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Benchmarking Hydraulic River Modelling Software Packages

Results – Test J (Bridges)

R&D Technical Report: W5-105/TR2J

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TECHNICAL REPORT W5-105/TR2J

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Statement of use
This document provides the results and findings from undertaking the Environment Agency's Benchmarking Test J (Bridges) for hydraulic river modelling software. The results only relate to the ISIS, MIKE 11 and HEC-RAS software packages and inference to the likely performance to other software packages should not be made.

The findings are intended to be a supplementary resource for Defra and Agency staff, research contractors and consultants, academics and students for assessing the applicability of any one of these software packages for their own modelling requirements. This report should not be considered in isolation and should be read in conjunction with the other tests reports produced as part of this R&D project.

Keywords
Hydraulic Modelling, River Modelling, Benchmarking, Test Specifications, Bridges, Arched Bridge, Flat Soffit Bridge

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EXECUTIVE SUMMARY

The undertaking of this test has proven to be possible with all software packages.

There were significant differences between the steady state and quasi-steady state solutions for MIKE 11 and HEC-RAS.

The results for ISIS are significantly different from the measured data and the other packages. The ISIS Technical Support Team have indicated that this is due to a deficiency in the software (at low flows) which is due to be corrected.

The low flows considered here may not be ideal for evaluating the packages and it is recommended that research be carried out with full-scale measurements and three-dimensional computation fluid dynamics.

It is concluded that whilst each software package can be used for modelling bridges the modeller may wish to consider the use of HEC-RAS in steady state mode as a cross check method/procedure when using ISIS or MIKE 11.

CONTENTS

Appendices

List of Tables

List of Figures

1 INTRODUCTION

1.1 Background

This report presents the results and findings from Test J (Bridges) of the Environment Agency of England and Wales (EA), Benchmarking and Scoping Study (2004). The study, which encompasses a series of tests, is intended to be an independent research investigation into the accuracy, capability and suitability of the following one-dimensional hydraulic river modelling software packages:

Software	Version		Developer
ISIS	User Interface:	2.0 (13/01/01)	Halcrow /
	Flow Engine:	5.0.1 (27/06/01)	Wallingford Software
MIKE11	User Interface:	Build 5-052 (2001b)	DHI Water and Environment
	Flow Engine:	5.0.5.5	
HEC-RAS	User Interface:	3.1.0 (Beta) (03/02)	US Corps of Engineers
	Pre-processor:	3.1.0 (Beta) (03/02)	
	Steady Flow Engine:	3.1.0 (Beta) (03/02)	
	Unsteady Flow Engine:	3.1.0 (Beta) (03/02)	
	Post-processor:	3.1.0 (Beta) (03/02)	

Each of the above software packages was tested in the previously undertaken benchmarking study (Crowder *et al*, 1997). They are currently on the EA's BIS-A list of software packages for one-dimensional hydraulic river modelling.

The test has been undertaken on behalf of the EA by the following team in accordance with the Benchmarking Test Specification - Test J (Bridges), (Crowder *et al,* 2004):

	Role	Affiliation
Mr Andrew Pepper	EA Project Manager	ATPEC River Engineering
Dr Richard Crowder	Study Project Manager/ Tester	Bullen Consultants Ltd
Dr Nigel Wright	Advisor	University of Nottingham
Dr Chris Whitlow	Advisor	Eden Vale Modelling Services
Dr Andrew Sleigh	Advisor	University of Leeds
Dr Chris Tomlin	Advisor	Environment Agency
Dr Mohammad Dastorani	Tester/Reporter	University of Nottingham

1.2 Aim of Test

The aim of the test is to:

- assess the ability of each software package to model flow through bridge structures; and

- present the particulars for developing and undertaking the tests (Model Build) with each of the software packages and the associated results so that others can repeat the test with their own software.

The test is based on experimental work carried out in a laboratory at the University of Birmingham. These data and a full description are contained in a technical paper presented for JBA Consulting Engineers & Scientists and the Environment Agency: "Scoping Study into Hydraulic Performance of Bridges and other Structures, including Effects of Blockages, at High Flows (Bridge Afflux Experiments in Compound Channels)" by S. Atabay and D. W. Knight (Jan. 2002).

2 MODEL BUILD

2.1 Test Configuration

This test configuration consists of a 22m laboratory flume with a bridge placed 10m from the inlet. The flume has a compound cross section containing a main channel and two flood plains on either side. For this test the experiments with a smooth main channel and smooth floodplain are used. Rather than model the full flume, a distance approximately 7m upstream and downstream of the bridge has been modelled to prevent the boundary conditions from affecting the flow at the bridge.

The experiments gave a Manning's *n* of 0.0091, but this was adjusted within each model to reflect different conveyance formulations and to ensure a uniform flow for the situation with no bridge in place.

Two types of bridges are modelled in this test and they are designated Arch Bridge and Flat Soffit Bridge.

Figure 2.1 shows the dimensions for the multiple opening semi-circular Arch Bridge. For this part of the test, two different simulations were carried out using upstream flow discharges from the experiments of 0.02097m^3/s and 0.03443m^3/s. Downstream depths were likewise set to 67mm and 80mm respectively.

Figure 2.1: Multiple Opening Semi-Circular Arch Bridge (MOSC) Model

(after Atabay and Knight 2002)

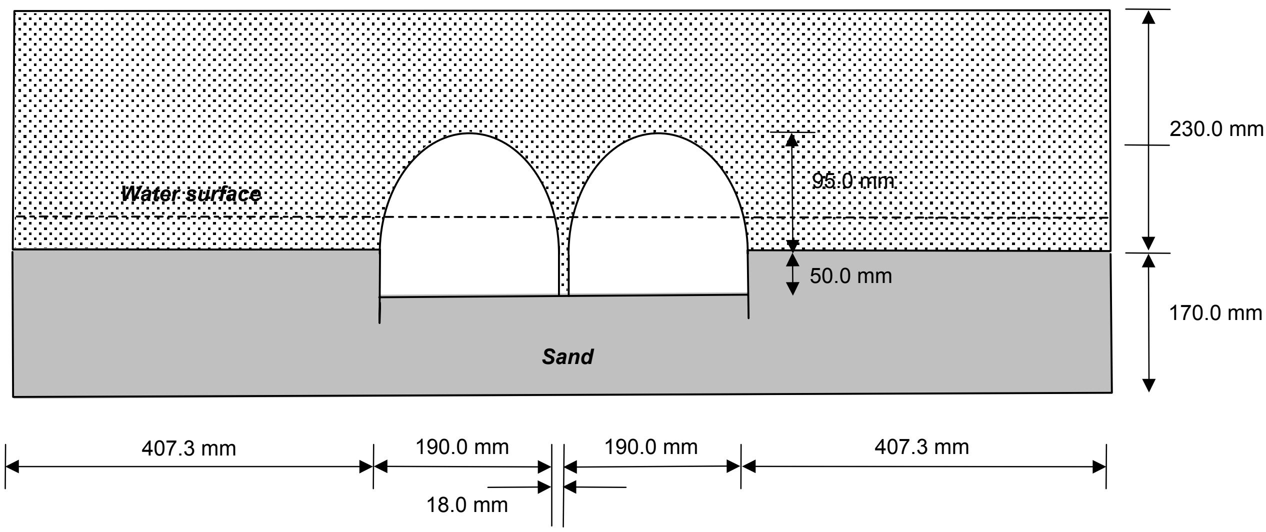
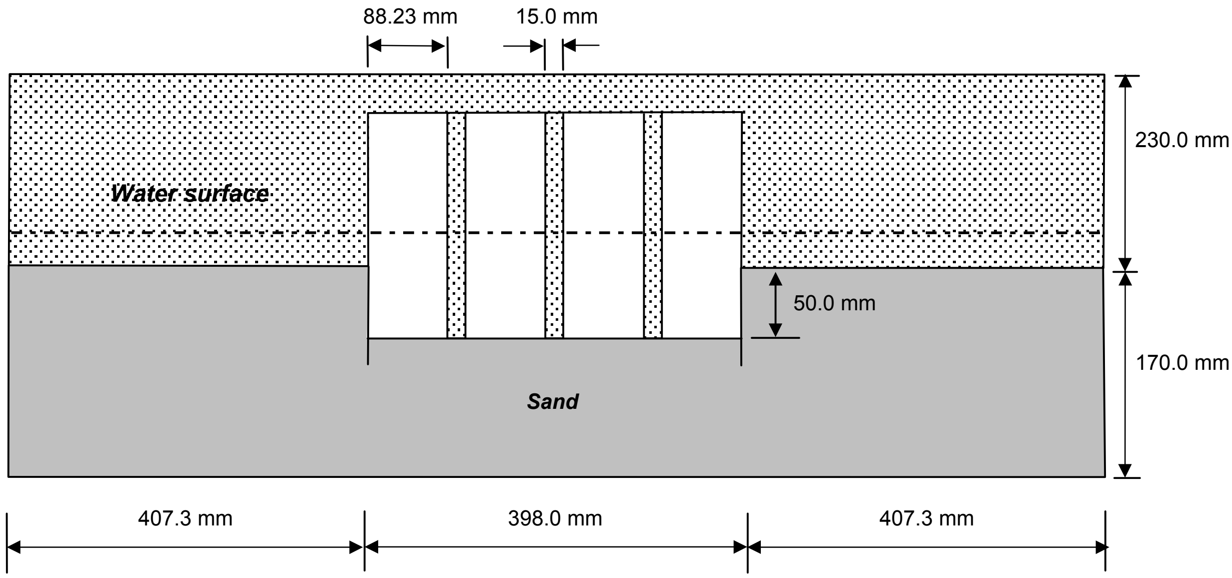


Figure 2.2 shows the dimensions for the Flat Bridge. For this part of the test, two simulations were carried out using discharges of 0.02098m^3/s and 0.03429m^3/s as in the experiments. Downstream depths were similarly set to 67mm and 80mm respectively.

Figure 2.2: Deck-Single Opening Straight Deck Bridge Model

(after Atabay and Knight 2002)



In the experiments there was no contact of the free surface with the soffit of the bridges so this is not considered here. However, all three packages have the capability of dealing with this situation.

Each of the tests was carried out using a steady state solver and an unsteady (quasi-steady flows) solver. In the latter, a time series was created with a constant value of discharge or water level as appropriate. This was designed to test whether the packages have consistency between steady and unsteady state computations.

2.2 Building the Model in ISIS

Before inserting a bridge into the model it was run without a bridge to establish uniform flow for the specified discharge and depth. This was achieved with a Manning's *n* of 0.012 and so this value was adopted in the bridge simulations for ISIS.

Through the ISIS interface it is only possible to set the discharge to three decimal places. The discharges were rounded before being entered into the package. It is not felt that this would make a significant difference to the results.

The modelling of a bridge within a river reach in ISIS is done using the bridge structure unit. This has two types: Arch and USBPR, both of which are used here.

ISIS requires one cross section immediately upstream and one immediately downstream of the bridge. In addition to the eight physical cross-sections, thirteen cross-sections were interpolated. These were spaced at 1m intervals throughout the flume and at 0.5m intervals in the vicinity of the bridge. This was done partly to increase accuracy, but primarily to provide output data at an appropriate number of points.

In ISIS an Arch Bridge is defined by specifying the cross section, the lateral extent of the arch, the springing level above datum and the soffit level above datum. ISIS can compute the afflux at bridges with arched soffits using a methodology developed at HR Wallingford, UK. This was developed from laboratory tests on model bridges and verified with data from prototype bridges in the UK. For a full description of the methodology please refer to the Afflux at Arch Bridges (1988) report. In this methodology the area under each arch is calculated from the soffit and the springing level, assuming that the arch shape is parabolic (ISIS User Manual). Road flow and flood culvert flow are not modelled by this unit; however, this can be considered by the use of a spill unit or culvert, respectively, if necessary.

To calculate bridge afflux for the Flat Soffit Bridge, ISIS uses the method described in Hydraulics of Bridge Waterways (1978).

The Flat Soffit Bridge was defined by specifying the springing and soffit levels as 0.280m. Using the option within ISIS three piers were defined with a total width of 0.045m.

The equation used for computation of headloss from a Flat Soffit Bridge constricting flow is:

$$h_1^* = K^* \alpha_2 \frac{V_B^2}{2g} + \alpha_1 \left[\left(\frac{A_B}{A_4} \right)^2 - \left(\frac{A_B}{A_1} \right)^2 \right] \frac{V_B^2}{2g}$$

where:

h_1* = total backwater (or afflux) (m)
K* = total backwater coefficient (m)
α_1 = kinetic energy coefficient at the upstream section
α_2 = kinetic energy coefficient in the constriction
V_B = average velocity in constriction (m/s)
A_B = gross water area in constriction (m^2)
A_4 = water area in downstream section (m^2)
A_1 = total water area in upstream section including that produced by the backwater (m^2)

2.3 Building the Model in MIKE 11

Before inserting a bridge into the model it was run without a bridge to establish uniform flow for the specified discharge and depth. This was achieved with a Manning's *n* of 0.012 and so this value was adopted in the bridge simulations for MIKE 11.

Four sections were used to represent the channel in MIKE 11, one at each end and two near to and either side of the bridge. In order to provide data at more points and to increase accuracy the maximum computational length DX_MAX was set to 0.5. This inserted computational h-points at an interval of 0.5m.

When modelling a bridge in MIKE 11 an upstream and downstream river cross section must be within a distance DX_MAX of the bridge.

MIKE 11 offers several options for modelling bridges:

- FHWA WSPRO bridge method;
- USBPR bridge method;
- Fully submerged bridge;
- Arch Bridge (Biery and Delleur);
- Arch Bridge (Hydraulic Research (HR));
- Bridge piers (D'Aubuisson's formula);
- Bridge piers (Nagler); and
- Bridge piers (Yarnell).

As can be seen from the above list two methods can be used for an Arch Bridge, the Biery and Delleur method and the Hydraulic Research (HR) method. For this test the Hydraulic Research (HR) method was used in order to aid comparison with the other packages and to reflect common practice in the UK.

The Arch Bridge opening is defined by giving the following data:

- the arch opening width;
- the number of arches;
- the level for the bottom of the arch curvature;
- the level for the top of the arch curvature; and
- the radius of the arch curvature.

For an Arch Bridge MIKE 11 uses the same method described for ISIS above.

The Flat Soffit Bridge was defined by specifying the cross section values and a length of 0.12m (in the direction of flow). Piers were defined as having total width 0.045m.

It is not clear why MIKE 11 requires the bridge length to be defined as this dimension is not used in the calculation and MIKE 11 does not provide a graphical representation of the structure or the upstream or downstream elevations.

For a Flat Soffit Bridge, MIKE 11 calculates the free surface flow assuming normal depth conditions. The headloss (H_1) is calculated using the following equation:

$$H_1 = k^* \frac{a_2 V^2{}_{N2}}{2g} + a_1 \left[\left(\frac{A_{N2}}{A_4} \right)^2 - \left(\frac{A_{N2}}{A_1} \right)^2 \right] \frac{V_{N2}^2}{2g}$$

where:

k^*	=	total backwater coefficient
V_{N2}	=	average velocity in bridge cross-section at normal depth
A_{N2}	=	cross-section area at normal depth
A_1	=	upstream cross-section area
A_4	=	downstream cross-section area
g	=	acceleration due to gravity (m/s^2)
a_1	=	velocity distribution coefficient
a_2	=	velocity distribution coefficient

2.4 Building the Model in HEC-RAS

Before inserting a bridge into the model it was run without a bridge to establish uniform flow for the specified discharge and depth. This was achieved with a Manning's n of 0.012 and so this value was adopted in the bridge simulations for HEC-RAS.

In HEC-RAS it is only possible to specify the discharge to three decimal places. The discharges were rounded before being entered into the package. It is not felt that this would make a significant difference to the results.

The modelling of a bridge requires a reach with a minimum of four cross-sections, two downstream and two upstream of the structure.

The first cross section should be located sufficiently downstream from the bridge (expansion length) so that the flow is not affected by the structure (i.e. the flow has fully expanded). Details on how to determine this expansion reach length, L_e, are provided in the HEC-RAS manual. As a 'rule of thumb' the Corps of Engineers suggests a distance of four times the average length of the side constriction caused by the structure abutments for the expansion reach length, L_e.

The second cross section should be located immediately downstream of the culvert (i.e. within a few metres). This cross section should represent the effective flow just outside the structure.

The third cross section should be located just upstream of the bridge and is intended to represent the effective flow area just upstream of the structure. The distance between this cross section and the bridge should be relatively short. This distance should only reflect the length required for the abrupt acceleration and contraction of the flow that occurs in the immediate area of the opening.

The fourth cross section should be upstream of the bridge where the flow lines are approximately parallel and the cross section is fully effective. Details on how to determine the contraction reach length, L_c, are provided in the HEC-RAS manual. However, as a 'rule of thumb' the Corps of Engineers suggests a distance of one times the average length of the side constriction caused by the structure abutments.

It is recommended in the HEC-RAS manual that at both the second and third cross-sections "ineffective flow areas" are defined on either side of the bridge opening. However, due to the similarity of the bridge and channel dimensions the test has omitted the inclusion of these "ineffective flow areas". Details on how to set the ineffective flow area stations and elevations are provided in the HEC-RAS manual.

The shape of a bridge is defined by inputting a sequence of points that define the opening. For the Arch Bridge, 44 points were used for this. For the Flat Soffit Bridge, six points were used and three piers were defined using the option in the software.

The length of the bridge was defined as being 0.10m with a 0.01m gap between the cross-sections immediately upstream and downstream of the bridge and the bridge structure.

At all cross-sections the default cross-section contraction and expansion coefficients of 0.1 and 0.3 were used respectively.

Six physical cross-sections were used and fourteen cross-sections were interpolated. In the upstream and downstream parts of the flume cross-sections were interpolated with 1m intervals while in the middle of the flume, just upstream and downstream of the bridge, cross-sections were interpolated with only 0.5m intervals.

The downstream boundary was set to the depth prescribed in the test specification.

3 RUNNING THE MODEL

3.1 Introduction

In all cases default options were used unless specified otherwise in this report.

It should be noted that the values of discharge and depth are very low compared with those usually encountered by these packages. It was therefore necessary to pay particular attention to any calculation tolerances that the packages used. Where it was necessary to change these, the new values are mentioned in the following.

3.2 Running the Model in ISIS

The experimental set-up had a Froude number in the regions of 0.6 to 0.8. Consequently, for the no bridge condition, the default parameters for the minimum and maximum Froude numbers were set to 0.99 and 1.0 respectively, so as to obtain a correct solution.

To generate results for the steady state part of the test the “Direct Method” within ISIS was used.

For the quasi-steady simulations the steady state solution was used as an initial condition. The boundary conditions were extended with constant values for a period of 10 hours. The adaptive time-stepping option within ISIS was used with an initial timestep of 5s. ISIS generally used a timestep of 320s.

No errors or warnings were observed.

3.3 Running the Model in MIKE 11

MIKE 11 generates a set of initial conditions automatically by running what the manual calls a quasi-steady solver. These values were extracted from the MIKE 11 results by extracting the values at time t = 0s and these were taken as the steady state results.

The simulation was carried out for a 10 hour period with a timestep of 10s and the final values were taken as the quasi-steady values required for this test.

When carrying out an unsteady simulation, MIKE 11 will automatically insert a slot at cross-sections if the water level falls to a depth less than *delh*. The slot extends down to a depth of 5.*delh* below the cross section. This is done to increase stability at low flows. The default value for *delh* is 0.1m which, in this test is significant relative to the depths of less than 100mm. In view of this the value was decreased to 0.001m (equivalent to 1mm).

No errors or warnings were observed.

3.4 Running the Model in HEC-RAS

In view of the low flows a number of calculation tolerances were changed in the steady state simulation for HEC-RAS. These are outlined below. This improved the prediction of uniform flow for the situation without a bridge.

Table 3.1: Calculation Tolerances Changed in Steady State HEC-RAS

	Default	Set to
Water Surface Calculation Tolerance	0.003m	0.001m
Critical Depth Calculation Tolerance	0.003m	0.001m
Flow Tolerance Factor	0.001 m^3/s	0.001m^3/s

A Manning's *n* of 0.012 was found to be best for reproducing uniform flow.

In view of the experience with steady state the following calculation tolerances were set in HEC-RAS for the unsteady simulation:

Table 3.2: Calculation Tolerances Changed in Unsteady HEC-RAS

	Default	Set to
Water Surface Calculation Tolerance	0.02m	0.001m

For the case with the Flat Soffit Bridge, under unsteady flow conditions, both the low flow and the high flow boundary conditions gave errors relating to convergence difficulties, particularly in the first few timesteps. Reducing the timestep and increasing the maximum number of iterations did not solve this problem. However, after these initial difficulties stable convergence was obtained.

As a precaution the mixed flow option was selected in the unsteady simulations; however, it should be noted that the upstream and downstream boundary conditions and calculated Froude numbers did not indicate regions of supercritical flow.

4 RESULTS

4.1 Introduction

For each part of the test the results from all the software packages have been discussed, compared and presented in combination so as to provide a direct comparison.

4.2 Analysis of Results

Graphs 1 to 4 show the water levels for each bridge and flow combination. Each graph contains data for the three packages in steady state and quasi-steady state mode. Additionally, the bed level is indicated along with the experimental values. Soffit levels are omitted in order to increase the vertical resolution of the graphs for clarity. In no case does the water level reach the soffit.

In comparing the results with the experimental values it should be borne in mind that the scale of this test case is very small. Therefore, it may not be appropriate to draw too firm conclusions from the results.

Each graph demonstrates that there is a backwater effect from the bridge. The packages generally over-predict for the Flat Soffit Bridge and generally under-predict for the Arch Bridge.

4.3 Comparison of the Results

Overall HEC-RAS steady state gives the results closest to the measured data. However, it is not the closest in every case.

The HEC-RAS unsteady results are further away from the measurements than the steady results in all cases. The developers of HEC-RAS have suggested that improved results can be obtained by adjustment of a number of parameters, namely:

- use of ineffective flow areas;
- refinement of HTAB parameters;
- refinement of contraction and expansion coefficients; and
- use of additional cross section interpolations.

Investigation with the above to improve model results was not undertaken as part of this study as the study was not focused on optimising model results.

ISIS under-predicts for the Arch Bridge and over-predicts for the Flat Soffit Bridge. Examination of the graphs shows that for each case ISIS is further away from the measured values than the other two packages. Possible reasons for this are discussed later (Section 5).

MIKE 11 shows consistent differences between steady and quasi-steady in all cases, although this is only slight for the Arch Bridge with the lower flow. The quasi-steady state is nearer to the measurements in all cases.

As an indication Table 4.1 gives the afflux for each package. The afflux definition is taken to be the same as that in the experimental report i.e. difference between depth at the cross section just upstream of the bridge in each package with and without the bridge in place. The RMS value indicates how close the packages are to the measurements overall. This shows that HEC-RAS steady and MIKE 11 quasi-steady are the best by this measure.

Table 4.1: Afflux in metres for each package and each simulation

	Arch Bridge		**Flat Soffit Bridge**		
Flow (m^3/s)	0.02097	0.03443	0.02098	0.03429	RMS of Difference
ISIS steady	0.010	0.021	0.050	0.099	0.033
ISIS quasi-steady	0.010	0.021	0.050	0.098	0.033
MIKE 11 steady	0.040	0.072	0.055	0.072	0.014
MIKE 11 quasi-steady	0.038	0.062	0.036	0.059	0.006
HEC-RAS steady	0.034	0.065	0.041	0.071	0.006
HEC-RAS quasi-steady	0.031	0.060	0.010	0.009	0.014
Measured	0.035	0.070	0.032	0.062	

5 DISCUSSION AND CONCLUSIONS

All three packages were able to model the Arch and Flat Soffit Bridges with the exception of HEC-RAS quasi-steady. Although the HEC-RAS model would run for the Flat Bridge quasi-steady case the results showed minimal influence of the Flat Bridge structure. It is, however, acknowledged that improved results may be achievable if calculation settings/parameters are refined or optimised.

The packages presented differing results. As mentioned in Section 4.2 it should be noted in making comparisons between the model results and the experiments that there may be a scaling effect between the lab-scale experiments and model techniques which have been designed for use at full-scale.

The difference between ISIS and MIKE 11 is not necessarily expected as they use the same technique to calculate the bridge effect for both the Arch and Flat Soffit case.

HEC-RAS steady and MIKE 11 gave results closest to the experimental values on the basis of RMS errors over all cases and bridge types.

It is noted that although each package is modelling the Flat Soffit Bridge with the same approach/method, the results differ noticeably. From this test it is unclear as to why this may be the case and hence, caution should be exercised in the application of these models.

There were significant differences between the steady state and quasi-steady state solutions for MIKE 11 and HEC-RAS. MIKE 11 appears to perform better in quasi-steady mode and HEC-RAS in steady state model.

MIKE 11 has no option to allow the user to visualise the bridge cross section unlike ISIS and HEC-RAS.

The ISIS technical support team are aware of the discrepancies observed in ISIS. They believe that they result from an inaccurate calculation of the blockage ratio at low flows, which is due to the approximation that conveyance is linearly interpolated between fixed water levels. They concluded that:

1. The linear interpolation of conveyance is much more accurate at higher water levels and the approximation would be better for full-scale bridges.

2. The fixed water levels at which conveyance is calculated exactly can be forced by adding further section points to improve matters and this is less likely to be an issue with natural channels. This has not been tested as part of this study.

6 RECOMMENDATIONS

From undertaking this test it is believed by the testers that the following improvements to the software packages would benefit the modeller:

- examination of changes to ISIS to give more accurate results when modelling bridges particularly at low flows; and

- development of a graphical view of the bridge in MIKE 11 for both model build and results.

Whilst each software package can be used for modelling bridges the modeller may wish to consider the use of HEC-RAS steady as a cross check method/procedure when using ISIS or MIKE 11.

It is recommended that further verification of bridge modelling is undertaken through studies at full-scale (laboratory or field) and with fully three-dimensional CFD models.

The test specification should be extended to consider flows that are in contact with the bridge soffit and flows that spill over and around the bridge structure and bridges that are at angle (i.e. skew) to the main flow direction.

Further investigations should be made into optimising the results from each of the software packages. This is particularly relevant to HEC-RAS, which with some adjustment of a number of modelling parameters and software settings/configuration, is likely to provide improved results.

7 REFERENCES

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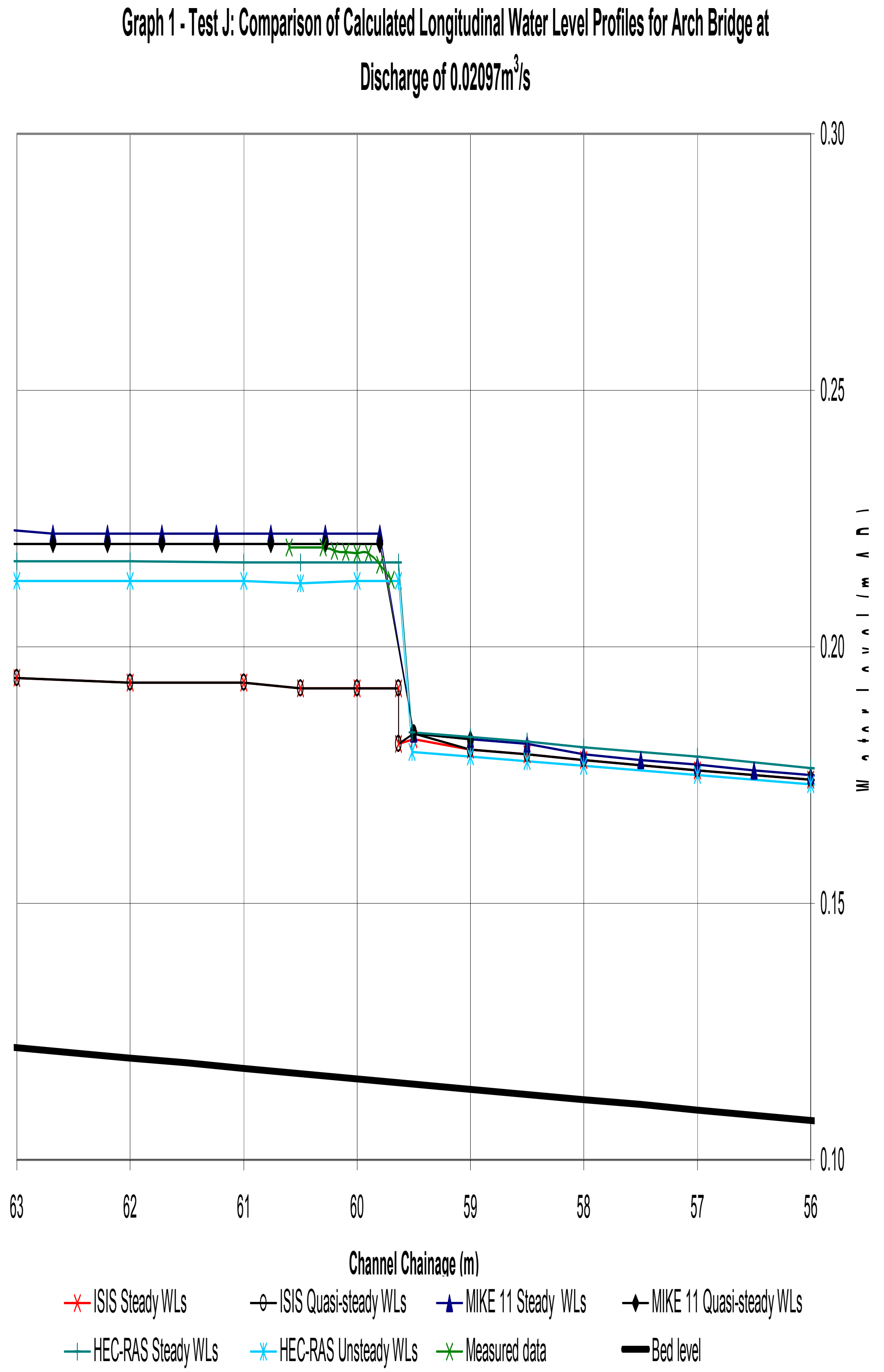
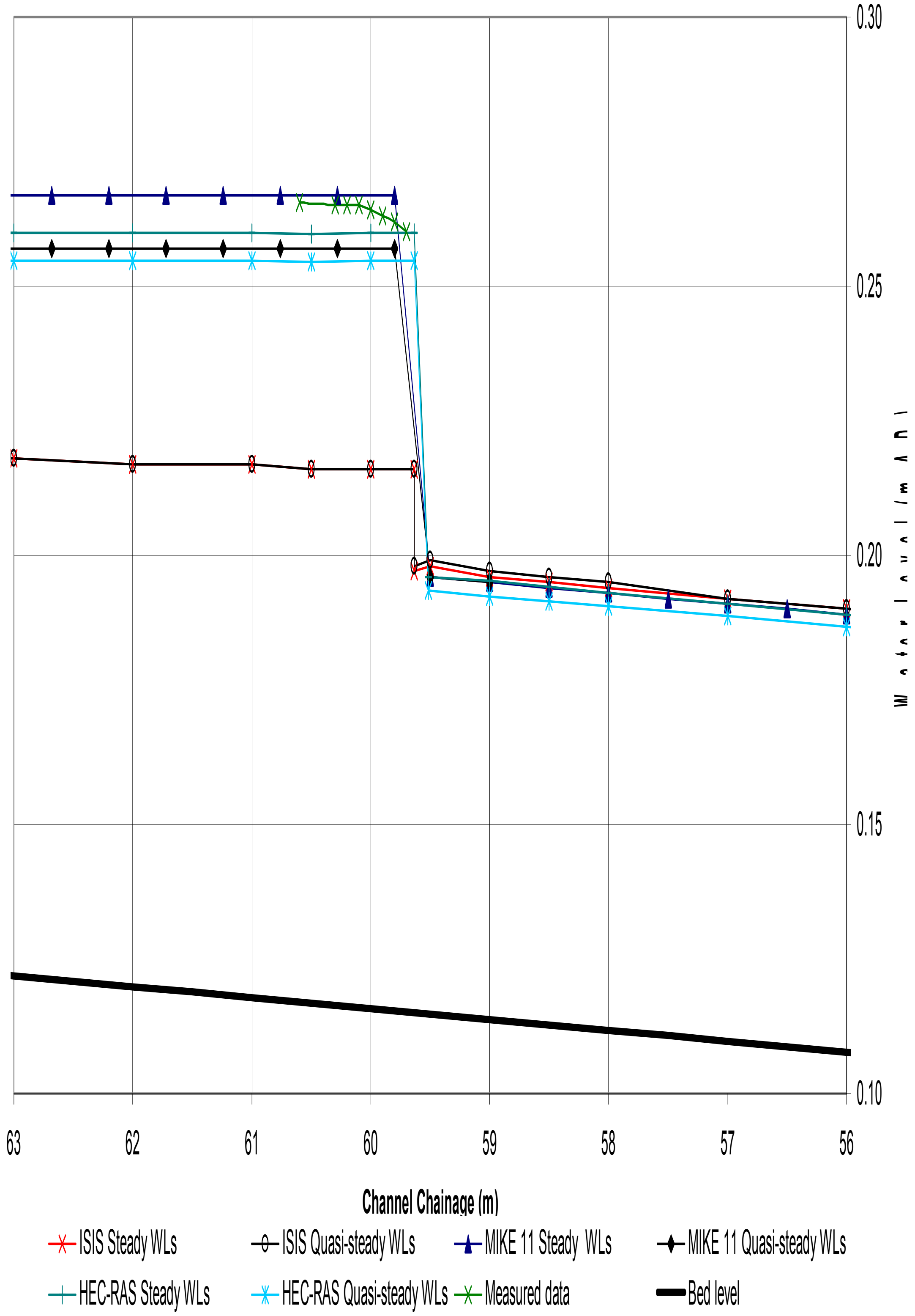
APPENDIX A RESULTS

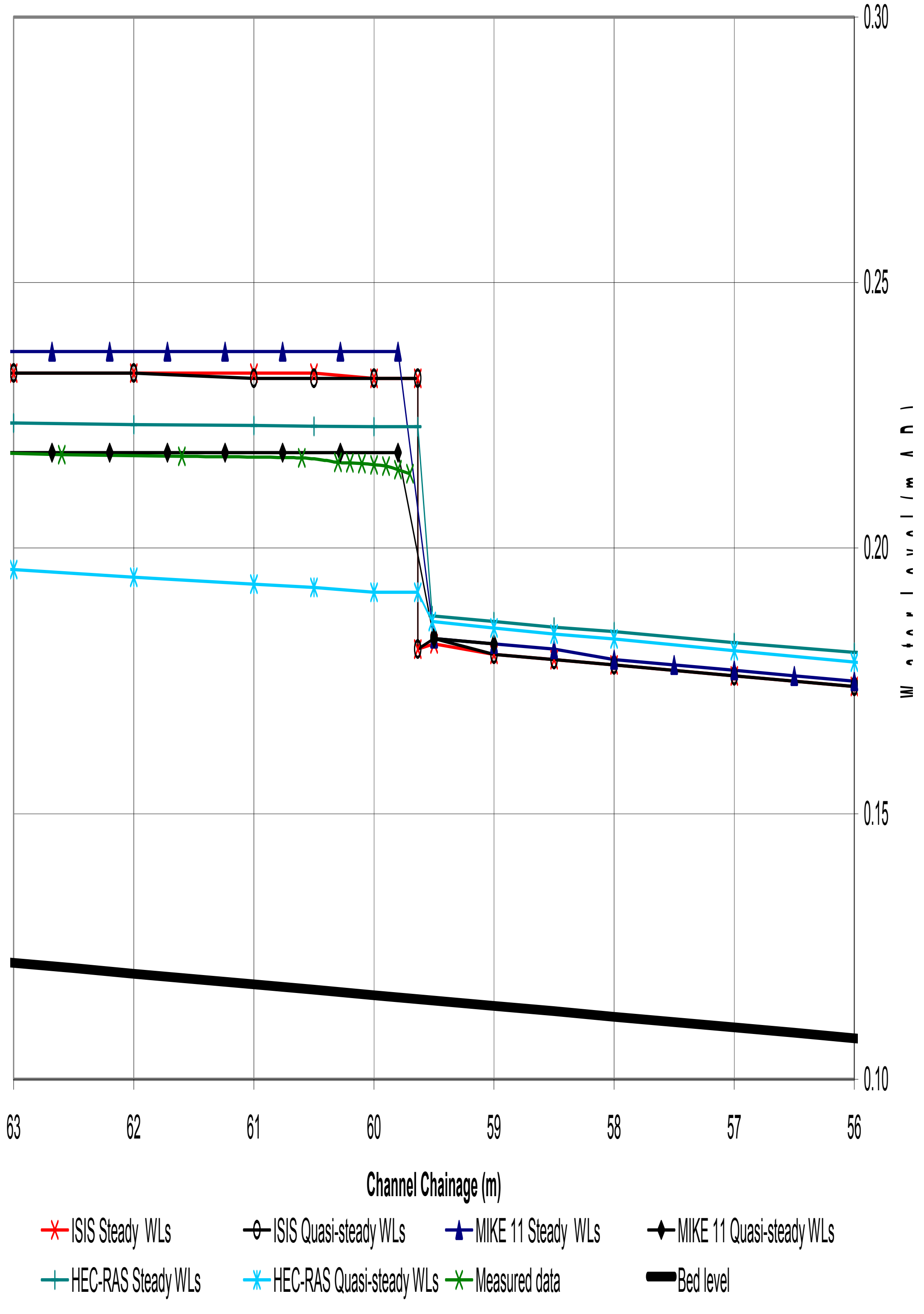


Graph 1 - Test J: Comparison of Calculated Longitudinal Water Level Profiles for Arch Bridge at Discharge of 0.02097m3/s
0.30
0.25
0.20
0.15
0.10
Water level (m AD)
63
62
61
60
59
58
57
56
Channel Chainage (m)
ISIS Steady WLs
ISIS Quasi-steady WLs
MIKE 11 Steady WLs
MIKE 11 Quasi-steady WLs
HEC-RAS Steady WLs
HEC-RAS Unsteady WLs
Measured data
Bed level

Graph 2 - Test J: Comparison of Calculated Longitudinal Water Level Profiles for Arch Bridge at Discharge of 0.03443m^3/s



Graph 3 - Test J: Comparison of Calculated Longitudinal Water Level Profiles for Flat Soffit Bridge at Discharge of 0.02098m^3/s



Graph 4 - Test J: Comparison of Calculated Longitudinal Water Level Profiles for Arch Bridge at Discharge of 0.03429m^3/s