observed during the field investigation.

5.3.2 Material Properties

Initially, four different materials were used to develop the culvert model namely:

- Concrete with a characteristic strength of 32 MPa for the box culvert.
- Sandy clay loam for the embankment fill material.
- Fine crushed rock to represent the road base.
- High strength compacted soil representing undisturbed adjoining soil.

The properties for the concrete, embankment fill and crushed rock road base are identical to those used in the verification model. The results for the soil classification testing from the field investigation was used to inform the material properties for the embankment fill.

In the absence of in situ soil strength testing, the properties for the sandy clay loam and fine crushed rock have been estimated based on published literature from Geotech data (2023), StructX (2022) and Greene (2018).

A summary of the material properties used for the model development are provided in table 5.4.

Table 5.4: Material Properties used for the culvert model.

Material	E (MPa)	ν	ρ (kg/m^3)	c (kPa)	ϕ (°)	K0	e
Concrete (32 MPa)	30,100	0.2	2400	-	-	-	-
Embankment Fill	30	0.3	1800	20	30	0.5	0.3
FCR Road Base	150	0.35	1800	10	35	0.5	0.4
Adjoining Soil	80	0.3	1800	75	40	0.5	0.3

5.3.3 Model Extents

In order to ensure that boundary restraints applied to the model did not over stiffen the model and heavily influence the results of the analysis, the extent of adjoining soil needed to be determined experimentally. This includes soil adjoining the ends of the embankment as well as soil beneath the base of the culvert. All adjoining soil was assigned properties representing high strength, compacted soil.

Restraints

The following node restraints were applied to the experimental models while determining the extents of adjoining soil:

- All external nodes along the base of the model were fully restrained against translation in the x, y and z direction.

- External nodes on both x oriented faces were restrained against translation in the x direction only, except those at the base which were fully restrained.

- For the adjoining soil at the base of the culvert, both z oriented were restrained against translation in the z direction only, except those at the base which were fully restrained.

- Nodes at the corners of the x and z oriented face were restrained in both the x and z direction.

Loading

The same 5 kPa vertical loading used in the verification model was also applied to the top of the culvert embankment and roadway. A 0.2 kPa shear stress in the z direction was also applied to the top of the embankment and roadway in the assumed direction of flow.

The non-linear static solver was used to determine the model extents as it more accurately predicts the deformation of the materials in all directions than the linear static solver and will be the solver used for analysis in the following chapter.

Side Soil

Additional adjoining soil of 2 m, 4 m and 6 m either side of the embankments were added to the base model (see figure 5.5) and displacements in the x, y and z directions were compared for each case.

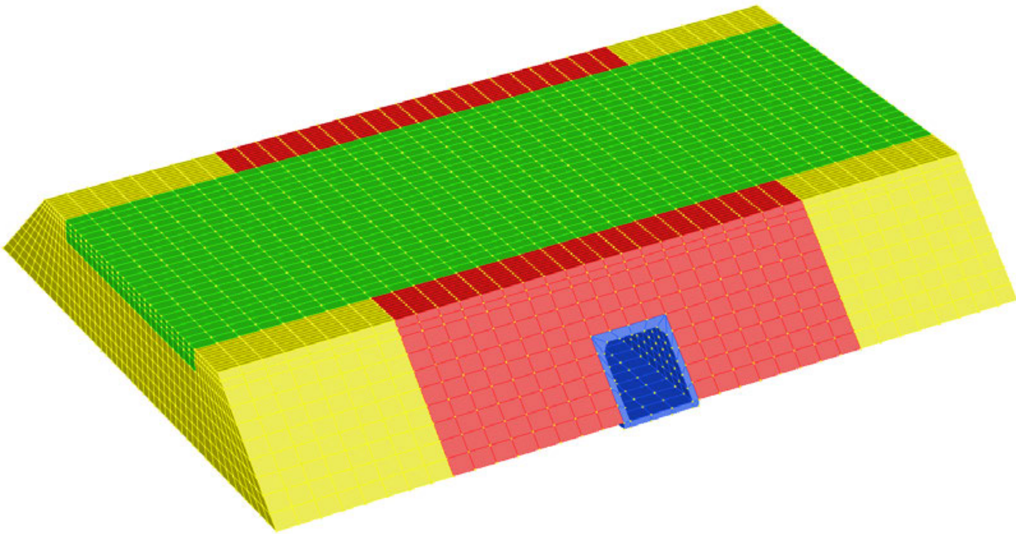

Figure 5.5: Culvert model with adjoining side soil.

These were also compared to having no adjoining soil and applying boundary restraints directly to the sides of the embankment of the base model. The results of the analysis are summarised in table 5.5 with the percentage difference for each case calculated using the 6 m adjoining value as the datum.

Table 5.5: Adjoining side soil analysis results.

Adjoining Soil (Side)	0m	2m	4m	6m
x Displacement (mm)	0.0530	0.0554	0.0565	0.0567
y Displacement (mm)	0.3371	0.3251	0.3255	0.3252
z Displacement (mm)	0.3292	0.2934	0.2925	0.2920

From the results, it was determined that 4 m of adjoining soil either side of the embankment achieved an acceptable level of accuracy (less than 1% difference) when compared to the datum value.

Base Soil

An adjoining soil depth of 1 m was added to the base of the model and extruded either side in the z direction by 0 m, 1 m, 2 m and 3 m (see figure 5.6).

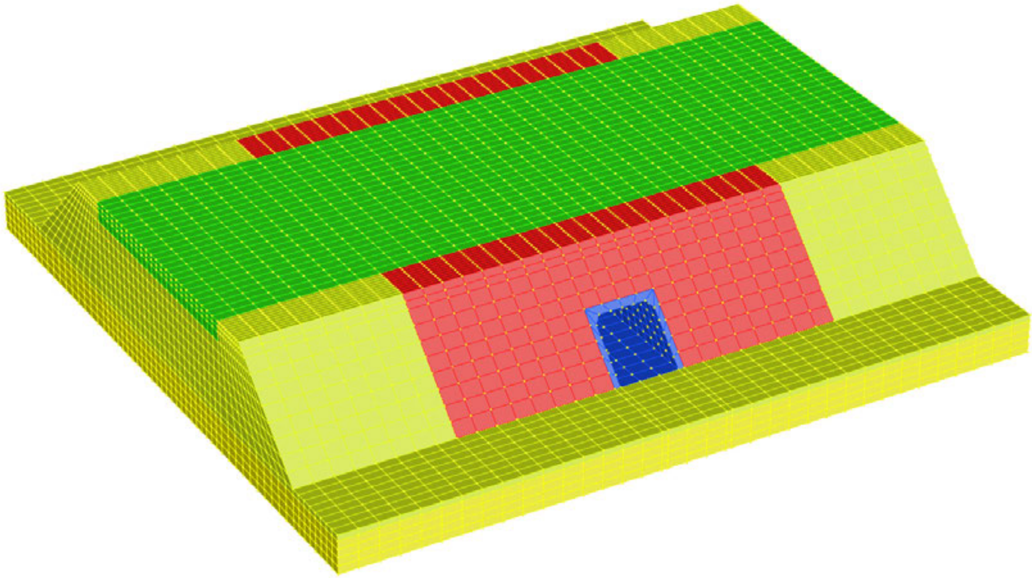

Figure 5.6: Culvert model with adjoining base and side soil.

It was found that adding more than 1 m of adjoining soil to the base of the model caused instability and non-convergence to occur when using the non-linear static solver thus, a depth of 1 m was adopted. The results of the analysis are summarised in table 5.6 with the percentage difference for each case calculated using the base soil extruded by 3 m as the datum.

Table 5.6: Adjoining base soil analysis results.

Adjoining Soil (Base)	1m x 0m	1m x 1m	1m x 2m	1m x 3m
x Displacement (mm)	0.0743	0.0696	0.0691	0.0690
y Displacement (mm)	0.3995	0.3860	0.3880	0.3885
z Displacement (mm)	0.3700	0.3412	0.3460	0.3474

From the results it was determined that 1 m of adjoining soil at the base of the culvert extruded by 2 m in the z direction past the end of the culvert achieved an acceptable level of accuracy (less than 1%) when compared to the datum value.

With the model extents determined, the geometry of the culvert model is finalised and shown in figure 5.7 below.

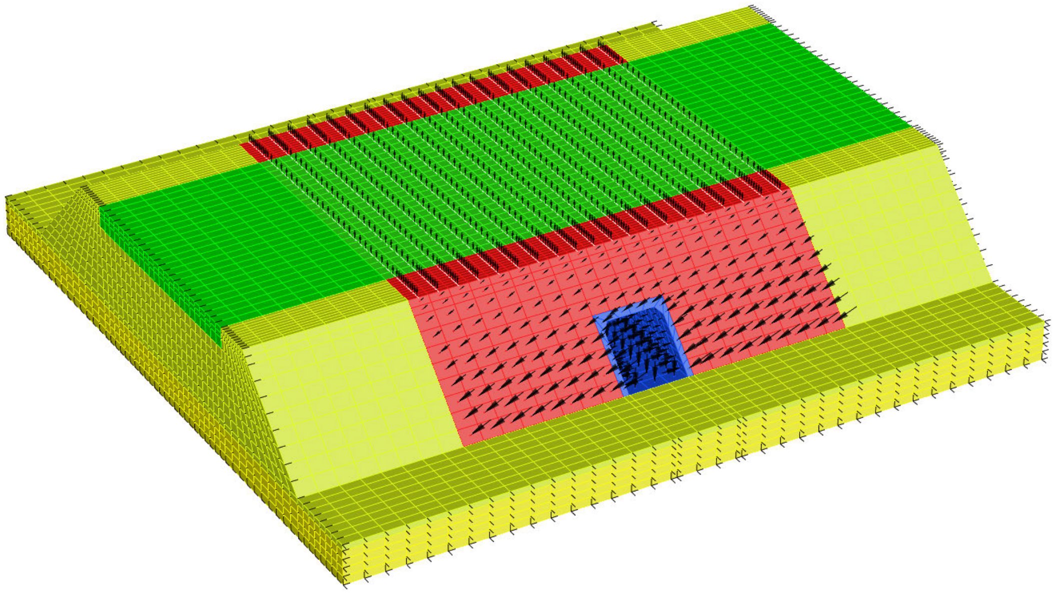

Figure 5.7: Final culvert model with adjoining base and side soil.

5.3.4 Restraints

The node restraints applied to the final model follow the same pattern as explained in section 5.3.3 and is summarised in table 5.7 and shown diagrammatically in figure 5.8.

Table 5.7: Restraints applied to the final culvert model.

Face	Restraint Type	x - axis	y - axis	z - axis
Bottom	Translational	Fixed	Fixed	Fixed
Top	Translational	Free	Free	Free
x Oriented	Translational	Fixed	Free	Free
z Oriented (Adjoining base)	Translational	Free	Free	Fixed
Corner of x/z faces	Translational	Fixed	Free	Fixed

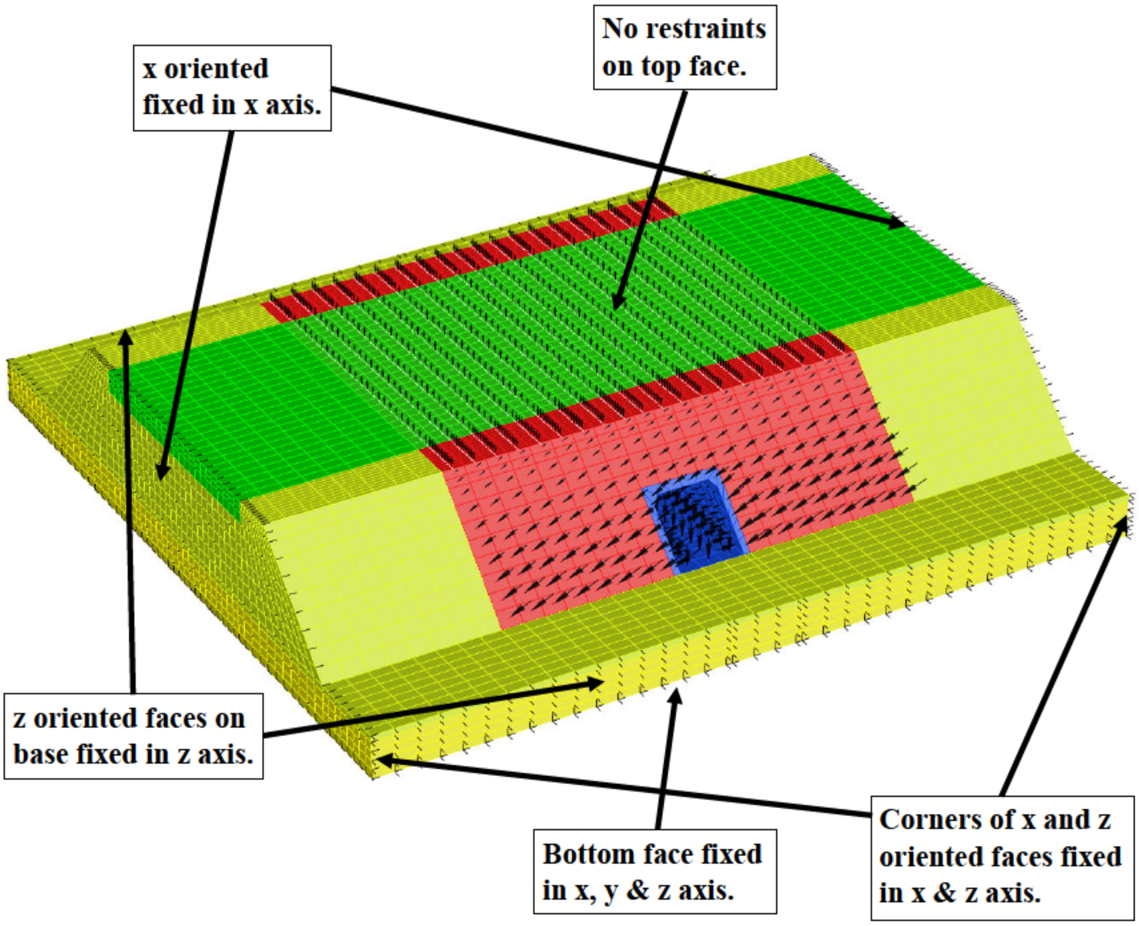

Figure 5.8: Restraints applied to the final culvert model.

The pattern of restraints was chosen in a manner to ensure stability in the model without over stiffening the key areas to be analysed.

5.3.5 Mesh Refinement

To determine a suitable mesh size for the final model, a course, medium and fine mesh were trialled with the same boundary and load conditions applied used to determine the model extents. A summary of the three mesh sizes is given in table 5.8.

Table 5.8: Summary of mesh sizes used for the mesh refinement process.

Mesh Size	Course	Medium	Fine
Total Nodes	5,315	30,693	77,332
Total Bricks	4,770	28,304	72,348

As the density of the mesh increases, the time required for a computer to solve the model also increases significantly. The purpose of the mesh refinement exercise is to find an ideal mesh size which produces accurate results without requiring an impractical solution time.

Displacement in the x, y and z direction were recorded for each mesh size and the percent difference calculated using the results for the fine mesh as the datum. The results from the analysis are shown in table 5.9.

Table 5.9: Summary of results from the mesh refinement analysis.

Mesh Size	Course	Medium	Fine
x Displacement (mm)	0.0784	0.0715	0.0662
y Displacement (mm)	0.3511	0.3883	0.4220
z Displacement (mm)	0.2879	0.3530	0.3469

It was determined that the medium mesh was the most suitable for this project as it was able to produce displacement results within 1% of the fine mesh. The solution time for the medium mesh was consistently around 2 minutes while the fine mesh took over 14 minutes to reach a fully converged solution.

Needing to wait 14 minutes for a solution after each adjustment would make the numerical investigation far too time consuming given the time constraints for this project therefore the medium mesh size is a much more practical option for this project.

5.3.6 Flood Loading

Many culverts are located at sags in the road making them vulnerable to overtopping if blockage occurs or their hydraulic capacity is exceeded. The maximum depth of the overtopping flow can vary significantly depending on the longitudinal geometry of the roadway.

For example, a culvert located along a relatively flat floodplain would likely have a very shallow overtopping depth compared to culvert located at a sag in hilly terrain with steep approach and departure grades.

Hydrostatic Loading

Hydrostatic pressures were applied to the upstream embankment and top of the embankment and roadway using the well-known hydrostatic pressure formula below:

$$P = \rho g h$$

Where:

P = Hydrostatic pressure (Pa)

ρ = Fluid density (taken as 1000 $\mathrm{kg/m^3}$ for water)

g = Acceleration due to gravity (taken as 9.81 $\mathrm{m/s^2}$)

h = Depth of water (m)

A summary of the loading applied at different elevations in the model is given in table 5.10.

Table 5.10: Hydrostatic pressure at different depths in the culvert model.

Depth (m)	0.5	0.631	0.894	1.156	1.419
Pressure (kPa)	4.905	6.193	8.768	11.343	13.918
Depth (m)	1.685	1.955	2.225	2.495	2.765
Pressure (kPa)	16.530	19.179	21.827	24.476	27.125

Hydrostatic Loading Within the Culvert

Hydrostatic pressure within a culvert can vary greatly depending on the flow regime through the culvert which can change depending on a number of factors as is explained in figure 5.9.

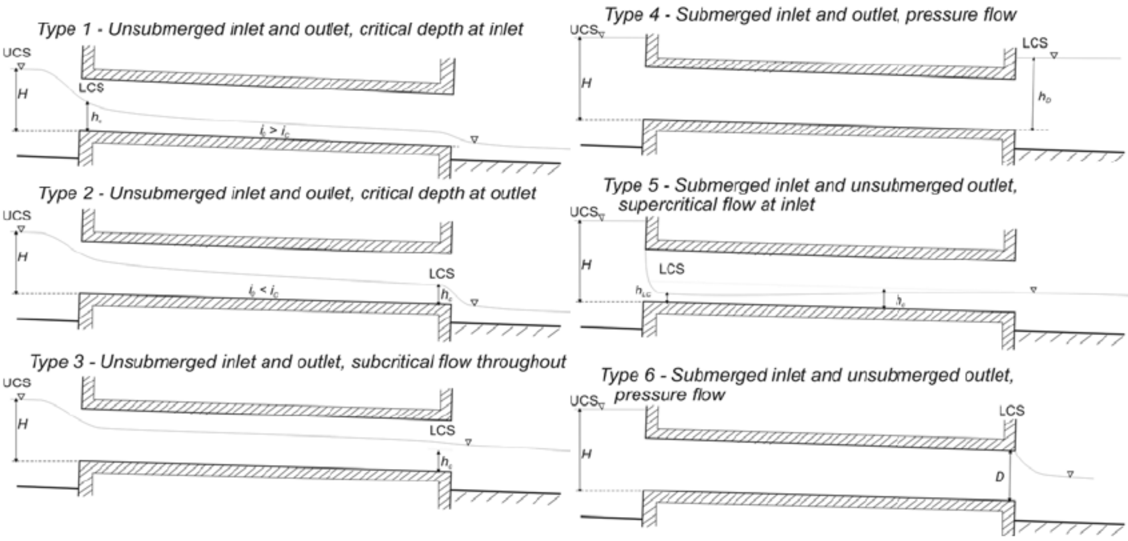

Figure 5.9: Typical culvert flow regimes (Szpakowski 2014).

In order to simplify the loading and take a conservative approach, it was assumed that the culvert would be flowing full and hydrostatic loading representing the full depth of flow was applied throughout the internal length of the culvert as shown in figure 5.10.

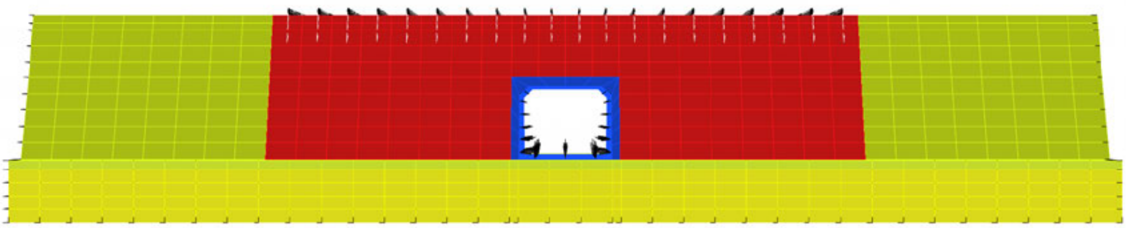

Figure 5.10: Internal hydrostatic loading applied to the culvert model.

A summary of the loads applied at different heights within the culvert itself is given in table 5.11.

Table 5.11: Hydrostatic pressure at different heights within the culvert.

Depth (m)	0.255	0.465	0.675	0.885	1.095	1.2
Pressure (kPa)	2.502	4.562	6.622	8.682	10.742	11.772

Shear Loading

In order to consider the effect of bed shear or drag forces caused by the movement or flow of water, the following formula was used to estimate the magnitude of this loading:

$$\tau_b = \rho g y S_0$$

Where:

τ_b = Bed shear stress (Pa)

ρ = Fluid density (taken as 1000 kg/m^3 for water)

g = Acceleration due to gravity (taken as 9.81 m/s^2)

y = Depth of water (m)

S_0 = Bed slope (Taken as 0.04 or 4%)

Bed shear stress was considered to mainly have an effect on the top of the embankment or roadway and the top portion of the downstream side of the embankment where overtopping water would spill over into the downstream channel. This was applied uniformly to the model considering an overtopping depth of 0.5 m producing a bed shear stress of 0.196 kPa.

It was determined that bed shear on the upstream side of the embankment would likely be non-uniform and would be difficult to predict the exact direction of the stress due to the complex flow regime expected on the upstream side of the culvert. For this reason and due to the calculated shear stress on top of the embankment being negligible compared to the hydrostatic pressure, no bed shear was considered on the upstream side of the embankment.

5.3.7 Other Loads

Traffic Loading

Due to the nature of the analysis undertaken, traffic loading was not applied to the model for the following reasons:

- Traffic loading does not relate to the failure mechanisms being investigated which only occur due to loading caused by extreme flood events.

- The structural design of the culvert itself is not the focus of this project and hence traffic and fatigue loading have little relevance.

- Traffic loading is generally applied as a single point load in a 'worst-case' location along the roadway which would skew the results of the analysis towards failure at that location resulting in an unrealistic output.

Impact Loads

Although additional impact forces resulting from floating debris is common in extreme flood scenarios, the magnitude and extent of these forces varies widely and is very unpredictable. Similar to traffic loading, the application of a single point load representing an impact force would likely skew the output to showing failure at the location of the applied load. It was therefore decided to omit impact loading from the model.

Chapter 6

Numerical Investigation

The model developed in chapter 5 has been solved using the non-linear static solver in Strand7 to analyse the distribution of stress in the embankment. A number of scenarios have then been simulated relating to the common failure mechanisms identified in chapter 4 to identify vulnerabilities and potential solutions to increase the resilience of similar culverts.

Due to the limitations of using Strand7 discussed at the beginning of chapter 5, it would be impractical to attempt to yield exact values which could be used in the design process of similar culverts. Instead, the numerical investigation will take more of an empirical approach where the general behaviour of the culvert and embankment are analysed under the major forces expected during an extreme flood event.

6.1 Downstream Embankment Analysis

The distribution of Mohr-coulomb stresses on the downstream side of the embankment is shown in figure 6.1.

From observing the internal stresses and displacement of soil on the downstream side, it can be seen how this section of the embankment is vulnerable to failure under the applied loading conditions. This is due to the soil being pushed out away from the embankment making it more likely to fail than if it were being compressed together.

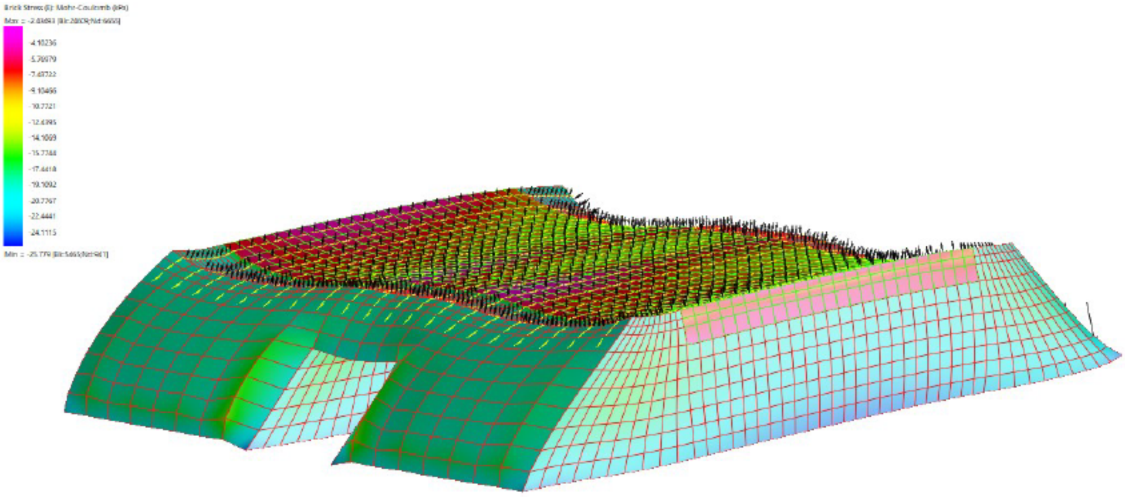

Figure 6.1: Downstream embankment with 5% displacement scale.

6.1.1 Failure Initiation

Identifying where failure is likely to initiate on the downstream side is important as it highlights the area most vulnerable to failure in an extreme flood scenario. In order to observe where failure would likely initiate, using Mohr-Coulomb's theory, we can either increase the applied loading or decrease the strength of the soil.

For this scenario, the cohesion for the embankment fill was reduced from 20 kPa to 5 kPa to initiate yielding in the model shown in figure 6.2.

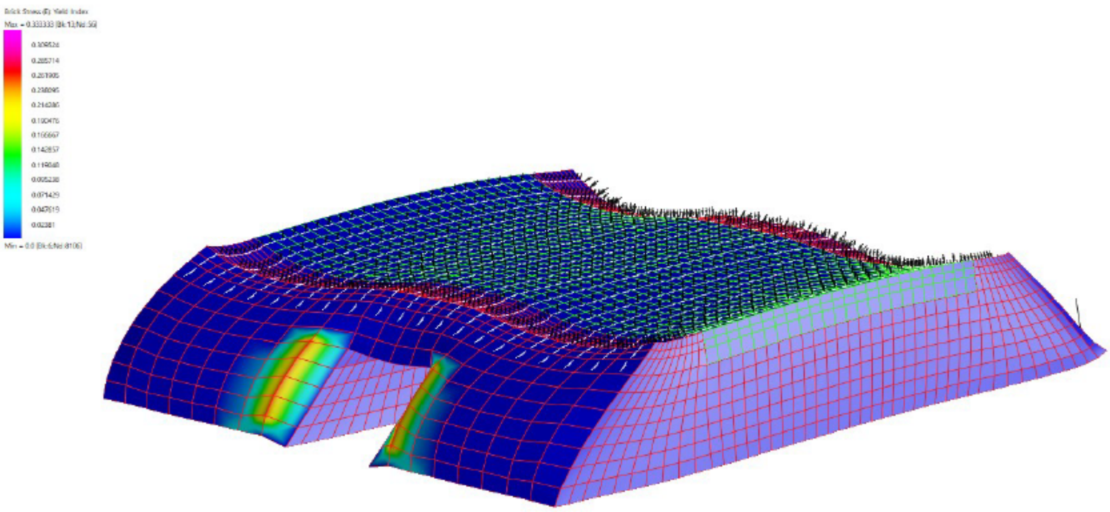

Figure 6.2: Location of failure initiation on the downstream embankment.

As can be seen from the figure, the embankment on the downstream side begins to yield directly adjacent to the box culvert on either side.

6.1.2 Addition of Headwall

From section 6.1.1 it was observed that failure of the embankment would begin to initiate directly adjacent to the box culvert in the outer layer of soil. Many culverts, particularly box culverts, have concrete or brick headwalls which protect the soil immediately around the culvert. Headwalls were not added to the original due to complexities in developing the exact geometry they generally take.

However, to ensure results were not undermined by not considering these in the numerical analysis, the effect of a headwall was simulated by changing the material properties of soil elements directly surrounding the culvert as shown in figure 6.3.

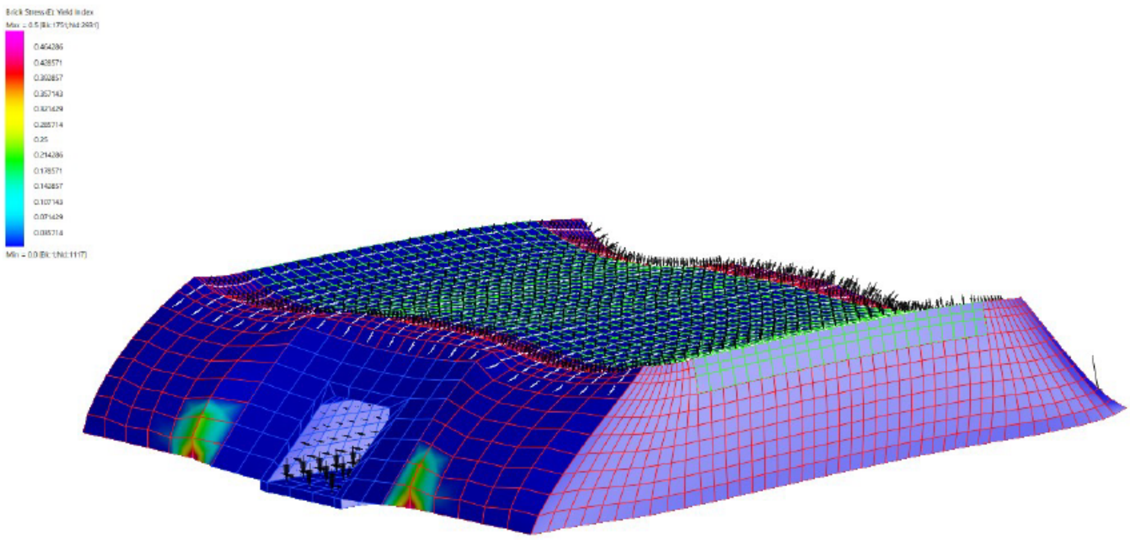

Figure 6.3: Downstream embankment with addition of concrete headwall.

The headwall was assigned the same concrete material properties as the box culvert itself.

Without increasing the strength of the embankment fill back to its original material properties, the model was solved with the addition of the concrete headwall on the downstream side.

The results for the Mohr-coulomb yield index were then analysed to observe the effect of the concrete headwall. As can be seen from figure 6.3, the addition of the headwall does not prevent failure from initiating and instead, the soil begins to yield directly adjacent to the headwall.

This is supported by figure 6.4 which shows the box culvert analysed in chapter 4 where the downstream side of the embankment failed despite the presence of a substantial concrete headwall.

Figure 6.4: A heavily damaged box culvert analysed during the field investigation.

6.1.3 Failure Prevention

The final modelling scenario for the downstream failure mechanism was aimed at identifying changes to the model which could prevent failure from initiating in the scenario presented in section 6.1.1.

While the obvious solution is to increase the strength of the embankment fill used in the model, it was found that manipulating the material properties for the outermost layer of soil on the downstream embankment had a significant effect on the failure initiation.

If only the outer layer of soil on the downstream side of the embankment is given the same high strength properties as that of the adjoining soil in the model, it can be seen in figure 6.5 that none of the soil in the model begins to yield.

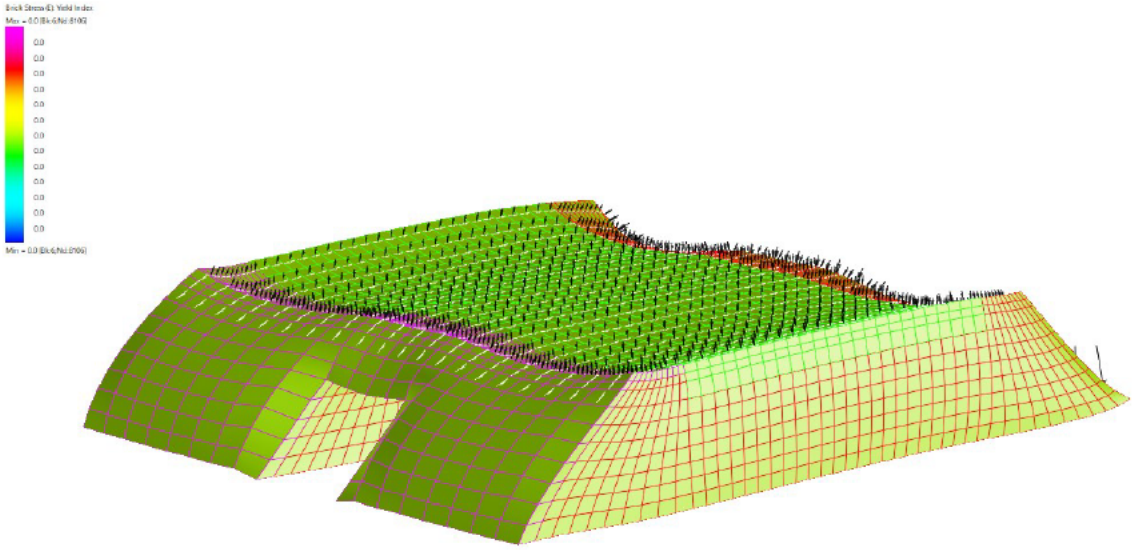

Figure 6.5: Yield index after strengthening outer layer of soil (downstream).

The same result is achieved if this layer of soil is changed to the same 32 MPa concrete used for the box culvert. This scenario represents full concrete armouring of the embankment and prevents the soil from being pushed out away from the embankment as demonstrated in section 6.1.

6.2 Upstream Embankment Analysis

In figure 6.6, the Mohr-coulomb stresses in the upstream side of the embankment is shown with the original flood loading and material properties applied.

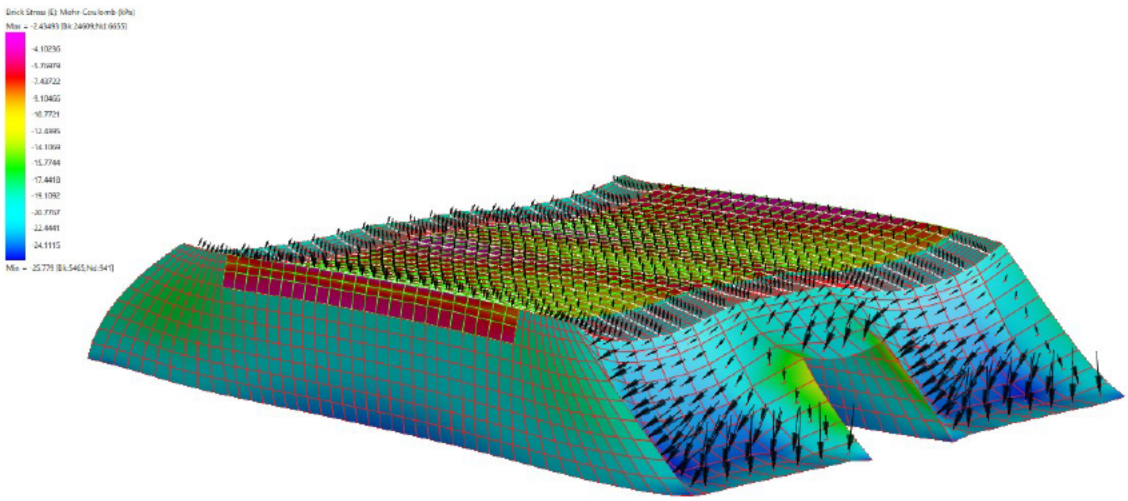

Figure 6.6: Upstream embankment with 5% displacement scale.

Although the stresses are higher on the upstream side due to the hydrostatic loading, the soil is being compressed into the embankment meaning it does not share the same vulnerability to failure as observed on the downstream side of the embankment.

6.2.1 Failure Initiation

Similar to the downstream failure scenario, in order to observe where failure is likely to initiate on the upstream side of the embankment, the cohesion of the embankment fill was reduced until yielding began to occur.

Since it had been observed that this failure mechanism generally occurs due to seepage through the embankment from the upstream side, only the strength of the material on the upstream portion of the embankment was reduced to almost zero to simulate a saturated soil condition and prevent failure from initiating on the downstream side.

The cohesion for the upstream section of the embankment was reduced from 20 kPa to 2 kPa and the results for the Mohr-Coulomb yield index is shown in figure 6.7.

From figure 6.7, it can be seen that yielding begins to initiate around the top corners of the box culvert. It would be expected that once the initial layer of soil failed, deeper layers of soil would continue to progressively failure as water seeps further throughout the embankment.

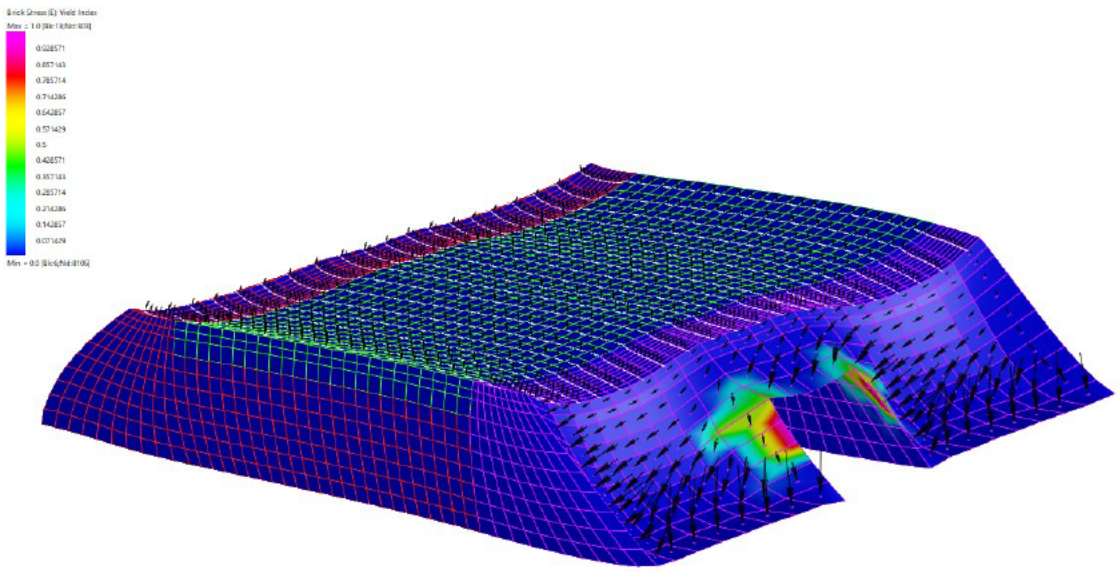

Figure 6.7: Location of failure initiation on the upstream embankment.

6.2.2 Addition of Headwall

As the failure began to initiate around directly around the box culvert in section 6.2.1, a headwall was added to the model on the upstream side. This was done using the same method as the headwall added to the downstream side in section 6.1.2. Similar to the downstream scenario, the addition of the headwall did not prevent failure from initiating as yielding still occurs at the top corners of the headwall as shown in figure 6.8.

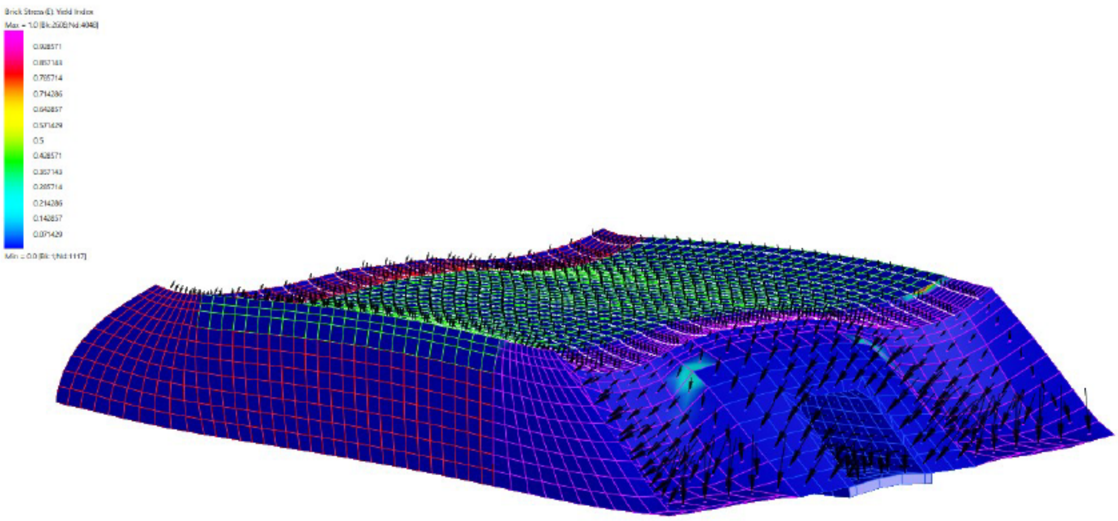

Figure 6.8: Upstream embankment with addition of concrete headwall.

The addition of the headwall did however decrease the extent of the yielding suggesting that its addition does have a significant positive effect in reduce failure on the upstream side of the embankment.

6.2.3 Failure Prevention

The final modelling scenario for the upstream failure mechanism was concerned with identifying options for preventing the failure of the embankment initiating. This failure mechanism differs slightly from the downstream failure mechanism as failure typically results from water seeping into the embankment reducing the strength of the soil.

Therefore, one solution for preventing failure from initiating on the upstream side is to prevent the seepage of water into the embankment altogether.

Similarly, if the strength of the material in the outer layer of soil is increased, like in section 6.1.3, failure does not initiate as shown in figure 6.9.

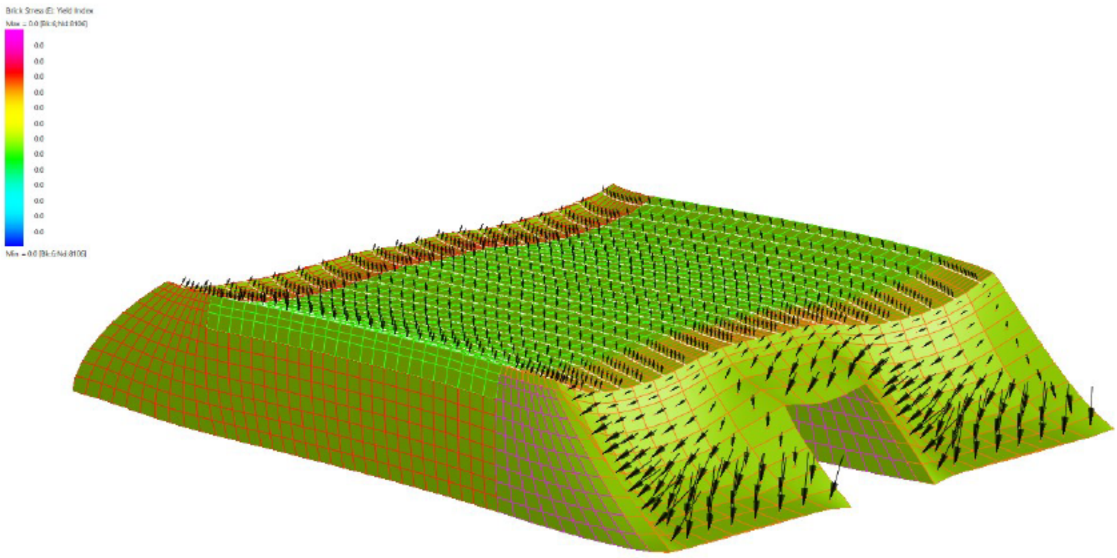

Figure 6.9: Yield index after strengthening outer layer of soil (upstream).

6.3 Improving Resilience

From the numerical investigation, it was found that the resilience of similar culverts in extreme flood events can be improved by:

- Using higher strength soil as the embankment fill
- Increasing the strength of the outer layer of soil on the upstream and downstream side of the embankment
- Decreasing the permeability of the soil on the upstream side of the embankment

There are a number of products and strategies that can achieve these requirements and are discussed in the following sections. Due to the nature of the modelling process, it was not possible to accurately model each possible solution and rank their effectiveness.

6.3.1 Rip Rap

Rip rap is possibly the most commonly used technique for providing protection against erosion and scouring, likely due to the guidance prescribed in part 5b of Austroads Guide to Road Design. It is an effective method for controlling scouring at culvert outlets and is also commonly used for protection around floodways and bridge piers for the same reason.

In many cases, rip rap or rock protection is also used as a method of embankment protection for culverts. Though it is somewhat effective at protecting embankments against failure from outlet scouring or erosion, it does not reduce the permeability of the soil or increase the strength of the embankment in any way.

Actual Repairs

It was noticed in some instances in the field investigation that rock protection was a common method of providing some protection to the embankment of culverts. In the time since the field investigation was completed, a number of the culverts analysed were fully repaired by local councils.

Figure 6.10 below shows the new culvert near Rutherglen which experienced a complete washout.

Figure 6.10: Replaced culvert near Rutherglen, Victoria (Indigo Shire Council 2023).

From figure 6.10, it can be seen that rip rap has been provided right around the base and headwall of the new box culvert.

Figure 6.11 shows the repaired state of the culvert in Bethanga which sustained substantial damage to the downstream side of its embankment.

Figure 6.11: Repaired culvert near Bethanga, Victoria.

In this case the original box culvert was preserved and the washed-out embankment fill replaced with crushed rock with rip rap placed over the top. It can be seen that a large amount of the rock protection on the left side of the embankment has already been fully dislodged. This is due to the presence of a low spot on the embankment caused by settlement during the flood event now resulting in water draining from the roadway down the left-hand side of the embankment.

Because no work was done to regrade the roadway, there is a significant risk of erosion continuing on the downstream side of the embankment every time a rain event occurs. This could lead to another failure of the embankment without an extreme flood event occurring.

A similar repair was made to one of the culverts personally inspected in the field investigation where a large amount of erosion occurred adjacent to the culvert outlet. Similarly, the eroded section was backfilled with crushed rock with rip rap placed over the top as shown in figure 6.12.

Figure 6.12: Culvert repair using crushed rock and rip rap.

6.3.2 Vegetation

Planting vegetation such as grass, shrubs or trees is commonly used in many applications to stabilise embankments and slow the effects of erosion. This is due to root systems having the effect of binding the outer layer of soil together and effectively increasing its cohesion.

Grass also has a tendency to slow or completely prevent the transportation of soil which mitigates the mechanics of erosion caused by water run-off.

It is difficult to predict or simulate the effectiveness of vegetation as a protection mechanism for culvert embankments due to a wide range of variables involved.

There are also a number of potential limitations when considering vegetation as a solution, the main limitations being:

- Maintenance: Sufficient water needs to be provided, particularly in hotter climates or the vegetation will simply die off. Once fully established, it also needs to be trimmed regularly to prevent overgrowing onto the roadway or potentially blocking or obstructing the culvert itself.

- Space: Not all culvert embankments have sufficient space to plant an effective amount of vegetation. It may also be difficult to plant and grow vegetation on embankments with steep slopes.

6.3.3 Cement/Lime Stabilisation

Cement and lime stabilisation is a commonly used technique for increasing the strength of soil layers in road pavements. Though there is limited literature available on their application for stabilising embankments, it is a potential solution worth considering for increasing the strength of outer layers of culvert embankments.

It would also need to be determined whether this could be a cost-effective approach for increasing the resilience of culverts.

6.3.4 Concrete Armouring

It was demonstrated in the numerical modelling that providing full concrete armouring of the downstream side of the embankment was effective at preventing failure initiation in an extreme food scenario.

Similarly, it is just as effective for reducing the likelihood of the upstream failure mechanism occurring due to the extremely low permeability of concrete and its ability to protect the soil from the forces applied under flood loading.

With full concrete armouring, the embankment would effectively function as a spillway in an extreme flood event and this option would have the highest likelihood of increasing a culverts resilience in such a scenario.

However, it would likely be an expensive solution and require a cost-benefit analysis to determine this solutions real-world viability.

6.3.5 Geotextiles

Geotextiles are another potential solution for increasing the resilience of culverts against the failure mechanisms analysed in this report. High strength geofabric could be used to reinforce the downstream side of the embankment and help prevent soil separating from the embankment.

Geomembranes could be used on the upstream side to prevent water seeping through the embankment if a blockage occurs or the capacity of the culvert is exceeded in an extreme flood event.

Once again, the actual effectiveness of geotextiles was not able to be tested in the finite element modelling and the cost of the material and its installation would need to be analysed for financial viability.

6.3.6 Embankment Slope

The steepness of the embankment would also likely have an impact on the resilience of a culvert. It was intended to create another model as part of the numerical investigation to analyze the effect of reducing the embankment slope however, this did not occur due to the time constraints for this project.

It would be expected that reducing the slope of the embankment as much as practical would reduce the likelihood of the downstream failure mechanism occurring.

Reducing the slope would also make protection such as rip rap more effective as it would be less likely to become completely dislodged.

Chapter 7

Conclusions and Future Research

7.1 Summary and Recommendations

The need to improve the resilience of road infrastructure in Australia has largely come into focus in recent years as a result of extensive damage to road networks across eastern Australia caused by widespread flooding. It is likely that extreme flood events will increase in frequency in the future due to the effects of climate change creating an urgent need for further research in this area.

There has been limited research focussed on the design of culverts and culvert protection in recent decades leading to little advancements in their design and resilience to extreme events. Though part 5b of Austroads Guide to Road Design does provide some details on outlet protection and end treatments for culverts, only Queensland's Department of Transport and Main Roads provides specific guidance on downstream embankment protection to improve the resilience of culverts in extreme scenarios.

It was found in the field investigation that failure or damage to the downstream side of culvert embankments due to overtopping flood waters is a very common failure mechanism for culverts subjected to extreme flood events.

It was also found that complete failure is likely if overtopping occurs for an extended period of time or if headwater is able to seep into the embankment from the upstream side such as in the scenario of a blocked culvert.

By developing a simplified finite element model of a typical culvert in Strand7, the vulnerability of the downstream side of a culvert embankment in an extreme flood scenario was able to be determined and analysed. It was found that providing a headwall at the downstream outlet of the culvert did little to prevent failure from actually occurring.

Instead, by increasing the strength of the outer layer of soil on the downstream embankment or providing full concrete armouring, this vulnerability could be controlled to an extent. Similar conclusions were drawn for preventing failure on the upstream side of the embankment however, preventing water seepage through the embankment would be the primary consideration for mitigating the risk of the upstream failure mechanism.

A number of potential solutions for improving the resilience of culverts against the failure mechanisms analysed were also discussed based on the numerical analysis. These include the utilisation of riprap, vegetation cover, cement or lime stabilisation, concrete armouring, geotextiles and reducing embankment slopes.

Although riprap is widely used as embankment protection, likely due to being the only culvert protection measure detailed in Austroads, it is not necessarily the best solution for protecting against embankment failure as it does not increase the strength of the underlying soil or prevent seepage.

Therefore, based on the outcomes of this project, it is recommended that local councils consider improving the resilience of major culverts to extreme flood events using either the alternative solutions proposed in this report or adopting section 9.21 of Queensland's Department of Transport and Main Roads Road Drainage Manual.

This could be done by either identifying vulnerable culverts and retrofitting or providing protection as part of repair or replacement works following a flood event. This would serve to not only benefit local communities in the aftermath of extreme flood events but also reduce the cost of road repairs during the disaster recovery period.

7.2 Project Outcomes

The aim of this project was to generate a better understanding of how culvert structures can be better protected or reinforced in a cost-effective manner to improve their resilience during major or extreme flood events. In order to satisfy this project aim, the following objectives were achieved:

1. *Identify the most common failure mechanisms for culverts based on recent flood events in northeast Victoria and identify similarities in geometry and mate rials used.*

   This was achieved in chapter 4 where a field investigation was completed and identified the common failure mechanisms to be analysed in the remainder of the project. During the field investigation, a number of damaged culverts where personally inspected and measurements were taken to help inform the development of a finite element of a culvert. Soil samples of the embankment fill used for each culvert were also taken to conduct basic soil classification testing to inform the material properties used in the finite element model.

2. *Develop a finite element model in Strand 7 of a culvert based on the identified similarities in geometry and materials.*

   Using the measurements and results from the soil classification testing conducted as part of the field investigation, a 3-dimensional finite element model of a box culvert was created in Strand7. The process of developing the model is detailed in chapter 5.

3. *Apply flood loadings to the model and simulate a range of scenarios to identify vulnerabilities and potential solutions to increase the resilience of culverts.*

   A simplified flood loading was applied to the model in chapter 5 taking into ac count hydrostatic and bed shear loads. A range of scenarios were simulated as part of the numerical investigation in chapter 6 including identifying the vulnerability to failure of the downstream side of the embankment and the location where failure is likely to initiate.

It was found that increasing the strength of the outer layer of soil of the embankment increased the resilience to failure. The upstream embankment failure scenario was also analysed with the primary cause of failure in this scenario being attributed to seepage from high headwaters.

4. Provide recommendations on how to best increase the resilience of culverts based on results from the finite element modelling and field investigation.

A number of potential solutions for increasing the resilience of similar culverts where also proposed in chapter 6. Final recommendations based on the project outcomes are detailed in section 7.1.

7.3 Future Research

The need to improve the resilience of current road infrastructure in Australia means there are many potential avenues for future research in this field. In terms of improving the resilience of culverts specifically and continuing from the findings of this project, it would be beneficial to society for future research to focus on the following areas:

- Developing a Computational Fluid Dynamics (CFD) of a culvert to better understand the forces imposed by flood waters in an extreme flood event.

- Develop a more accurate and less simplified finite element model of a culvert to be analysed under loads deduced from a CFD analysis.

- Further investigate and quantify the effectiveness of potential protection measures proposed in this report.

- Complete a cost-benefit analysis for each protection measure and establish a framework to help inform which measure would be best suited for a particular scenario.

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Appendix A

Project Specification

ENG4111/4112 Research Project
Project specification

For:	Philip Stahl
Title:	Investigation of culvert failures during extreme flood events.
Major:	Civil engineering
Supervisors:	Weena Lokuge Karu Karunasena
Enrolment:	ENG4111 – ONL S1, 2023 ENG4112 – ONL S2, 2023
Project Aim:	To identify common failure mechanisms of culverts in the Lake Hume area during extreme flood events and identify practical methods of increasing the resilience of similar structures based on numerical modelling.

Programme: Version 2, 3rd May 2023

1. Complete a review of existing literature relating to culvert design and culvert damage/failure during flood events.

2. Document local culvert damage and establish similarities in failure mechanisms, geometries and materials used.

3. Determine a ‘typical’ geometry, estimate the forces acting during an extreme flood event and estimate typical material properties to be used in the numerical analysis.

4. Develop a model of a culvert structure using Strand7 and adjust forces to simu late the commonly observed failure modes.

5. Establish the main material or geometrical properties which most effect the structures vulnerability to the observed failure modes.

6. Determine practical methods that can be employed to decrease the structures vulnerability based on results from the numerical model and rank their effectiveness.

   If time and resources permit:

7. Perform a cost-benefit analysis of the methods identified in the part 6.

Appendix B

Ethics and Consequences

The outcomes of any research project can be seriously compromised if the research is not conducted ethically and responsibly. The following ethical issues have been identified as having the potential to create negative consequences from this research project:

- Purposely ignoring data or results which could impact the conclusions of the research.

- Manually altering data or results to suit the objectives of the research.

- Repeating research or claiming someone else's research as your own.

- Interpreting results from studies which are beyond your level of knowledge or outside your area of competency.

- Advising solutions which are not sustainable or could have negative effects on communities and the environment.

If any of the ethical issues above were to occur, the following consequences could arise:

- The conclusions in the report could be incorrect and lead to someone being misinformed and implementing an inadequate solution.

- A large amount of money could be wasted implementing a solution which is inadequate.
- Copyright infringement could occur.
- The conclusions of the report may encourage unsustainable practices in the community.

It is the intention of this project to ensure that research has been conducted ethically to ensure none of the above consequences as a result of this report.

Appendix C

Risk Management

Appendix C contains the risk management plan completed prior to the commencement of research activities associated with this project. The purpose of this exercise is to ensure the safety of those immediately conducting the research and the wider community.

2480	RISK DESCRIPTION	TREND	CURRENT	RESIDUAL
	Honours Project - Investigation of Culvert Failures		Low	Low

RISK OWNER	RISK IDENTIFIED ON	LAST REVIEWED ON	NEXT SCHEDULED REVIEW
Philip Stahl	23/05/2023	23/05/2023	23/05/2024

RISK FACTOR(S)	EXISTING CONTROL(S)	CURRENT	PROPOSED CONTROL(S)	TREATMENT OWNER	DUE DATE	RESIDUAL
Snake bites.	Control: Wear long pants and enclosed boots. Take measurements during cooler months when snakes are less active.	Low	No Control:			Low
Insect bites.	Control: Wear long sleeve clothing and insect repellent.	Low	No Control:			Low
Collecting measurements in close proximity to roadways.	Control: Take a second person to spot for traffic and only work on roads with low traffic.	Low	No Control:			Low
Slipping/falling while collecting measurements or inspecting a culvert.	Control: Only inspect/measure culverts where safe access is possible.	Low	No Control:			Low
Injury from sitting at desk for too long.	Control: Take regular breaks and stretch regularly.	Low	No Control:			Low
Inaccurate conclusions from project.	Control: Conduct research ethically and with integrity.	Low	No Control:			Low