SCOUR AT COMPLEX BRIDGE STRUCTURES – THE BENEFITS OF TWO-DIMENSIONAL HYDRAULIC MODELLING IN THE ESTIMATION OF SCOUR DEPTHS

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Abstract

Assessing scour potential at bridge structures is a complicated and subjective procedure. A number of methodologies for the prediction of bridge scour exist, which are generally expressed as functions of the hydraulic inputs (velocity, depth etc.); which are derived from hydraulic modelling of the bridge structure. At times, small variations in these hydraulic inputs can result in vast differences in scour depth estimates, often resulting in predicted scour depths which appear overly conservative for the expected flow behaviour at a particular bridge structure.

Traditionally, hydraulic inputs into scour equations have been derived from 1D hydraulic models of the bridge structure. However this approach can prove problematic in practice, particularly for situations which fall outside of the limitations of 1D modelling, such as at river bends, skewed bridge crossings or multiple bridge openings. In such situations, 2D hydraulic modelling can be utilised to generate more accurate estimates of the hydraulic inputs, and also for analysing the wider floodplain behaviour. On occasions, scour depths can be justifiably reduced by observing where peak flows and depths through a particular structure do not coincide (as can be the case with floodplain bridges) and amending the inputs into the applicable scour equations accordingly.

This paper reports on the methods employed for predicting scour depths at bridge structures where complex flow behaviour is expected, and illustrates the differences in deriving scour inputs from either 1D hydraulic models; or coarse resolution 2D models; and more accurate finer-resolution 2D models specifically developed for the hydraulic analysis of bridge structures. Examples contained herein have been taken from the detailed design stage of a recent infrastructure project with multiple bridge structures.

Introduction

The assessment of scour at bridge structures is an essential component for the design of new bridges over waterways. Scour is a major cause of bridge failure (Zevenbergen et al, 2012) and designing bridge structures to withstand anticipated scour is of vital importance. Even with well-established methodologies available (such as within HEC-18, 5th Edition, 2012), estimating scour depths remains a challenging exercise. Many of the widely-used scour methodologies have been developed based on laboratory flume studies, which model idealised flow scenarios. In practice, many bridges are located in settings in which flow behaviour is quite different from that assumed in the studies used to derive the scour equations. Consequently, care needs to be taken to ensure the hydraulic inputs adopted for estimating scour depths are representative of the expected flow conditions at the bridge structure being assessed, particularly as scour estimation methodologies can be quite sensitive to small changes in hydraulic variables.

Recent guidance has outlined the benefits that 2D hydraulic modelling offers for obtaining inputs for scour depth estimation compared with 1D models (Zevenbergen et al, 2012), particularly where complex flow behaviour is expected at a particular structure.

Advantages of 2D hydraulic modelling for estimating scour at bridge structures

Many bridges are difficult to represent in 1D hydraulic models (such as HEC-RAS) without significant assumptions needing to be applied to adequately represent flow behaviour through the structure. Examples include bridge structures at a significant skew to the direction of flow, and bridges that are located in floodplains (particularly where multiple openings are present).

2D modelling of these structures is considered to provide significant improvement in determining hydraulic variables at bridge structures over 1D hydraulic models (Zevenbergen et al, 2012). Notably, the horizontal variation in both velocity and flow depth can be viewed easily from the 2D modelling outputs, and the flow distribution through multiple bridge openings in the floodplain can be more accurately determined using 2D hydraulic models, without applying the assumptions usually required to model such structures using 1D methods. Flow direction can also easily be ascertained from 2D modelling, which is important in determining the angle of attack in calculating local pier scour.

An example of a structure where 2D modelling can provide significant benefit to obtaining scour inputs is seen in Figure 1. The alignment of this structure was at a significant skew to the predominant direction of flow in the water course resulting in the northern abutment being located approximately 150m downstream of the southern abutment. The flow behaviour differs across the upstream face of the bridge between the two abutment locations due to this skew. The southern abutment is located at a flow contraction, and consequently the model predicted that high velocities would occur near the southern abutment and the adjacent piers. However at the northern abutment, some expansion of flow had taken place from the upstream contraction, resulting in lower velocities adjacent to the abutment.

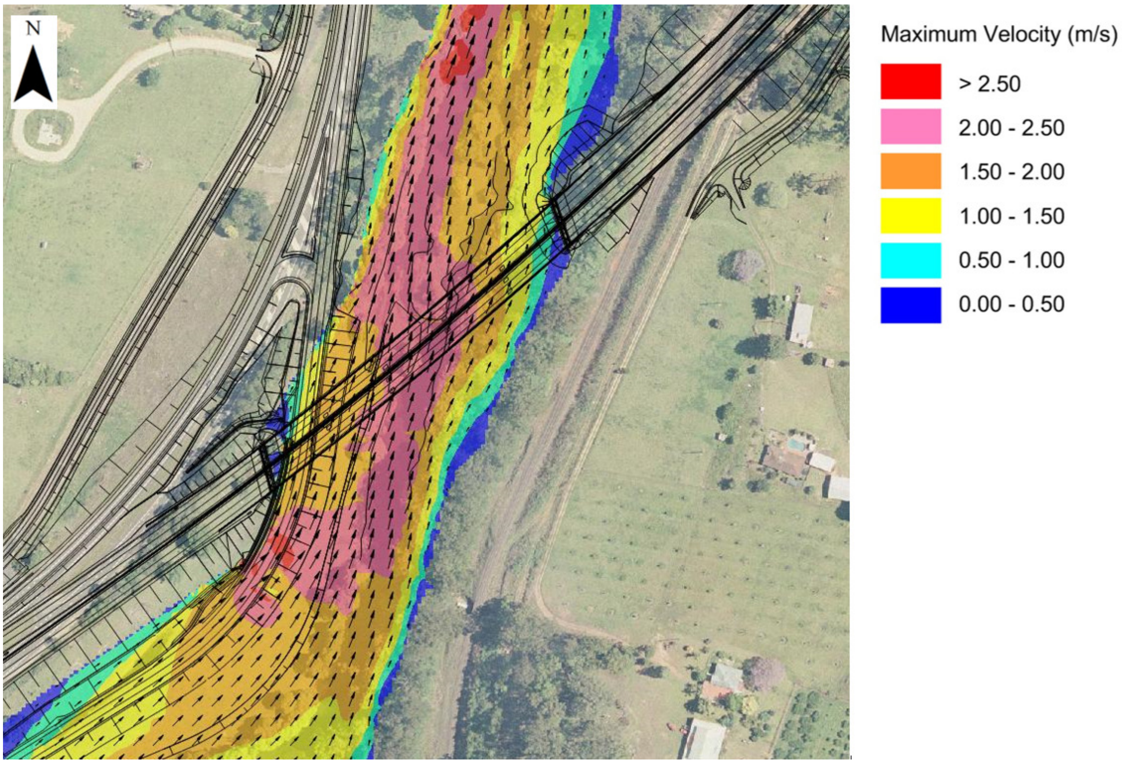

Figure 1 - Velocity distribution across a structure skewed to the flow

The velocity distribution through this structure can be more accurately represented using a 2D hydraulic modelling package such as TUFLOW, as opposed using 1D models. Flow distribution in 1D packages, such as HEC-RAS, is approximate and the water level would be assumed to be constant along the upstream face of the bridge. For the structure in Figure 1, TUFLOW would be able to capture the variation in both the velocity and the water level across the upstream face of the structure.

Due to the flow contraction, the highest velocities impacting this structure are predicted by the TUFLOW model to be at the southern abutment, and therefore the estimated abutment scour depths reflected this in the scour assessment for this particular structure.

The angle of attack of flow on the piers can also easily be determined by utilising flow vector outputs from the TUFLOW model. For modelling the above structure in 1D, the angle of attack would need to be estimated prior to running the model, which is not necessarily a straightforward task, particularly in floodplain areas.

2D hydraulic models can also be used to assess instances where peak flow depth and peak flow through the structure are not coincident. Analysis of the time series outputs can result in scour depth estimates being reduced to levels more commensurate with the peak velocities or flows through these structures. However care should be taken to ensure scour estimates account for a range of scenarios if the structure in question can be subject to variable flow behaviour.

2D model setup for assessing scour at bridge structures

Bridge structures can be modelled in several ways in 2D hydraulic models. Previous research has suggested that different methods will produce reasonably similar results provided that bridge form losses are applied in line with standard practise, even where the grid resolution is fairly coarse relative to the width of the structure (Ryan, 2013). For the purpose of obtaining hydraulic inputs for scour depth estimation, the model should be set up such that the variation in flow depth and velocity across the structure can be readily observed from the model outputs. Ideally the grid resolution should be sufficiently fine to capture the full variation of the depths and velocities across the structure.

In fixed-grid models, the grid orientation ideally should be such that the edges of the cells align with the face of the abutments of the proposed structure. Previous experience has shown that where this isn't the case, artificially high velocities can sometimes be observed where water gets "trapped" in the corners of the cells directly adjacent to the bridge abutments. This makes it difficult to extract reliable flow velocity estimates and therefore accurately assess scour potential at the bridge abutments. Where a sub-optimal grid orientation is unavoidable, reducing the cell size through the structure was observed to reduce this problem. Analysis of the full results files can also determine if high velocities adjacent to bridge abutments are a result of model instabilities, and can be used to help ascertain the true peak velocities.

Case studies

The benefits of 2D modelling for scour purposes from a recent infrastructure project are summarised in the following sections. For the comparisons below, the 2D hydraulic modelling was undertaken using TUFLOW "Classic" software, whilst 1D modelling was undertaken using HEC-RAS. The HEC-RAS model in the example below was initially built to verify the form losses through the structures, however it was subsequently considered to be sufficient for using the hydraulic outputs for scour analysis.

Scour depths presented have been determined using the methodologies available in HEC-18 5th Edition (2012).

Bridge 1

Bridge 1 is located at a significant bend of a major water course, as seen in Figures 2 and 3. The TUFLOW outputs show the main flow path to be at the northern end of the structure, with the peak velocities primarily impacting the northern abutment and the two northernmost piers. The flow within the right overbank area (facing downstream), near the southern bank of the river is acting as a storage area, and is not actively contributing to conveyance through the structure. Consequently the peak velocities in this region are generally low (< 0.5m/s).

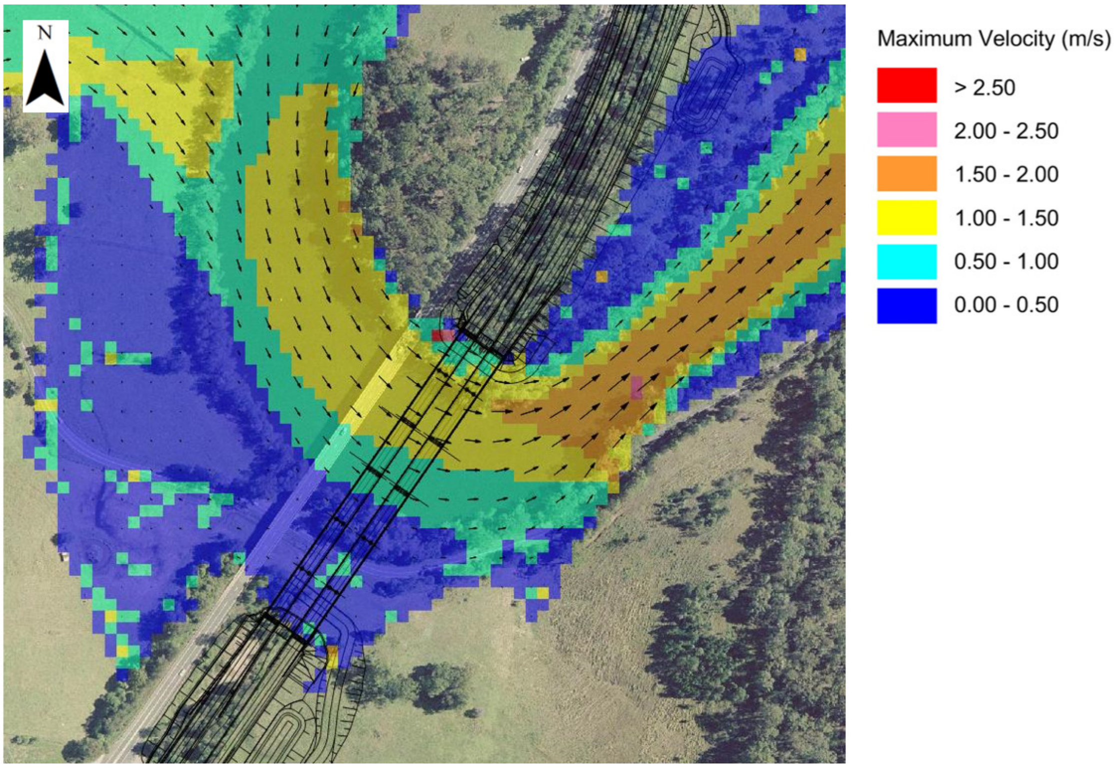

Figure 2 - Bridge 1 velocity distribution (TUFLOW – 100 year ARI event)

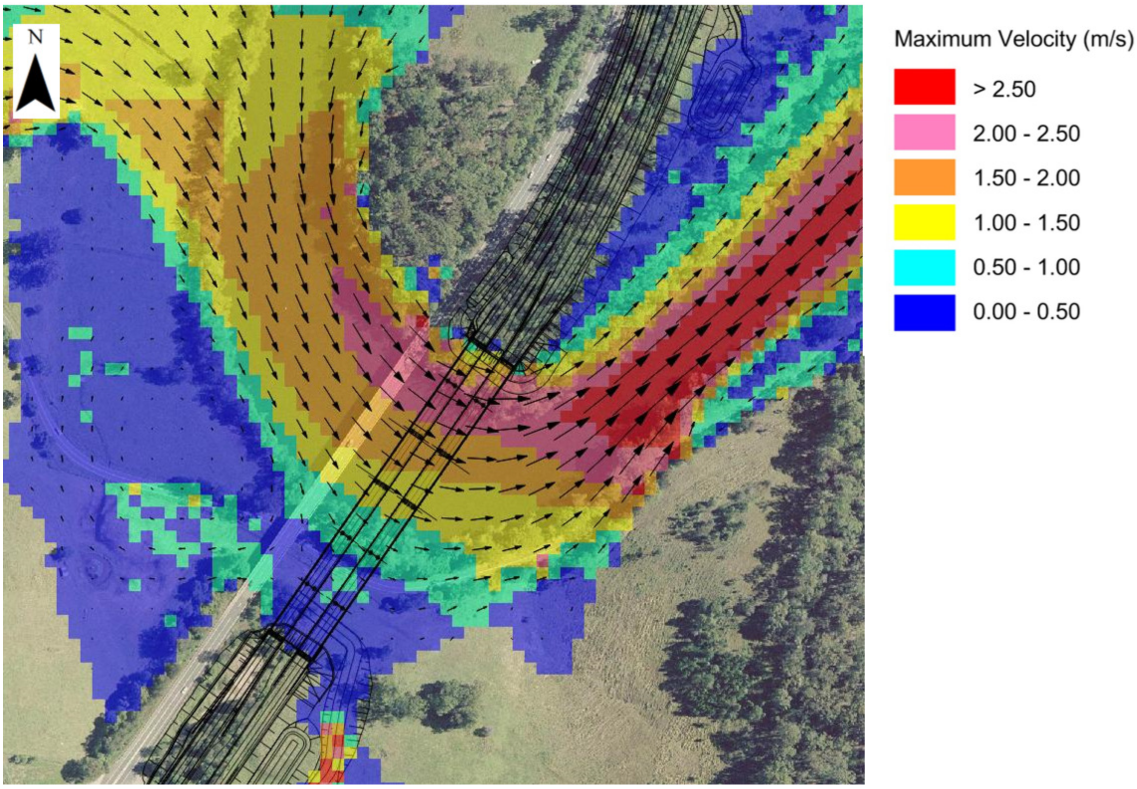

Figure 3 - Bridge 1 velocity distribution (TUFLOW – 2000 year ARI event)

The velocity distribution in the HEC-RAS model was noted to be different that from the TUFLOW model. Velocities in the left overbank area were estimated to be significantly lower in HEC-RAS than in the TUFLOW model, whilst velocities in the right overbank where estimated to be slightly higher. Figure 4 shows the average HEC-RAS velocities for both overbank areas and the main channel in the 100 year ARI event at the structure.

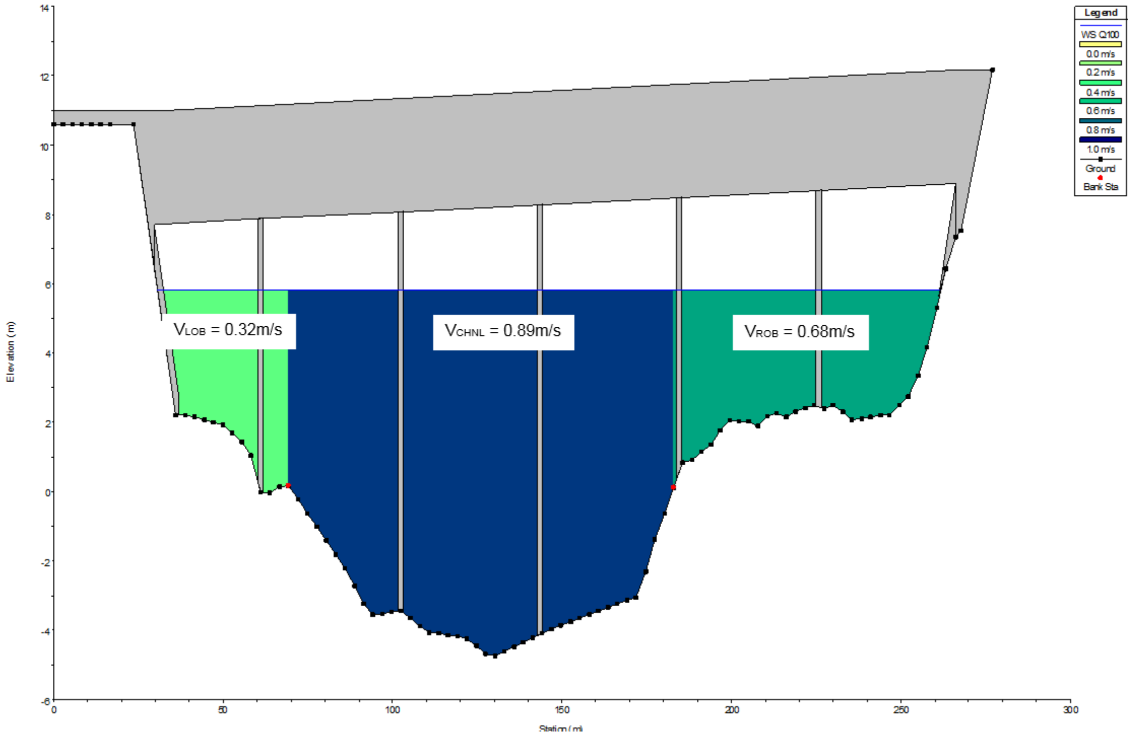

Figure 4 - Bridge 1 velocity distribution (HEC-RAS) – average velocities (100 year ARI event)

Peak flow depths and velocities are required as inputs for estimating the local scour component at piers. The flow distribution function was used to estimate the peak velocities in each area in HEC-RAS for computing the local pier scour component. The HEC-RAS estimated peak velocities are shown in Figures 5 and 6. In the 2000 year ARI event, the water level is predicted to impact the bridge superstructure, causing HEC-RAS to likely over-estimate the velocities in the right overbank.

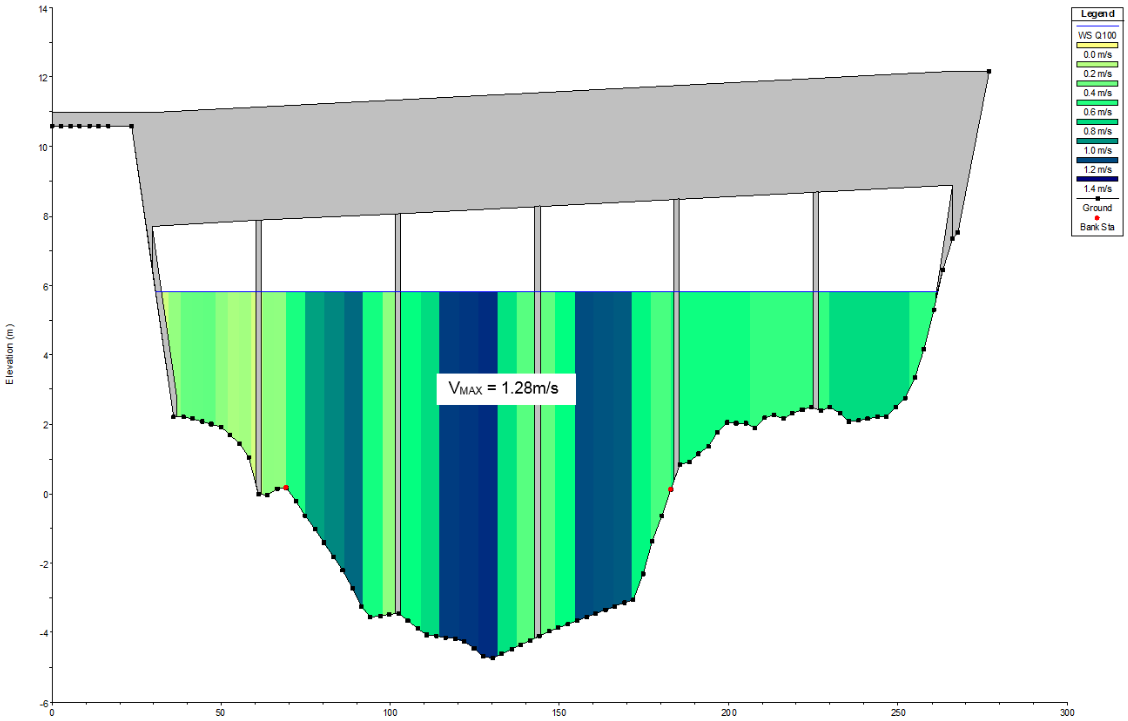

Figure 5 - Bridge 1 peak velocity (HEC-RAS - 100 Year ARI event)

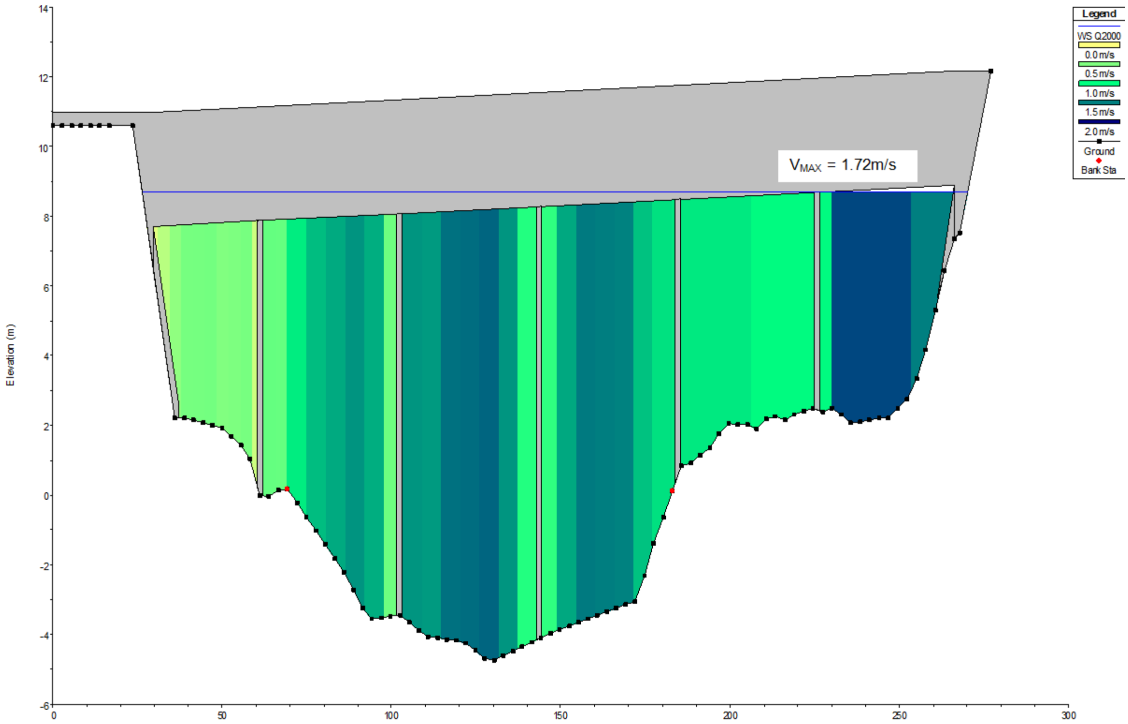

Figure 6 - Bridge 1 peak velocity (HEC-RAS - 2000 year ARI event)

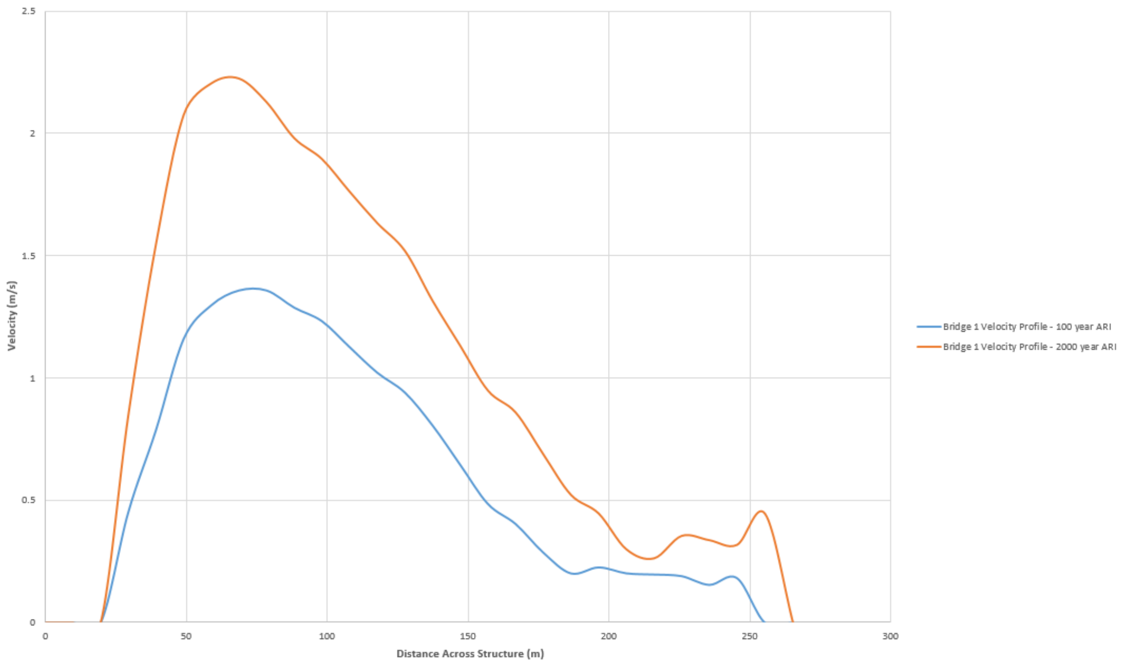

Figure 7 - Velocity profiles (TUFLOW) across Bridge 1

The velocity profiles are quite different between the TUFLOW and HEC-RAS models. The TUFLOW model results illustrate that the peak velocities are occurring close to the inside of the bend of the creek, with the peak velocity occurring near the northern end of the structure in both flood events. In the 100 year ARI event, the HEC-RAS model predicts that the peak velocities occur near the centre of the channel, and the flow velocity in the overbank area between the edge of channel and the northern abutment to be relatively small. In the 2000 year ARI event, the HEC-RAS model predicts the peak velocity to occur in the right overbank, although this is likely a consequence of the water level impacting the superstructure.

A comparison of the velocities from both models is given in Table 1.

Table 1 - Comparison of velocities from TUFLOW and HEC-RAS results

	100 year ARI event			2000 year ARI event		
	Left overbank	channel	Right overbank	Left overbank	Channel	Right overbank
Average velocity - HEC-RAS (m/s)	0.31	0.83	0.61	0.48	1.22	1.29
Peak velocity - HEC-RAS (m/s)	0.43	1.28	0.80	0.61	1.60	1.72
Peak velocity - TUFLOW (m/s)	1.38	1.38	0.61	2.24	2.24	0.63

Local pier scour depths were estimated using inputs from both the TUFLOW and HEC-RAS models, with the results shown in Table 2.

Table 2 - Comparison of local pier scour depths from TUFLOW and HEC-RAS results

	100 year ARI event			2000 year ARI event		
	Left overbank	Channel	Right overbank	Left overbank	Channel	Right overbank
Local pier scour depth - HEC-RAS (m)	1.76	3.03	2.11	2.11	3.45	3.10
Local pier scour depth - TUFLOW (m)	2.90	3.13	1.88	3.69	3.98	2.01
Difference (m)	1.14	0.10	-0.23	1.58	0.53	-1.09

In the left overbank (on the northern side), the estimated local pier scour depths are considerably higher when using the TUFLOW inputs, as opposed to inputs from HEC-RAS. This is reflective of the flow velocity outputs from the two models. It can be seen that if HEC-RAS results were to be used to compute the local pier scour depths, that the pier in the left overbank may have had the local pier scour component underestimated, whereas the local pier scour component for the piers in the right overbank area may have been overestimates, particularly in the 2000 year ARI event. The local scour depths for piers in the channel were also predicted to be slightly higher using the TUFLOW results.

It was considered that the TUFLOW model was likely to give scour depths more representative of the flow behaviour to be expected at this structure. The assumptions inherent in 1D modelling meant that it was difficult to obtain an accurate picture of the flow/velocity distribution across the structure using HEC-RAS, and hence the TUFLOW results were utilised in the scour assessment for this bridge.

Bridge 2

Bridge 2 is located in a large floodplain approximately 1km away from a major river crossing. In large flood events, water breaches the bank of the river and inundates the floodplain, therefore Bridge 2 was designed to provide connectivity across the floodplain during major flood events (refer to Figure 8).

Figure 8 - Location of Bridge 2 relative to river channel

The bridge was initially modelled using a grid resolution of 20 metres from the catchment wide regional model (refer to Figure 9). For the purposes of modelling this structure in isolation however, the coarse resolution of the model did not provide sufficiently accurate detail of the flow profile through the structure. A fine-resolution, 6 metre grid model was therefore developed for the purposes of assessing scour (refer to Figure 10).

The difference in the two velocity profiles can be seen in Figure 11. Whilst the peak velocity is relatively similar between the two models, the 6m grid results illustrate that the velocity is fairly similar across the whole section, whereas the 20m grid results suggest the velocity reduces somewhat at the right abutment.

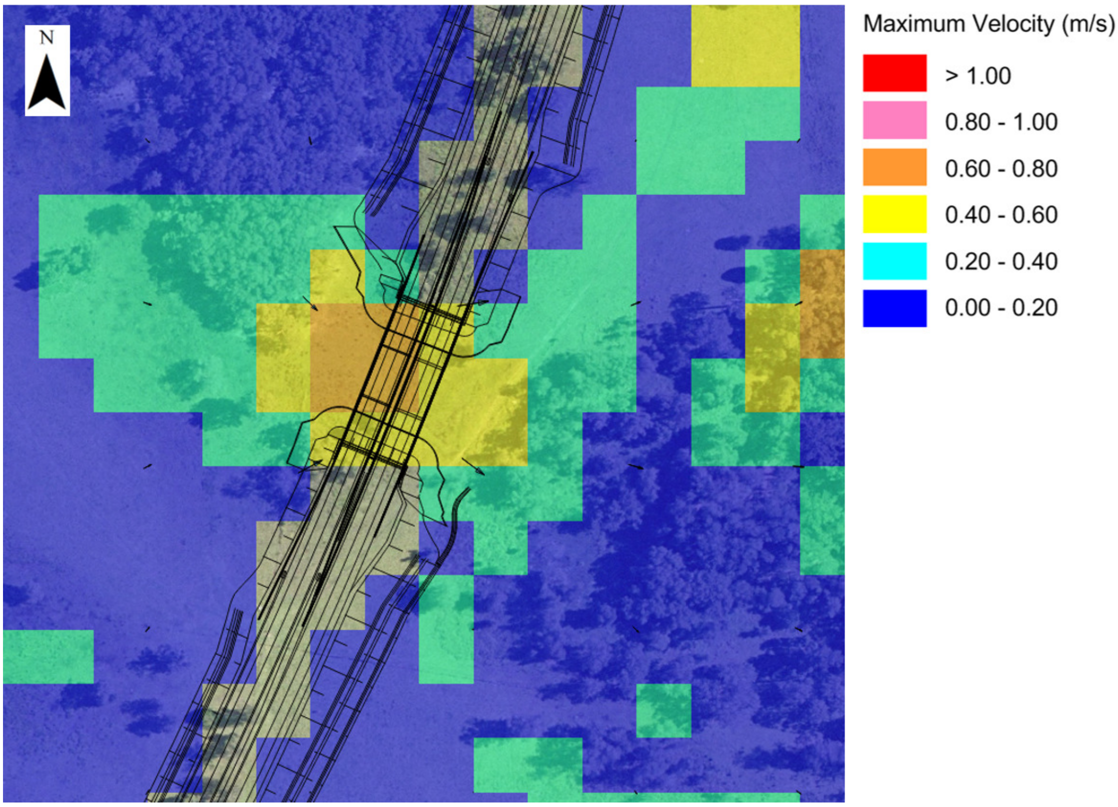

Figure 9 - Bridge 2 velocity distribution (100 year ARI event - 20m grid resolution)

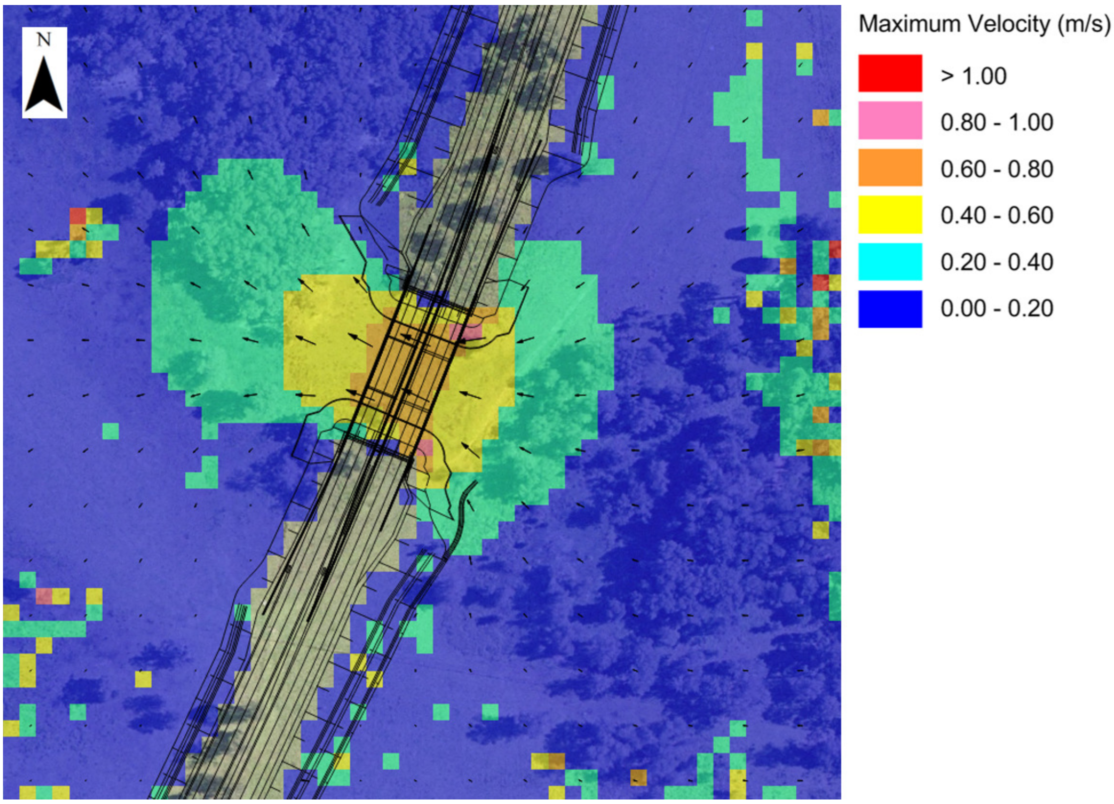

Figure 10 - Bridge 2 velocity distribution (100 year ARI event - 6m grid resolution)

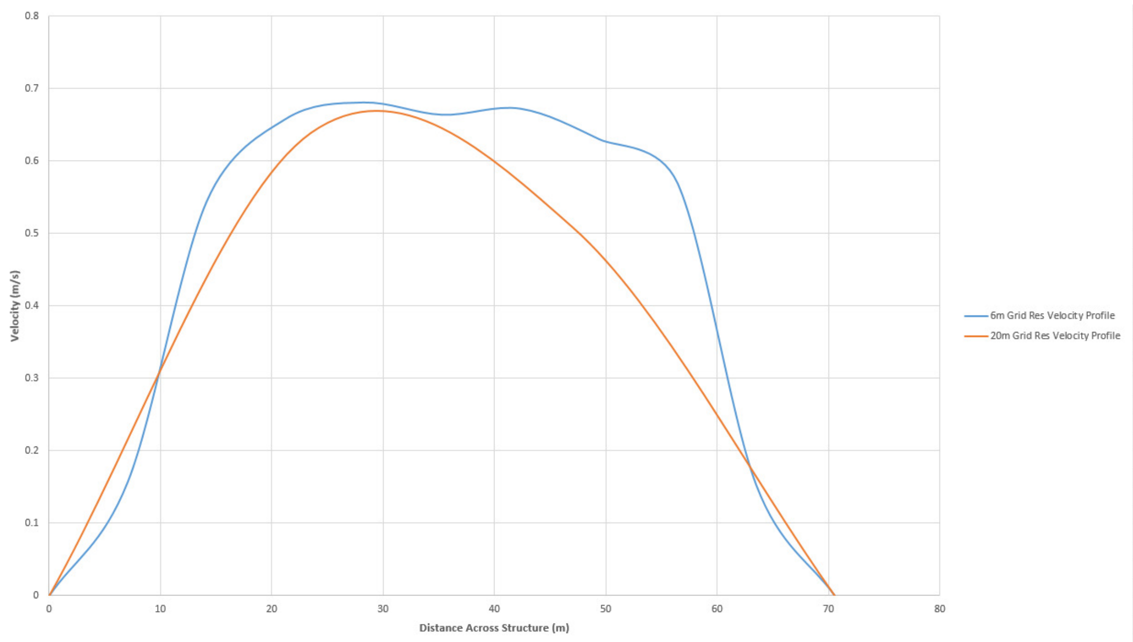

Figure 11 - Bridge 2 velocity profile comparison (100 year ARI event)

The 2D hydraulic modelling illustrated that water flows through the bridge structure in both directions over the course of a major flood event. The peak flows through the structure occur relatively early during the flood event, however the peak water level was not reached until much a later stage, at a point when flow (and velocity) through the bridge is much smaller. The implication on the scour estimates at this structure was that adopting the peak velocity/flow and peak depth combinations may overestimate the scour depths.

Initial estimates of the scour depths at Bridge 2 (adopting the peak flow and depth values assuming they occur concurrently) resulted in higher than expected scour depths. Time-series TUFLOW outputs were therefore analysed to determine the times of peak flow and depth through the structure. It was ascertained that the peak depth and peak flow through Bridge 2 did not occur concurrently (refer to Figures 13 and 14) and therefore there was potential the scour depths could be reduced by adopting inputs more representative of the flow conditions expected at the structure. Various scenarios were analysed to check which scenario resulted in the greatest depth of scour.

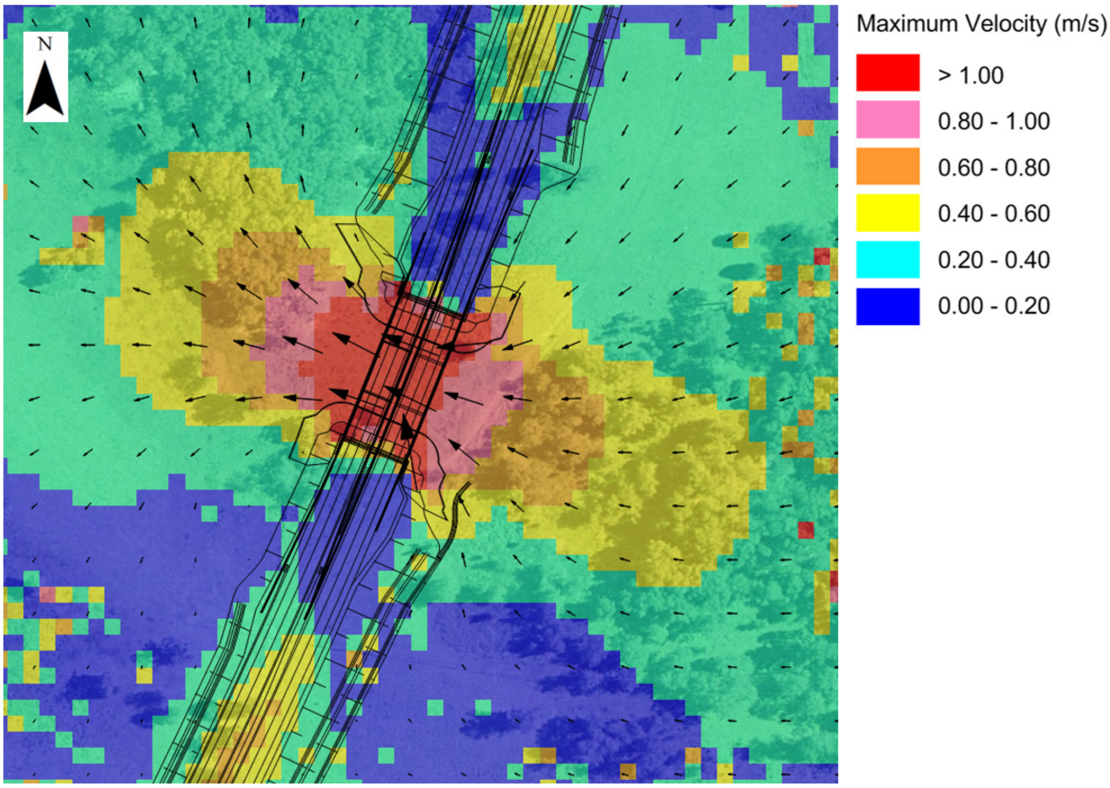

Figure 12 - Bridge 2 velocity distribution (2000 year ARI event)

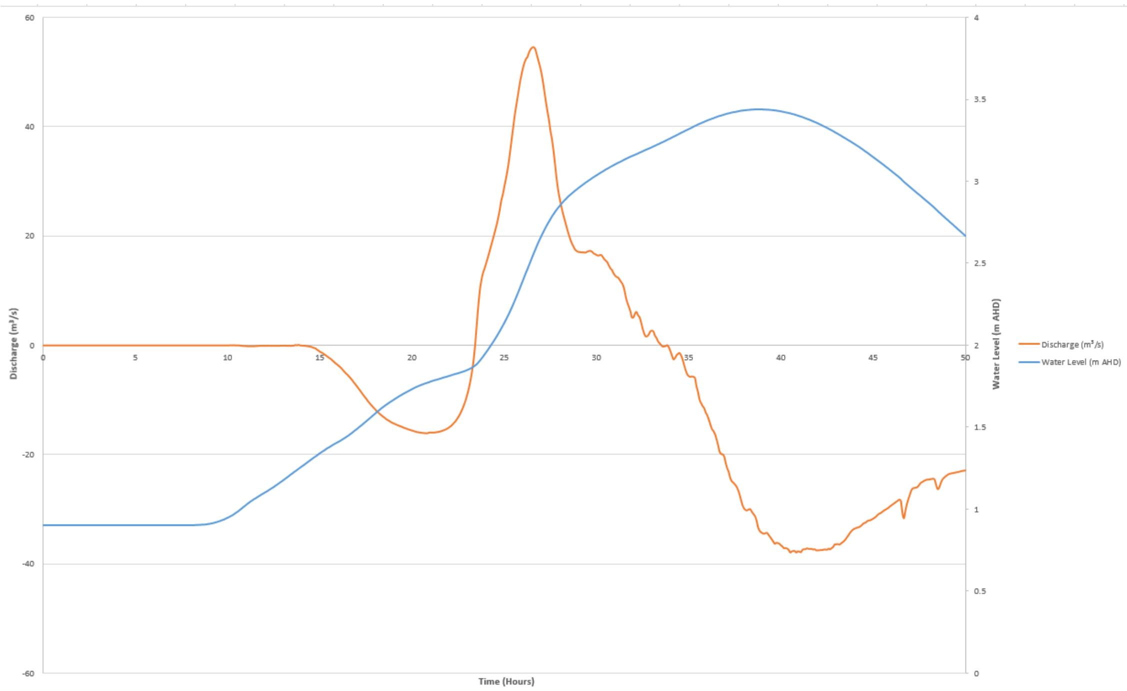

Figure 13 - Bridge 2 - Discharge and water level plots (100 year ARI event)

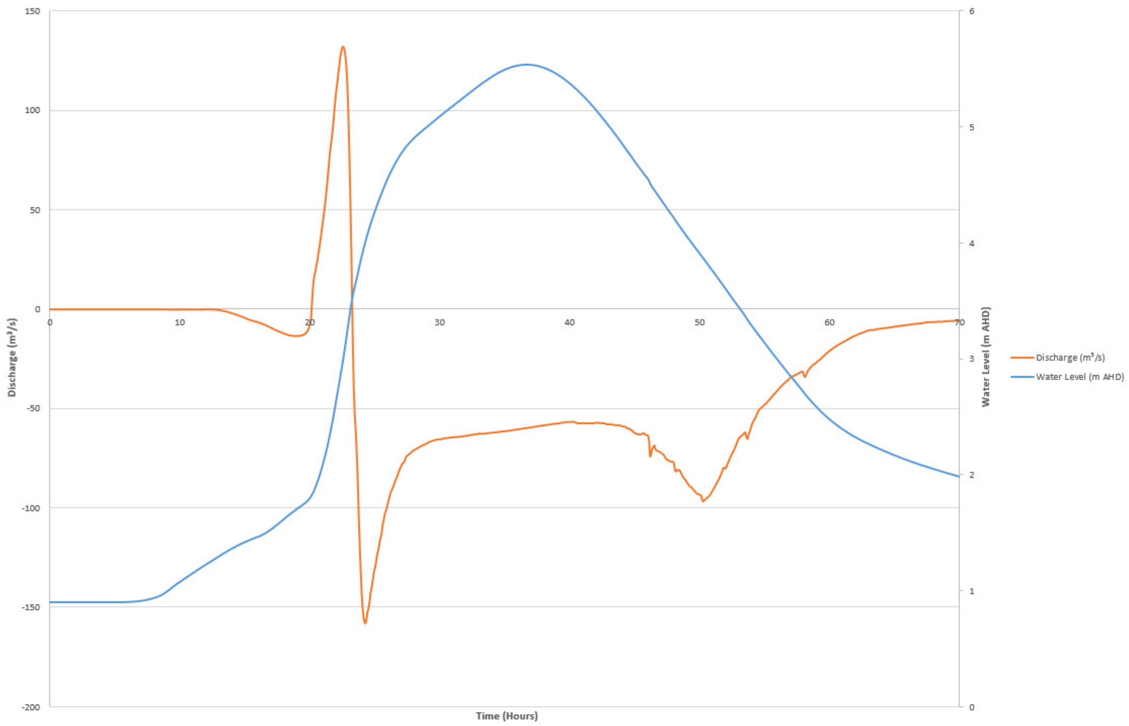

Figure 14 - Bridge 2 - Discharge and water level plots (2000 year ARI event)

Following assessment of the various flow/depth combinations that could potentially occur throughout the flood event, it was determined that the highest scour depth resulted at the occurrence of the peak discharge through the structure. The peak discharge occurred approximately 12 hours prior to the water level peaking, at a point at which the water level in the floodplain is still rising.

Table 3 illustrates the difference in estimated scour depths at the abutments in the 2000 year ARI event, resulting from adopting an average water depth likely to be expected at the occurrence of the peak flow through the structure, as opposed to adopting the peak average depth value directly from the TUFLOW outputs.

Table 3 - Bridge 2 - Comparison of abutment scour depths

	Peak value from model outputs	Value adopted for scour assessment
Discharge (m^3/s)	157.84	157.84
Average depth through structure (m)	4.29	3.45
Estimated scour depth at abutments (m)	7.91	5.74

By looking more closely at the model time-series outputs, a reduction in the estimated abutment scour depth was able to be achieved as it could be recognised that adopting the peak values would likely overestimate the scour depths. This illustrates one benefit of using TUFLOW over a steady state 1D model to assess scour. The structure would have been difficult to model even as an unsteady 1D model for the purpose of the scour assessment, due to the change in the flow direction during the flood event.

Conclusion

The use of 2D modelling for obtaining inputs for scour assessments is advocated in recent guidelines on scour analysis (Zevenbergen et al, 2012). With 2D hydraulic modelling now commonplace it is expected that the use of outputs from these models will increasingly be used to inform bridge scour assessments, particularly with further advances in scour prediction methodologies. The creation of finer resolution 2D models to obtain more accurate inputs for scour was observed to improve the accuracy of inputs for scour depth computations at bridges where complex flow behaviour can be expected.

Whilst 2D hydraulic models can potentially provide these benefits for undertaking scour assessment, whether the models are required to obtain accurate scour inputs should be considered on a case by case basis. Engineering judgement should be utilised by practitioners as to whether a 2D model is suitable for conducting a scour assessment for a particular structure. For some bridges, 1D hydraulic models can be considered sufficient for obtaining inputs for assessing bridge scour, however where these are used, care should be taken in analysing the wider flow behaviour around the relevant bridge structure prior to undertaking the scour assessment. Where 2D models are used, consideration should be given as to whether modifications are required to improve the accuracy of hydraulic inputs for the scour assessment, particularly if the model was initially created for a different purpose (e.g. wider catchment flood study). In extremely complex cases, computational fluid dynamics software packages or physical modelling may be the best means of obtaining accurate scour depth estimates.

Verification of the outcomes from the examples above through physical modelling would be of interest and potentially provide further guidance on how to approach scour estimation for structures where complex flow behaviour can be expected.

References

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