ANALYSIS OF SPECIAL PERFORMANCE VEHICLE-BARRIER CRASH AND ITS IMPACT ON THE FOUNDATION OF AN INTEGRAL BARRIER-WALL SYSTEM

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Statement of Authentication

Date: 24/06/2018

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The work presented in this thesis is, to the best of my knowledge and belief, original except as acknowledged in the text. I hereby declare that I have not submitted this material, either in full or in part, for a degree at this or any other institution.

Author’s Signature

.................................
Abstract

Use of roadside safety barriers has greatly enhanced highway safety and reduced the severity of traffic accidents and injuries. Generally speaking, safety barriers should be sufficiently designed to contain and redirect the vehicle away from its errant travel without causing any severe injuries to vehicle occupants and road pedestrians. A significant body of literature already exists on designing roadside safety barriers to achieve high standards of safety to road users, but the literature, in general, does not provide clear insights on the effects of vehicular impact on the foundation of the barrier systems. Although the 2D plane-strain approach is commonly used for the stability design of the retaining structures including barrier systems, none of the design codes in Australia, USA and Europe provide adequate guidance to convert the vehicular impact loading to an equivalent plane-strain loading. The consequence of this is that there is a lot of guesswork without much rational basis currently being applied within the geotechnical community to analyse vehicular impact loading on foundations.

This thesis is concerned with a finite element study of a vehicle crash against the safety barrier system and its impact loading on the system foundation. The possible combinations of vehicle-barrier system crash are extremely large, but this thesis is only focused on the combination of a 44t special performance vehicle crashing against the barrier crash of a 3m high reinforced concrete integral barrier-wall system. The integral barrier-wall is a type of system where the barrier is fully integrated with and located at the top of the retaining wall. Moreover, a 44t special performance vehicle is the largest class of vehicle by weight to which the safety barrier is to be designed against based on current design codes. This class of safety barrier is known as the “44t special performance level” barrier and it is the highest class specified in AS5100.2:2017. It has been chosen for this study because of the potential catastrophic effects of such a crash not just on the vehicle and its occupants, but also on the integrity of the foundation of the barrier-system.

One of the main reasons numerical modelling is such an important tool in vehicle-barrier crash study is because full-scale physical crashes are very expensive to conduct, and the larger the crash the more costly will be the test. Very few full-scale tests have actually been conducted for the vehicle-barrier crash of the 44t special performance level. The lack of real test data is also compounded by the fact that vehicle-barrier crash tests were mainly concerned with the performance of the safety barriers, and paid little heed to the...
performance of the barrier system foundation.

Therefore, the main goal of this thesis is to develop a 3D finite element model of the 44t special performance vehicle-barrier crash which impacts a 3m high integral barrier-wall system. The model was created and analysed using Abaqus/Standard and Abaqus/Explicit software. It was calibrated against the design impact loading for a 44t special performance vehicle specified in AS5100.2:2017, and the calibrated model was then used to perform further numerical simulations to investigate the foundation responses due to the impact loading. This study has defined foundation responses as: (1) mobilised normal reaction (2) mobilised moment reaction (3) mobilised shear resistance of the foundation at the foundation-soil interface. Based on these analyses, an effective length corresponding to the length to which the impact loading of the vehicle-barrier crash has dispersed along the foundation is established. The effective length is then used to calculate the equivalent 2D plane-strain loading to apply in the stability design of the 3 m integral barrier-wall system.

In addition, a sensitivity study was carried out to assess the mobilised effects on the foundation by varying the impact angle and impact velocity. It is found that the effective length is only marginally sensitive to these variations. Hence it may be surmised that the recommended effective length and 2D-plane strain loadings are reasonably robust.
Acknowledgment

Completing the Masters of Research degree has been a responsible and a challenging goal for me in the last two years, especially during second-year (research year) of this degree. Despite me working hard on this research project, there are few other people whom I would like to thank for helping me to achieve the target and make my research successful.

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<td>( \Delta t )</td>
<td>Time increment</td>
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<td>( \mu )</td>
<td>Viscosity parameter</td>
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<td>( 2D )</td>
<td>Two-dimensional</td>
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<tr>
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<td>( AS/NZS )</td>
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<td>( Km/hr )</td>
<td>Kilometre per hour</td>
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kN/m  Kilonewton per meter
$L_L$  Vehicle contact length for longitudinal loads
$LRFD$  Load Resistance Factor Design
$L_T$  Vehicle contact length for transverse loads
$L_V$  Vehicle contact length for vertical load
$m$  Meter
$mm$  Millimetre
$MSE$  Mechanically stabilised earth
$MwRSF$  Midwest Roadside Safety Facility
$NCHRPI$  National Cooperative Highway Research Program
$Pa$  Pascal
$P_u^*$  Ultimate design transverse load
$RSW$  Reinforced soil wall
$s$  Second
$S_i$  Stress state
$t$  Tonne / Time
$\Delta t$  Time increment
$T.M.$  Tensile meridian
$TL$  Test level
$TTI$  Texas A&M Transportation Institute
$US$  United states of America
$V$  Velocity
$VCB$  Vertical concrete road safety barrier
$VRS$  Vehicle restraint system
$WHO$  World Health Organization
$I$  Internal load vector
$M$  Diagonal lumped mass matrix
$R$  Applied load vector
$u$  Displacement
$\ddot{u}$  Acceleration vector
$\ddot{u}$  Velocities
Chapter 1

Introduction

1.1 Background and impetus for research

With increasing road infrastructure developments around the world, a key challenge for engineers is in achieving not only a cost-effective infrastructure design but also in ensuring high standards of safety to road users. A critical aspect of safeguarding highway safety is the installation of roadside safety structures such as barriers, railing and crash cushions to reduce vehicle-infrastructure crash fatalities and injuries. There is already a considerable volume of literature on designing roadside safety structures to contain, redirect and decelerate an errant vehicle away from the safety structure, and to stop it safely. However, the literature, in general, does not emphasize cost-effective design that ensures infrastructure stability when subjected to vehicular impact. To make matters worse, the stability design of retaining structures in practice is mainly based on 2D plane-strain approach for which the specification of impact loading is highly ambiguous. When design engineers refer to design codes, these references provide little or no guidance to help translate the vehicular impact loading to equivalent 2D plane-strain loading.

This master thesis is focussed on the effects caused by a heavy vehicle impact loading (of the “44t special performance level” defined in AS5100.2:2017) on the foundation of an integral reinforced concrete barrier-wall system and the establishment of the equivalent 2D plane-strain loading to use in design. The integral barrier-wall is a special type of road infrastructure consisting of a roadside safety barrier integrated with a retaining wall system (see Figure 1.1). The barrier is situated at the top of and fully integrated with the retaining wall system, which is typically supported by a foundation base slab. During a vehicle-barrier crash, the impact loading is first transmitted to the barrier, then dispersed and eventually transferred to “shake-up” the system foundation. Therefore, a deep understanding of the magnitude and distribution of the impact loading to the foundation is required to establish a proper stability design of the integral barrier-wall system.
The difficulty of the subject of this study is compounded by the fact that very few if any, heavy vehicle-barrier crash tests have been carried out to establish the relevant data for design of a barrier-wall system. Most of the full-scale vehicle-barrier crash tests and designs of barrier structures are concerned with low, regular and medium performance level barriers, and very few investigations performed for special performance level barriers of AS5100.2:2017 corresponding to a 44t vehicle crash. The consequences of a heavy vehicle collision with traffic safety barriers could be highly catastrophic not only to road users but to the infrastructure as well. It can, for instance, cause severe damage, sliding or toppling of the roadside structures. Past full-scale vehicle-barrier crash tests were moreover mainly focused on the barrier performance and passenger safety, but paid little heed to establishing how the impact loads are transferred from the barrier to the barrier-wall foundation.

Full-scale heavy vehicle-barrier crash tests are also expensive to perform. Numerical modelling, on the other hand, provides a cheaper alternative to investigate vehicle-barrier crash and the effects of various impact conditions on the foundation of the barrier-wall system. Hence, it could be used to some extent to overcome the lack of heavy vehicle-barrier crash tests. That said, although numerical simulations of vehicle crashes against barriers are widely reported in literature, the studies on the effects of the crash on the foundation systems
are virtually non-existent or not reported. Therefore, numerical simulations of the foundation response of an integral barrier-wall system due to impact loading would provide useful insights to account for heavy vehicle-barrier crash in stability design of an integral barrier-wall system that entails check against sliding, overturning and excessive bearing pressure. Clearly, there are existing gaps in the knowledge required to establish the equivalent 2D plane-strain loadings for stability design of retaining systems of road infrastructure subjected to vehicular impact loadings in a geotechnically rational way. The missing knowledge provides the motivation for this study.

1.2 Aim and Objectives

The number of possible combinations of vehicle-barrier crash is very large. Hence, the scope of this thesis is confined to that of a 44t special performance truck crashing against the barrier of a 3 m high integral barrier-wall system. The primary aim is to investigate the effects of such a crash (which corresponds to impact loading of 44t special performance level barrier specified in AS5100.2:2017) on the foundation of the barrier-wall system and establish the equivalent plane-strain loading required for stability design. The specific aims are as follows:

1. Undertake a comprehensive literature review on vehicular crash against safety barrier with particular respect to design codes and guidelines on the magnitude and distribution of the impact loading for stability design.

2. Develop a three-dimensional finite element model using Abaqus/Standard and Abaqus/Explicit to simulate a 44t special performance vehicle crash against the barrier of a 3m high integral barrier-wall system.

3. Calibrate the finite element model to ensure the impact loadings from the simulated crash are consistent with the design loadings for the 44t special barrier performance level specified in AS5100.2:2017.

4. Using the calibrated model, study the effects on the foundation of the barrier-wall system due to the impact loadings and establish the equivalent plane-strain loadings required for stability design of the system.

5. Undertake a sensitivity study to investigate the foundation effects as a function of the impact angle and impact velocity.
1.3 Structure of the thesis

The structure of this thesis is as follows:

Chapter 1 – Introduction

Chapter 2 – Literature Review

This chapter provides a comprehensive review of published background information on vehicle-barrier crash and the design standards for barrier systems. Particular focus is given to the Australian, US and European design codes that may provide guidance on how to apply the impact loadings for stability design of retaining structures based on 2D plane-strain approach. The gaps in knowledge corresponding with the research of this master thesis are identified in this chapter.

Chapter 3- Research Methodology

The finite element approach using Abaqus/Explicit and Abaqus/Standard to simulate vehicle-barrier crash is presented in Chapter 3. The development of the 3D finite element model of a 3m high integral barrier-wall system subjected to the impact loadings of a 44t special performance level barrier of AS5100.2:2017 is discussed in relation to prescribed material properties, interaction properties of model parts and boundary conditions.

Chapter 4- Analysis of special performance vehicle-barrier crash calibrated to AS5100.2:2017 design loadings

The calibration of the finite element model to conform with the impact loadings of a 44t special performance vehicle as specified in AS5100.2:2017 is presented and discussed in this chapter. The calibrated finite element model (referred to as the “Baseline Case” model) is then used to investigate the effects of the impact load due to a heavy vehicle-barrier crash on the barrier-wall system foundation in respect of the mobilised normal reaction force, mobilised reaction moment and mobilised shear resistance. The comprehensive analyses of the mobilised effects on system foundation, leading to the establishment of the equivalent length and the equivalent plane-strain impact loadings are presented and discussed.
Chapter 5- Sensitivity analysis of foundation response with respect to impact speed and impact angle

This chapter presents the effects of different impact conditions on foundation response by benchmarking the simulated crash results at different speeds and angles of impact against those of the Baseline Case model (see Chapter 4). The additional cases investigated were impact angles at 12 degrees and 20 degrees without any changes in the impact velocity, and impact velocities at 90 km/h and 110 km/h without any changes in the impact angle. A comparative analysis of the simulation results from these five different cases (including the Baseline Case) was performed to establish the sensitivity of the equivalent length, hence equivalent plane-strain loadings, with respect to changes in impact angle and impact velocity.

Chapter 6- Conclusions and future works

In this chapter, the conclusions derived from the baseline case analysis and the sensitivity analysis in addition to the recommendations for the future studies are presented.
Chapter 2

Literature Review

2.1 Introduction

Traffic safety barriers are roadside appurtenances used to protect road users and maintain highway safety when an errant vehicle leaves the roadway uncontrollably. In the event the vehicle loses control, the role of the safety barrier is to perform one or more of the following functions (AASHTO 2008):

a) Contain and redirect the vehicle away from a roadside obstacle or hazard,
b) Readily break or fracture or yield to allow a controlled penetration,
c) Decelerate the vehicle to a safe stop.

In each of these cases, the safety barrier is intended to lessen the severity of impact without causing severe injuries to the vehicle’s occupants, other motorists, pedestrians, or work zone personnel. According to data from World Health Organization (WHO) in 2015, 31% of all road traffic deaths are of car occupants on the world’s roads. These statistics highlight the importance of having adequate design standards for road safety barriers on improving the survivability of occupants in a crash.

Among the different types of barrier structures, the concrete barrier is regularly used in practice because of its higher stiffness and crash resilience. The concrete barrier is effective in obstructing the entry of errant vehicle to more dangerous places and steering it away from hazards. It is used as median structures, bridge barriers, and roadside barriers. Concrete barriers constructed on a concrete pavement can be rigidly tied to the pavement so that it can resist the impact load of the errant vehicle. However, in the case of asphalt pavement, the barrier itself needs to include a foundation substructure to withstand the impact load. In this case, a moment slab system integrated with the barrier often constitutes the system used in practice, where resistance is provided by the inertia force required to shift or lift the moment slab. A third type of design consists of integrating the concrete barrier with a reinforced concrete retaining wall when the latter is available. This is known as the “integral barrier-wall” system, and it is the system of interest in this thesis.
2.1.1 Integral barrier wall system

A barrier-wall system is commonly built as an L-shape or inverted T-shape structure. The vertical part of the structure is the retaining wall, and on top of which the barrier is situated. The base of the system is the foundation slab used to spread the loading, resist sliding and overturning moment. Since the barrier in a barrier-wall system is structurally integrated with the retaining wall structure, the stability of the entire system is directly affected by any loading applied to the barrier. Because of this, the proper design of barrier needs to be considered as an integral part of the design of the entire barrier-wall system. One of the main concerns is how should the impact of a vehicle-barrier crash be considered in the design of the barrier-wall system as the relevant design standards (e.g. AS 5100.2, AASHTO, Austroads) and literature are quite vague in this respect. A deep understanding of how the impact load will “shake up” the foundation, in turn, requires knowledge of the magnitude of impact load, failure modes, and distribution of impact load on the system foundation. It is important also because the stability design of retaining systems are largely based on 2D plane-strain approach, and the localised nature of the impact needs to be re-established as an equivalent dispersed effect for the purpose of plane-strain design. In short, a clear understanding of the foundational response due to the impact loading particularly against very heavy vehicles (the main focus of this thesis), is a necessary pre-requisite for the safe design of the barrier-wall system.

2.2 Existing standards and guidelines for design of safety barriers system

The provisions in current design standards for impact loading on traffic barriers in Australia and internationally may differ from each other, either by the interpretation or by the magnitude of the impact loading applied on traffic barriers. Hence, it is worth comparing the design standards in order to recognise any differences in practices in particular with reference to, if any, the dispersion of impact load and effects on foundational stability of the barrier system.

2.2.1 Australian Standards

Design specifications for traffic barriers in Australia can be found in AS 5100.2 (2017) and Austroads Bridge Design Code (2017) – Section 2. Each guideline specifies design loads based on different performance levels of the barrier.
2.2.1.1 AS 5100 Bridge Design – part 2: Design Loads (2017)

AS 5100 Bridge Design – Part 2 (2017) specifies the ultimate design loads and load distribution lengths for traffic barriers with varying performance levels, as presented in Table 2.1. It specifies that a load factor of 1.0 shall be applied to the design of traffic barriers and the design loads should be uniformly applied over the relevant specified contact lengths.

**Table 2.1 Traffic barrier design loads and contact lengths (AS 5100.2:2017)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Barrier performance level</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low</td>
</tr>
<tr>
<td>Ultimate transverse load (F_T)</td>
<td>150 kN</td>
</tr>
<tr>
<td>Ultimate longitudinal load (F_L)</td>
<td>50 kN</td>
</tr>
<tr>
<td>Ultimate vertical downward load (F_V)</td>
<td>22 kN</td>
</tr>
<tr>
<td>Vehicle contact length for transverse loads (L_T) and longitudinal loads (L_L)</td>
<td>1.1 m</td>
</tr>
<tr>
<td>Vehicle contact length for vertical load (L_V)</td>
<td>5.5 m</td>
</tr>
<tr>
<td>Minimum effective height (H_e)</td>
<td>0.6 m</td>
</tr>
</tbody>
</table>

The load combinations to be considered in the design of traffic barrier using these design forces would be;

(a) Applying transverse and longitudinal loads simultaneously.

(b) Applying vertical loads alone.

(c) Applying ultimate load factor of 1.

(d) AS 5100.2:2017 does not explicitly specify whether the ultimate design loads on traffic barriers as presented in Table 2.1 shall be considered as the equivalent static loads. However, it can be inferred from reading other sections of the code that the ultimate design loads specified in the code are equivalent static loads corresponding to each performance level.
(e) The design loads for “regular” barrier performance presented in the updated AS 5100.2 are quite similar to the values in the AASHTO-2012 Load Resistance Factor Design (LRFD) specification for test level 3 (TL-3). This is to ensure that the barrier systems can be successfully tested in accordance with the requirements specified in NCHRP Report 350 (Ross et al., 1993), which specifies the performances and testing criteria for different types of traffic barriers (AS 5100.2 Supplement 1).

(f) Australian standard for earth-retaining structures (AS 4678:2002) also recommends that the live loads on earth retaining structures should include vehicle impact loading. Page 110 of AS 4678:2002 states that where retaining structures support other amenities such as traffic barriers, the effect of traffic impact loads should be checked for the global and internal stability of the retaining structure. However, it does not specify the type of load (e.g., equivalent static or dynamic impact load) or the magnitude to be considered in the design of retaining structures.

### 2.2.1.2 Austroads Bridge Design Code (2017) – Section 2: Design Loads

The 2017 Austroads Bridge Design Code discusses three levels of barrier design loads. According to the code, Level 1 traffic barrier design loads shall be determined with reference to specialist literature and also considering the level of risk involved, size of vehicle to be contained, design speed of traffic and curvature of bridge deck together with possible angles of impact.

Ultimate design transverse loads ($P_{u^*}$) are specified in the Austroads Bridge Design Code for Level 2 traffic barriers where;

\[
P_{u^*} = 90 \text{ kN} \quad \text{for } h \leq 850 \text{ mm} \quad (2.1)
\]

\[
P_{u^*} = 90 \left(1 + \frac{h-850}{450}\right) \text{ kN} \quad \text{for } h \geq 850 \text{ mm} \quad (2.2)
\]

where $h$ is the height to the top rail of the traffic barrier or height of the barrier if it is a concrete barrier. $P_{u^*}$ is applied as a point load.

In designing Level 2 post and rail barriers, the connections between rails and posts shall be designed to transmit;

(a) The appropriate portion of the outward design load ($P_u$) for which the rail is designed.
(b) A vertical load (either upward or downward) equal to 0.25 times the outward railing load.
(c) An inward load equal to 0.25 of the outward rail load.
Posts should be designed for the same outward loads as applied to the rails with an additional longitudinal load equal to 0.5 times the outward load. Posts are supposed to withstand an inward load of 0.25 times the outward load.

Level 2 concrete barriers are designed by spreading the transverse load over a longitudinal distance of 1.5 m at the top of the barrier. This load is then distributed at 45 degrees down to the supporting slab.

Integral concrete or post and rail barriers catering Level 2 category shall be designed by distributing the transverse load between the various concrete barrier faces, which are higher than 380 mm above the reference surface, and the rail members. The resulting loading on the individual posts, rails and concrete elements of the integral barrier shall be treated as discussed above (for post and rail barriers and concrete barriers).

Level 3 traffic barrier performance corresponds to those for standard roadway barriers, such as the flexible steel W-beam guardrail barrier. The barrier elements shall be detailed in accordance with the normal design assumptions made for the standard barrier, and the strength of the associated bridge deck connections shall be at least equal to that of the posts.

However, Austroads Bridge Design Code (2017) - Section 2 does not specify the transfer of those impact loads to the retaining wall supporting the barriers.

2.2.1.3 Austroads – Guide to Road Design – Part 6: Roadside design safety and barriers (2009)

Austroads Guide to Road Design – Part 6: Roadside design safety and barriers (2009) recommends designing the traffic barriers in accordance with AS/NZS 3845:1999. However, it is possible that these design values are outdated as the types of vehicles, and their capacities have increased over the years, increasing the design loads required to contain such vehicles. For barriers associated with bridges, it recommends using AS 5100.1:2017, which then directs the designers to AS 5100.2:2017 to extract the design loads for traffic barriers.

2.2.1.4 Austroads Research Report – Standardised Bridge Barrier Design (2013)

The Austroads research report ‘Standardised Bridge Barrier Design’ published in 2013 provide design loads for traffic barriers based on AS 5100.2:2004. Design loads and the contact lengths specified in the report are therefore less than those tabulated in Table 2.1 which has updated the values from the 2004 version.
2.2.3 AASHTO LRFD Bridge Design Specifications (2012)

AASHTO LRFD Bridge Design Specifications (2012) specifies design forces for traffic barriers based on six test levels, as shown in Table 2.2. These design forces are equivalent static forces that represent the relevant dynamic forces imparted to a railing system by a specified vehicle impacting a railing at a designated speed and angle. Design forces are originally presented in kips (kilo-pounds-force) and feet in the design specifications but are converted to SI units and presented here for clarity.

The notation TL stands for test level, which is defined according to NCHRP Report 350 testing requirements.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Railing test levels</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TL-1</td>
</tr>
<tr>
<td>$F_T$ Transverse</td>
<td>60 kN</td>
</tr>
<tr>
<td>$F_L$ Longitudinal</td>
<td>20 kN</td>
</tr>
<tr>
<td>$F_V$ Vertical downward</td>
<td>20 kN</td>
</tr>
<tr>
<td>Vehicle contact length for transverse loads ($L_T$) and longitudinal loads ($L_L$)</td>
<td>1.22 m</td>
</tr>
<tr>
<td>Vehicle contact length for vertical load ($L_V$)</td>
<td>5.5 m</td>
</tr>
<tr>
<td>Effective height $H_e$ (min)</td>
<td>0.46 m</td>
</tr>
<tr>
<td>Rail height (min)</td>
<td>0.685 m</td>
</tr>
</tbody>
</table>
Figure 2.1 shows the distribution of design forces for traffic railings (AASHTO, 2012) on a post and rail traffic barrier system. The forces and the distribution lengths (Table 2.2) can be used for any type of railing design.

Figure 2.1 Distribution of design forces for traffic barriers on a post and rail barrier system (AASHTO, 2012)

AASHTO Bridge Design Specifications recommend using a horizontal load of 44.5 kN distributed over a barrier length of 1.5 m in designing soil reinforcements in upper layers of a mechanically stabilised earth (MSE) wall in a non-integral barrier-wall system. The upper layer(s) of soil reinforcement shall have sufficient pull-out capacity to resist a horizontal load of 44.5 kN distributed over a 6 m longitudinal length of the base slab.

The design forces provided in AASHTO Bridge Design Specifications are only for designing mechanically stabilised earth (MSE) retaining walls and justifications for impacts from heavier vehicles, and the severe colliding conditions were not given. No reference has been made to the design forces which should be considered in designing other types of retaining walls including integral barrier-wall systems which the main interest of this thesis.

2.2.4 Eurocode 1 (2003) – Actions on structures – Part 2: Traffic loads on bridges

Horizontal loads transferred by traffic barriers (vehicle restraint system: VRS; as referred in Eurocode 1) to bridge deck due to the collision forces are defined in Eurocode 1 – Actions on structures – Part 2: Traffic loads on bridges (BS EN 1991-2:2003 and EN 1991-2:2003). These forces are represented in the form of equivalent static loads as shown in Table 2.3.
Table 2.3. Recommended classes for the horizontal force transferred by traffic barriers to bridge decks (Eurocode 1:2003)

<table>
<thead>
<tr>
<th>Horizontal Force</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100 kN</td>
<td>200 kN</td>
<td>400 kN</td>
<td>600 kN</td>
</tr>
</tbody>
</table>

The horizontal force is acting transversely and shall be applied 0.1 m below the top of the selected VRS or 1.0 m above the level of the carriageway or footway, whichever is the lowest, and on a line of 0.5 m. The structure supporting the VRS should be designed to sustain locally an accidental load effect corresponding to at least 1.25 times the characteristic local resistance of the traffic barrier. Following this specification, the accidental design load corresponding to Class B (1.25*200=250 kN) is roughly similar to the regular performance design load of AS5100.2.

In summary, the ultimate transverse outward loads acting on traffic barriers due to vehicular collision, as specified in AS 5100.2, varies from 125 – 1000 kN depending on the performance level. In AASHTO LRFD Bridge design specifications, the outward transverse load on traffic barriers varies from 60 – 779 kN. According to Eurocode 1, the characteristic design load transferred by traffic barriers to bridge decks varies from 100 – 600 kN (or 125-750 kN for the accidental design load). The range of the design collision loads from the different codes (AS 5100.2:2017, AASHTO LRFD Bridge design specifications 2012 and Eurocode 1:2003) overlap to a substantial degree.

2.3 Current design practices for retaining walls against impact loading

It is apparent that impact loads have been subjected to different interpretations in various barrier-retaining wall system designs. These systems include both integral as well as non-integral barrier-wall systems, and it is necessary to make a distinction here between the two in terms of interpreting the effects of impact loading. A common example of the latter system is a roadside traffic barrier placed on a reinforced soil wall (RSW) or in American parlance, a mechanically stabilized earth (MSE) retaining wall.
There are also different aspects of design practices of barrier-wall systems to consider, including:

(a) Wall stability (sliding, overturning, global stability)
(b) Barrier stability (sliding and overturning), for non-integral type of barrier-wall
(c) Structural design of wall
(d) Structural design of barrier

In MSE or RSW systems, it is furthermore necessary to delineate between internal and external wall stability. Therefore, different interpretations of impact loadings have arisen because the standards have not been explicit in relation to these aspects of design and to the type of barrier-wall system. For design approaches based on quasi-static analysis, the establishment of equivalent static loading or the equivalent plane strain static loading of the dynamic impact loading has implications on structural and stability design considerations. The plane strain analysis is still primarily used in practice for geotechnical stability calculations. It also apparent that the equivalent plane strain loading may be linked to the dispersion or spread of transverse impact loading, at least according to one interpretation (see discussion below).

### 2.3.1 Spread of transverse impact loading

AS 5100.2:2017 recommends that the traffic barrier design loads specified in the code (Table 2.1) shall be applied uniformly over the relevant specified contact length. All loads shall be applied to the longitudinal barrier elements. It further states that the distribution of the longitudinal loads to posts shall be consistent with the continuity of rail elements. Distribution of transverse loads shall be consistent with the assumed failure mechanism of the barrier system.

Based on that, the ultimate transverse load is tabulated (see Table 2.4) as the force applied per unit length. Values are calculated by dividing ultimate transverse outward load by the vehicle contact lengths specified for each performance level.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Barrier performance level</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low</td>
</tr>
<tr>
<td>Ultimate transverse outward load</td>
<td>136.3 kN/m</td>
</tr>
</tbody>
</table>

Table 2.4. Traffic barrier design loads per unit length (AS 5100.2:2017)
AASHTO (2012) recommends that all forces shall be applied to the longitudinal rail elements. The distribution of longitudinal loads to posts shall be consistent with the continuity of rail elements. Distribution of transverse loads shall be consistent with the assumed failure mechanism of the railing system. A similar recommendation is found in AS 5100.2 (2017) for the application of design loads over barrier elements.

The distribution of collision forces along a retaining wall with an integrated traffic barrier recommended by California Department of Transportation (Caltrans, 2014) is presented in Figure 2.2 It can be seen that the transverse collision load applied along the vehicular contact length for specified test level has a 1:1 intensity distribution towards the base of the retaining wall. It can be seen that the minimum distribution of the force at the base of the retaining wall is 12.2 m (40’).

![Figure 2.2 Collision force distribution for a retaining wall integrated with a traffic barrier (Caltrans, 2014)](image)

The literature on design practices for integral concrete barrier-wall systems is rather scant, but discussions with practicing engineers indicate that the ultimate equivalent static loadings specified in AS 5100.2 (see Table 2.1) have been widely applied in all design aspects (stability and structural) enumerated in the above in accordance with the required barrier performance level.
The equivalent static loading may, furthermore, be converted to a plane strain “1m strip” type loading for plane strain geotechnical stability design. Here it appears a couple of interpretations are being used to deal with wall or barrier stability analysis (sliding and overturning):

(a) One interpretation is to consider that the design transverse load shall be spread over a longitudinal distance of 1.5 m at the top of the barrier and then distributed at 45 degrees down to the supporting slab, as specified in Austroads Bridge Design Code (see also discussion in the following section). Based on this approach, say in a typical case of a 1.2m concrete barrier integrated with a 5m reinforced concrete retaining wall, the design transverse load will have spread across a longitudinal length of 13.9 m down at the base of the retaining wall. Though not explicitly specified in any standards, engineers usually then convert the collision traffic loading to a plane strain “1m strip” loading case simply by dividing the design transverse load by this length. The rationale for this practice is not entirely clear, though it is presumed that this is because the spread of the transverse load corresponds to the damage profile and that the resistance at the base across the longitudinal length affected by the spread of the transverse load has been mobilized.

(b) A second and simpler interpretation is to treat the integral barrier-wall system as a single unit extending from joint to expansion. The collision traffic loading is then converted to a plane strain “1m strip” loading case by dividing the design transverse loading by the distance between the adjacent joints. This interpretation is analogous to that recommended in an NCHRP report for traffic barriers placed on MSE walls (see discussion below).

2.3.2 Design of traffic barriers placed on MSE walls

Although traffic barriers placed on MSE walls are non-integral barrier-wall systems and do not form part of the scope of this study, it is nonetheless instructive to highlight some of their design practices as these may have implications on integral barrier-wall systems. Moreover, as mentioned in the above, the literature on design practices of integral barrier-wall systems is thin and mostly non-explicit.

Design of traffic barriers and MSE walls in USA incorporates AASHTO LRFD Bridge design specifications. When allowable stress design was in practice, AASHTO ASD (2004) bridge design specification used an equivalent static design load of 44.5 kN for the design of both traffic barrier (TL-3) and MSE wall. This load was applied for both stability and structural design. AASHTO TL-3 is the nearest equivalent of AS 5100.2 regular barrier performance level.
When AASHTO guidelines changed their approach to load and resistance factor design (AASHTO LRFD, 2007), the traffic barrier (TL-3) is designed to withstand an impact load of 240 kN while a 44.5 kN design load is considered in the stability design of the MSE wall and traffic barrier. The 240 kN load level comes from measurements made on an instrumented barrier during impact and, therefore, is a dynamic load. The increase from 44.5 kN to 240 kN for the structural design of the barrier does not increase the size of the barrier significantly because the 44.5 kN load is used with an elastic design analysis while the 240 kN is used with an ultimate strength analysis (Briaud and Saez, 2012). However, the use of 240 kN design load in designing the moment slab will result in a much wider moment slab which would be unreasonably conservative according to the experience of practitioners (Kim 2009). According to NCHRP Report 663 (2010), this difference in slab width arises because the 240 kN is taken as a static load when in fact it is a dynamic load. In short, the NCHRP Report 663 (2010) recommend the use of 240 kN and 44.5 kN ultimate equivalent static loads, respectively, for structural and stability design of the traffic barriers for TL-3. Contrast this with a 250 kN ultimate equivalent static load in AS 5100.2 which is commonly interpreted as the ultimate equivalent static load for both structural and stability design of the traffic barrier for regular performance level.

AASHTO recommends a $\gamma$ load factor of 1.0 (extreme event) for sliding and overturning, and a $\phi$ resistance factor of 0.8 and 0.9 for sliding and overturning respectively of the traffic barrier. Moreover, the factored equivalent static load should be applied to the length of the moment slab between joints (i.e. factoring down for the plane strain case) for sliding mode analysis.

2.4 Barrier Crash Testings

Physical vehicle-barrier crash tests are an essential and inherent part of verifying the adequacy of safety barrier and its design. Very few real crash tests were performed for heavy vehicles in the categories corresponding to “regular” performance level and above of AS5100.2:2017. This section reviews previously carried out full-scale crash tests of these vehicles.

1. Texas A&M Transportation Institute (TTI) Test No. 7046-3

Mak (1988) conducted oblique angle crash tests of loaded heavy trucks into an instrumented wall. In this research, a 36,323 kg loaded semi-trailer truck with a van-type trailer was crashed against a 90 inch (2.3 m) instrumented wall at 55 miles per hour (88.5 km/h) at an
oblique angle of 15 degrees. The test was specifically conducted to determine the lateral impact force in a heavy vehicle collision with an instrumented wall. The test found that the vehicle was contained and redirected without any significant damage to the instrumented wall. The peak force recorded was approximately 978 kN and was associated with the final impact of the trailer with the wall. Impact severity of the tested vehicle was measured at 764 N-m.

2. TTI Test No. 7046-4

A similar kind of test as TTI Test No. 7046-3 was conducted by Mak (1988) and his co-researchers with a 36,242 kg semi-trailer truck with a tank-type trailer. The impact velocity was maintained at 88 km/hr, but angle of impact of was increased marginally to 16 degrees. The impact severity for the tested vehicle was recorded as 826.23 N-m, which is almost equal to the tested vehicle used in Test No. 7046-3. The maximum impact force was much higher, at approximately 1814 kN, again during the final impact of the trailer with the wall. The damage to the vehicle was found to be major, although the vehicle was contained and redirected without any significant damages on the wall.

3. TTI Test No. 7046-9

Beason, Hirsch, and Campise (1989) reported that out of 10 full-scale crash, three tests: test no. 7046-3 and test no. 7046-4 were completed with 36,323 kg and 36,242 kg loaded truck respectively, and the third one, test no. 7046-9 with a 22,679 kg truck were of vehicles of AASHTO class TL-3 and above (i.e. corresponding to medium and above performance level of AS5100.2:2017). The angle of impact and impact velocity was maintained 14.6 degrees and 50.4 mph (81.1 km/h), respectively at lower impact velocity and angle than earlier tests. The maximum lateral dynamic impact load imparted to the wall was measured to be 667 kN by the rear tandem axles for the case with 36,323 kg. The impact severity measured for the tested vehicle was 365 N-m.

4. TTI Test No. 7069-10

Buth (1993) reported that TTI tested a 42 inch (1.07m) F-shaped bridge railing for performance Level 3 in Guide Specifications for Bridge Railings. Here a 22,679 kg test vehicle impacted the railing at a nominal speed of 50 mph (80.5 km/hr) at angle of 15 degrees. Based on the data records at the time of the crash test, the vehicle was safely redirected from the railing wall without any significant damage on the wall (Buth, 1993). The maximum force that imparted on a barrier wall was measured as 637 Kn.
5. TTI Test No. 405511-2

After 22,680-kg tractor/van trailer rolled onto side of 30-meter length 1.07 m vertical bridge railing under NCHRP Report 350 test level 5 conditions (Buth, 1997), Alberson, Zimmer and Menges (1997) reported that TTI did a further test under the same condition with a heavier truck by extending the length of bridge railing from 30 m to a total length 40 m. As per TL-5 test conditions, the test was conducted with a 36,000-kg tractor/van trailer at a nominal speed and angle of 80 km/hr and 15 degrees respectively. The vertical wall bridge railing performed satisfactorily as stated in NCHRP Report 350 (1993). The test article successfully redirected the vehicle without significant damages on the wall.

6. TTI Test No. NOACBR-1

Polivka et al. (2005) described Test No. NOACBR-1 performed at Midwest Roadside Safety Facility (MwRSF) on August 28, 2003. The full-scale crash test was carried out on TL-5 aesthetic open concrete bridge railing system by impacting a 35,822-kg (78,975-lb) tractor/trailer vehicle against it at a speed of 79.6 km/h and an angle of 16.3 degrees. The 1,067-mm high bridge rail was constructed 37.03-m long with fifteen bridge posts. The safety performance of the bridge rail was found to be acceptable according to TL-5 evaluation criteria specified in NCHRP Report 350. Most of the damages on the barrier was found as a moderate, except some of the cracks were reported as a “major cracking” (see Figure 2.3 and Figure 2.4). The maximum dynamic lateral deflection on the barrier was recorded at 285 mm.

![Figure 2.3: Vehicle position at the time of impact, Test ACBR-1(Polivka, 2005)](image-url)
From information gathered from published literature, it can be concluded that there were few real crash tests carried out for the truck-trailer vehicle type of AASHTO class TL-3 and above (corresponding to regular to special performance levels of AS2100.2:2017), and few parametric analysis of the possible angle of impact and impact velocity. The relationship between lateral impact force and impact severity was deduced by evaluation of three tests: Test no. 7046-3, Test no. 7046-4 and Test no. 7046-9. In addition, none of these tests had focused on identifying the dynamic impact load distribution on a barrier-wall, and most significantly, the effects on the foundational substructure were not investigated.

### 2.5 Numerical analysis

Because of diverse real-world vehicle-barrier crashes due to continuous changes in vehicle fleet characteristics, mix traffic conditions and different vehicle flow patterns, it seems impossible and costly to perform physical tests for all probable conditions. To overcome this costly and lengthy process, computer simulation is the best way to perform the analysis. However, results from dynamic computer simulation cannot be completely relied upon, and it is necessary to validate the model using data from similar real crash tests as discussed in the previous section. This section is a short review of the numerical techniques used to study vehicle-barrier crash and the effects on the barrier thereof.
Though finite element computer simulation model is a low-cost approach, refinement and advancement of the numerical model to replicate the the real case scenario is also a significant challenge. After 1960s, road designers started to use computer simulation program for the barrier design and research practice (Jiang, Grzebieta & Zhao 2004). Engineers prepared barrier model according to the experimental tests and vehicle models to represent the different classes of vehicle specified in design standards. This program involved the development of dynamic models using springs, dashpots, beams, and links to study vehicle-barrier collisions. After the continuous development of simple analytical models to examine dynamics of vehicle and strength of barrier, subsequent extensions (e.g., HVOSM-RD2) of Highway Vehicle Object Simulation Model (HVOSM) developed by McHenry was the first model gain some insight into vehicle collision with rigid structures (Mak & Sicking 1990). A two-dimensional code, named as BarrierVII program developed by Powell in 1970s has been widely accepted to predict the dynamic deflection of flexible barrier systems (Powell 1973). Since the program is two-dimensional, the model is unable to address realistic three-dimensional geometric features of vehicle and barrier. Numerical simulation using computer simulation programs based on non-linear finite element techniques (e.g., DYNA3D, MADYMO) have been successfully introduced into practice (Jiang, Grzebieta & Zhao 2004). These software received wide acceptance and have been extensively used in the vehicle-barrier crash analysis. The easy adaption of the vehicle model for crash analysis using LS-DYNA: a commercial version of DYNA3D, help made LS-DYNA a predominant software for crash simulation. Besides this, ABAQUS/EXPLICIT has also demonstrated its practicability for the simulation of full-scale crash test (Gholami, Lescheticky & PaBmann 2003). After the 2012 Simulia Community Conference, a paper was published to correlate the simulated result with a real crash test and confirmed the vehicle-barrier crash model as having given proper attention to relevant details (Xavier Latorre 2012).

2.6 Necessity of current research work

Australian Standards AS5100.2:2017 is the latest publication of the AS5100 series which included revisions of impact loading on safety barriers reflecting the changes in size and mass of current vehicular traffic. These changes have yet to be translated into new design guidelines for the stability design of barrier-wall systems. Before the new guidelines can be implemented, however, a clear understanding of the effects caused by possible vehicle crashes against the barrier, and transmission of these effects to “shake up” the foundation must be established.
From the earlier sections of literature review, it is also evident physical barrier crash testing yielded limited data in comparison with the possible range of real-world crash conditions. Tests were mainly focused on barrier response to the dynamic lateral impact load without sufficient parametric analysis of angle of impact and impact velocity of moving vehicle. Moreover, the results were solely concerned with whether the barrier configurations were capable of resisting dynamic impact load without causing any significant damage to barrier-wall and injury to occupants. Previous crash tests were also unable to isolate lateral dynamic load response on a barrier structure and did not provide any clear insights about the impact loading on soil-structure interactions. It would seem from published literature that no significant study had been carried out to investigate the dispersion of impact loading leading to a “shake up” of the system foundation in relation to very heavy vehicles.

The primary objective of this research is to perform a detailed numerical analysis of a barrier-wall crash by a heavy vehicle of the 44t special performance category specified in AS5100.2:2017. Through the numerical analysis, the study has established the effects of the impact loading on the foundation of the barrier-wall system. These effects which capture the “shake up” of the foundation comprises the following reactions from the foundation soil to the system foundation induced by the impact loading:

(a) Mobilised normal reaction
(b) Mobilised reaction moment
(c) Mobilised shear resistance

Both the total effects and the distribution of these effects along the length of the barrier-wall have been analysed to determine the dispersion of the impact loading to the system foundation and, therefore, provides a rational basis to establish design guidelines using the plane-strain approach taking into consideration the effects of impact loading.
Chapter 3

Research Methodology

3.1 Introduction

This chapter discusses the procedures and steps adopted to develop the finite element (FE) models to meet the research aims and objectives. The chapter provides detailed information of all the sequential steps carried out to formulate a complete vehicle-barrier-wall crash model, including explanations of the assumptions and simplifications imposed for simplicity. The complexity of the contact formulation due to complex dynamics of barrier-vehicle interactions is a significant challenge. However, other aspects of modelling such as appropriate prescription of material properties of the vehicle model and integral barrier-wall (IBW) model needed to capture a vehicle-barrier crash accurately cannot be ignored as well. Some of the modelling properties (such as vehicle speed, mass of vehicle, contact barrier-vehicle friction) must be iteratively calibrated within the typical ranges until satisfactory results of the crash are obtained. The results of the calibration must further be verified against the barrier design load specified in AS5100.2:2107 before further analysis may proceed. The sequential steps that are essential to execute and achieve the final results are schematically shown in Figure 3.1.

![FE Modelling flowchart](image_url)

Figure 3.1: FE Modelling flowchart
3.2 Finite Element Modelling

Finite element method is a numerical technique for in-depth analysis of engineering and mathematical physics by subdividing the entire domain into simpler finite elements. This technique is applied to reformulate the governing equations into an extensive system of algebraic equations, assembled, subjected to appropriate boundary conditions and time-stepped from initial state to the current time to give the approximate solutions for the entire continuum.

For this research, the model was prepared in Abaqus/CAE, and the analysis were carried out using Abaqus/Explicit and Abaqus/Standard. Abaqus is a finite element program developed by Dassault Systèmes. The broad applications of Abaqus range from simple linear analysis to complex non-linear dynamic problems, and because of its user-friendly characteristics, Abaqus is considered particularly suitable for this project which concerns a non-linear dynamic problem. Abaqus is equipped with a broad range of element types to draw upon and a varied list of material models such as steel, concrete, aluminium, soil and rock to assign for the vehicle-barrier-wall crash model. Abaqus comes with three different analysis programs Abaqus/Standard, Abaqus/Explicit and Abaqus/CFD. Each has a different set of capability and performance attributes to the other two, thus providing different options to users depending on the needs and characteristics of the problem. Abaqus/Standard and Abaqus/Explicit are both used for linear and non-linear problems encompassing static, dynamic and other engineering problems. The only the difference between these two programs is the numerical technique used to integrate the time variable: Abaqus/standard employs an implicit method, while Abaqus/explicit uses an explicit dynamic integration procedure. Although Abaqus/standard has both static/implicit and dynamic/implicit functionalities and both can be used to solve linear and nonlinear problems, the analysis in this thesis was performed using Abaqus/standard for the initial static part to establish the overburden stresses and Abaqus/explicit for the dynamic part. The Abaqus/implicit method is suitable for smooth non-linear problems, but it incurs more computational cost and disk space and is less amenable to achieve convergence when applied to transient dynamic problems with extremely large deformation. Therefore, Abaqus/standard was only used to obtain the solutions for the initial equilibrium state, which were then propagated as the initial conditions to obtain the dynamic response of the integral barrier-wall due to a vehicle-barrier crash using Abaqus/explicit. As the program starts to analyse the problem, it calculates the nodal acceleration at the beginning of each increment using dynamic equilibrium equation (Dassault Systèmes 2014), equation 3.1,
\[ M^{(i)} \ddot{U}^{(i)} = R^{(i)} - I^{(i)} \]  

(3.1)

\( M \) is the diagonal lumped mass matrix, \( \ddot{U} \) is the acceleration vector, \( R \) is the applied load vector and \( I \) is the internal load vector. The superscript \((i)\) refers to the increment number. The acceleration vector \( \ddot{U} \) at any nodal point is then used to advance “explicitly” the velocities \( \dot{u} \) and displacement \( u \) using the central difference rule for each time increment \( \Delta t \) as shown in following equations:

\[
\begin{align*}
\dot{u}_{i+\frac{1}{2}} &= \dot{u}_{i-\frac{1}{2}} + \frac{\Delta t_{i+1} + \Delta t_i}{2} \ddot{u}_i \\
\dot{u}_{i+1} &= \dot{u}_{i+\frac{1}{2}} + \frac{1}{2} \Delta t_{i+1} \ddot{u}_{i+1} \\
u_{i+1} &= u_i + \Delta t_{i+1} \dot{u}_{i+\frac{1}{2}}
\end{align*}
\]  

(3.2)  

(3.3)  

(3.4)

### 3.2.1 Vehicle Model

The Heavy Vehicle National Law (HVNL) provides the General Mass Limits (GML), Concessional Mass Limits (CML) and Higher Mass Limits (HML) for heavy vehicles operating on the national road network in Australia. This fact sheet summarises the conditions for operating general access and restricted access vehicles, and information relating to axle mass and configurations. The vehicle model for this thesis was constructed by considering the geometric configurations, material properties and element connectivity as specified in HVNL. It was assembled as a collection of different component parts together to form a complete vehicle model. Emori (1970) suggested that the main parts of the vehicle act as a rigid body for both unidirectional and two-dimensional collisions, such as for head-on collisions, vehicle-barrier crashes and accidents at intersections. In consequence, the vehicle model used for the analysis was a standard three axle rigid truck. The inertial weight of the truck model was ultimately calibrated to be 40640 kg, which is a near equivalent representation of high-performance barrier crash analysis using a 44 tonne articulated van (the special performance truck specified in AS5100.2:2017). The research was carried out to analyze the response of integral barrier-wall and the foundation system of barrier-wall due to the dynamic impact load caused by a special performance truck crashing against the barrier of the integral barrier-wall system. As mentioned above the truck was assigned as a rigid body composed of 4-node three dimensional (3D) bilinear rigid quadrilateral (R3D4) elements and 3-node 3D linear rigid triangular elements. The truck was modelled by 1033 elements containing a total of 1022 nodes. The vehicle used for the analysis is shown in Figure 3.2.
3.2.1.1 Geometry of Vehicle model

The geometry of vehicle model was prepared by considering prescribed dimensions for heavy vehicles in correspondence with Heavy Vehicle (Mass, Dimension and Loading) National Regulation 2013 as mentioned in the previous section. The adopted geometrical dimensions for the truck model and their prescribed limits as per regulation are listed in Table 3.1. For the simplification of the analysis, and to reduce the analysis cost, the geometry of the vehicle model was considerably reduced, but assigned with the identical mass and inertia properties which represent the 44t heavy truck vehicle.

Table 3.1: Geometry limits and adopted dimensions of vehicle model

<table>
<thead>
<tr>
<th>Geometrical elements</th>
<th>HVNL maximum dimensions (m)</th>
<th>Model dimensions (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width</td>
<td>2.5</td>
<td>1.85</td>
</tr>
<tr>
<td>Height</td>
<td>4.3</td>
<td>2.88</td>
</tr>
<tr>
<td>Rear Overhang</td>
<td>lesser of 3.7m or 60% of wheelbase</td>
<td>1.7</td>
</tr>
<tr>
<td>Length of vehicle</td>
<td>12.5</td>
<td>6.3</td>
</tr>
</tbody>
</table>
3.2.2 Modelling of the concrete integral barrier-wall system

Concrete safety barriers are the best option among other types of roadside structures to obstruct the travel of errant heavy vehicles. Therefore, the use of the concrete barriers is highly recommended as bridge barriers and as the roadside barriers where unsafe objects are close to road edges. Generally, there are four different types of concrete barriers used in practice around the world: i) Vertical wall, ii) F-shape, iii) New Jersey, iv) single slope. The cross-section profiles of the different rigid road safety barriers are shown in Figure 3.3.

![Cross-section profiles of different types of concrete barriers](image)

**Figure 3.3: Cross-section profile for different types of concrete barriers**

However, only the F-shape road safety barrier and vertical concrete road safety barrier (VCB) are recommended for use on Australian roads (Australian/New Zealand Standard 1999). The cross-sectional diagram of the 3m integral barrier-wall system with VCB which is being investigated in this thesis as shown in Figure 3.4 was created in Abaqus/CAE, for the barrier-wall part of the entire model. The cross-section was extruded to a distance of 30m along the longitudinal direction to create a 3D model of the integral barrier-wall system (see Figure 3.5). Solid homogeneous concrete section was generated and assigned to the barrier-wall. Since the
research work is intended to analyse the capability of the concrete structure under dynamic loading (for special 44t performance level), the concrete damaged plasticity material model was selected after due consideration for potential large deformation of barrier-wall, and with the concrete material expected to be damaged constitutively in the damaged-plastic regime. The elastic and plastic material properties used for the 51.2 MPa concrete are tabulated in Table 3.2 and Table 3.3, respectively. All other fundamental properties were assigned in accordance with normal concrete. Approximate global seeds sizes of 0.4m were prescribed for the finite element mesh using the linear hexahedral elements of type C3D8R. The meshed integral barrier-wall consisted of a total 3751 nodes and 2072 elements as shown in Figure 3.6.

Figure 3.4: Cross-sectional of the integral barrier-wall with designed dimensions
Figure 3.5: Extruded 3D barrier-wall

Figure 3.6: The meshed integral barrier-wall
Table 3.2: Material properties used for the integral barrier-wall system

<table>
<thead>
<tr>
<th>Material properties</th>
<th>Abaqus inputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material type</td>
<td>Nonlinear elasto-plastic concrete material</td>
</tr>
<tr>
<td>Element Type</td>
<td>8 node linear hexahedral elements</td>
</tr>
<tr>
<td>Mass density(kg/m$^3$)</td>
<td>2400</td>
</tr>
<tr>
<td>Young’s Modulus (Pa)</td>
<td>$3.7 \times 10^{10}$</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Table 3.3: Concrete damaged plastic properties

<table>
<thead>
<tr>
<th>Dilation angle</th>
<th>Eccentricity (m)</th>
<th>$f_b/f_c$</th>
<th>K</th>
<th>Viscosity parameter($\mu$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>36.31°</td>
<td>0.1</td>
<td>1.16</td>
<td>0.666</td>
<td>0.0005</td>
</tr>
</tbody>
</table>

where,

- $f_b/f_c = \text{ratio of the strength in the biaxial state to the strength in the uniaxial state and Abaqus gives its default value of 1.16.}$
- $K$ = it is the ratio of the second stress invariant on the tensile meridian, to that on the compressive meridian, see Figure 3.7. The value of $K$ must satisfy the condition $0.5 < K_c \leq 1.00$ (the default value is 2/3) (Dassault Syst`emes 2017).
- $\mu$ defines the viscosity parameter representing the relaxation time of the visco-plastic system.
The post-failure behaviour for reinforced concrete was modelled using the concrete damaged plasticity model by providing post failure stress as a function of cracking strain as shown in Table 3.4. This stress-strain relation data is used as a tensile stiffening data to define the strain-softening behaviour for cracked concrete. Moreover, compressive data for the outside elastic range were provided as a function of inelastic strain (see Table 3.5). The inelastic strain is the residual strain obtained after deducting the elastic strain of the undamaged material from the total strain.

**Table 3.4: Concrete compressive behaviour**

<table>
<thead>
<tr>
<th>Yield stress (Pa)</th>
<th>Inelastic strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>25600000</td>
<td>0</td>
</tr>
<tr>
<td>36400000</td>
<td>0.0001</td>
</tr>
<tr>
<td>44900000</td>
<td>0.000281</td>
</tr>
<tr>
<td>49700000</td>
<td>0.000587</td>
</tr>
<tr>
<td>51200000</td>
<td>0.00101</td>
</tr>
<tr>
<td>49000000</td>
<td>0.00176</td>
</tr>
<tr>
<td>44300000</td>
<td>0.0026</td>
</tr>
<tr>
<td>38900000</td>
<td>0.00346</td>
</tr>
</tbody>
</table>
Table 3.5: Concrete tensile behaviour

<table>
<thead>
<tr>
<th>Yield stress (Pa)</th>
<th>Cracking strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>2360000</td>
<td>0</td>
</tr>
<tr>
<td>1890000</td>
<td>4.07E-005</td>
</tr>
<tr>
<td>945000</td>
<td>0.000293</td>
</tr>
<tr>
<td>213000</td>
<td>0.000807</td>
</tr>
</tbody>
</table>

3.2.3 Modelling of the reinforcement

The steel reinforcements are embedded in the concrete of the barrier-wall. These consisted of 500Y steel mesh of 16 mm diameter and 250 mm spacing, as shown in Figure 3.8. The placing of the steel mesh is shown in Figure 3.9. The global seeds size of 0.25m was assigned for the finite element mesh of the steel reinforcement.

![Figure 3.8: Section of steel reinforcement along the transverse direction](image_url)
Figure 3.9: Distribution of reinforcement along the longitudinal direction

The steel reinforcement was modelled as a elasto-perfectly plastic material. The elastic properties assigned for steel are summarised below in Table 3.6, and plastic strains were provided as a function of yield stress for plastic characterisation as shown in Table 3.7.

<table>
<thead>
<tr>
<th>Table 3.6. Elastic properties of steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density of steel (kg/m$^3$)</td>
</tr>
<tr>
<td>Young’s modulus (N/m$^2$)</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 3.7: Plastic properties of steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield stress (Pa)</td>
</tr>
<tr>
<td>4.2*10$^8$</td>
</tr>
<tr>
<td>4.8*10$^8$</td>
</tr>
</tbody>
</table>
3.2.4 Modelling of the soil embankment and foundation
A solid homogeneous soil section was created and allocated to the soil embankment and foundation of the integral barrier-wall system. Its cross-section with labelled dimensions is shown in Figure 3.10. The foundation soil was extended by 5.10m from wall face, and its total width was 13m in the transverse direction of the impact load. The cross-section was extruded longitudinally to the same length as previously done with integral barrier-wall and reinforcement. The three-dimensional soil embankment and foundation were meshed using 0.5m global seed size in Abaqus/CAE as shown in Figure 3.11. A total of 37926 linear hexahedral elements of type C3D8R were generated for the soil embankment and foundation.

Figure 3.10: Cross-section of the soil embankment and foundation (labelled dimensions in meters)
The Mohr-Coulomb plasticity model was used for the soil material as it allows the material to harden and soften isotopically under impact loading (DASSAULT System 2017). The soil properties given for the Mohr-coulomb model are listed in Table 3.8.

Table 3.8: Material properties of the soil

<table>
<thead>
<tr>
<th>Soil properties</th>
<th>Abaqus input</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass density(kg/m$^3$)</td>
<td>1800</td>
</tr>
<tr>
<td>Young’s modulus(N/m$^2$)</td>
<td>$4 \times 10^7$</td>
</tr>
<tr>
<td>Poisson’s Ratio</td>
<td>0.33</td>
</tr>
<tr>
<td>Friction Angle</td>
<td>30</td>
</tr>
<tr>
<td>Dilation Angle</td>
<td>5</td>
</tr>
<tr>
<td>Cohesion yield stress(N/m$^2$)</td>
<td>300</td>
</tr>
<tr>
<td>Abs Plastic Strain</td>
<td>0</td>
</tr>
</tbody>
</table>

3.2.5 Modelling of the road pavement

A continuum shell of a homogeneous section of 0.2m thickness was created in Abaqus/CAE for the road pavement as shown in Figure 3.12. The pavement was modelled as a concrete
material having the same properties as that used for the integral barrier-wall. A maximum global seed size of 0.35m was assigned to the road pavement, and the generated mesh consists of 1806 linear quadrilateral elements of type S4R as shown in Figure 3.13.

Figure 3.12: Dimensions (in meters) used for road pavement

Figure 3.13: The meshed road pavement
3.2.6 Assembled Model

All the parts created for the simulation were assembled to give the final model that represents the integral vehicle-barrier-wall system with soil embankment and foundation, and pavement that was subjected to a 44t special performance level (equivalent to AASTHO Test level 6) impact loading (AS5100.2:2107). The front end of the truck was initially positioned at 10.5m longitudinally from upstream end and 0.25 m transversely from the face of the barrier-wall system, inclined at an angle of 15 degrees with the longitudinal axis as shown in Figure 3.14. The initial separation of the truck and the barrier is shown in Figure 3.15.

![Figure 3.14: The assembled final model for crash analysis](image1)

![Figure 3.15: Vehicle position before impact](image2)
3.2.7 Analysis Step
The total time of the vehicle crash simulation is relatively short, in the order of half a second. However, the other basic information such as time increment and mass scaling also influence the program in reaching a converged solution. A dynamic, explicit procedure was chosen with a step time of 0.5s and Nlgeom was toggled on by default. “Nlgeom on” is the command to perform the explicit analysis for geometric nonlinearity during the analysis steps. Automatic increment was selected to calculate the time increment automatically, and global was toggled on as the stable time increment estimator with time scaling factor of 0.1. The “use scaled mass” and “throughout step” definitions from the previous step were chosen as mass scaling options to propagate the mass scaling to the current step. Linear bulk viscosity parameter and quadratic bulk viscosity parameter were left to default values of 0.06 and 1.2 respectively.

3.2.8 Interaction
The interaction module defines the interaction between model parts and constraints applied between regions of a model. The interaction module requires specifications for surface-to-surface and surface-to-node contact interactions, and these options must be appropriately imposed based on the type of problem analysed. Interactions are step-dependent properties, which means that particular contact properties can be activated or deactivated for a specific step of analysis. The following sections discuss the different interaction properties created to define the interactions, the contact definitions to prevent penetration between two contact surfaces and the constraints applied on the designed model.

3.2.8.1 Contact definition and interaction property
The contact frictional behavior between the contact surfaces is enforced as the “penalty” method. Three friction coefficients of 0.5, 0.3 and 0.1 were prescribed for the contacts between barrier-soil surface, vehicle-barrier surface, and road pavement-vehicle wheel surfaces respectively. Penalty formulation allowed some relative motion of the surfaces when they were adhering to each other, and this function adjusts itself to allow Abaqus to control the magnitude of sliding less than the elastic slip. A low value of friction was chosen for the interaction between the truck and the barrier wall surface so as to prevent the truck from being lifted up on the rear side. The propensity for the truck to lift is higher in the simulations of this thesis as it is modelled as a rigid body. Similarly, a low value of friction coefficient was assigned for the surface between the road surface and vehicle tires to minimise the shear stress on highway
surface and the deceleration of the vehicle. The prepared model with the active surfaces in an interaction module is shown in Figure 3.16.

Figure 3.16: The interactions between different surfaces in a model

3.2.8.2 Constraints

In the model, three different types of constraints were created, and these were the rigid body constraints, tie constraints and embedded region constraint. The embedded region constraint was used to embed the reinforcement in a concrete integral barrier-wall so that the translational degrees of freedom of the rebar reinforcement nodes are constrained to the values of the corresponding degrees of freedom of the barrier-wall nodes. The geometrical tolerance and fractional exterior tolerance method were selected using default values to specify how far an embedded node can come outside the surface of the concrete barrier wall. Similarly, rigid body constraint was created in between truck reference point and whole truck region to restrain the motion of the rigid body region and their relative positions during the analysis. Node-to-surface tie formulation was created between soil surface beneath the concrete road and the pavement surface. In general, tie constraints were also used to restrict relative motion between two tied surfaces and to enforce continuity.

3.2.9 Load and boundary conditions

A gravity load with a magnitude of \( g = 9.8 \text{m/sec}^2 \) was assigned for the whole model in a vertically downward direction. The truck velocity was provided as a predefined field velocity under mechanical category in the initial step. As the truck was maintained in such a condition that it would impact the barrier of the barrier-wall at an angle of 15 degrees, the two velocity
components V1 (transverse x-direction) and V3 (longitudinal z-direction) were set to -7.19 m/s and +26.83 m/s respectively. These two components give the resultant velocity of 27.73 m/s (100 km/hr) as per test designation. Each side of the model was provided with fixed boundary conditions of displacement/rotation type along the normal direction of the corresponding axes.

3.3 Simplifying assumptions and analysis of the Vehicle-barrier model

The model created should be as close as possible to the real-life crash scenario, and yet it should be sufficient robust to avoid numerical crashes. Therefore, the analysis was done in two steps to account for the nonlinear kinematics and deformations as (1) Static analysis (2) Dynamic analysis

3.3.1 Gravity effect analysis

The gravity effect analysis was performed to obtain the initial equilibrium stress for the created model due to the effect of gravity load using only Abaqus/Standard. A static general time step of 20s was used, and all the parts were meshed with the same size and element type as those mentioned in earlier sections. In this simulation a distributed vertically downward gravity load was applied for the whole model, but the truck was deactivated with boundary conditions to prevent its displacement and rotation in all directions. All the other model properties remained same as the one prepared for the dynamic/explicit analysis which was described in earlier sections.

3.3.2 Impact effect analysis

The impact effect analysis using Abaqus/Explicit followed the static analysis after all the parts in a model were in static equilibrium due to the gravitational effects. In the impact effect analysis step, the truck was accelerated with a velocity of value 27.78 m/sec towards barrier of the barrier-wall using pre-defined field velocity. The meshed assembled model used for the static analysis was propagated to be used for Abaqus/Explicit analysis but with reduced integration method.

3.4 Parametric analysis at various speeds and angle of impact

After the simulation of vehicle-barrier crash analysis for the calibrated model of 40t which is in correspondence with special 44t barrier performance level specified in AS5100.2:2017 at impact velocity of 100 km/h and angle of 15 degrees (known as the “Baseline Case”), the same
analysis was carried out for other angles of impact and truck velocities. Two different sets of results were collected at the 10-degree and 20-degree of the angle of impact. Similarly, two different analyses were performed for the truck impact velocity of value 25m/s (90km/h) and 30.56m/s (110km/h). The cases are tabulated in Table 3.9.

<table>
<thead>
<tr>
<th>Test name</th>
<th>Angle of impact</th>
<th>Impact velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline Case (Case 1)</td>
<td>15°</td>
<td>100Km/h</td>
</tr>
<tr>
<td>Case 2</td>
<td>12°</td>
<td>100Km/h</td>
</tr>
<tr>
<td>Case 3</td>
<td>20°</td>
<td>100Km/h</td>
</tr>
<tr>
<td>Case 4</td>
<td>15°</td>
<td>90Km/h</td>
</tr>
<tr>
<td>Case 5</td>
<td>15°</td>
<td>110Km/h</td>
</tr>
</tbody>
</table>
Chapter 4

Analysis of special performance truck-barrier crash in accordance with AS5100.2:2017 design loadings

4.1 Introduction

Developing a deep understanding of the effects of impact loading on the foundation of a barrier-wall system according to the design loads specified in AS5100.2:2017 for special barrier performance level is a primary objective of this finite element analysis. The analysis the impact loading on the barrier of an integral barrier-wall system which is propagated to the system foundation will provide essential information on the distribution of effects of the impact loading in terms of the following foundation response:

i) Normal reaction
ii) Reaction moment
iii) Shear resistance

These information will help to fill the existing knowledge gap on what should be the dispersed impact loadings to apply in the geotechnical stability design of the foundation of the integral barrier-wall system. This is especially important because practical geotechnical stability design todate is still mainly based on a plane-strain approximation of the 3-dimensional localised impact. Hence, the study of these effects will help to resolve the most rational way to transform the design impact loading from AS5100.2:2017 to equivalent plane-strain design loadings. AS5100.2:2017 design code and geotechnical literature, in general, do not provide any guidance for plane-strain impact loadings.

This chapter will firstly discuss the calibration of the critical parameters involved with the vehicle crash (namely mass of vehicle, speed, impact angle and contact friction) so that the impact loadings will correspond to those specified in AS5100.2:2017. It will then discuss the effects of the impact loading described above, as obtained by the calibrated model. Finally, the findings on the dispersion of the impact loadings and the recommendations to establish the “effective length” of dispersion which is used to calculate the equivalent plane-strain impact loadings are discussed.
Before analysing the model using Abaqus, four different parts of modal; vehicle model, integral barrier-wall, soil embankment and foundation and road pavement were created and assembled in Abaqus/CAE and analysed using Abaqus/Explicit. Details of this model are found in Chapter 3. The simulated model of the vehicle-barrier crash analysis was prepared and performed in accordance with the 44 tonne special barrier performance level as specified in AS5100.2:2017.

4.2 Vehicle impact loadings from AS5100.2:2017

The impact loadings for design of safety barriers from AS5100.2:2017 for the different barrier performance levels are presented in Table 4.1 below, and the schematic of the loadings is shown in Figure 4.1. This thesis investigates the effects of impact loadings due to special (44t) performance level vehicle crash (highlighted in bold in the right column). The FE model of the vehicle crash representing the case defined as the “Baseline Case” in Chapter 3 was calibrated to these loadings (see discussion in section below).

Table 4.1: Traffic barrier design loads, contact lengths and effective heights (AS5100.2:2017)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Low</th>
<th>Regular</th>
<th>Medium</th>
<th>Special (36t)</th>
<th>Special (44t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate transverse load (F_T)</td>
<td>125 kN</td>
<td>300 kN</td>
<td>600 kN</td>
<td>750 kN</td>
<td>1200 kN</td>
</tr>
<tr>
<td>Ultimate longitudinal load (F_L)</td>
<td>40 kN</td>
<td>100 kN</td>
<td>200 kN</td>
<td>250 kN</td>
<td>400 kN</td>
</tr>
<tr>
<td>Ultimate vertical downward load (F_V)</td>
<td>20 kN</td>
<td>100 kN</td>
<td>300 kN</td>
<td>375 kN</td>
<td>600 kN</td>
</tr>
</tbody>
</table>
4.3 FE simulation of impact load on traffic barrier for model calibration

The calibration of the FE vehicle crash model involves a trial and error process of adjusting the vehicle mass, speed, angle of impact and contact friction to obtain impact loads in correspondence with AS5100.2:2017. This process has been simplified based on observations that the majority of vehicular speeds on freeways are less than 100 km/h, crash studies having found that the angle of impact generally varies from $12^\circ$ to $20^\circ$, and the contact vehicle-barrier coefficient of friction typically varies from 0.2 to 0.5. Hence, the vehicular speed was set to 100 km/h, the angle of impact to $15^\circ$ and the contact coefficient of friction (between vehicle and barrier) at 0.3. Only the mass of vehicle was adjusted and after some trial and error analysis, a mass of 40.6 tonne was established to have provided the impact loadings in correspondence with AS5100.2:2017, though it is slightly less than the 44 tonne mentioned in the standard.

The total time of impact analysis of the vehicle crash against the barrier lasts about 0.5 seconds. The truck starts to hit the barrier wall at 0.01s, and the contact with barrier lasts until $t = 0.27s$. However, the magnitude of impact loads was substantially decreased after 0.18s as it started to deviate from the initial angle of impact, and moved away from the barrier-wall. After the maximum impact loads had occurred at 0.08s, the truck continued to hit the barrier with lesser
impact loads until 0.27s of analysis, and it started to decrease dramatically after front side of the truck separate from the barrier. The considerations of the three components of traffic barrier design loads and their distribution length for all performance levels are illustrated in Figure 4.1.

The impact loads with time were calculated by summing up the element loads (obtained by integrating the stress at the Gauss points over the element area) of the entire barrier and wall. The results of the time history of the impact loads in the transverse, vertical and longitudinal directions are presented in Figure 4.2, Figure 4.3 and Figure 4.4, respectively. The components of the maximum impact loads from the calibrated model are presented against those specified by AS5100.2:2017 for the 44t special performance barrier in Table 4.2.

Figure 4.2: Time history of transverse load ($F_T$)
Figure 4.3: Time history of vertical downward load ($F_v$)

Figure 4.4: Time history of longitudinal load ($F_L$)
Table 4.2: Comparison between maximum (ultimate) impact load components of the calibrated model and the barrier design loads specified by AS5100.2:2017 for the 44t special performance barrier

<table>
<thead>
<tr>
<th>Traffic Barrier design loads</th>
<th>Calibrated model</th>
<th>Special (44t) barrier performance level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate transverse load ((F_T))</td>
<td>1155.40 kN</td>
<td>1200 kN</td>
</tr>
<tr>
<td>Ultimate longitudinal load ((F_L))</td>
<td>363.199 kN</td>
<td>400 kN</td>
</tr>
<tr>
<td>Ultimate vertical downward load ((F_V))</td>
<td>531.045 kN</td>
<td>600 kN</td>
</tr>
</tbody>
</table>

As shown in Table 4.2, the simulated FE ultimate impact loadings are comparable and almost similar with the loadings from AS5100.2:2107. It is moreover noted that the results from the FE analysis were obtained from a rigid vehicle-barrier crash. Therefore, it is generally expected to be somewhat higher than that for a deformable vehicle. These results thus confirm that the calibrated model is now ready to be used to study the effects of impact loading on the system foundation.

### 4.4 FE simulation to investigate the effects of impact loading due to vehicle-barrier crash (Baseline Case) on system foundation

Baseline Case vehicle-barrier crash (see Chapter 3 for different cases of analysis) is the case which is in correspondence with the specified impact loadings of AS5100.2:2017. The initial 3D perspective from the front at the start of simulation (\(t = 0.0s\)) is shown in Figure 4.5. The evolution of the front and top views in 3D perspective of the vehicle-barrier-crash with time is presented from Figure 4.5 to Figure 4.13.

The truck started to hit the barrier at 0.01s and at the same time, the barrier started to deflect in the direction of the impact load. The truck begun to roll after 0.09s and analysis was continued for 0.5s to cover the critical period of impact loading. All of these results were collected from the crash analysis for an angle of impact 15 degrees and velocity of vehicle at
27.78 m/s, simulating a vehicle crash corresponding to loading for 44 tonne special barrier performance level.

Figure 4.5: 3D perspective of simulation of vehicle-barrier crash from the front view at start ($t=0.0s$)

Figure 4.6: 3D perspective of simulation of vehicle-barrier crash from the front and top views at $t=0.02s$
Figure 4.7: 3D perspective of simulation of vehicle-barrier crash from the front and top views at t = 0.05s

Figure 4.8: 3D perspective of simulation of vehicle-barrier crash from the front and top views at t = 0.1s
Figure 4.9: 3D perspective of simulation of vehicle-barrier crash from the front and top views at $t = 0.15s$

Figure 4.10: 3D perspective of simulation of vehicle-barrier crash from the front and top views at $t = 0.2s$
Figure 4.11: 3D perspective of simulation of vehicle-barrier crash from the front and top views at $t = 0.25s$

Figure 4.12: 3D perspective of simulation of vehicle-barrier crash from the front and top views at $t = 0.3s$
4.4.1 Effects on system foundation due to initial self-weight of system

It is worth noting that some of the impact effects studied are in fact the net effects attributed to the vehicle crash only, that is these are established after deducting the effects of the static case due to self-weight of the system from the total effects of the vehicle crash. In consequence, the effects of the self-weight of the system on system foundation in respect of the mobilised normal reaction force, mobilised reaction moment and mobilised shear resistance have also been analysed and are presented below.

The mobilised normal reaction stress contours on the foundation of the barrier-wall system for the initial static loading (i.e. due to system self-weight) are shown in Figure 4.14. The gravity analysis was run for both 10s and 20s, and the results from both analysis converge to the same values. Hence, it can be concluded that the results shown in Figure 4.14 are the final converged results of the static analysis.
Figure 4.14: Contours of the mobilised normal reaction stress on the system foundation due to static loading from self-weight of the integral barrier-wall system

It is also noted that the effects here are often evaluated in per metre section in the longitudinal direction, and the units of these effects are presented in per meter length (e.g. kN/m for the mobilised normal reaction force). Hence when plotted longitudinally, these plots show the distribution of these effects in the longitudinal direction. Figure 4.15 shows the mobilised normal reaction force distribution in the longitudinal direction to be fairly constant. Figure 4.14 and Figure 4.15 (mobilised normal reaction force distribution in longitudinal direction) thus suggest that the effects are quite uniform along the longitudinal direction. The uniform distribution is consistent with a plane-strain case which applies for a long uniform primatic system.

Figure 4.15: Mobilised normal reaction force distribution on the integral barrier-wall system foundation due to self-weight (dead load) effect only
Similarly, mobilised reaction moment and mobilised shear resistance distribution on the integral barrier-wall system foundation due to dead-load effect only are calculated per meter length (Nm/m) and plotted longitudinally along the longitudinal direction of the barrier-wall. Figure 4.16 presents the mobilised reaction moment distribution, and Figure 4.17 shows the mobilised shear resistance distribution, and both of these results indicate that the effects are relatively uniform along the longitudinal direction of the integral barrier-wall system.

**Figure 4.16: Mobilised reaction moment distribution on the integral barrier-wall system foundation due to self-weight (dead load) effect only**

**Figure 4.17: Mobilised shear resistance distribution on the integral barrier-wall system foundation due to self-weight (dead load) effect only**
4.4.2 Effects on mobilised normal reaction force of system foundation due to impact loading (Baseline Case)

Figure 4.18 shows the distribution of the total mobilised normal reaction force for the Baseline Case in the longitudinal direction at different times of interest. The vertical stress transferred longitudinally to the foundation system was analysed at each time step of the analysis, and it was found that due to the dynamic impact loading, the stress values are changing temporally during the crash analysis period. Therefore, in order to find the most impactful effect of the mobilised normal reaction force of system foundation, the mobilised reaction curves at various time of interests ($t=0.0s$, $t=0.14s$, $t=0.15s$ and $t=0.16s$) are studied. It may be observed from the reaction curves that foundation of the barrier-wall are changing temporally during the crash. The horizontal curve with approximately constant values at $t=0.0s$ is the mobilised reaction force distribution along the longitudinal direction on system foundation prior to impact. It is the same as the mobilised normal reaction force on the system foundation due to gravity load only. The most impactful curve is considered as the one with the greatest absolute area between the curve at time $t$ and the curve at $t=0.0s$. In Figure 4.18, the most impactful curve is established to occur at $t=0.16s$.

![Figure 4.18: Distribution of mobilised normal reaction forces of system foundation at different times of interests](image)

The longitudinal extent to which the impact loading has been dispersed to the foundation of the system is established based on the most impactful curve. Two criteria are used, namely as follows,
- Criterion A - based on the threshold of the normal reaction force being \( = 10\% \) of the peak normal reaction force (see Figure 4.19).
- Criterion B - based on the longitudinal extent which covers 95\% of the total area under the most impactful curve (see Figure 4.20).

**Figure 4.19: Graphical description of criterion A**

**Figure 4.20: Graphical description of criterion B**
Based on these criteria, the dispersion or effective length along the longitudinal direction to which the impact of the vehicle crash is dispersed in respect of the mobilised normal reaction force are: Criterion A – 13.1 m; Criterion B – 13.95 m.

4.4.3 Effects on mobilised reaction moment of system foundation due to impact loading (Baseline Case)

The mobilised reaction moment distribution of system foundation along the longitudinal direction of the barrier-wall due to the total effect of the impact load (impact load + gravity load) for the base case at different time of interests ($t=0.0s, t=0.14s, t=0.15s$ and $t=0.16s$) is shown in Figure 4.22. The comparision of the size of the area of the curves at time $t$ and datum curve $t = 0.0 s$ shows that the mobilised reaction moment distribution curve at $t = 0.16s$ yielded the maximum area and it is, therefore, the most impactful curve. The most impactful curve is plotted based on net effect (mobilised reaction moment at $t = 0.16s$ minus mobilised reaction moment at $t= 0.0s$) in Figure 4.23.
Figure 4.22: Distribution of total mobilised reaction moment of system foundation at different times of interests

Figure 4.23: Net mobilised reaction moment distribution due to impact load along the longitudinal direction of the integral barrier-wall when the effects are most impactful

The mobilised reaction moment distribution along the longitudinal direction of the most impactful curve was used to establish the effective length of the mobilised reaction moment based on the two different criteria as previously done for the mobilised normal reaction force (see Section 4.3.2). The effective dispersion length in respect of the mobilised reaction moment is found to be: Criterion A- 30.0m; Criterion B-26.15m.
4.4.4 Effects on mobilised shear resistance of system foundation due to impact loading (Base Case)

The total mobilised shear resistance of the system foundation due to the impact load along the longitudinal direction of the barrier-wall at different time of interests ($t=0.0s, t=0.14s, t=0.15s$ and $t=0.16s$) is shown in Figure 4.24. Similarly, the most impactful shear resistance distribution curve was found by comparing the absolute area between the curve at time $t$ and the datum curve at time $t=0.0s$.

![Distribution of total mobilised shear resistance of system foundation at different times of interests](image)

**Figure 4.24: Distribution of total mobilised shear resistance of system foundation at different times of interests**

The absolute net area under the curve at $t=0.16s$ is the largest during the crash period (see Figure 4.25). Therefore, the curve of the mobilised shear resistance distribution at $t=0.16s$ is considered as the most impactful curve and used to establish the longitudinal dispersion of the impact load. Based on two criteria as previously described, the effective length of dispersion of impact load in respect of the mobilised shear resistance force is: Criterion A – 26.6 m; Criterion B – 24.5 m.
4.4.5 Summary

The tabulated summary of the effective extent of distribution of effect of impact loading in terms of three different foundation response is shown in Table 4.3.

Table 4.3: Effective length of dispersion of effect of impact loading

<table>
<thead>
<tr>
<th>Effects on system foundation</th>
<th>Dispersion length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Criterion A</td>
</tr>
<tr>
<td>Normal reaction force</td>
<td>14.0</td>
</tr>
<tr>
<td>Reaction moment</td>
<td>30.0</td>
</tr>
<tr>
<td>Shear resistance</td>
<td>26.6</td>
</tr>
</tbody>
</table>

The tabulated data shows that the effective length of impact load distribution in respect of mobilised normal reaction force on a system foundation is less than the effective dispersion lengths for the reaction moment and shear resistance.

The dispersion/effective length may be considered as the length to which the impact loading has been uniformly distributed and utilised to calculate the equivalent plane-strain loading of the impact load as follows:
equivalent plane – strain loading = \frac{\text{Impact loading specified in AS5100.2:2017}}{\text{Effective length}} \quad (4.1)

The equivalent plane-strain loading using Equation 4.1 for each reaction forces using two different criteria are summarised in Table 4.4. The design ultimate transverse load specified in AS5100.2:2017 for 44t special performance barrier (1200 kN) is used to calculate the equivalent plane-strain loading in the table.

Table 4.4: Equivalent plain-strain loading

<table>
<thead>
<tr>
<th>Effects on system foundation</th>
<th>Equivalent plane-strain loading (kN/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Criterion A</td>
</tr>
<tr>
<td>Normal reaction force</td>
<td>85.71</td>
</tr>
<tr>
<td>Reaction moment</td>
<td>40</td>
</tr>
<tr>
<td>Shear resistance</td>
<td>45.12</td>
</tr>
</tbody>
</table>

In practice, the effective length should a singular value estimated based on all effects, and not just the one effect, mobilised at the system foundation. Hence, a criterion is needed to enable the singular value to be established. One possibility is to take the average of the effective lengths of all effects, but approach adopted here is to use the lowest effective length of all the effects mobilised. This also happens to be the effective lengths in respect of the mobilised normal reaction force. On this basis, the recommended effective length of a 3 m high integral barrier-wall system for a 44 t special performance vehicle-barrier crash is 14 m (based on the rounded values of Criterion A and B in Table 4.3). The corresponding equivalent plane-strain transverse loading is 85.71 kN/m, calculated using Equation (4.1).
Chapter 5

Sensitivity analysis of foundation response at various speeds and angles of impact

5.1 Introduction

The finite element analysis of five different cases of impact loading in correspondence with a parametric study of the vehicle-barrier crash by varying the speed and angle of impact is tabulated in Table 5.1.

Table 5.1: Five different cases of vehicle-barrier crash analysis at various speeds and angles of impact

<table>
<thead>
<tr>
<th>Test type</th>
<th>Peak (maximum) normal reaction force (N/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline case (Case 1)</td>
<td>-88529.1</td>
</tr>
<tr>
<td>Case 2</td>
<td>-70349.2</td>
</tr>
<tr>
<td>Case 3</td>
<td>-116965</td>
</tr>
<tr>
<td>Case 4</td>
<td>-68440.1</td>
</tr>
<tr>
<td>Case 5</td>
<td>-118881</td>
</tr>
</tbody>
</table>

The Baseline Case (Case 1) as discussed in Chapter 4 is considered as a reference case to which all other cases are benchmarked against. Case 2 and Case 3 were performed by varying the angle of impact to 12 degrees and 20 degrees, respectively from the Case 1 crash test model while keeping all other parameters constant. Case 5 and Case 4 vary the impact velocity by ±10 km/h with respect to the benchmark 100 km/h respectively, without any other changes to the Case 1 crash test model. The barrier-wall system foundation responses have been analysed to establish the distribution of the normal reaction force, reaction moment and shear resistance mobilised along the longitudinal direction of the barrier-wall due to the (net) effect of impact load only.
5.2 Comparison of effects on mobilised normal reaction force of system foundation due to impact loading

To analyse the variations on normal reaction force for all cases of impact conditions, the most impactful temporal curve during the period of crash for each case is used for the comparison. The normal reaction force variation of system foundation at the most impactful instant for each of the five cases due to the impact loading is shown in Figure 5.1.

![Figure 5.1: Distribution of most impactful mobilised normal reaction force on the integral barrier-wall system foundation for all five cases](image)

The peak (maximum) normal reaction force for all cases are compared and summarised in Table 5.2.

<table>
<thead>
<tr>
<th>Test type</th>
<th>Peak (maximum) normal reaction force (N/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline case (Case 1)</td>
<td>-88529.1</td>
</tr>
<tr>
<td>Case 2</td>
<td>-70349.2</td>
</tr>
<tr>
<td>Case 3</td>
<td>-116965</td>
</tr>
</tbody>
</table>
The vehicle crashed the barrier wall at 10.5m longitudinally from the upstream end of barrier-wall, and the maximum mobilised effect of all cases is mostly located within close vicinity of the crash location. It is observed from the mobilised normal reaction curves (Figure 5.1) and tabulated results (Table 5.2) that the angle of impact and the impact velocity have a significant effect on the peak normal reaction force at the integral barrier-wall system foundation. Comparing Case 1, Case 2 and Case 3 it is apparent that there is a strong correlation between the peak normal reaction force and the angle of impact. The higher the angle of impact, the higher will be the peak normal reaction force, a result which is in accordance with engineering intuition. Moreover, a comparison of Case 1, Case 4 and Case 5 shows that the peak reaction force increases as the impact velocity increases.

The effective dispersion length of the mobilised normal reaction force of the system foundation for all the five cases is established and summarised in Table 5.3.

**Table 5.3: Effective length of dispersion of mobilised normal reaction force due to impact loading**

<table>
<thead>
<tr>
<th>Normal reaction force</th>
<th>Effective dispersion length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Criterion A</td>
</tr>
<tr>
<td>Baseline case</td>
<td>14</td>
</tr>
<tr>
<td>Case 2</td>
<td>12</td>
</tr>
<tr>
<td>Case 3</td>
<td>12.5</td>
</tr>
<tr>
<td>Case 4</td>
<td>7.2</td>
</tr>
<tr>
<td>Case 5</td>
<td>14.5</td>
</tr>
</tbody>
</table>
The comparison between Baseline case, Case 2 and Case 3 shows that the angle of impact, however, has a marginal effect on the effective dispersion length of the impact loading (based on mobilised normal reaction force). This suggests that the dispersion of the normal reaction force is not very sensitive to the impact angle, which seems somewhat counter intuitive. Case 1 and Case 5 also show marginal differences, although the results for Case 4 are significantly different. It may be surmised that contrary to the peak mobilised normal reaction, the dispersion or spread of impact loading is generally only marginally sensitive to impact velocity except for the anomaly of Case 4.

5.3 Comparison of effect on mobilised reaction moment of system foundation due to impact loading

Similarly, the (longitudinal) distributions of the mobilised reaction moment of the system foundation due to impact loading for each of the five cases were analysed. The most impactful distribution curve of the reaction moment in time for each case was obtained in the manner discussed in Chapter 4. Figure 5.2 compares the most impactful distribution curves in time for all the cases.

Figure 5.2: Distribution of most impactful mobilised reaction moment on the integral barrier-wall system foundation for all five cases
The mobilised reaction moment curves of each case show that the mobilised reaction moment of the system foundation is most significant in the section close to the location where the vehicle crashes against the barrier. A comparison of Case 1, Case 2 and Case 3 shows that the mobilised reaction moment (which is computed about the longitudinal centreline of the system foundation) generally increases with the impact angle. It is in keeping with the increase in transverse impact force as the impact angle increases, leading to higher reaction moment. This is also true for Case 1, Case 4 and Case 5 in having higher mobilised reaction moment with increased impact velocity. An examination of Table 5.4 would further show that the peak (maximum) reaction moment follows a similar trend of response. The effective length of distribution in respect of mobilised reaction moment due to impact loading for all the five cases of crash tests are calculated and shown in Table 5.5. It shows that the mobilised reaction moment is not very sensitive to variations in the impact angle and impact velocity.

Table 5.4: Peak (maximum) reaction moment of most impactful mobilised reaction moment distribution

<table>
<thead>
<tr>
<th>Test type</th>
<th>Peak (maximum) reaction moment of system foundation (Nm/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline Case (Case 1)</td>
<td>145012.8</td>
</tr>
<tr>
<td>Case 2</td>
<td>118617.9</td>
</tr>
<tr>
<td>Case 3</td>
<td>180453.8</td>
</tr>
<tr>
<td>Case 4</td>
<td>103876.7</td>
</tr>
<tr>
<td>Case 5</td>
<td>188376.3</td>
</tr>
</tbody>
</table>
Table 5.5: Effective length of dispersion of mobilised moment reaction due to impact loading

<table>
<thead>
<tr>
<th>Reaction moment</th>
<th>Effective dispersion length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Criterion A</td>
</tr>
<tr>
<td>Baseline case</td>
<td>30.0</td>
</tr>
<tr>
<td>Case 2</td>
<td>30.0</td>
</tr>
<tr>
<td>Case 3</td>
<td>30.0</td>
</tr>
<tr>
<td>Case 4</td>
<td>30.0</td>
</tr>
<tr>
<td>Case 5</td>
<td>30.0</td>
</tr>
</tbody>
</table>

5.4 Comparision of effects on mobilised shear resistance of system foundation due to impact loading

The distribution of the mobilised shear resistance along the longitudinal direction of the system foundation was calculated by integrating the shear stress over the elemental area and summing the results for all elements within each 1 m strip in the longitudinal direction. The most impactful mobilised shear resistance curve of the foundation system at a particular instance in time during the duration of the crash and for each case is shown in Figure 5.3.

The maximum shear resistance value mobilised at the system foundation and time at which the most impactful shear resistance distribution occurred for each case of crash analysis test are summarised in Table 5.6.
Figure 5.3: Distribution of most impactful mobilised shear resistance on the integral barrier-wall system foundation for all five cases.

It may be observed from Figure 5.3 that the mobilised shear resistance of the foundation system is varying throughout the longitudinal length, and it is marginally influenced by different angles of impact and impact velocities. The maximum mobilised shear resistance force (Table 5.6) due to the crash load is located near to the impact positions where the vehicle was in contact with the barrier-wall. The increased angle of impact (Case 3) and increased impact velocity (Case 5) led to slight increase in the shear resistance, but with almost the same effective length of distribution as for the Baseline Case (Table 5.7). The results show that the effective length estimation based on mobilised shear resistance is on a whole only slightly sensitive to the impact angle and impact velocity.
Table 5.6: Peak (maximum) mobilised shear resistance of most impactful mobilised shear resistance distribution of system foundation

<table>
<thead>
<tr>
<th>Test type</th>
<th>Peak (maximum) shear resistance of system foundation (Nm/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline case</td>
<td>-102918</td>
</tr>
<tr>
<td>Case 2</td>
<td>-96739.9</td>
</tr>
<tr>
<td>Case 3</td>
<td>-112296</td>
</tr>
<tr>
<td>Case 4</td>
<td>-97211.4</td>
</tr>
<tr>
<td>Case 5</td>
<td>-113674</td>
</tr>
</tbody>
</table>

Table 5.7: Effective length of dispersion of mobilised shear resistance due to impact loading

<table>
<thead>
<tr>
<th>Shear resistance</th>
<th>Dispersion length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Criterion A</td>
</tr>
<tr>
<td>Baseline case</td>
<td>26.6</td>
</tr>
<tr>
<td>Case 2</td>
<td>25.5</td>
</tr>
<tr>
<td>Case 3</td>
<td>26.4</td>
</tr>
<tr>
<td>Case 4</td>
<td>27.0</td>
</tr>
<tr>
<td>Case 5</td>
<td>30.0</td>
</tr>
</tbody>
</table>
5.5 Effective length due to impact loading based on all effects mobilised at system foundation

Table 5.8: Effective length of dispersion by considering all effects mobilised on system foundation due to impact loading

<table>
<thead>
<tr>
<th>Shear resistance</th>
<th>Dispersion length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Criterion A</td>
</tr>
<tr>
<td>Baseline case</td>
<td>14</td>
</tr>
<tr>
<td>Case 2</td>
<td>12</td>
</tr>
<tr>
<td>Case 3</td>
<td>12.5</td>
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<tr>
<td>Case 4</td>
<td>7.2</td>
</tr>
<tr>
<td>Case 5</td>
<td>14.5</td>
</tr>
</tbody>
</table>

Table 5.8 shows that the effective length is marginally sensitive to the impact velocity and impact angle, except for the anomaly in Case 4 (impact velocity = 90 km/h). This suggests that the recommendations of the effective length and equivalent plane-strain loading for 44t special performance level impact loading as described in Chapter 4 (Baseline Case) are reasonably robust.
Chapter 6

Conclusion and Future Work

6.1 Conclusion

A 3D finite element model of a heavy vehicle crash against the barrier of a 3 m high integral barrier-wall system was developed in this thesis. The model was calibrated against the impact loading corresponding to a 44t special performance level barrier as specified in AS5100.2:2017. The foundation response of the calibrated model in respect of the mobilised normal reaction force, reaction moment and shear resistance were analysed to understand the dispersion of the impact loading and capture the most impactful dispersion of each mobilised effect in time. The most impactful dispersion of each mobilised effect provides the basis to establish the effective length of dispersion using two criteria:

- Criterion A - based on the threshold of the normal reaction force being $= 10\%$ of the peak normal reaction force of the most impactful curve
- Criterion B - based on the longitudinal extent which covers $95\%$ of the total area under the most impactful curve

This study recommended an effective length of 14 m, based on the minimum of all the established effective lengths. The corresponding equivalent plane-strain transverse loading is 85.71 kN/m, calculated using Equation (4.1) and the transverse impact loading of 1200 kN for a 44 t special performance vehicle crash specified in AS5100.2:2017.

A sensitivity analysis was also conducted to assess the robustness of the recommended effective length of dispersion when the impact velocity and the impact angle were varied. The analysis showed that the effective length is only marginally sensitive to the changes in the impact angle and impact velocity. However, the variations in the two parameters significantly affect the peak mobilised normal reaction force.
6.2 Future works

As previously mentioned, the possible combinations with vehicle and barrier systems are very large, whereas this thesis investigated only one of the several combinations. Consequently, the scope to perform numerical simulations of vehicle-barrier crash and to derive deeper understandings of its impact on the system foundations is extremely wide. Much remains to be learned regarding foundation design of barrier systems from exploring the full scope of vehicle-barrier crashes. The studies would not only help to establish simpler design approaches (such as the equivalent plane-strain approach discussed in this thesis), they also provide the means to develop more cost-effective holistic design of the barriers and retaining systems including the connections between the component parts.

There are insufficient field data on vehicle-barrier crash and its impact on system foundation to properly calibrate and validate the finite element models and the results. The lack of full-scale test data is particularly acute for crashes involving very large vehicles, which are costly to perform. This is an area of research, which needs bolstering.

There is also a need to develop risk and reliability based approaches for the design of the safety barriers and retaining systems based on the methodology developed in this thesis. The volume of computational work required for such an approach is extremely high, but the effort would further rationalise and raise the confidence of the design to a new level.

The vehicle model is an important and integral part of the methodology and modelling approach of this thesis. It is in fact a very complicated model defined by several degrees of freedom, connectivity, material behaviour and properties of its components. It has been a challenge to establish all these parameters accurately to produce the right kinematics and crash behaviour of the vehicle. The vehicle model would benefit from further refinement and calibration against real crash data.
References


