

Cell Based Modelling of Bridge Piers Using TUFLOW

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Abstract: Recent large infrastructure projects in Brisbane have highlighted the importance of accurately predicting the hydraulic impacts of individual bridge piers located in complex flood flows. A new methodology using the 2D hydrodynamic modelling package TUFLOW has been developed by Arup. The process involves modifying a specific TUFLOW form loss coefficient at the cell corresponding to a pier, depending on the local depth, velocity, cell size and pier diameter. Empirical curves to determine the TUFLOW coefficient were calibrated to US FHWA Hydraulics of Bridge Waterways' headloss predictions.

The procedure was applied on one of the largest Australian infrastructure projects, the Brisbane Airport Link, for historical verification and design. The hydraulic impacts of 400 proposed piers were assessed and offset to control flood levels in a heavily urbanised floodplain.

This methodology provides TUFLOW users with a tool comparable to the use of drag coefficients in other 2D hydrodynamic modelling packages.

Keywords: bridge pier, energy loss, afflux, TUFLOW.

1. INTRODUCTION

Since 2004, the city of Brisbane has been upgrading its urban road network at a scale rarely seen in Australia. In conjunction with the Queensland State, the city's "TransApex" transport plan has resulted in the successful delivery of one major tunnel project and three bridged crossings of the Brisbane River. Another large infrastructure project, the Airport Link, comprising three interchanges that are encroaching on significant city creeks, is currently under construction. With the existing urban environment already impinging on floodplains, all of these projects are under scrutiny to demonstrate a sustainable design with no increase in flood damages.

The technical developments of the flood modelling industry have resulted in advanced computer softwares that are effective at predicting the water levels associated with large catchment flood flows. River channels and floodplains can be discretised into fine 2D scales that enhance the applicability of the shallow water equations. As a result, it is accepted by the industry that the commercially available 2D hydraulic modelling packages can predict open channel flow impacts by accurately representing flow path constrictions and expansions. This industry agreement has however shown to be challenged when dealing with localised impacts generally described by empirical methods.

Specifically, the treatment of bridge piers and the prediction of their induced afflux have proven to be a potentially contentious point unless carefully justified. Arup, the design consultant on a number of these recent infrastructure projects in Brisbane, experimented with different techniques using the TUFLOW modelling software to better predict the hydraulic impacts of bridge piers for more optimised designs.

This paper describes the methodology behind the preferred technique, its validation through comparison with empirical curves, and its application on the Airport Link project.

2. EMPIRICAL ASSESSMENT OF PIER LOSSES

In flood engineering, two main techniques are used to set-up or to calibrate pier losses in a computer model:

- The use of standard empirical curves. The Australian body that provides uniform standards and general procedures for the design, construction and maintenance of roads, AUSTRROADS, refers to the US Federal Highway Administration for best practices in the assessment of pier losses (AUSTRROADS, 1994); and/or
- The calculation of drag forces.

While the first technique can be applied directly in TUFLOW, the calculation of drag forces is not part of the software algorithm. However, depending on the bridge configuration, the calculation of energy losses through drag effects can provide more flexibility. In particular, it integrates the location of the pier in the flow path as a design parameter, which can provide significant benefits on large infrastructure projects.

Prior to discussing improved techniques in TUFLOW, the key elements of FHWA and drag assessments are summarised in the following two sub-sections.

2.1. Federal Highway Administration (FHWA) Curves

The FHWA Hydraulics of Bridge Waterways guidelines (US FHWA, 1978) are based on a comprehensive flume experimental study by Lui *et al* (1957). Using Froude similitude, the study measured the afflux associated with the variation of individual bridge elements, which included pier shape, configuration and dimension.

The research derived incremental backwater coefficients, Δk_p , that relate the incremental bridge afflux to the average energy head across the channel. Δk_p can be obtained for relevant pier shapes and combinations based on the ratio of projected pier area to flow area. The recognisable FHWA incremental backwater coefficient curves for piers are presented in Figure 1:

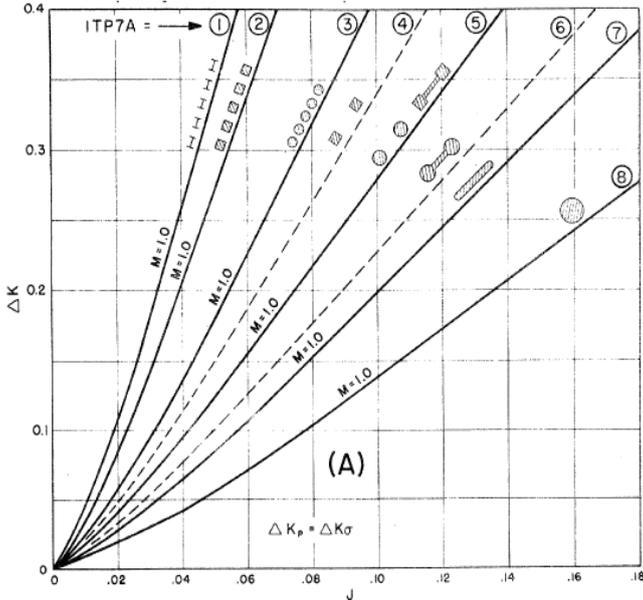


Figure 1 Incremental backwater coefficient for piers. (US FHWA, 1978).

As the FHWA method has been derived from flume data, it is really only applicable to uniform uni-directional flow. As a result, while powerful in situations where the flow is evenly distributed and perpendicular to the bridge, the direct application of the FHWA method in 2D can be inaccurate and can lead to undesired conservatism.

2.2. Drag Effects

2.2.1. Drag force

In fluid dynamics, drag refers to forces that oppose the relative motion of an object through a fluid. It is an essential component of the external forces applied to a fluid particle in the momentum conservation equation. In the instance of bridge piers, the effects of drag forces directly balance the increase of upstream energy of the body of water.

The total drag on a body is the sum of the skin friction and form drag. The ratio between the two types of drag varies between objects, but for cylindrical piers, the shape of the pier accounts for approximately 90% of the total drag force. The expression of the drag force experienced by the relative motion of an object through a fluid is:

$$F_D = C_D \rho \frac{V^2}{2} A \quad (1)$$

where, F_D is the drag force, C_D is the drag coefficient of obstruction, ρ is the density of fluid, V is the velocity of fluid, and A is the projected area of obstruction (Daugherty *et al*, 1989).

Eq. (2) shows the momentum equation incorporating energy loss converted to a drag force for a control structure as derived by Franz & Melching (2006).

$$\frac{\frac{1}{2} \rho C_D A V^2}{\frac{1}{2} \rho g W h^2} = \frac{1}{2} \left(1 + \frac{h}{h + \Delta h} \right) k \left(\frac{V}{\sqrt{gh}} \right)^2 \quad (2)$$

where C_D is the drag coefficient, g is acceleration due to gravity, W is the width of channel, h is the depth of fluid, and Δh is the afflux caused by the obstruction. Providing C_D is known, Eq. (2) can determine the energy loss due to the drag force.

2.2.2. Drag coefficient

Drag coefficients have been tested experimentally for a full range of flow conditions. Prandtl derived empirical curves from laminar flows to turbulent flows (Prandtl, 1923). Figure 2 presents an update of these curves for various two dimensional shapes including finite and infinite circular cylinders. The range of conditions applied on the Airport Link project, which is described in Section 4, were clearly in the turbulent flow regime with the Reynolds number varying between 4.9×10^3 and 2.6×10^6 , with an average value of 9.6×10^5 . The empirical curves show significant variation in the drag coefficient within this range, which makes Eq. (2) difficult to solve automatically.

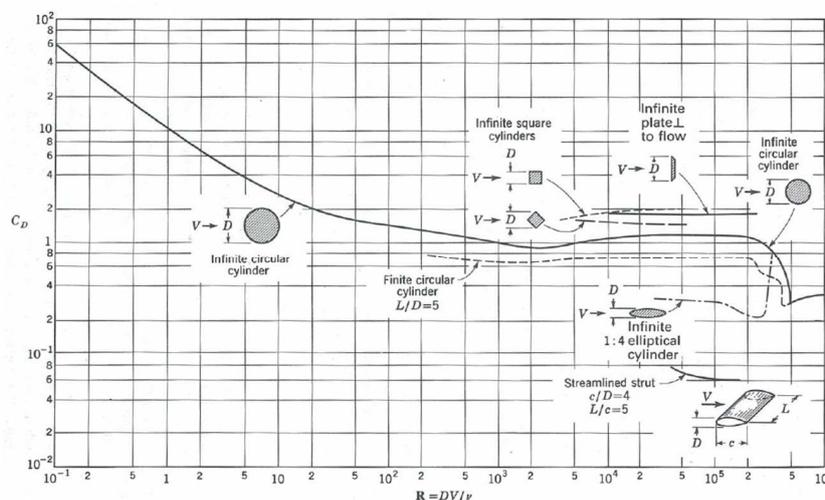


Figure 2 Drag coefficient for two-dimensional bodies. (Daugherty *et al*, 1989).

3. BRIDGE MODELLING IN TUFLOW

3.1. Introduction to TUFLOW

TUFLOW is one-dimensional (1D) and two-dimensional (2D) flood and tide simulation software. It simulates the complex hydrodynamics of floods and tides using the full 1D St Venant equations and the full 2D free-surface shallow water equations. It is a proven reliable hydro-dynamic engine that accurately predicts flood inundation patterns.

Using a finite difference scheme, TUFLOW solves the 2D equations at each of the model's square cells, predicting depth, water level and velocities.

When using TUFLOW in its full 2D configuration with a relatively small grid cell size to represent open channel flows in wide channels and floodplains, the model can efficiently predict the majority of "macro" losses due to the expansion and contraction of the flow through a bridge opening. As a result, the afflux generated by a one-span bridge can easily be computed by blocking the cells corresponding to the bridge abutments.

The simulation of "micro" losses, which bridge piers fall into, is not integrated in the shallow water equations and requires additional modelling parameters. TUFLOW allows adding additional punctual energy losses to selected cells, using Flow Constriction (FC) cells, which can also partially or totally block the conveyance at the the cell sides.

The current guidelines in the TUFLOW Manual for the use of FC cells to represent bridge piers are limited and suggest two methods, one based on a width average setup inspired by the FHWA method, and one based on a cell base setup, which offers a similar punctual discretisation as the drag effects. However, in relation to the latter option, the instructions do not extend to the selection of the parameters. This paper presents the exhaustive calibration exercise that was undertaken for the Airport Link project, which ultimately led to the derivation of punctual energy loss coefficient curves.

3.2. Direct FHWA Δk_p method

A flume model was developed in TUFLOW to replicate the experiments of Lui *et al* (1957) in order to validate the direct applicability of the Δk_p coefficient in a line of FC cells across the flow. Assuming a bridge spanning the entire channel with only the piers impeding the uniform flow, the FHWA coefficient can be applied as the TUFLOW FC cell additional energy loss. However, the coefficient must be applied equally in the one row of cells representing the bridge.

Figure 3 shows the change in water level gradient near the line of FC cells, with closer 5mm intervals, where the piers generate their afflux.

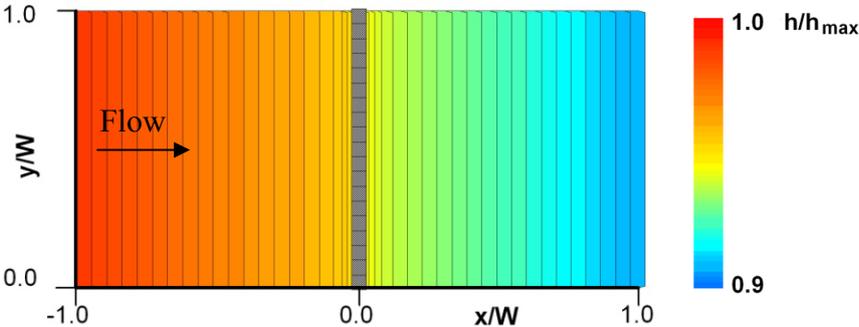


Figure 3 Impact of direct FHWA Δk_p coefficient on 5mm water level contours.

Tests were undertaken for fluvial slopes with the flow conditions ranging from 0.5m to 25m deep, and from 0.5m/s to 5m/s. The resulting energy loss generated by the FHWA Δk_p direct method corresponded to the empirical predictions in all cases up to a Froude number of 0.5. Under higher Froude conditions, it was found that the FC cell additional energy loss coefficient needed to be greater than the FHWA value, up to 20% higher close to the critical flow conditions.

3.3. Discrete energy loss method

Using the same TUFLOW flume model as for the FHWA Δk_p direct method, the bridge setup was modified so that the additional energy loss would be concentrated on the one cell representing the pier. The FC cell coefficient could be calculated by replacing $\Delta h = k_{FC} \frac{V^2}{2g}$ in Eq. (2), with k_{FC} representing the TUFLOW coefficient. However, this would require the knowledge of the drag coefficient, which was found to vary within the flow range considered. Instead, the actual value of the FC cell coefficient was derived through iterations until the upstream afflux in the uniform flow zone was the same as the FHWA predictions.

The process was further explored by including a blockage ratio to the pier cell corresponding to the actual pier dimensions. While the FC cell coefficient would be less than in Eq. (2), the introduction of this blockage was found to lead to a better representation of the streamlines around the pier, which could be significant where multiple piers are in close proximity. The resulting effect on water level contours is presented in Figure 4 for the tests (a) without and (b) with blockages.

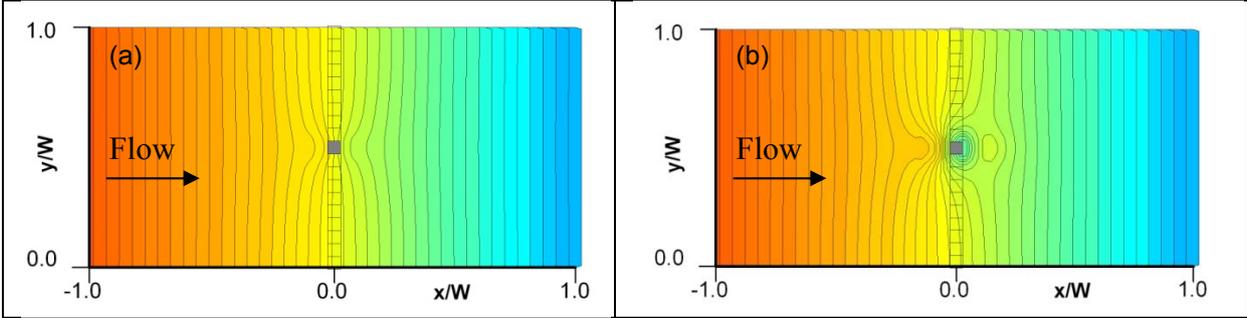


Figure 4 Impact of discrete energy loss method on 5mm water level contours (a) without and (b) with blockage.

The discrete energy loss method was tested in the TUFLOW model for the same range of depths as the FHWA Δk_p direct method, and for velocities up to 2.5m/s, with the cell blockage ratio corresponding to the piers designed for the Airport Link project. The results revealed a systematic variation in the TUFLOW additional energy loss coefficient with both velocity and depth, Figure 5.

The review of the best fit curves showed that the coefficients closely follow an Arctan function where:

$$\begin{aligned}
 k_{FC} &= A \arctan(Bh) & (3) \\
 A &= a_1 V^4 + a_2 V^3 + a_3 V^2 + a_4 V + a_5 \\
 B &= b_1 V^4 + b_2 V^3 + b_3 V^2 + b_4 V + b_5
 \end{aligned}$$

The polynomial equation parameters depend on the pier diameter, the bridge span and the model cell size. They can be calculated with trendline functions in computer spreadsheets. Once set, these equations can automatically determine the suitable TUFLOW FC cell's additional energy loss coefficient for all piers of the same dimensions, either already constructed or proposed, situated in the river or the floodplain.

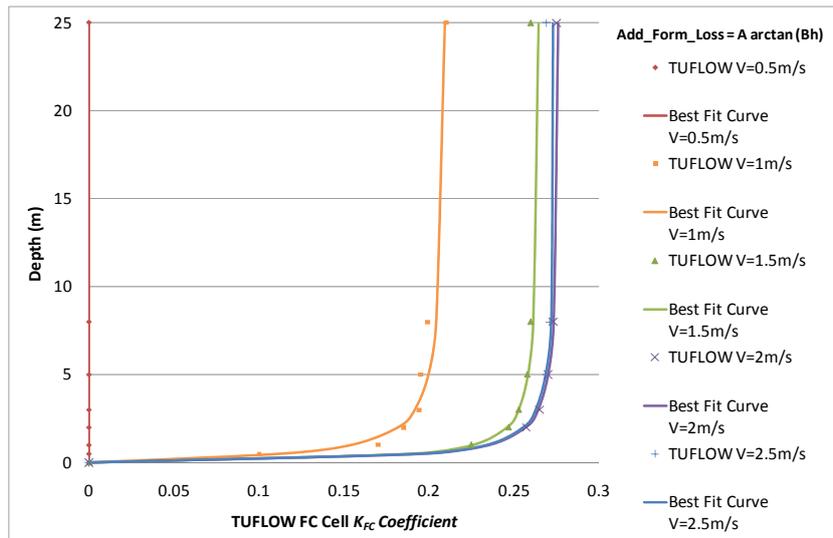


Figure 5 Discrete energy loss method's coefficient variation with depth and velocity.

Verification was also provided at intermediate depths and velocities, where the afflux predicted by the discrete additional energy loss coefficients corresponded to that predicted by the FHWA Δk_p direct method.

The initial tests using one pier only were extended to multiple pier configurations often encountered in infrastructure projects, and documented in FHWA (1978). Figure 6 presents how water level contours are affected around multiple piers perpendicular to the flow, and from skewed and dual structures. Each cell representing one of the multiple piers was discretised with the FC cell additional energy coefficient derived from Eq. (3). The comparison between the TUFLOW model results and the FHWA predictions showed that the discrete energy loss method was accurate to within 5% of the benchmark in all geometric and flow configurations. The testing process also highlighted that the dual structure energy loss depended on the distance between the pile bent columns.

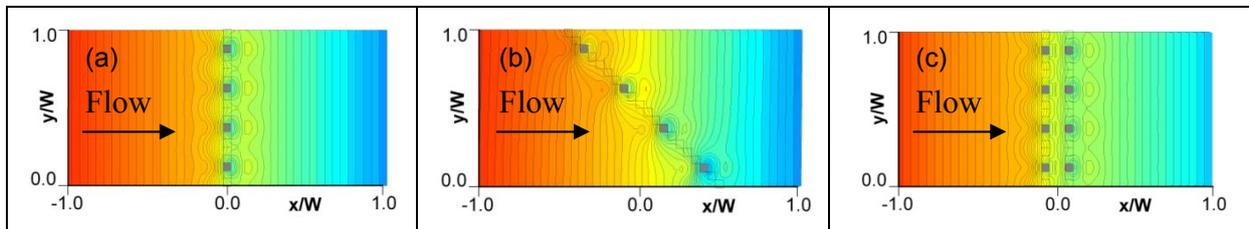


Figure 6 Impact of discrete energy loss method on 5mm water level contours (a) with multiple piers, (b) with skewed piers and (c) dual structures.

The TUFLOW discrete energy loss method was initially tested by Arup to demonstrate the validity of the modelling assumptions for the Airport Link project. As a result, most of the test cases are based on the geometric and flow characteristics encountered on the project (bridge pier, span, depth, velocity). However, once the results revealed the Arctan profile of the TUFLOW additional energy loss coefficient, additional geometric configurations were tested and the results confirmed the applicability of the Eq. (3), with updated polynomial coefficients, to the new scenarios.

In addition to the high-quality correlation between the TUFLOW discrete energy loss method and the FHWA benchmark flume predictions, the derived methodology was further validated through historical verification during the Airport Link project, and applied to its design.

4. AIRPORT LINK FLOOD MODELLING

Brisbane's Airport Link (AL) project is one of the largest and most expensive infrastructure projects

ever undertaken in Australia. The works comprise the construction of over 7km of new roadway, 6km of this being within tunnel, and four major interchanges.

The AL Southern Connection at Bowen Hills is situated in the heavily urbanised floodplain of Breakfast Creek. As part of the design joint venture, Arup led the flood impact assessment for the AL project and developed a 6km long advanced 2D TUFLOW model of Breakfast Creek to confirm the AL design's flood immunity and hydraulic impacts.

The Southern Connection consists of a complex elevated interchange that provides connectivity between the northbound AL tunnels, the Northern Busway and the recently opened CLEM7 tunnel. Between them, these projects involve the construction of over 400 piers, numerous embankments and extensive lengths of new road barrier within the floodplain of Breakfast Creek. A 3D view of the infrastructure elements at Bowen Hills is presented in Figure 7.



Figure 7 Perspective of the AL Southern Connection Layout.

As extensive areas of urban development are already predicted to be severely inundated in the upstream floodplain during the 100 year ARI flood, the control of flood conditions was paramount to the overall project design. The AL design investigated the management and mitigation of hydraulic impacts associated with not only the AL works, but also those of the Northern Busway and the CLEM7 tunnel. Prior to developing flood mitigation strategies, an accurate prediction of the afflux associated with each project was necessary. The geometric configuration of 400+ piers scattered over the creek and the floodplain fitted the application of the TUFLOW discrete energy loss method perfectly. The location of the piers compared to the 100 year ARI flowpaths is presented in Figure 8.

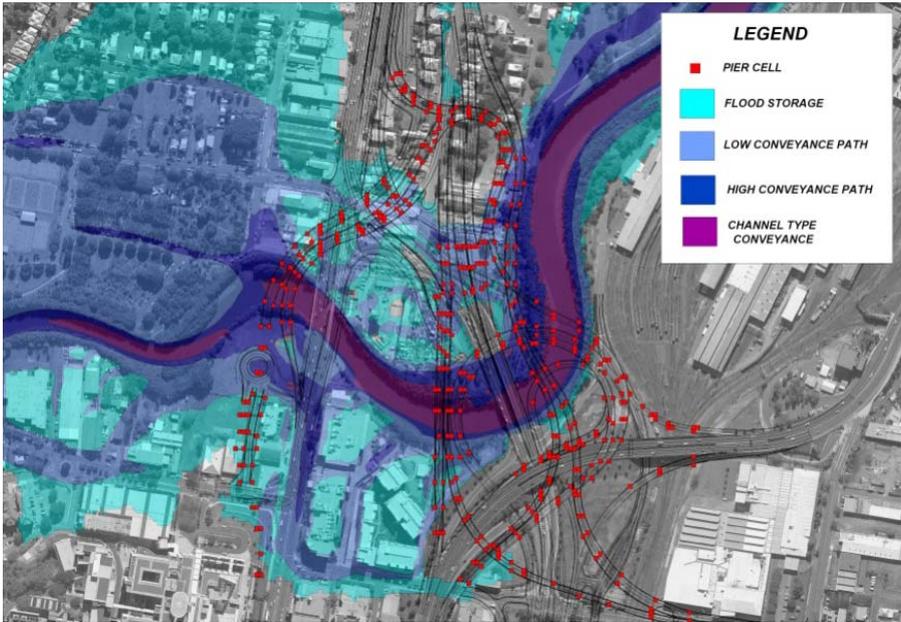


Figure 8 Location of AL Southern Connection piers in Breakfast Creek 100 year ARI floodplain.

All the model pier cells were discretised with the results of Eq. (3). A validation of the TUFLOW discrete energy loss methodology was made possible following the 19-20 May 2009 flood event on Breakfast Creek. Estimated at just under a 10 year ARI event, it was still the largest flood experienced in almost 40 years and at this magnitude was large enough to be affected by the already constructed CLEM7 piers, but with limited additional macro losses. The modelling of the historical event yielded excellent results when compared to numerous recorded flood marks upstream and downstream of the project area. The successful verification of the AL TUFLOW model using the FC cell discrete energy loss method further demonstrates the validity of this approach.

When applied to the full design, the discrete energy loss method showed that the afflux associated solely with the 400+ bridge piers was less than 50mm. It was also found that the majority of this afflux was attributable to approximately 10% of these piers i.e. those situated in zones of high conveyance. Mitigation strategies could then be developed and incorporated into the AL design to successfully alleviate the upstream hydraulic impacts.

When comparing the AL afflux predictions against previous preliminary 1D analyses, which predicted impacts of several hundred millimeters, the discrete energy loss method provides many benefits including an optimised mitigation design that ensures cost efficiency for the project.

5. CONCLUSION

Following the need to derive a methodology within TUFLOW, a popular and effective open channel flow 2D modelling package, to represent the micro energy losses generated by piers in the water column, Arup has reviewed the available theories and detailed a new applicable method. Named the discrete energy loss method, it uses a TUFLOW FC cell parameter (k_{FC}) to add a calibrated energy loss coefficient in parallel with a blockage at the cell representing the pier. The suitable value of the parameter was achieved through iterations on a flume type model replicating the US Federal Highway Administration's *Hydraulics of Bridge Waterways* (1978) guidelines. This calibration exercise encompassed a wide range of flood flow conditions typically encountered in fluvial rivers and floodplains. The result showed that k_{FC} followed a systematic variation with depth and velocity, which has been formulated in a set of equations. The method was validated for configurations of multiple piers in the flume model. It also provided predictions matching historical flood records along Breakfast Creek for the Brisbane Airport Link Southern Connection project, where it was applied to determine the hydraulic impacts associated with more than 400 new piers. The modelling accuracy reaped from applying the micro loss at the pier cell facilitated the development of flood mitigation strategies and significantly improved the design's effectiveness.

6. REFERENCES

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