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FLOODWAY DESIGN PROCESS REVISITED

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Abstract. *Floodways are small road structures that are meant to be overtopped by floodwater during a flood event with relatively low average recurrence interval and expected to be in complete functional stage after the flood water recedes. The severity of 2011 and 2013 flood events in Queensland damaged the floodways in the state causing a huge impact mainly to the rural community during the recovery and rehabilitation stage. Therefore, the resilience of these small critical road structures is of great importance for the survival, safety and recovery stages during such events. Using a case study region in Lockyer Valley Regional Council area, the authors found that majority of the structural damage was caused due to the heavy impact load from the boulders/logs that came with the flood water. Another aspect reviewed was the damage sustained by floodway aprons due to excessive debris loading. This is of particular concern since aprons are the most expensive component of a floodway to repair or replace. Since floodways encounter many forces throughout their service life thorough review and investigation of current design standards are required in order to improve floodway resilience. In an attempt to develop a floodway design process, this paper focusses on the analysis of two types of floodways and reports the procedure used to develop design charts. Detailed finite element analysis is demonstrated by using one type of floodway. Finally, the contribution that resulted from the structural analysis is linked with the current floodway design guide.*

Keywords: Floods; Infrastructure; Bridge failure; Resilience; Impact load

1 INTRODUCTION

Floodways are infrastructure utilised within road design to allow safe vehicle passage across creeks, rivers and streams during flood events generated by relatively low average recurrence intervals (DTMR 2010). This is facilitated through hydraulic design which allows the floodway structure to act as a hydraulic control.

Floodways are a cost effective and practical solution for road authorities since typically flood durations are of a short nature and tend to be infrequent (BNHCRC 2015). Road authorities generally specify the use of a floodway within routes which do not service sufficient people to warrant a large and expensive structure like culverts and bridges (GHD 2012). Floodways also give the designer freedom to control the over-topping water at designated discharge points, often spreading the flow more widely improving creek stability and reducing damage caused by scour and erosion from concentrated flows (Austroads 2013)

Over the past decade, both the intensity and frequency of flood events has increased causing road structures like floodways to sustain frequent damage and failure causing major disruption to rural communities both during and after such events (BNHCRC 2015). The burden to repair these structures is often placed on the local road authority with limited assistance of state funding. GHD (2012) explains how Councils have to cope up with only limited budgets, personnel and design resources to adequately reinstate floodways, and due to these limitations, 'patch' repairs are often undertaken consequently heightening the risk of catastrophic failure within subsequent flood events.

2 AVAILABLE DESIGN GUIDELINES

Guide to Road Design- Part 5B: Drainage- open channels, culverts and flooways (ARRB 2013) is the nationally accepted design guideline for floodways in Australia. However, Road Drainage manual of Queensland Department of Main Roads (Road Drainage Manual 2010) devotes one chapter to floodway design and Main Roads Western Australia has developed an independent floodway design guide for the state of Western Australia (Floodway design guide 2006). Department of Main Roads, Queensland recommends the use of five typical floodway designs which vary based on protection type used i.e. concrete, rock mattress, bitumen sealed and dumped rock-riprap and the Floodway Design Guide by Main Roads Western Australia recommends three types of floodways based on low, medium and high flow velocities. Both of these design guidelines are based on hydraulic design principals with slight variations in the recommended practises by the two organisations.

Recent extreme flood events in Queensland revealed that floodways frequently sustain damage due to the presence of high debris and impact loadings, thus creating a need to further investigate the factors contributing to floodway vulnerability by investigating the structural adequacy of floodways designed and built in accordance with the current recommended best practises.

3 FINITE ELEMENT MODEL DEVELOPMENT

The methodology for this research includes modelling one of four commonly used floodways within the Lockyer Valley region (LVR) in Queensland, Australia using finite element analysis software, Strand7 (Strand7 2010). The chosen Type 2 floodway (Figure 1) is a standard engineering design of a universal nature and is best suited for roads crossing creeks of relatively flat grade.

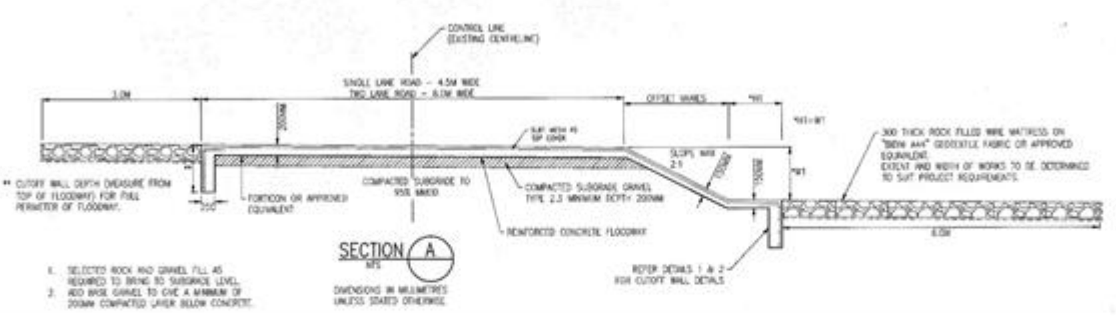


Figure 1 Cross section of floodway Type 2

3.1 Assumptions

In developing the finite element model several assumptions were made to simplify the floodway structure and load application to allow for modelling in Strand7. These assumptions are as follows;

- The surrounding adjoining soil is of one type throughout the model's

- depth, as opposed to layered;
- The floodway is of a single lane width of 4.5m;
- The creek's channel has vertical embankments at 90 degrees relative to the creek bed;
- Rock protection is defined as a soil material defined by Mohr-Coulombs criterion i.e. a homogeneous, elastic-plastic and isotropic material;
- Steel reinforcement within concrete is neglected to determine actual tensile forces so reinforcement could be designed accordingly; and
- Boulder impact loading is only applicable when the flow depth and velocity is greater than 1 m and 5 m/s, respectively. In addition, a factor of 0.5 was applied to the log impact equation given in Clause 16.7 of AS 5100.2:2017. The 0.5 factor was considered appropriate since the boulder is not a suspended article like a log, rather it will remain in contact with the creek bed. Figure 2 provides a chronological account of the methods employed within this research to construct the finite element model.

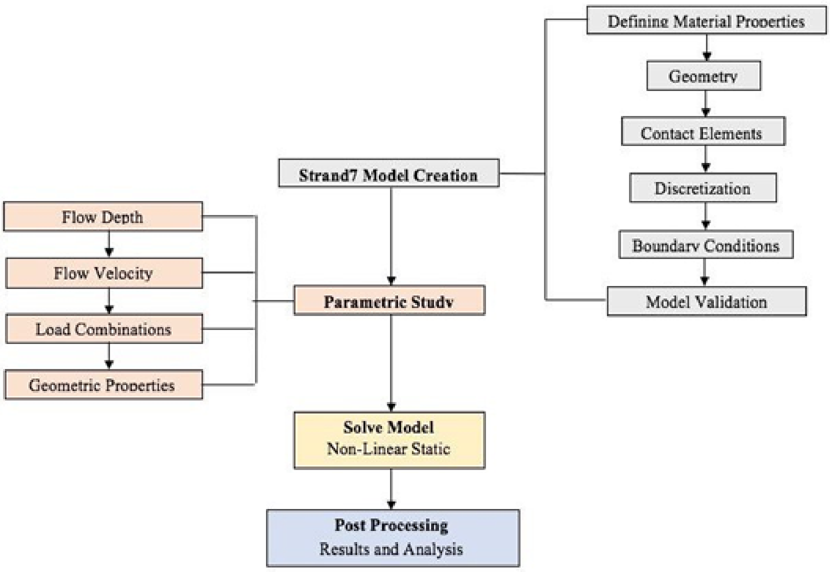


Figure 2 Modelling process

3.2 Modelling Process

To correctly restrain the model, boundary conditions were assigned to the outer model extents to imitate in-situ support conditions. Specifically, the nodes on the outer faces were restrained by assuming a roller type support and the bottom face a rigid support i.e. no translation movement, thus causing the side faces to be fixed in the horizontal plane, however still enabling movement in the vertical direction. The bottom of the floodway was completely restrained (fixed) in the X, Y and Z axis. The effect of the extent of the natural earth was examined using 12, 21.6, 26.4 and 36 m model length extents of the floodway. As a result, a profile length of 26.4 m was selected for the floodway model based on the displacements and Von Mises stresses. The 3D finite element model of the floodway was developed to depict the Type 2 floodway in LVR with suitable material properties for concrete and soil adopted (Table 1). During the mesh refinement, it was concluded that a medium mesh size consisting of 16,718 nodes and 15,896 bricks exhibited reasonable accuracy of the solution along with reasonable solution time, enabling a nonlinear solution to be obtained (Figure 3).

Further to this a 'with' and 'without' contact element case was considered in terms of accuracy and computational time and it was concluded that the use of without contact elements provided reasonable solution accuracy for flood velocities less than or equal to 8 m/s.

Table 1 Material properties

Material	Modulus (MPa)	Poisson ratio	Density (kg/m^3)	Cohesion (MPa)	Friction angle (deg)
Concrete	31000	0.2	2400		
Adjoining natural earth	40	0.3	1700	0.01	25
Rock	100	0.3	1400	1.0	30
Natural subgrade (95% MDD)	150	0.3	1900	0.1	30
Gravel sub base	200	0.3	2000	0.1	35

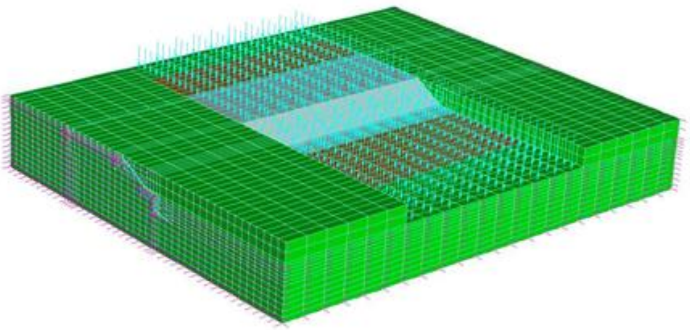


Figure 3 Floodway model with medium mesh size

4 RESULTS AND DISCUSSION

Three different load combinations presented below were selected in response to the relevant findings in the literature review and ultimate design loadings applied based on AS 5100.2:2017.

A. Hydrostatic loading;
B. Boulder impact and hydrostatic loading; and
C. Vehicular, debris and hydrostatic loading.

Stress and displacement results from the model were used to determine the worst case loading combination. This was then followed by trialling different design configurations including cut-off wall depths, degraded downstream rock protection and undrained/drained case to determine the most vulnerable floodway configuration. The worst case loading combination in conjunction with the most vulnerable floodway configuration was then selected and analysed further to determine a number of strength capacity design charts, M* (design bending moment) and V* (design shear force), based on four different sets of soil mechanical properties.

The following sections describe the analysis of load combination B – boulder impact and hydrostatic loading, the load combination which was found to produce the worst case loading.

4.1 Sample Load Combination B- Boulder Impact and Hydrostatic Loading

The simulation of a moving boulder contacting the floodway structure was conducted by subjecting the floodway to iterative loadings based on an assumed maximum boulder mass of 2-tonnes in conjunction with different flow velocities and depths.

4.1.1 Displacements (Dx)

Maximum displacement results in the horizontal direction (direction of flow) were found to increase proportionally to flow velocity, corresponding with an increase in impact loading (Figure 4a). In addition, since vertical downward loading controls frictional force, horizontal displacement slightly increases as hydrostatic loading decreases. The highest horizontal displacement occurs when flow depth is at a minimum and velocity is at a maximum.

4.1.2 Von Mises stress

Increases in flow depth have a greater effect on stress at flow velocities of less than 3 m/s (Figure 4b). Once flow velocity increases past 3 m/s impact loading becomes the dominate force and the three flow depths converge and increase exponentially with flow velocity. The Type 2 floodway exhibits the highest vulnerability to stress when flow velocity is at a maximum relating to the largest impact loading case.

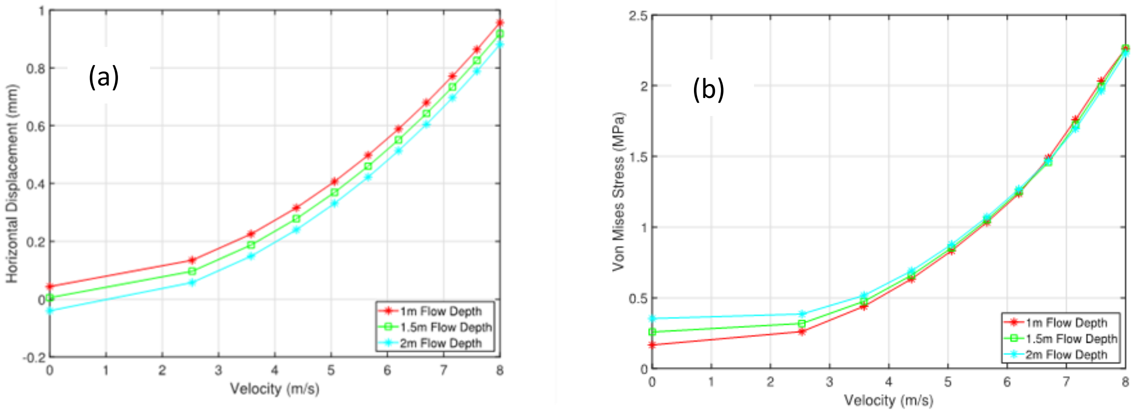


Figure 4 Horizontal displacement and Von Mises stress with increasing flow depth and velocity

The sample impact load combination shown above consistently produced the highest stress and horizontal displacement results indicating that this is the case which the Type-2 floodway structure is most vulnerable to. As a result of these findings further detailed analysis will be undertaken into this load combination.

4.2 Boulder mass

Increasing the boulder mass to 4-tonne provides the unfactored equivalent impact of a 2-tonne floating log, the minimum mass in which AS 5100.2:2017 states should be considered for ultimate impact loading. Both the horizontal and vertical displacement results in the 4-tonne boulder case diverge from the 2-tonne boulder case as flow velocity increases. At the maximum velocity the horizontal (Figure 5a) and vertical displacement were 52.8% and 24.9% greater respectively than the 2-tonne boulder case. Similarly, Von Mises stresses of the 4-tonne boulder case also diverge as flow velocity increases. At the maximum velocity the stresses were 49.9% greater than the 2-tonne boulder case (Figure 5b).

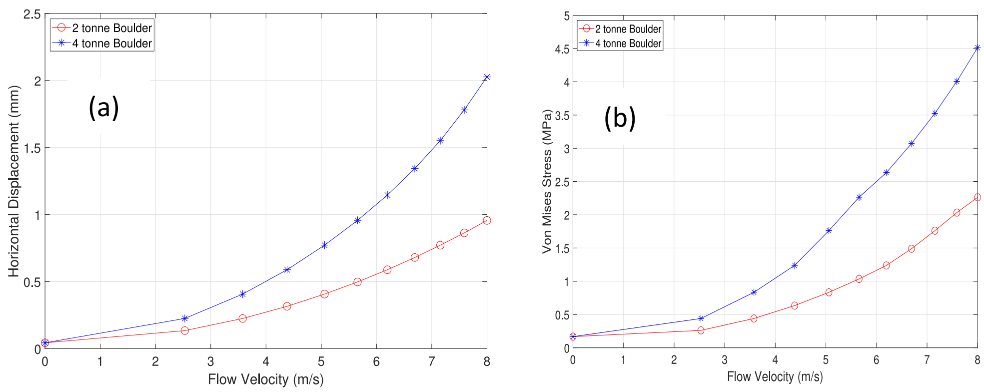


Figure 5 Effect of 2 and 4 tonne boulder impact

4.3 Cut-off Wall Configuration

In response to the investigation work currently been undertaken by Lockyer Valley Council, a second cut-off wall length of 1100 mm defined as treatment option 2 is trialed and compared to the standard 900 mm cut-off wall depth. Combination B, being the worst case loading with 2-tonne boulder is used within this simulation. Maximum horizontal and vertical deflection reduces by 3.34% and 2.66% respectively when the cut-off wall depth is increased from 900 mm to 1100 mm (Figure 6). Increased cut-off wall depth further prevents displacement under both lateral and vertical loading as a result of the greater distribution of forces to the adjoining soil, subsequently increasing stabilising moment.

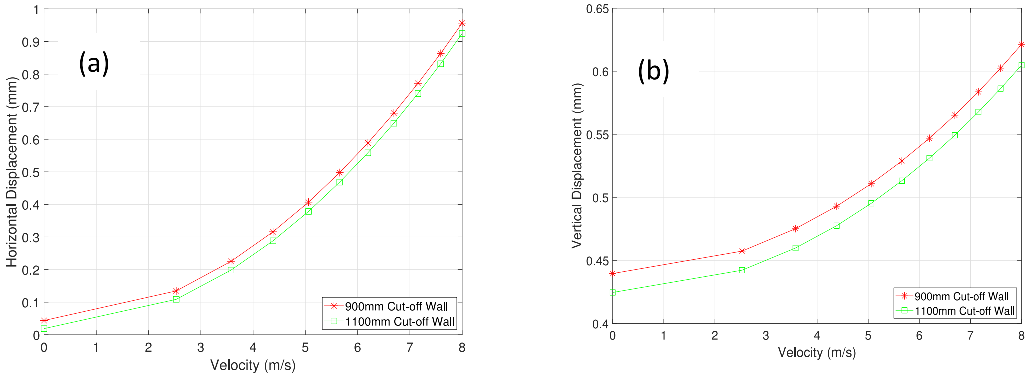


Figure 6 Effect of 2 cut off wall configurations

4.4 Downstream Rock Protection

Eroding downstream rock protection as a result of a localised head cut at the downstream end of the floodway was identified within the literature review as one of the most pronounced failures caused by extreme flood events. This scenario can be simulated by a reduction in the amount of rock protection and adjoining soil adjacent the downstream cut-off wall. Three cases were considered in the analysis (Full downstream rock protection, No downstream rock protection; and No downstream rock protection or soil adjacent the downstream cut-off wall).

Horizontal displacement increases in magnitude as material adjacent to the cut-off wall decreases. This is caused by the decrease in stabilising moment of the concrete apron along with its ability to prevent displacement under lateral loading. The “with” downstream rock protection case has the greatest resistance to lateral loading and has 8.36% less horizontal deflection than the case “without” downstream rock protection. The case with no rock protection or soil adjacent the downstream cut-off wall is the most vulnerable to lateral loading and horizontally deflects 18.6% greater than the “with” rock protection case. Similar, vertical displacement increases in magnitude as material adjacent the cut-off wall decreases due to the lack of supporting soil adjacent the cut-off wall. The Von Mises stresses converge at a flow velocity of approximately 3.5 m/s, after which the results follow a similar increasing trend as flow velocity increases.

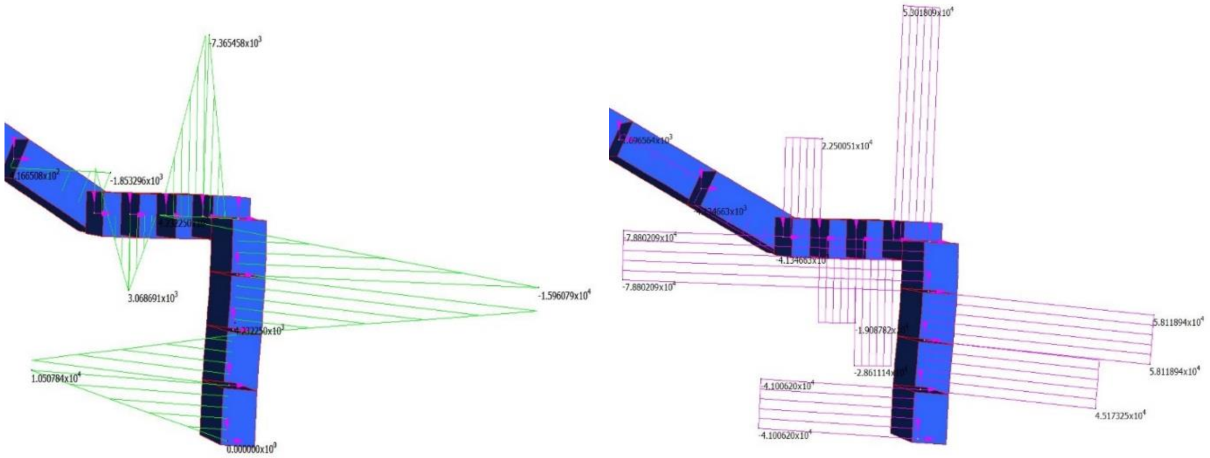
4.5 Undrained Condition

Undrained and drained scenario of the surrounding soil were considered in the analysis and the results are not presented due to the limitation of the length of the paer.

4.6 Design Charts

Based on the above analysis the worst case scenario in terms of loading combination, with or without downstream rock protection and drained and undrained conditions will be selected for each cut off wall configuration and each soil type. The mechanical properties of the surrounding soil in which the floodway is to be positioned in also significantly affects the floodway’s resulting moment and shear force and, therefore, will remain case dependent and graphed independently. To determine the design bending moments M* and design shear forces V* the following process is adopted:

- The worst case loading combination with ultimate limit state loading for permanent and imposed actions in accordance with AS1170:2002 (1.2G + 1.5Q) was applied to the 3D finite element model.
- The model was then solved and the line of action with the largest sigma xx stress and horizontal displacement in the direction of flow (longitudinal) was observed and values for horizontal and vertical deflection at set intervals either side of the concrete floodway slab, batters and cut-off wall were recorded.
- The line of action was then represented as a 2D frame model using beam elements connected rigidly at joints. The 2D model was assumed to be of a nominal 1 m length in the z direction (perpendicular to flow). The displacements recorded from the full-size model were then applied as restraints (specified displacements) to the nodes within the 2D beam model by taking the average of the upper and lower Dy and Dx displacements. This interpolation method was considered reasonable as little variation existed between the top and bottom values due to the relatively stiff mechanical properties of concrete.
- The 2D frame was then solved using the non-linear solver in Strand7 to get the M* and V* distribution (Figure 7). To ensure accuracy of the 2D beam model the Dx and Dy displacements were compared to that of the 3D cut-plane model.



(a) Bending moment (b) Shear force

Figure 7 Sample of 2D frame model for M* and V* distribution

For four commonly encountered soil types and the two cut off wall treatment options, the maximum bending moments (M*) and shear forces (V*) will be plotted as design charts for a range of velocities and flow depths.

5 PROPOSED FLOODWAY DESIGN

Based on the strength capacity design charts, M* and V* can be determined for commonly encountered soil types, flow depths and flow velocities. Reinforcement can then be adequately designed in accordance with AS 3600:2009. It is anticipated that the designer will utilise readily available software to determine the design discharge, maximum flow depth and flow velocity, along with geotechnical testing to determine soil type for the selected location. One of the two cut off wall configurations will be selected based on the importance level of the structure and the associated cost. The proposed floodway design process can be summarised as shown in Figure 8 and authors are currently doing further research to propose a recommendation that current design guidelines in Australia endorse such procedure.

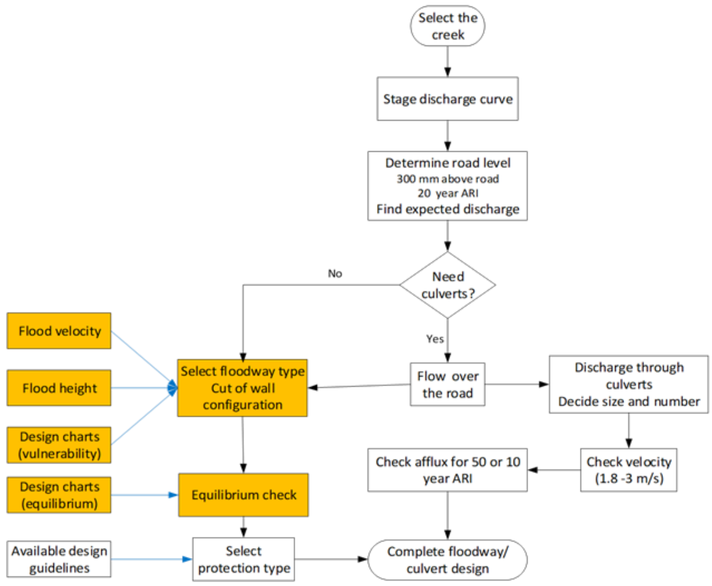


Figure 8 Floodway design process

6 CONCLUSION

This research presents a Finite Element Modelling approach to include structural analysis for the floodway design. Currently, floodways are designed based on hydraulic analysis. A detailed finite element model was developed and tested for Type 2 floodways available within Lockyer Valley Regional Council. Based on the load combinations, a process to develop the design charts for this particular floodway type is proposed. A simplified approach to use the developed design charts is formed and linked with the available design guidelines for floodways. The entire design process needs to consider the current hydraulic design practise and a simplified structural design method i.e. strength capacity design charts that are based on comprehensive structural analysis for a range of flood intensities and the presence of scour.

Although the development of design charts for one floodway type is demonstrated here, this research is still ongoing for other 3 types of floodways available within the Lockyer Valley region.

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