Synopsis

The 1992 Austroads Bridge Design Code introduced the requirement to consider water flow force effects acting on bridges for floods up to the 1 in 2000 year average recurrence interval (ARI). Prior to that time it was common practice to design bridges for flood events up to the 1 in 100 year ARI.

With the requirement to consider flood events up to the 1 in 2000 year ARI, the superstructures of many bridges are partially or completely submerged and a large range of superstructure types are subject to submergence.

AS 5100 introduced new provisions for the calculation of water flow forces on bridges, with significantly increased water flow effects on bridge superstructures and increased debris loadings.

This paper reviews the new design provisions and examines its effects on the design of a low level shared path bridge over South Creek at Windsor.

Description of the South Creek Shared Path Bridge

The shared path bridge over South Creek was designed to complete the off-road cycleway from Mulgrave to Windsor.

The bridge has a total length of 63.5 m with span lengths of 17.2 m, 28.5 m and 17.2 m. The bridge is straight, on a longitudinal grade of -1.5% and has a clear width between handrails of 3.5 m.

Figure 1 Bridge Elevation
The deck level of the bridge varies from RL 9.353 m to 8.4 m. The 1 in 2 ARI flood level is estimated to be RL 8.3 and the 1 in 20 ARI flood level is RL 13.7 so it is apparent the bridge will be subject to reasonable frequent submergence.

The superstructure consists of twin Type 4 prestressed concrete I girders composite with a reinforced concrete deck slab. The deck slab consists of Transfloor precast units with integral kerbs and an insitu concrete overlay.

![Figure 2 Typical cross section](image)

Link slabs were provided over the Piers to provide a continuous deck between the deck joints provided at the Abutments. A collapsible baluster style pedestrian/cyclist railing with integral handrailing is provided on both sides of the bridge.

The Piers consist of a single blade wall column with headstocks supported on permanently cased bored piles socketed into sandstone. The close proximity of fibre optic cables meant that vibration had to be strictly limited during pile installation.

The Abutments consists of sill beams supported on permanently cased bored piles.
Concrete shear keys and tie downs of the superstructure are provided on all Piers and Abutments to prevent the superstructure being dislodged during submergence due to water flow forces.

**Hydraulic Investigations**

South Creek is a minor tributary of the Hawkesbury River that discharges into the river just downstream of the town of Windsor. The new Shared Path bridge is located immediately upstream of the an existing road bridge (Fitzroy Bridge) on Windsor Road.

The bridge is subject to submergence due to backwater effects from flooding of the Hawkesbury River. During a typical Hawkesbury River flood event, the lower reaches of South Creek experience 3 separate stages of flooding. Initially, floodwaters from the local South Creek catchment flow down South Creek towards the Hawkesbury River. As flooding increases in the main river, the floodwaters back up and the flow direction reverses to fill the floodplain. Once the peak flow begins to recede, the flow reverses as the floodplain storage drains out of South Creek.

The design flood levels at Fitzroy Bridge were estimated as follows:

<table>
<thead>
<tr>
<th>Event (year ARI)</th>
<th>Design Flood Level (AHD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>8.3</td>
</tr>
<tr>
<td>5</td>
<td>10.8</td>
</tr>
<tr>
<td>10</td>
<td>12.2</td>
</tr>
<tr>
<td>20</td>
<td>13.7</td>
</tr>
<tr>
<td>50</td>
<td>15.7</td>
</tr>
<tr>
<td>100</td>
<td>17.3</td>
</tr>
<tr>
<td>1000</td>
<td>21.9</td>
</tr>
<tr>
<td>PMF</td>
<td>26.4</td>
</tr>
</tbody>
</table>

For a 100 year storm event the stream flow velocities for various flood levels at the shared path bridge site are calculated as follows:

<table>
<thead>
<tr>
<th>Design Flood Level (AHD)</th>
<th>Stream velocity (m/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.3</td>
<td>-2.9</td>
</tr>
<tr>
<td>10.8</td>
<td>-2.3</td>
</tr>
<tr>
<td>12.2</td>
<td>-2.5</td>
</tr>
<tr>
<td>13.7</td>
<td>-2.3</td>
</tr>
<tr>
<td>15.7</td>
<td>-1.5</td>
</tr>
<tr>
<td>17.3</td>
<td>±0.04</td>
</tr>
</tbody>
</table>

**Summary of Jempson’s and Apelt’s research**

Apelt and Jempson undertook a detailed study of hydrodynamic forces on partially and fully submerged bridge superstructures with and without debris as part of a
research project sponsored by the National Cooperative Highway Research Program (NCHRP).

This involved a comprehensive program of laboratory testing of 6 different bridge superstructure types in a rectangular flow channel to derive drag, lift and moment coefficients.

The coefficients were related to flow parameters of relative submergence and proximity ratio. The relative submergence $S_r$ is defined as the ratio of the (depth of the water measured from the flood level to the soffit of the superstructure) to the (total depth of the superstructure and traffic barriers if the bridge is totally submerged or to the distance from the water level to the soffit of the superstructure if the bridge is partially submerged).

The proximity ratio $P_r$ is defined as the ratio of the (distance from the soffit of the superstructure to bed level) to (the distance from the soffit of the superstructure to the top of the concrete parapets or kerbs if the bridge is fully submerged or to the distance from the soffit of the superstructure to the water level if the bridge is partially submerged).

One of the interesting outcomes of the research is that downward forces on superstructures can be very high. In fact for the South Creek Shared Path Bridge the downward forces due to water flow were slightly larger than the pedestrian loading.

The second major outcome of their research is that the moment acting on the superstructure due to the transverse water flow forces and the eccentricity of any vertical (negative or positive) lift force is significantly larger than the moment calculated as the drag force acting at the mid-height of the superstructure.

They therefore introduced a coefficient for moment acting at the centreline of the deck at soffit level.

They also studied the effects of debris on the substructure and superstructure of bridges and derived new drag coefficients to calculate the forces due to these water flow effects.

This work formed the basis of the new water flow force provisions of AS 5100.

Provisions of Water Flow Forces on the Substructure in AS 5100.2

The provisions of AS 5100 for water flow forces on bridge piers are very similar to the 1992 Austroads Bridge Design Code with a range of drag and lift coefficients for various pier shapes.

However, a load factor on water flow forces dependent on the average recurrence interval for the critical flood condition was introduced in AS 5100.2.

The load factor is given as:

$$\gamma_{WF} = 2 - 0.5 \log \left( \frac{ARI}{20} \right)$$

This gives a load factor of 1 for a 2000 year ARI flood, 1.65 for a 100 ARI flood and 2.0 for a 20 year ARI flood.

On a wide flood plain, the 2000 year ARI flood level and flow velocity may only be marginally higher than the 100 year HFL, so the application of the load factor would
mean that the water flow forces for the 100 year flood say are significantly larger than the “ultimate” 2000 year ARI water flow forces. This is counterintuitive and inconsistent with the application of load factors for other load effects. For all other loading effects, the load factor is independent of the frequency of the loading.

Clause C15.2.1 of the Commentary to AS 5100.2 indicates that intermediate stages of the flood height only need be investigated if the superstructure is overtopped. Accordingly, where the 2000 year ARI flood level is below the soffit of the superstructure, it is not clear if the intention is for the piers be designed for lower recurrence interval floods with a load factor greater than 1.0.

The omission of the ultimate load factor symbol in the formulas for the ultimate design drag and lift forces in the subsequent clauses of the Standard contributes to the uncertainty in the application of this new “ultimate” limit state load factor.

Provisions of Water Flow Forces on the Superstructure

AS5100 introduces revised coefficients for drag, lift and moment to calculate water flow forces on bridge superstructures.

The coefficient for drag is given in the range of 1.3 to 3.35 dependent on the relative submergence $Sr$ and the proximity ratio $Pr$.

Coefficients for lift in the upward and downward direction are given with a range of -2.0 to -0.8 for downward lift and 0.6 to 0.0 for the upward lift dependent on the relative submergence $Sr$.

The model testing indicated that calculating the moment due to transverse water flow forces as the drag force acting at the mid-height of the superstructure is unconservative. Accordingly a coefficient for the moment calculated at soffit level at the centreline of the superstructure was introduced.

The Code recognises that the 2000 year flood may not be the event that causes the largest water flow forces as the fastest water flow velocities normally occur just as the bridge and approach embankments are overtopped.

Provisions for Water Flow Forces due to Debris

In addition to the water flow acting directly on the bridge elements, the water flow forces on debris built up on the bridge is also considered. Where the flood level is 600 mm below the soffit of the superstructure a debris mat between 1.2 and 3.0 m deep and one half of the adjacent span lengths long or 20 m, whichever is the shorter is considered.

Where the flood level is above 600 mm below the soffit of the superstructure the debris load is applied over the full length of the superstructure. It is assumed to extend to the top of the traffic barriers including any railings. Coefficients of drag are given for substructure debris loading and superstructure debris loading. The substructure debris coefficient of drag varies from 3.4 to 1.4 dependent on the velocity and average depth of flow.

The superstructure debris coefficient of drag varies from 5.6 to 0.8 and is dependent on the Froude Number.

The debris loading is significantly increased compared to the 1992 Austroads Bridge Design Code requirements where a drag coefficient of 1.04 was used to calculate all debris force loadings.

Water Flow Forces on Bridges by Bennett & Ponnampalam
The water flow drag force is not taken to act concurrently with the debris loading over the depth of the structure where the debris mat is located. However, normal water forces apply away from the debris mat. Also, where the superstructure is partially or fully submerged and subject to debris loading, the lift force is still taken to apply but with a reduced lift coefficient $C_L$ equal to -0.5.

**Bridge Design**

Some difficulties were experienced during the design of the South Creek Shared Path bridge with regard to the implementation of the Clause 15 of AS 5100.2 Forces Resulting From Water Flow.

After the initial evaluation, the following flood events were determined to be critical:

<table>
<thead>
<tr>
<th>ARI years</th>
<th>Flood level (AHD)</th>
<th>Flow Velocity m/sec</th>
<th>Ultimate load factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8.0</td>
<td>3.01</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>8.96</td>
<td>2.55</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>10.29</td>
<td>2.35</td>
<td>2</td>
</tr>
<tr>
<td>20</td>
<td>13.7</td>
<td>2.0</td>
<td>2</td>
</tr>
</tbody>
</table>

In general, the application of the “ultimate” load factor requires a large number of intermediate flood levels to be considered, because the variation in drag, lift and moment coefficients with proximity ratio and submergence ratio and the application of a variable load factor the critical load case producing the largest water flow forces is not apparent.

In this case the water flow forces acting on the structure are significantly higher for low recurrence interval floods than the 2000 year ARI “ultimate” flood, even without the application of the “ultimate” load factor.

For the various elements and failure mechanisms of the bridge the Code qualifies the application of the water flow forces in a fairly arbitrary manner. It would be simpler for the designer to develop the critical load cases for the various elements of the bridge from first principles.

Further the Code provides inconsistent requirements for the provisions of tie downs. Clause 15.4.3 appears to require positive tie downs on any superstructure subject to upward lift forces, irrespective of the concurrent downward load. Clause 15.7 requires the positive tie down system to be designed for a force of $1.5F_{LU} + \gamma g DL$. However this formula ignores the uplift effects due to the water flow moment acting on the superstructure. For the South Creek Bridge the moment resulted in significant uplift in the “upstream” bearings. For this design the ultimate bearing reactions were calculated from first principles for the load case $1.5F_{LU} + \gamma g DL \pm M_{gu} /\text{lever arm}$ and the tie down designed for the resulting ultimate force.
Conclusion
The implementation of the research carried out by Jempson and Appelt for the calculation of water flow forces on bridges in AS 5100 represents a considerable advance in the development of the Bridge Design Code. As a comparison, it is noted that the AASHTO LRFD Bridge Design Code does not contain any guidance on the design of partially and completely submerged bridge superstructures.

Compared to the requirements of the 1992 Austroads Bridge Design Code, the water flow forces on bridges have been significantly increased.

However, it is considered that some of the design provisions in Clause 15 of AS 5100.2 are ambiguous and are subject to misinterpretation.

Also, the reasoning behind introducing a variable “ultimate” load factor for water flow forces load dependent on the average recurrence interval for the flood is unclear and considerably complicates the design process.

The adoption of a constant load to be applied to the critical flood event is considered to be more rational and would simplify the design process.

The design requirements for tie downs of bridge superstructures need to be reviewed and clarified.

These matters shall be referred to the code committee for AS 5100 for their consideration for future revision of the Code.

Figure 3  South Creek Shared Path Bridge under construction
Figure 4  South Creek Shared Path Bridge under construction

Acknowledgement

The authors wish to thank the Chief Executive of the Roads and Traffic Authority of NSW for permission to publish this paper.

Disclaimer

The opinions expressed in this paper are entirely those of the author and do not necessarily represent the policy of the Roads and Traffic Authority of NSW.

References
