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ORIGINAL ARTICLE

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Qualitative investigations into floodways under extreme flood loading

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Abstract

The Australian use of the term floodway refers to a trafficable transverse structure designed to facilitate the safe crossing of watercourses. Floodways are also commonly referred to as fords and causeways. This research explores areas of focus through experimental, numerical and survey methods to improve floodway resilience with regard to flood risk management. The industry-based survey provides a dataset relating to user experiences, deduces the likeliness of floodways to sustain damage, defines several key focus areas, and reveals that the current risk levels are primarily managed without significant investigation into design. A floodway experimental and numerical simulation program was developed to investigate the lateral forces induced through debris impact using scaled models in a soil box and finite element analysis. Qualitatively, crack propagation and displacement correlated closely with the strain concentrations and displacements in the numerical simulation, with failure attributed to tensile strength being exceeded, followed by plastic strain development within the soil elements. It was concluded through this research that floodway failure during flood is complex and can be attributed to several different failure modes including concrete failure, yielding of adjoining soil material, and hydraulically via scour.

KEYWORDS

debris flow, flood damages, floods, floodways, hydraulic structures, infrastructure, modeling, resilience

1 | INTRODUCTION

Following a series of natural disasters and the expectation that weather induced events will become more severe due to changing climatic conditions, research into resilient infrastructure strategies has received growing attention (Bocanegra & Frances, 2021; De Bruijn, 2003; Kuang & Liao, 2020). Floods are a frequently occurring and damaging natural disaster causing significant economic loss and damage to the built environment (Xiao et al., 2021). Small road structures, such as floodways (Figure 1), are designed to assist in the safe and expedient vehicular crossing of waterways, increasing the connectedness of rural communities. Well-connected

FIGURE 1 A typical concrete floodway structure.

communities are critical to efficient functionality and economic prosperity, providing vital links between services such as schools, hospitals, and major trade centers (Singh et al., 2021).

Flood risk management has been researched extensively throughout history, with strategies focusing on two main factors; reducing the flood risk (resistance strategies) and reducing the consequences of flooding (resilience strategies) (Vis et al., 2003). De Bruijn (2003) explains that modern approaches typically focus on resilience strategies due to the significant number of variables and uncertainties relating to floods. Disse et al. (2020) and Gouldby et al. (2009) describe resilience in a flood risk management context as reducing negative impacts due to extreme events, which would otherwise have devastating effects on communities.

Floodways are structures designed to facilitate safe vehicular movement across waterways through improvements to the stability and predictability of the trafficable surface. The Australian usage of the term floodway differs from that used in other countries where it is often understood to be a flood relief channel or natural flood plain that actively conveys excess flow rather than a transverse structure across a watercourse. Floodways in the international context are commonly referred to as fords or causeways.

Floodways in the Australian context have received very little research attention until the Queensland floods of 2011 and 2013 (Wahalathantri et al., 2018). Research into floodway failures resulting from these flood events typically found the failure to result from extreme loads and velocities associated with flooding (GHD, 2012; Wahalathantri et al., 2015). Currently, no studies documented in literature have investigated, through experiment, the behavior of concrete floodways under loadings equivalent to actual flood events. Research conducted by Lokuge et al. (2019) identified common structural attributes relating to vulnerable floodways and summarized the limitations of using finite element analysis to design floodways. Greene et al. (2020a) utilized finite element analysis to extensively investigate floodways and reported that the worst-case loading scenario, using load combinations documented in AS5100.2:2017, *Bridge Design – Design loads* was impact loading. Impact loading can be considered as an accidental loading, like an earthquake, which a resilient structure shall withstand as an ultimate limit state loading. Impact loading in a floodway structure occurs when the floodway is submerged, and debris, such as floating logs or rolling boulders impact the superstructure.

Greene et al. (2020b) undertook a comprehensive Australian-based industry survey in 2020 to investigate

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the experiences of asset owners concerning extreme flood events and the prevalence of impact-related failures, thus providing a qualitative dataset in relation to practical experiences post extreme flood events. In the international context, two other floodway specific surveys were undertaken by Lohnes et al. (2001) and Gautam and Bhattarai (2018). The survey conducted by Lohnes et al. (2001) was in response to developing a design guideline with respondents from various municipals within the United States. The survey outcomes suggested a strong dependence on in-house design standards, a preference towards vented floodways, as well as providing a summary of floodway applications. The survey by Gautam and Bhattarai (2018) summarized the consensus of floodway uses as being within rural settings, on roads with low average daily traffic volumes, to provide an economical alternative to bridges and culverts, and that the overtopping duration should be based on utilization category and limited to less than 5% per year.

To enable the effective design and redistribution of stresses within the structure and to enhance the resilience of concrete floodways, it is important to understand the crack distribution within the concrete structure (Metwally, 2017). Concrete floodway structures, like bridges, are large and complex, creating difficulties in undertaking full-scale experimental analysis (Al-Rousan et al., 2020). Alternative methods are therefore required to analyze the behavior of these types of structures. Finite element analysis is a widely accepted and versatile engineering tool that can be used to analyze the behavior of structures (Venkatachalam et al., 2021). Finite element analysis can provide solutions for non-linear behaviors that are reliable and realistic, enabling it to be used to enhance the fundamental understanding of structural response and optimizing design (Metwally, 2017). Further, scale model test specimens enable a physical representation of the structure's response under loading to be observed, providing numerical model confidence based on agreeance.

The novelty of this research is the investigation of floodway structures through qualitative experimental, numerical and survey methods to identify key focus areas in relation to structural resilience and flood risk. An industry-based survey was used to determine the key focus areas in practice, prior to using experimental and numerical investigations to explore a single area of focus (debris impact loading). It was identified that undertaking a combination of approaches resulted in a general understanding of the key focus areas of flood risk management in relation to floodways, provides a dataset of experiences relating to floodways, and a scaled model test method to failure test floodways. These outcomes enable resilience strategies to be further developed based on reported outcomes.

2 | INDUSTRY SURVEY

A survey targeting Australian engineers and industry professionals was undertaken to develop a data set in relation to floodway structural resilience, observed failure mechanisms and to determine recent improvements undertaken in floodway design in the context of flood events and risk management.

The survey was commissioned in 2020 and utilized an online survey instrument developed through Lime Survey (2020). The survey instrument consisted of 12 predominantly objective-based questions, but also incorporated short answer responses (refer Supplementary Information S1). Recruitment of the target audience was restricted to professional engineering forums, email distribution within professional institutes, as well as government organizations who had received grant funding for floodway construction and repair within Australia. The target audience was randomly sampled and was largely self-recruited, however, had a known bias of individuals and asset owners with direct experience in floodway design, construction, maintenance, and disaster response. Participation was from the States of Queensland, New South Wales, Victoria, and South Australia, providing a good geographical cross-section of the east coast of Australia. The survey was accessed 96 times, of which 64 complete responses were received. Partial or incomplete surveys were not considered. The completion rate of 66.7% was concluded as a good representation of the target audience (Gillham, 2007). The survey took respondents an average of 9 min to complete.

2.1 | Susceptibility to failure based on floodway type (questions 1 and 2)

Survey respondents stated that floodway structures were "highly likely" (42.2%) and "likely" (40.6%) to be damaged, inclusive of rock protection during an extreme flood event (Figure 2). The remaining respondents stated that floodways were "neither likely nor unlikely" (10.9%), "unlikely" (4.7%) and "very unlikely" (1.6%) to sustain failure due to extreme flood events.

Investigating this further, respondents stated that downstream floodway components (Figure 3), including downstream rock protection (65.6%), the downstream batter (12.5%) and the downstream cut-off wall (7.8%) were the most likely components to sustain failure (Figure 4). The apron and upstream floodway components, such as upstream rock protection and the upstream cut-off wall were relatively unlikely to fail and received 4.7%, 7.8%, and 1.6%, respectively.

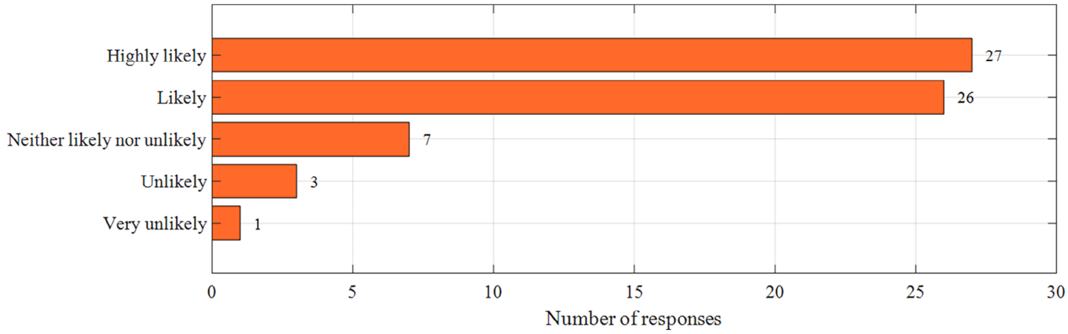

FIGURE 2 Survey question: In your experience what is the likelihood that a floodway, inclusive of protection, will sustain damage during extreme flood events? (Greene et al., 2020b).

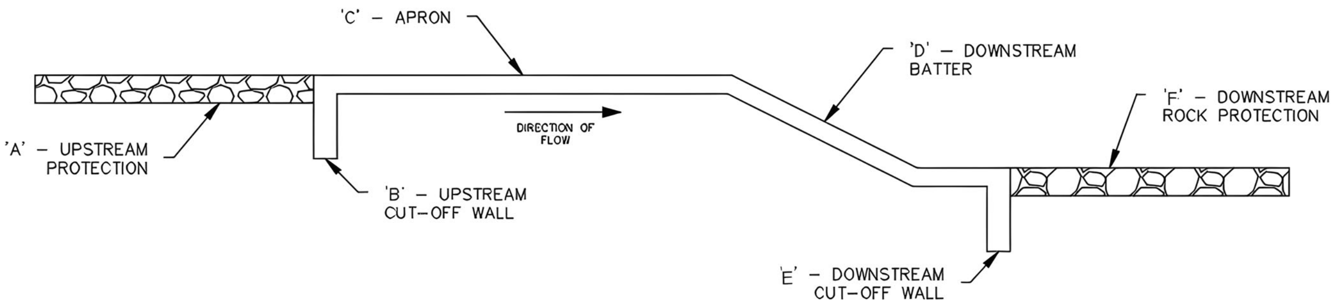

FIGURE 3 Components of a typical concrete floodway (Greene et al., 2020b).

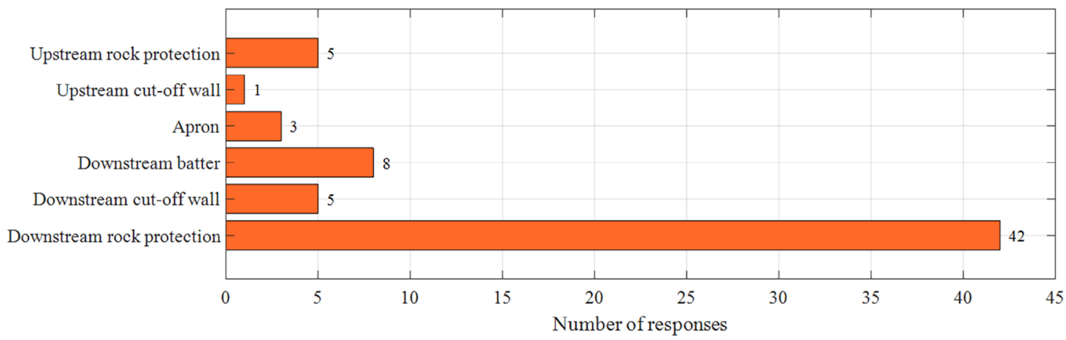

FIGURE 4 Survey question: In your experience which floodway component is most susceptible to damage during an extreme flood event? What is the likely cause of this damage? (Greene et al., 2020b).

Comments received suggested that downstream floodway components were most likely to fail due to the formation of a hydraulic jump and associated turbulent conditions within the vicinity of the downstream cut-off wall and apron. MRWA (2006) explains that flow accelerates down the downstream batter of a raised floodway structure until it penetrates the tailwater, causing the flow to suddenly deaccelerate in a turbulent and non-steady state. This phenomenon is known as a hydraulic jump, and results from the supercritical (rapid and unstable) flow reverting to a subcritical flow regime when it makes contact with the slower moving tailwater. The formation of a hydraulic jump represents an area of high energy loss and increased erosive potential (increased bed shear stress), aligning with the comments provided in the survey, and therefore forming a key focus area of flood risk management strategies for floodways.

2.2 | Susceptibility to failure based on floodway type (question 3)

87.5% of survey respondents stated that raised floodway structures relative to the creek bed were more susceptible to failure than floodways situated level with the creek bed.

Raised floodway structures create a significant hydraulic control on the watercourse, resulting in an increase in backwater level and supercritical flows over the structure (rapid and unstable). For level floodway structures flow remains subcritical throughout the reach, and therefore expected to behave in a stable and predictable manner.

From a resilience perspective, level floodway structures offer the ability to minimize the adverse impact of flooding due to the presence of reduced lateral loading and unaltered flow regimes, however, at the expense of increased road closure time.

2.3 | Susceptibility to failure based on soil type (questions 4 and 5)

78.1% of survey respondents stated that soil type significantly influenced the prevalence of floodway failure. Out of the available multiple-choice selections, a "Sandy Soil" type received the highest response of 56% (Figure 5). The option to select "Other" and specify a soil type also existed, which received 14% of responses. Soil types defined in the "Other" category consisted of sodic and highly dispersive soils. Other options were "Clay Soils" and "Silty Soils" which received 12% and 8%, respectively. This suggests that highly erodible bed soils and soils that lack cohesion tend to disperse and scour during elevated velocities associated with extreme flood events.

This response also aligned with the international survey by Lohnes et al. (2001), which concluded that floodway constructions on loess (sedimentary soils) should be avoided due to its increased erosive potential. Furthermore, it aligns with various sources of literature such as Postacchini and Brocchini (2015) who explain that the action of scour and particle movement within cohesive and non-cohesive soils is vastly different. The movement threshold for non-cohesive granular sediments is a product of particle size, density, shape, packing, and orientation, while erosion within non-cohesive sediments is reliant on shear stress, shear strength, and also the chemical and physical bonding of soil particles (Najafzadeh et al., 2013). Postacchini and Brocchini (2015) further explained that for cohesive soils, much larger forces are often required for particles to detach and for movement to be initiated, as opposed to non-cohesive particles which require much lower forces to be entrained.

2.4 | Susceptibility to failure due to debris impact (questions 6 and 7)

62.5% of survey respondents reported that floodways were more susceptible to failure due to increased debris load conveyed by extreme floodwaters (Figure 6). More specifically, of the 62.5% of respondents, 37.5% stated that the impact from boulders was a significant contributing factor to failure.

This failure mode was also well supported by the findings in the literature review (GHD, 2012; Wahalathantri et al., 2015) and will form the loading case to be investigated further within the experimental program and numerical simulation.

2.5 | Investigations and improvements being implemented to increase floodway resilience (questions 8–11)

Although survey respondents stated that floodway failure was highly probable during extreme flood events, very few respondents (35.9%) indicated that they had investigated improving floodway resilience and reducing flood impact through improvements to standard floodway designs. This low response suggests that although there is a high likelihood of failure occurring during flood events, this risk is currently being managed without significant investigation into design improvements. The main improvements discussed cover the four main topics as follows:

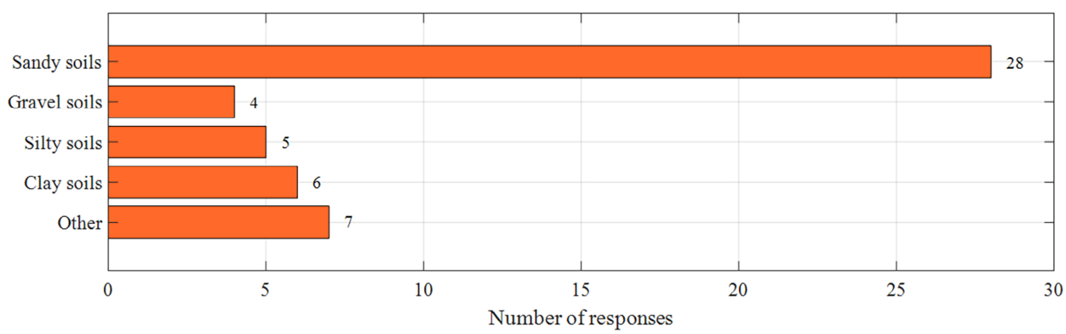

FIGURE 5 Survey question: Which soil type have you found floodway failure to be most common in? (Greene et al., 2020b).

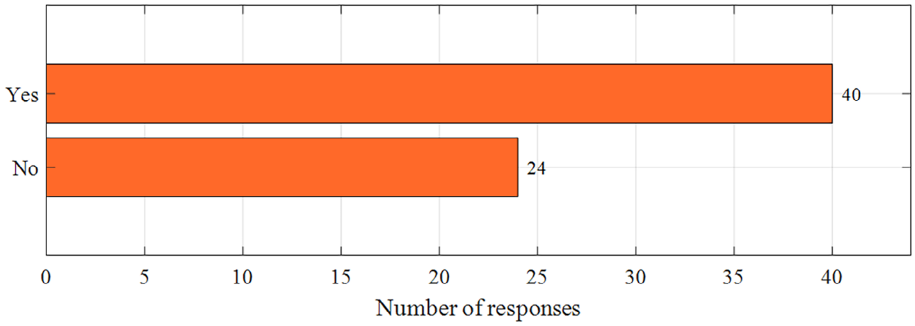

FIGURE 6 Survey question: During extreme flood events, have you found increased sediment load, such as organic debris (logs) and boulders from landslides, bank erosion and other processes, contributed to floodway failure as a result of being conveyed by floodwaters and impacting the floodway structure? (Greene et al., 2020b).

- Concrete cut-off wall configuration: Only 10.9% of respondents had investigated cut-off walls, including varying depth, width, and steel reinforcement requirements. Increasing cut-off wall depth increased stabilizing moment as the surface available to resist overturning and displacement increases. From the survey results, it was inferred that adequate resistance to flood loading was achieved with a cut-off wall extending to the entire perimeter of the floodway structure and at a depth greater than 900 mm.
- Geometric alignment: Several respondents favored level floodway structures instead of raised structures based on observing reduced damage post-extreme flood events. This aligns with the responses and discussions in sub-Section 2.2.
- Floodway structure: Monolithic concrete floodway structures were suggested to significantly improve floodway resilience as opposed to sealed and unsealed floodway formations. Illangakoon et al. (2019) explains that cold joints in concrete structures result in premature deterioration due to water leakage and strength reduction. Monolithic structures are cast within one pour, creating greater connection integrity (Li et al., 2022).
- Pavement materials: Adopting a lean mix concrete or a foam bitumen pavement material had been trialed instead of traditional granular materials to ensure that the pavement could retain its strength while in a saturated state. A porous pavement, such as no fines concrete enables the efficient flow of liquid through the pavement to an incorporated drainage system, thus significantly reducing pore pressure within the pavement layer during periods of inundation (JTTE Editorial Office, 2021). Wilton (2014) undertook a case study in Inglewood, NSW into unsealed foam bitumen stabilized granular pavements and conventional granular pavements, which had been exposed to a 6-week deluge of rain totaling 142 mm. As a result, the conventional granular pavements were reported as destroyed, while the stabilized pavements only required light patching. This is largely due to the foam bitumen binding the pavement to form a water-tight matrix yet providing greater flexibility due to the rubber content within the bitumen.

The industry-based survey provides a dataset of industry experiences and a cross-section of relevant focus areas to improve floodway structural resilience and resistance against flood. The survey deduced that floodways, particularly downstream elements, are likely to sustain damage during flooding; however, the current levels of risk have primarily been managed without significant investigation into design improvements. Lateral loads induced through debris impact due to flood waters was reported as a major contributing factor to floodway failure (62.5%). An experimental program and finite element analysis using equivalent static forces will be used to analyze the effects of impact loading in subsequent sections of this research. This will enable the specific failure mode, displacement, and crack propagation within a floodway structure to be explored.

3 | EXPERIMENTAL PROGRAM

An experimental program was developed to test model floodway structures in a soil box using a 1:7.5 scaled concrete floodway model exposed to equivalent static forces to analyze the effects of lateral loading. This experiment aims to determine the response of concrete using monotonic compression test conditions, and is an initial step in validating the applicability of numerical models, which, once validated, can be used to analyze more complex dynamic and cyclic response. The results of this experiment provide initial observation of the mode of failure, stress formation, as well as failure locations/localizations. In Section 4, the experiment is numerically simulated under the same conditions to validate the ability of constitutive models to reproduce the behavior of the experiment concrete floodway model.

3.1 | Test specimen

"Concrete Floodway Type-1," a standard engineering drawing from the Lockyer Valley Regional Council in Queensland, Australia, was selected for use as the geometrical test specimen dimensions (LVRC, 2008). This

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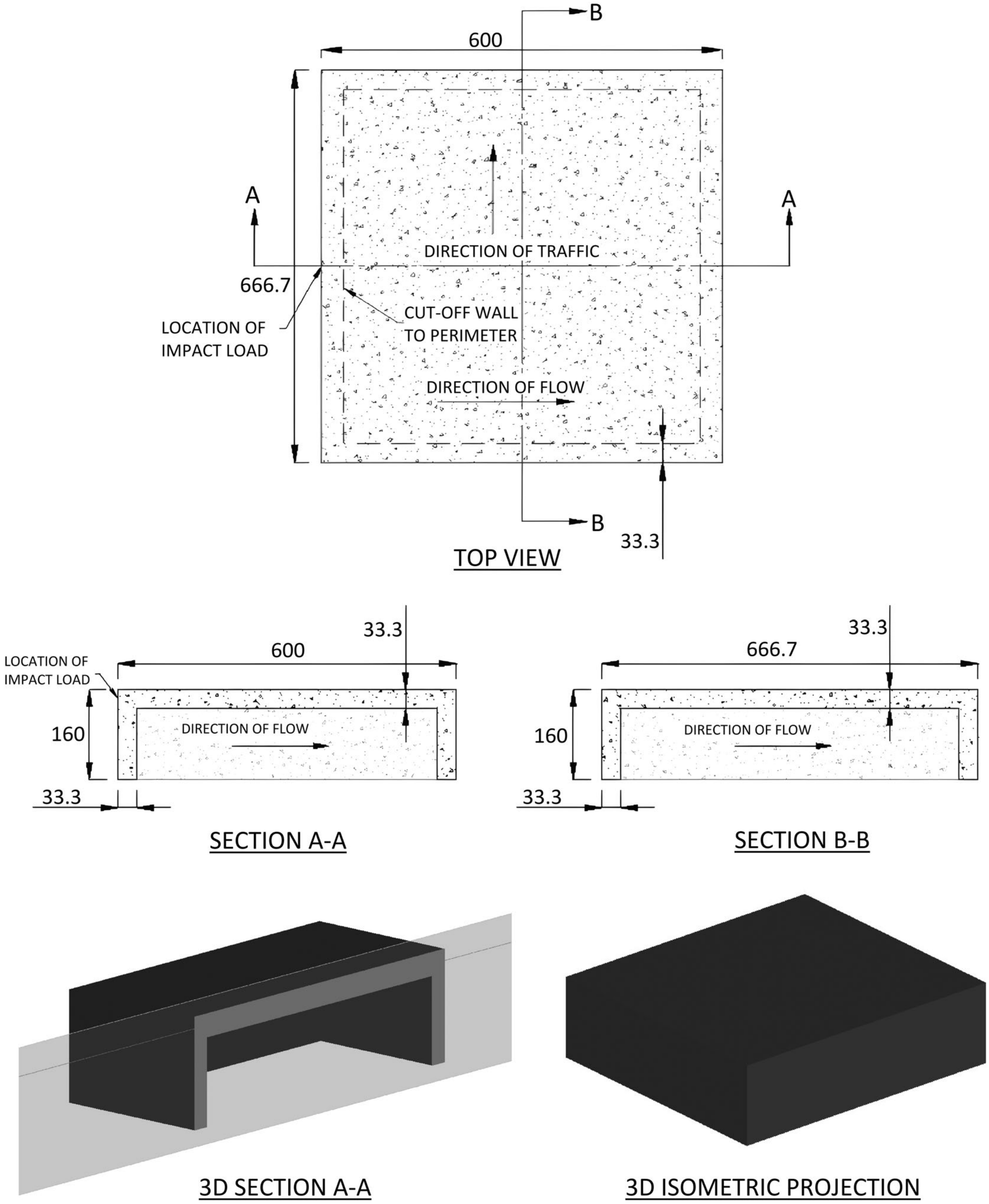

FIGURE 7 1:7.5 scale floodway apron model.

experimental floodway is geometrically identical to that implemented in practice, however, scaled to 1:7.5 and with a slight amendment to the deck thickness (33.33 mm as opposed to 26.67 mm) to provide an adequate thickness for the use of traditional casting methods (Figure 7). The scale of the floodway was selected based on the maximum size permitted for use in the available laboratory facilities. Reinforcement was omitted within the specimen enabling mode of failure, stress formation, and areas of stress localization to be clearly identified. Reinforcement can then be designed and positioned appropriately based on force and moment envelopes to increase shear strength, control crack propagation and supplement compressive strength. During the laboratory experiment, the floodway was assumed to be in an unsubmerged (drained) state. That is, the liquid in the soil is assumed to be free flowing when the load is applied, and pore pressure remains unaffected.

A B2 exposure classification was adopted in terms of durability as floodway structural members are subjected to constant wetting and drying from their continuous contact with water in accordance with AS3600:2019, "*Concrete Structures*" (Standards Australia, 2019). This exposure classification resulted in the requirement of a

TABLE 1 Concrete mix design used for casting the floodway test specimens.

Target compressive strength = f'_c 32 MPa					
Portland cement (kg/m³)	**Water/cement ratio**	**Water (kg/m³)**	**Fine aggregates (kg/m³)**	**Coarse aggregates (kg/m³)**	**Target slump (mm)**
450	0.50	225	644	1218	155

target compressive strength of 32 MPa. Further, standard formwork and compaction techniques were used, and the formwork retained to ensure adequate moisture was maintained until the commencement of curing, thus, ensuring that target compressive strength was achieved.

A summary of the mix design used for casting the test specimens is provided in Table 1. General Portland cement was the binder type specified. The maximum coarse aggregate size was limited to no more than one-fourth of the thickness of the minimum member (33.33 mm). This equated to the selection of a 7 mm maximum aggregate size. A high slump value was also selected to ensure workability when forming the test specimens. As a result of choosing a high water/cement ratio, the corresponding reduction in compressive strength needed to be factored into the mix design. Three concrete test cylinders were cast to measure the compressive strength obtained in practice, and the 28-day compressive strengths were tested; these strengths correlated closely with the 32 MPa target strength. A total of three test specimens were built for experimental testing.

3.2 | Test set-up and procedure

A soil box with dimensions 1000 mm long, 1000 mm wide, and 400 mm deep was constructed to house the floodway model (Figure 8). The dimensions of the soil box were determined through a sensitivity check in Strand7 to ensure no boundary influence within the load range existed. For this sensitivity analysis, it was assumed that the floodway was centrally positioned. The soil box was used to emulate the conditions of a floodway that has been cast in-situ, such as that observed in practice. The soil box was fully restrained, precluding displacement and rotation in all axes. The soil box was then filled to a depth of 240 mm with soil compacted at optimum moisture content via tamping before placing the floodway test specimen and load cell within the soil box. As a result of constraints with the load cell configuration, the final positioning of the floodway specimen within the soil box was much closer to the downstream edge of the soil box (Figure 8). This resulting in a minor boundary influence, causing a slight underestimation of displacement (less freedom) and an overestimation of stresses within the test specimen. The remainder of the soil box was then filled and compacted homogenously, with the area around the load cell being the exception. Therefore, the floodway test specimen is entirely unrestrained and relies upon the subgrade reaction and frictional force between concrete and soil for support. This support is therefore a function of the shape and size of the concrete cut-off wall surface area, the distribution, and intensity of the load and the mechanical characteristics of the soil. The model is thus expected to resist movement up to the maximum frictional force (limiting load) before displacement occurs, or until the soil material yields due to the distribution and intensity of the load being applied.

Loading was applied centrally and monotopically progressed up to the point of failure (Figure 9). This load application method represents that used in AS 5100.2:2017, *Bridge Design – Design Loads* which utilizes equivalent static forces to analyze the effects of impact loading. This formula is an equation of work, where force is equal to the kinetic energy of the object impacting the structure (Equation 1).

$$F = 0.5\left(\frac{mv^2}{2d}\right) \tag{1}$$

where F, force (N); m, objects mass (kg); v, objects velocity (m/s); d, stopping distance (m).

The soil material was obtained from a Melbourne land excavation site, which was used as engineering fill/subgrade material in other recent soil-based experiments at the laboratory (Karami et al., 2021; Pooni et al., 2020; Pooni et al., 2021). Pooni et al. (2020) explains that the soil is classified as a lean clay with sand (CL) and has a target maximum dry density (MDD) and optimum moisture content (OMC) of 1.62 g/cm^3 and 22.9%, respectively.

3.3 | Experimental results and discussion

Two identical specimens referred to herein as Specimens 1 and 2 were tested, with loading applied progressively up to the point of failure. A third specimen was untested because of failure occurring during the demolding phase.

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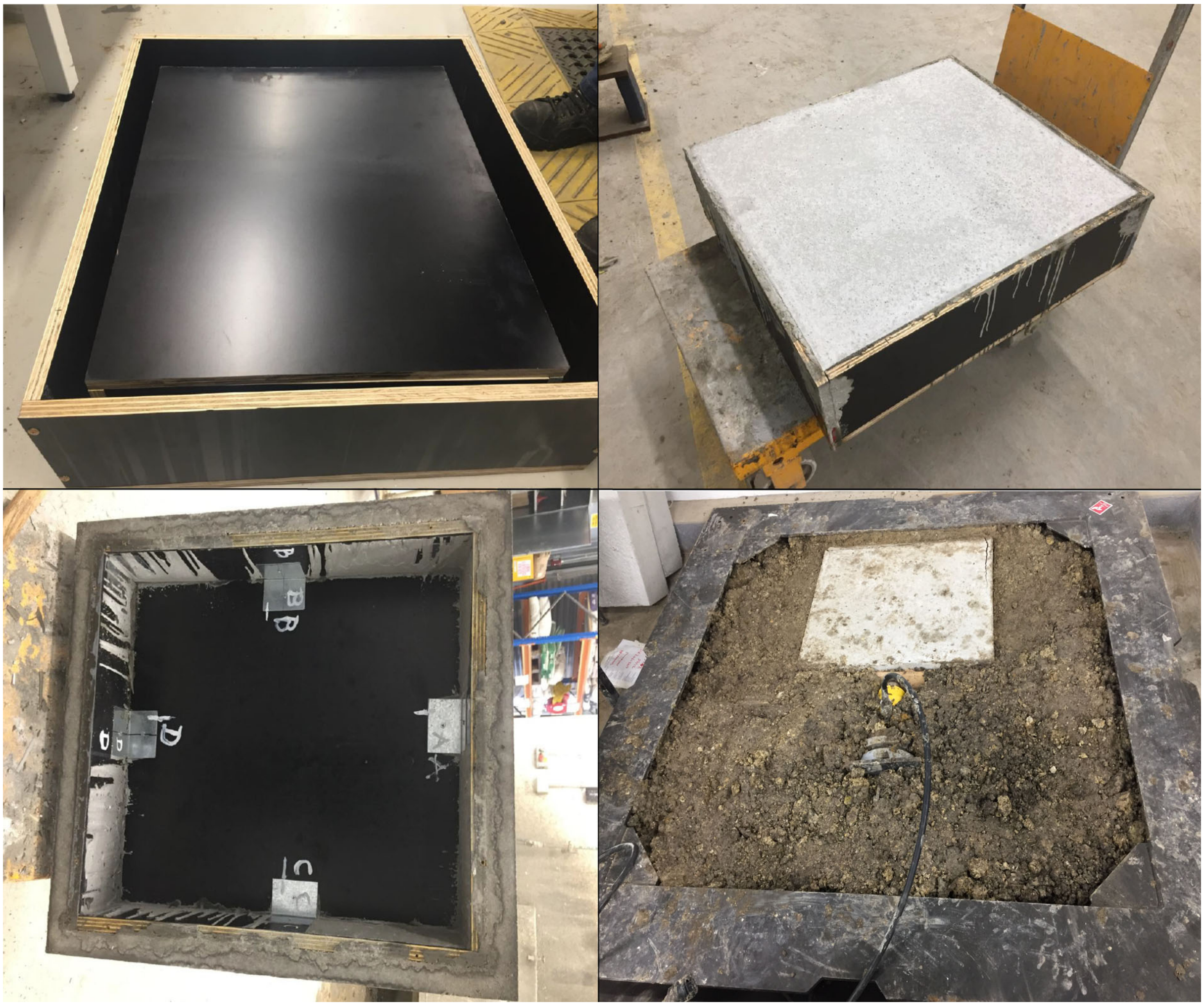

FIGURE 8 Formwork and casting of the concrete test specimen.

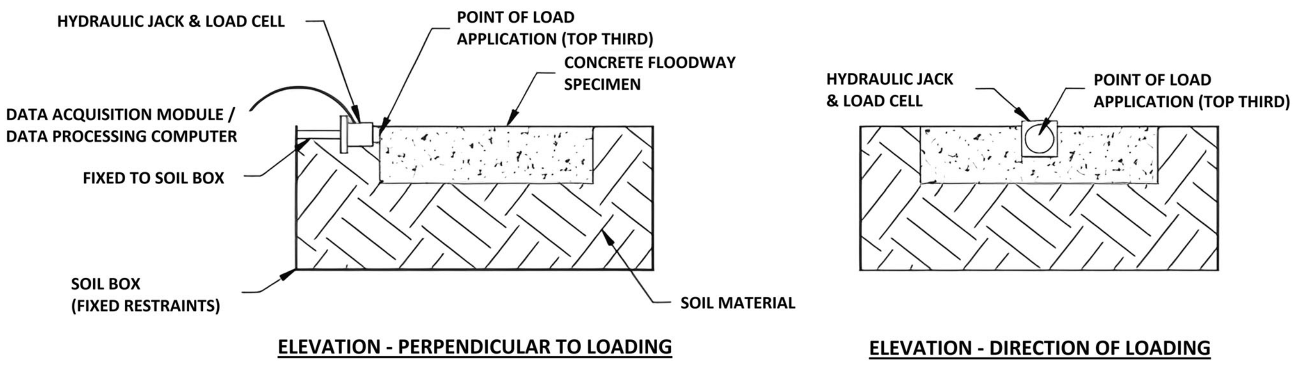

FIGURE 9 Sketch indicating how the load was applied to the test specimens.

In all instances, the specimens failed at relatively low load applications (Table 2), resulting in significant variability in recorded strain results. This was a function of scaling and attributed to the relatively thin thickness adopted in the specimens of only 33.33 mm, which presented casting and demolding challenges and significantly decreased the concrete's ability to resist tensile force alone.

The visual crack propagation pattern of the structure in Specimen 1 (Figure 10) first occurred at the downstream end (C1), propagating parallel to the load along the interface between the apron and the side cut-off walls. As the load application increased, cracking propagated along the interface of the upstream cut-off wall perpendicular to the loading direction (C2) before complete failure occurred (C3). Significant deflection and failure were observed within the failed specimen at the downstream cut-off wall, at the point of load application and the interface between the apron and perimeter cut-off walls, with the apron becoming dislodged. The visual failure pattern of concrete at the point of loading indicates the presence of significant strain localization at this point. Further, the damage and deflection resulting in the downstream and upstream cut-off walls resulted from the cut-off walls attempting to distribute the loading to the adjoining soil while also providing a stabilizing moment (a resistance to overturning) for the structure.

The failure observed within Specimen 2 resulted from the specimen dislodging early within the soil box (upon load application), thus yielding any numerical results errorsome. From a visual perspective the final crack propagation pattern of the structure (Figure 11) was similar to Specimen 1. The initial failure occurred at the loading point, propagating along the upstream cut-off wall and apron interface (C1) before tracking down the side cut-off wall and apron interface parallel to the loading (C2), before complete failure of the upstream cut-off wall occurring (C3).

Within Specimen 2, the structure displaced upwards due to the soil material yielding under the load application (Figure 12). This displacement providing an important insight into the significant overturning moment

TABLE 2 Description of specimen failure observed.

Description	Failure load (kN)	Cause
Specimen 1	4.69	The specimen failed at both the upstream and downstream cut-off wall/apron interface (Figure 12).
Specimen 2	0.98	The specimen dislodged upwards within the soil material and failed at the point of load application (Figure 13).

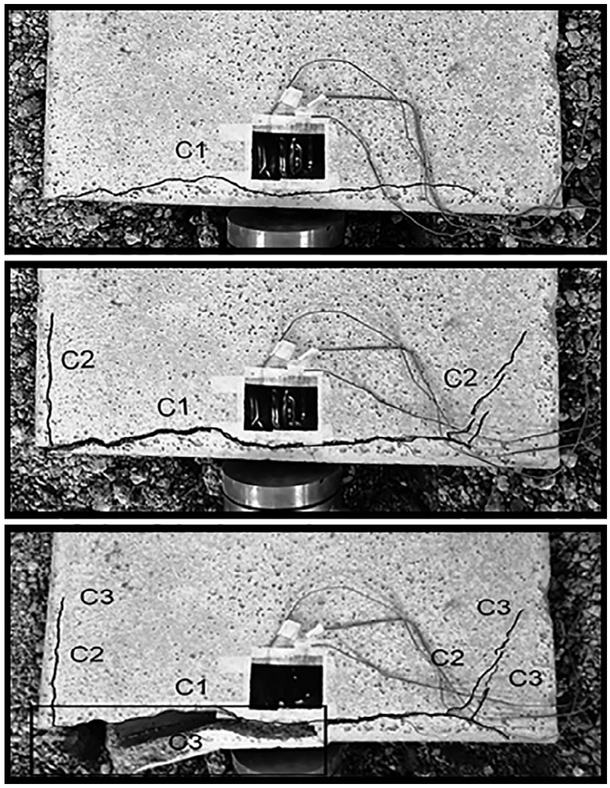

FIGURE 11 Crack propagation within concrete floodway Specimen 2.

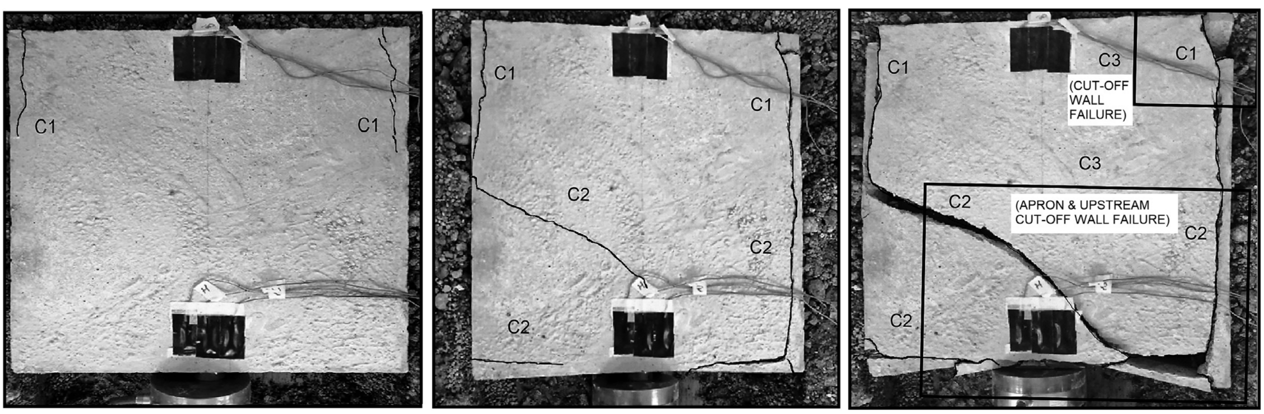

FIGURE 10 Crack propagation within concrete floodway Specimen 1.

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FIGURE 12 Vertical displacement of concrete floodway Specimen 2 at failure.

present and the tendency for the structure to overturn due to a concentrated centrally placed load.

The experimental program deduced the crack propagation pattern for the concrete floodway specimen and enabled visualization of the displacement present under a horizontal load up to the point of failure. The crack propagation and displacement experienced within the experimental program will be validated by comparing results with a three-dimensional finite element model.

4 | NUMERICAL SIMULATION

Numerical simulation of the experiment case under the same conditions investigates and verifies the ability of constitutive models to reproduce the behavior of the experimental concrete floodway model. The need to scale concrete elements within large-scale concrete experiments is a commonly reported limitation in literature (Marzec & Tejchman, 2022), thus the importance of establishing a realistic numerical model that can reproduce the behavior of the scaled laboratory test specimen.

4.1 | Model description

Strand7 finite element computational software was used to develop the numerical model (Strand7, 2018a). The finite element floodway model was created using four node tetrahedra Strand7 brick elements geometrically identical to the floodway test specimen (Figure 7). Table 3 outlines the mechanical properties of the materials used in the finite element model. The material properties used are typical materials detailed in Austroads (2012) for subgrade material (engineered fill).

TABLE 3 Material properties assigned to elements within the numerical model.

Properties	Concrete	Gravelly clay
Modulus (MPa)	31,000	100
Poisson ratio	0.2	0.45
Density (kg/m^3)	2400	1900
Cohesion (MPa)	N/A	0.1
Friction angle (degrees)	N/A	20

To emulate the boundary conditions of a floodway situated in-situ the concrete was unrestrained, and the outer soil extent was fully restrained precluding displacement and rotation in all axes. Further, as the load applied was below the limiting load it was assumed that the contact surface between the concrete floodway and soil was fully bonded. This assumption, therefore, may result in a minor underprediction of deflection due to an increased bond, and an overestimation of stresses only if the limiting load is approached. To account for the non-linearity in material behavior, constitutive models were assigned to concrete and soil material types. Max stress yield criterion was used to define the non-linear elastic behavior of concrete. This required a stress versus strain curve to be assigned in Strand7 to define the non-linear material behavior of concrete. The material is said to have yielded when stress components exceed the assigned yield strength in either tension or compression. Mohr-Coulomb Yield criterion was used to define the soil's elastic–plastic and isotropic behavior. The Mohr-Coulomb Soil Model within Strand7 (2018a) utilizes a generalized form of the Coulomb Friction Failure Law and is an extension of Tresca Failure Criterion. The yield line defines the values that the stress can take, with the failure envelope at tangents to all Mohr's circles (Strand7, 2018c).

Mesh and model refinement was undertaken for the experimental scenario. Mesh and model extent refinement is essential to improving the solution's accuracy and ensuring that the model is not over restrained. The methodology for refinement is based on an iterative approach where the model extents and density of the mesh are iteratively increased until results asymptotically converge. At the point of convergence, the answer approximates the correct answer for the least mesh density and model size, thus providing an efficient model for the least amount of computational time. The mesh density was iteratively increased for the experimental scenario until convergence resulted in a minimum of three parameters (Figure 13). This occurred for a model consisting of 1374 nodes and 648 brick elements.

The load applied within the numerical simulation is a horizontal load placed centrally on the upper edge of the upstream cut-off wall and incrementally increased until model failure occurs. This load is intended to represent debris impact load in a flood scenario.

4.2 | Simulation results and discussion

Non-linear numerical simulation was performed, enabling the stress, displacement, and strain behaviors to be visually and numerically defined for the concrete floodway structure under a significant horizontal loading. Yielding within the supporting soil was discovered as the initial failure mode within the numerical simulation producing a maximum compressive strain in concrete of −0.0011 (Von Mises strain value), being well below the maximum limit of −0.0022, where −0.0022 corresponds to the strain at the peak stress assigned in the stress versus strain curve for 32 MPa concrete (Strand7, 2018b). The simulation results did, however, exceed the maximum flexural tensile strength of concrete of 3.39 MPa at a loading of approximately 12.5 kN (1275 kg).

During load application, positive displacement in the *y*-axis was experienced at the upstream end of the floodway. In contrast, negative displacement in the y-axis was experienced at the downstream end of the floodway. The most significant stress concentration occurred at the point of loading and linearly increased to a maximum stress value of 17.18 MPa. Similarly, the largest horizontal deflection occurred at the loading point and in the positive *z*-direction. The largest horizontal deflection in the negative *z*-direction occurred centrally at the end of the downstream cut-off wall.

Figure 14 illustrates the significant strain localizations within the numerical model. The most significant strain localization occurred centrally towards the upper edge of the downstream cut-off wall. Strain was also concentrated at the load application point and extended towards the two side cut-off walls.

4.2.1 | Soil model

As the soil was set as drained, the stress contours in Figure 15 represent the effective stress, which is the stress

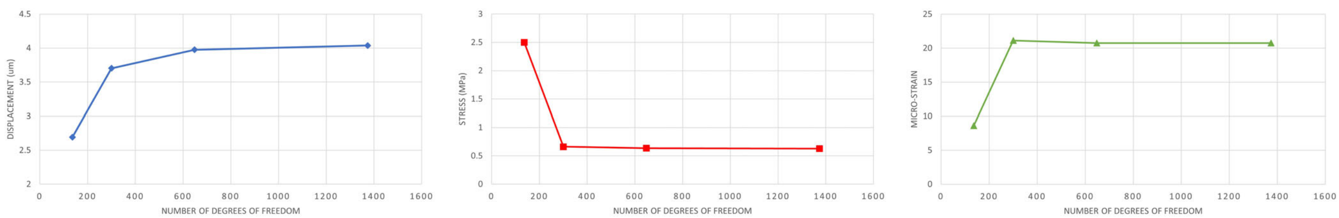

FIGURE 13 Finite element model convergence graphs.

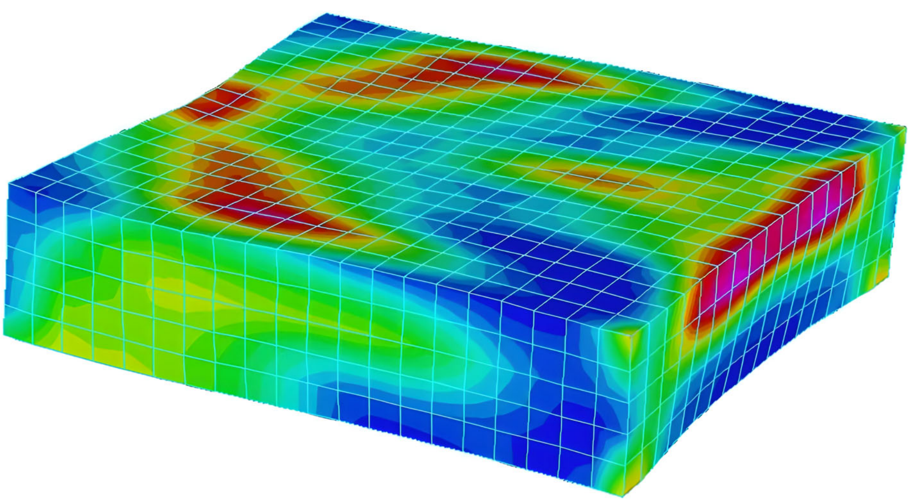

FIGURE 14 Von Mises strain concentrations.

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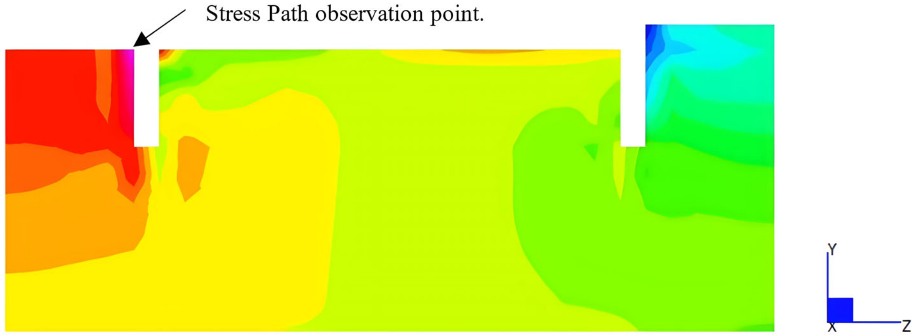

FIGURE 15 Peak effective stresses within the soil model (z-axis cutting plane).

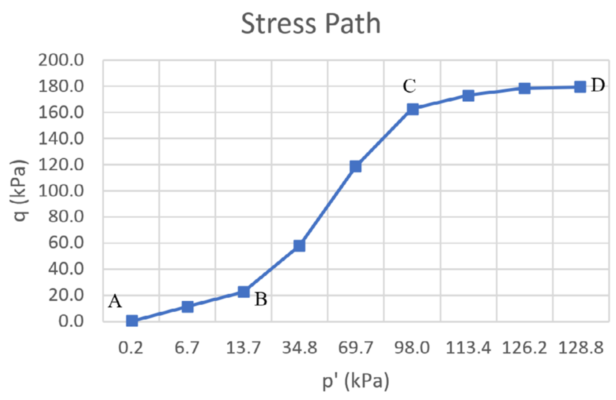

FIGURE 16 Stress path of Mohr Coulomb soil model during horizontal load application.

experienced by the soil skeleton without adding additional stress due to pore pressure.

Figure 16 plots the stress path for the observation point where the soil yield region was identified. The stress path initially follows an elastic path (AB) due to the initial loading of the floodway structure. At Point B the stress path begins to follow the yield surface, until Point C. At Point C stress increases significantly, as plastic shear strains begin to develop and continue to take place along the path CD.

Yield Index is a criterion that describes the stress level with respect to the failure criterion employed in the soil model. The yield regions can be identified based on the Yield Index's contour. If the soil model has not yielded in reference to the Gauss point, then a result of 0.0 will be displayed, and if the soil has, then a result of 1.0 will be displayed. Figure 17 illustrates the significant yielding region that exists within the vicinity of the upstream cut-off wall. This yielding results from the soil becoming displaced due to deflection in the cut-off wall as it attempts to distribute the loading to the adjoining soil. Yielding within the adjoining soil material was discovered to be the failure mode for the numerical simulation model.

5 | DISCUSSION

The survey deduced that floodways, particularly downstream elements, are likely to sustain damage during flooding; however, the current levels of risk in practise have primarily been managed without significant investigation into design improvements. The susceptibility of failure was also variable based upon the structure's configuration and creek bed soil type, with raised structures and soils that are dispersive or lack cohesion being the most likely to fail. Lateral loads induced through debris impact due to flooding were also reported as a major contributing factor to floodway failure.

In the experimental results, Specimen 2 prematurely failed at a relatively low load application, which was a function of scaling and the relatively thin thickness adopted in the test specimen of only 33.33 mm, thus presenting demolding challenges and significantly decreasing the ability of concrete to resist tensile force alone. Specimen 1 failed at a load application of 4.69 kN (479 kg). Within the numerical model the maximum compressive strain did not exceed the maximum strain of concrete of −0.0022 (32 MPa), however it did exceed the maximum flexural tensile strength of concrete of 3.39 MPa. This occurred at a load of approximately 12.5 kN (1275 kg) and would be characterized by cracking in a very localized area at the point of load application and within the outer tensile face. Further load application past this point resulted in plastic strain development and yielding within the soil material surrounding the floodway model.

Within the experiment, the visual crack propagation pattern of the concrete test specimens under a concentrated horizontally placed load correlated to the significant strain localizations observed within the numerical simulation results (Figure 18). For experimental scenarios, initial cracking was observed at the downstream cut-off wall and apron interface in Specimen 1 and at the loading point in Specimen 2. This was then followed by

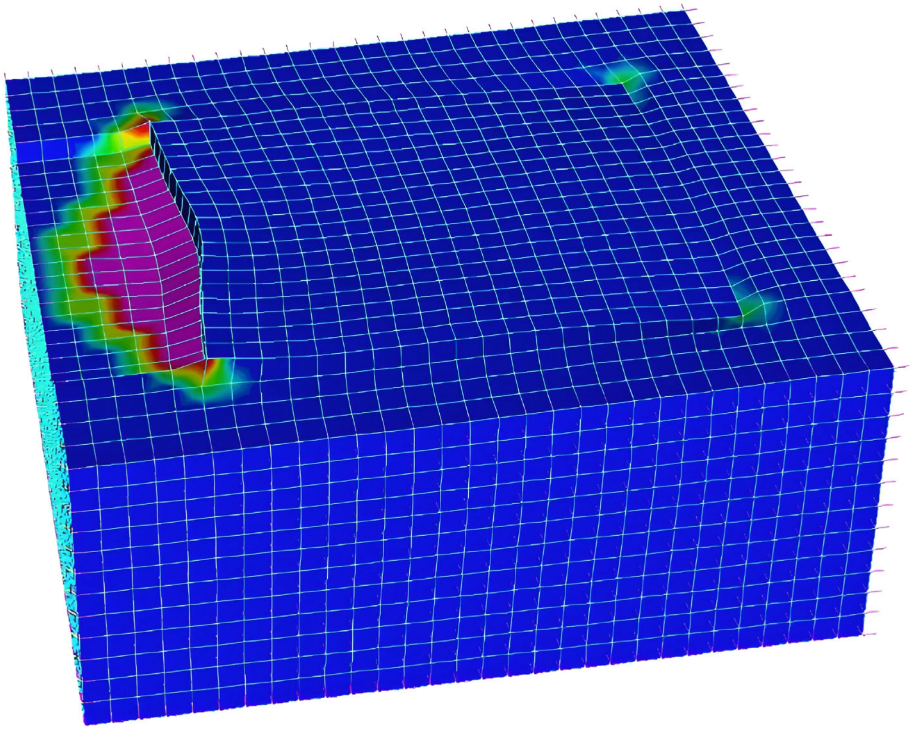

FIGURE 17 Soil yield index contours.

crack propagation along the side cut-off walls and apron interface before complete failure of either the downstream or upstream cut-off wall or both were experienced. Similarly, in the numerical simulation results, significant strain localizations were observed first at the point of loading, followed by strain propagation to the side cut-off walls, which was closely followed by significant strain being recorded at the downstream cut-off wall.

The respondents within the survey also stated that downstream components were found to be most susceptible to failure due to hydraulic causes (supercritical flows reverting to subcritical), thus exacerbating the situation if an accidental loading such as a boulder impacting the superstructure was experienced. Furthermore, the failure pattern from the experiment and numerical simulation (structural failure or displacement) verified the response received in the survey regarding debris loading being a significant contributing factor to floodway failure.

Through visual comparison of deflection within the experiment and the numerical model (Figure 19), significant vertical displacement was observed in both the numerical and experiment cases as the soil material yielded. This vertical displacement caused the upstream side of the floodway to lift in the positive *y*-direction and the downstream side to move downwards in the negative *y*-direction. In the case of Specimen 2, the significant displacement occurred early in the load application, potentially influencing the crack propagation pattern; however, providing important insight into the significant overturning moment present because of a concentrated centrally placed load. The perspectives gained through the industry survey and also the survey conducted by Lohnes et al. (2001) suggested that floodways situated within soil materials that lack cohesion had a higher tendency to fail than those that were not. This failure type is predominately due to the soils increased potential to erode; however, it was also noted within the experiment and modeling to contribute to a reduction in the ability of the soil to resist horizontal loading. Furthermore, the successful investigations reported by respondents through increasing cut-off wall depth were discovered to increase stabilizing moment through increasing the surface area of the cut-off wall available to resist overturning.

6 | CONCLUSION

This research explores through experimental, numerical, and survey methods key focus areas to improve floodway resilience relating to flood risk management. As an outcome of this research, focus areas for floodway structural resilience through an industry-based survey were formally captured and defined. These focus areas included downstream floodway components, raised floodway structures, dispersive soils or soils that lack cohesion and debris impact. Furthermore, current improvements being undertaken to minimize flood risk were recorded; however, suggested that the current levels of risk are primarily being managed without significant investigation into design improvements.

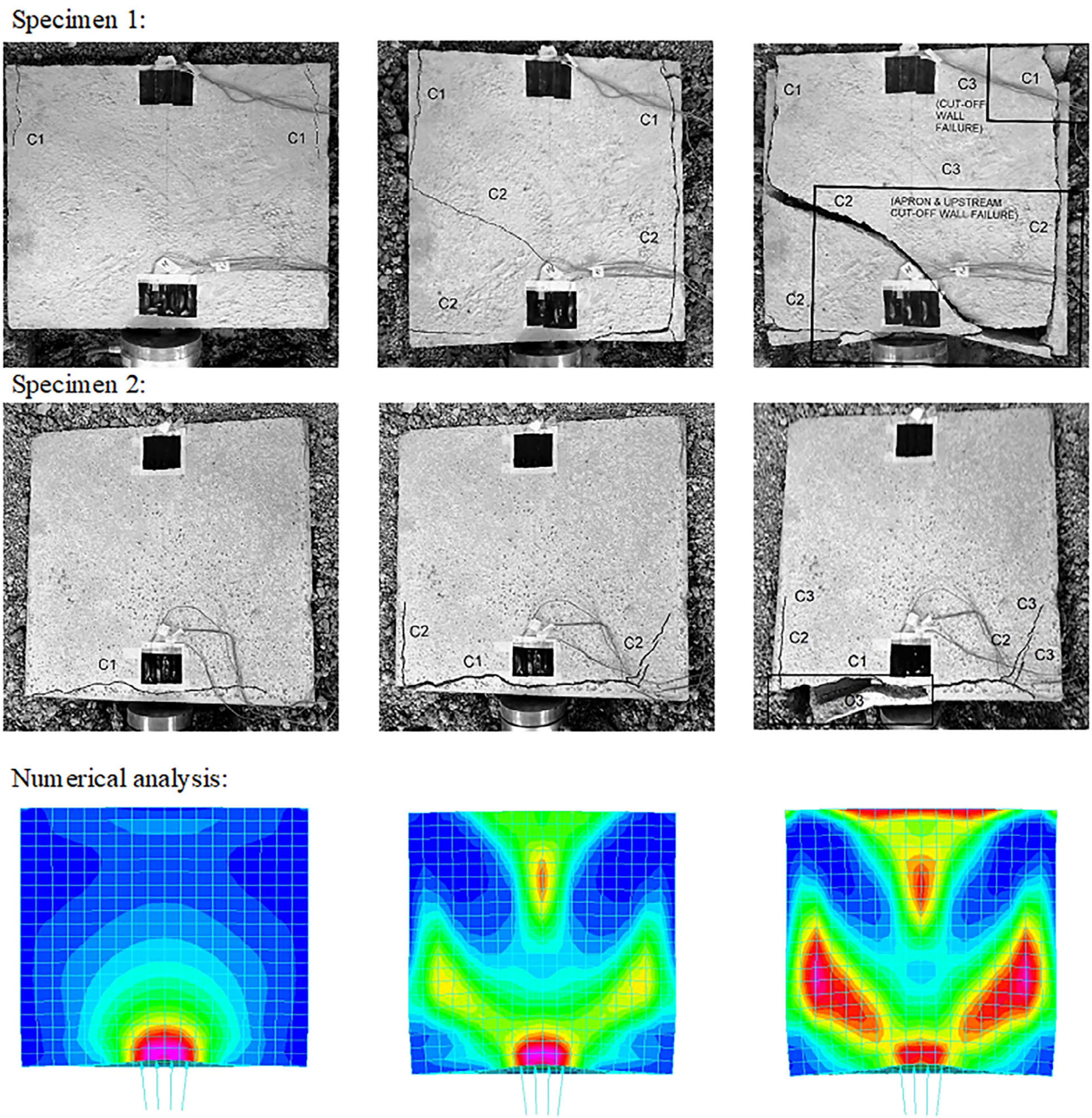

FIGURE 18 Comparison of crack propagation in experimental results with strain concentrations in numerical model.

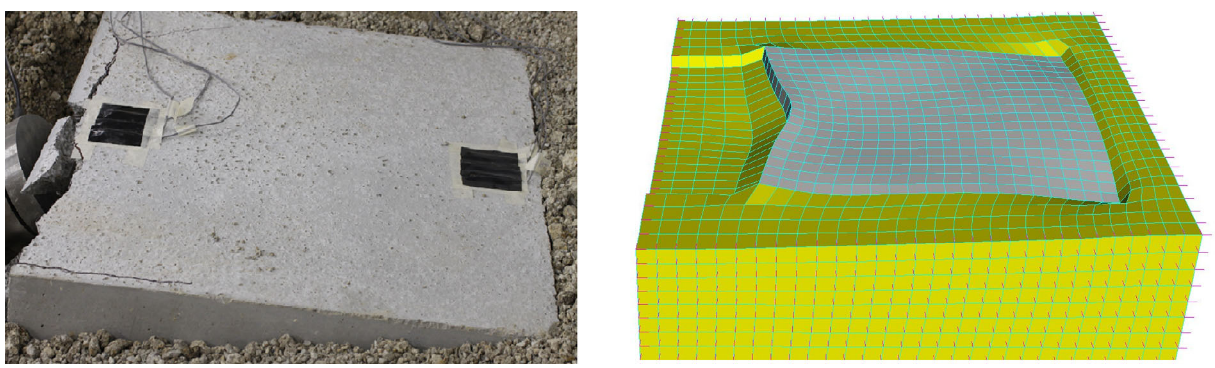

FIGURE 19 Visual comparison of vertical displacement between experiment and numerical model (10% exaggeration).

A floodway specific experimental and numerical simulation program was developed to evaluate the focus area of debris impact using scaled models within a soil box. This provides a practical alternative to the complexities associated with full-scale experimental testing yet enables a physical representation of the structure's response under loading to be observed. Similarly, the numerical simulation provided a reliable and realistic method to understand full-scale structural response and the ability to optimize design. The crack propagation within the experiment test specimens closely correlated with the significant strain localizations identified within the numerical simulation results. Further, the vertical displacement tendency aligned closely across both the experiment and the numerical simulation results, illustrating the significant overturning moment present from a centrally placed horizontal load. It was concluded that the structure fails due to exceeding the tensile strength of concrete, followed by plastic strain development and yielding within the soil material surrounding the floodway model. The research method and deduced areas of observed stress formation, crack propagation and displacement for the debris impact scenario provide a critical starting position for the resilient design of floodway structures through the iterative design of geometrical elements such as cut-off wall depth, member thickness, steel reinforcement and the use of engineered fill material.

As floodways are critical road infrastructure and are required to ensure community connectedness, an increase in floodway resilience will result in increased flood risk management from a resilience strategy perspective. Future opportunity exists to build upon the experimental method to develop a robust quantitative data set to validate the applicability of numerical models, enabling floodways to be assessed under dynamic and cyclic impact loading conditions. Furthermore, rapid repair methods for floodway structures could be explored to increase community preparedness in the wake of an extreme flood event and as a cost-effective alternative resilience measure for existing structures.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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