Review of Tsunami Impact on Bridges

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Abstract
Coastal bridges are often lifeline structures and their failure as a result of tsunami incident can significantly obstruct disaster relief and rehabilitation efforts. Hundreds of coastal bridges were washed away or heavily damaged by the major tsunamis in Indonesia (2004), South Pacific (2009), Chile (2010), and Japan (2011). Developing resilient infrastructure that can withstand and remain operational following a tsunami impact would significantly improve the post-disaster recovery of the affected areas.

In this literature study, the most common bridge failure mechanisms were investigated from post-tsunami reconnaissance surveys following the 2004 Indian Ocean, 2009 South Pacific and 2011 Japan tsunamis. Considering the limited codified design guidance available for tsunami resistant bridges, proposed equations for tsunami loadings on bridges from a number of researchers have been collated. A review of the theoretical and experimental studies was carried out to identify and quantify tsunami forces acting on bridges. None of the sources of guidance are sufficient in themselves for determining the requirements for estimating tsunami loads on bridge superstructures. All available guidance depends on accurate information about tsunami flow depth or tsunami flow velocity, or both. Comparison of the currently available equations shows that there is no consensus on the general form of equations for estimating forces; that is, whether the equations should have a hydrostatic form, a hydrodynamic form, or a combination of both.

Keywords: Tsunami, bridge, force, failure mechanism.

1. Introduction
Tsunami hazard in New Zealand (NZ) is no less significant than the earthquake hazard. There are over 1,500 bridges that connect road and rail networks in NZ, and many of these are on or near NZ’s 15,000km of coastline. Any major damage to these bridges could result in traffic disruption and impede post-event emergency response. Tsunamis can cause severe damage or destruction of bridges that are up to 3km upstream from the coast [21].

Large earthquakes are the most common source of tsunamis, and 80% of all large earthquakes occur in the Pacific Ocean. It is not surprising that NZ has been affected by many tsunamis in the past. No part of NZ's coast is free of tsunami hazard, but some parts of the coast are more exposed than others because of proximity to local sources, orientation with respect to distant sources, shape of the coastline, and inland topography [21]. The aim of this paper is to provide relevant background about bridge failure mechanisms due to tsunami effects, and to review existing guidance in bridge design codes for tsunami loadings on superstructure.

2. Bridge Failure During Tsunami Events
Field reconnaissance and damage investigations following large tsunamis provide valuable information on the bridge failure mechanisms and the vulnerability of bridges during tsunamis, which is also helpful for designing tsunami-resilient structures. Field investigators observed damaged bridges in the adjacent coastal zone following the 2004 Indian Ocean and the 2011 Japan tsunami events [1, 2, 10, 11, 12, 17, 18, 22, 23, 24, 25, 26]. Important findings from the review of these investigations include:

- The most common damage was washout of bridge superstructures, often with bridge piers left standing.
- Many bridge superstructures were rotated (about a vertical axis) as they were washed away, but some remained in place because of non-uniform lateral movement and subsequent interlocking of spans.
- The most common failure mechanism was failure of the superstructure to substructure connections. In many bridges the seaward connections failed first under uplift loadings with subsequent shear failure of the inland connections, while in other bridges the connections sheared under direct lateral loading.
- Reinforced concrete (RC) bridges, prestressed concrete girder bridges, and RC moment-resisting frame bridges appeared to fare better than steel truss or steel girder bridges.
- Low bridges and high bridges often survived, because their superstructures were deeply submerged or above the tsunami height.
- Other failure mechanisms included scour around bridge abutments and supporting piers, foundation or pier failure, and failure due to debris impact.
The observed failure mechanisms indicate that tsunami loadings for bridges should account for uplift, lateral, overturning, rotational loadings, and floating debris impacts.

3. Types of Tsunami Effects and Forces
Accounts of recent tsunamis suggest that tsunami events can be classified as one of two types: (a) a turbulent tsunami bore that formed when the tsunami wave broke before reaching the shoreline, or (b) a rapid rise in water level, possibly in the form of an asymmetric unbroken wave [13, 14]. The type of tsunami occurring at a particular location depends on factors such as the width and depth of the continental shelf, coastline shape, and steepness of the land immediately inland of the shoreline [20, 28]. Any actual tsunami event could be one of these two types, somewhere in between them, or a combination of both. For both types, there will be large horizontal and vertical forces with the same order of magnitude [14].

The following types of tsunami forces have been identified by researchers: (a) horizontally: impulsive, hydrostatic, and hydrodynamic; and (b) vertically: impulsive, hydrodynamic drag, uplift (upward), buoyancy, and additional gravity (from water accumulating on the bridge deck) [4, 6, 7, 14, 15]. Also, previous studies revealed that horizontal force has two phases in their measured time history: (a) an impulsive phase of short duration (order of milliseconds) that occurs at the first arrival of the bore front at the structure, and (b) a quasi-steady phase with longer duration (order of seconds) that starts from the time of the full inundation of the structure.

4. Estimation of Tsunami Loads
This section presents a review of tsunami flow loads on bridge superstructure. Review of the impact of floating debris, loads on piles and bridge scour is not the scope of this paper. Debris impact loading can be extremely large and complex. Piles generally experience smaller force than superstructures.

4.1 Tsunami Design Standards
Several publications have been prepared by regulatory authorities to provide specific guidance for estimating tsunami loads on buildings [4, 6, 9]. In the absence of specific guidance for estimating tsunami loads on bridges, some researchers have adapted the recommendations for buildings [16, 19, 29]. The recommendations by Yim et al. [29] for estimating tsunami forces on bridge superstructures are partly based on a proposed method for estimating tsunami hydrodynamic forces on buildings [28].

Livermore [16] evaluated the CCH building code [6], FEMA [9] and 2010 edition of ASCE [4] equations (refer to Sections 4.1.1, 4.1.2 and 4.1.3) for estimating tsunami forces on buildings, and with some modifications adapted the equations for estimating tsunami loads on bridge superstructures. The main modifications for equations that have a hydrostatic form are (a) the replacement of the height of the tsunami above the ground level with the height of the tsunami above the underside of the bridge superstructure, and (b) for the height over which the force acts, replacement of the height of the tsunami above the ground level with the vertical depth of the bridge superstructure. For equations with a hydrodynamic form that are a function of the maximum momentum flux, the main change is the replacement of the term with the corresponding expression in the standard hydrodynamic equation. The use of the maximum momentum flux term assumes that the tsunami momentum over the full depth of the tsunami is transferred to the building. For a bridge this is not the case, because part of the tsunami momentum passes under the bridge superstructure and part passes over. The Livermore approach was adapted in Sections 4.1.1, 4.1.2 and 4.1.3 below. Figure 1 shows the notation relating to the parameters used in equations presented in Section 5.

![Figure 1](image.png)

Figure 1 Notation relating to tsunami characteristics and bridge dimensions.

4.1.1 City and County of Honolulu (CCH) Building Code
The guidance for the structural design of buildings and structures subject to tsunamis in Chapter 16 of the CCH Building Code [6] contains equations for hydrostatic and hydrodynamic (drag) forces. The Building Code equations are not directly applicable to bridges and have been adapted for bridge superstructures as below:

\[
F_{hs} = \frac{\rho g (d_{wgs} - 0.5d_{sp} + 0.5u_b^2g^{-1})d_{sp}}{2} \quad (1)
\]

\[
F_{hd} = 0.5 \rho C_{hid} u_b^2 d_{sp} \quad (2)
\]

where \(F_{hs}\) = hydrostatic horizontal force in the flow direction per unit length of the bridge; \(\rho\) = the density of the sea water; \(g\) = acceleration of gravity; \(d_{wgs}\) = height from the soffit of the bridge girders to the surface of the tsunami; \(d_{sp}\) = bridge deck height including any railings or parapets; \(u_b\) = tsunami horizontal flow velocity; \(F_{hd}\) = drag horizontal force in the flow direction, per unit length of the bridge; and \(C_{hid}\) = coefficient of hydrodynamic horizontal (drag) force (assumed to have a value of 2.0).

Equation 1 has a hydrostatic form with velocity head added to the height of the tsunami bore. The
Building Code impulsive force \( F_{Hi} \) is estimated as the sum of the hydrostatic and hydrodynamic forces when the building height is less than three times the tsunami flow depth in front of the building. This practical approach can be applied to a bridge overtopped by a tsunami bore. The resulting equation for impulsive force for a bridge deck is:

\[
F_{Hi} = F_{Hs} + F_{Hd} \quad (3)
\]

CCH does not recommend any equation for vertical hydrodynamic force estimation.

4.1.2 Federal Emergency Management Agency Guidelines (FEMA P646)

The document “Guidelines for Design of Structures for Vertical evacuation from Tsunamis” [9] provides guidelines on tsunami loads and their effects on buildings, which is based largely on a report by Yeh et al. [28]. FEMA P646 provides equations for hydrostatic, hydrodynamic, and horizontal impulsive forces, and hydrodynamic vertical and buoyant forces. The adapted equations to estimate tsunami forces on bridge superstructures are as follows:

\[
F_{Hs} = \rho g (d_{wgs} - 0.5d_{sp})d_{sp} \quad (4)
\]

\[
F_{Hd} = 0.5\rho C_{Hd}(u_{b}^2 d_{sp}) \quad (5)
\]

FEMA P646 recommends a value of 2.0 for a \( C_{Hd} \). The horizontal impulsive force is recommended as 1.5 times the hydrodynamic force. FEMA P646 states that the impulsive horizontal force only applies to the part of the structure where the tsunami bore front is situated as it passes through the structure, and that the part of the structure behind the bore front experiences only a hydrodynamic drag force. It is specified that the maximum combination of impulsive forces and hydrodynamic forces should be used in design. FEMA P646 recommends that buoyant and hydrodynamic forces are applied concurrently to the structure.

The vertical velocity component of the tsunami flow proposed by FEMA P646 to estimate the hydrodynamic vertical force is:

\[
F_{Vu} = 0.5\rho C_{Vu} u_{b}^2 W_L \quad (6)
\]

\[
u_{b} = \frac{u_{b} \tan \alpha}{2} \quad (7)
\]

where \( F_{Vu} \) = vertical uplift force per unit length of the bridge; \( C_{Vu} \) = coefficient of vertical hydrodynamic lift force; \( u_{b} \) = tsunami vertical flow velocity; \( W_L \) = bridge deck width; and \( \alpha \) = ground slope at the structure. FEMA P646 recommends a value of 3.0 for \( C_{Vu} \).

4.1.3 American Society of Civil Engineers (ASCE) Guidelines (ASCE/SEI 7-16)

The 2016 edition of ASCE Minimum Design Loads for Buildings and Other Structures, ASCE/SEI 7-16 [4] Chapter 6 covers tsunami loads and effects on buildings. It can be used for other structures by replacing relevant parameters [16]. ASCE/SEI 7-16 defines two load cases that might be relevant to bridges after appropriate adaption: (1) the height from the soffit of the bridge girders to the surface of the tsunami \( (d_{wgs}) \) is equal to two-thirds of the maximum \( d_{wgs} \), and \( u_{b} \) is the maximum horizontal velocity, and (2) \( d_{wgs} \) is at its maximum value and \( u_{b} \) is one-third of the maximum. The adapted equations from ASCE/SEI 7-16 for tsunami forces applicable to bridges are as follows:

\[
F_{Hs} = \rho g (d_{wgs} - 0.5d_{sp})d_{sp} \quad (8)
\]

\[
F_{Hd} = 0.5\rho l_{tsu} C_{Hd} C_{Cx}(u_{b}^2 d_{sp}) \quad (9)
\]

\[
F_{Hi} = 0.75\rho l_{tsu} C_{Hd} C_{Cx}(u_{b}^2 d_{sp}) \quad (10)
\]

\[
F_{Vu} = 1.5\rho l_{tsu} u_{b}^2 W_L \quad (11)
\]

where \( C_{Cx} \) = coefficient for the proportion of closure (assumed to be 1.0 for bridges); and \( l_{tsu} \) = importance factor with a value dependent on the risk category according to ASCE/ICE 7-10 (assumed to be 1.2 for bridges in Risk Category III of ASCE/ICE 7-10).

ASCE/SEI 7-16 recommends \( C_{Hd} \) be based on the ratio of the span length to \( d_{wgs} \) with a minimum of 1.25. The tsunami vertical flow velocity \( u_{b} \) is as for FEMA P646.

4.1.4 Oregon Department of Transportation (ODT) Guideline for Tsunami Loads on Bridges

The ODT proposed a dedicated guideline, prepared by Yim et al. [29], which is unique because it was specifically designed for the estimation of tsunami loads on bridges.

Yim et al. [29] numerically investigated the tsunami effects on three highway bridges in Oregon, USA. They also undertook an exhaustive review of the previous studies on the impact of wind-driven waves on bridges [7] and the tsunami effects on buildings [27]. Their numerical outputs and the review of the previous research form the basis of their proposed guideline. Yim et al. [29] combined and adapted the earlier methods by Douglass et al. [7] on the effect of wind-driven forces on bridges and by Yeh [27] on the impact of tsunami loads on buildings.

The proposed horizontal tsunami force on a bridge deck by Yim et al. [29] is the sum of the hydrostatic force [7] and the hydrodynamic force [27].

\[
F_{Ht} = F_{Hs} + F_{Hd} \quad (12)
\]

\[
F_{Hs} = (1 + C_r(n - 1)) C_{hs} \rho g d_{wgs} d_{sp} \quad (13)
\]

\[
F_{Hd} = 0.5\rho C_{Hd}(u_{b}^2 d_{wgs})_{max} \quad (14)
\]

where \( F_{Ht} \) = total (or maximum) horizontal force (as indicated by context) in the flow direction per unit length of the bridge; \( C_r \) = coefficient of reduced pressure on interior girders; and \( C_{Hs} \) = coefficient of
hydrostatic horizontal force. The recommended value for $C_r$, $C_{hs}$ and $C_{hd}$ are 0.4, 1.0 and 3.5, respectively.

Yim et al. [29] proposed that the vertical tsunami force on a bridge deck is the sum of the hydrostatic force applied to the underside of the bridge deck and the hydrodynamic force.

$$F_{Vt} = (\rho g d_{wgs} + 0.5 \rho u_b^2)W_i$$

where $F_{Vt}$ = total (or maximum) vertical force (as indicated by context) per unit length of the bridge.

4.1.5 Standard hydraulic equations method for comparison of bridge failures

Yokoi et al. [30] investigated the main bridge failure mechanisms on 85 bridges and used standard hydraulic equations to estimate the horizontal and vertical forces on bridges mostly damaged and inundated after the 2011 Japan tsunami. They recommended the calculation of the maximum horizontal force on a bridge deck as the sum of the equations provided by Kosa et al. [14] for the hydrostatic and hydrodynamic forces.

$$F_{Ht} = F_{Hs} + F_{Hd}$$

where $h_d$ = bridge clearance; $h_b$ = tsunami flow depth at the bridge; $F_{vb}$ = buoyancy force, per unit length of the deck; $V_b$ = the volume of the deck; and $F_{Vt}$ = total (or maximum) vertical force (as indicated by context) per unit length of the bridge.

Yokoi et al. [30] proposed that the $C_{hd}$ value should decrease as the $W/d_{sp}$ increases. They used the Japanese “Specifications for Highway Bridges” to provide the following values, which are all based on the inundated bridges after the 2011 Japan tsunami:

$$C_{hd} = 2.1 - 0.1W_i/d_{sp} \text{ for } 1 \leq W_i/d_{sp} < 8$$

$$C_{hd} = 1.3 \text{ for } 8 \leq W_i/d_{sp}$$

The ratios proposed by Yokoi et al. [30], indicating the failure or survival of the structure, were evaluated by applying them to 85 selected bridges. Failure of 60 out of 85 bridges were predicted correctly. It appears that Yokoi et al.’s approach is unconservative unless debris loads caused the other 25 bridges to fail.

4.1.6 Numerical modelling studies of tsunami forces on bridges

There are several studies reporting the effect of tsunamis on bridges from a numerical point of view by including the mechanism of the tsunami flow generation, its propagation, and the resultant forces. Some of the estimated forces using numerical modelling are plotted in Figure 2 and Figure 3 for comparison purpose.

Kosa et al. [14] developed a physical model of the Lueng le Bridge, a reinforced concrete slab-on-girder bridge on the West Coast of Sumatra, near Banda Ache, that was damaged in the 2004 Indian Ocean Tsunami. For both the maximum horizontal force and the maximum vertical force, Kosa et al. [14] derived relationships using their experimental results, and from these relationships they derived the following equations for estimating the horizontal and vertical tsunami forces.

$$F_{Ht} = \rho g d_{sp} \int_{h_d}^{(h_d+d_{sp})} (2.61h_b - 1.85y) dy$$

$$F_{Vt} = \rho g W_i(0.53h_b - 0.459h_d)$$

Lau et al. [15] proposed that for estimation of the tsunami forces on the bridge superstructure the pressures acting on the superstructure could be considered to be amplifications of the hydrostatic pressure resulting from the height of the tsunami above the superstructure. They further proposed that estimates of all the horizontal and vertical forces could be derived from the quasi-steady horizontal force, which they used as a reference force. Lau et al.’s approach was reviewed and used in the preliminary comparison of the tsunami forces in this paper. Considering their simplistic approach, the results are found to be outliers compared with the other approaches presented in this paper. Hence, the results of Lau et al. [15] are not shown in the final tsunami loads comparison (refer to Figure 2 and Figure 3 in Section 5).

4.1.7 Waka Kotahi NZ Transport Agency (NZTA) Guideline for Tsunami Loads on Bridges

There has been little discussion on the characterisation of tsunami loads on bridges, especially in the NZ context. Recently, the Waka Kotahi NZTA Bridge Manual incorporated the tsunami effects on coastal bridges that have been developed from research undertaken by the University of Auckland [19]. The Bridge Manual suggests that the most appropriate form of the envelope equation is a hydrodynamic-type (drag-type) equation; that is, with forces related to the square of the velocity of the tsunami bore. The adoption of hydrodynamic-type equations aligns with equations in AS5100.2 [3] for estimating flood flow loads (refer to Section 4.1.8), and will allow direct comparison with these.

$$F_{Hd} = C_{hd}(0.5\rho u_b^2 d_{sp})$$

$$F_{Vd} = C_u(0.5\rho u_b^2 W_i)$$
where $C_H$ is suggested to be taken as 4.5 for horizontal loading, and, for vertical loading, $C_V$ of either 3.0 for vertically upward loading or the appropriate negative value from Figure 15.4.3 in AS 5100.2 Bridge design part 2 Design loads for vertically downward loading [3].

4.1.8 Flood Loads in the Waka Kotahi NZTA Bridge Manual
It is widely accepted that tsunami loads on bridges are large and, because of higher velocities and unsteady flow conditions, the forces can be larger than flood flow forces for the same inundation depth (e.g. [5]). Therefore, the flood loads specified in the Waka Kotahi NZTA Bridge Manual, which is based on AS5100.2 [3] as outlined in Section 4.1.7–Equations 26 and 27, constitute a minimum requirement for estimating tsunami loads. $C_H$ and $C_V$ values are specified in Figures 15.4.2 and 15.4.3 of AS 5100.2, respectively.

4.1.9 The University of Auckland Experimental Investigations (Farvizi [8])
Farvizi [8] has recently completed experimental studies of the interaction of a tsunami bore with coastal bridges. Physical modelling of the tsunami bore in the laboratory was conducted by investigation of the followings:

- Impact of a tsunami bore on a box section bridge deck with different deck clearances.
- Impact of a tsunami bore on a deck-girder section bridge with different deck clearances.
- Effect of contraction (i.e. restriction of the area under bridge) on the tsunami induced pressures and forces on a box section bridge deck with wing wall and spill-through abutments with different lengths and deck clearances.
- Impact of a tsunami bore on a skewed box section bridge deck with different skew angles and deck clearances.
- Performance of a skewed deck-girder section bridge under tsunami bore impact with different skew angles, deck clearances and handrails.

Based on the experimental results, equations have been proposed for estimating the maximum tsunami horizontal, lateral and uplift forces for a box section bridge deck and a deck-girder section bridge including the effects of contraction and skewness.

\[
F_x = C_{Hi} e^{-A_{x} \tan \theta} R^{0.29} \ln S_r (0.5 \rho u_b^2 A_v) \quad (28)
\]

\[
F_z = C_{Vu} e^{-0.3 \tan \theta} R (1.95 - 1.7R) \ln S_r (0.5 \rho u_b^2 A_v) \quad (29)
\]

where $\theta$ = skew angle; $A_x$ = 1.25 for the box section deck and 1.75 for the deck girder section deck; $R$ = opening ratio; $S_r$ = submergence ratio; $A_v$ = vertical projected area; $A_h$ = horizontal projected area; $C_{Hi}$ = 1.8 for both skewed box section and skewed deck girder section bridges; and $C_{Vu}$ = 0.14 for the skewed box section bridge deck and 0.18 for the skewed deck girder section bridge.

5. Comparison of the Available Guidelines and Modelling
The equations in Section 4 were compared by plotting values estimated by using them for an "average" NZ road bridge, for a range of tsunami flow depths and velocities in which the superstructure is inundated. The relevant dimensions and parameters are given in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bridge deck height including any railings or parapets, $d_u$ (m)</td>
<td>2.4</td>
</tr>
<tr>
<td>Bridge deck height excluding any railings or parapets, $d_s$ (m)</td>
<td>1.4</td>
</tr>
<tr>
<td>Number of girders supporting the bridge superstructure, $n$</td>
<td>4</td>
</tr>
<tr>
<td>Volume of the superstructure, $V_s$ (m$^3$)</td>
<td>8.8</td>
</tr>
<tr>
<td>Self-weight of bridge, $W_b$ (kN/m)</td>
<td>45</td>
</tr>
<tr>
<td>Bridge superstructure width, $W_l$ (m)</td>
<td>9.5</td>
</tr>
<tr>
<td>Height from the soffit of the bridge girders to the surface of the tsunami, $d_{ss}$ (m)</td>
<td>4.4</td>
</tr>
<tr>
<td>Proximity ratio, $d_{avg}/d_{ss}$</td>
<td>3.2</td>
</tr>
<tr>
<td>Depth (m)</td>
<td>6, 7, 8, 9, 10, 11, 12</td>
</tr>
<tr>
<td>Velocity, $u_b$ (m/s)</td>
<td>7.7, 8.3, 8.9, 9.4, 9.9, 10.4, 10.8</td>
</tr>
</tbody>
</table>

The dimensions of the "average" bridge were determined as simple averages of the values from five real bridges: Kakanui River (Otago), Kowhai River (Canterbury), Ngaruroro River Diversion (Hawkes Bay), and Waimakariri River (Belfast, Canterbury). Tsunami flow velocities were estimated based on the assumed tsunami flow depths and using Froude Number of $F_r = 1$.

Plots of estimated horizontal and vertical forces are shown in Figure 2 and Figure 3, respectively. Also included in Figure 2 and Figure 3 are values of maximum horizontal and vertical forces obtained from reported results of physical and numerical modelling studies.

Figure 2 and Figure 3 show clearly the large amount of variation in values obtained from proposed equations for estimating the maximum horizontal force. However, most of the estimated values are of the same order of magnitude. A significant divergence can be seen between some of the equations in Figure 2 and Figure 3.
The maximum horizontal force in Waka Kotahi Bridge Manual [19] sit in the middle of the range. This is in good agreement with predictions from Yokoi et al [30] which are known to be somewhat unconservative. The vertical force proposed in the Waka Kotahi Bridge Manual [19] appears to be a conservative approach.

If a value of \( C_D = 3.0 \) is used for the drag coefficient in the basic hydrodynamic equation, the curve of horizontal force per unit length (\( F_{Ht} \)) versus tsunami flow depth (Figure 2) envelopes the values from Yokoi et al. [30], Kosa et al. [14] for flow depth of up to about 9.5 m, and Yim et al. [29] for flow depth of up to about 8.0 m. It also envelopes two of the three modelling results that plot on Figure 2. The curve's values are about 100 kN larger than those from AS5100 [3]. If a value of \( C_D = 4.5 \) is used for the drag coefficient in the basic hydrodynamic equation, the horizontal force curve envelopes all the values from the equations. If a value of \( C_D = 3.0 \) is used in the basic equation for upward vertical force, the curve of upward vertical force per unit length versus tsunami height (Figure 3) overlaps with Waka Kotahi’s proposed equation [19] and envelopes the values from most of the equations except that of ASCE [4].

6. Summary

Based on the literature reviews, the following conclusions are drawn about bridge failure during tsunami events:

- The most common damage observed is washout of bridge superstructures.
- The most common bridge failure mechanism observed is failure of the superstructure to substructure connections.
- There is also evidence that some bridges were destroyed by the impact of large floating debris and some bridge piers failed due to scouring.

From the review of available guidance, the following list summarises the currently available guidance and its limitations:

- There is no general agreement on the types of force applied to bridges due to tsunami impact. Some of the equations for maximum horizontal force have a hydrostatic form (e.g., [14, 15]), and some have adopted a hydrostatic component and a hydrodynamic component, and combine them to give the maximum force (e.g., [29, 30]). Some researchers acknowledge the existence of an impulsive force, but some researchers did not consider it [15, 30].
- From a qualitative viewpoint, most researchers agree that tsunami forces on bridges are large and, the forces can be larger than flood flow forces for the same inundation depth (e.g., [5]).
The horizontal and vertical forces obtained from the empirical equations proposed by different studies had a broad range of values and were difficult to correlate with the hydraulic theories.

7. Recommendations

Whilst extensive research has been undertaken it appears that the available guidance offers inconsistent advice and that there is a requirement for better guidance and design recommendations in this area. In the meantime, guidelines in the Waka Kotahi’s Bridge Manual [19] would be an appropriate approach to be used for estimation of tsunami loads on superstructure.

8. References


