The Effects of Impact Loading on Integral Barrier-Retaining Wall System

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Abstract

An integral barrier-retaining wall system is a reinforced concrete retaining wall with a fully integrated traffic barrier. When a vehicle hits the barrier, this collision impact must be resisted by the barrier, the retaining wall and the soil foundation. In fact, the vehicle collision is a very short transient dynamic loading over a small impact zone. However, for geotechnical design, when considering stability of the whole system, the establishment of equivalent uniformly distributed loads for the plane-strain case is perhaps more important than the ultimate dynamic loading. To obtain these equivalent loads, it is essential to understand fundamentally how the impact loading transmits from the impact point and time to the broader structure. Hence, in this paper, a full-scale Test Level 4 (TL-4, corresponding to regular traffic in AS5100.2) vehicle crash test on a 3-m-high concrete retaining wall integrated with a 1.2-m-high traffic barrier was performed numerically and the effects of the impact loading on such integral barrier-retaining wall system were studied. The magnitude and duration of the impact loading from vehicle collision were obtained from the model. An influence length, which is used to establish equivalent uniformly distributed loads, has been discussed. According to the numerical results, the maximum loads in the transverse, longitudinal and vertical (downwards) directions are 279.65 kN, 78.44 kN and 71.04 kN, respectively. These forces correspond to the design loads specified in AS 5100.2:2004.

Keywords: Integral Barrier-Retaining Wall System, Spread of Transverse Force, Impact Loading, Influence Length, Finite Element Model

1. INTRODUCTION

Retaining wall forms a common part of road and highway infrastructures, which is normally used to retain the soil laterally at two levels on either side of a highway. Because vehicular traffic normally uses the road above the retaining wall, traffic barriers are required to be installed along retaining walls to provide for the safety. In the case of a reinforced concrete retaining wall with a fully integrated traffic barrier which is referred to as an integral barrier-retaining wall system in this study, the impact loads generated by a collision of an errant car or truck must be resisted by the barrier, retaining wall and soil foundation.

The impact load due to vehicle collision is well known as a very short term transient dynamic load over a very small impact zone. It is spatially and temporally transmitted from the point and time of collision to the broader structure. To understand the effects of the impact loading on the integral barrier-retaining wall system, the first question that needs to be answered is "What is the impact load created by the vehicle collision?" Recommendations have been made in several local and international design codes. However, the recommended loads from these codes are different to each other. For instance, the ultimate transverse impact load for a regular performance level barrier in Australian standard 5100.2 (Bridge Design-Part 2: Design Loads) is 300 kN (AS5100.2:2017) and this load in Eurocode 1 is 250 kN (Eurocode 1:2003). However, in the United States, the AASHTO allowable stress design (ASD) bridge specifications (2002) recommend that the barrier with Test Level 4 (or TL-4, which is close to a regular performance level barrier in Australia) needs to be designed for an equivalent static load of 44.5 kN. For the same vehicle impact, the AASHTO load and resistance factor design (LRFD) bridge specifications (2012) recommend a design load of 240 kN. The difference between codes causes confusion when designing such wall systems. Furthermore, for a geotechnical stability design, the equivalent uniformly distributed static loading per unit length for a plane-stain case is perhaps more important than the ultimate impact loading. Then the other question that needs to be answered is "How the impact load spreads over the wall and then over the foundation of the wall system?" For this question, most of design codes focus only on the localized impact loads on the traffic barrier and they are silent on the spread of impact loads. Both AS5100.2 and AASHTO 2012 recommend that the design loads shall be applied uniformly over the relevant specified contact lengths, i.e., 1.2 m and 1.22 m for the regular performance barrier in Australia and TL-4 barrier in America, respectively. Neither of them recommends how the impact loading spreads to the retaining wall. According to the recommendation of California Department of Transportation (2014), the transverse impact load applied along the contact length has a 1:1 intensity distribution towards the base of the retaining wall. It also recommends a minimum distribution length of 12.2 m.

However, up to now, the answers to these two questions are unclear and virtually no literature is available on the effects of impact loading on an integral barrier-retaining wall system. There are no explicit guidelines published in relation to impact loading on geotechnical stability of such systems. Due to the lack of clarity, most current designs of the integral barrier-retaining wall systems tend to be overly conservative, thus, a fundamental understanding of how the impact loads affect the integral barrier-retaining wall system is critically required.

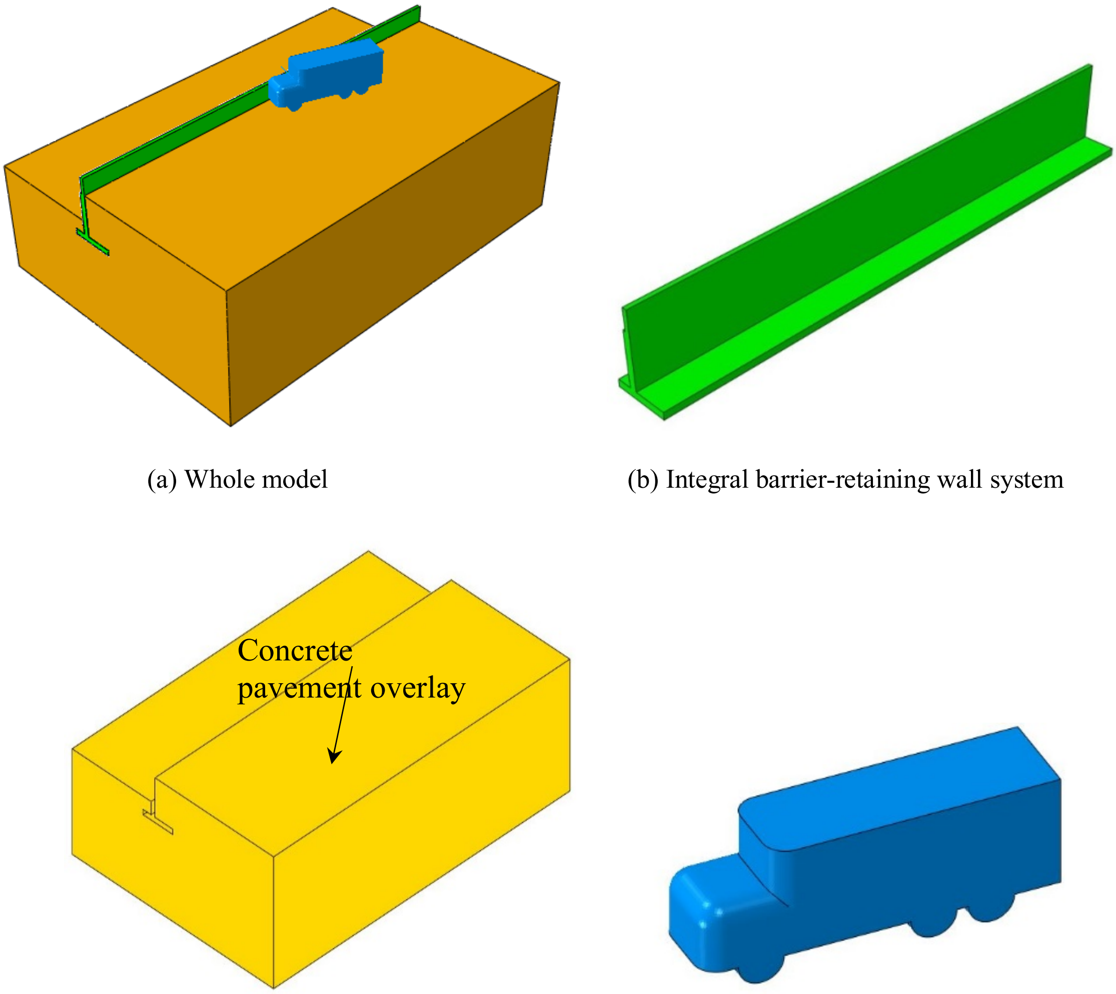
In this study, corresponding to regular traffic performance in AS5100.2, a full-scale TL-4 crash test (2016) on a 3-m-high concrete retaining wall integrated with a 1.2-m-high regular was performed numerically using a finite element (FE) software, Abaqus. The impact loading was created by a collision of a rigid truck. The FE model created is used to simulate the entire process of the collision and to capture the ultimate impact loads during the collision in three orthogonal directions: transverse, longitudinal and vertical. These loads are compared with the design loads recommended in the current code. After that, the spatial distribution of moment, normal force and shear resistance mobilized from the soil foundation will be discussed. Finally, the influence length which is used to establish the equivalent uniformly distributed loading in a 2D plane strain configuration from the localised impact loading based on the FE model is discussed.

2. FINITE ELEMENT MODELLING

In order to investigate the effects of impact loading on the integral barrier-retaining wall system, a 3D FE model has been created using Abaqus/CAE. There are three main parts included in the model as shown in Fig. 1. They are the integral barrier-retaining wall system (Fig.1b), the soil backfill-foundation system (Fig.1c) and the rigid truck (Fig.1d). According to NCHRP report 350 (1993), for impact testing, the length of a metal corrugated barrier should be larger than 30 m and that of a rigid barrier should be larger than 23 m. Consequently, a 3D model with a length of 30 m is used in this study. This length was also established to be sufficiently long to avoid boundary effects of the model.

For the integral barrier-retaining wall system, the height of retaining wall is 3 m and the barrier is 1.2-m high. In the 3D FE model, the integral barrier-wall system was defined as a deformable part made out of reinforced concrete (2011). The solid element, C3D8, and Abaqus's damage plasticity material model were used to simulate the mechanical behaviour of the reinforced concrete. The reinforcement within the concrete was modeled as steel bars and simulated using the beam element, B31. The material behaviour was modelled as elastic-plastic.

The soil backfill-foundation system includes two components, (i) soil mass (comprising backfill and foundation soil) and (ii) rigid pavement which overlays the soil backfill. The pavement is made of concrete with a thickness of 100 mm. The shell-element S4R and concrete damage plasticity material model were used to simulate this pavement. Soil mass was modelled with the solid-element C3D8R and the material behaviour is simulated using the Mohr-Coulomb model. The soil mass was assumed to have a friction angle of 35° and a small value of cohesion of 3 kPa.



(a) Whole model

(b) Integral barrier-retaining wall system

(c) Soil backfill-foundation system

(d) Rigid truck

Figure 1 3D finite element model

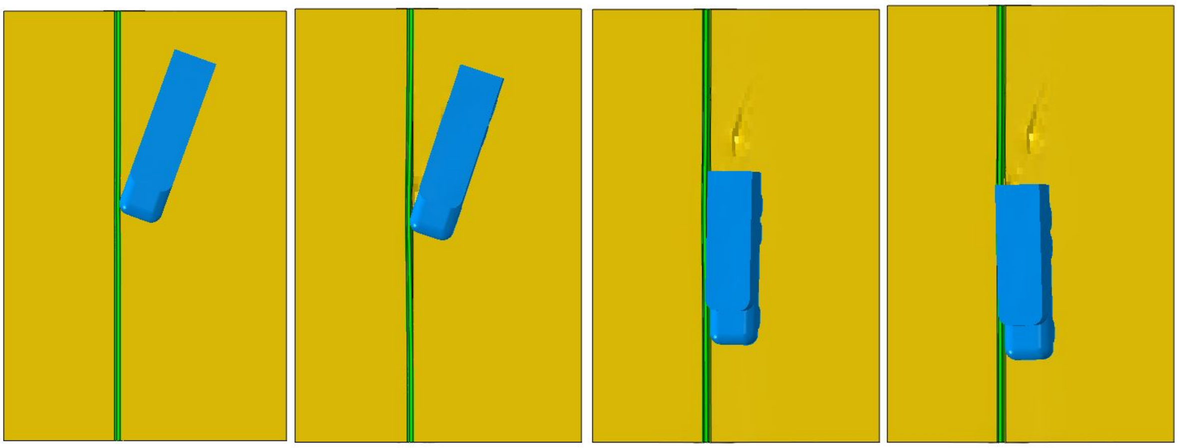
A rigid truck with a weight of 22 tons was simulated to produce the impact loads with regular performance level traffic barrier (AS5100.2). An impact speed of 100 km/h and an impact angle of 20° degrees have been used in this model.

Friction contacts with a friction coefficient of 0.5 (2017) are used to define the interfaces behaviour between different materials including soil to concrete and concrete to rigid truck. The bottom boundary of the soil mass is held immobile whereas tangential movements of the side boundaries are allowed, corresponding to roller constraints.

3. RESULTS AND DISCUSSION

3.1. Numerical crash test

Fig.2 shows the sequence of images of the truck hitting the barrier during impact obtained from the numerical crash test. At t=0 sec, the rigid truck was travelling at an impact speed of 100 km/h, and it then hit the integral barrier-retaining wall system at an impact angle of 20º at t=0.035 sec, as shown in Fig.2a. Approximately 0.015 sec after the impact, the truck began to deviate (Fig.2b). Then, at t=0.325 sec shown in Fig.2c, the truck was travelling almost parallel with the barrier at a speed of 89.81 km/h. At 0.375 sec, the truck is no longer in contact with the barrier and was travelling at a reduced speed of 73.9 km/h and at an angle of 5.71º as shown in Fig.2d. The contact length between the truck and barrier was 7.21 m. The simulation results match well with the field test results provided by NCHRP (2010) and Winkler (2003).

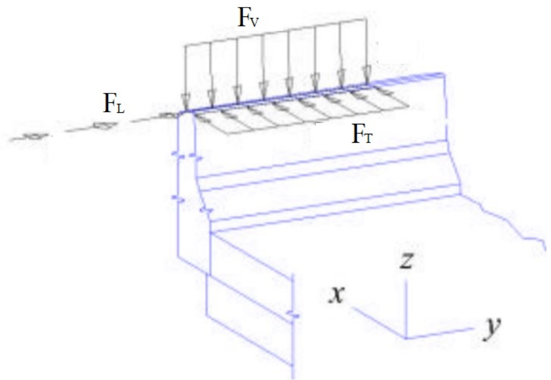


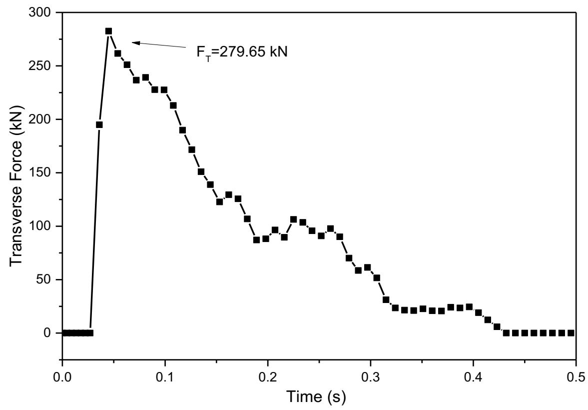
(a) t=0.035 sec (b) t=0.050 sec (b) t=0.325 sec (b) t=0375 sec

Figure 2 Sequence of images during impact

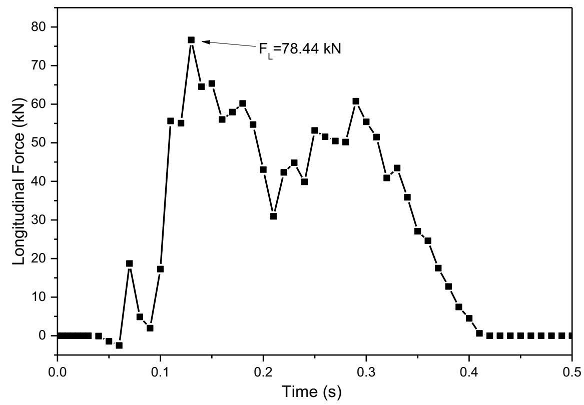
3.2. Impact loads

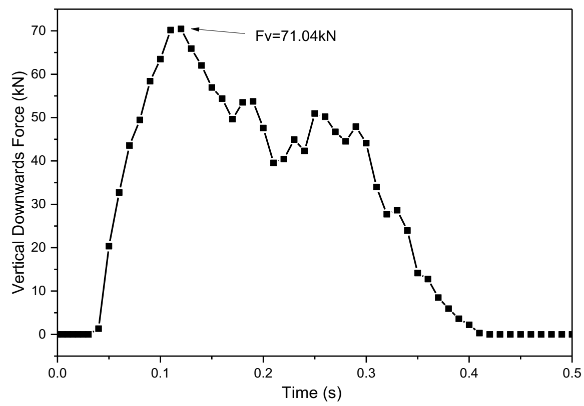
The impact loading generated by the collision of the truck can be obtained from the FE model directly, as shown in Fig.3. The impact loading includes three components as shown in Fig.3a. They are the transverse force, F_T, longitudinal force, F_L, and vertical force, F_V, respectively. For the transverse force, F_T, shown in Fig.3b, the impact force increases rapidly at the beginning of the collision (t=0.035 sec) and reaches the ultimate value of 279.65 kN at t=0.05 sec when the truck begins to deviate. Then, as the truck begins to deviate, the impact transverse force starts decreasing. When the truck's position is parallel to the barrier (t=0.325 sec), the impact force is almost negligible. The whole impact lasts 0.4 sec. Similar evolutions can be observed for the longitudinal vertical forces as shown in Figs.3c and 3d. However, the maximum longitudinal and vertical forces do NOT occur at the same time. The maximum values of F_L and F_V are 78.44 kN and 71.04 kN, respectively. Theses impact forces correspond to the design loads specified in AS 5100.2:2004 for F_T =250 kN, F_L=80 kN and F_V=80 kN.





(a) Three components of impact loading (b) Transverse force, F_T



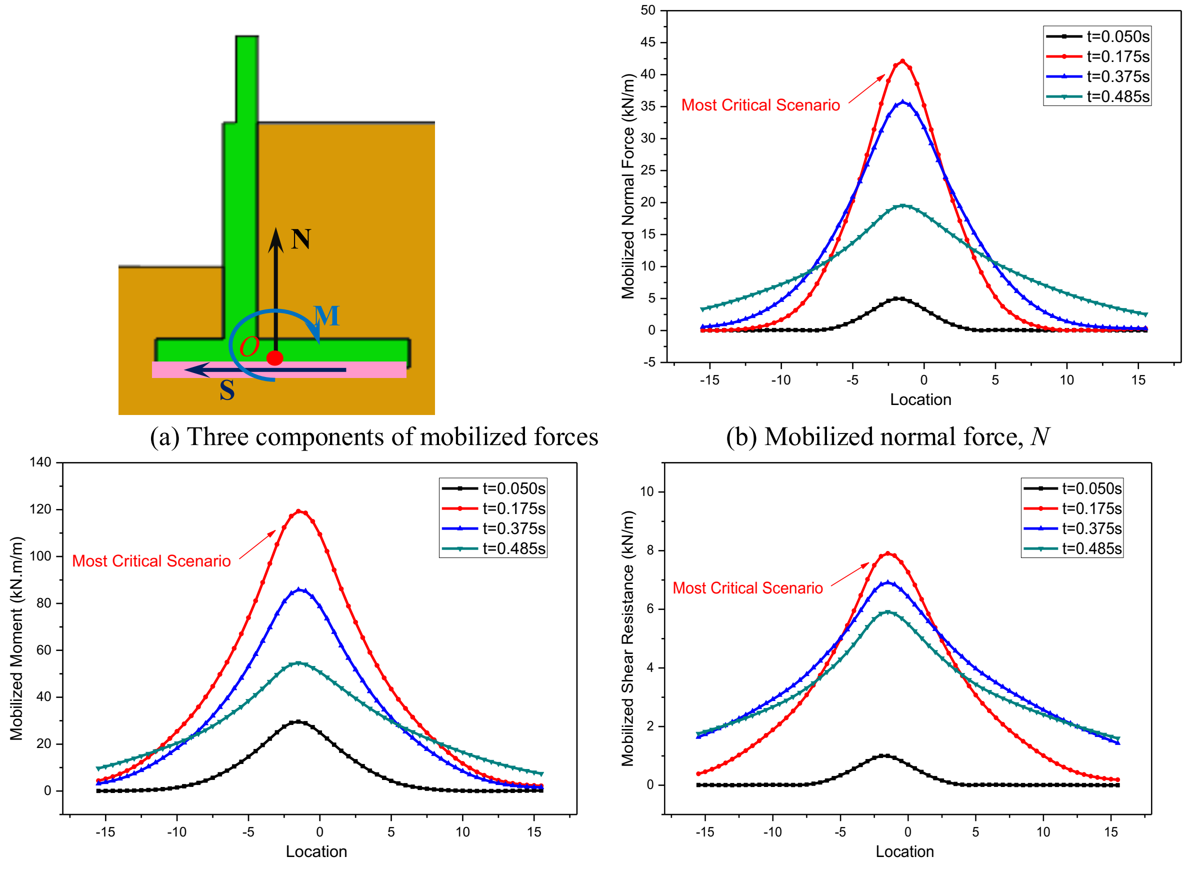


(c) Longitudinal force, F_L (d) Vertical downwards force, F_V

Figure 3 Impact loading time history curves

3.3. Mobilized forces of soil foundation

When a vehicle hits a barrier, the integral barrier-retaining wall system may fail due to sliding and/or overturning. Thus, to study the stability of such systems in response to an impact, it is essential to investigate the effects of impact loading on the mobilized forces from soil foundation. As shown in Fig.4a, the mobilized forces include normal force *N*, moment *M*, and shear force *S*. The spatial distributions of these mobilized forces per unit length along the longitudinal direction of the integral barrier-wall system at different times, obtained from the numerical simulations are shown in Figs.4b-4d.



(a) Three components of mobilized forces

(b) Mobilized normal force, *N*

(c) Mobilized moment, *M*

(d) Mobilized shear resistance, *S*

Figure 4 Longitudinal distributions of mobilized forces

These figures show that the maximum mobilized forces from the soil foundation occur at 0.175 sec. The maximum values of the normal force, moment and shear force are 41.2 kN/m, 109.8 kNm/m and 8.0 kN/m, respectively. As discussed in the above, the ultimate impact loading occurs at t=0.05 sec, which is approximately 0.125 sec earlier than the maximum mobilized forces have occurred. This delay indicates the finite speed of dispersion of the impact loading in the integral barrier-retaining wall.

3.4. Influence length analysis

For the geotechnical design purpose, the equivalent uniformly distributed loading for a plane-strain case is perhaps more important than the ultimate impact force discussed earlier in Section 3.2. Thus, a parameter referred to as *influence length* is defined to compute the equivalent uniformly distributed loading for 2D plane-strain analysis. As recommended by Caltrans, the minimum influence length for an integral barrier-wall system with a 3 m high wall and a 1.2 m high regular performance level barrier is 12 m. In the current study, the influence length is defined as the longitudinal length of the influence area where the impact load can cause significant effects on the forces, i.e., greater than the 10% of maximum force values. Based on the results shown in Fig. 4, the influence lengths for mobilized normal force, moment and shear force at the foundation are 14.3 m, 18.6 m and 21.6 m, respectively. These findings are reasonably consistent with the recommendation by Caltrans.

4. CONCLUSION

This study presented an investigation into the effects of a localised impact loading on the integral barrier-retaining walls system. A finite element model was created to perform a numerical crash test on a 1.2-m-high barrier integrated with a 3-m-high reinforced concrete retaining wall. The impact loading includes transvers, longitudinal and vertical forces. The maximum values for F_T, F_L and F_V are 279.65 kN, 78.44 kN and 71.04 kN, respectively, which correspond to the design loads specified in the Australia Standard,AS5100.2:2004 for regular traffic. The effects of impact loading on the mobilized forces of soil foundation have also been discussed. The concept of influence lengths was introduced to compute the equivalent uniformly distributed loading to be employed in a traditional geotechnical stability design based on a 2D plane-strain configuration. According to the numerical results, the influence lengths for mobilized normal force, moment and shear force are 14.3 m, 18.6 m and 21.6 m, respectively.

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REFERENCES

AASHTO. (2002). Standard specifications for highway bridges, 17th Ed., AASHTO, Washington, D.C.

AASHTO. (2004). AASHTO LRFD bridge design specifications, 3rd Ed., AASHTO, Washington, D.C.

AASHTO. (2016). Manual for assessing safety hardware, 2nd Ed., AASHTO Washington, DC.

Bligh R. P.; Briaud J.; Kim K. M. and Abu-Odeh A. (2010), Design of roadside barrier systems placed on MSE retaining walls, National Corporative Highway Research Program Report 663, Transport Research Board, National Research Council, Washington, DC

Caltrans (2014), 'Memo to designers', California Department of Transportation.

Eurocode 1 (2003), 'Actions on structures – Part 2: Traffic loads on bridges', BS EN 1991– 2: 2003, British Standards Institution, UK.

Ross H. E., Sicking D. L., Zimmer R. A. and Michie J. D. (1993). NCHRP Report 350: Recommended Procedures for the Safety Performance Evaluation of Highway Features, Transportation Research Board, National Research Council, Washington, DC.

Standards Australia (2004), Bridge design Part 2: Design loads, AS 5100.2:2004, Standards Australia, NSW.

Standards Australia (2017), Bridge design Part 2: Design loads, AS 5100.2:2017, Standards Australia, NSW.

Wahalathantri B.L., Thambiratnam D.P., Chan T.H.T. and Fawzi S. (2011). A material model for flexural crack simulation in reinforced concrete elements using Abaqus, eddBE2011 Proceedings, 260 pp.

Winkler, D. J. (2003) Simplified Testing of Traffic Barrier Systems. MPC Report # 01-143, North Dakota State University, Fargo, N.D.

Zhang, Z., Chen Y. and Liu H. (2017). Numerical investigation on the impact resistance of road barriers of Micropile-MSE Wall for subgrade, Computers and geotechnics vol. 82, 249pp.