Backwater Effects of Piers and Abutments in 2D - Replication of Physical Model Tests in a 2D Hydrodynamic Computer Model

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November 2010

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Title :	Backwater Effects of Piers and Abutments in 2D - Replication of Physical Model Tests in a 2D Hydrodynamic Computer Model
Author :	Joel Gavin Leister (353049)
Synopsis :	This report documents the methodology and results of the research project into the backwater effects of piers and abutments in a 2D computer model. This report constitutes the final submission for 421-659: Research Project and has been undertaken as part of the Master of Environmental Engineering at the University of Melbourne.

REVISION/CHECKING HISTORY

REVISION NUMBER	DATE OF ISSUE	CHECKED BY		ISSUED BY	
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EXECUTIVE SUMMARY

Bridge embankments and structures can significantly influence flooding patterns and flood levels on floodplains. The literature (Austroads 1994; Bradley 1978) provides details of how to estimate contraction and expansion losses and pier losses of bridge embankments and structures for desktop analysis. However, limited guidance is provided as to the application of these losses in a 2D modelling environment.

The author undertook research to ascertain the accuracy of a 2D hydraulic model, TUFLOW, in calculating the energy losses associated with the contraction and expansion of flow through a constriction and to ascertain the most appropriate method/s for reliably modelling the energy losses associated with bridge piers. To undertake the research 2D model results were compared to physical flume test undertaken by Liu et al (1957).

The research involved the development of a series of flumes within TUFLOW that were used to simulate a number of scenarios that were modelled in a physical flume by Liu et al (1957). These scenarios included constriction widths varying between 2 and 6 feet, as well as a number of pier combinations involving square shaft, single shaft, double shaft and round-ended narrow pier types. The TUFLOW flumes were of varying grid sizes to test the model's ability to replicate the physical models results at varying grid resolutions. The afflux predicted by each of these scenarios within TUFLOW was compared to the results obtained from the physical flume tests.

The results from the analysis undertaken have shown that TUFLOW can, within reasonable bounds, reproduce the results of the physical model. Recommendations regarding the modeling of constrictions and piers within a 2D hydraulic model are made.

STATEMENT

This work has not been previously submitted for a degree or diploma in any university. To the best of my knowledge and belief, this report contains no material previously published or written by another person except where due reference is made in the report itself.

Joel Gavin Leister

BEnvEng

(Student Number 353049)

14/11/2010

ACKNOWLEDGEMENTS

The author would like to acknowledge the following people who have provided support and advice throughout this research project:.

- Dr Mark Jempson for his advice and guidance throughout the project;
- Dr Graham Moore for his assistance throughout the project;
- The staff and management of BMT WBM for their support and assistance; and
- Kerryn Leister for supporting me during the past 2 years of study and being there when I needed anything

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1 INTRODUCTION

Backwater calculations for bridge design in Australia are based primarily on the Austroads publication "Waterway Design – A Guide to the Hydraulic Design of Bridges, Culverts and Floodway" (Austroads, 1994). The section on bridge design is based on the publication, "Hydraulics of Bridge Waterways" (Bradley, 1978) resulting from work undertaken by Bradley for the National Highway Institute in 1978. The findings published in Bradley are based on a series of flume tests undertaken by Liu et al at the Colorado State University and documented in the publication "Backwater Effects of Piers and Abutments" (Liu, Bradley, & Plate, 1957).

The methods presented in Austroads (1994) are intended for desktop analysis techniques. No guidance is provided on the application of the losses in a 2D modelling environment. As 2D modelling is now relatively common, guidance on the use of the data available in Austroads (1994) and associated literature is needed within industry. Two cases in point are contraction and expansion losses and pier losses.

A 2D modelling scheme will inherently model the energy losses associated with contraction and expansion, but the reliability of the representation of the losses is dependent on the scale of the contraction relative to the model element size and the model's ability to replicate the energy losses associated with the varying scales of turbulence from sub-grid to larger than grid. There may be other modelling imperatives that dictate an element size that is too large to reliably represent the losses, in which case additional losses should be built into the model. The losses in Austroads (1994), which are presented as coefficients of velocity head, could be useful in this regard, but there is no basis for the modeller to make such a judgement.

In most situations the 2D model element will be larger than the pier width and so the 2D model will not reliably represent losses associated with piers. Therefore additional losses are normally applied to the 2D model. Austroads (1994) provides useful information in this regard in that pier losses are given as coefficients of velocity head. These coefficients can be applied directly to the 2D scheme but it is unclear if the losses should be applied to all elements across the width of the bridge and if element width should be reduced to allow for blockage.

The uncertainty regarding the modelling of structures in 2D hydraulic models has been highlighted by the work currently being completed on the revision to Australian Rainfall and Runoff as part of Project 15: Two Dimensional (2D) Modelling in Urban Areas.

The research documented herein aims to determine appropriate techniques for modelling energy losses associated with bridge constrictions and structures when using a two-dimensional (2D) hydraulic modelling scheme. Specifically, the following hypothesises will be tested:

1. That a 2D modelling scheme can reproduce, within reasonable bounds of uncertainty, the contraction and expansion losses associated with flow through a bridge opening as indicated by physical model tests undertaken by Liu et al (Liu, Bradley, & Plate, 1957); and

2. That the energy loss coefficients associated with bridge piers as reported in Liu et al can be applied in a 2D modelling scheme to reproduce, within reasonable bounds, the increase in water level reported by Liu et al.

This report documents the methodology and results from the research undertaken.

2 LITERATURE REVIEW

Hydraulic engineers have been exploring the behaviour of flow through constrictions since the late 18th century. Research undertaken in the early 20th century (including Yarnell (1934)) laid the groundwork for the study into the backwater effects caused by bridge abutments and piers. Up until the mid 1950's, the vast majority of research related to backwater effects had either been through mathematical methods or empirical methods (Liu et al, 1957). Liu et al (1957) provides a detailed summary of the work that has been undertaken in relation to backwater effects up until the mid 1950's.

The work by Liu et al (1957) undertaken at Colorado State University in cooperation with the US Department of Public Roads, was the first major piece of research undertaken where the backwater effects of abutments of piers were studied with flume tests. The research undertaken by Liu et al (1957) involved completion of over 1400 flume tests that analysed a series of abutment and pier types and configurations. The outcomes from this research were a series of graphs that can be utilised for the determination of "maximum backwater and the differential level of water surface across the embankment" (Liu, Bradley, & Plate, 1957). To the knowledge of the author, the results obtained by Liu et al (1957) have never been replicated through the use of 2D hydrodynamic model.

The research by Liu et al (1957) and work subsequently undertaken by Mattai (1976) formed the foundation for the publication, 'Hydraulics of Bridge Waterway' by Bradley (1978), which has become the industry standard for use in the determination of backwater caused by bridges. Whilst utilising the data collected by Liu et al (1957), Bradley also utilised numerous field observations and measurements obtained by the United States Geological Survey (USGS) in developing the practical design charts, procedures and examples contained within the publication. There is no advice contained within Bradley (1978) as to application of design charts and associated loss coefficients to either 1D or 2D hydraulic models. Bradley (1978) was adopted as the basis for the AUSTROADS (1994) publication, 'Waterway Design - A Guide to the Hydraulic Design of Bridges, Culverts and Floodways' which is considered to be the Australian guidelines for bridge design.

Numerous studies have been undertaken to determine a 1D model's ability to simulate the backwater caused by a bridge constriction (Seckin, Yurtal, & Haktanir (1998); Crowder, Pepper, Whitlow, Sleigh, Wright, & Tomlin (2004); Seckin & Atabay (2005); Sowinski (2006); Seckin, Haktanir, & Knight (2007); Seckin, Knight, Atabay, & Seckin (2008); Atabay & Seckin (2009); and numerous other studies). These studies have been limited to the validation of 1D models (or the calculation methods contained within) against experimental/laboratory data (flume tests) or methods presented in literature (primarily Bradley (1978)). Consequently, the ability of the various 1D model schemes available to represent the backwater caused by a bridge constriction is relatively well understood.

In more recent times, work has been undertaken in order to improve the understanding of a 2D model scheme's ability to represent the backwater effects of a bridge constriction. This research commenced in the mid 1980's, but has become more prevalent over the last 10 years as 2D hydraulic model schemes have become the industry standard for flooding (both fluvial and tidal) investigations.

Syme et al (1998) undertook some testing of different 2D model schemes in order to assess their ability to represent head loss through hydraulic structures. A variety of software packages, including

TUFLOW, Mike21, FESWMS and RMA, were assessed using a test model to determine their respective performance through a horizontally constricted and then a vertically constricted test model. Whilst Syme et al (1998) have demonstrated that “2D schemes adequately predict the head loss across a horizontal flow constrictions when compared to the theoretical calculations”, “a comparison between 2D schemes and physical model results would be highly worthwhile” (Syme, Nielson, & Charteris, 1998). Syme et al (1998) also states that a number of other factors, including model timestep, model resolution and viscosity formulation will impact upon the model’s prediction of backwater due to a hydraulic structure.

Barton (2001) sought to address the “perceived lack of understanding in the ability of 2D models to portray the energy losses associated with the turbulent nature of water flow” (Barton, 2001) through a contraction. In a particular, Barton (2001) studied the ability of two hydrodynamic models, TUFLOW and RMA2, to represent flow through an abrupt constriction using a variety of spatial representations. The research presented by Barton (2001) provided “confirmation that the spatial resolution of 2D models does have an impact on the ability of these models to predict energy losses due to turbulent effects” (Barton, 2001). One of the key outcomes of Barton (2001) was the comparison of energy losses predicted by the 2D models (TUFLOW and RMA2) when compared to some 1D models (Mike11 and HEC-RAS) and the values presented in literature (AUSTROADS (1994). Barton (2001) showed that a large amount of variability exists between the results derived from both the literature and the 1D model schemes. The challenge faced by Barton (2001) was a lack of a suitable standard for which to compare the tested 2D model schemes to. The research currently being undertaken hopes to address this lack of a suitable standard (as discussed by Barton (2001)) by attempting to validate the 2D hydraulic model, TUFLOW, to physical flume test data.

Syme (2001), although not specifically focussed on the determination of backwater from hydraulic structures, discusses a number of important points in relation to the way a 2D model will account for form loss through a structure. Syme (2001) discusses 2D model performance in relation to water surface profiles around a bend, through a box culvert and over a weir through the comparison of results to a 1D scheme. “The 1D approach typically uses special structure flow equations requiring specification of contraction and expansion loss coefficients”, however, “this approach is not applicable or readily applied in the 2D schemes” (Syme, 2001). Consequently, Syme (2001) recommends that “on-going research and testing of 2D models to develop guidelines for adjustment of form loss related parameters when modelling hydraulic structures in 2D” (Syme 2001) should be undertaken. Syme (2001) also recommends that there should be the “establishment of guidelines and standard tests (preferably based on experimental results) for validation of 2D schemes” (Syme 2001).

Syme et al (2009) discusses that for complex structures, like a bridge with abutments and piers, “the modeller relies on judgment as to the energy losses that occur” (Syme, Jones, & Arneson, 2009). Syme et al (2009) describes how the 2D modelling scheme will inherently model some of losses associated with the expansion and contraction of flow through the structure and hence the pure application of loss values for literature (eg Bradley, 1978) would actually over-estimate the loss through a structure. Syme et al (2009) suggests that “the dilemma for the modeller is how much additional energy losses should be applied when using a 2D scheme” (Syme, Jones, & Arneson, 2009). Throughout the paper, Syme et al (2009) discusses the need for additional research into the application of loss coefficients from the literature in the 2D modelling environment. Syme et al (2009) also discusses a number of other factors that will influence the ability of the 2D hydraulic model to simulate the flow through a constriction, including the work undertaken by Barton (2001) and Syme

(2001). The outcomes from the current research will inform the modeller how much additional form loss will be required to account for the loss not inherently modelled by the 2D scheme. It is expected that the additional loss required will be dependent upon the model resolution and constriction width.

Craven (2009) undertook some research that aimed to help guide modellers as to the amount of ‘extra’ form loss that would need to be applied when modelling structures in TUFLOW, a 2D hydrodynamic model. The work by Craven (2001), compared the results obtained from TUFLOW (a 2D scheme) with those from HEC-RAS and CES-AES (both 1D schemes), as well as the results expected from the literature (Austroads, 1994). The research undertaken by Craven (2001) showed that the results from the TUFLOW model varied when compared to those from AUSTROADS (1994) and consequently additional research into the application 2D form losses in a TUFLOW model is recommended. Particular emphasis is placed upon the varying afflux achieved when the model grid size is varied (implications of grid size are also discussed in detail in Barton (2001)), and the variation that was observed between the 1D and 2D model results. The research suggests that a “major limitation of this study was the fact that no field or experimental data was used to verify TUFLOW afflux predictions” (Craven, 2009). This limitation will be overcome with the current research whereby the flume tests undertaken by Liu et al (1957) will be replicated in the TUFLOW hydrodynamic model. This will enable a better understanding of how the values presented in literature (Bradley (1978) and Austroads (1994)) can be applied to a 2D hydrodynamic model and in particular TUFLOW.

The review of the available literature has indicated that although vast amounts of previous research has been undertaken in the area of the backwater effects due to bridge constrictions, there is a need for further study. Further study (as suggested by Craven (2009), Seckin & Attabay (2005) and Syme (2001) in the area of model validation against experimental (flume test) data and the understanding of how the loss coefficients presented in the literature should be applied to a 2D model is of particular importance.

The research documented in this report has sought to address some of the gaps identified by the available literature and to help improve the understanding of how a 2D hydraulic model can reliably predict the afflux due to the presence of a hydraulic structure in a given floodplain.

3 METHODOLOGY

The computer modelling of the test flume used by Liu et al (1957) was undertaken using the hydraulic modelling package TUFLOW (BMT WBM, 2008). TUFLOW is a two-dimensional finite difference model that uses the 2D Shallow Water Equations to determine the water surface. The TUFLOW model is based upon a regular square grid of uniform elements that each contains information regarding the surface roughness (Manning's 'n' value) and topography.

The analysis was undertaken in three parts, broadly:

- Calibration of the test flume under normal flow conditions;
- Determination of the afflux due to the constriction of an abutment; and
- Determination of the afflux due to the presence of piers in the flowpath.

The results from each of these three analyses were compared to the results obtained from the physical flume, as presented in Liu et al (1957) in order to determine the ability of TUFLOW to reproduce, within reasonable bounds, the results of the physical flume.

These three components of the research are described in more detail in the subsequent sections.

The work by Liu et al (1957) was undertaken using imperial measurements (feet and inches), whilst TUFLOW relies on metric dimensions. Consequently, both imperial and metric dimensions are used throughout the description of the methodology.

3.1 Base Case

3.1.1 The Test Flume

The test flume used by Liu et al (1957) was 73.5 feet (224.2 metres) long, 7.9 feet (2.4 metres) wide and 2 feet (0.6 metres) deep. The longitudinal slope and surface roughness (Manning's 'n' value) of the test flume were able to be changed depending upon the test that was being undertaken. For the flumes used in this analysis, the slope was either 0.0012 m/m or 0.002 m/m and the roughness was described as either bar (Manning's 'n' of 0.024) or baffle (Manning's 'n' of 0.045). The flume used by Liu et al (1957) is represented diagrammatically in Figure 3-1.

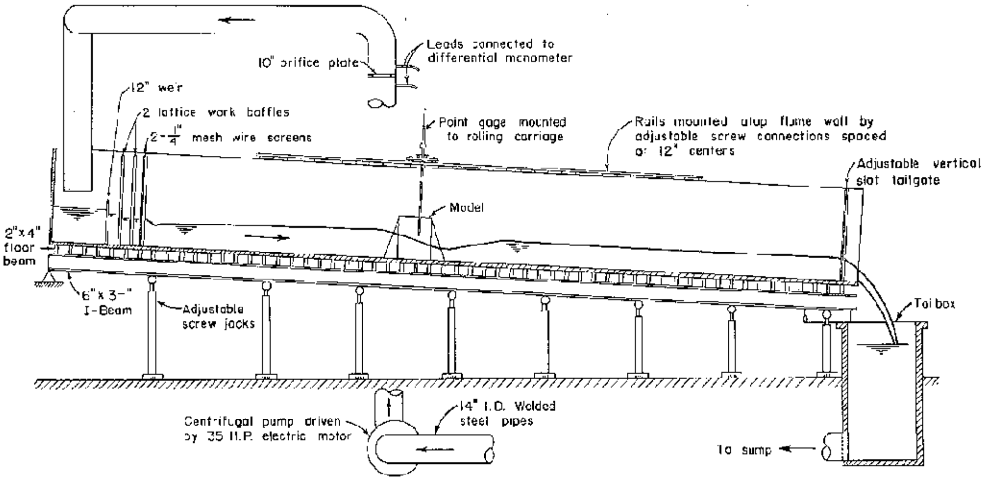


Figure 3-1 The Physical Flume used by Liu et al (1957)

The flow rate was varied between 2.5 cubic feet per second (cfs) (70.79 litres/second (l/s)) and 5 cfs (141.58 l/s) and for each test case; normal flow was achieved within the test flume.

One of the objectives within this research was to determine the influence of grid size on TUFLOW's ability to reproduce the afflux from a given constriction. Consequently, a number of test flumes were created in TUFLOW using a variety of different element (grid) sizes. In total, 9 test flumes were set up, each using a different element size. These tests flumes are named according to the number of elements across the width of the flume (Table 3-1) and displayed diagrammatically in Figure 3-2.

Table 3-1 TUFLOW flume details

Flume Name	Element Size (inches)	Element Size (metres)
RP03	31.60	0.803
RP04	23.70	0.602
RP05	18.96	0.482
RP06	15.80	0.401
RP08	11.85	0.301
RP10	9.48	0.241
RP12	7.90	0.201
RP15	6.32	0.161
RP20	4.74	0.120

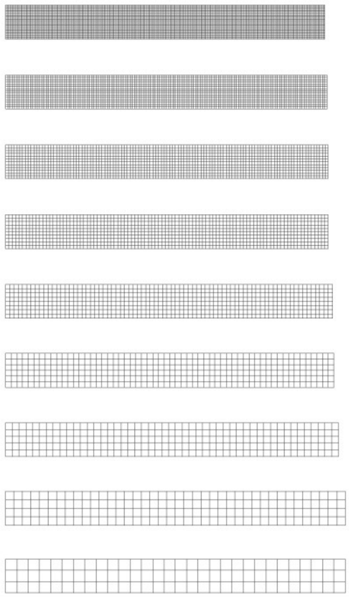


Figure 3-2 Varying element sizes of the TUFLOW flume

Model elements larger than 0.803 metres were not considered in this analysis as a number of the constrictions to be tested would have been smaller than the element size. Such constrictions would be deemed as ‘sub-grid scale’ and are best modelled using a 2D-1D linked model, in which the constriction would be modelled as part of the 1D scheme. Whilst numerous hydraulic modelling packages are capable of linking 1D elements to the 2D domain (TUFLOW included), such an analysis was beyond the scope of this research project.

Model elements finer than 0.120 metres were not considered in this analysis due to the expected depths within the flume expected to significantly exceed the element width. The work by Barton (2001) and the advice of BMT WBM (2008) indicate that caution must be used when the modelling involves a fine grid and deep water as the model may start to violate the assumptions of the 2D shallow water equations and result in erroneous solutions.

Nine individual flume scenarios were required to be modelled, as these models provided the basis for all future abutment and pier test models.

Table 3-2 Base Case Flume Scenarios

Scenario Name	Flowrate (cfs)	Roughness	Slope	Normal Depth (ft)
E01	2.50	Bar	0.0012	0.333
E02	2.5	Baffle	0.0012	0.523
E08	2.72	Baffle	0.002	0.478
E09	3.0	Bar	0.0012	0.360
E17	5.0	Bar	0.0012	0.484
E18	5.0	Baffle	0.0012	0.718
E19	5.0	Bar	0.002	0.416

The results from the base case flume calibration are presented in the results section of this report.

3.2 Abutment Tests

The abutment flume tests were based upon eight of the base case flume models. In total 40 abutment tests were undertaken which modelled five constrictions ranging in width from 2 feet to 6 feet. Each of the tests was conducted on the TUFLOW flumes which consist of 9 individual flumes of varying element size. The aim of these tests was to determine the influence of element size versus constriction width when determining the afflux, and more importantly, does TUFLOW replicate, within reasonable bounds, the results from the physical flume tests.

The constriction was modelled by varying the topography to create an opening in the flume of the required size. In each of the tests, a feature of TUFLOW known as a flow constriction (FC) was utilised. A flow constriction within TUFLOW allows the user to modify the properties of a given element to reduce the available flow width and therefore model a partially blocked cell (BMT WBM 2008).

Figure 3-3 shows the use of both topography modification and flow constrictions to model the required opening within the test flume. In this figure, the brown triangles located in the centre of flume show where the topography of the flume has been modified to represent the vertical board obstruction that is used to represent the abutment. The red squares indicate the cells that have had a flow constriction applied to reduce the available flow width of the these cells to match the modelled opening within the abutment.

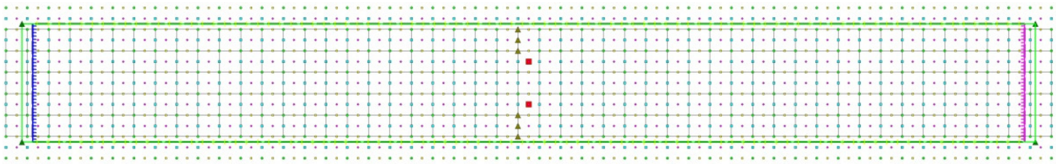


Figure 3-3 Model Schematisation for Abutment Test

3.3 Pier Tests

The pier tests were undertaken using two distinct methods to determine their applicability in the determination of the afflux as a consequence of the presence of piers. The pier tests were undertaken on piers only and did not include any influence of significant abutment constrictions or the presence of a bridge deck, both of which would be of importance in any real-world analysis.

A number of different pier types, including square shaft piers, round-ended narrow piers, single shaft piers and double shaft piers, were analysed using a number of the flumes modelled as part of the base case calibration. The pier were tested in a number of different configurations of pier size and pier numbers as documented in the various tests undertaken by Liu et al (1957).

The pier tests were undertaken using three different methodologies; the use of form loss coefficients (two methods) and the blockage (or partial blockage) of elements containing piers. Both of these methodologies are documented in the subsequent sections of this report.

For all piers, other than the square shaft piers, only Method One and Method Two were used. This is due to the fact that the rounded faces of all the other piers types would not have been effectively modelled by the process used in Method Three.

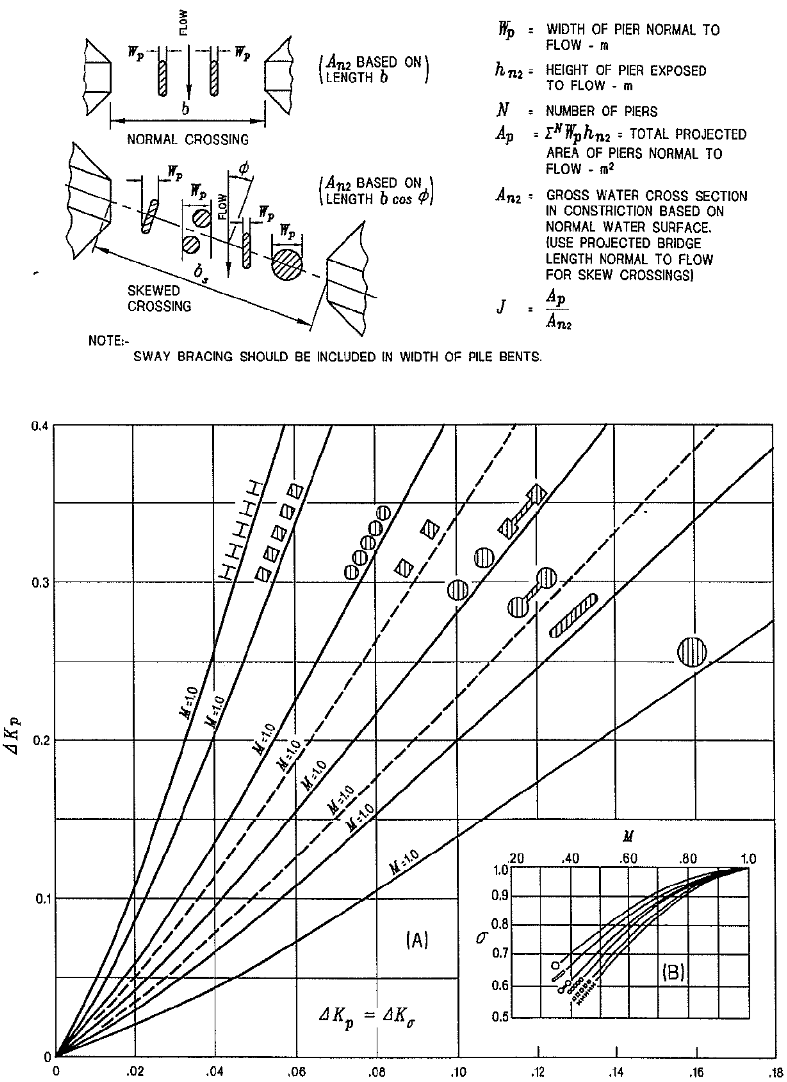
3.3.1 Method One (Form Loss Coefficients – Option One)

Austroads (1994) documents the methodologies to determine backwater coefficients due to the presence of bridges in a floodplain. Specifically, it documents the methodology to determine the incremental backwater coefficient due to the effects of piers present in the flowpath and has been re-produced below:

> *Backwater caused by the introduction of piers in a bridge constriction is treated as an incremental backwater designated ΔK_P, which is added to the base curve coefficient. The value of the incremental backwater coefficient, ΔK_P, is dependent on the ratio that the area of the piers bears to the gross area of the bridge opening, the type of piers, the value of the bridge opening ratio, M, and the skew of the piers to the direction of flood flow. The ratio of the water area occupied by piers, A_P, to the gross water area of the constriction, A_{n2}, both based on the normal water surface, is assigned the letter J. In computing the gross water area, A_{n2}, the presence of piers in the constriction is ignored. The procedure is to enter chart A on* Figure 3-4 *with the proper value of J and read ΔK, and then obtain the correction factor, σ, from chart B for the opening ratios other than unity. The incremental backwater coefficient is then $\Delta K_P = \sigma\Delta K$.*
>
> *Austroads (1994)*

The methodology as described above was used to determine ΔK_P values for each of the pier flume tests undertaken. These ΔK_P values were applied to the TUFLOW model through the use of a form loss coefficient. The form loss coefficient is applied as an energy loss based on the dynamic head equation below:

$$\Delta \boldsymbol{h} = \Delta \boldsymbol{k_P} \frac{\boldsymbol{V^2}}{\boldsymbol{2g}} \qquad \textbf{Equation 1}$$



(Figure 5.7, Austroads, 1994)

Figure 3-4 Backwater Coefficient Base Curves (Subcritical Flow)

Whilst Figure 3-4 shows the backwater coefficient base curve, it does not include a curve that could be applied to a single square shaft pier. In order to determine the curve for a single square pier, the ratio between the twin circular and single circular piers was determined and applied to the twin square piers. This resulted in a curve located between the single circular pier and the round-ended narrow pier. It is likely the form loss coefficients determined from this curve will not be as accurate as those determined for the other piers and may result in some degree of inaccuracy in the results from the square pier analysis.

The derived form loss coefficients were applied across the entire width of the flume (as shown in Figure 3-5). This method does not discretely model each individual pier; rather it treats the blockage caused by the piers in a holistic manner across the entire cross section of the bridge. In Figure 3-5, the light blue diamonds indicate the cells to which the form loss coefficients have been applied.

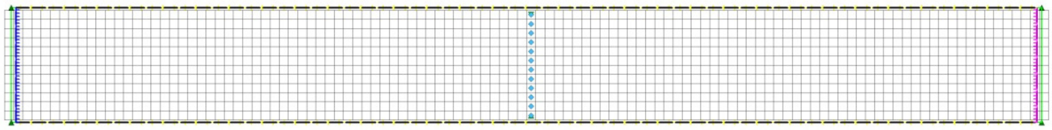


Figure 3-5 Model Schematisation for Pier Models (Method One)

3.3.2 Method Two (Form Loss Coefficients – Option Two)

Method Two is almost identical to the method previously described; however, it differs in one key component. This method applies the form loss coefficients (as calculated using the process described in section 3.3.1) only to the cells that would contain a pier. In some models, depending on the number of piers and the size of the grid cell, this would result in the same model as developed as part of Method One. In other models, however, the number of cells to which the form loss coefficient is applied would be reduced and some cells would have no form loss coefficients applied to them.

Figure 3-6 shows the same flume setup as presented in Figure 3-5; however, as per Method Two, the form loss coefficients have only been applied to the cells that contain a pier. Consequently, there are cells across the width of the flume that do not have any form loss coefficients applied due to no pier being present in the element (grid).

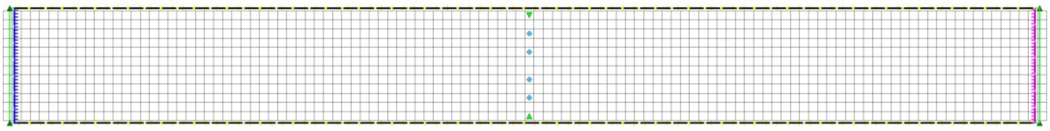


Figure 3-6 Model Schematisation for Pier Models (Method Two)

For some of the flume tests there was no difference between Method One and Method Two due to number of piers within the cross section and the number of elements across the width of the flume. For example if 20 piers existed within the cross section, then there would be no difference between the two methods as each cell in all TUFLOW flumes would have included a pier.

3.3.3 Method Three (Blocked and Restricted Model Elements)

This method utilises flow constrictions (as previously described) to model the blockage of each individual pier. No additional form loss coefficients have been applied and hence this method is designed to model the contraction and expansion of the flow around the piers.

Individual flow constrictions have been determined to represent the piers that fall within a particular model element. At the larger grid sizes, this will result in multiple piers within a single element and the given flow constriction would represent multiple piers. However, at the smaller grid sizes, there will be flow constriction representing a single pier and elements will exist where no pier influence will be evident.

The schematisation of Method Three is identical to that of Method Two (Figure 3-6), however, instead of a form loss coefficient being applied to an individual cell, a flow constriction is applied. As discussed previously, a flow constriction is used to reduce to the available flow width of the cell and in this case, the individual cells have had their respective flow width reduced dependent upon the size and number of piers that is located within the given element.

4 RESULTS AND DISCUSSION

For each flume test, TUFLOW produced a geo-referenced data set detailing water surface levels, depths and velocity throughout the entire model domain (all 9 flumes) at the corner of each computational cell. These water levels, depths and velocities were extracted from these cell corners (known as h-points) and were used to generate the results presented in the subsequent sections.

4.1 Base Case

4.1.1 Test Flume Calibration

Once the various test flumes had been set up in TUFLOW, they were calibrated to the results observed in the original physical model tests. The models were initially run using the same parameters as determined by Liu et al (1957). The results from these initial runs are documented in Table 4-1.

Table 4-1 Initial Flume Calibration Results

Run ID	Normal Depth (m) (Liu et al, 1957)	Normal Depth obtained from TUFLOW (across all 9 test flumes)		
		Mean (m)	Median (m)	Standard Deviation
E01	0.101	0.097	0.097	0.00
E02	0.159	0.141	0.141	0.00
E08	0.146	0.127	0.127	0.00
E09	0.110	0.108	0.108	0.00
E17	0.148	0.147	0.147	0.00
E18	0.219	0.214	0.214	0.00
E19	0.127	0.126	0.126	0.00

As seen in the results of the initial flume runs (Table 4-1), TUFLOW under predicted the normal depth. Whilst this may seem to indicate that TUFLOW is unable to reproduce the results o the physical flume test, it actually highlights an issue between the physical model and the flume that has been set up in TUFLOW.

The Manning's 'n' value that was documented in Liu et al (1957) has been back-calculated using Manning's equation for each of the flume tests undertaken. This back-calculated Manning's 'n' value has been influenced by the friction loss experienced by the flow against the side walls of the flume.

TUFLOW does not account for the friction loss caused by the flow against the side walls of the flume. Consequently, to enable TUFLOW to replicate the normal flow depths observed in Liu et al (1957), a higher Manning's 'n' value would be required. The increase required is dependent upon the flow rate, flume slope and flume roughness, in other words, the terms that make up Manning's equation. The Manning's 'n' values that are needed to reproduce the normal depth documented by Liu et al (1957) are presented in Table 4-2 and Table 4-1 has been replicated as Table 4-3 to show the normal depths obtained by TUFLOW when using these revised values of Manning's 'n'.

Table 4-2 Calibrated Manning's 'n' values

Run ID	Manning's 'n' value (Liu et al, 1957)	Required Manning's 'n' value
E01	0.024	0.0258
E02	0.045	0.0550
E08	0.045	0.0565
E09	0.024	0.0248
E17	0.024	0.0244
E18	0.045	0.0468
E19	0.024	0.0244

Table 4-3 Initial Flume Calibration Results

Run ID	Normal Depth (m) (Liu et al, 1957)	Normal Depth obtained from TUFLOW (across all 9 test flumes)		
		Mean (m)	Median (m)	Standard Deviation
E01	0.101	0.101	0.101	0.000
E02	0.159	0.159	0.159	0.001
E08	0.146	0.146	0.146	0.000
E09	0.110	0.110	0.110	0.000
E17	0.148	0.148	0.148	0.000
E18	0.219	0.219	0.219	0.001
E19	0.127	0.127	0.127	0.000

4.2 Abutment Tests

4.2.1 Influence of Viscosity Coefficient

TUFLOW, by default, uses the Smagorinsky viscosity formulation to model the eddy viscosity which is used to approximate the effect of sub-grid scale turbulence. The work of Barton (2001) showed that the spatial resolution of a 2D model does have an impact on the ability of the model to predict the energy losses due to turbulent effects (Barton 2001).

A series of abutment tests were simulated within TUFLOW to determine the influence of the viscosity coefficient. The tests were undertaken using viscosity coefficients of 0.1, 0.2 (the default) and 0.4 and were all run using the Smagorinsky viscosity formulation. The results from one of these tests, in this case using a 5 foot opening, as presented in Figure 4-1.

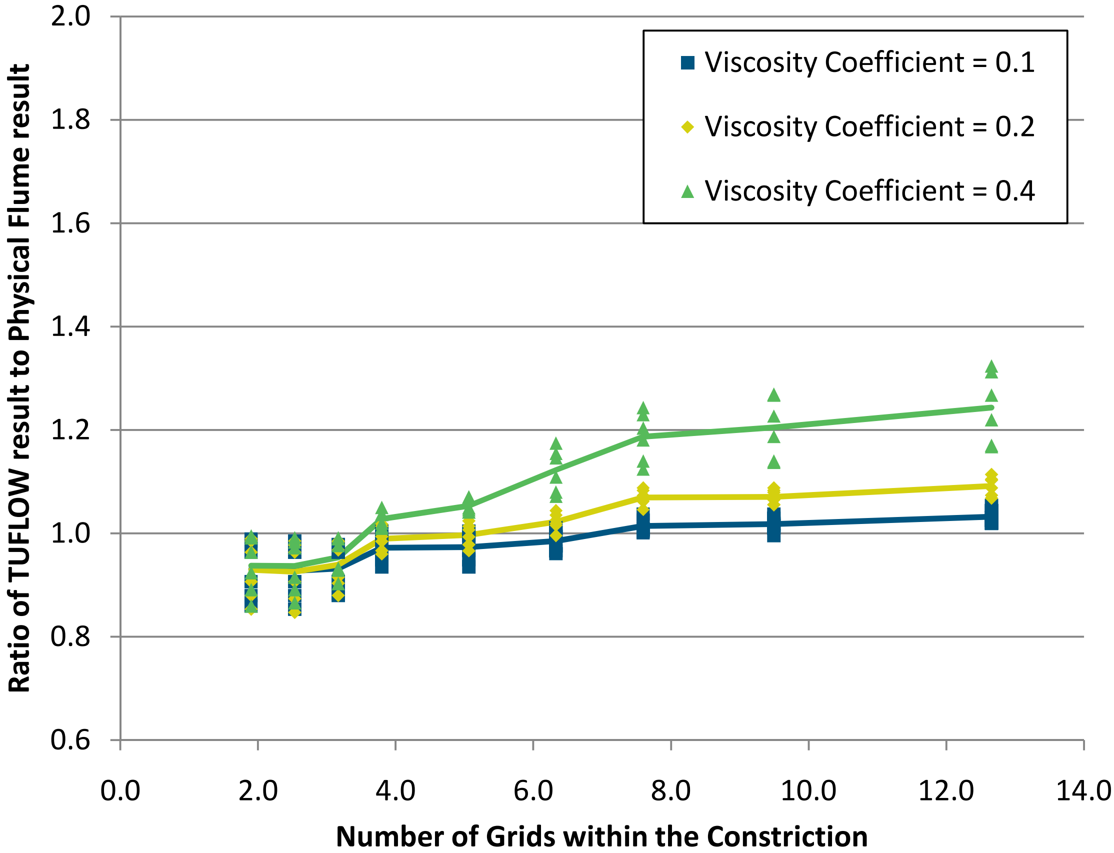


Figure 4-1 Influence of Viscosity Coefficient

The results from these tests indicate that the viscosity coefficient has minimal influence over the model's predictive performance when the models are on a large grid (the left hand side of the figure). However, as the model's grid size becomes finer, the results using the different viscosity coefficients start to diverge. The spread of values appears to increase as the viscosity coefficient increases, and this is particularly evident for the fine grid scale models (the right hand side of the figure).

These results are not surprising. As the grid becomes finer relative to the scale of the turbulence the model inherently represents more of the losses and hence relies less on the viscosity formulation and so a small coefficient is required. For the current modelling, these results suggest the adoption of a viscosity coefficient equal to 0.1 would be appropriate to obtain a better match between the predictive results of TUFLOW and the recorded results of Liu et al (1957), especially at a fine grid scale.

These results are consistent with those of Barton (2001) and BMT WBM (2008) that indicates caution should be used when using very fine grids as the influence of the viscosity term can be particularly relevant.

A viscosity coefficient equal to 0.1 was adopted for the current research. This coefficient is different to that recommended in BMT WBM (2008), however, the model results support its use in this research. Additional research would be advantageous to confirm the applicability of the current TUFLOW default viscosity coefficient of 0.2 in a number of flow conditions, including the contraction and expansion of flow through a constriction.

4.2.2 Abutment Analysis

The results from the abutment tests were plotted to determine the influence of two components of the blockage on TUFLOW's predictive ability. The first of this components was the influence of the number of grids contained within the constriction (Figure 4-2) and secondly the influence of the number of grids adjacent to the blockage (Figure 4-6).

In each of these figures, the plotted points can be used to determine some details about the particular scenario being modelled. The squares, diamonds, triangles, circles and dashes correspond to models with a 2 foot, 3 foot, 4 foot, 5 foot and 6 foot constriction opening respectively, whilst each colour indicates a series of models running under the same set of conditions (inflow, slope, roughness).

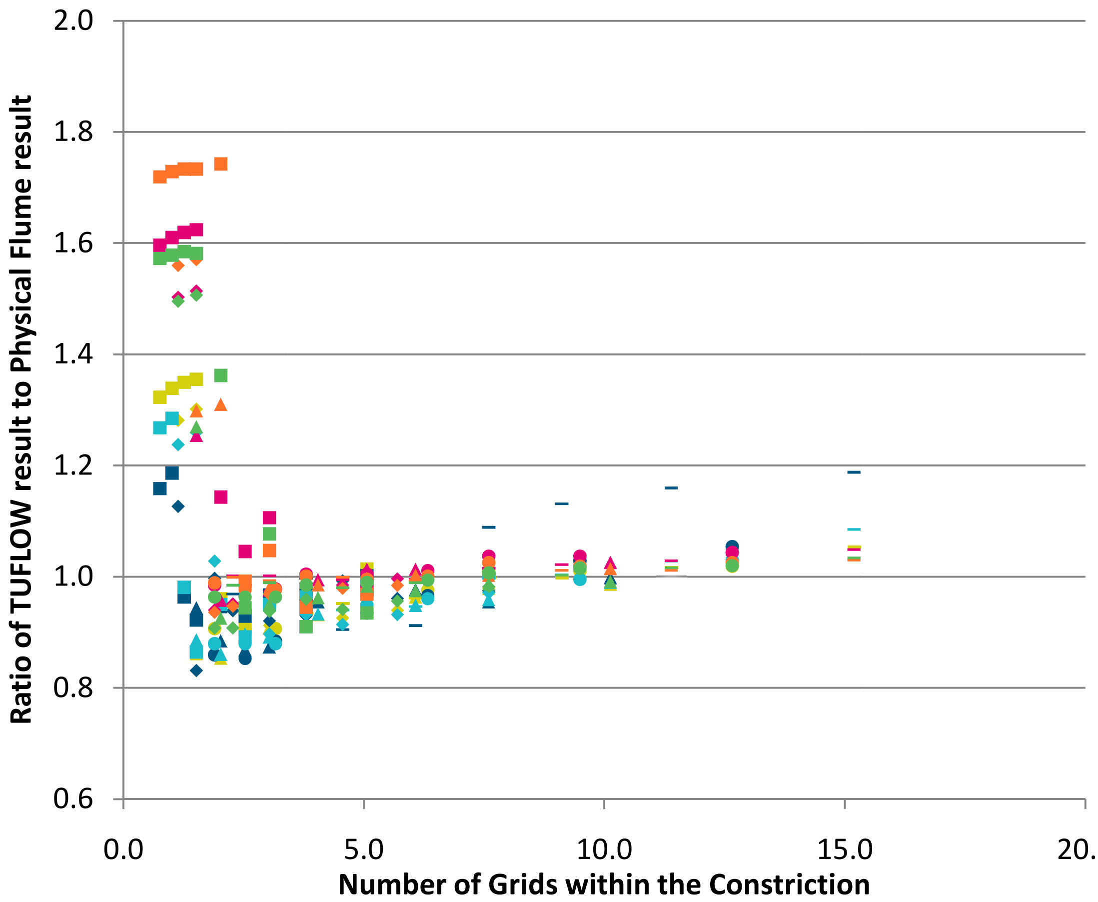


Figure 4-2 Abutment Analysis – Influence of Grid: Constriction Ratio

These results suggest that once 6 elements exist within the constriction, the TUFLOW models will, within reasonable bounds, replicate the results recorded in Liu et al (1957). It was thought that the main influence on the model's ability to replicate the afflux would be related to its ability to represent the sub-grid scale turbulence. Whilst the model will never fully be able to represent the sub-grid scale turbulence due to limitation within the viscosity formulation, the representation of this turbulence would improve with finer grid scales. However, the expectation that at a large grid size, the TUFLOW model would under-predict the afflux when compared to the physical model is not supported by the results shown in Figure 4-2

Figure 4-2 suggests that models with less than 2 grids within the constriction will result in a poor correlation to the afflux determined by the physical flume model (TUFLOW results in a higher afflux). As seen in this figure, the models with poor correlation were generally simulating either a 2 foot or 3 foot opening, suggesting that there may be other factors influencing the results, rather than simply the representation of the sub-grid scale turbulence through contraction and expansion of the constriction.

A subset of Figure 4-2 is shown in Figure 4-3 and is displaying the results from the flumes with a 3 foot opening only. This figure clearly demonstrates the poor predictive performance of TUFLOW for a number of the flume tests when on a large grid scale. Figure 4-3 (and Figure 4-2) shows that as the grid size decreases, the model's predictive performance improves. It also highlights that, as mentioned previously, there are other factors influencing the results when the flume has a large grid size.

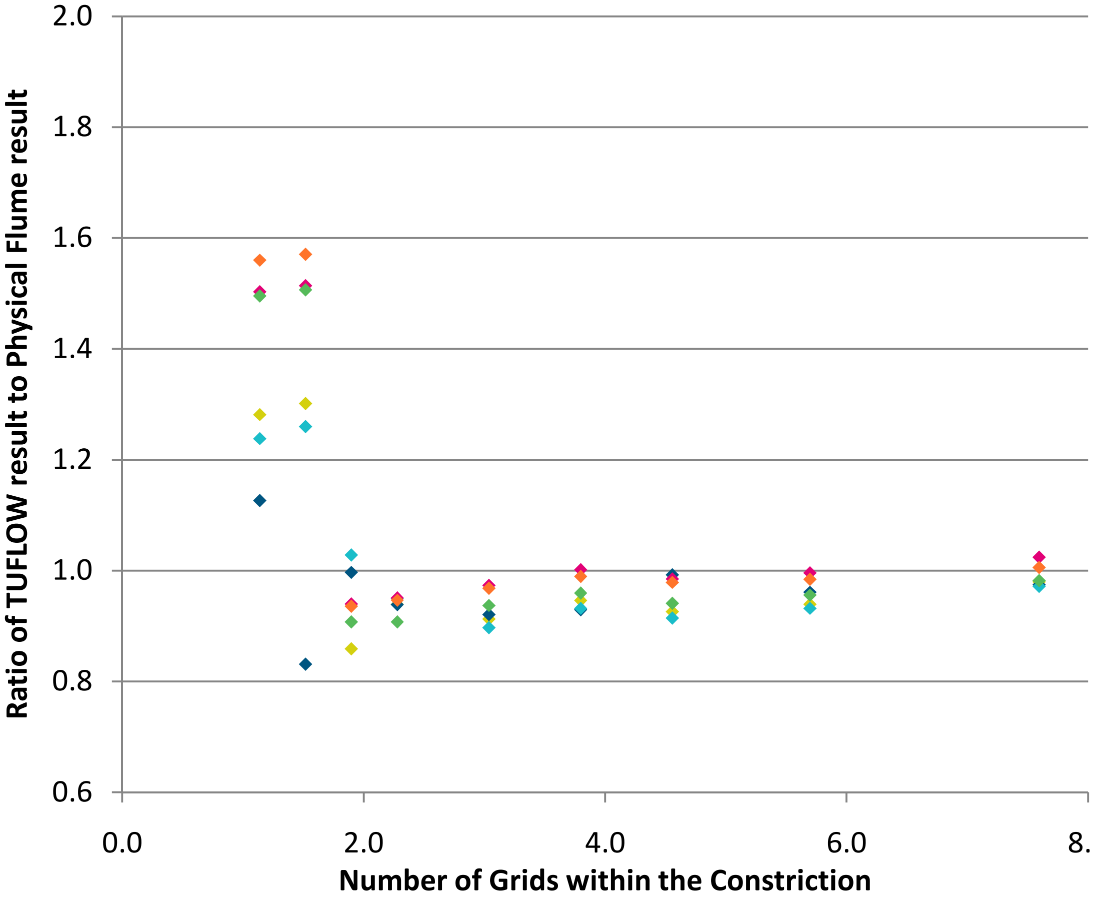


Figure 4-3 Abutment Analysis – Influence of Grid: Constriction Ratio (3 Foot Opening)

In exploring the poor correlation between TUFLOW and the physical flume when modelling a small opening on a large grid, the same results were plotted against the Froude Number (calculated at the location where the maximum afflux). The results from this analysis are plotted in their entirety in Figure 4-4, whilst a subset showing only the results from the models with a 3 foot opening is displayed in Figure 4-5.

Figure 4-4 and Figure 4-5 both show that for flow conditions resulting in a Froude Numbers that are very low, the TUFLOW model will over-predict the afflux. However, when the flow conditions change, resulting in a increased Froude Number, the model performance improves.

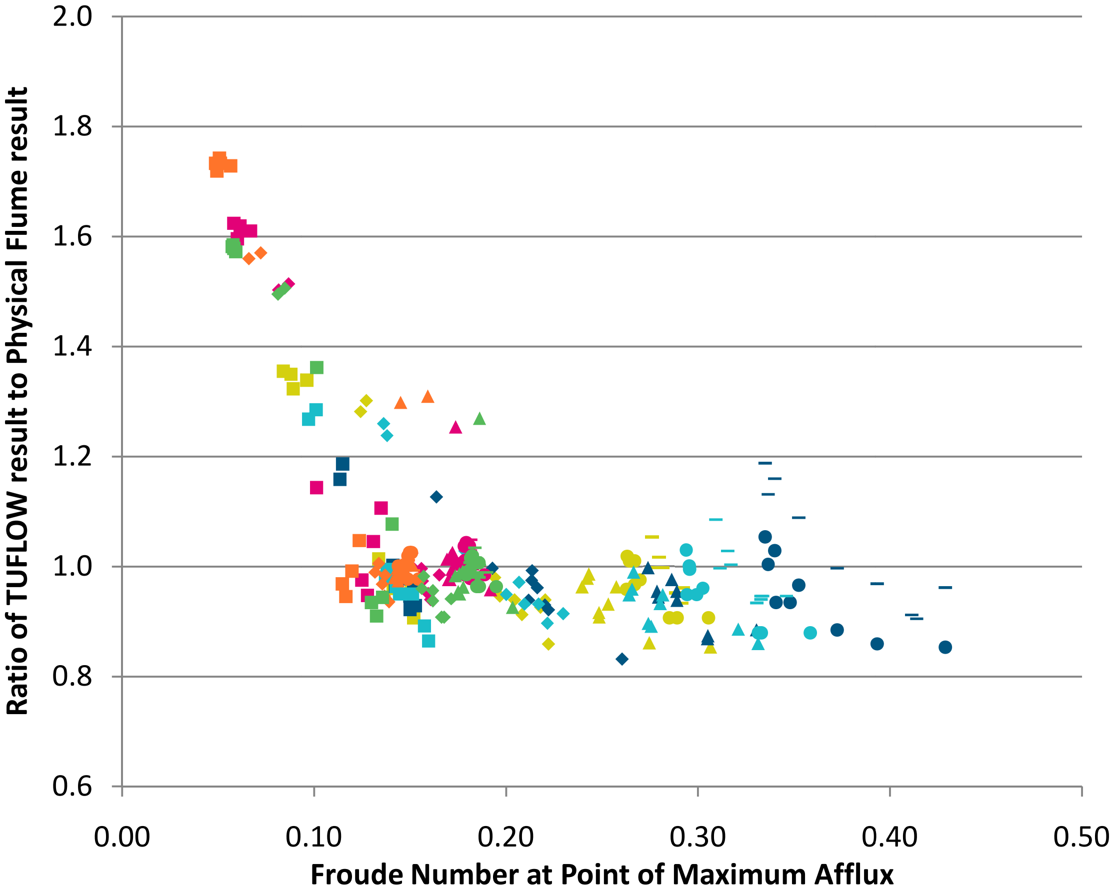


Figure 4-4 Abutment Analysis – Influence of Froude Number

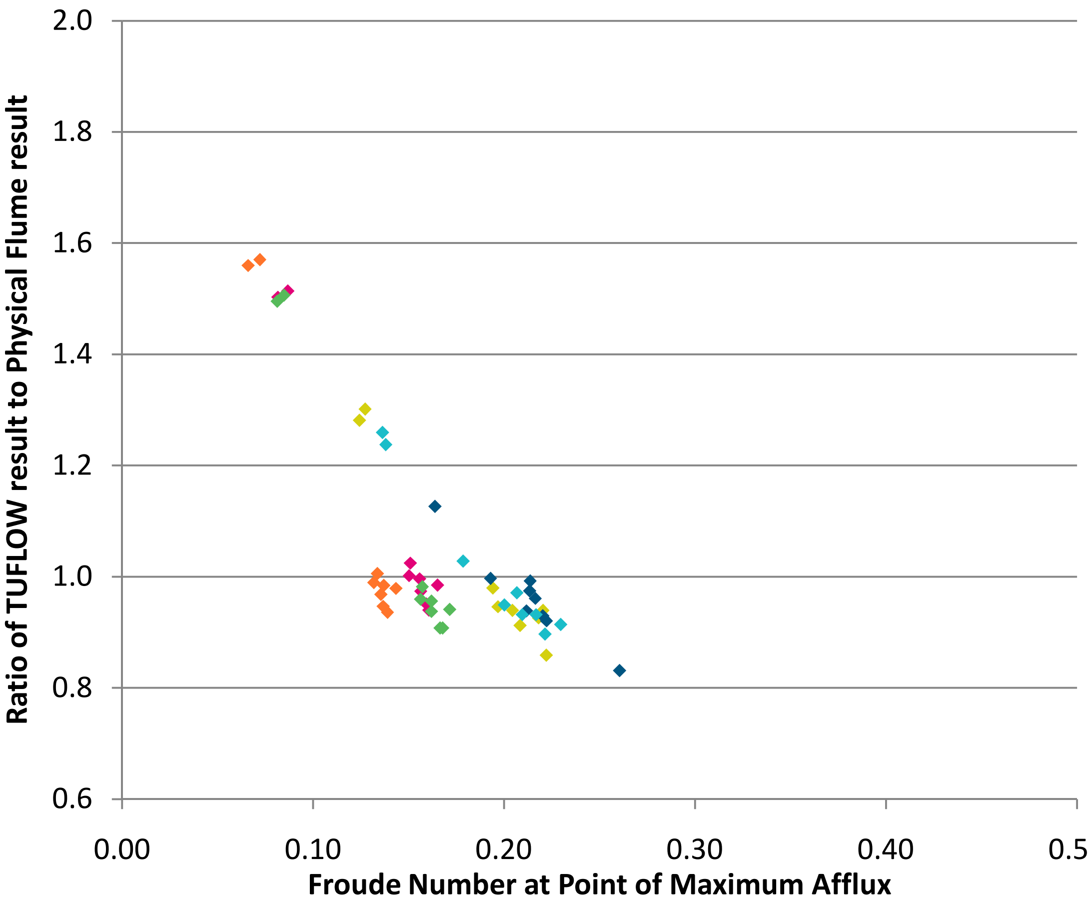


Figure 4-5 Abutment Analysis – Influence of Froude Number (3 Foot Opening)

The results presented in Figure 4-4 indicate that for flow conditions resulting in a Froude Number of less than 0.1, the predictive performance of TUFLOW will be poor. However, when the flow conditions result in a Froude Number at the point of maximum afflux greater than 0.20, the results from the TUFLOW model have, within reasonable bounds, reproduced the results of the physical flume tests.

The abutment analysis was also undertaken to determine the influence, if any, of the number of grids located adjacent to the blockage. The results from this analysis are presented in Figure 4-6.

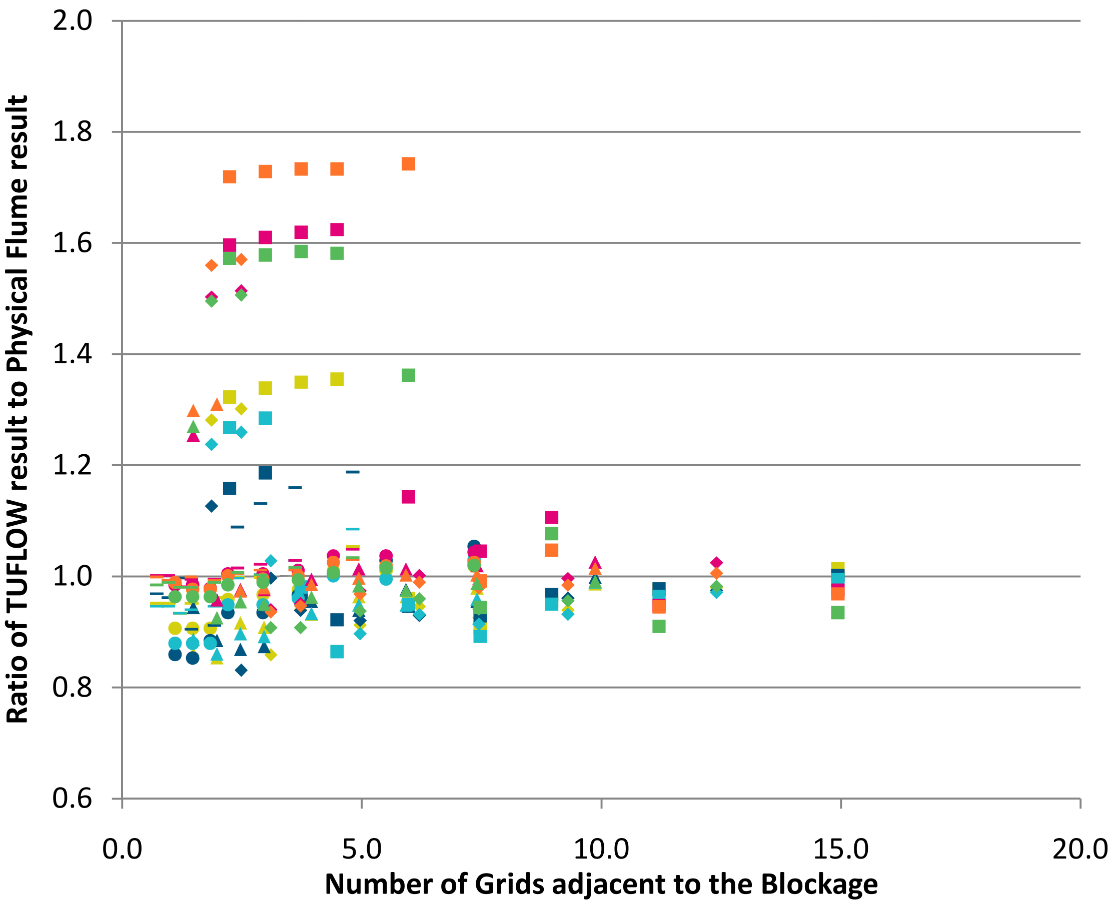


Figure 4-6 Abutment Analysis – Influence of Grid: Blockage Ratio

Unlike the results seen in Figure 4-2, Figure 4-6 shows no clear trend that the number of cells located adjacent to the blockage is having a significant influence on the results. In general terms, the results appear to indicate that if more than 6 grids exist adjacent to the blockage, the TUFLOW model will reproduce the results of the physical model within reasonable bounds. However, there are also a number of results where there are less than 6 grids adjacent to the blockage that also provides a good replication of the physical model results.

As discussed previously, the afflux determined by the models with a 2 foot and 3 foot opening appear to have other factors at play rather than simply the contraction and expansion through the opening. Therefore, if the results from these models were removed from Figure 4-6, the plot would look like Figure 4-7. Figure 4-7 shows that regardless of the number of grids adjacent to the blockage, there are TUFLOW models that are able to reproduce, within reasonable bounds, the results of the physical flume test.

Consequently, it could be argued that the number of grids within a constriction will be more important than the number of grids adjacent to the blockage when determining if a TUFLOW model will be able to reliable reproduce the results of a physical model.

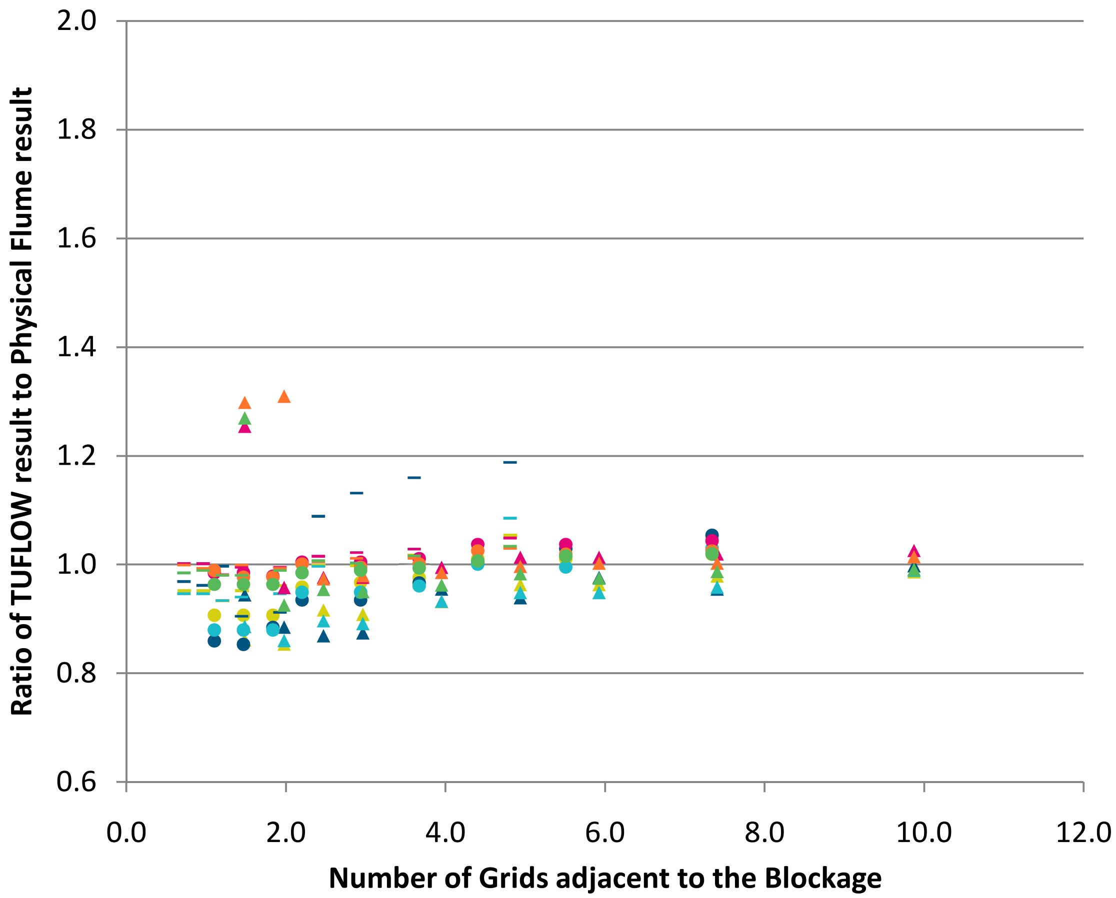


Figure 4-7 Abutment Analysis – Influence of Grid: Blockage Ratio (Excluding 2 and 3 Foot Openings)

4.3 Pier Analysis

The pier analysis was undertaken for four distinct types of piers; square shaft, single shaft, double shaft and round-ended narrow. As discussed previously, the pier losses were applied to the model in three distinct methods with the intention of determining an appropriate method to model piers within a 2D hydraulic model. The results from this analysis are presented in Figure 4-8 (Square Shaft Piers), Figure 4-9 (Single Shaft Piers), Figure 4-10 (Double Shaft Piers) and Figure 4-11 (Round-Ended Narrow Piers).

In general, the direct application of the pier loss coefficients obtained from the literature to the hydraulic model will result in the determination of a slightly conservative afflux, although the results are within reasonable bounds when compared to the physical flume results.

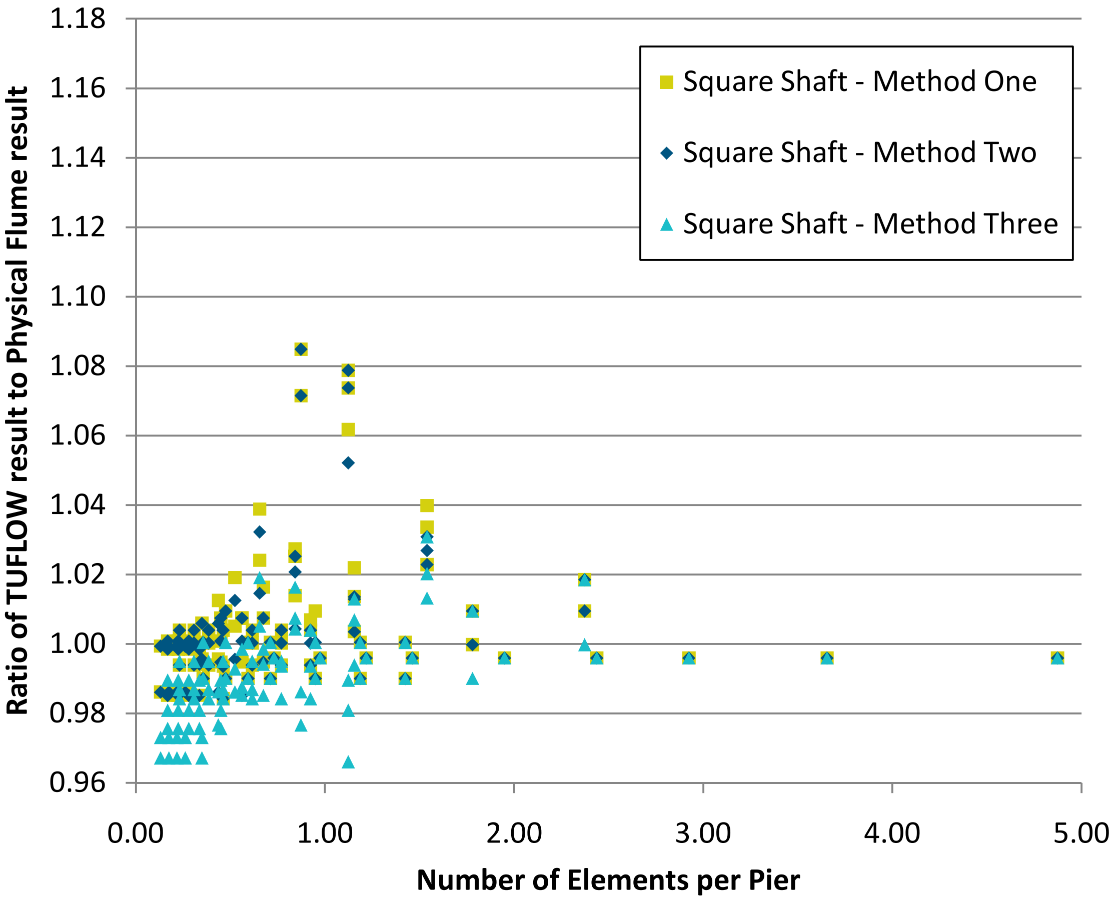


Figure 4-8 Pier Analysis – Square Shaft Piers

Figure 4-8 shows the results from the various methods of modelling a square shaft pier. These results are the only ones to include the piers modelled as a partial blockage of the model cell (light blue triangles). As shown in the figure, modelling a pier as a partial blockage of an individual element will almost certainly result in an afflux lower than that observed through the physical flume testing. Although the differences in this case are quite small, it would be expected that the differences would increase in real-world applications.

The square shaft piers are the only ones that result in a modelled afflux lower than the physical flume test when using either Method One (yellow squares) or Method Two (dark blue triangles) to apply the form loss coefficients to the hydraulic model. It is thought that this is likely due to inaccuracies that have been introduced to the model in developing the form loss coefficients for the square shaft.

The following figures (Figure 4-9, Figure 4-10 and Figure 4-11) show the results from the single shaft piers, double shaft piers and round-ended narrow piers respectively. In general, the results between the two methods (Method One and Method Two) will be identical when the number of elements per pier is less than 1; however, this is not always the case due the way in which the piers are arranged across the cross section. In each of these figures, it can be seen that once number of elements per pier is greater than 1; the results from Method Two provide a closer match to those observed in the physical model.

These results indicate that it is more appropriate to apply the form loss coefficient calculated from the literature (eg: Austroads, 1994) to only the cells in which a pier will be located. Whilst this method will still result in slightly conservative predictions of afflux, they will less conservative when compared to the results when the form loss coefficient is applied across the entire cross section.

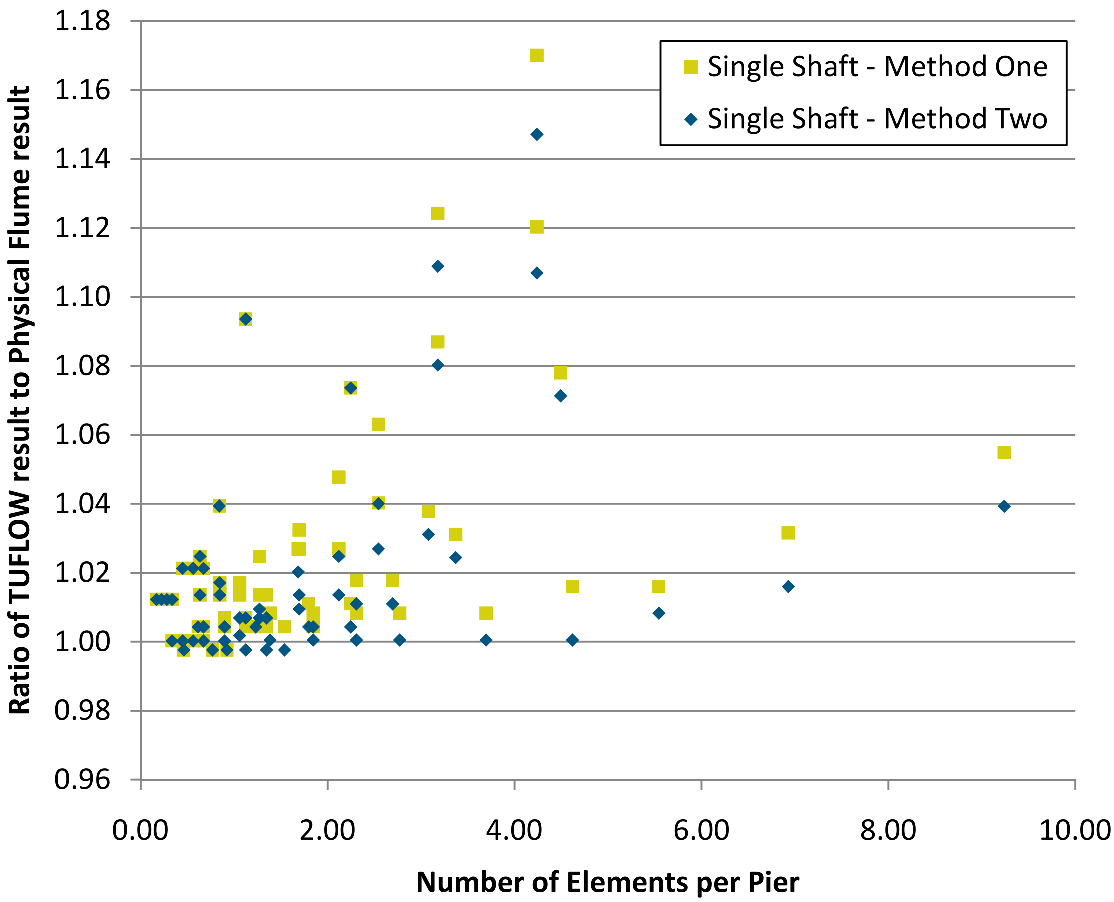


Figure 4-9 Pier Analysis – Single Shaft Piers

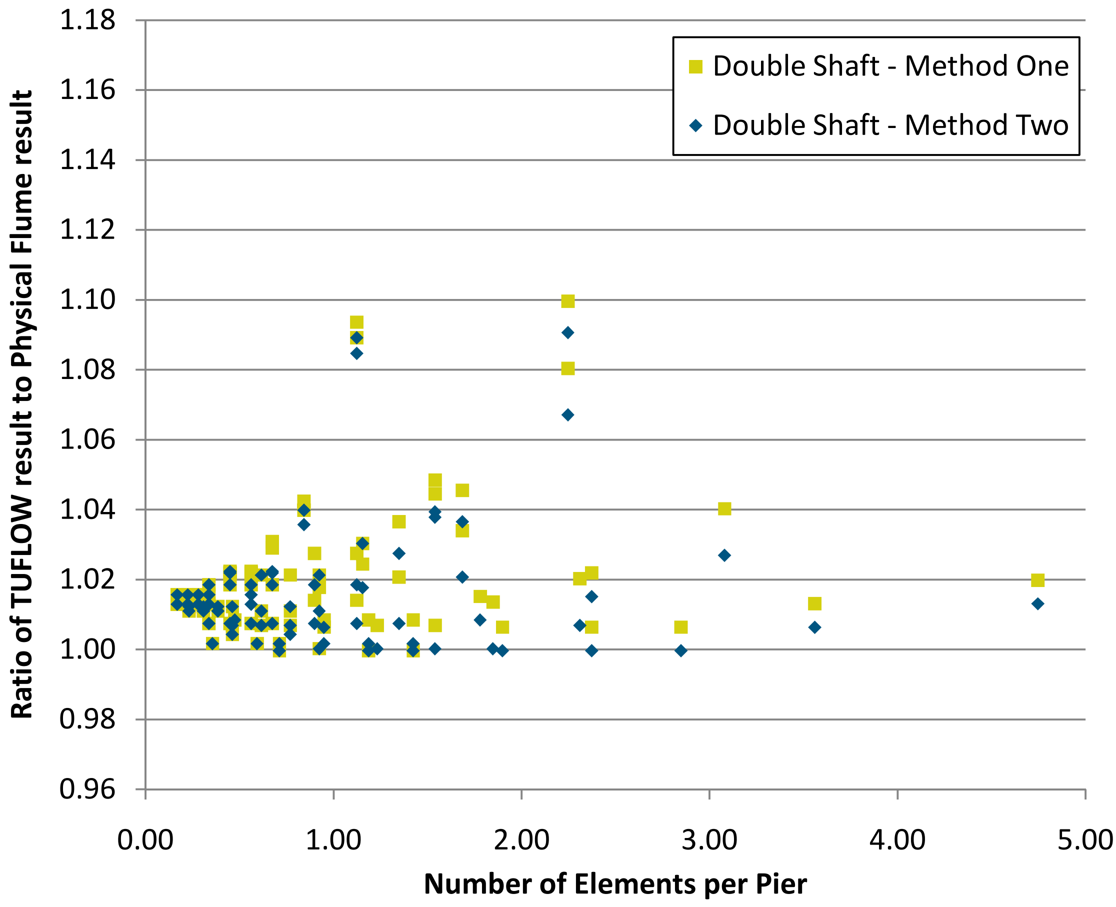


Figure 4-10 Pier Analysis – Double Shaft Piers

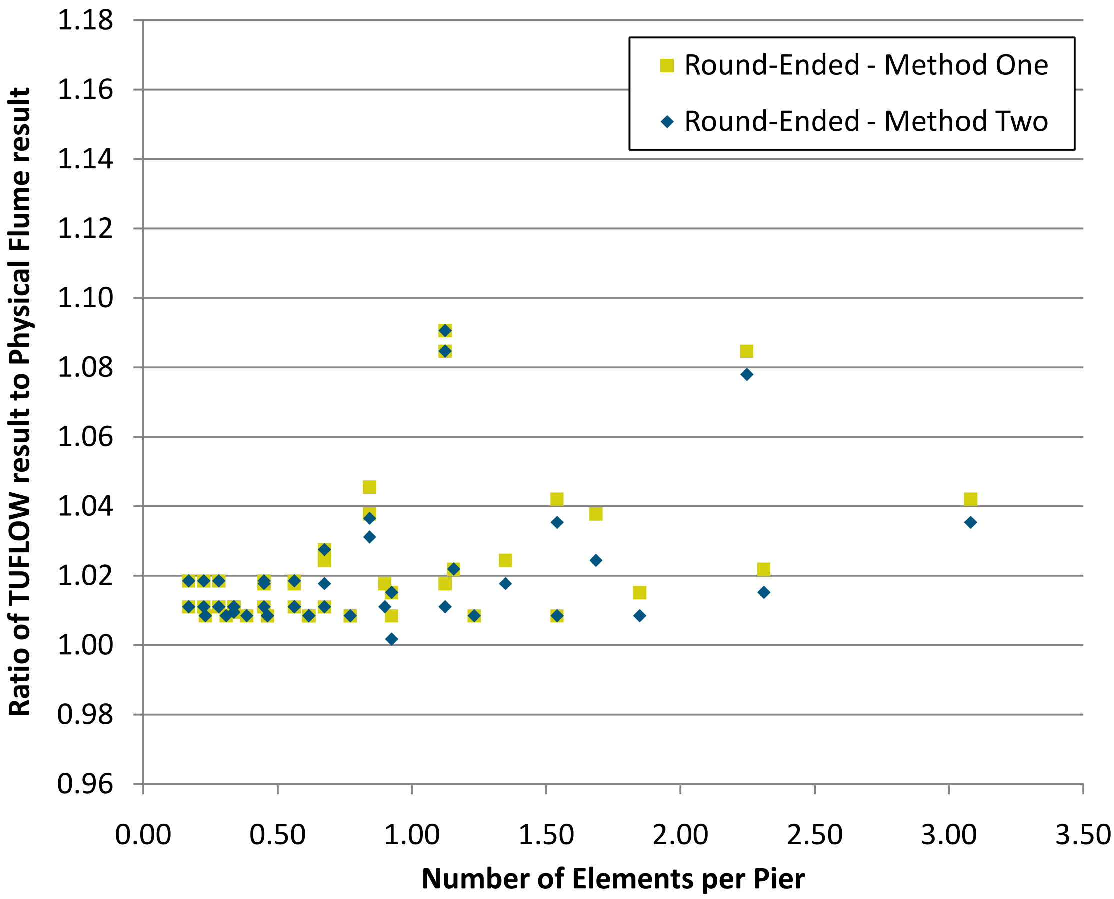


Figure 4-11 Pier Analysis – Round-Ended Narrow Piers

5 CONCLUSIONS AND RECOMMENDATIONS

The research that has been undertaken sought to test two specific hypothesises:

1. That a 2D modelling scheme can reproduce, within reasonable bounds of uncertainty, the contraction and expansion losses associated with flow through a bridge opening as indicated by physical model tests undertaken by Liu et al (Liu, Bradley, & Plate, 1957); and

2. That the energy loss coefficients associated with bridge piers as reported in Liu et al can be applied in a 2D modelling scheme to reproduce, within reasonable bounds, the increase in water level reported by Liu et al (1957).

The research that has been presented in this report has shown that for the majority of modelled flumes tested, these hypothesises can be considered true. However, a number of conclusions and recommendations have been determined based upon the results of the research and have been documented below:

- The importance of the viscosity coefficient increases as the grid size decreases and the turbulence associated with the flow conditions can be modelled as a grid scale rather than at a sub-grid scale.

- The predicted afflux of small constrictions relative to the grid size should be checked against additional methods to ensure the afflux is not significantly over-predicted.

- The results suggest that a modeller should try to include at least 6 model elements within a constriction to enable an accurate prediction of the afflux due to the contraction and expansion. The number of elements adjacent to the blockage is not a significant factor in the afflux predictions.

- The research has shown that the modelling of pier through the partial or complete blockage of individual elements will result in an under-prediction of the afflux due to the pier when compared against a physical flume result.

- The application of form loss coefficients obtained from the literature to individual elements where a pier is expected to occur is the best method (of the tested methods) to use in the modelling of piers within a 2D hydraulic model.

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APPENDIX A: LIU ET AL (1957) FLUME DATA – EMBANKMENT MODELS

TABLE 1 : SIMPLE NORMAL CROSSING
vertical board model

Measured Data | Computed Data

Run No	Model Type	Model height [ft]	Model length [ft]	b [ft]	B [ft]	Q [cfs]	h_n [ft]	Bottom Rdg.	Rough-ness	Slope	h_1 [ft]	R_{UR}	R_{UL}	R_{DR}	R_{DL}	L*	h_1* [ft]	h_U [ft]	h_D [ft]	$\frac{h_1}{h_n}$	$(\frac{h_1}{h_n})^3$	F_n	F_n^2	M	$(\frac{1}{M^2}-1)F_n^2$	$\frac{B}{h_n}$
357	VB	1.67	-	2.0	7.9	2.50	0.333	0.834	Bar	.0012	0.615	1.454	1.455	1.110	1.121	3.5	0.282	0.621	0.282	1.849	6.30	0.289	.0835	0.253	1.220	23.70
358	VB	1.67	-	3.0	7.9	2.50	0.333	0.834	Bar	.0012	0.489	1.331	1.330	1.127	1.118	3.5	0.156	0.497	0.289	1.468	3.16	0.289	.0835	0.38	0.496	23.70
359	VB	1.67	-	4.0	7.9	2.50	0.333	0.834	Bar	.0012	0.419	1.261	1.259	1.132	1.128	2.5	0.086	0.426	0.296	1.258	2.00	0.289	.0835	0.505	0.244	23.70
360	VB	1.67	-	5.0	7.9	2.50	0.333	0.834	Bar	.0012	0.380	1.224	1.223	1.141	1.137	3.6	0.047	0.390	0.305	1.140	1.49	0.289	.0835	0.633	0.125	23.70
361	VB	1.67	-	6.0	7.9	2.50	0.333	0.834	Bar	.0012	0.355	1.200	1.200	1.145	1.145	4.0	0.022	0.366	0.311	1.066	1.21	0.289	.0835	0.760	0.061	23.70
267	VB	1.67	-	2.0	7.9	2.91	0.352	0.833	Bar	.0012	0.687	1.526	1.524	1.124	1.134	3.2	0.335									
598	VB	1.67	-	6.0	7.9	5.00	0.416	0.864	Bar	.002	0.464	1.349	1.352	1.225	1.224	4.0	0.048	0.487	0.361	1.110	1.370	0.415	.172	0.760	0.126	19.00
599	VB	1.67	-	5.0	7.9	5.00	0.416	0.864	Bar	.002	0.523	1.409	1.407	1.210	1.208	3.6	0.107	0.544	0.345	1.255	1.975	0.415	.172	0.633	0.258	19.00
600	VB	1.67	-	4.0	7.9	5.00	0.416	0.864	Bar	.002	0.608	1.492	1.490	1.205	1.183	3.6	0.192	0.627	0.330	1.460	3.102	0.415	.172	0.505	0.503	19.00
601	VB	1.67	-	3.0	7.9	5.00	0.416	0.864	Bar	.002	0.734	1.614	1.614	1.177	1.189	2.7	0.318	0.750	0.319	1.760	5.460	0.415	.172	0.380	1.025	19.00
602	VB	1.67	-	2.0	7.9	5.00	0.416	0.864	Bar	.002	0.943	1.819	1.818	1.156	1.132	2.9	0.527	0.955	0.280	2.260	11.50	0.415	.172	0.253	2.510	19.00
266	VB	1.67	-	2.0	7.9	3.95	0.418	0.833	Bar	.0012	0.835	1.673	1.673	1.167	1.182	3.5	0.417									
754	VB	1.67	-	4.0	7.9	5.00	0.484	0.862	Bar	.0012	0.633	1.512	1.512	1.296	1.274	-	0.149	0.650	0.423	1.307	2.238	0.332	.110	0.505	0.321	16.35
755	VB	1.67	-	3.0	7.9	5.00	0.484	0.862	Bar	.0012	0.750	1.631	1.624	1.277	1.254	3.5	0.266	0.766	0.404	1.550	3.724	0.332	.110	0.380	0.650	16.35
756	VB	1.67	-	2.0	7.9	5.00	0.484	0.862	Bar	.0012	0.960	-	-	-	-	3.18	0.476	-	-	1.983	7.80	0.332	.110	0.253	1.608	16.35
757	VB	1.67	-	5.0	7.9	5.00	0.484	0.862	Bar	.0012	0.567	1.448	1.447	1.290	1.302	2.62	0.083	0.586	0.434	1.171	1.610	0.332	.110	0.633	0.165	16.35
758	VB	1.67	-	6.0	7.9	5.00	0.484	0.862	Bar	.0012	0.520	-	-	-	-	-	0.036	-	-	1.074	1.239	0.332	.110	0.760	.0805	16.35
872	VB	1.67	-	3.00	7.9	5.00	0.484	0.855	Bar	.0012	0.758	1.624	1.619	1.280	1.258	2.90	0.274	0.767	0.414	1.566	3.840	0.332	.110	0.380	0.650	16.35
873	VB	1.67	-	4.00	7.9	5.00	0.484	0.855	Bar	.0012	0.645	1.518	1.510	1.298	1.283	3.3	0.161	0.659	0.436	1.335	2.39	0.332	.110	0.505	0.321	16.35
874R	VB	1.67	-	4.97	7.9	5.00	0.484	0.855	Bar	.0012	0.577	1.449	1.441	1.305	1.294	2.7	0.093	0.590	0.445	1.192	1.700	0.332	.110	0.630	0.167	16.35
875	VB	1.67	-	5.96	7.9	5.00	0.484	0.855	Bar	.0012	0.534	1.415	1.402	1.319	1.315	2.1	0.050									
301	VB	1.67	-	5.97	7.9	5.00	0.484	0.834	Bar	.0012	0.519	1.374	1.366	1.283	1.275	-	0.035	0.536	0.445	1.071	1.240	0.332	.110	0.756	0.083	16.35
302	VB	1.67	-	5.00	7.9	5.00	0.484	0.834	Bar	.0012	0.567	1.419	1.410	1.274	1.260	4.3	0.083	0.581	0.433	1.171	1.606	0.332	.110	0.633	0.165	16.35
303	VB	1.67	-	4.00	7.9	5.00	0.484	0.834	Bar	.0012	0.636	1.481	1.479	1.243	1.257	4.3	0.152	0.646	0.416	1.314	2.269	0.332	.110	0.505	0.322	16.35
304	VB	1.67	-	3.00	7.9	5.00	0.484	0.834	Bar	.0012	0.758	1.602	1.595	1.248	1.223	4.4	0.274	0.765	0.402	1.566	3.840	0.332	.110	0.380	0.650	16.35
305	VB	1.67	-	2.00	7.9	5.00	0.484	0.834	Bar	.0012	0.968	1.804	1.800	1.236	1.186	4.1	0.484	0.968	0.377	2.000	8.00	0.332	.110	0.253	1.598	16.35
225	VB	1.67	-	6.00	7.9	5.00	0.484	0.834	Bar	.0012	0.520	1.369	1.371	1.282	1.279	4.7	0.036	0.536	0.447	1.074	1.239	0.332	.110	0.760	0.080	16.35
226	VB	1.67	-	5.00	7.9	5.00	0.484	0.834	Bar	.0012	0.564	1.412	1.412	1.272	1.261	3.4	0.080	0.578	0.433	1.165	1.581	0.332	.110	0.633	0.165	16.35
227	VB	1.67	-	4.00	7.9	5.00	0.484	0.834	Bar	.0012	0.637	1.487	1.481	1.260	1.246	4.2	0.153	0.650	0.419	1.316	2.279	0.332	.110	0.505	0.322	16.35
228	VB	1.67	-	3.00	7.9	5.00	0.484	0.834	Bar	.0012	0.757	1.606	1.601	1.251	1.231	4.4	0.273	0.770	0.407	1.564	3.826	0.332	.110	0.380	0.650	16.35
229	VB	1.67	-	2.00	7.9	5.00	0.484	0.834	Bar	.0012	0.962	1.802	1.800	1.201	1.239	3.2	0.478	0.967	0.386	1.988	7.857	0.332	.110	0.253	1.598	16.35
234	VB	1.67	-	2.00	7.9	5.00	0.484	0.834	Bar	.0012	0.965	1.804	1.808	1.239	1.199	4.5	0.481									
261	VB	1.67	-	2.00	7.9	5.00	0.484	0.834	Bar	.0012	0.965	1.807	1.807	1.218	1.231	3.3	0.481	0.973	0.391	1.994	7.928	0.332	.110	0.253	1.598	16.35
603	VB	1.67	-	6.00	7.9	2.72	0.478	0.864	Baffle	.002	0.488	1.360	1.360	1.324	1.326	2.3	0.010	0.496	0.461	1.020	1.060	0.184	.0339	0.760	0.025	16.20
604	VB	1.67	-	5.00	7.9	2.72	0.478	0.864	Baffle	.002	0.503	1.377	1.378	1.319	1.323	2.4	0.025	0.514	0.457	1.052	1.164	0.184	.0339	0.633	0.051	16.20
605	VB	1.67	-	4.00	7.9	2.72	0.478	0.864	Baffle	.002	0.531	1.406	1.406	1.316	1.317	2.5	0.053	0.542	0.452	1.111	1.370	0.184	.0339	0.505	0.099	16.20
606	VB	1.67	-	3.00	7.9	2.72	0.478	0.864	Baffle	.002	0.583	1.457	1.457	1.313	1.312	2.7	0.105	0.593	0.449	1.220	1.816	0.184	.0339	0.380	0.201	16.20
607	VB	1.67	-	2.00	7.9	2.72	0.478	0.864	Baffle	.002	0.703	1.573	1.575	1.301	1.306	2.5	0.225	0.710	0.440	1.471	3.190	0.184	.0339	0.253	0.496	16.20
450	VB	1.67	-	6.00	7.9	2.50	0.523	0.866	Baffle	.0012	0.532	1.401	1.401	1.376	1.376	2.4	0.009	0.535	0.510	1.018	1.052	0.148	.0219	0.760	0.16	15.10
451	VB	1.67	-	5.00	7.9	2.50	0.523	0.866	Baffle	.0012	0.544	1.415	1.414	1.373	1.373	3.0	0.021	0.549	0.507	1.040	1.130	0.148	.0219	0.633	0.033	15.10
452	VB	1.67	-	4.00	7.9	2.50	0.523	0.866	Baffle	.0012	0.566	1.437	1.436	1.371	1.372	2.9	0.043	0.571	0.506	1.082	1.172	0.148	.0219	0.505	0.064	15.10
453	VB	1.67	-	3.00	7.9	2.50	0.523	0.866	Baffle	.0012	0.610	1.482	1.479	1.365	1.367	3.0	0.087	0.615	0.500	1.168	1.590	0.148	.0219	0.380	0.129	15.10
454	VB	1.67	-	2.00	7.9	2.50	0.523	0.866	Baffle	.0012	0.708	1.580	1.581	1.362	1.362	2.7	0.185	0.715	0.496	1.354	2.490	0.148	.0219	0.253	0.320	15.10
262	VB	1.67	-	2.00	7.9	5.75	0.523	0.834	Baffle	.0012	1.057	1.895	1.895	1.256	1.269	3.4	0.573									
459	VB	1.67	-	6.00	7.9	5.00	0.718	0.866	Baffle	.0012	0.733	1.609	1.610	1.565	1.566	4.2	0.015	0.744	0.700	1.020	1.060	0.184	.0339	0.760	0.025	11.00
460	VB	1.67	-	5.00	7.9	5.00	0.718	0.866	Baffle	.0012	0.756	1.634	1.633	1.556	1.557	2.5	0.038	0.768	0.691	1.053	1.168	0.184	.0339	0.633	0.051	11.00
461	VB	1.67	-	4.00	7.9	5.00	0.718	0.866	Baffle	.0012	0.801	1.676	1.676	1.552	1.556	-	0.083	0.810	0.688	1.116	1.390	0.184	.0339	0.505	0.099	11.00
462	VB	1.67	-	3.00	7.9	5.00	0.718	0.866	Baffle	.0012	0.882	1.754	1.760	1.545	1.547	3.6	0.164	0.891	0.680	1.228	1.852	0.184	.0339	0.380	0.201	11.00
463	VB	1.67	-	2.00	7.9	5.00	0.718	0.866	Baffle	.0012	1.060	1.929	1.930	1.541	1.535	3.5	0.342	1.064	0.672	1.476	3.216	0.184	.0339	0.253	0.496	11.00
858	VB	1.67	-	2.98	7.9	2.50	0.333	0.855	Bar	.0012	0.492	-	-	-	-	2.95	0.159									
859	VB	1.67	-	3.99	7.9	2.50	0.333	0.855	Bar	.0012	0.420	-	-	-	-	3.45	0.087									
860	VB	1.67	-	4.98	7.9	2.50	0.333	0.855	Bar	.0012	0.380	-	-	-	-	4.05	0.047									
861	VB	1.67	-	6.00	7.9	2.50	0.333	0.855	Bar	.0012	0.354	-	-	-	-	3.85	0.021									
1373	VB	1.67	-	3.00	7.9	5.00	0.484	0.855	Baffle	.0012	0.881	1.745	1.745	1.539	1.537		0.397									
1374	VB	1.67	-	4.00	7.9	5.00	0.484	0.855	Baffle	.0012	0.796	1.660	1.659	1.543	1.541		0.312									
1375	VB	1.67	-	5.00	7.9	5.00	0.484	0.855	Baffle	.0012	0.755	1.623	1.619	1.553	1.546		0.271									
1376	VB	1.67	-	6.00	7.9	5.00	0.484	0.855	Baffle	.0012	0.736	1.597	1.597	1.557	1.556		0.252									

APPENDIX B: LIU ET AL (1957) FLUME DATA – PIER MODELS

TABLE 7 : PIERS WITHOUT ABUTMENTS

refer p534 for legend

	Measured Data											Computed Data				
Run No.	b [ft]	B [ft]	Q [cfs]	h_n [ft]	Bottom Rdg.	Rough-ness	Slope	Type of Piers	Number of Piers	Diameter of Piers [in]	h_1 [ft]	h_1° [ft]	$\frac{h_1}{h_n}$	$\frac{ND}{B}$	δ_o	C_{DA}
1133	7.1	7.9	3.00	0.360	0.855	Bar	.0012	rn	16	0.625	0.364	0.004	1.011	0.105	4.15	1.060
1134	7.3	7.9	3.00	0.360	0.855	Bar	.0012	rn	12	0.625	0.362	0.002	1.006	0.079	2.85	1.055
1135	7.5	7.9	3.00	0.360	0.855	Bar	.0012	rn	8	0.625	0.361	0.001	1.003	0.053	2.19	1.039
1136	7.1	7.9	3.00	0.360	0.855	Bar	.0012	rn	8	1.25	0.362	0.002	1.006	0.105	2.01	1.083
1137	7.3	7.9	3.00	0.360	0.855	Bar	.0012	rn	6	1.25	0.361	0.001	1.003	0.079	1.38	1.067
594	7.1	7.9	5.00	0.416	0.864	Bar	.0012	rn	4	2.4	0.423	0.007	1.017	0.101	3.42	1.076
595	7.5	7.9	5.00	0.416	0.864	Bar	.0012	rn	2	2.4	0.419	0.003	1.007	0.051	3.20	1.035
1118	7.7	7.9	5.00	0.484	0.855	Bar	.0012	rn	4	0.625	0.485	0.001				
1119R	7.5	7.9	5.00	0.484	0.865	Bar	.0012	rn	8	0.625	0.487	0.003				
1120	7.3	7.9	5.00	0.484	0.855	Bar	.0012	rn	12	0.625	0.488	0.004	1.008	0.079	3.68	1.044
1121	7.1	7.9	5.00	0.484	0.855	Bar	.0012	rn	16	0.625	0.490	0.006	1.012	0.105	4.00	1.065
1122	7.1	7.9	5.00	0.484	0.855	Bar	.0012	rn	8	1.25	0.490	0.006	1.012	0.105	4.00	1.065
1123	7.3	7.9	5.00	0.484	0.855	Bar	.0012	rn	6	1.25	0.488	0.004	1.008	0.079	3.55	1.044
1124	7.5	7.9	5.00	0.484	0.855	Bar	.0012	rn	4	1.25	0.487	0.003	1.006	0.053	4.28	1.030
1125	7.7	7.9	5.00	0.484	0.855	Bar	.0012	rn	2	1.25	0.485	0.001	1.002	0.026	3.00	1.015
1145	7.1	7.9	3.00	0.360	0.855	Bar	.0012	ss	16	0.625	0.363	0.003	1.008	0.105	3.20	1.073
1147	7.3	7.9	3.00	0.360	0.855	Bar	.0012	ss	12	0.625	0.361	0.001	1.003	0.079	1.45	1.066
1151	7.1	7.9	3.00	0.360	0.855	Bar	.0012	ss	8	1.25	0.362	0.002	1.006	0.105	2.10	1.093
1152	7.3	7.9	3.00	0.360	0.855	Bar	.0012	ss	6	1.25	0.361	0.001	1.003	0.079	1.45	1.066
1154	7.5	7.9	3.00	0.360	0.855	Bar	.0012	ss	4	1.25	0.361	0.001	1.003	0.053	2.40	1.038
596	6.7	7.9	5.00	0.416	0.864	Bar	.002	ss	4	3.6	0.429	0.013	1.031	0.152	4.21	1.108
597	7.3	7.9	5.00	0.416	0.864	Bar	.002	ss	2	3.6	0.423	0.007	1.017	0.076	4.34	1.042
608	7.3	7.9	5.00	0.484	0.866	Bar	.0012	ss	2	3.6	0.486	0.002	1.004	0.076	2.00	1.067
609	6.7	7.9	5.00	0.484	0.866	Bar	.0012	ss	4	3.6	0.492	0.008	1.017	0.152	3.75	1.112
610	7.5	7.9	5.00	0.484	0.866	Bar	.0012	ss	2	2.4	0.487	0.003	1.006	0.051	4.81	1.030
611	7.1	7.9	5.00	0.484	0.866	Bar	.0012	ss	4	2.4	0.490	0.006	1.012	0.101	4.45	1.018
1110	7.8	7.9	5.00	0.484	0.855	Bar	.0012	ss	2	1.25	0.485	0.001				
1111	7.5	7.9	5.00	0.484	0.855	Bar	.0012	ss	4	1.25	0.487	0.003	1.006	0.053	4.82	1.005
1112	7.3	7.9	5.00	0.484	0.855	Bar	.0012	ss	6	1.25	0.490	0.006	1.012	0.079	5.95	0.990
1113	7.1	7.9	5.00	0.484	0.855	Bar	.0012	ss	8	1.25	0.492	0.008	1.017	0.105	5.69	0.988
1126	7.5	7.9	5.00	0.484	0.855	Bar	.0012	ss	8	0.625	0.486	0.002	1.004	0.053	3.20	1.020
1127	7.3	7.9	5.00	0.484	0.855	Bar	.0012	ss	12	0.625	0.487	0.003	1.006	0.079	2.93	0.990
1128	7.1	7.9	5.00	0.484	0.855	Bar	.0012	ss	16	0.625	0.487	0.003	1.006	0.105	2.06	1.018
1146	7.1	7.9	3.00	0.360	0.855	Bar	.0012	ds	16	0.625	0.366	0.006	1.017	0.105	6.60	0.968
1148	7.3	7.9	3.00	0.360	0.855	Bar	.0012	ds	12	0.625	0.363	0.003	1.008	0.079	4.56 ?	1.008
1149	7.5	7.9	3.00	0.360	0.855	Bar	.0012	ds	8	0.625	0.361	0.001	1.003	0.053	2.29	1.028
1150	7.1	7.9	3.00	0.360	0.855	Bar	.0012	ds	8	1.25	0.364	0.004	1.011	0.105	4.34	1.012
1153	7.3	7.9	3.00	0.360	0.855	Bar	.0012	ds	6	1.25	0.362	0.002	1.006	0.079	3.02	1.028
1155	7.5	7.9	3.00	0.360	0.855	Bar	.0012	ds	4	1.25	0.362	0.002	1.006	0.053	4.64	1.000
623	7.3	7.9	5.00	0.484	0.853	Bar	.0012	ds	2	3.5	0.490	0.006	1.012	0.074	6.28	0.990
624	7.5	7.9	5.00	0.484	0.853	Bar	.0012	ds	2	2.4	0.488	0.004	1.008	0.051	6.30	0.990
1114	7.1	7.9	5.00	0.484	0.855	Bar	.0012	ds	8	1.25	0.495	0.011	1.023	0.105	7.68	0.954
1115	7.3	7.9	5.00	0.484	0.855	Bar	.0012	ds	6	1.25						
1116	7.5	7.9	5.00	0.484	0.855	Bar	.0012	ds	4	1.25	0.489	0.005	1.010	0.053	7.48	0.975
1129	7.1	7.9	5.00	0.484	0.855	Bar	.0012	ds	16	0.625	0.491	0.007	1.014	0.105	4.84	1.005
1130	7.3	7.9	5.00	0.484	0.855	Bar	.0012	ds	12	0.625	0.490	0.006	1.012	0.079	5.83	0.990
1131	7.5	7.9	5.00	0.484	0.855	Bar	.0012	ds	8	0.625	0.488	0.004	1.008	0.053	5.98	0.990
1132	7.7	7.9	5.00	0.484	0.855	Bar	.0012	ds	4	0.625	0.485	0.001	1.002	0.026	3.39	1.009
771	7.4	7.9	2.50	0.535	0.855	Baffle	.0012	r	10	0.625	0.538	0.003	1.006	0.066	18.80	0.862
772	7.2	7.9	2.50	0.536	0.855	Baffle	.0012	r	14	0.625	0.539	0.003	1.007	0.092	13.15	0.884
773	7.0	7.9	2.50	0.536	0.854	Baffle	.0012	r	18	0.625	0.540	0.004	1.008	0.119	12.80	0.855
848	7.7	7.9	2.50	0.333	0.855	Bar	.0012	r	4	0.625	0.337	0.004	1.011	0.026	24.20	0.913
849	7.5	7.9	2.50	0.333	0.855	Bar	.0012	r	8	0.625	0.338	0.005	1.015	0.053	14.35	0.915
850	7.3	7.9	2.50	0.333	0.855	Bar	.0012	r	12	0.625	0.339	0.006	1.018	0.079	11.10	0.920
851	7.1	7.9	2.50	0.333	0.855	Bar	.0012	r	16	0.625	0.343	0.010	1.030	0.105	13.50	0.865
852	6.9	7.9	2.50	0.333	0.855	Bar	.0012	r	20	0.625	0.345	0.012	1.036	0.132	12.30	0.855
1138	7.1	7.9	3.00	0.360	0.855	Bar	.0012	r	16	0.625	0.368	0.008	1.022	0.105	8.55	0.930
1139	7.3	7.9	3.00	0.360	0.855	Bar	.0012	r	12	0.625	0.365	0.005	1.014	0.079	7.35	0.962
1140	7.5	7.9	3.00	0.360	0.855	Bar	.0012	r	8	0.625	0.362	0.002	1.006	0.053	4.54	1.000

TABLE 7 : PIERS WITHOUT ABUTMENTS [continued]

	Measured Data											Computed Data				
Run No.	b [ft]	B [ft]	Q [cfs]	h_n [ft]	Bottom Rdg.	Rough-ness	Slope	Type of Piers	Number of Piers	Diameter of Piers [in]	h_1 [ft]	h_1^* [ft]	$\frac{h_1}{h_n}$	$\frac{ND}{B}$	δ_o	C_{DA}
939	7.7	7.9	5.00	0.484	0.855	Bar	.0012	r	4	0.625	0.485	0.001	1.002	0.026	3.40	1.010
940	7.5	7.9	5.00	0.484	0.855	Bar	.0012	r	8	0.625	0.488	0.004	1.010	0.053	5.82	0.995
941	7.3	7.9	5.00	0.484	0.855	Bar	.0012	r	12	0.625	0.497	0.013	1.027	0.079	12.40	0.905
942	7.1	7.9	5.00	0.484	0.855	Bar	.0012	r	16	0.625	0.498	0.014	1.029	0.105	9.60	0.917
943	6.9	7.9	5.00	0.484	0.855	Bar	.0012	r	20	0.625	0.503	0.019	1.039	0.132	10.00	0.894
980	7.7	7.9	5.00	0.484	0.855	Bar	.0012	r	4	0.625	0.488	0.004				
981	7.3	7.9	5.00	0.484	0.855	Bar	.0012	r	12	0.625	0.497	0.003				
774	7.0	7.9	2.50	0.536	0.854	Baffle	.0012	Sq	18	0.625	0.541	0.005	1.009	0.119	16.10	0.815
775	7.2	7.9	2.50	0.536	0.854	Baffle	.0012	Sq	14	0.625	0.539	0.003	1.006	0.092	13.15	0.887
776	7.4	7.9	2.50	0.536	0.854	Baffle	.0012	Sq	10	0.625	0.538	0.002	1.004	0.066	12.62	0.915
853	6.9	7.9	2.50	0.333	0.855	Bar	.0012	Sq	20	0.625	0.346	0.013	1.039	0.132	13.30	0.839
854	7.1	7.9	2.50	0.333	0.855	Bar	.0012	Sq	16	0.625	0.343	0.010	1.030	0.105	13.51	0.868
855	7.3	7.9	2.50	0.333	0.855	Bar	.0012	Sq	12	0.625	0.340	0.007	1.021	0.079	13.08	0.900
856	7.5	7.9	2.50	0.333	0.855	Bar	.0012	Sq	8	0.625	0.338	0.005	1.015	0.053	14.20	0.910
857	7.7	7.9	2.50	0.333	0.855	Bar	.0012	Sq	4	0.625	0.336	0.003	1.009	0.026	18.10	0.940
1141	7.1	7.9	3.00	0.360	0.855	Bar	.0012	Sq	16	0.625	0.368	0.008	1.022	0.105	8.70	0.935
1142	7.3	7.9	3.00	0.360	0.855	Bar	.0012	Sq	12	0.625	0.366	0.006	1.017	0.079	9.10	0.945
1143	7.5	7.9	3.00	0.360	0.855	Bar	.0012	Sq	8	0.625	0.364	0.004	1.011	0.053	9.34	0.959
1144	7.7	7.9	3.00	0.360	0.855	Bar	.0012	Sq	4	0.625	0.362	0.002	1.006	0.026	9.78	0.977
944	7.7	7.9	5.00	0.484	0.855	Bar	.0012	Sq	4	0.625	0.485	0.001	1.002	0.026	3.18	1.010
945	7.5	7.9	5.00	0.484	0.855	Bar	.0012	Sq	8	0.625	0.486	0.002	1.004	0.053	2.96	1.023
946	7.3	7.9	5.00	0.484	0.855	Bar	.0012	Sq	12	0.625	0.492	0.008	1.017	0.079	7.76	0.962
947	7.1	7.9	5.00	0.484	0.855	Bar	.0012	Sq	16	0.625	0.495	0.011	1.023	0.105	7.43	0.950
948	6.9	7.9	5.00	0.484	0.855	Bar	.0012	Sq	20	0.625	0.499	0.015	1.031	0.132	8.05	0.932

APPENDIX C: TUFLOW MODEL RESULTS – ABUTMENT MODELS

		A01		A02		A03		A04		A05	
	Opening (m)	0.610		0.914		1.219		1.524		1.829	
	h1 (m)	0.187		0.149		0.128		0.116		0.108	
	Grid Size	h1 (calc)	% of Exp	h1 (calc)	% of Exp	h1 (calc)	% of Exp	h1 (calc)	% of Exp	h1 (calc)	% of Exp
RP03	0.80264	0.248	132%	0.191	128%	0.110	86%	0.105	91%	0.103	95%
RP04	0.60198	0.251	134%	0.194	130%	0.109	85%	0.105	91%	0.103	95%
RP05	0.48158	0.253	135%	0.128	86%	0.117	92%	0.105	91%	0.101	93%
RP06	0.40132	0.254	136%	0.140	94%	0.116	91%	0.111	96%	0.103	95%
RP08	0.30099	0.180	96%	0.136	91%	0.119	93%	0.112	97%	0.104	96%
RP10	0.24079	0.170	91%	0.141	95%	0.123	96%	0.113	98%	0.108	100%
RP12	0.20066	0.179	95%	0.138	93%	0.123	96%	0.117	101%	0.108	100%
RP15	0.16053	0.183	98%	0.140	94%	0.125	98%	0.117	101%	0.110	102%
RP20	0.12040	0.190	101%	0.146	98%	0.126	99%	0.118	102%	0.114	105%

		A06		A07		A08		A09		A10	
	Opening (m)	0.610		0.914		1.219		1.524		1.829	
	h1 (m)	0.287		0.224		0.185		0.159		0.141	
	Grid Size	h1 (calc)	% of Exp	h1 (calc)	% of Exp	h1 (calc)	% of Exp	h1 (calc)	% of Exp	h1 (calc)	% of Exp
RP03	0.80264	0.333	116%	0.252	113%	0.175	94%	0.137	86%	0.137	97%
RP04	0.60198	0.341	119%	0.186	83%	0.164	88%	0.136	85%	0.136	96%
RP05	0.48158	0.277	96%	0.223	100%	0.161	87%	0.141	88%	0.141	100%
RP06	0.40132	0.265	92%	0.210	94%	0.162	87%	0.149	93%	0.128	91%
RP08	0.30099	0.272	95%	0.206	92%	0.177	96%	0.149	93%	0.129	91%
RP10	0.24079	0.267	93%	0.208	93%	0.174	94%	0.154	97%	0.154	109%
RP12	0.20066	0.278	97%	0.222	99%	0.181	98%	0.160	100%	0.160	113%
RP15	0.16053	0.281	98%	0.215	96%	0.177	96%	0.164	103%	0.164	116%
RP20	0.12040	0.288	100%	0.218	97%	0.185	100%	0.168	105%	0.168	119%

		A11		A12		A13		A14		A15	
	Opening (m)	0.610		0.914		1.219		1.524		1.829	
	h1 (m)	0.293		0.229		0.193		0.173		0.158	
	Grid Size	h1 (calc)	% of Exp	h1 (calc)	% of Exp	h1 (calc)	% of Exp	h1 (calc)	% of Exp	h1 (calc)	% of Exp
RP03	0.80264	0.371	127%	0.283	124%	0.171	89%	0.152	88%	0.150	95%
RP04	0.60198	0.376	128%	0.288	126%	0.166	86%	0.152	88%	0.150	95%
RP05	0.48158	0.287	98%	0.235	103%	0.173	90%	0.152	88%	0.148	93%
RP06	0.40132	0.253	86%	0.217	95%	0.172	89%	0.164	95%	0.149	94%
RP08	0.30099	0.278	95%	0.205	90%	0.180	93%	0.164	95%	0.150	95%
RP10	0.24079	0.261	89%	0.213	93%	0.183	95%	0.166	96%	0.158	100%
RP12	0.20066	0.278	95%	0.209	91%	0.183	95%	0.173	100%	0.159	100%
RP15	0.16053	0.282	96%	0.213	93%	0.185	96%	0.172	100%	0.163	103%
RP20	0.12040	0.291	99%	0.222	97%	0.191	99%	0.178	103%	0.172	109%

		A16		A17		A18		A19		A20	
	Opening (m)	0.610		0.914		1.219		1.524		1.829	
	h1 (m)	0.214		0.178		0.162		0.153		0.149	
	Grid Size	h1 (calc)	% of Exp	h1 (calc)	% of Exp	h1 (calc)	% of Exp	h1 (calc)	% of Exp	h1 (calc)	% of Exp
RP03	0.80264	0.342	160%	0.267	150%	0.203	125%	0.151	98%	0.149	100%
RP04	0.60198	0.345	161%	0.269	151%	0.155	96%	0.151	98%	0.149	100%
RP05	0.48158	0.347	162%	0.167	94%	0.158	98%	0.150	98%	0.146	98%
RP06	0.40132	0.348	162%	0.169	95%	0.158	98%	0.154	100%	0.148	100%
RP08	0.30099	0.245	114%	0.173	97%	0.161	99%	0.154	100%	0.148	100%
RP10	0.24079	0.224	105%	0.178	100%	0.164	101%	0.155	101%	0.151	102%
RP12	0.20066	0.237	111%	0.175	98%	0.164	101%	0.159	104%	0.152	102%
RP15	0.16053	0.203	95%	0.177	100%	0.165	102%	0.159	104%	0.153	103%
RP20	0.12040	0.209	98%	0.182	102%	0.166	103%	0.160	104%	0.156	105%

		A21		A22		A23		A24		A25	
	Opening (m)	0.610		0.914		1.219		1.524		1.829	
	h1 (m)	0.216		0.186		0.173		0.166		0.162	
	Grid Size	h1 (calc)	% of Exp	h1 (calc)	% of Exp	h1 (calc)	% of Exp	h1 (calc)	% of Exp	h1 (calc)	% of Exp
RP03	0.80264	0.371	172%	0.290	156%	0.224	130%	0.164	99%	0.162	100%
RP04	0.60198	0.373	173%	0.292	157%	0.226	131%	0.162	98%	0.161	99%
RP05	0.48158	0.374	173%	0.174	94%	0.168	97%	0.162	98%	0.159	98%
RP06	0.40132	0.374	173%	0.176	95%	0.169	98%	0.166	100%	0.162	100%
RP08	0.30099	0.376	174%	0.180	97%	0.170	99%	0.165	100%	0.161	99%
RP10	0.24079	0.214	99%	0.184	99%	0.172	100%	0.166	100%	0.163	101%
RP12	0.20066	0.226	105%	0.182	98%	0.173	100%	0.170	103%	0.164	101%
RP15	0.16053	0.204	95%	0.183	98%	0.173	100%	0.169	102%	0.164	101%
RP20	0.12040	0.209	97%	0.187	101%	0.175	101%	0.170	103%	0.167	103%

		A26		A27		A28		A29		A30	
	Opening (m)	0.610		0.914		1.219		1.524		1.829	
	h1 (m)	0.323		0.269		0.244		0.230		0.223	
	Grid Size	h1 (calc)	% of Exp	h1 (calc)	% of Exp	h1 (calc)	% of Exp	h1 (calc)	% of Exp	h1 (calc)	% of Exp
RP03	0.80264	0.508	157%	0.402	150%	0.310	127%	0.222	96%	0.220	98%
RP04	0.60198	0.510	158%	0.405	151%	0.226	93%	0.222	96%	0.221	99%
RP05	0.48158	0.512	158%	0.244	91%	0.233	95%	0.222	96%	0.219	98%
RP06	0.40132	0.511	158%	0.244	91%	0.232	95%	0.227	99%	0.219	98%
RP08	0.30099	0.440	136%	0.252	94%	0.235	96%	0.228	99%	0.221	99%
RP10	0.24079	0.305	94%	0.258	96%	0.240	98%	0.229	99%	0.225	101%
RP12	0.20066	0.348	108%	0.253	94%	0.238	97%	0.232	101%	0.224	100%
RP15	0.16053	0.294	91%	0.257	96%	0.241	99%	0.234	102%	0.227	102%
RP20	0.12040	0.302	93%	0.264	98%	0.242	99%	0.235	102%	0.231	103%

APPENDIX D: TUFLOW MODEL RESULTS – PIER MODELS

Model	Domain	Grid Size (m)	Pier Type	Pier Diam. (m)	No. Piers	h1	Method One		Method Two		Method Three	
							h1 (calc)	% exp	h1 (calc)	% exp	h1 (calc)	% exp
P01	RP03	0.803	sq	0.016	20	0.105	0.104	98.61%	0.104	98.61%	0.102	96.72%
	RP04	0.602	sq	0.016	20	0.105	0.104	98.61%	0.104	98.61%	0.102	96.72%
	RP05	0.482	sq	0.016	20	0.105	0.104	98.61%	0.104	98.61%	0.102	96.72%
	RP06	0.401	sq	0.016	20	0.105	0.104	98.61%	0.104	98.61%	0.102	96.72%
	RP08	0.301	sq	0.016	20	0.105	0.105	99.56%	0.105	99.56%	0.102	96.72%
	RP10	0.241	sq	0.016	20	0.105	0.105	99.56%	0.104	98.61%	0.103	97.67%
	RP12	0.201	sq	0.016	20	0.105	0.106	100.51%	0.105	99.56%	0.104	98.61%
	RP15	0.161	sq	0.016	20	0.105	0.108	102.41%	0.107	101.46%	0.106	100.51%
	RP20	0.120	sq	0.016	20	0.105	0.113	107.15%	0.113	107.15%	0.103	97.67%
P02	RP03	0.803	sq	0.016	16	0.105	0.103	98.52%	0.103	98.52%	0.102	97.56%
	RP04	0.602	sq	0.016	16	0.105	0.103	98.52%	0.103	98.52%	0.102	97.56%
	RP05	0.482	sq	0.016	16	0.105	0.103	98.52%	0.103	98.52%	0.102	97.56%
	RP06	0.401	sq	0.016	16	0.105	0.103	98.52%	0.103	98.52%	0.102	97.56%
	RP08	0.301	sq	0.016	16	0.105	0.104	99.48%	0.104	99.48%	0.102	97.56%
	RP10	0.241	sq	0.016	16	0.105	0.104	99.48%	0.103	98.52%	0.103	98.52%
	RP12	0.201	sq	0.016	16	0.105	0.104	99.48%	0.104	99.48%	0.103	98.52%
	RP15	0.161	sq	0.016	16	0.105	0.106	101.39%	0.105	100.43%	0.105	100.43%
	RP20	0.120	sq	0.016	16	0.105	0.111	106.17%	0.11	105.22%	0.101	96.61%
P03	RP03	0.803	sq	0.016	12	0.104	0.103	99.39%	0.103	99.39%	0.102	98.43%
	RP04	0.602	sq	0.016	12	0.104	0.103	99.39%	0.103	99.39%	0.102	98.43%
	RP05	0.482	sq	0.016	12	0.104	0.103	99.39%	0.103	99.39%	0.102	98.43%
	RP06	0.401	sq	0.016	12	0.104	0.102	98.43%	0.102	98.43%	0.102	98.43%
	RP08	0.301	sq	0.016	12	0.104	0.103	99.39%	0.103	99.39%	0.102	98.43%
	RP10	0.241	sq	0.016	12	0.104	0.103	99.39%	0.103	99.39%	0.102	98.43%
	RP12	0.201	sq	0.016	12	0.104	0.103	99.39%	0.103	99.39%	0.102	98.43%
	RP15	0.161	sq	0.016	12	0.104	0.104	100.36%	0.104	100.36%	0.103	99.39%
	RP20	0.120	sq	0.016	12	0.104	0.106	102.29%	0.106	102.29%	0.105	101.32%
P04	RP03	0.803	sq	0.016	8	0.103	0.102	99.01%	0.102	99.01%	0.102	99.01%
	RP04	0.602	sq	0.016	8	0.103	0.102	99.01%	0.102	99.01%	0.102	99.01%
	RP05	0.482	sq	0.016	8	0.103	0.102	99.01%	0.102	99.01%	0.102	99.01%
	RP06	0.401	sq	0.016	8	0.103	0.102	99.01%	0.102	99.01%	0.102	99.01%
	RP08	0.301	sq	0.016	8	0.103	0.102	99.01%	0.102	99.01%	0.102	99.01%
	RP10	0.241	sq	0.016	8	0.103	0.102	99.01%	0.102	99.01%	0.102	99.01%
	RP12	0.201	sq	0.016	8	0.103	0.102	99.01%	0.102	99.01%	0.102	99.01%
	RP15	0.161	sq	0.016	8	0.103	0.103	99.98%	0.103	99.98%	0.102	99.01%
	RP20	0.120	sq	0.016	8	0.103	0.104	100.95%	0.104	100.95%	0.103	99.98%
P05	RP03	0.803	sq	0.016	4	0.102	0.102	99.60%	0.102	99.60%	0.102	99.60%
	RP04	0.602	sq	0.016	4	0.102	0.102	99.60%	0.102	99.60%	0.102	99.60%
	RP05	0.482	sq	0.016	4	0.102	0.102	99.60%	0.102	99.60%	0.102	99.60%
	RP06	0.401	sq	0.016	4	0.102	0.102	99.60%	0.102	99.60%	0.102	99.60%
	RP08	0.301	sq	0.016	4	0.102	0.102	99.60%	0.102	99.60%	0.102	99.60%
	RP10	0.241	sq	0.016	4	0.102	0.102	99.60%	0.102	99.60%	0.102	99.60%
	RP12	0.201	sq	0.016	4	0.102	0.102	99.60%	0.102	99.60%	0.102	99.60%

Model	Domain	Grid Size (m)	Pier Type	Pier Diam. (m)	No. Piers	h1	Method One		Method Two		Method Three	
							h1 (calc)	% exp	h1 (calc)	% exp	h1 (calc)	% exp
	RP15	0.161	sq	0.016	4	0.102	0.102	99.60%	0.102	99.60%	0.102	99.60%
	RP20	0.120	sq	0.016	4	0.102	0.102	99.60%	0.102	99.60%	0.102	99.60%
P09	RP03	0.803	sq	0.016	16	0.112	0.112	99.85%	0.112	99.85%	0.111	98.96%
	RP04	0.602	sq	0.016	16	0.112	0.112	99.85%	0.112	99.85%	0.111	98.96%
	RP05	0.482	sq	0.016	16	0.112	0.112	99.85%	0.112	99.85%	0.111	98.96%
	RP06	0.401	sq	0.016	16	0.112	0.112	99.85%	0.112	99.85%	0.111	98.96%
	RP08	0.301	sq	0.016	16	0.112	0.113	100.74%	0.113	100.74%	0.111	98.96%
	RP10	0.241	sq	0.016	16	0.112	0.113	100.74%	0.113	100.74%	0.112	99.85%
	RP12	0.201	sq	0.016	16	0.112	0.114	101.63%	0.113	100.74%	0.112	99.85%
	RP15	0.161	sq	0.016	16	0.112	0.115	102.53%	0.115	102.53%	0.114	101.63%
	RP20	0.120	sq	0.016	16	0.112	0.121	107.88%	0.121	107.88%	0.111	98.96%
P10	RP03	0.803	sq	0.016	12	0.112	0.112	100.40%	0.112	100.40%	0.111	99.50%
	RP04	0.602	sq	0.016	12	0.112	0.112	100.40%	0.112	100.40%	0.111	99.50%
	RP05	0.482	sq	0.016	12	0.112	0.112	100.40%	0.112	100.40%	0.111	99.50%
	RP06	0.401	sq	0.016	12	0.112	0.112	100.40%	0.112	100.40%	0.111	99.50%
	RP08	0.301	sq	0.016	12	0.112	0.112	100.40%	0.112	100.40%	0.111	99.50%
	RP10	0.241	sq	0.016	12	0.112	0.112	100.40%	0.112	100.40%	0.111	99.50%
	RP12	0.201	sq	0.016	12	0.112	0.112	100.40%	0.112	100.40%	0.112	100.40%
	RP15	0.161	sq	0.016	12	0.112	0.114	102.19%	0.113	101.29%	0.113	101.29%
	RP20	0.120	sq	0.016	12	0.112	0.116	103.98%	0.115	103.09%	0.115	103.09%
P11	RP03	0.803	sq	0.016	8	0.111	0.111	100.05%	0.111	100.05%	0.111	100.05%
	RP04	0.602	sq	0.016	8	0.111	0.112	100.95%	0.112	100.95%	0.111	100.05%
	RP05	0.482	sq	0.016	8	0.111	0.111	100.05%	0.111	100.05%	0.111	100.05%
	RP06	0.401	sq	0.016	8	0.111	0.111	100.05%	0.111	100.05%	0.111	100.05%
	RP08	0.301	sq	0.016	8	0.111	0.112	100.95%	0.111	100.05%	0.111	100.05%
	RP10	0.241	sq	0.016	8	0.111	0.111	100.05%	0.111	100.05%	0.111	100.05%
	RP12	0.201	sq	0.016	8	0.111	0.111	100.05%	0.111	100.05%	0.111	100.05%
	RP15	0.161	sq	0.016	8	0.111	0.112	100.95%	0.112	100.95%	0.112	100.95%
	RP20	0.120	sq	0.016	8	0.111	0.113	101.85%	0.113	101.85%	0.113	101.85%
P15	RP03	0.803	sq	0.016	12	0.150	0.15	100.03%	0.15	100.03%	0.148	98.69%
	RP04	0.602	sq	0.016	12	0.150	0.15	100.03%	0.15	100.03%	0.148	98.69%
	RP05	0.482	sq	0.016	12	0.150	0.15	100.03%	0.15	100.03%	0.148	98.69%
	RP06	0.401	sq	0.016	12	0.150	0.149	99.36%	0.149	99.36%	0.148	98.69%
	RP08	0.301	sq	0.016	12	0.150	0.15	100.03%	0.15	100.03%	0.148	98.69%
	RP10	0.241	sq	0.016	12	0.150	0.15	100.03%	0.15	100.03%	0.149	99.36%
	RP12	0.201	sq	0.016	12	0.150	0.151	100.69%	0.15	100.03%	0.149	99.36%
	RP15	0.161	sq	0.016	12	0.150	0.152	101.36%	0.152	101.36%	0.151	100.69%
	RP20	0.120	sq	0.016	12	0.150	0.155	103.36%	0.154	102.69%	0.153	102.03%
P16	RP03	0.803	sq	0.016	16	0.151	0.151	100.08%	0.151	100.08%	0.148	98.09%
	RP04	0.602	sq	0.016	16	0.151	0.151	100.08%	0.151	100.08%	0.148	98.09%
	RP05	0.482	sq	0.016	16	0.151	0.151	100.08%	0.151	100.08%	0.148	98.09%
	RP06	0.401	sq	0.016	16	0.151	0.15	99.42%	0.15	99.42%	0.148	98.09%
	RP08	0.301	sq	0.016	16	0.151	0.151	100.08%	0.151	100.08%	0.148	98.09%

Model	Domain	Grid Size (m)	Pier Type	Pier Diam. (m)	No. Piers	h1	Method One		Method Two		Method Three	
							h1 (calc)	% exp	h1 (calc)	% exp	h1 (calc)	% exp
	RP10	0.241	sq	0.016	16	0.151	0.152	100.74%	0.151	100.08%	0.149	98.76%
	RP12	0.201	sq	0.016	16	0.151	0.152	100.74%	0.152	100.74%	0.15	99.42%
	RP15	0.161	sq	0.016	16	0.151	0.155	102.73%	0.154	102.07%	0.152	100.74%
	RP20	0.120	sq	0.016	16	0.151	0.162	107.37%	0.162	107.37%	0.148	98.09%
P17	RP03	0.803	sq	0.016	20	0.152	0.152	99.94%	0.152	99.94%	0.148	97.31%
	RP04	0.602	sq	0.016	20	0.152	0.152	99.94%	0.152	99.94%	0.148	97.31%
	RP05	0.482	sq	0.016	20	0.152	0.152	99.94%	0.152	99.94%	0.148	97.31%
	RP06	0.401	sq	0.016	20	0.152	0.152	99.94%	0.152	99.94%	0.148	97.31%
	RP08	0.301	sq	0.016	20	0.152	0.153	100.59%	0.153	100.59%	0.148	97.31%
	RP10	0.241	sq	0.016	20	0.152	0.154	101.25%	0.153	100.59%	0.15	98.62%
	RP12	0.201	sq	0.016	20	0.152	0.155	101.91%	0.154	101.25%	0.151	99.28%
	RP15	0.161	sq	0.016	20	0.152	0.158	103.88%	0.157	103.22%	0.155	101.91%
	RP20	0.120	sq	0.016	20	0.152	0.165	108.48%	0.165	108.48%	0.15	98.62%
P18	RP03	0.803	rn	0.016	16	0.111	0.113	101.85%	0.113	101.85%		
	RP04	0.602	rn	0.016	16	0.111	0.113	101.85%	0.113	101.85%		
	RP05	0.482	rn	0.016	16	0.111	0.113	101.85%	0.113	101.85%		
	RP06	0.401	rn	0.016	16	0.111	0.112	100.95%	0.112	100.95%		
	RP08	0.301	rn	0.016	16	0.111	0.113	101.85%	0.113	101.85%		
	RP10	0.241	rn	0.016	16	0.111	0.113	101.85%	0.113	101.85%		
	RP12	0.201	rn	0.016	16	0.111	0.114	102.75%	0.114	102.75%		
	RP15	0.161	rn	0.016	16	0.111	0.116	104.55%	0.115	103.65%		
	RP20	0.120	rn	0.016	16	0.111	0.121	109.06%	0.121	109.06%		
P27	RP03	0.803	rn	0.016	12	0.149	0.15	100.85%	0.15	100.85%		
	RP04	0.602	rn	0.016	12	0.149	0.15	100.85%	0.15	100.85%		
	RP05	0.482	rn	0.016	12	0.149	0.15	100.85%	0.15	100.85%		
	RP06	0.401	rn	0.016	12	0.149	0.15	100.85%	0.15	100.85%		
	RP08	0.301	rn	0.016	12	0.149	0.15	100.85%	0.15	100.85%		
	RP10	0.241	rn	0.016	12	0.149	0.15	100.85%	0.15	100.85%		
	RP12	0.201	rn	0.016	12	0.149	0.151	101.52%	0.151	101.52%		
	RP15	0.161	rn	0.016	12	0.149	0.152	102.19%	0.152	102.19%		
	RP20	0.120	rn	0.016	12	0.149	0.155	104.21%	0.154	103.53%		
P28	RP03	0.803	rn	0.016	16	0.149	0.151	101.10%	0.151	101.10%		
	RP04	0.602	rn	0.016	16	0.149	0.151	101.10%	0.151	101.10%		
	RP05	0.482	rn	0.016	16	0.149	0.151	101.10%	0.151	101.10%		
	RP06	0.401	rn	0.016	16	0.149	0.151	101.10%	0.151	101.10%		
	RP08	0.301	rn	0.016	16	0.149	0.152	101.77%	0.152	101.77%		
	RP10	0.241	rn	0.016	16	0.149	0.152	101.77%	0.151	101.10%		
	RP12	0.201	rn	0.016	16	0.149	0.153	102.44%	0.152	101.77%		
	RP15	0.161	rn	0.016	16	0.149	0.155	103.78%	0.154	103.11%		
	RP20	0.120	rn	0.016	16	0.149	0.162	108.47%	0.162	108.47%		
P29	RP03	0.803	rn	0.032	8	0.149	0.151	101.10%	0.151	101.10%		
	RP04	0.602	rn	0.032	8	0.149	0.151	101.10%	0.151	101.10%		
	RP05	0.482	rn	0.032	8	0.149	0.151	101.10%	0.151	101.10%		

Model	Domain	Grid Size (m)	Pier Type	Pier Diam. (m)	No. Piers	h1	Method One		Method Two		Method Three	
							h1 (calc)	% exp	h1 (calc)	% exp	h1 (calc)	% exp
	RP06	0.401	rn	0.032	8	0.149	0.151	101.10%	0.151	101.10%		
	RP08	0.301	rn	0.032	8	0.149	0.152	101.77%	0.151	101.10%		
	RP10	0.241	rn	0.032	8	0.149	0.152	101.77%	0.151	101.10%		
	RP12	0.201	rn	0.032	8	0.149	0.153	102.44%	0.152	101.77%		
	RP15	0.161	rn	0.032	8	0.149	0.155	103.78%	0.153	102.44%		
	RP20	0.120	rn	0.032	8	0.149	0.162	108.47%	0.161	107.80%		
	RP03	0.803	rn	0.032	6	0.149	0.15	100.85%	0.15	100.85%		
	RP04	0.602	rn	0.032	6	0.149	0.15	100.85%	0.15	100.85%		
	RP05	0.482	rn	0.032	6	0.149	0.15	100.85%	0.15	100.85%		
	RP06	0.401	rn	0.032	6	0.149	0.15	100.85%	0.149	100.17%		
P30	RP08	0.301	rn	0.032	6	0.149	0.15	100.85%	0.15	100.85%		
	RP10	0.241	rn	0.032	6	0.149	0.15	100.85%	0.15	100.85%		
	RP12	0.201	rn	0.032	6	0.149	0.151	101.52%	0.15	100.85%		
	RP15	0.161	rn	0.032	6	0.149	0.152	102.19%	0.151	101.52%		
	RP20	0.120	rn	0.032	6	0.149	0.155	104.21%	0.154	103.53%		
	RP03	0.803	ss	0.016	16	0.111	0.112	101.23%	0.112	101.23%		
	RP04	0.602	ss	0.016	16	0.111	0.112	101.23%	0.112	101.23%		
	RP05	0.482	ss	0.016	16	0.111	0.112	101.23%	0.112	101.23%		
	RP06	0.401	ss	0.016	16	0.111	0.112	101.23%	0.112	101.23%		
P33	RP08	0.301	ss	0.016	16	0.111	0.113	102.13%	0.113	102.13%		
	RP10	0.241	ss	0.016	16	0.111	0.113	102.13%	0.113	102.13%		
	RP12	0.201	ss	0.016	16	0.111	0.113	102.13%	0.113	102.13%		
	RP15	0.161	ss	0.016	16	0.111	0.115	103.94%	0.115	103.94%		
	RP20	0.120	ss	0.016	16	0.111	0.121	109.36%	0.121	109.36%		
	RP03	0.803	ss	0.091	4	0.131	0.134	102.48%	0.134	102.48%		
	RP04	0.602	ss	0.091	4	0.131	0.133	101.71%	0.133	101.71%		
	RP05	0.482	ss	0.091	4	0.131	0.133	101.71%	0.131	100.18%		
	RP06	0.401	ss	0.091	4	0.131	0.134	102.48%	0.132	100.95%		
P38	RP08	0.301	ss	0.091	4	0.131	0.135	103.24%	0.132	100.95%		
	RP10	0.241	ss	0.091	4	0.131	0.137	104.77%	0.134	102.48%		
	RP12	0.201	ss	0.091	4	0.131	0.139	106.30%	0.136	104.01%		
	RP15	0.161	ss	0.091	4	0.131	0.147	112.42%	0.145	110.89%		
	RP20	0.120	ss	0.091	4	0.131	0.153	117.01%	0.15	114.71%		
	RP03	0.803	ss	0.091	2	0.129	0.13	100.83%	0.129	100.05%		
	RP04	0.602	ss	0.091	2	0.129	0.13	100.83%	0.129	100.05%		
	RP05	0.482	ss	0.091	2	0.129	0.13	100.83%	0.129	100.05%		
	RP06	0.401	ss	0.091	2	0.129	0.13	100.83%	0.129	100.05%		
P39	RP08	0.301	ss	0.091	2	0.129	0.13	100.83%	0.129	100.05%		
	RP10	0.241	ss	0.091	2	0.129	0.131	101.61%	0.129	100.05%		
	RP12	0.201	ss	0.091	2	0.129	0.131	101.61%	0.13	100.83%		
	RP15	0.161	ss	0.091	2	0.129	0.133	103.16%	0.131	101.61%		
	RP20	0.120	ss	0.091	2	0.129	0.136	105.48%	0.134	103.93%		
P41	RP03	0.803	ss	0.091	4	0.150	0.152	101.36%	0.152	101.36%		

Model	Domain	Grid Size (m)	Pier Type	Pier Diam. (m)	No. Piers	h1	Method One		Method Two		Method Three	
							h1 (calc)	% exp	h1 (calc)	% exp	h1 (calc)	% exp
	RP04	0.602	ss	0.091	4	0.150	0.152	101.36%	0.152	101.36%		
	RP05	0.482	ss	0.091	4	0.150	0.152	101.36%	0.151	100.69%		
	RP06	0.401	ss	0.091	4	0.150	0.152	101.36%	0.151	100.69%		
	RP08	0.301	ss	0.091	4	0.150	0.154	102.69%	0.152	101.36%		
	RP10	0.241	ss	0.091	4	0.150	0.154	102.69%	0.152	101.36%		
	RP12	0.201	ss	0.091	4	0.150	0.156	104.03%	0.154	102.69%		
	RP15	0.161	ss	0.091	4	0.150	0.163	108.69%	0.162	108.03%		
	RP20	0.120	ss	0.091	4	0.150	0.168	112.03%	0.166	110.70%		
P43	RP03	0.803	ss	0.061	4	0.149	0.15	100.43%	0.15	100.43%		
	RP04	0.602	ss	0.061	4	0.149	0.15	100.43%	0.15	100.43%		
	RP05	0.482	ss	0.061	4	0.149	0.15	100.43%	0.149	99.76%		
	RP06	0.401	ss	0.061	4	0.149	0.15	100.43%	0.149	99.76%		
	RP08	0.301	ss	0.061	4	0.149	0.151	101.10%	0.15	100.43%		
	RP10	0.241	ss	0.061	4	0.149	0.151	101.10%	0.15	100.43%		
	RP12	0.201	ss	0.061	4	0.149	0.152	101.77%	0.151	101.10%		
	RP15	0.161	ss	0.061	4	0.149	0.154	103.11%	0.153	102.44%		
	RP20	0.120	ss	0.061	4	0.149	0.161	107.80%	0.16	107.13%		
P46	RP03	0.803	ss	0.032	6	0.149	0.149	99.76%	0.149	99.76%		
	RP04	0.602	ss	0.032	6	0.149	0.15	100.43%	0.15	100.43%		
	RP05	0.482	ss	0.032	6	0.149	0.149	99.76%	0.149	99.76%		
	RP06	0.401	ss	0.032	6	0.149	0.149	99.76%	0.149	99.76%		
	RP08	0.301	ss	0.032	6	0.149	0.15	100.43%	0.15	100.43%		
	RP10	0.241	ss	0.032	6	0.149	0.15	100.43%	0.149	99.76%		
	RP12	0.201	ss	0.032	6	0.149	0.15	100.43%	0.15	100.43%		
	RP15	0.161	ss	0.032	6	0.149	0.152	101.77%	0.151	101.10%		
	RP20	0.120	ss	0.032	6	0.149	0.155	103.78%	0.154	103.11%		
P47	RP03	0.803	ss	0.032	8	0.150	0.15	100.03%	0.15	100.03%		
	RP04	0.602	ss	0.032	8	0.150	0.15	100.03%	0.15	100.03%		
	RP05	0.482	ss	0.032	8	0.150	0.15	100.03%	0.15	100.03%		
	RP06	0.401	ss	0.032	8	0.150	0.15	100.03%	0.15	100.03%		
	RP08	0.301	ss	0.032	8	0.150	0.151	100.69%	0.15	100.03%		
	RP10	0.241	ss	0.032	8	0.150	0.151	100.69%	0.151	100.69%		
	RP12	0.201	ss	0.032	8	0.150	0.152	101.36%	0.151	100.69%		
	RP15	0.161	ss	0.032	8	0.150	0.154	102.69%	0.153	102.03%		
	RP20	0.120	ss	0.032	8	0.150	0.161	107.36%	0.161	107.36%		
P51	RP03	0.803	ds	0.016	16	0.112	0.113	101.29%	0.113	101.29%		
	RP04	0.602	ds	0.016	16	0.112	0.113	101.29%	0.113	101.29%		
	RP05	0.482	ds	0.016	16	0.112	0.113	101.29%	0.113	101.29%		
	RP06	0.401	ds	0.016	16	0.112	0.113	101.29%	0.113	101.29%		
	RP08	0.301	ds	0.016	16	0.112	0.114	102.19%	0.114	102.19%		
	RP10	0.241	ds	0.016	16	0.112	0.114	102.19%	0.113	101.29%		
	RP12	0.201	ds	0.016	16	0.112	0.115	103.09%	0.114	102.19%		
	RP15	0.161	ds	0.016	16	0.112	0.116	103.98%	0.116	103.98%		

Model	Domain	Grid Size (m)	Pier Type	Pier Diam. (m)	No. Piers	h1	Method One		Method Two		Method Three	
							h1 (calc)	% exp	h1 (calc)	% exp	h1 (calc)	% exp
	RP20	0.120	ds	0.016	16	0.112	0.122	109.36%	0.121	108.46%		
P52	RP03	0.803	ds	0.016	12	0.111	0.112	101.23%	0.112	101.23%		
	RP04	0.602	ds	0.016	12	0.111	0.112	101.23%	0.112	101.23%		
	RP05	0.482	ds	0.016	12	0.111	0.112	101.23%	0.112	101.23%		
	RP06	0.401	ds	0.016	12	0.111	0.112	101.23%	0.112	101.23%		
	RP08	0.301	ds	0.016	12	0.111	0.113	102.13%	0.113	102.13%		
	RP10	0.241	ds	0.016	12	0.111	0.113	102.13%	0.112	101.23%		
	RP12	0.201	ds	0.016	12	0.111	0.113	102.13%	0.113	102.13%		
	RP15	0.161	ds	0.016	12	0.111	0.114	103.03%	0.114	103.03%		
	RP20	0.120	ds	0.016	12	0.111	0.116	104.84%	0.115	103.94%		
P54	RP03	0.803	ds	0.032	8	0.111	0.113	101.85%	0.113	101.85%		
	RP04	0.602	ds	0.032	8	0.111	0.113	101.85%	0.113	101.85%		
	RP05	0.482	ds	0.032	8	0.111	0.113	101.85%	0.113	101.85%		
	RP06	0.401	ds	0.032	8	0.111	0.113	101.85%	0.113	101.85%		
	RP08	0.301	ds	0.032	8	0.111	0.114	102.75%	0.113	101.85%		
	RP10	0.241	ds	0.032	8	0.111	0.114	102.75%	0.113	101.85%		
	RP12	0.201	ds	0.032	8	0.111	0.115	103.65%	0.114	102.75%		
	RP15	0.161	ds	0.032	8	0.111	0.116	104.55%	0.115	103.65%		
	RP20	0.120	ds	0.032	8	0.111	0.122	109.96%	0.121	109.06%		
P57	RP03	0.803	ds	0.032	8	0.151	0.152	100.74%	0.152	100.74%		
	RP04	0.602	ds	0.032	8	0.151	0.152	100.74%	0.152	100.74%		
	RP05	0.482	ds	0.032	8	0.151	0.152	100.74%	0.152	100.74%		
	RP06	0.401	ds	0.032	8	0.151	0.152	100.74%	0.152	100.74%		
	RP08	0.301	ds	0.032	8	0.151	0.153	101.41%	0.152	100.74%		
	RP10	0.241	ds	0.032	8	0.151	0.153	101.41%	0.152	100.74%		
	RP12	0.201	ds	0.032	8	0.151	0.154	102.07%	0.152	100.74%		
	RP15	0.161	ds	0.032	8	0.151	0.156	103.40%	0.154	102.07%		
	RP20	0.120	ds	0.032	8	0.151	0.163	108.04%	0.161	106.71%		
P58	RP03	0.803	ds	0.032	6	0.150	0.151	100.69%	0.151	100.69%		
	RP04	0.602	ds	0.032	6	0.150	0.151	100.69%	0.151	100.69%		
	RP05	0.482	ds	0.032	6	0.150	0.151	100.69%	0.151	100.69%		
	RP06	0.401	ds	0.032	6	0.150	0.15	100.03%	0.15	100.03%		
	RP08	0.301	ds	0.032	6	0.150	0.151	100.69%	0.15	100.03%		
	RP10	0.241	ds	0.032	6	0.150	0.151	100.69%	0.15	100.03%		
	RP12	0.201	ds	0.032	6	0.150	0.152	101.36%	0.15	100.03%		
	RP15	0.161	ds	0.032	6	0.150	0.153	102.03%	0.151	100.69%		
	RP20	0.120	ds	0.032	6	0.150	0.156	104.03%	0.154	102.69%		
P59	RP03	0.803	ds	0.032	4	0.149	0.149	99.97%	0.149	99.97%		
	RP04	0.602	ds	0.032	4	0.149	0.15	100.64%	0.15	100.64%		
	RP05	0.482	ds	0.032	4	0.149	0.149	99.97%	0.149	99.97%		
	RP06	0.401	ds	0.032	4	0.149	0.149	99.97%	0.149	99.97%		
	RP08	0.301	ds	0.032	4	0.149	0.15	100.64%	0.149	99.97%		
	RP10	0.241	ds	0.032	4	0.149	0.15	100.64%	0.149	99.97%		

Model	Domain	Grid Size (m)	Pier Type	Pier Diam. (m)	No. Piers	h1	Method One		Method Two		Method Three	
							h1 (calc)	% exp	h1 (calc)	% exp	h1 (calc)	% exp
	RP12	0.201	ds	0.032	4	0.149	0.15	100.64%	0.149	99.97%		
	RP15	0.161	ds	0.032	4	0.149	0.151	101.31%	0.15	100.64%		
	RP20	0.120	ds	0.032	4	0.149	0.152	101.98%	0.151	101.31%		
P60	RP03	0.803	ds	0.016	16	0.150	0.152	101.57%	0.152	101.57%		
	RP04	0.602	ds	0.016	16	0.150	0.152	101.57%	0.152	101.57%		
	RP05	0.482	ds	0.016	16	0.150	0.152	101.57%	0.152	101.57%		
	RP06	0.401	ds	0.016	16	0.150	0.152	101.57%	0.152	101.57%		
	RP08	0.301	ds	0.016	16	0.150	0.153	102.23%	0.153	102.23%		
	RP10	0.241	ds	0.016	16	0.150	0.153	102.23%	0.152	101.57%		
	RP12	0.201	ds	0.016	16	0.150	0.154	102.90%	0.153	102.23%		
	RP15	0.161	ds	0.016	16	0.150	0.156	104.24%	0.155	103.57%		
	RP20	0.120	ds	0.016	16	0.150	0.163	108.92%	0.163	108.92%		
P61	RP03	0.803	ds	0.016	12	0.149	0.151	101.10%	0.151	101.10%		
	RP04	0.602	ds	0.016	12	0.149	0.151	101.10%	0.151	101.10%		
	RP05	0.482	ds	0.016	12	0.149	0.151	101.10%	0.151	101.10%		
	RP06	0.401	ds	0.016	12	0.149	0.15	100.43%	0.15	100.43%		
	RP08	0.301	ds	0.016	12	0.149	0.151	101.10%	0.151	101.10%		
	RP10	0.241	ds	0.016	12	0.149	0.151	101.10%	0.15	100.43%		
	RP12	0.201	ds	0.016	12	0.149	0.152	101.77%	0.151	101.10%		
	RP15	0.161	ds	0.016	12	0.149	0.153	102.44%	0.152	101.77%		
	RP20	0.120	ds	0.016	12	0.149	0.156	104.45%	0.155	103.78%		
P62	RP03	0.803	ds	0.016	8	0.149	0.149	100.17%	0.149	100.17%		
	RP04	0.602	ds	0.016	8	0.149	0.15	100.85%	0.15	100.85%		
	RP05	0.482	ds	0.016	8	0.149	0.149	100.17%	0.149	100.17%		
	RP06	0.401	ds	0.016	8	0.149	0.149	100.17%	0.149	100.17%		
	RP08	0.301	ds	0.016	8	0.149	0.15	100.85%	0.149	100.17%		
	RP10	0.241	ds	0.016	8	0.149	0.15	100.85%	0.149	100.17%		
	RP12	0.201	ds	0.016	8	0.149	0.15	100.85%	0.149	100.17%		
	RP15	0.161	ds	0.016	8	0.149	0.151	101.52%	0.15	100.85%		
	RP20	0.120	ds	0.016	8	0.149	0.152	102.19%	0.151	101.52%		

APPENDIX E: ABSTRACT SUBMITTED TO THE 7TH BIENNIAL VICTORIAN FLOODPLAIN MANAGERS CONFERENCE

Backwater Effects of Bridge Piers and Abutments in 2D – Replication of Physical Model Tests in a 2D Hydrodynamic Model

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Abstract

Bridge embankments and structures can significantly influence flooding patterns and levels on floodplains. It is important to reliably estimate these influences to properly understand and mitigate their impacts to properties and communities on the floodplain. The literature (Austroads 1994; Bradley 1978) provides details of how to estimate contraction and expansion losses and pier losses for desktop analysis. However, limited guidance is provided as to the application of these losses in a 2D modeling environment. As 2D flood modeling is now the industry standard for floodplain investigations, further guidance is required as to the application of the data presented in the literature.

BMT WBM is currently undertaking research that involves the replication of physical flume models tests (undertaken at Colorado State University by Liu, Bradley and Plate, 1957) in the 2D hydraulic model, TUFLOW. The data from these physical flume tests formed the basis of all current literature into the contraction and expansion losses and pier losses of bridges. This paper will present the research that has been undertaken by BMT WBM and discuss its implications for the representation of key structures in 2D flood models.

APPENDIX F: PRESENTATION MADE TO THE 7TH BIENNIAL VICTORIAN FLOODPLAIN MANAGERS CONFERENCE

BMT WBM

"Where will our knowledge take you?"

TUFLOW

Flood and Tide Simulation Software

Backwater Effects of Piers and Abutments in a 2D Hydraulic Model

Joel Leister and Mark Jempson

Bendigo - 9 November 2010

Outline

- Introduction to the Research
- Brief Introduction into Bridge Hydraulics
- What does the Literature Say?
- Methodology
- Results / Discussion
- Recommendations and Conclusions

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Introduction to the Research

- To determine appropriate techniques for modelling energy losses associated with bridge constrictions when using a 2D hydraulic modelling scheme (TUFLOW).
- Specifically, the research was aimed at two hypothesises:
  - That a 2D modelling scheme can reproduce the contraction and expansion losses associated with flow through a constriction; and
  - That the energy loss coefficients documented in the literature for bridge piers can be applied to a 2D modelling scheme to determine the upstream afflux.
- Why is this important?
  - There is currently no guidance in industry on the application of losses in a 2D modelling environment, in particular, the losses associated with contraction and expansion through a constriction and piers.

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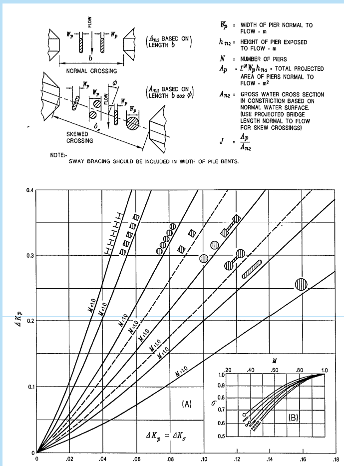
Brief Introduction into Bridge Hydraulics

- The backwater of a structure is the result of the energy losses from a number of factors associated with the constriction of flow, including:
  - Presence of Abutments
  - Number, Type and Size of Piers
  - Eccentricity
  - A Submerged Bridge Deck
- The methods and values of calculating backwater are based on the work of Bradley (1978). The methods documented by Bradley (1978) are based the results of model tests (Liu et al 1957) and verified by field measurements.



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What does the literature say?

- “Backwater Effects of Piers and Abutments”, Liu et al (1957)
- “Hydraulics of Bridge Waterways”, Bradley (1978)
- “Waterway Design – A Guide to the Hydraulic Design of Bridges, Culverts and Floodways”, Austroads (1994)

- A large volume of work has been undertaken to determine a 1D model’s ability to simulate the backwater caused by a bridge constriction.
- Barton (2001) sought to address the “perceived lack of understanding in the ability of 2D models to portray the energy losses” through a contraction.
- Syme et al (2009) describes how a 2D modelling scheme will inherently model some of the losses associated with the expansion and contraction of flow and that the dilemma for the modeller is how much additional energy loss needs to be applied.
- In recent times, research has been undertaken to improve the understanding of 2D model’s ability to represent the backwater effects of a bridge constriction.

BMT WBM TUFLOW

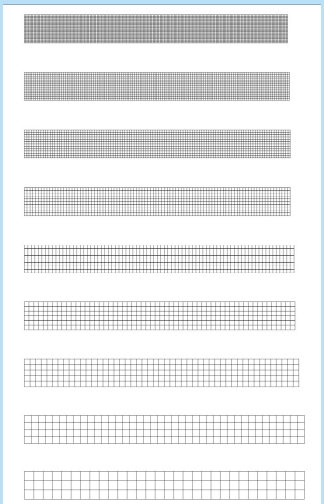
Methodology

Base Case Flume Models

- The physical flume used by Liu et al (1957) was replicated in TUFLOW using a variety of element (grid) sizes (9 grid sizes were used).

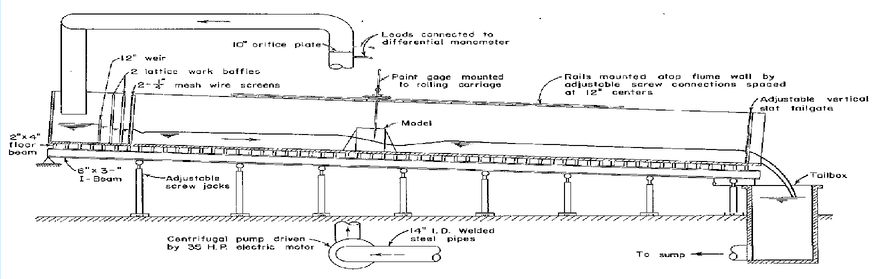
- Each base case model was run to determine if the normal depth determined by TUFLOW replicated (within reasonable bounds) the normal depth measured by Liu et al (1957).

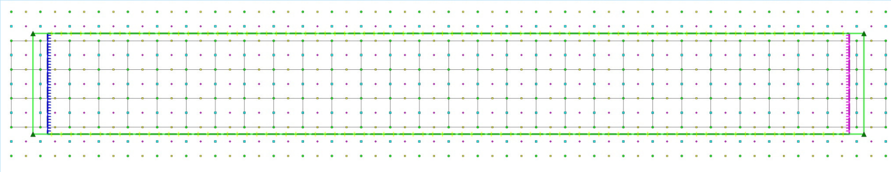
- The Manning’s ‘n’ value was adjusted until a match was achieved.



BMT WBM TUFLOW

Methodology





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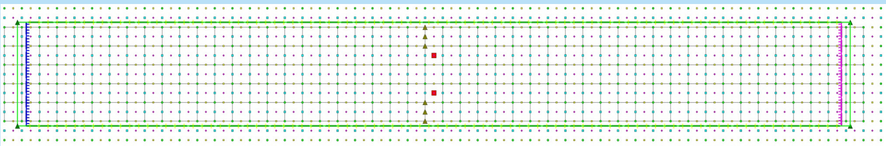
TUFLOW

Methodology

Abutment Flume Models

- Constrictions of varying sizes (2, 3, 4, 5 and 6 foot) were modelled in TUFLOW.
- The abutments were modelled by modifying the topography of the flume to ensure the available flow width matched the modelled opening.



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TUFLOW

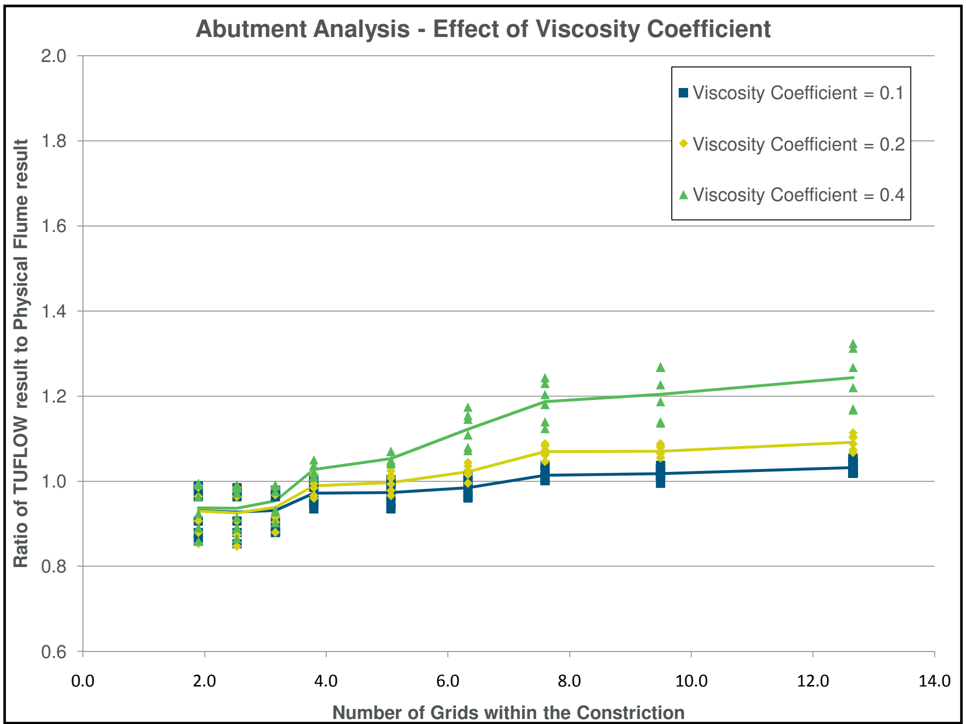
Methodology

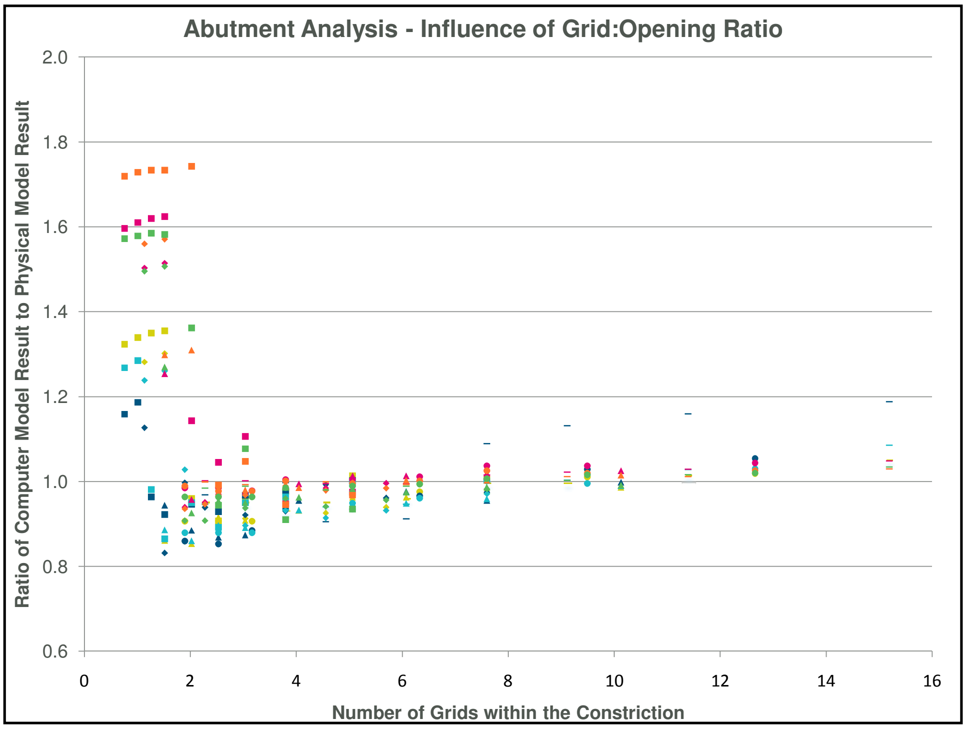
Pier Flume Models

- Four piers types were modelled (Single Circular Column, Twin Circular Column, Square Column and Blade with Rounded Nose)

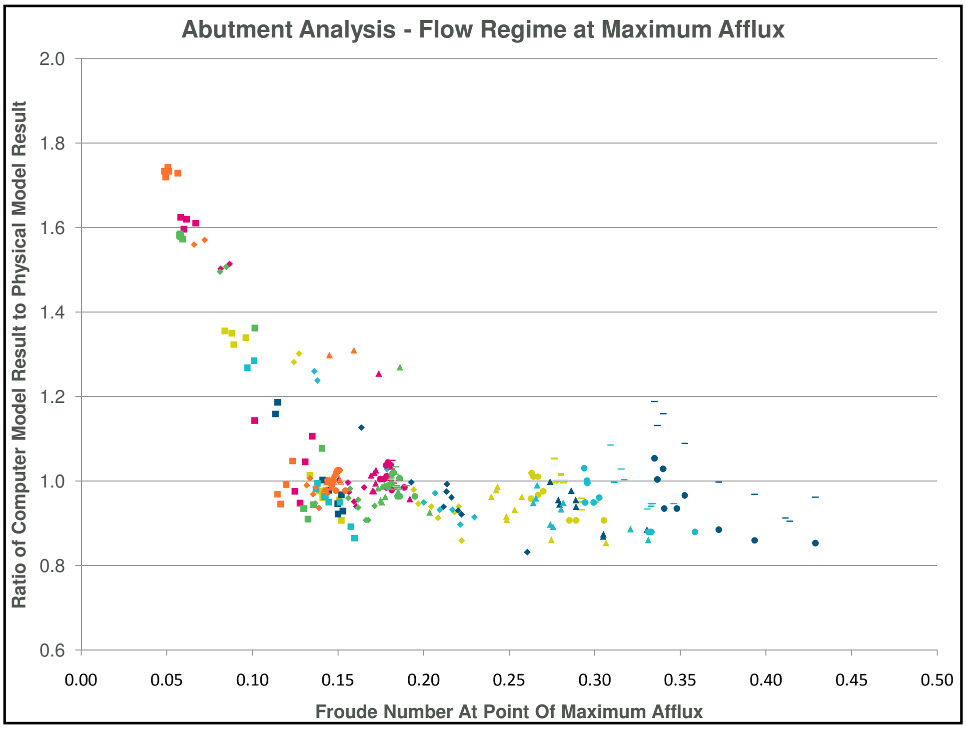
- Piers are traditionally modelled in three ways:
  - Apply a form loss coefficient to represent the energy losses due to the pier
    - Either across all cells within the cross section
    - Only to the cells that contain a pier
  - Blocking part of an individual cells that contain a pier
  - A Combination of the methods above

BMT WBM TUFLOW





Abutment Analysis - Influence of Grid:Opening Ratio
Ratio of Computer Model Result to Physical Model Result
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0
2
4
6
8
10
12
14
16
Number of Grids within the Constriction



Abutment Analysis - Flow Regime at Maximum Afflux
Ratio of Computer Model Result to Physical Model Result
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
Froude Number At Point Of Maximum Afflux

Recommendations and Conclusions

- Across most flow conditions, the 2D model was able to reproduce the physical model results
- The default viscosity coefficient of 0.2 provides reasonable performance when modelling constrictions but decreasing it to 0.1 would marginally improve performance when number of grids within the constriction exceeds about 6
- The number of elements within a constriction can significantly influence the model's ability to reproduce losses through a constriction
  - Significantly over-estimate losses if small opening is only 1 or 2 grids wide
  - Ideally, 6-8 grids should exist within the constriction

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Recommendations and Conclusions

- Modelling piers through the partial blockage of cells will underestimate the afflux when compared to results from the physical model
- The direct application of an energy loss derived from the literature (eg Austroads) will result in a modelled afflux comparable to the physical model results
- Applying the form loss coefficient to only the cells that contain piers provides a closer match to the physical model results.
- Where available, calibration data should always be used to verify the performance of structures within the floodplain

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Thankyou / Questions

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