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Bridge Deck Afflux Modelling – Benchmarking of CFD and SWE Codes to Real-World Data

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ABSTRACT

Many bridge decks become partially or completely submerged during significant rain events, with the bridge creating afflux resulting in increased water levels and flood extents upstream of the structure. There is meaningful uncertainty on how best to model bridge decks in 1D and 2D hydraulic models, so to better understand this problem, the Queensland Department of Transport and Main Roads (TMR), partnered with TUFLOW researchers to investigate and produce guidelines for modelling bridge deck losses. Initially, simple bridge deck structures were modelled numerically by means of two different computational fluid dynamics (CFD) codes to determine energy loss mechanisms and coefficients. The energy loss factor as a function of water level was found to fit a simple function that could be parametrised according to the basic bridge dimensions, resulting in a new parametric formulation being integrated into the TUFLOW 2D Shallow Water Equation (SWE) code. In a parallel development, TUFLOW's 3D SWE code new functionality to represent bridge decks and blockages within the 3D layered mesh.

The second stage was to validate the developments with real-world data by installing gauges upstream and downstream of a low-level bridge in a collaborative effort between Moreton Bay Regional Council and TMR to provide measurements of bridge deck energy losses and affluxes. The Queensland 2022 floods, and some minor events in 2021, have now provided invaluable data on affluxes upstream of the bridge from the deck surcharging to full submergence. Video footage taken during the 2022 floods provides useful visualisation of the hydraulic formations over the deck. Two CFD and 1D, 2D and 3D hydrodynamic models were developed and benchmarked to the measurements resulting in beneficial findings for industry practitioners. These findings are being used by TMR to provide guidance on empirical approaches to modelling bridge deck energy losses, thus reducing modelling uncertainty and producing better civil road and bridge designs.

BACKGROUND

The hydraulic design of bridges is today predominantly undertaken with the aid of two-dimensional hydrodynamic models. These models use simple loss coefficients to replicate bridge losses that cannot be resolved directly within the two-dimensional computational scheme due to the complex three-dimensional flow patterns around bridges. While different numerical 2D schemes use different methods to derive head loss, most of these methods apply empirical form loss values based on limited data to validate the applied form loss coefficients, especially in events when bridge decks are becoming submerged or overtopped (Bradley, 1978, Austroads, 1994 and TMR, 2019). The lack of industry-wide accepted common head loss values for standard bridge decks or a "best practice" approach in cases where only limited or no calibration data is available has led to the fact that calculated bridge affluxes can vary significantly, depending on the experience of the modeller.

The high degree of uncertainty in the resulting afflux values for a submerged/overtopped bridge deck can have significant implications to the bridge design. Overestimated head loss values could lead to a very costly over-design of the bridge structure, while underestimated values could lead to widespread hydraulic impacts, potentially worsening flood conditions upstream of the bridge structure.

The primary objective of this work is to provide guidance on applicable form loss values for standard bridge decks which will reduce the uncertainty in bridge affluxes, lead to an improved representation of bridges in hydraulic models and ultimately result in improved bridge designs.

2D CFD MODELLING

A two-dimensional CFD model was developed to derive head loss values for various typical TMR bridge deck configurations. The bridge deck was simulated as a 2D slice through a typical TMR pre-stressed bridge deck consisting of standard deck units, standard kerb units and standard bridge safety barriers. The total deck obstruction (*T*) was defined as the distance from the soffit of the deck to top of the kerb, the bridge height (h_B) was defined as the height to the soffit of the bridge deck from the bed. These definitions and a typical velocity distribution of flows past a bridge deck are shown in Figure 1. The term tailwater (*TW*) is used to define the water depth downstream *above* the soffit.

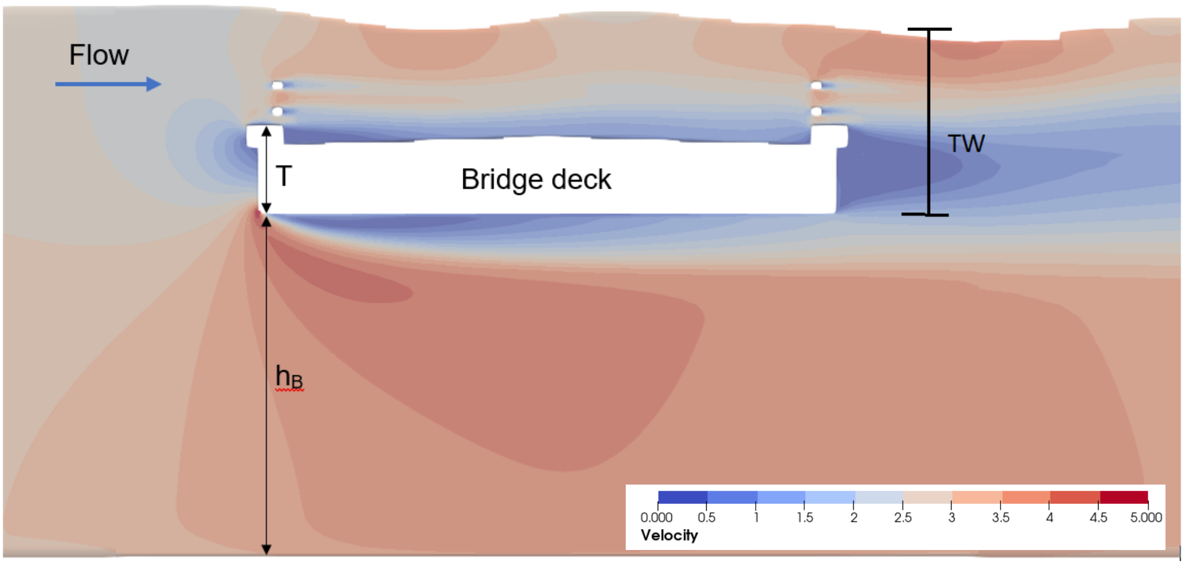

Figure 1 Definition of the Total Deck Obstruction (T), the Bridge Opening Height (h_B), Tailwater Level (TW) and typical velocity distribution

The CFD simulations were developed using FLOW-3D HYDRO with a regular rectangular grid with grid spacing of 50mm in the direct vicinity of the bridge geometry, 100mm in the near field of the bridge and 200mm for the rest of the domain. The CFD model utilises a Volume of Fluid (VoF) approach with air and water phases including free surface pressure. The Renormalized Group (RNG) κ–ε turbulence model with dynamically computed maximum turbulent mixing length and 1st order momentum advection approximation with immersed boundary near-wall momentum flux calculation was adopted for all simulations.

The simplified 2D model of flow past a bridge deck was run for various combinations of geometries and flow velocities. Three different deck thicknesses were studied: 0.900m, 1.200m, and 1.500m. For each deck thickness, three under-bridge heights were studied as listed in Table 1. The ratio h_B/T of under bridge height to deck was set to 2, 4 and 6 for scenarios A, B and C, respectively. Each of the 9 cases were run at various tailwater (*TW*) levels (i.e. downstream water level above deck obvert) for both 2 m/s and 3 m/s downstream exit velocity.

Table 1. Bridge Deck 2D CFD cases – under bridge heights, h_B

	Deck thickness 0.90 m	Deck thickness 1.20 m	Deck thickness 1.50 m
Scenario A (h_B/T) = 2	1.800 m	2.400 m	3.000 m
Scenario B (h_B/T) = 4	3.600 m	4.800 m	6.000 m
Scenario C (h_B/T) = 6	5.400 m	7.200 m	9.000 m

The total energy levels (water surface level plus $U^2/2g$) were extracted from the CFD results. Figure 2 shows the upstream to downstream delta in energy levels plotted against tailwater level for Scenario B. There are four essential features evident in the results (a) the curves are of the same generic shape and appear to form a family of results, (b) the energy loss rises quickly, peaks, and decays slowly as the deck becomes progressively "drowned out", (c) the tailwater level at which the energy loss peaks appears to be related to deck thickness, (d) the energy losses at 3 m/s flow are substantially higher than at 2 m/s flow.

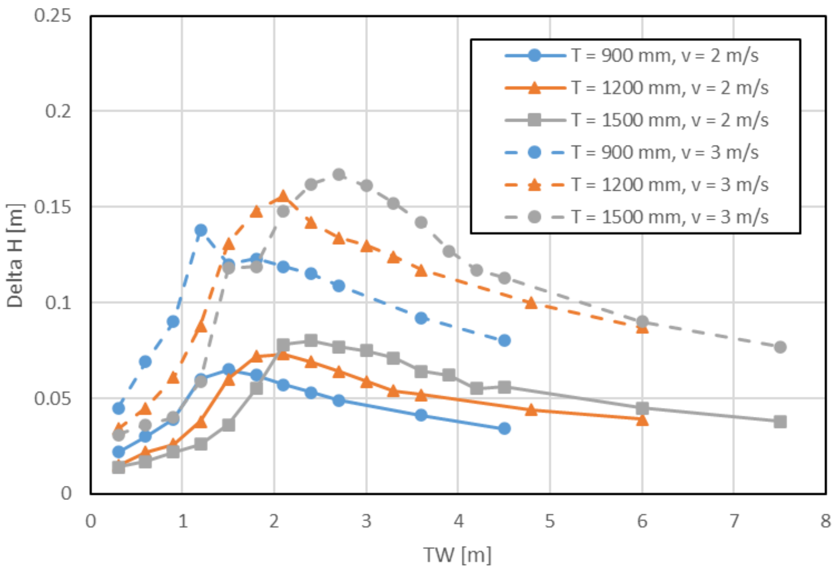

Figure 2. Energy loss vs tailwater level for Scenario B, (h_B/T) = 4.

Given that the results appear to form a family of curves, further analysis was performed to determine if there is a more generic non-dimensional result. This can be found by normalising the tailwater against the deck thickness, *T*, and by normalising the energy loss against a reference energy head ($H_{ref}=U_{ref}^2/2g$). For this, we found the best reference velocity, U_{ref}, was the 'downstream structure velocity', which is the unit flow divided by the downstream water depth less the minimum of deck thickness or tailwater. After these normalisations, the family of curves collapses as shown in Figure 3. From this result, it appears that the peak loss coefficient is around 0.28 and occurs at a tailwater level that is about 1.6 times the deck thickness. The results for Scenarios A and C are very similar, with the peak form loss coefficient decreasing as the ratio of h_B/T increases. The results are summarised in Table 2.

2D SWE IMPLEMENTATIONS

The depth-averaged Shallow Water Equations cannot model 3D flow around structures and require some form of sub-model to account for the presence of the structure. There are two independent choices to be made. The first is whether to represent the bridge with a 1D network element, or with a line of modified cells or faces within the 2D domain. If the primary flow path is already represented as a 1D channel within the model, then it is logical that the bridge is also represented with a 1D element. However, there is a growing trend to keeping the flow channels in the 2D model, in which case a 2D representation may advantageous – particularly for long bridges that span both channel and adjacent flood plains. The second choice is whether to represent the bridge with a stage-flow rating curve, or a head loss based on flow depth and velocity. The former assumes upstream flow control which may cause it to be inaccurate once the flow becomes downstream controlled. The latter is applicable regardless of flow regime. Both methods can be applied in dynamic and diffusive wave solvers.

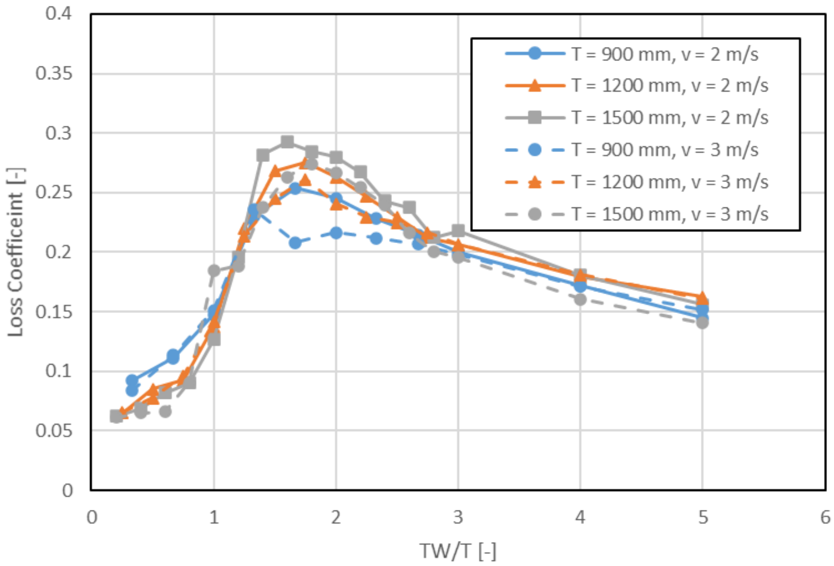

Figure 3. Nondimensional energy loss vs nondimensional tailwater level for Scenario B.

Table 2. Peak form loss coefficients

Deck height to thickness ratio	Peak Form Loss Coefficient
Scenario A (h_B/T) = 2	0.42
Scenario B (h_B/T) = 4	0.28
Scenario C (h_B/T) = 6	0.20

FULL-SCALE BRIDGE AFFLUX MEASUREMENTS

As there was only limited data available for the validation of the CFD analysis, additional calibration and validation data was required to benchmark the CFD results with the aim to reduce uncertainty in the reliability of the CFD results.

An opportunity arose in 2020 to install water level sensors upstream and downstream of a bridge in collaboration with Moreton Bay Regional Council to gather data. Figure 4 shows the bridge and Figure 5 the location of the installed water level sensors upstream and downstream of the bridge.

The water level gauges were installed in September 2020 but were only fully functional in April 2021. The Queensland 2022 floods, and some minor events in 2021, have resulted in several overtopping events of the bridge and therefore provided invaluable data on affluxes upstream of the bridge from deck surcharging to full submergence. Upstream and downstream water levels at the bridge for the February 2022 event are shown in Figure 6.

3D CFD MODELLING OF FULL-SCALE BRIDGE

CFD modelling of hydraulic flows has matured significantly over the last two decades – to the point that a correctly setup model commonly agrees well with experimental data. Therefore, we can gain additional confidence in the gauge data for the Gordon Road bridge by comparing with a full 3D CFD calculation of the flow. Two mature CFD codes were used: Flow-3D and OpenFOAM. In both cases, a 0.1m resolution digital elevation model (DEM) was used for the surrounding land and creek bed, and a detailed topographic survey of the creek bed under the bridge including the bridge abutments.

Figure 4: Gordon Road Bridge site

Figure 5: Water level sensor locations

The FLOW-3D model utilised a regular rectangular grid with grid spacing of 0.125 m in the direct vicinity of the bridge geometry, 0.25 m in the near field of the bridge and 0.50 m for the rest of the domain. The model domain extended from approximately 15 m upstream of the bridge to 50 m downstream. The upstream boundary was a defined flow rate pressure boundary. The downstream boundary was set as a fixed water level pressure boundary based on water levels extracted from 2d modelling. To be consistent with the 2D bridge deck modelling, the adopted physical models have been kept unchanged from the 2D bridge deck models. The FLOW-3D model domain is shown in Figure 8. The upstream and downstream water level results were extracted at the physical gauge locations.

The OpenFOAM CFD model utilised the "InterFoam" transient incompressible two-phase volume of fluid solver with the k-Epsilon turbulence model. The CFD mesh was predominantly hexahedral cells of 125 mm resolution around the bridge, transitioning to 1m horizontal by 0.5 m vertical away from the bridge. The model domain spanned from 200 m upstream of the bridge to 100 m downstream. The upstream boundary was a defined flow rate source, and the downstream boundary was zero-gradient for pressure and velocity. The water level results were extracted as area averages over 10 m wide (in flow direction) regions upstream and downstream of the bridge.

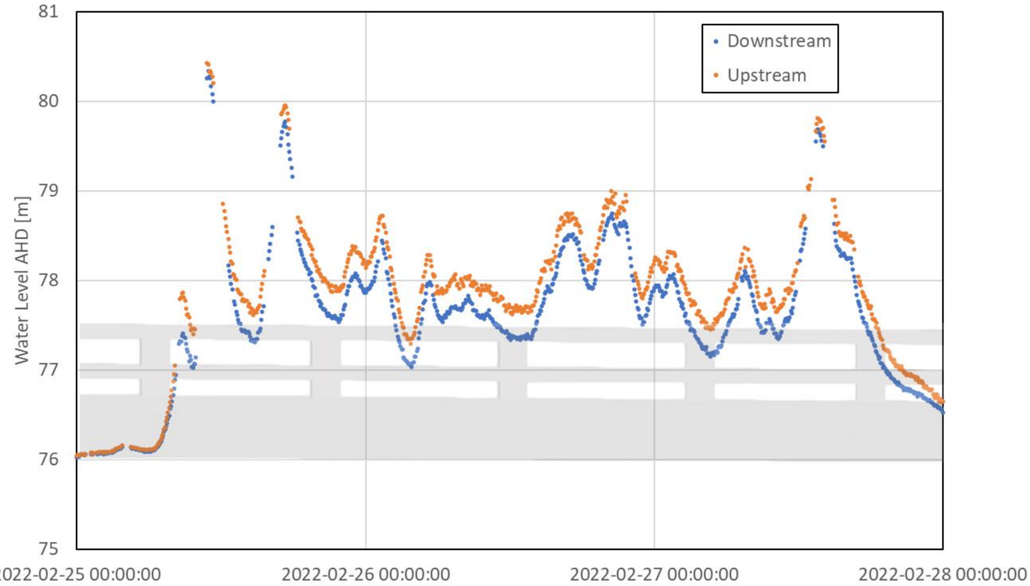

Figure 6: Gauge recordings February 2022

Figure 7: Gordon Road Bridge during flood event February 2022

The results for both models are shown in Figure 9 along with the measured loss data. Both CFD models predict peak losses when the water is at or above the top of the guard rails, with both being in reasonable agreement with the measured data. Both the Flow-3D predicted losses and the measured losses show a similar shape to the 2D CFD results with a rapid rise in loss once the water level passes the soffit of the deck, peaking at a water level well above the top of the deck, and then slowly decaying for water levels well above the guard rails. There is some noise apparent in the Flow-3D results with the water level just above the deck, possibly due to using single points for the water level measurements. Unfortunately, due to time constraints, the OpenFOAM model was not run to sufficiently high flow rates to obtain the full shape of the loss curve. The differences between the Flow-3D and OpenFOAM results are somewhat expected due to different turbulence model selection and water level extraction methods.

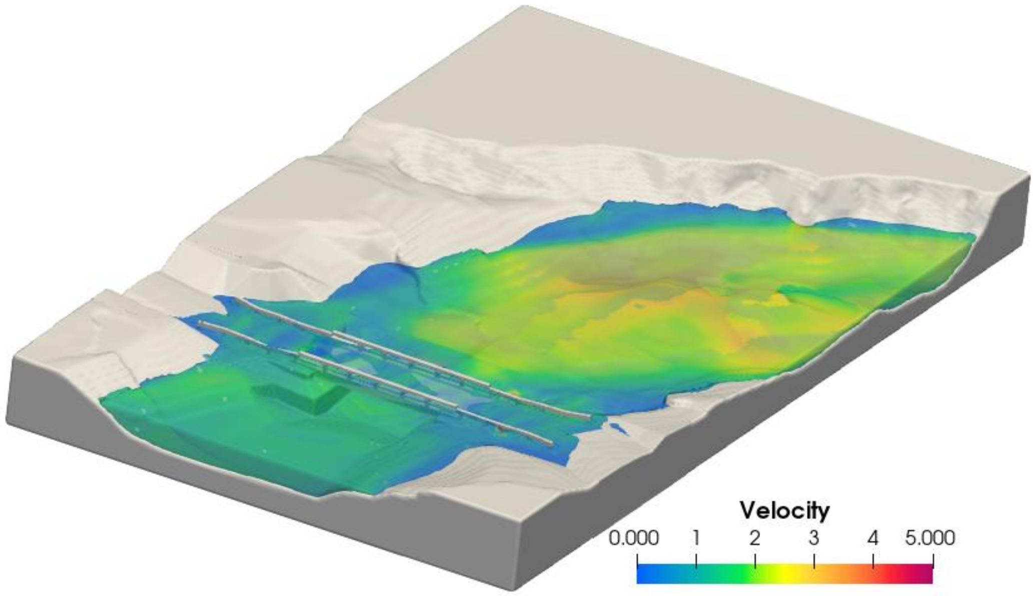

Figure 8: FLOW-3D model domain

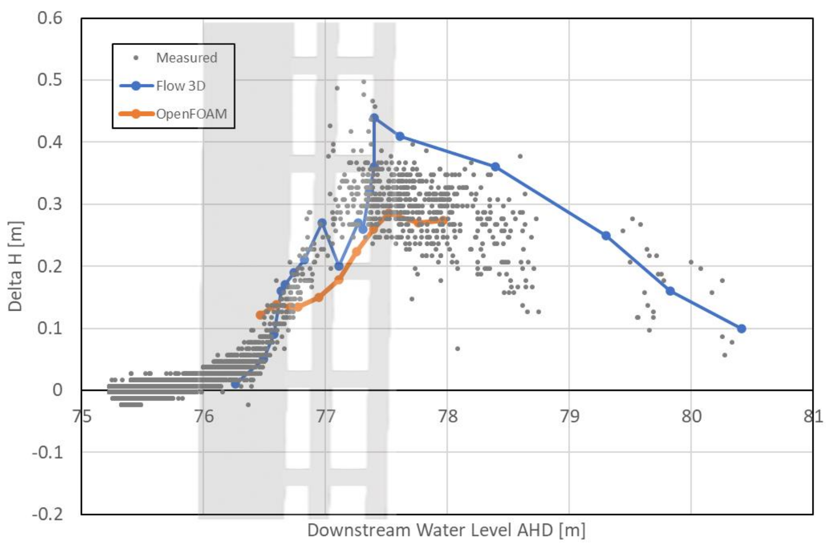

Figure 9. Comparison of 3D CFD results with measured data for Gordon Road Bridge.

2D TUFLOW HPC MODELLING OF FULL-SCALE BRIDGE

A 2D Shallow Water Equation model of the Gordon Rd bridge and immediate surrounds was constructed using TUFLOW HPC. A number of methods for the energy losses associated with the bridge are available, but for brevity we only detail the approach selected, "Method D". The approach selects a line of cell faces at the location of the bridge and applies a momentum loss term (calculated using a form loss coefficient) at these faces, noting that TUFLOW uses cell-centred depths and face-centred velocities. The form loss coefficient is depth dependent, according to Equations 1-3:

$$K = \left(\begin{array}{c|c} h < h_1 & K_1 \\ h_1 \leq h < h_2 & K_1 + \xi K_2 \\ h_2 < h & (K_1 + K_2)\dfrac{h_2}{h} \end{array} \right) \tag{1}$$

$$\xi = \frac{h - h_1}{h_2 - h_1} \quad (2)$$

$$h_2 = h_1 + F_{ex}[h_{deck} + (1 - P_{rail})h_{rail}] \quad (3)$$

where h is the downstream side water depth, h_1 is height of the underside of the deck above the river bed, h_2 is the height (above river bed) at which the form loss coefficient peaks, h_{deck} is the vertical thickness of the bridge deck, h_{rail} is the height of the top of the guard rail above the deck, P_{rail} is the porosity of the guard rail, and F_{ex} is an expansion factor representing the ratio between the tailwater depth at which the peak loss occurs and the total solid thickness of the deck and rails. K_1 is the loss coefficient of the piers (not present for the Gordon Rd bridge), K_2 is the additional loss coefficient of the deck and guard rails, and ξ the linear transition variable used when h is between h_1 and h_2. For the Gordon Rd bridge, h_1=2.1m, h_{deck}=0.7m, h_{rail}=0.8m, P_{rail}=0.5, F_{ex}=1.6. Using this geometry, the peak form loss coefficient would be around 0.35 from interpolating Table 2. However, models with K_2 of 0, 0.28, 0.5, and 0.8 were run (with $K_1 = 0$) to bracket the results. The face flux calculations account for the blockage of the structure, so the reported face velocities are in fact structure velocities. For this, the porosity of the area up to the underside of the deck (i.e. the non-existent piers) was unity and the porosity of the deck was zero. The resulting form loss coefficient using this geometry and K_2=0.28 is shown as a function of depth in Figure 10.

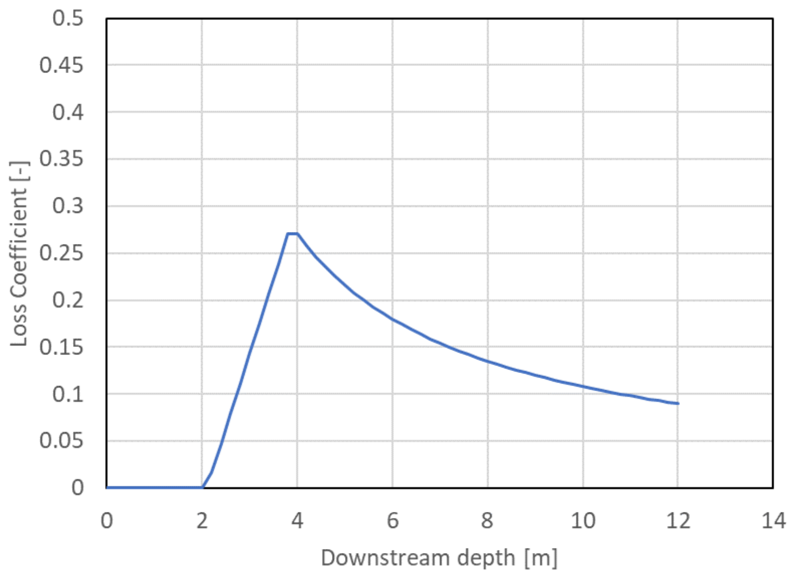

Figure 10. Depth dependent loss coefficient for Gordon Rd bridge, TUFLOW method D

The TUFLOW model used a fixed flow source at the upstream boundary, and a stage-discharge rating curve for the downstream boundary. However, both boundaries were sufficiently removed from the bridge such that they did not significantly influence the flow field at the bridge. The model used a uniform cartesian grid with cell size 1.0 m, and a channel Manning's bed friction coefficient of 0.035. The fixed flow source was stepped incrementally over time and the water levels upstream and downstream of the bridge, at the locations of the physical gauges, were extracted after each flow step had stabilised. Finally, the Wu eddy viscosity model was selected, using a coefficient of 2.0 for the depth.U*, or "3D", term, and zero for the velocity gradient tensor magnitude, or "2D", term. An example water surface is shown in Figure 11.

The predicted bridge afflux is shown in Figure 12 for the selected peak form loss coefficients, along with the measured data. The three numbers in the legend are $K_1/K_2/F_{ex}$. The solid curves show the difference in water surface level, and the dashed curves the difference in total energy level. Note that the DEM includes the bridge abutments and the flow over these is very three-dimensional. It is to be expected that the surface wave pattern downstream of the bridge, using 2D depth averaged flow equations, may not match reality that well – hence the negative afflux based on water surface elevations at higher water levels. However, the afflux based on energy appears to be a more reliable indicator of head loss. The result for form loss coefficient 0.28 appears to be an acceptable fit to the measured data.

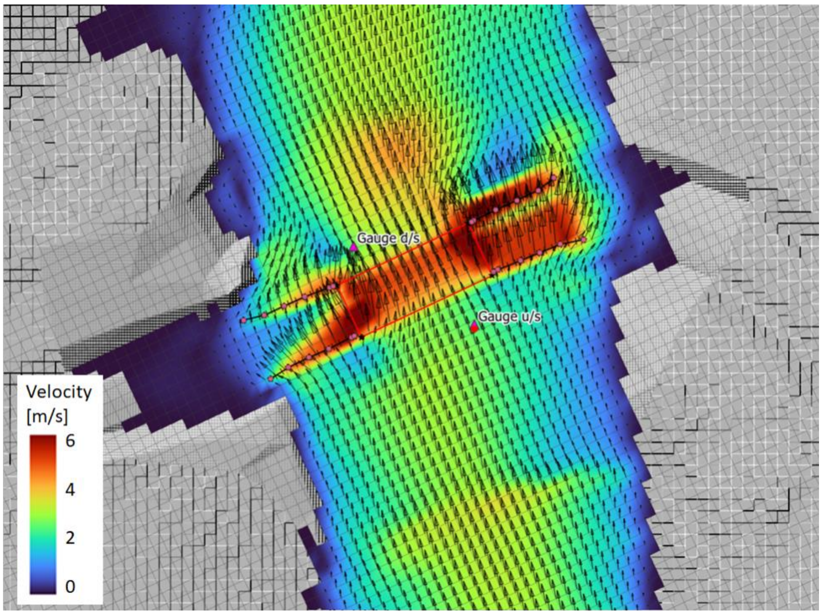

Figure 11. Example TUFLOW water surface and velocity

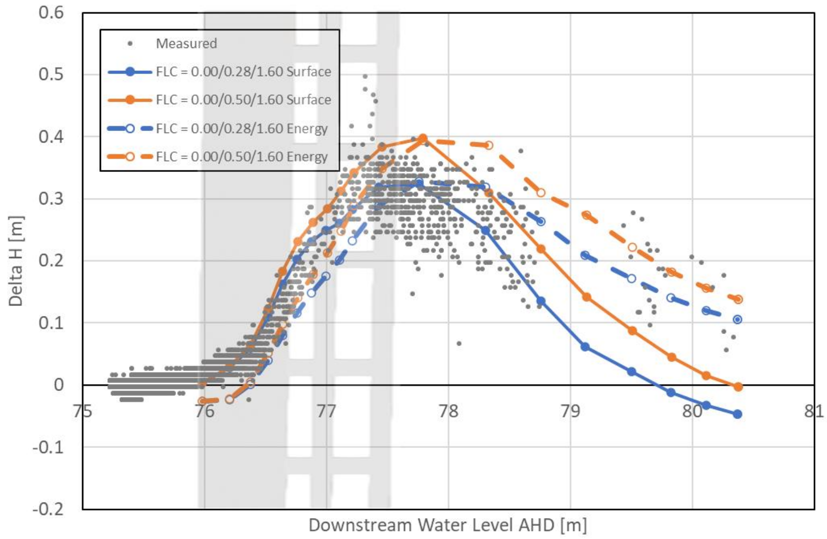

Figure 12. TUFLOW simulated afflux vs downstream water level

3D TUFLOW FV MODELLING OF FULL-SCALE BRIDGE

The Gordon Road Bridge was also modelled in the 3D finite volume code "TUFLOW FV". This code uses the hydrostatic pressure assumption and split mode evolution where the shallow water wave propagation is solved in 2D on a sub-timestep to the main 3D advection updates. The code has new functionality for implementing structure losses by considering which 3D cells contain the structure and assigning blockage factors and drag coefficients on a pro-rata basis within these cells. The water surface velocity and a long-section curtain plot (through the bridge) of velocity are shown in Figure 13 – note the model had 10 variable sigma layers vertically. The volume of the bridge shows as a zone of very low velocity in the curtain plot. The predicted head drop across the bridge as a function of downstream water level is shown in Figure 14 for two different 2D viscosity models and two different drag coefficient options.

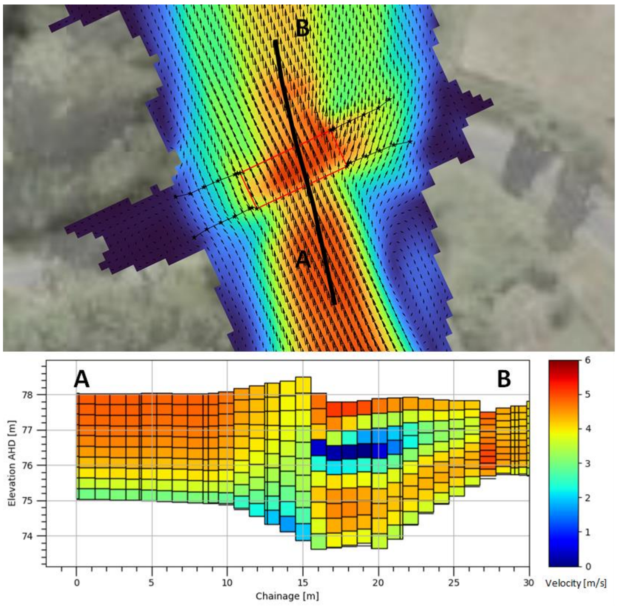

Figure 13. TUFLOW FV water surface velocity (top) and curtain plot velocity (bottom)

The Wu viscosity model is the depth.U* model described previously, and the Smagorinsky model is a Large Eddy Simulation (LES) formulation based on cell area and magnitude of the 2D velocity gradient tensor. The choice of 2D eddy viscosity model and coefficients strongly influences the velocity distribution across the flow channel has therefore has a material impact on the loss result. For the first drag coefficient option, a uniform value of 1.0 was used for both deck and guard rails (based on solid flow area), and for the second option a value of 1.5 was used for the deck and 2.0 for the guard rails. The result with Smagorinsky eddy viscosity and drag coefficient 1.0 fits the measured data particularly well.

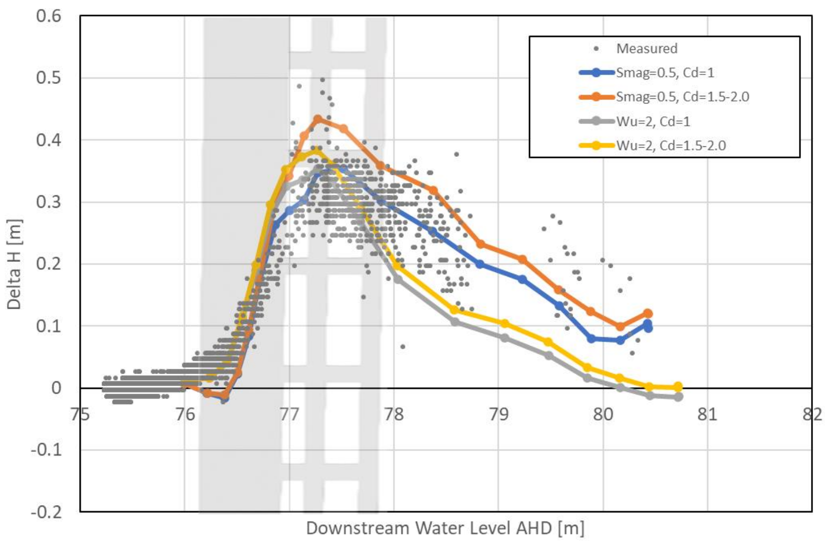

Figure 14. TUFLOW FV afflux vs downstream water level

CONCLUSIONS

2D CFD models of a bridge deck with guard rails display a characteristic shape for head loss as a function of downstream water level whereby the head loss (afflux) peaks when the water level is well above the top of the bridge deck, and decays slowly as the bridge becomes progressively drowned out.

A real bridge was instrumented with upstream and downstream water level gauges, and flood event data was captured in February 2022. The measured data shows an almost identical shape for head loss as a function of downstream water level.

3D CFD models of the same bridge were constructed and both Flow-3D and OpenFOAM software yielded results in close agreement with the measured data.

A depth-varying form loss coefficient of a generic shape was implemented in a 2D SWE equation solver (TUFLOW HPC) and models of the bridge and surrounds were found to reproduce the measured afflux data.

Peak form loss coefficients applied in TUFLOW HPC Method D are listed in Table 2 for various ratios of under bridge height to deck thickness. Further work is needed to extend this table. For h_B/T values in the range of 2 to 6 it is suggested interpolating between the peak form loss coefficients listed, however for values outside of this range it is suggested clamping to the nearest end value.

The bridge was also modelled in 3D with TUFLOW FV utilising new structure loss functionality. The results were in excellent agreement with the measured afflux data using the Smagorinsky 2D eddy viscosity model and a drag coefficient of 1.0 applied to the blocked flow area. 3D models of structures in TUFLOW FV using this functionality represent a robust path for determining structure afflux.

Reference List

Austroads (2018), *Guide to Bridge Technology Part 8: Hydraulic Design of Waterway Structures*, prepared by Hanson Ngo, Project Managers: Phanta Khamphounvong and Henry Luczak, Sydney, NSW, Australia.

Bradley, J. N., (1978), *Hydraulic Design Series No. 1. Hydraulics of Bridge Waterways*. US Department of Transportation, Federal Highway Administration, Washington, DC, USA.

Department of Transport and Main Roads, (2019) *Technical Guideline: Hydrologic and Hydraulic Modelling*. Queensland Department of Transport and Main Roads, Australia.

BIOGRAPHY

Greg Collecutt is the principle GPU software developer at TUFLOW. He has degrees in mechanical engineering and a PhD in theoretical physics, and has spent most of the last twenty years working in computational fluid dynamics and flood modelling. In this role he is primarily involved with the implementation and benchmarking of new modelling features in the TUFLOW HPC 2D engine.

Urs Baeumer graduated in 2000 from the University of Karlsruhe (TU), Germany and relocated to Australia in 2007. After working in the private sector for over 15 years, Urs joined the Queensland Department for Transport and main Roads in 2015 and is the manager of TMR's Hydraulics and Flooding team. Urs has a passion for water engineering and applied hydraulics and has led the hydraulic design of many large infrastructure projects.

Shuang Gao graduated from Tokyo Institute of Technology with a PhD degree in Environmental Hydraulic Engineering. He joined the TUFLOW software development team in 2017, and has been involved in varieties of R&D projects, flood and coastal modelling, technical support and training. His main interests lie in the development of cutting-edge modelling methods applied to real-world engineering problems.

Bill Syme has 37 years' experience primarily in the flood hydraulics field. During this time, he successfully managed and led a wide range of studies in Australia and overseas. The widely used TUFLOW hydrodynamic modelling software was first developed by Bill starting in 1989. Today, Bill is BMT's Software Business Lead, managing TUFLOW's global operations, and continues to provide specialist hydraulic modelling and flood risk management advice. He was the Project Manager for the award-winning Brisbane River Flood Study Hydraulic Assessment, and in 2022, Bill was the recipient of the FMA Allan Ezzy Flood Risk Manager of the Year Award.