CONSIDERATIONS FOR DYNAMIC FLOOD-BORNE DEBRIS IMPACT LOADS

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ABSTRACT (500 WORDS MAXIMUM)

Flood flows have the potential to carry fast-moving debris, posing significant risks to both human life and downstream infrastructure. The nature of flood-borne debris can vary depending on upstream catchment characteristics, encompassing a wide range of types, shapes, and sizes. These debris loads can be classified into two categories: static and dynamic. Static loads involve the accumulation of debris, such as tree branches, which increase drag resistance and overall hydraulic loads on structures. Dynamic loads occur when flood flow forces floating debris onto structures. While established guidelines like the Australian Standard 5100 Bridge Design (AS 5100) provide guidance for assessing static loads, there is a scarcity of resources available for calculating and evaluating dynamic debris impact loads.

This paper presents an assessment framework that specifically addresses the dynamic loads resulting from the impact of flood-borne debris on buildings and pedestrian bridges located in flood-prone areas. The scope of the study included a comprehensive review of the available literature to explore various approaches for estimating impact loads induced by floating debris, the application of these approaches to carefully chosen case studies, the comparison of debris impact loads with existing flood and wind loads, and the formulation of an appropriate assessment framework tailored to buildings and pedestrian bridges at risk of experiencing significant impact loads due to flood-borne debris.

The three most common approaches for estimating the debris impact load on a structure are contact-stiffness, impulse-momentum, and work-energy. For each approach, the load is a function of the mass and velocity of the debris. An additional parameter is required depending on the approach: effective contact stiffness for contact-stiffness, the stopping time for impulse-momentum, and the stopping distance for work-energy. Based on a comparative analysis of different approaches, it was determined that Haehnel and Daly's impulse-momentum equation is the most suitable method for integrating debris impact load into the proposed framework. The case studies yielded valuable insights into the criticality of debris loading. It was observed that debris raft loading had a greater impact compared to flood loading in both building and bridge cases. Furthermore, the structural response to dynamic debris impact loads has the potential to result in localised damage to structural elements, including deformation, cracking, or even failure.

Based on the research findings, the following framework for debris impact loading assessment in flood-prone areas is proposed.

- Conduct site-specific debris hazard assessment to identify an appropriate design debris size and mass.
- Assess the debris raft loading based on the AS5100 guidelines.
- Assess the debris impact load in accordance with Haehnel and Daly's Impulse-Momentum approach and using the recommended factors.

- Evaluate the structural response and potential damage resulting from debris impact. The debris raft and debris impact loads should not be considered concurrently. A preliminary suggestion is to utilise a load factor of 1.0.
- Develop mitigation measures based on the analysis and assessment.

KEYWORDS

DEBRIS, FLOOD-BORNE, DEBRIS VELOCITY, DEBRIS MASS, FORCE

1 INTRODUCTION

The occurrence of flood-borne debris introduces a spectrum of potential actions and consequences for structures. Among these are static load phenomena, where debris accumulates to form rafts or mats, exerting significant pressure on structures. Additionally, there are dynamic load scenarios, characterised by the forceful impact of debris propelled by floodwaters, which can inflict substantial damage upon structures. These manifestations underscore the diverse and complex challenges posed by debris in flood-prone areas, necessitating comprehensive mitigation and response strategies.

1.1 STATIC LOAD (DEBRIS RAFT/MAT)

Static load arises from the accumulation of solid objects such as branches, logs, or debris at the entrances of bridges or buildings during flood events, forming a debris raft or mat. As debris gathers, it expands the surface area facing the oncoming flow, significantly altering the hydrodynamic loads exerted on the structure. This enlarged area can impose additional static loads on the structure, potentially compromising its stability and structural integrity.

The evaluation of static load effects resulting from debris accumulation during flood events can adhere to the guidelines outlined in AS 5100. This approach is particularly applicable to bridges and buildings supported by pole foundations. For buildings with solid walls and openings, such as doors and windows, the calculation of static load should consider all openings blocked by debris.

1.2 DYNAMIC LOAD (DEBRIS IMPACT FORCE)

Dynamic load forms when flood flow forces floating debris onto a structure, presenting a distinct challenge due to the sudden and transient nature of the resulting impact loads. This type of load is characterised by the collision of floating debris with the structure, which can induce immediate damage or contribute to long-term structural degradation.

Assessing the impact of dynamic debris loads during floods is particularly challenging due to the limited availability of resources and guidelines for their calculation. While established standards like AS 5100 offer valuable insight into evaluating static load effects from debris accumulation, they often lack comprehensive methodologies for quantifying the dynamic forces associated with debris impact.

The magnitude and nature of these dynamic loads are influenced by various factors, including the size, shape, and velocity of the debris, as well as the structural characteristics of the impacted elements. However, there is an absence of specific resources or standardised procedures for calculating dynamic debris impact loads.

This paper seeks to address the current gaps in resources and guidelines concerning the computation of dynamic debris impact loads. By tackling this crucial aspect, the study endeavours to deepen comprehension of debris-structure interactions and facilitate the advancement of more accurate and reliable methodologies for designing resilient structures capable of withstanding the impact challenges presented by debris during flood occurrences. To establish a practical methodology, this study encompasses an examination of existing literature to investigate available methods for estimating impact loads caused by floating debris. This investigation extends to the application of these methods in select case studies, followed by a comparative analysis of debris impact loads against established flood and wind loads. Subsequently, the study aims to develop a specialised assessment framework designed specifically for structures vulnerable to substantial loads from flood-borne debris.

2 THEORETICAL APPROACHES

The three most common approaches for estimating the debris impact force on a structure are contact-stiffness, impulse-momentum, and work-energy. For each approach, the impact force is a function of the mass and velocity of the debris. An additional parameter is required depending on the approach: effective contact stiffness for contact-stiffness, the stopping time for impulse-momentum, and the stopping distance for work-energy.

Haehnel and Daly (2002) concluded that these approaches are theoretically equivalent for a rigid structure. Using a single degree of freedom model, they demonstrated that the additional parameters for the different approaches were not independent; the stopping time depends on the debris mass and effective contact stiffness, and the stopping distance depends on debris mass, velocity, and effective contact stiffness. The following sections provide details of these theoretical approaches used to address the debris impact forces.

2.1 CONTACT-STIFFNESS APPROACH

The contact-stiffness approach is based on the assumption of a one-degree-of-freedom spring mass. The effective stiffness of the interaction between the debris and the structure is required. The contact-stiffness equation is presented below (Haehnel and Daly, 2002):

$$F_{di} = u_d \sqrt{k\,(m_d + C\,m_f)} \qquad (1)$$

where, F_{di} is the debris impact force, u_d is the debris velocity, k is the effective contact stiffness of the interaction, m_d is the debris mass, C is the added mass coefficient, and m_f is the mass of the displaced fluid.

Assuming that the collision occurs over a short duration, damping can be neglected, and the following equation can be used to estimate the effective contact stiffness of the interaction:

$$\frac{1}{k} = \frac{1}{k_s} + \frac{1}{k_d} \qquad (2)$$

where, k_s is the effective stiffness of the structure, and k_d is the effective stiffness of the debris.

Haehnel and Daly (2002) chose to use the contact-stiffness approach as the basis of analysing the data in their study. They found that the effective contact stiffness for woody debris striking a rigid structure is approximately 1.1–2.4MN/m. They concluded that

2.4MN/m is a good upper-bound (yet slightly conservative) estimate and can be used in the contact-stiffness approach over a wide range of debris mass and velocity.

The contact-stiffness approach is adopted by the Federal Emergency Management Agency (FEMA) of US Guidelines for Design of Structures for Vertical Evacuation from Tsunamis (FEMA P-646).

$$F_{di} = 1.3\, u_d \sqrt{k\, m_d (1 + c)} \qquad (3)$$

where, c is a hydrodynamic mass coefficient which represents the effect of fluid in motion with the debris.

The hydrodynamic mass coefficient, denoted as c, arises from the fact that a decelerating object also momentarily affects or disrupts a certain volume of the surrounding fluid flow. This coefficient is heavily influenced by factors such as the size, shape, and orientation of the object relative to the direction of the flow. FEMA P-646 recommends design mass and stiffness values for various standard waterborne floating debris types.

Stolle (2019) concluded that the effective stiffness model proposed by Haehnel and Daly (2002) was best suited to provide a conservative estimation of the impact force.

2.2 IMPULSE-MOMENTUM APPROACH

The impulse-momentum approach equates the momentum of the debris and the impulse imparted on the structure. This approach requires an estimation of the stopping time (contact duration). This parameter is dependent on the debris mass and effective contact stiffness. The impulse-momentum equation is presented below (Haehnel and Daly, 2002):

$$F_{di} = \frac{\pi}{2} \frac{u_d\, m_d}{\Delta t} \qquad (4)$$

where, Δt is the stopping time. The Π/2 term in the equation represents the impact angle or the angle at which the debris strikes the structure. In the context of the research study, the authors made the assumption that the maximum impact force occurs when the debris strikes the structure at a perpendicular angle (90 degrees).

The impulse-momentum approach is adopted by the American Society of Civil Engineers Minimum Design Loads for Buildings and Other Structures (ASCE 7). Additional coefficients allow calibration of the resulting force to local flood, debris, and building characteristics.

$$F_{di} = \frac{\pi}{2} \frac{u_d\, m_d\, C_I\, C_O\, C_D\, C_B\, R_{max}}{\Delta t} \qquad (5)$$

where, C_I is the importance coefficient, C_O is the orientation coefficient, C_D is the depth coefficient, C_B is the blockage coefficient, and R_{max} is the maximum response ratio for impulsive load.

Hamid (2014) recommends the use of the impulse-momentum approach as presented in ASCE 7 for the calculation of debris impact forces on residential dwellings (both slab-on-grade structures and pile-elevated structures) in storm events.

The US Coastal Construction Manual (FEMA P-55) has provided a simplified form of the ASCE 7 approach:

$$F_{di} = u_d\, m_d\, C_D\, C_B\, C_{Str} \qquad (6)$$

where, C_{Str} is the building structure coefficient. ASCE 7 suggests a value of 0.03 seconds be used for impact duration. Recent experimental procedures by Spreitzer et al. (2022) found the impact duration varied between 0.01s and 0.04s across a range of flow rates and structures. The wide range of values for Δt can lead to large differences in the estimated force

Shafiei et al. (2016) developed a generalised form of the basic impulse-momentum formula through experimental investigations with empirical coefficients to describe effects on the basic variables. A comparison of the calculated forces from the proposed equation with the measured forces, indicates that the equation can adequately estimate the peak debris impact force.

$$F_{di} = C_{add} C_u \, C_{sh} C_{DD} C_{ss} \, \frac{\pi}{2} \, \frac{u_d \, m_d}{\Delta t} \qquad (7)$$

where, C_{add} is an added mass coefficient, C_u is a debris impact velocity coefficient, C_{sh} is a debris shape coefficient, C_{DD} is a deformability coefficient, and C_{ss} is a structure stiffness coefficient.

2.3 WORK-ENERGY APPROACH

This approach equates the energy of the debris with the work done on the structure. An estimate of the distance that the debris travels from the point of contact with the structure until the debris is fully stopped is required. This parameter is dependent on the debris mass, velocity, and effective contact stiffness. The work-energy equation is presented below (Haehnel and Daly, 2002):

$$F_{di} = \frac{m_d \, {u_d}^2}{S} \qquad (8)$$

where, S is the distance that the debris travels from the point of contact with the structure until the debris is fully stopped. The following equation can be used to determine the stopping distance, S.

$$S = u_d \sqrt{\frac{m_d}{k}} \qquad (9)$$

This approach is adopted by Australian Bridge Design Code AS5100. The standard suggests the following stopping distances for structures impacted by a 2-tonne log: 300mm for timber, 150mm for hollow concrete, and 75mm for solid concrete.

2.4 EMPIRICAL APPROACHES

In addition to the theoretical approaches outlined earlier, experimental investigations have also been conducted to study the impact force of objects. For instance, researchers such as Ikeno et al. (2001, 2003) and Matsutomi (2009) have developed empirical equations aimed at estimating the impact force of floating debris. These empirical methods have been reviewed to enhance our understanding of debris impact behavior and the forces involved. However, it's worth noting that these empirical approaches are not detailed in this paper.

2.5 OTHER CONSIDERATIONS

2.5.1 DEBRIS VELOCITY EQUATIONS

The majority of standards and references state that the debris velocity should be adopted as the flow velocity at the water level. FEMA P-55 gives upper and lower bound of debris velocity in coastal areas using the following equations:

$$u_d = \frac{d_s}{t} \quad \text{(lower bound)} \quad (10)$$

$$u_d = \sqrt{g d_s} \quad \text{(upper bound)} \quad (11)$$

where, d_s is the flood depth, and t=1s.

FEMA P-646 (for the tsunami situation) specifies that when a suitable numerical simulation model is unavailable, the maximum flow velocity carrying lumber, or a wooden log (with essentially no draft) can be estimated using the following equation:

$$u_d = \sqrt{2gR\left(1 - \frac{z}{R}\right)} \quad (12)$$

where, R is the is the design runup height that is 1.3 times the ground elevation at the maximum tsunami penetration, and z is the ground elevation at the structure (the datum must be at the sea level).

Shafiei et al. (2016) developed an equation for debris velocity for the tsunami situation:

$$u_d = u_b - \left(\frac{C_c \rho_w A_d}{2m_d} t + \frac{1}{u_b}\right)^{-1} \quad (13)$$

where, u_b is the tsunami bore velocity, C_d is the shape coefficient for the debris, ρ_w is the water density, and A_d is the projected area of the debris.

Spreitzer (2022) found that the conventional approaches to calculating debris impact force overestimate the actual impact force at higher flow rates. This is due to the use of averaged log velocity rather than the actual log velocity at impact.

2.5.2 UPSTREAM CATCHMENT DEBRIS HAZARD ASSESSMENT

This section presents an overview of the approach employed to assess the risk of debris hazards to a structure originating from the upstream catchment.

SITE SPECIFIC DEBRIS HAZARD ASSESSMENT

When assessing the debris hazards associated with a specific structure from the upstream catchment, a site-specific debris hazard assessment can be conducted by employing the following approaches:

- Desktop Study: A desktop study involves conducting a comprehensive review of available data and resources to identify potential sources of debris in the upstream catchment. This can include examining maps, hydrological data, and historical records of flood events. By analysing this information, it becomes possible to gain insights into the types of debris that may be generated upstream and the likelihood of their transportation towards the structure of interest.

- Site Walkover: A site walkover involves physically visiting the location and its immediate surroundings to assess the debris hazards. During the walkover, the investigator examines the terrain, vegetation, and nearby water bodies to identify potential debris sources. This on-site assessment provides an opportunity to visually inspect the catchment area, including riverbanks, adjacent forests, and areas prone to erosion. By observing signs of previous debris accumulation or potential sources of future debris, a more accurate assessment of the hazards can be made.
- Aerial Imagery: Aerial imagery, particularly through the use of drones, can be a valuable tool for conducting a detailed assessment of the catchment area. By capturing high-resolution images or videos, drones provide a bird's-eye view that allows for the identification of potential debris sources, such as fallen trees, large branches, or other objects. Aerial imagery can cover larger areas more efficiently than ground-based surveys, providing a comprehensive understanding of the catchment and helping to prioritise areas for further investigation.

DEBRIS CHARACTERISTICS

In the absence of a site-specific assessment, resources such as the Waka Kotahi NZTA (New Zealand Transport Agency) Bridge Manual and FEMA P-646 provide information that can be utilised to estimate the mass of debris, which is required to calculate the resultant dynamic force exerted on a structure.

DEBRIS MOBILISATION BY FLOW

The ARR (Australian Rainfall and Runoff) book 6 offers information and guidelines for assessing the risk of debris mobilisation in relation to flow power. Flow power refers to the energy carried by water in a river or channel and is determined by the depth and velocity of the flow. Book 6 of the ARR provides specific data on the flow power required to mobilise different types of objects.

The AAR book 6 standard provides guidelines to identify the critical flow power thresholds required to initiate the mobilisation of specific types of debris. By comparing the flow conditions at a location with the mobilisation thresholds provided in the ARR, it can be assessed if identified debris hazards are likely to become mobile.

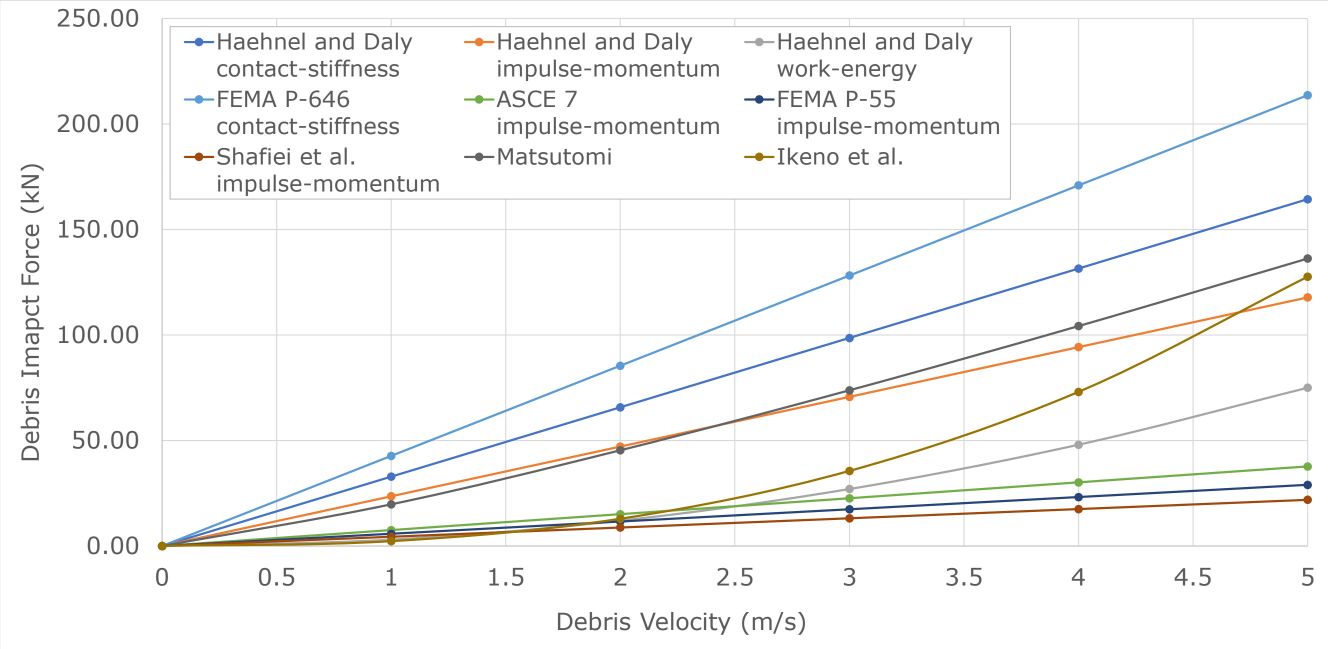
3 DEBRIS IMPACT FORCE APPROACH COMPARISON

This section compares the debris impact loads arising from the different approaches outlined in the literature study, aiming to ascertain the most appropriate approach for formulating an assessment framework. The estimated debris impact force for each approach has been plotted against velocity, as shown in Figure 1. Table 1 below presents the key parameters utilised for comparing the debris impact loads.

Table 1 Parameters used to compare debris impact loading approaches

Parameter	Value	Reference
Mass, m	450kg	Recommended by FEMA P-646
Effective contact stiffness, k	2.4 x 10^6 N/mm	
Stopping time, Δt	0.03s	Recommended by ASCE 7-16
Stopping distance, S	0.15m	Recommended by AS5100

Figure 1 Plot of debris impact force vs. debris velocity



The plot shows that there is poor agreement between the different approaches, with a large range of resulting impact force depending on the formula used.

Haehnel and Daly's Impulse-Momentum approach (Equation 4) has been identified as the most appropriate approach to proceed with in developing an assessment framework for the following reasons:

- Average result among plotted approaches: The fact that this approach yielded approximately average results when plotted against other approaches suggests that it falls within a reasonable range of outcomes. This can be seen as a desirable characteristic because it indicates that the approach is not an outlier and is consistent with the general trend observed in the plotted data. Opting for an approach with average results can provide a balanced assessment and reduce the risks associated with extreme outcomes.
- Adoption by well-regarded standards: Haehnel and Daly's Impulse-Momentum approach has been adopted by standards such as ASCE 7-16 and FEMA P-55 which adds credibility to this decision.
- Input parameters: Another advantage of selecting Haehnel and Daly's Impulse-Momentum approach is the ease of finding the necessary input parameters for the calculation. When working with complex methodologies, it is essential to consider the availability and accessibility of the required data. In this case, Haehnel and Daly's approach may offer the advantage of using input parameters that are relatively easier to obtain or estimate compared to other approaches.

In summary, the choice to adopt Haehnel and Daly's Impulse-Momentum approach as the preferred method for calculating debris impact loads in developing an assessment framework is supported by several factors. These include its endorsement by respected standards, alignment with industry practices, its satisfactory performance relative to other approaches in the plotted data, and the ease of obtaining required input parameters.

4 CASE STUDIES

This section employs a case study methodology to contrast debris loading with other types of loading and examines the structural response to these various loads. The following structures in flood-prone areas in Auckland have been selected as case studies:

- 112 Opanuku Road, Waitakere (residential dwelling)
- Harbutt Reserve Bridge, Mount Albert (pedestrian bridge)

4.1 LOADINGS

The study will compare the debris loads (both static and dynamic) to the loads induced by floods and wind, and discuss the possible structural responses to determine the critical types of loading to be considered in areas susceptible to floods.

4.1.1 DEBRIS LOADING

Debris characteristics have been selected following a review of the catchment's areas and suggested parameters from reference material outlined in Section 2.5.2 of this report.

STATIC LOAD (DEBRIS RAFT/MAT)

The debris raft loading has been calculated based on the AS5100 guidelines, considering forces resulting from debris. The loading values for the debris raft/mat were determined using the 1% Annual Exceedance Probability (AEP) flood velocity.

DYNAMIC LOAD (DEBRIS IMPACT LOAD)

The debris impact load was determined by employing Haehnel and Daly's Impulse-Momentum method, which was deemed the most appropriate approach for constructing an evaluation framework, as discussed in detail in section 3 of this report. The dynamic load calculations were performed using the 1% AEP flood velocity.

4.1.2 FLOOD LOAD

Flood loads were estimated using the data provided by Auckland Council and calculated using the guidance for forces resulting from water flow in AS5100. 1% AEP flood loads have been calculated. Note that hydrostatic force has not been considered in the assessment of debris loading or flood loading.

4.1.3 WIND LOAD

The wind loads on the case study building were estimated using the procedures specified in AS/NZS 1170.2. Please note that the wind load has not been taken into account when assessing the pedestrian bridge because the forces are expected to be comparatively smaller due to the limited exposed surface area.

4.1.4 BERTHING ENERGY

A suggestion was made to compare the loading caused by debris impact to the berthing loads generated by vessels. However, this comparison may not be appropriate for several reasons. Firstly, the forces involved in berthing events are much greater than those of debris impact loading. Berthing forces can be significantly higher due to the size and weight of vessels, resulting in different design considerations for structures.

Houses and pedestrian bridges are usually not built to withstand the force of berthing vessels. To design structures that can handle these loads, engineers need to consider things like impact resistance, structural strength, and the ability to absorb and distribute high-energy forces.

4.2 CASE STUDY 1 - 112 OPANUKU ROAD, WAITAKERE

112 Opanuku Road is a two-storey house in the Waitakere Ranges. The dwelling is situated adjacent to the Parekura Stream (catchment area of 1.44 km2). It is a timber framed house with timber cladding on a concrete slab with driven timber piles.

Figure 2 No. 112 Opanuku Road location plan (Auckland Council Geomaps)

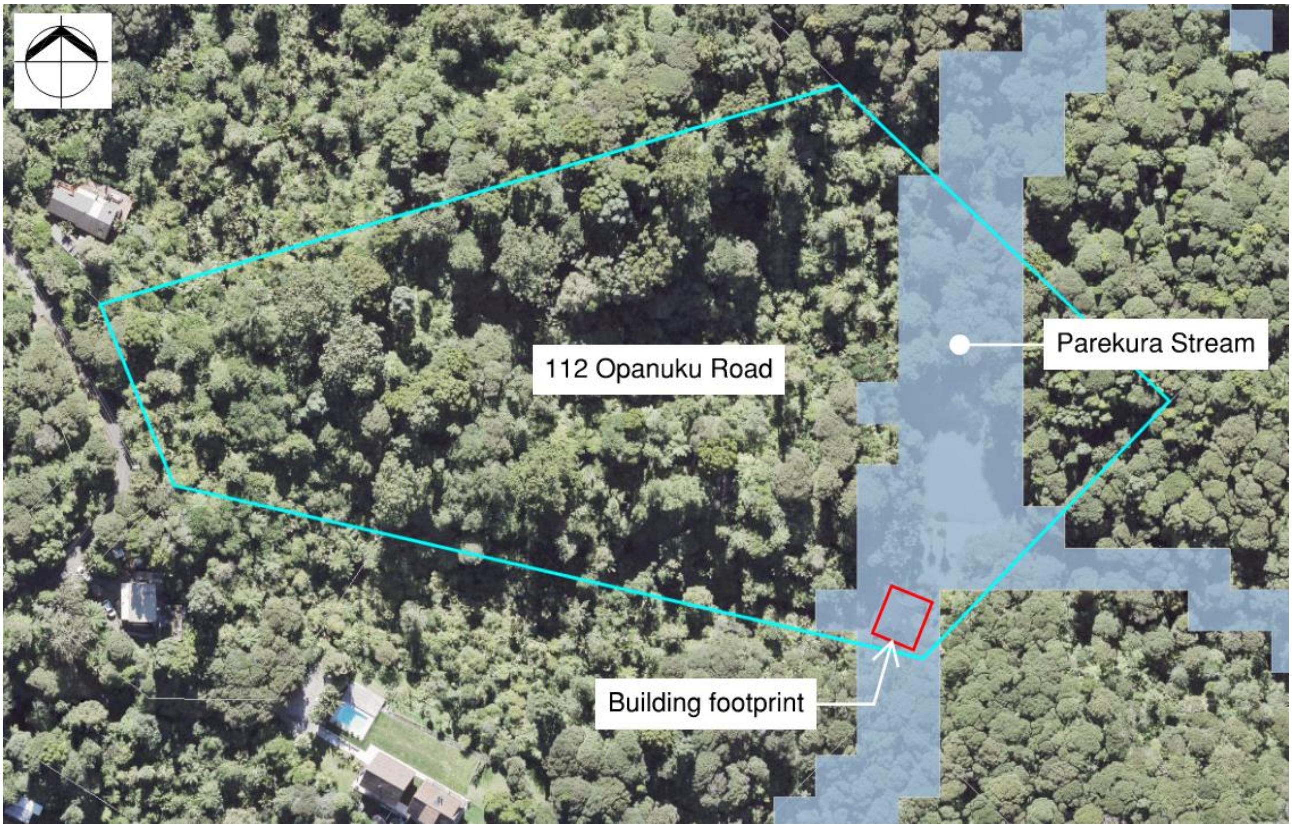
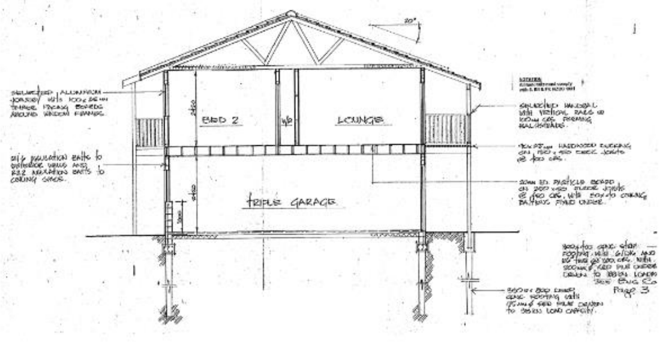
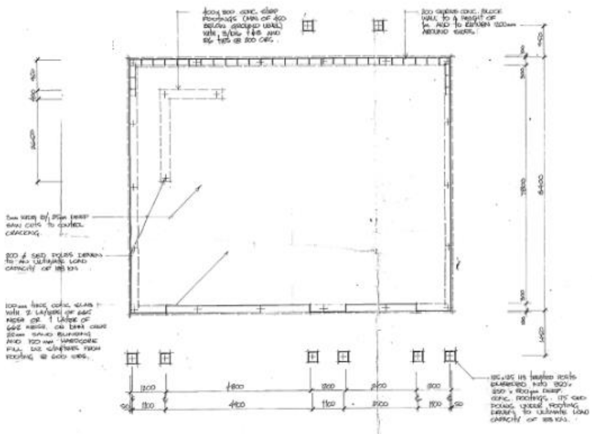


Figure 3 No. 112 Opanuku framing and foundation plan





The parameters used for this case study are outlined in Table 2 below:

Table 2 Case Study 1 parameters

Parameter	Value	Reference
Flood velocity	2.15 m/s	100-year flood ARI flood
Flood depth	0.47 m	100-year flood ARI flood
Debris mass	450 kg	FEMA P-646
Debris raft area	5 m^2	Building consent drawings / NZTA Bridge Manual

Table 3 below shows the forces acting on the building face perpendicular to the stream's flow.

Table 3 Case Study 1 forces

Load	Load Distribution	Magnitude
Debris Raft/Mat	Distributed across debris raft	23.1 kN (4.6 kPa)
Debris Impact Load	Point load	50.7 kN
Flood	Distributed across submerged face	15 kN (3.0 kPa)
Wind	Distributed across windward face	63.5 kN (1.3 kPa)

The debris raft/mat load has the potential to cause lateral forces on the foundation and driven timber piles. However, in this case, as the debris raft/mat load is less than the wind load, it is unlikely that this can result in structural instability. For greater depths and velocity of water flow, the relative magnitude of load will change. The debris impact load, concentrated at specific points, poses a risk of localised damage to the cladding and structural elements, including deformation, cracking, or even failure. The flood load, distributed across the submerged face, exerts pressure on the exterior walls and foundation. This can lead to structural stresses and potential water ingress, compromising the integrity of the house. The wind load can exert significant pressure on the cladding system, potentially causing displacement or damage to the overall structure.

Comparing these loads directly can be challenging due to their different distribution patterns and effects on the structure. The debris raft loading and flood loading impact the building in a similar way, with the raft loading being larger than the flood loading in this case. The debris impact load, due to its concentrated nature, can cause severe damage if not adequately considered during the design phase. This force is of similar magnitude to the wind load which acts across the entire face of the building. Each load has unique effects on different structural elements, necessitating specific design considerations to ensure the overall integrity and safety of the timber-framed house.

4.3 CASE STUDY 2 – HARBUTT RESERVE BRIDGE, MOUNT ALBERT

The Harbutt Reserve Bridge is a timber pedestrian bridge crossing Oakley Creek in Mount Albert (catchment area of 12.09 km^2). The bridge consists of glulam timber beams, timber decking planks, and timber piles at the abutments.

Figure 4 Harbutt Reserve pedestrian bridge location plan (Auckland Council Geomaps)

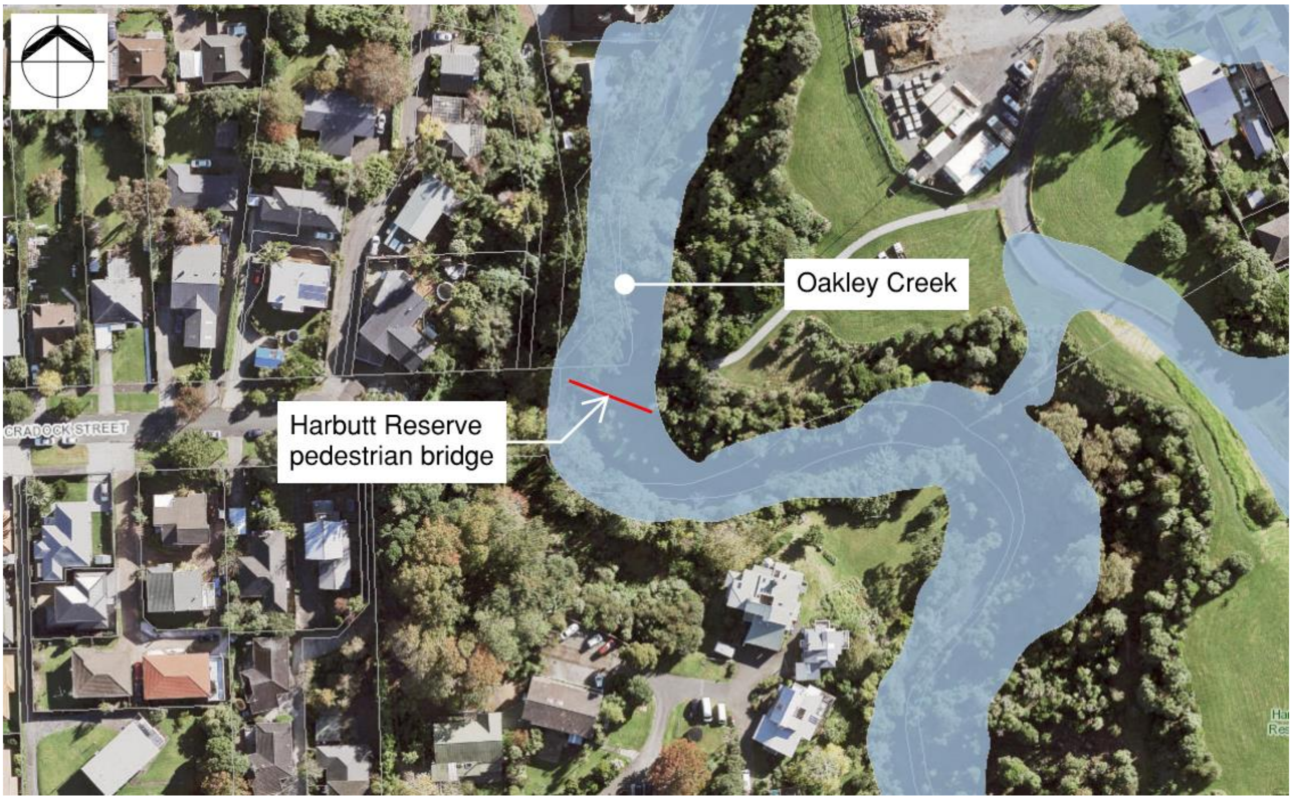
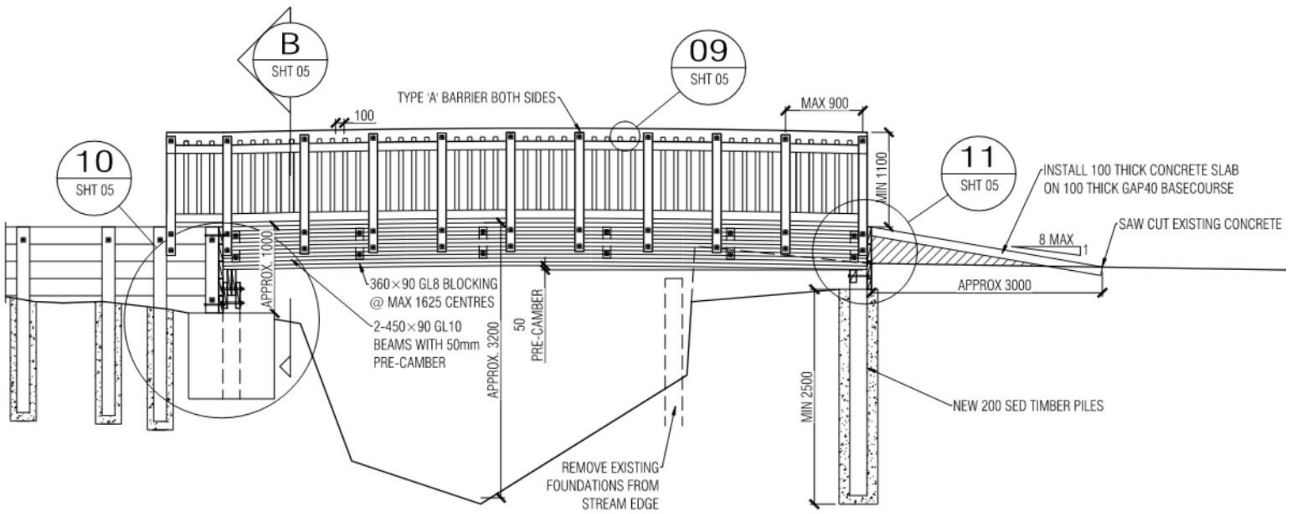


Figure 5 Harbutt Reserve Bridge elevation



The parameters used for this case study are outlined in Table 4 below.

Table 4 Case Study 2 parameters

Parameter	Value	Reference
Flood velocity	1.00 m/s	100-year flood ARI flood

Wetted depth of superstructure	0.5m (fully submerged)	100-year flood ARI flood
Debris mass	450 kg	FEMA P-646
Debris raft area	3.75 m2	Building consent drawings / NZTA Bridge Manual

The forces acting on the pedestrian bridge deck are shown in Table 5.

Table 5 Case Study 2 forces

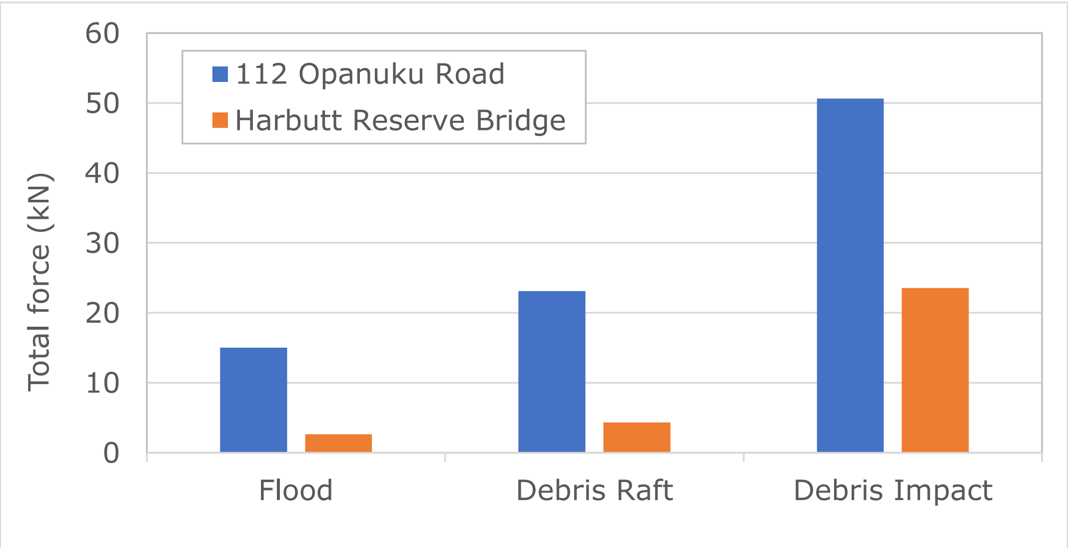
Load	Load Distribution	Magnitude
Debris Raft/Mat	Distributed across debris raft	4.3 kN (1.2 kPa)
Debris Impact Load	Point load	23.6 kN
Flood	Distributed across submerged face	2.7 kN (0.7 kPa)

The debris impact load surpasses other forces significantly, exerting a pronounced influence on both local and global structural effects. Thus, it is crucial to account for this impact during the design phase. This substantial load can induce deformation, cracking, or even structural failure, necessitating reinforcement and preventative measures to uphold structural integrity.

4.4 FORCE COMPARISON

Figure 6 compares the total force exerted on the case study structures by the flood and debris loading. Different structural responses are anticipated based on the distinctive nature of the loading. For instance, the debris impact load functions as a concentrated point load, while flood loading acts as a distributed load, as elaborated in the case study sections above. Nonetheless, it is noteworthy that the debris impact forces outweigh the other flood-related forces significantly in both scenarios.

Figure 6 Harbutt Reserve Bridge elevation



5 ASSESSMENT FRAMEWORK

Recognising the significant impact debris can impose on structures compared to other design loads underscores the importance of evaluating debris loading during the design process. This assessment is crucial for maintaining structural integrity and safety, thereby safeguarding lives and minimising damage. Integrating considerations for debris impact enables structures to enhance resilience, meet regulatory standards, and optimize cost-effectiveness over time. It constitutes a critical component in the design of structures situated in flood-prone areas.

The following steps are suggested for the development of a comprehensive framework for debris impact loading when considering design loads in flood-prone areas.

- Conduct Site Specific Hazard Assessment: A comprehensive hazard assessment to identify potential debris sources, as outlined in Section 2.5.2.
- Assess the Debris Raft Loading: Assess the static load caused by debris accumulation using relevant guidelines such as AS5100 or other applicable resources. Determine the hydrodynamic forces on the structure resulting from debris accumulation at bridge openings or buildings.
- Assess the Debris Impact Loading: Utilise Haehnel and Daly Impulse-Momentum Equation (Equation 4): Implement the Haehnel and Daly impulse-momentum equation to calculate the debris impact load. Using an impact duration of 0.03 seconds and the mass and velocity identified in the hazard assessment.
- Perform Structural Analysis: Incorporate the calculated debris loading into the structural analysis of the buildings or pedestrian bridges. Assess the structural response and evaluate the potential damage caused by the debris impact. It should be noted that the debris raft and debris impact loads shall not be considered concurrently. A preliminary recommendation is that the debris impact loading is utilised with a load factor of 1.0. However, the potential variability of impact force for a given object mass and velocity illustrated in Figure 1 should be noted.
- Develop Mitigation Measures: Based on the analysis and assessment, develop appropriate mitigation measures to enhance the resilience of the structures. This may include strategies such as debris barriers, strengthening vulnerable structural components, or employing resilient construction materials.

By following these proposed steps, the framework for designing buildings or pedestrian bridges to withstand debris loading can be made robust and efficient in mitigating the risks stemming from debris impact originating from the upstream catchment area.

6 CONCLUSIONS

This paper reviewed the research literature on various methods for estimating dynamic floating debris-induced loads, applied these methods to specific case studies, compared debris loads with flood and wind loads, and formulated a suitable assessment framework for buildings susceptible to flood-borne debris loads.

The case study findings shed light on the importance of debris loading. In both cases, debris raft loading had a more severe impact than flood loading, with the potential for dynamic debris impact loads to cause localised damage to structural elements, including deformation, cracking, or failure.

Directly comparing these loads to wind and flood loading presents challenges due to their differing distribution patterns and effects on structures. Therefore, it's essential to consider the design requirements and standards for each load type individually, ensuring that each element can withstand the specific loads it will encounter.

Based on the research findings, a framework for assessing debris loading in flood-prone areas is proposed. This framework includes steps such as conducting a site-specific hazard assessment, evaluating debris raft loading and debris impact loading, performing structural analysis, and devising mitigation measures.

By following this framework, designers can effectively evaluate and mitigate the risks associated with debris impact. Implementing appropriate mitigation measures, such as debris barriers or strengthening vulnerable components, will bolster the resilience of structures and enhance their ability to withstand debris impact.

In conclusion, this paper offers insights and a practical framework for integrating debris loading considerations into the design of structures in flood-prone regions. By incorporating debris impact into design practices, the safety, integrity, and resilience of buildings and pedestrian bridges can be significantly bolstered, safeguarding occupants and valuable assets in flood-prone areas.

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