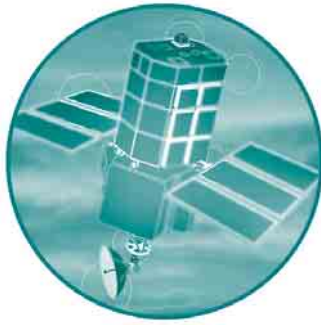


Defra / Environment Agency Flood and Coastal Defence R&D Programme



Benchmarking of hydraulic river modelling software packages

Test Specifications

R&D Technical Report: W5-105/TR1

**Defra/Environment Agency
Flood and Coastal Defence R&D Programme**

**BENCHMARKING OF HYDRAULIC RIVER
MODELLING SOFTWARE PACKAGES**

Test specifications

R&D Technical Report: W5-105/TR1

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Statement of use

These specifications are intended to be a supplementary resource for Defra and Agency staff, research contractors and consultants, academics and students for assessing the applicability of river modelling software packages for their own modelling requirements. They are also intended to be used by others for one or more of the following purposes: a) by novice modellers as a training exercise, b) by vendors with updates of the packages tested, and c) by other software houses to test their products against those already tested.

This report should not be considered in isolation and should be read in conjunction with the other tests reports produced as part of this project. It is intended that this test specifications will be reviewed, updated and expanded as suitable data sets become available and as modelling software develops. As such individuals should ensure that they have obtained the latest version of the test specification from the Defra / Environment Agency webpages for Flood and Coastal Defence R&D.

Keywords

Hydraulic modelling, river modelling, software, benchmarking, test specifications

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EXECUTIVE SUMMARY

As part of the Environment Agency/Defra R&D Programme, a new generic test dataset and specification, which has built upon the strengths of the previous work (Harpin *et al*, 1995 and Crowder *et al*, 1997), has been devised to enable river modelling software packages to be benchmarked.

The specifications provide a range of different tests that cover a broad range of modelling scenarios. A total of twelve test specifications are published specifically to provide methods of assessing a) numerical accuracy, b) capability, and c) reproducibility. However, it is important to stress that these specifications may only assess a limited range of model capabilities.

It is acknowledged that specifications need to be enhanced and expanded in order to enable benchmarking of software as improvements and capabilities are made and so as to consider more complex hydraulic issues and real-life modelling problems that are relevant to river management. Improvements to test specifications have already been identified and, as part of the testing undertaken as part of this study, may be included in future revision of the specifications and supporting datasets, which will be published on the Agency's web site.

The specifications could be applied to 1D, 2D and 3D software packages; however, it is acknowledged that for 2D and 3D models some judgement may be required in defining physical geometry and structures. Furthermore, similar specifications could be developed to benchmark software for modelling, sewer modelling, coastal and estuarine modelling, and groundwater modelling etc.

It is intended that by the publication of the test specifications and datasets others will be able to carry out these tests, for one or more of the following purposes:

- by novice modellers as a training exercise;
- by vendors with updates of the packages tested; and
- by other software houses to test their products against those already tested.

If tests for upgraded or new packages are carried out appropriately, and have been independently verified, then the Agency will also consider placing those results on the Agency's website. In due course, a framework is to be developed so as to enable others to submit test results to the Agency.

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1 INTRODUCTION

1.1 Objectives and Layout

Benchmarking can be undertaken in many different guises; however, this project has considered that benchmarking of software should ideally embrace methods of assessing the following criteria:

- numerical accuracy;
- capability;
- reproducibility;
- adaptability; and
- form and function.

A total of twelve test specifications have been published, aimed at covering as many of the above criteria as possible.

Numerical accuracy

The numerical accuracy of a software package can only be assessed if an analytical solution exists for the physical situation/configuration that is being modelled, which for real world modelling probably never exists. However, for a number of contrived situations/configurations there are known analytical solutions. The following four tests, which all have analytical solutions, were developed so as to assess numerical accuracy:

Test A: Subcritical and Supercritical Flows – An assessment of the ability of the software package to calculate subcritical, supercritical and transitional flows and assess the numerical accuracy of the software packages with reference to analytical results.

Test C: Triangular Channel – An assessment of the capability of the software package to calculate the normal subcritical flow depth and the normal supercritical flow depth in a triangular channel.

Test E: Ippen Wave – A comparison of results generated by the software package with an analytical solution based on the hydrodynamic theory of tidal wave propagation in a horizontal channel of uniform cross-section and finite length.

Test F: Monoclinical Wave – An assessment of the ability of the software package to recreate the special case of unsteady flow, known as the monoclinical rising wave, as a typical case of uniformly progressive flow.

Capability

The capability of a software package can be assessed objectively by testing the most commonly required features of a software package. The following “can do” tests have been defined specifically to assess capability:

- Test B: Looped System – An assessment of the capability of the software package to calculate a diverging and converging flow scenario, i.e. a looped system.
- Test D: Weirs – An assessment of the capability of the software package to model a Crump weir and Broad Crested weir.
- Test H: Rules (Pumps and Gates) – An assessment of the capability of the software package to implement a rule based methodology to simulate the operation of hydraulic structures.
- Test I: Side Spill – An assessment of the capability of the software package to model flow over an embankment (side spill).
- Test K: Culverts – An assessment of the capability of the software package to model unsteady fluid flow in a circular culvert and the changes from free surface open channel flow to fully pressurised pipe flow.
- Test O: Outfalls – An assessment of the capability of the software package to model flapped outfalls that are influenced by both tidal and fluvial boundary conditions.

Reproducibility

The following series of comparison tests, i.e. numerical results that have been compared with experimental or real world datasets, have been developed so assess reproducibility:

- Test J: Bridges – An assessment of the ability of each software package to model an Arch Bridge (Part A) and a US BPR Bridge (Part B) under steady boundary conditions and reproduce the flows as observed in experimental work.
- Test L: Contractions and Expansions – An assessment of the ability of the software package to replicate the behaviour of a surge wave, caused by the sudden collapse of a large body of water, in a channel with a local constriction and expansion and compare the numerical results against laboratory results.

Three other tests, namely Tests G, M and N, are not published in this report due to the need for further refinement and development.

Specifications for all twelve tests of hydrodynamic river models have been prepared as stand-alone documents for use by future testers, with the results reported separately. All these specifications have been placed on the Environment Agency website www.environment-agency.gov.uk/floodresearch.

The specifications are presented as separate chapters in this report and are reported on in alphabetical test order.

Data files have been prepared for each test in an appropriate form for each of the three software packages. These files have also been placed on the Environment Agency website www.environment-agency.gov.uk/floodresearch.

The test specifications have been developed with 1D hydraulic river modelling software in mind; however, many of the specifications could be used for testing higher order hydrodynamic modelling.

The development and publication of these test specifications will enable others to carry out these tests, for one or more of the following purposes:

- by novice modellers as a training exercise;
- by vendors with updates of the packages tested; and
- by other software houses to test their products against those already tested.

If tests for upgraded or new packages are carried out appropriately, and have been independently verified, then the Agency will consider also placing those results on the website.

1.2 Background

The National Rivers Authority (NRA) initiated a ‘Benchmarking Study’ of hydraulic river models in 1993, with Stage 1 defining a series of tests for both steady-state and unsteady-state applications (Harpin *et al*, 1995).

In 1995 Stage 2 of this project was initiated, which involved all river modelling packages then in use by the NRA being subjected to the tests defined by Stage 1 of the project. The versions current at the start of this stage of the project (September 1995) were used throughout the project, and comprised six steady-state models and five unsteady-state modelling packages. The project was completed under the Environment Agency in 1997, and the title amended to ‘Benchmarking and Scoping Study of Hydraulic River Models’ so as to reflect the overall substance of the study (Crowder *et al*, 1997).

Many of the eleven packages in the original test are no longer supported, and the others have undergone significant upgrades since the 1995 versions previously tested. In addition, the Environment Agency has since rationalised the software provided to its staff, leaving just three river modelling packages currently supported:

- ISIS;
- MIKE 11; and
- HEC-RAS.

Both ISIS and MIKE 11 are unsteady-state packages, which have been upgraded since 1995. A major change to HEC-RAS is that it now has an unsteady-state module, so a direct comparison of its capabilities with those of ISIS and MIKE 11 is now possible.

There are ever-increasing demands for hydraulic river modelling by the Agency and its consultants for a wide range of plans, strategies, flood risk mapping, and flood alleviation scheme option appraisals. In addition, the requirements of PPG 25 – Development and Flood Risk – mean that flood risk assessments have to be carried out for any development within the floodplain, and in many cases this requires modelling of a river reach.

Many such flood risk assessments will be carried out by smaller consultants, for whom HEC-RAS is particularly attractive, being available to download free of charge from the internet.

With the widespread use of HEC-RAS, and its recent ability to model unsteady-state flows, the Agency became concerned that the capabilities of this new package had not been tested, as apart from its use by the Agency's own staff. It was anticipated that large numbers of sites may be modelled using this package for flood risk assessments associated with planning applications. However, it was realised that the testing should not be of HEC-RAS alone, as the other two packages supported within the Agency had also undergone significant changes since the previous series of tests. It was also recognised that by producing these test specifications others will be able to carry out these tests.

2 TEST ‘A’ – SUBCRITICAL AND SUPERCRITICAL FLOWS

2.1 Aim of Test

The aim of the test is to:

- assess the ability of each software package to calculate subcritical, supercritical and transitional flows;
- assess the numerical accuracy of the software packages with reference to analytical results, as derived by MacDonald (1994), where appropriate; 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.

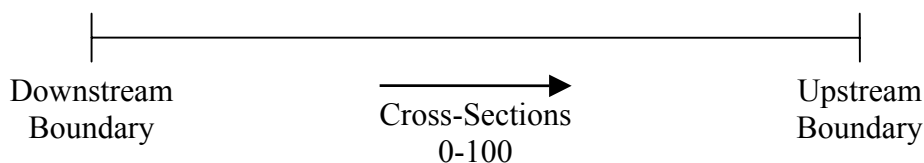
2.2 Test Configuration

The test is to be undertaken in six separate parts as defined below in Table 2.1.

Table 2.1: TEST A – Definition of Parts 1 to 6 of Test A

	Steady State	Quasi Steady	Unsteady
Part 1: Subcritical Flow	✓	✓	
Part 2: Supercritical Flow	✓	✓	
Part 3: Subcritical to Supercritical Flow	✓	✓	
Part 4: Subcritical to Supercritical to Subcritical Flow	✓	✓	
Part 5: Supercritical to Subcritical to Supercritical Flow	✓	✓	
Part 6: Supercritical to Subcritical to Supercritical Flow			✓

Figure 2.1: TEST A - Schematic Illustration of Test Configuration



For each part of the test 101 cross-sections of rectangular shape (10.0m wide) are defined at 1.0m spacing, as defined by the dataset (see Section 3) and as illustrated in Figure 2.1. The elevation of each cross section is defined such that the required flow regime is produced.

Additional cross sections (i.e. interpolated) should not be added to the test configurations.

It is noted that it may be more appropriate to use the term ‘forewater’ instead of ‘backwater’ when referring to supercritical flows; however, for simplicity the term backwater should be used throughout.

A constant Manning’s n value of 0.03 is to be used throughout the reach for all parts of the test.

For parts 1 to 5 of the test, the software package is to be tested with the steady state (Note 1 Section 2.5) flow and water level boundary conditions as defined in Table 2.2 below.

Table 2.2: TEST A – Boundary Conditions (Parts 1 to 5)

	Downstream Level (mAD)	Upstream Discharge (m ³ /s)
Part 1: Subcritical Flow	0.87803	20
Part 2: Supercritical Flow	0.67341	20
Part 3: Subcritical to Supercritical Flow	0.61801	20
Part 4: Subcritical to Supercritical to Subcritical Flow	2.87904	20
Part 5: Supercritical to Subcritical to Supercritical Flow	0.61801	20

The software package is to be tested under quasi-steady (Note 2 Section 2.5) flow boundary conditions.

The steady state boundary conditions, as defined for each part of the test, are to be used at time $t=0$ and extended through to 01:00hrs respectively. The data time intervals should be chosen to suit the specific software being tested.

Part 6 of the test uses the same test configuration as that used for part 5, with the exception of the boundary conditions.

For Part 6 of the test the upstream boundary is to be fixed at 20.0m³/s for a period of 24:00hrs. The downstream boundary is to be set at 0.602m for the first 06:00hrs and then it should linearly increase from 0.602m to 2.0m between 06:00hrs and 18:00hrs, after which it should remain at this level for a further 06:00hrs.

There is no stipulation on the time-step that should be used for the quasi-steady or unsteady simulations; however, the software’s default calculation settings should be used (Note 3 Section 2.5).

Results from the respective steady state flow simulation can be used as the initial conditions to the quasi-steady or unsteady simulations.

2.3 Dataset

The dataset is provided in the ISIS, HEC-RAS and MIKE 11 data formats as part of the benchmarking test data series. The dataset are available for download via the Environment Agency's website (<http://www.environment-agency.gov.uk/floodresearch>).

2.4 Reporting

The reporting of the results should follow the format and style of the Environment Agency Benchmarking Study (Crowder *et al*, 2004) results for Test A and should be in SI units.

Where appropriate results should be compared to the analytical results presented in Appendix A.

The reporting should specifically cover the following:

- the method of deriving any initial conditions for use in the quasi-steady and unsteady simulation; and
- list of any notes, errors or warnings etc. that the software provides as part of the calculation process.

For parts 1 through to 5 inclusive, the following results should be presented and discussed for both the steady state and quasi-steady simulations:

- longitudinal water surface profile, with comparison to analytical solution;
- longitudinal profile showing the percentage difference between analytical and numerical solution for longitudinal water surface profile; and
- Root Mean Square (RMS) Error over the length of the reach for each part of the test.

For part 6 of the test the following results should be presented and discussed:

- Stage verses Time at 20.0m, 40.0m, 60.0m and 80.0m from the downstream boundary.

2.5 Test Notes

The following notes should be considered when undertaking Test A:

1. Steady state (SS) flow refers to the undertaking of a backwater analysis with a given set of fixed boundary conditions.
2. Quasi-steady (QS) flow refers to the undertaking of a fully hydrodynamic simulation (solution of the Saint Venant equations) with a given set of constant boundary conditions that are extended over a prescribed time period.
3. Default calculation settings as defined by the installation of the software and/or any user guide provided by the software should in the first instance be used for undertaking the test. If the software is unable to perform the test or provides unstable results as a

consequence of the default settings, then alternative calculations settings can used. This requirement must be reported upon.

3 TEST 'B' – LOOPED SYSTEM

3.1 Aim of Test

The aim of the test is to:

- assess the ability of each software package to calculate a diverging and converging flow scenario, i.e. a looped system; and
- assess the solution criteria and the stability of each software package under both steady state (Note 1 Section 3.5) and quasi-steady (Note 2 Section 3.5) boundary conditions.

3.2 Test Configuration

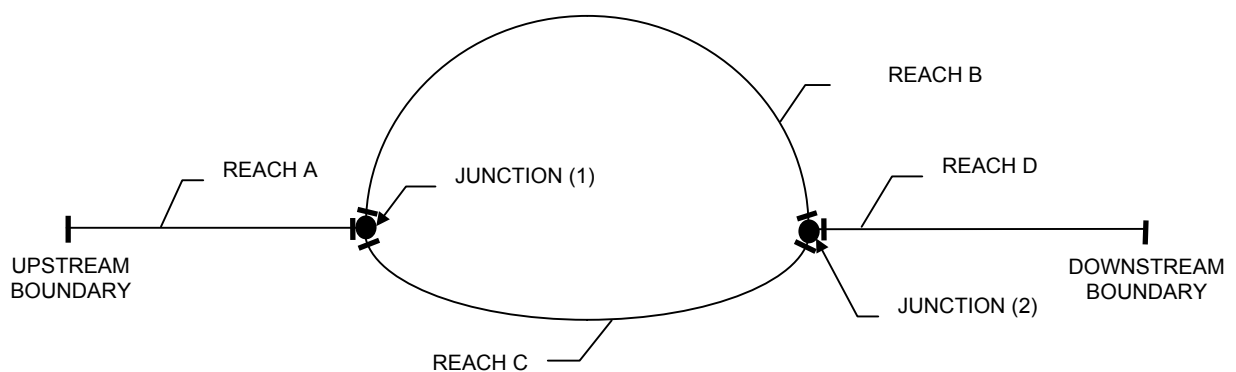
The test configuration is taken from a paper by Chaudhry (1986). The test configuration is illustrated schematically in Figure 3.1. There are four reaches: Reach A, Reach B, Reach C and Reach D with a cross-section spacing of 25m, 375m, 100m and 25m respectively, as defined by the dataset (see Section 3.3).

Interpolated cross sections (Note 3 Section 3.5) may be used to improve model stability and provide velocity and water level results at the locations identified in Section 3.4.

At the downstream end of Reach A the system diverges (splits) into Reaches B and C, which then converge to Reach D at their downstream sections.

A constant Manning's n value of 0.012, 0.0125, 0.013 and 0.0135 is to be used for Reaches A through to D respectively. It should be noted that Reach B is three times as long as Reach C with the same vertical drop between the two junctions.

Figure 3.1: TEST B - Schematic Illustration of Test Configuration



The configuration can be summarised as follows:

	<i>Length (m)</i>	<i>Cross-Section Spacing (m)</i>	<i>Gradient</i>	<i>Manning's n</i>
Reach A	100.0	25.0	1:2000.0	0.0120
Reach B	1500.0	375.0	1:2500.0	0.0125
Reach C	500.0	100.00	1:833.3	0.0130
Reach D	100.0	25.0	1:2000.0	0.0135

By definition three cross sections are defined at junctions 1 and 2. The distance between the cross-sections is 0.0m. The ability of the software to consider i) a distance greater than 0.0m, ii) head losses, iii) skew-angles, or iv) other features, are not required as part of the test; however, the ability of the software to consider these may be reported upon (see Section 3.4).

The software package is to be tested with two separate steady state (Note 1 Section 3.5) flow boundary conditions as follows.

- SS1: Upstream inflow boundary of 250m³/s
Downstream water level of 3.0m
- SS2: Upstream inflow boundary of 250m³/s
Downstream water level of 1.6m

The software package is to be tested under two separate quasi-steady (Note 2 Section 3.5) boundary conditions: QS1 and QS2. The same conditions specified for SS1 and SS2 are to be used at 00:00hrs and extended through to 01:00hrs respectively. The data time intervals should be chosen to suite the specific software being tested.

There is no stipulation on the time-step that should be used for the quasi-steady simulation; however, the software's default calculation settings should be used (Note 4 Section 3.5).

Results from the steady state flow simulation (SS1 and SS2) can be used as the initial conditions to the quasi-steady simulation if preferred.

3.3 Dataset

The dataset is provided in ISIS, MIKE 11 and HEC-RAS data formats as part of the benchmarking test data series. The dataset is available for download via the Environment Agency's website (<http://www.environment-agency.gov.uk/floodresearch>).

3.4 Reporting

The reporting of the results should follow the format and style of the Environment Agency Benchmarking Study (Crowder *et al*, 2004) results for Test B and should be in SI units.

The reporting should specifically cover the following:

- method and details of any cross-section interpolations;
- solution criteria at the junctions, i.e. water level or energy balance;
- method of deriving the split flow during quasi-steady simulations;
- the method of developing the initial conditions for the quasi-steady state calculation should be reported upon; and
- a comment on or list of any notes, errors or warnings etc. that the software provides as part of the calculation process.

Results for the quasi-steady simulation should be reported upon at 01:00hrs.

For both the steady state and quasi-steady simulations results for discharge and water level should be reported upon in tabular form at each of the cross sections defined by the dataset.

3.5 Test Notes

The following notes should be considered when undertaking Test B:

1. Steady state (SS) flow refers to the undertaking of a backwater analysis with a given set of fixed boundary conditions.
2. Quasi-steady (QS) flow refers to the undertaking of a fully hydrodynamic simulation (solution of the Saint Venant equations) with a given set of constant boundary conditions that are extended over a prescribed time period.
3. Interpolated cross-sections can be used to improve model stability and/or provide results at a prescribed location in the model. The interpolated sections should take one of the following forms:
 - a) Geometric cross-section data (i.e. x-y co-ordinates) that represent the physical form of a cross-section at the required location.
 - b) Software specific routines/capabilities that provides interpolated section properties at the required location.

Alternative methods of interpolation can be tested and reported upon in addition to the above.

4. Default calculation settings, as defined by the installation of the software and/or any user guide provided by the software, should in the first instance be used for undertaking the test. In addition, alternative calculation settings can be tested and reported upon if deemed appropriate by the tester.

4 TEST 'C' – TRIANGULAR CHANNEL

4.1 Aim of Test

The aim of the test is to:

- assess the ability of each software package to calculate the normal subcritical flow depth (Part 1) and the normal supercritical flow depth (Part 2) in a triangular channel with a side slope of 1:2 (V:H) under steady state (Note 1 Section 4.5) and quasi-steady (Note 2 Section 4.5) boundary conditions.

4.2 Test Configuration

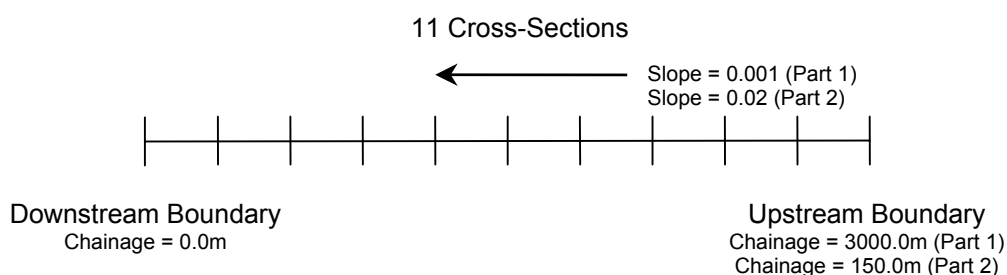
The test configuration is illustrated schematically in Figure 4.1.

For Part 1, the triangular channel is defined by eleven cross-sections that are placed 300m apart each with a side slope of 1:2 and a constant Manning's n value of 0.035. There is a constant bed slope of 0.001.

For Part 2, the triangular channel is defined by eleven cross-sections that are placed 15m apart each with a side slope of 1:2 and a constant Manning's n value of 0.035. There is a constant bed slope of 0.02.

Interpolated cross sections should not be used in the test.

Figure 4.1: TEST C - Schematic Illustration of Test Configuration



For parts 1 and 2 of the test the software package is to be tested with the steady state (Note 1 Section 4.5) flow and water level boundary conditions as defined in Table 4.1 below.

Table 4.1: TEST C – Boundary Conditions (Parts 1 and 2)

	Downstream Level (mAD)	Upstream Discharge (m ³ /s)
Part 1: Subcritical Flow	3.0	20.0
Part 2: Supercritical Flow	1.7	20.0

In the supercritical runs it should be noted that while a downstream boundary level should not be necessarily needed for the calculations, a software package may require a downstream boundary as an input, even if it is not then used.

It is noted that it may be more appropriate to use the term ‘forewater’ instead of ‘backwater’ when referring to supercritical flows; however, for simplicity the term backwater should be used throughout.

The software package is to be tested under quasi-steady (Note 2 Section 4.5) flow boundary conditions. To form these boundary conditions the steady state boundary conditions, as defined for each part of the test, are to be used at time 00:00hrs and extended through to 01:00hrs. The data time intervals should be chosen to suit the specific software being tested.

There is no stipulation on the time-step that should be used for the quasi-steady simulation; however, the software’s default calculation settings should be used (Note 3 Section 4.5).

Results from the respective steady state flow simulation can be used as the initial conditions to the quasi-steady simulations.

4.3 Dataset

The dataset is provided in the ISIS, HEC-RAS and MIKE 11 data formats as part of the benchmarking test data series. The dataset are available for download via the Environment Agency’s website (<http://www.environment-agency.gov.uk/floodresearch>).

4.4 Reporting

The reporting of the results should follow the format and style of the Environment Agency Benchmarking Study (Crowder *et al*, 2004) results for Test C and should be in SI units.

The reporting should specifically cover the following:

- the method of developing the initial conditions for the quasi-steady calculation; and
- a comment on or list of any notes, errors or warnings etc. that the software provides as part of the calculation process.

For both the steady state and quasi-steady simulations results for water level at every cross section should be reported upon in tabular and graphical form.

The results from each of the software packages are to be compared to the normal depth for the channel as determined by the following formula based on Manning’s equation:

$$h = 5^{\frac{1}{8}} \left(\frac{Q.n}{2\sqrt{S}} \right)^{\frac{3}{8}}$$

where: Q = flow (m³/s)
 n = Manning’s n roughness
 S = bed slope

From the above equation, the normal depth of flow for Part 1 of the test can be calculated as 3.012m.

From the above equation the normal depth of flow for Part 2 of the test can be calculated as 1.718m.

4.5 Test Notes

1. Steady state (SS) flow refers to the undertaking of a backwater analysis with a given set of fixed boundary conditions.
2. Quasi-steady (QS) flow refers to the undertaking of a fully hydrodynamic simulation (solution of the Saint Venant equations) with a given set of constant boundary conditions that are extended over a prescribed time period.
3. Default calculation settings as defined by the installation of the software and/or any user guide provided by the software should, in the first instance, be used for undertaking the test. In addition, alternative calculation settings can be tested and reported upon if deemed appropriate by the tester.

5 TEST 'D' - WEIRS

5.1 Aim of Test

The aim of the test is to:

- assess the ability of each software package to model a Broad Crested weir (Part 1) and Crump weir (Part 2) under steady (Note 1 Section 5.5) and unsteady (Note 2 Section 5.5) boundary conditions; and
- assess water level and head loss results for the respective weirs under both free flow and drowned flow conditions.

5.2 Test Configuration

The test configuration is illustrated schematically in Figure 5.1. There are two reaches: Reach A and Reach B, both of which have two cross sections at a spacing of 100m, a constant Manning's n roughness of 0.014 and a bed slope of 0.005 and 0.001 respectively.

Between Reaches A and B there is a weir. For Part 1 of the test this is a Broad Crested weir and for Part 2 it is a Crump weir. The parameters defining the Broad Crested and Crump weirs are given in Tables 5.1 and 5.2 respectively.

Interpolated cross sections (Note 3 Section 5.5) can be used if considered appropriate.

Figure 5.1: TEST D - Schematic Illustration of Test Configuration

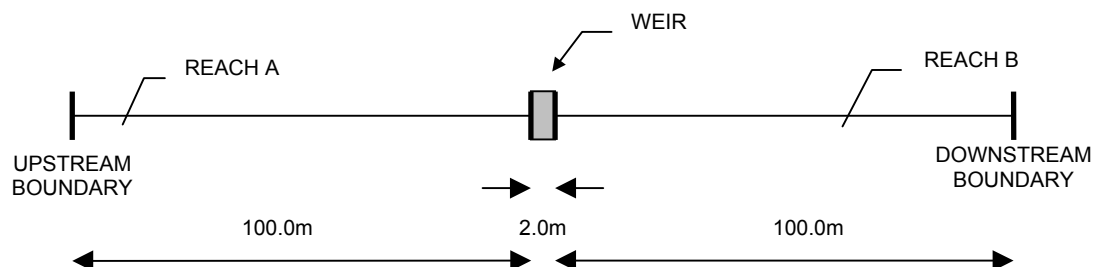


Table 5.1: TEST D – Broad Crested Weir Parameters

Parameter	<i>Broad Crested</i>
Calibration coefficient (if required)	Default*
Coefficient of velocity (if required)	Default*
Coefficient of discharge (if required)	Default*
Modular Limit*	Default*
Height of weir crest above bed - upstream	0.45m
Height of weir crest above bed - downstream	0.45m
Elevation of crest	0.5m
Breadth (perpendicular to flow)	0.9m
Length (in direction of flow)	2.0m

*Default/Software recommended values to be used

Table 5.2: TEST D – Crump Weir Parameters

Parameter	<i>Crump</i>
Calibration coefficient (if required)	Default*
Coefficient of velocity (if required)	Default*
Coefficient of discharge (if required)	Default*
Modular Limit*	Default*
Profile Shape	Triangular
Front Face Slope	1:2
Back Face Slope	1:5
Height of weir crest above bed - upstream	0.45m
Height of weir crest above bed - downstream	0.45m
Elevation of crest	0.5m
Breadth	0.9m
Length (in direction of flow)	2.0m

*Default/Software recommended values to be used

For both Parts 1 and 2 of the test the software package is to be tested with the following steady state (Note 1 Section 5.5) flow boundary conditions:

- SS1: Upstream inflow boundary of $0.15\text{m}^3\text{s}^{-1}$ (Free Flow)
Downstream water level of 0.3m
- SS2: Upstream inflow boundary of $0.15\text{m}^3\text{s}^{-1}$ (Drowned Flow)
Downstream water level of 0.8m

For both parts of the test the software package is to be tested with unsteady boundary conditions (Note 2 Section 5.5). The upstream boundary is to be fixed at $0.15\text{m}^3/\text{s}$ for a period of 24:00hrs. The downstream boundary is to be set at 0.3m for the first 06:00hrs and then it should linearly increase from 0.3m to 0.8m between 06:00hrs and 18:00hrs, after which it should remain at this level for a further 06:00hrs.

There is no stipulation on the time-step that should be used for the unsteady simulation; however, the software's default calculation settings/tolerances should be used (Note 4 Section 5.5).

Results from the steady state flow simulation (SS1) can be used as the initial conditions to the unsteady simulation if preferred.

5.3 Dataset

The dataset for the test is provided in the ISIS, HEC-RAS and MIKE 11 data formats as part of the benchmarking test data series. The dataset is available for download via the Environment Agency's website (<http://www.environment-agency.gov.uk/floodresearch>).

5.4 Reporting

The reporting of the results should follow the format and style of the Environment Agency Benchmarking Study (Crowder *et al*, 2004) results for Test D and should be in SI units.

The reporting should specifically cover the following:

- method and details of any cross-section interpolations;
- solution criteria/method at the weir;
- the method of developing the initial conditions for the unsteady calculation; and
- a comment on or list of any notes, errors or warnings etc. that the software provides as part of the calculation process.

For the steady state simulations results for water level should be reported upon in tabular form for the cross-sections immediately upstream and downstream of the weir.

For the unsteady simulation results should be presented as a stage verses time plot for the cross-sections immediately upstream and downstream of the weir.

5.5 Test Notes

1. Steady state (SS) flow refers to the undertaking of a backwater analysis with a given set of fixed boundary conditions.
2. Quasi-steady (QS) flow refers to the undertaking of a fully hydrodynamic simulation (solution of the Saint Venant equations) with a given set of constant boundary conditions that are extended over a prescribed time period.
3. Interpolated cross-sections can be used to improve model stability and/or provide results at a prescribed location in the model. The interpolated sections should take one of the following forms:
 - a) Geometric cross-section data (i.e. x-y co-ordinates) that represent the physical form of a cross-section at the required location.
 - b) Software specific routines/capabilities that provide interpolated section properties at the required location.

Alternative methods of interpolation can be tested and reported upon in addition to the above.

4. Default calculation settings, as defined by the installation of the software and/or any user guide provided by the software, should in the first instance be used for undertaking the test. In addition, alternative calculation settings can be tested and reported upon if deemed appropriate by the tester.

6 TEST 'E' – IPPEN WAVE

6.1 Aim of Test

The aim of the test is to:

- compare the results generated by the software package, with an analytical solution based on the hydrodynamic theory of tidal wave propagation in a horizontal channel of uniform cross-section and finite length, as presented by Ippen (1966).

6.2 The Ippen Flood Wave

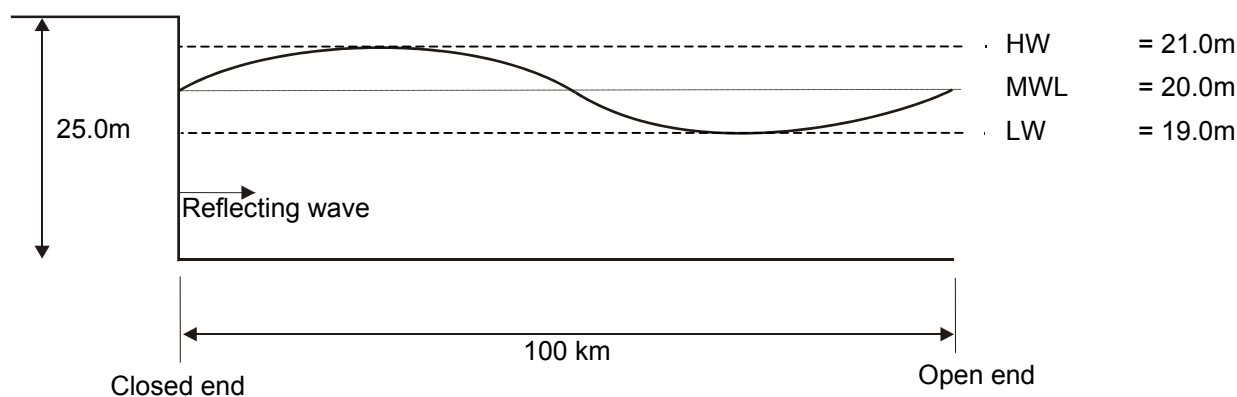
The analytical solution for the Ippen Flood Wave, which is for a channel of finite length, is based upon two crucial assumptions:

- bed friction may be linearised; and
- the non-linear advective acceleration term may be neglected.

These assumptions are acceptable when the ratio of wave amplitude to the mean water depth is relatively small.

The analytical solution calculates the water elevation in a channel of finite length with a closed end by superimposing the incident wave with the reflecting wave, as schematically illustrated in Figure 6.1.

Figure 6.1: Schematic Diagram of Tidal Wave in the Idealised Estuarial Channel.



The analytical solution (which follows that of Ippen) used to compare with the numerical solutions is outlined in Appendix A. In addition, an Excel spreadsheet is available with the data set, which can be downloaded from the Environment Agency's web site (<http://www.environment-agency.gov.uk/floodresearch>).

6.3 Test Configuration

The model should be set up such that a rectangular channel of 100km length and uniform elevation, i.e. no bed slope, is appropriately represented.

The software package should be set up using 201 cross-sections of rectangular channel width of 1000m and a side wall height of 25m at an equal spacing of 500m. It is recommended that a constant Manning's n roughness value of 0.025 be used along the complete length of the channel.

Cross-sections should be defined with a physical geometry and not interpolated cross-sections.

A flow/time boundary of zero inflow for the duration of the simulation should be defined at the upstream boundary of the channel so as to represent the closed boundary. The open boundary at the downstream end of the channel should be specified with a head/time boundary, simulating a sinusoidal wave profile of time period 2.0hrs and amplitude 1.0m.

Suitable initial conditions should be developed so as to enable satisfactory completion of the simulation.

In the first instance default calculation values should be used to undertake the simulation (Note 1 Section 6.6).

6.4 Dataset

The dataset for the test is provided in the ISIS, HEC-RAS and MIKE 11 data formats as part of the benchmarking test data series. The dataset is available for download via the Environment Agency's website (<http://www.environment-agency.gov.uk/floodresearch>). A spreadsheet with the analytical solution is also provided as part of the dataset.

6.5 Reporting

The reporting of the results should follow the format and style of the Environment Agency Benchmarking Study (2004) results for Test E and should be in SI units.

The reporting should specifically cover the following:

- test configuration;
- representation of boundary conditions;
- method of deriving any initial conditions;
- adjustments to default calculation settings (Note 1 Section 6.6);
- calculated water levels and velocities verses analytical values over the duration of the simulation at the closed boundary and at each location 25km downstream of the closed boundary up-to a chainage of 75km;

- calculated longitudinal water level and velocity profiles verses analytical solutions over the length of the channel at the fixed simulation times of 2.0hrs, 2.5hrs, 3.0hrs, 3.5hrs and 4.0hrs; and
- a comment on or list of any notes, errors or warnings etc. that the software provides as part of the calculation process.

6.6 Test Notes

1. Default calculation settings, as defined by the installation of the software and/or any user guide provided by the software, should in the first instance be used for undertaking the test. If the software is unable to perform the test or provides unstable results as a consequence of the default settings, then alternative calculations settings can used. This requirement must be reported upon.

7 TEST 'F' – MONOCLINAL RISING WAVE

7.1 Aim of Test

The aim of the test is to:

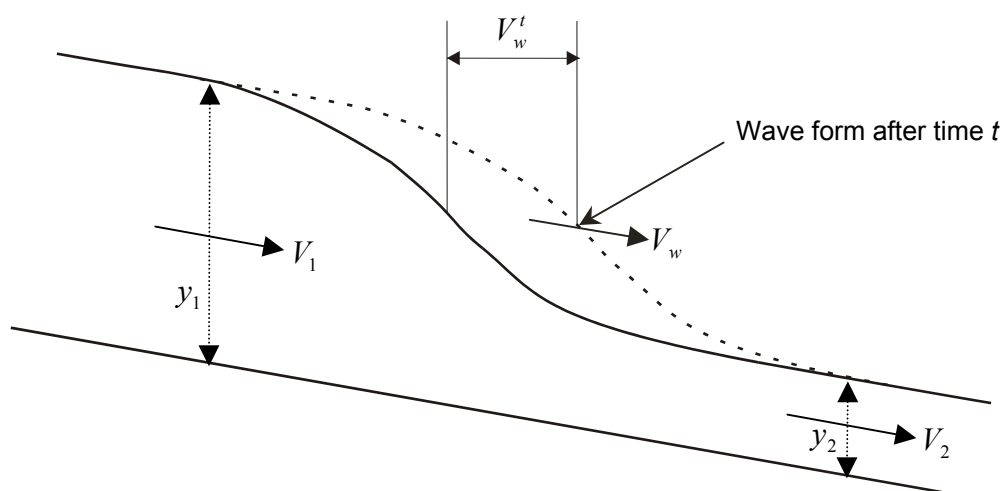
- determine whether each software package is able to recreate the special case of unsteady flow, known as the monoclinal rising wave, described by Chow (1959) as a typical case of uniformly progressive flow; and
- present the particulars for developing and undertaking the test (Model Build) with each of the software packages and the associated results so that others can repeat the test with their own software.

7.2 The Monoclinal Flood Wave

The Monoclinal Rising Wave described by Chow, is an example of uniformly progressive flow. It is referred to by Chow, as “A special case of unsteady flow which is nearly possible in prismatic channels”, the solution to which may be regarded as an approximation to the propagation of storm event flood waves, in natural channels.

The wave may be regarded as a special case of unsteady flow as it describes the transition from one set of steady state conditions to another. The theoretical analysis of the wave is such that for a given channel of uniform cross-section and slope, the flow at the upstream end increases uniformly over a given length of time, from an initial constant value to a subsequent constant value. The resultant wave is one which possesses a stable longitudinal profile, of the form shown in Figure 7.1, the shape of which remains unaltered as the wave travels through the channel.

Figure 7.1: Monoclinal Wave Profile



Being an example of uniformly progressive flow, the monoclinal wave demonstrates the following three properties:

- the front of the wave remains parallel at each successive position of the wave over time;
- the velocity of the wavefront, or the celerity, is greater than the mean velocity of flow at any section of the wave; and
- the complete wave configuration travels down the channel at a constant velocity.

As the monoclinal wave is of a stable form, and uniformly progressive (essentially the velocity of the wavefront V_w is constant), the wave is such that it translates the properties of the flow in the channel from an initial uniform state, having depth y_2 , velocity V_2 , and discharge Q_2 , downstream of the wave, to a different state of uniform flow, having depth y_1 , velocity V_1 , and discharge Q_1 , upstream of the wave.

As the wave travels down the channel, it takes in a steady discharge relative to upstream flow of $Q_0 = (V_w - V_1)A_1$, (where A is the cross-sectional area of flow), and, since the wave is of stable form and constant volume, leaves behind an equivalent steady discharge relative to the downstream flow of $Q_0 = (V_w - V_2)A_2$, Q_0 being referred to as the overrun, the discharge which flows through the wave in the upstream direction.

By equating these equivalent terms for the overrun, it can be shown that the velocity of the wavefront is related to the flows both upstream and downstream of the wave by the following relationship:

$$V_w = \frac{Q_1 - Q_2}{A_1 - A_2} \quad \text{Equation (7.1)}$$

As the wave propagates through the channel at this constant velocity V_w , the wavefront will always travel the same distance downstream over a fixed time period. This distance travelled over a given length of time t , as shown in Figure 7.1, is equal to the wave velocity multiplied by the time, hence $V_w t$.

The analytical solution (which follows that of Chow, 1959) is used to compare with the numerical solutions is outlined in Appendix C. In addition, an Excel spreadsheet is available with the data set, which can be downloaded from the Environment Agency's web site (<http://www.environment-agency.gov.uk/floodresearch>).

7.3 Test Configuration

The software package should be set up using 201 rectangular cross-sections at an equal spacing of 5000m with a width of 1000m and a side wall height of 50m. The slope of the channel is to be set at 0.0004.

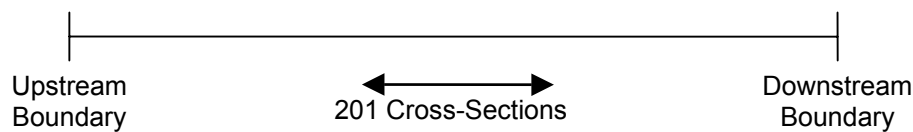
The test is to be defined such that the monoclinal wave joins two regions of normal flow from upstream depth $y_1 = 8.0\text{m}$ to downstream depth $y_2 = 3.0\text{m}$. The corresponding upstream and downstream discharges are $Q_1 = 24693.4 \text{ m}^3/\text{s}$ and $Q_2 = 5698.7 \text{ m}^3/\text{s}$ respectively. This arrangement is defined by appropriate boundary and/or initial conditions (see below).

Channel roughness should be defined with a Chézy friction coefficient, C , of 55; however, if this is not possible then an equivalent Manning's n value should be used and appropriately reported upon.

Cross-sections can be defined with either a physical geometry or interpolated cross section (Note 1 Section 7.6).

The test configuration is illustrated schematically in Figure 7.2.

Figure 7.2: TEST F - Schematic Illustration of Test Configuration



The upstream boundary should be defined with a $Q/h/t$ boundary derived for the above slope, width, friction and depth conditions. This requires the analytical solution of the monoclinal wave equations. To facilitate the development of this an Excel spreadsheet is available, for download from the Environment Agency's web site (<http://www.environment-agency.gov.uk/floodresearch>).

The downstream boundary should be specified with a h/t boundary with constant stage of 3.0m. The initial condition in the channel should be equal to the downstream conditions of the monoclinal wave solution.

It is recognised that the definition of a $Q/h/t$ upstream boundary may not be possible in all software packages (for reasons of numerical stability and solution method), in this case it is recommended that a second choice arrangement for this test be undertaken as defined here. The upstream boundary condition should be a Q/t boundary with a constant Q equal to $Q_I = 24693.395 \text{ m}^3/\text{s}$, and the downstream boundary as above, a h/t boundary with a constant stage of 3.0m. To enable simulation of the monoclinal wave this must be specified via the initial conditions. The analytical solution of the wave profile (including discharge) must be imposed along the channel. The Excel spread sheet, referred to above, again facilitates the solution and provides appropriate initial conditions.

7.4 Dataset

The dataset for the test is provided in the ISIS, HEC-RAS and MIKE 11 data formats as part of the benchmarking test data series. The dataset is available for download via the Environment Agency's website (<http://www.environment-agency.gov.uk/floodresearch>). A spreadsheet with the analytical solution is also provided as part of the dataset.

7.5 Reporting

The reporting of the results should follow the format and style of the Environment Agency Benchmarking Study (Crowder *et al*, 2004) results for Test E and should be in SI units.

The reporting should specifically cover the following:

- test configuration;
- representation of boundary conditions;
- method of deriving any initial conditions (if different from provided condition);
- adjustments to default calculation settings (Note 2 Section 7.6);
- calculated longitudinal water level profiles versus analytical solutions over the length of the channel at the simulation times of 0.0hrs, 10.0hrs, 15.0hrs, and 20.0hrs; and
- a comment on or list of any notes, errors or warnings etc. that the software provides as part of the calculation process.

7.6 Test Notes

1. Interpolated cross-sections can be used to improve model stability and/or provide results at a prescribed location in the model. The interpolated sections should take one of the following forms:
 - a) Geometric cross-section data (i.e. x-y co-ordinates) that represent the physical form of a cross-section at the required location.
 - b) Software specific routines/capabilities that provide interpolated section properties at the required location.

Alternative methods of interpolation can tested and reported upon in addition to the above.

2. Default calculation settings, as defined by the installation of the software and/or any user guide provided by the software, should in the first instance be used for undertaking the test. If the software is unable to perform the test or provides unstable results as a consequence of the default settings, then alternative calculations settings can used. This requirement must be reported upon.

8 TEST 'G'

8.1 Comment

Due to technical constraints and revisions to the test specifications Test G is not published within this report. It is possible that this test specification will be published on the Environment Agency's web site (<http://www.environment-agency.gov.uk/floodresearch>) in due course.

9 TEST ‘H’ – OPERATIONAL STRUCTURES

9.1 Aim of Test

The aim of the test is to:

- assess the ability of each software package to implement a rule-based methodology to simulate the operation of hydraulic structures, namely a pump and a sluice gate; 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.

9.2 Test Configuration

The test configuration for the pump test represents a generic case where a tributary discharges into a defended watercourse.

The configuration is illustrated schematically in Figure 9.1.

The test configuration comprises cross-sections and predefined locations for interpolated sections along with a culvert, reservoir and a downstream tidal exclusion structure.

The interpolated cross-sections (Note 1 Section 9.5) can be removed, added to or replaced by alternatives if deemed appropriate so as to improve model stability and/or provide velocity and water level results at the locations identified in Section 9.4.

The reservoir is connected to the watercourse via two pumps, which operate at different water levels. Both pump units are connected to the watercourse just upstream of the culvert and exclusion structure. Pump 1 is switched on when the water level in the river rises to 2.75m and then turns off when the water level has fallen to 2.25m. Pump 2 is switched on when the water level in the river rises to 3.25m and then turns off when the water level has fallen to 2.5m.

The pump rating details is the same for both pumps and is given in Table 9.1. The optimal point data for the pump rating should be defined as 3.75m for head, 0.95m³/s for flow and 0.80 for efficiency.

Between the pumps and the downstream boundary there is a culvert of length 33m, diameter 1.7m and Manning’s *n* of 0.03.

Figure 9.1: TEST H - Schematic Illustration of Test Configuration

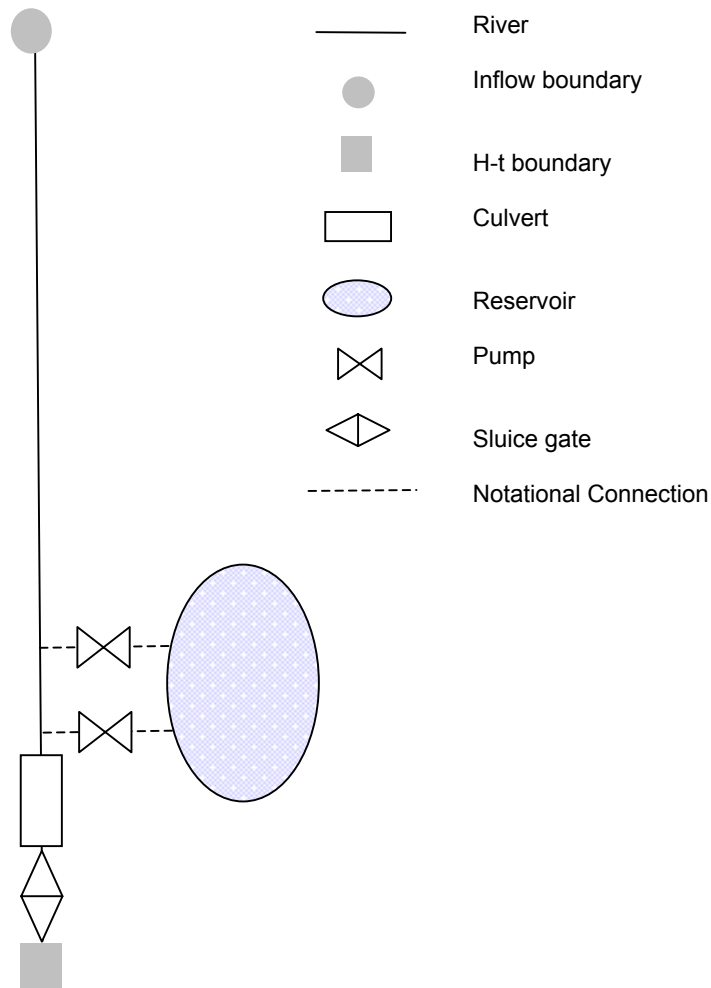


Table 9.1: TEST H – Pump Rating Details

Pumping Head (m)	Flow (m ³ /s)	Efficiency
5.250	0.725	0.700
5.100	0.750	0.700
5.000	0.800	0.700
4.600	0.850	0.740
4.500	0.875	0.760
4.250	0.900	0.780
4.000	0.925	0.800
3.750	0.950	0.800
3.600	0.970	0.800
3.500	0.980	0.780
3.300	1.000	0.780
2.750	1.025	0.760

The downstream boundary is modelled as a single tide curve (H-t boundary). Just upstream of this boundary there is a tidal exclusion structure (sluice gate) with operating rules. These rules state that the structure is closed if the downstream depth is greater than the upstream depth. The dimensions used are as follows:

Elevation of crest	1.711m
Length of crest	0.100m
Breadth of crest	2.100m
Height of crest above bed upstream	0.100m
Height of crest above bed downstream	0.100m
Number of gates	1
Height of gate	5.000m

The upstream boundary of the model is an unsteady flow hydrograph and is defined by the dataset.

There is no stipulation on the time-step that should be used for the unsteady simulation. If changes to the software's default calculation settings are required then these should be appropriately reported upon (Note 2 Section 9.5).

9.3 Dataset

The dataset is provided in the ISIS data format as part of the benchmarking test data series. The dataset is available for download via the Environment Agency's website (<http://www.environment-agency.gov.uk/floodresearch>).

The dataset has been provided in the ISIS format only as it has come from a practical modelling case. It provides a succinct and accurate account of the physical conditions and configuration to be tested. It is acknowledged that other software packages may require some engineering and modelling judgement when interpreting the dataset (i.e. when connecting/locating structures and structure coefficients/parameters); however, this should be minimal.

Where a software package may have a "software specific workaround" or "alternative approach" to modelling the physical conditions/configuration, as defined by the dataset, then a one page method statement for the "workaround" or "alternative" can be made in the reporting. The results of any "workaround" or "alternative" should not be reported in any way.

9.4 Reporting

The reporting of the results should follow the format and style of the Environment Agency Benchmarking Study (Crowder *et al*, 2004) results for Test H and should be in SI units.

The reporting should specifically cover the following:

- statement of any;
- method and details of any cross-section interpolations;

- the method adopted for developing initial conditions for undertaking the unsteady simulation;
- longitudinal plot of water levels and discharge at 0, 2, 4, 6, 8, 10 and 12hrs;
- details of the hydraulic parameters and methods used to calculate the flow through the pump structure. Details of any additional capabilities/features of the software, which are not being tested, can also be reported upon;
- a plot of the discharge with respect to time into the reservoir;
- a plot comparing water levels at pump control point(s);
- a plot of the discharge with respect to time through the downstream structure;
- a plot of the accumulative mass error; and
- a summary of any notes, errors or warning etc. that the software provides as part of the calculation process should be provided.

9.5 Test Notes

1. Interpolated cross-sections can be used to improve model stability and/or provide results at a prescribed location in the model. The interpolated sections should take one of the following forms:
 - a) Geometric cross-section data (i.e. x-y co-ordinates) that represent the physical form of a cross-section at the required location.
 - b) Software specific routines/capabilities that provide interpolated section properties at the required location.

Alternative methods of interpolation can be tested and reported upon in addition to the above.

2. Default calculation settings, as defined by the installation of the software and/or any user guide provided by the software, should in the first instance be used for undertaking the test. If the software is unable to perform the test or provides unstable results as a consequence of the default settings, then alternative calculations settings can be used. This requirement must be reported upon.

10 TEST 'I' - EMBANKMENTS

10.1 Aim of Test

The aim of the test is to:

- assess the ability of each software package to model a) flow between two channels over an embankment (Part 1), and b) flow from a single channel into a reservoir over an embankment (Part 2); 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.

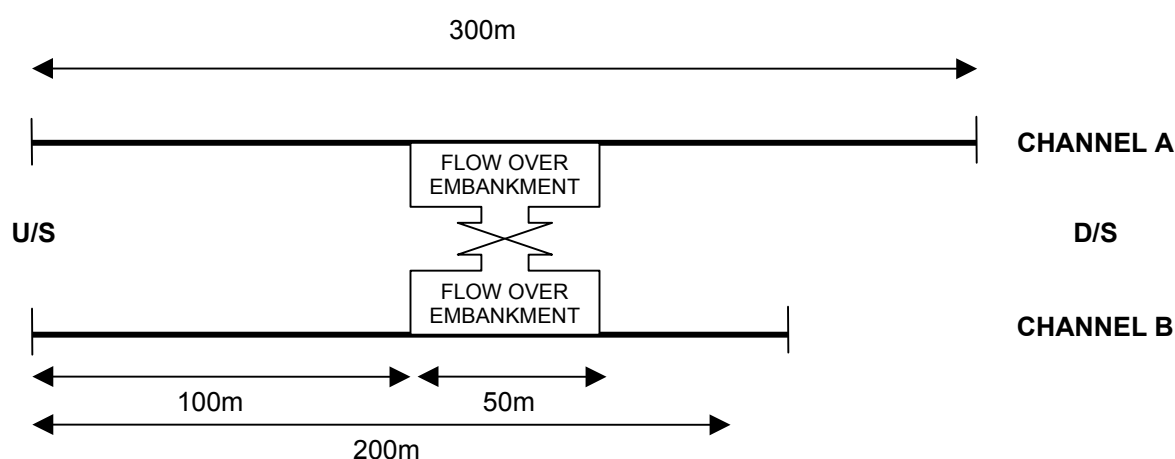
10.2 Test Configuration – Part 1

The test configuration is defined by the dataset (Section 10.4) and is illustrated schematically in Figure 10.1.

There are two trapezoidal channels designated Channel A and Channel B of length 300m and 200m respectively.

The channels are hydraulically connected such that flow between the two channels can occur between 100m and 150m from the upstream boundary.

Figure 10.1: TEST I Part 1 - Schematic Illustration of Test Configuration



Cross-sections are specified at 50m intervals in each of the channels with a Manning's n value of 0.025 used to define channel roughness.

Interpolated cross-sections (Note 1 Section 10.6) should be used so as to improve model stability and/or provide velocity and water level results at the locations identified in Section 10.5.

The width of the embankment is set at 5m and by definition its length is 50m. The elevation of the embankment along its length is defined in Table 10.1.

Table 10.1: TEST I Part 1 – Embankment Dimensions

Distance from Upstream Boundary	Embankment Elevation	
	CHANNEL A	CHANNEL B
100m	1.90m	1.90m
150m	1.85m	1.85m

The numerical representation of the embankment should, where possible, be in the form of a side weir and/or link-channel such that the physicality of the embankment is appropriately represented.

The discharge over the embankment should, if possible, be based on the basic weir equation as given below. An equivalent and/or alternative method is acceptable such that the discharge over the embankment is appropriately controlled/defined.

$$Q = C_d b h^{3/2}, \quad \text{where} \quad C_d = 1.7$$

The software package is to be tested with four separate steady state (Note 2 Section 10.6) flow boundary conditions as defined by Table 10.2.

Table 10.2: TEST I Part 1 – Steady State Boundary Cases

Boundary Case		CHANNEL A		CHANNEL B	
		Upstream Flow (m ³ /s)	Downstream Water Level (m)	Upstream Flow (m ³ /s)	Downstream Water Level (m)
SS1	Free Flow A → B	10.00	1.547	5.00	1.850
SS2	Drowned Flow A → B	10.00	1.547	7.00	1.835
SS3	Free Flow B → A	5.00	1.550	7.00	1.900
SS4	Drowned Flow B → A	3.50	1.900	7.00	1.900

The software package is to be tested under four separate quasi-steady (Note 3 Section 10.6) boundary conditions: QS1, QS2, QS3 and QS4. The same conditions specified for SS1, SS2, SS3 and SS4 are to be used at time t=0 and extended through to 24:00hrs respectively. The data time intervals should be chosen to suite the specific software being tested.

There is no stipulation on the time-step that should be used for the quasi-steady simulation; however, the software's default calculation settings should be used (Note 4 Section 10.6).

Results from the steady state flow simulation can be used as the initial conditions to the quasi-steady simulation if preferred.

In addition to the default calculation settings alternative settings can be tested and reported upon if deemed appropriate.

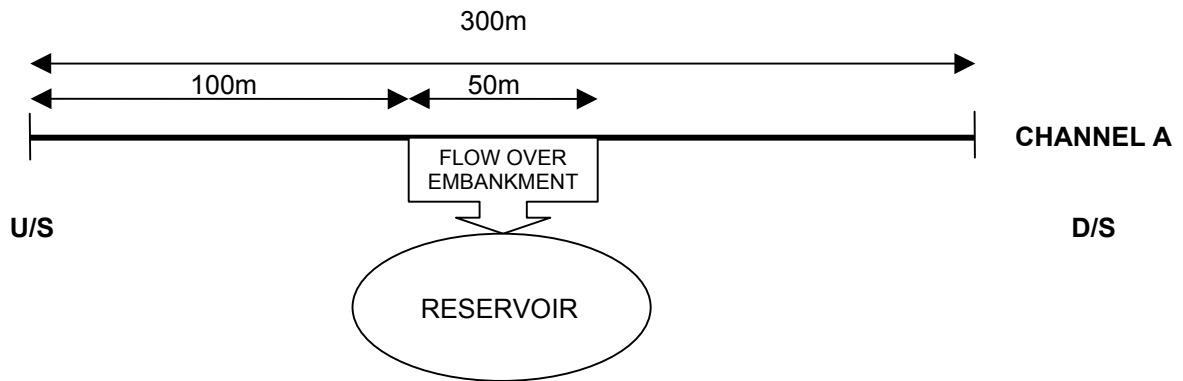
10.3 Test Configuration – Part 2

The test configuration is defined by the dataset (Section 10.4) and is illustrated schematically in Figure 10.2.

There is a single trapezoidal channel designated Channel A of length 300m, which is hydraulically connected to a reservoir such that flow can occur between the channel and reservoir between 100m and 150m from the upstream boundary.

The flow from the channel to the reservoir is via an embankment that has a width of 5m and by definition length of 50m. The elevation of the embankment is the same as that defined for Channel A in Part 1 of the test.

Figure 10.2: TEST I Part 2 - Schematic Illustration of Test Configuration



Cross-sections are specified at 50m intervals with channel roughness being defined by a Manning's n value of 0.025.

Interpolated cross-sections (Note 1 Section 10.6) should be used so as to improve model stability and/or provide velocity and water level results at the locations identified in Section 10.5.

The discharge over the embankment should, if possible, be based on the basic weir equation as given below. An equivalent and/or alternative method is acceptable such that the discharge over the embankment is appropriately controlled/defined.

$$Q = C_d b h^{3/2}, \quad \text{where} \quad C_d = 1.7$$

The reservoir should be defined so that it has a constant plan area of 100m^2 between -100m and 0.0m (i.e. a total volume of $10,000\text{m}^3$ below 0.0m). The reservoir should initially be empty, i.e. the water level set to -100m . If a level higher than -100m is required for model stability/solution then this should be reported upon.

The software package is to be tested with the same SS1 steady state and QS1 quasi-steady (Note 2 Section 10.6) boundary conditions as used for Part 1 of the test.

There is no stipulation on the time-step that should be used for the quasi-steady simulation; however, the software's default calculation settings should be used (Note 4 Section 10.6).

Results from the steady state flow simulation SS1 can be used as the initial conditions to the quasi-steady simulation. Alternative methods and values should be appropriately reported upon.

In addition to the default calculation settings alternative settings can be tested and reported upon if deemed appropriate.

10.4 Dataset

The dataset for Part 1 and Part 2 is provided in the ISIS and HEC-RAS formats as part of the benchmarking test data series. The dataset is available for download via the Environment Agency's website (<http://www.environment-agency.gov.uk/floodresearch>).

10.5 Reporting

The reporting of the results for both Parts 1 and 2 should follow the format and style of the previously published Environment Agency Benchmarking Study (Crowder *et al*, 2004) results for Test I and should be in SI units.

Steady state results for water level, velocity and discharge are required in tabular format at each physical and interpolated cross-section.

Water level, velocity and discharge results are required in tabular format for the quasi-steady simulations at each physical and interpolated cross-section at 24:00hrs.

For each of the quasi-steady runs, a plot of the reservoir water level verses time and flow-rate into the reservoir versus time is required.

The reporting should specifically cover the following:

- method and details of any cross-section interpolations;
- solution method and criteria at the embankment, i.e. weir flow, velocity head loss, water level or energy balance;
- the method of developing the initial conditions for the quasi-steady state calculation should be reported upon;
- list of any notes, errors or warning etc. that the software provides as part of the calculation process;
- details of the hydraulic equations, parameters and methods used to calculate the flow over the embankment;
- details of any additional capabilities/features of the software, which are not being tested can also be reported upon; and
- the method of developing the initial conditions for the quasi-steady state calculation should be reported upon.

10.6 Test Notes

1. Interpolated cross-sections can be used to improve model stability and/or provide results at a prescribed location in the model. The interpolated sections should take one of the following forms:
 - a) Geometric cross-section data (i.e. x-y co-ordinates) that represent the physical form of a cross-section at the required location.
 - b) Software specific routines/capabilities that provide interpolated section properties at the required location.

Alternative methods of interpolation can be tested and reported upon in addition to the above.

2. Steady state (SS) flow refers to the undertaking of a backwater analysis with a given set of fixed boundary conditions.
3. Quasi-steady (QS) flow refers to the undertaking of a fully hydrodynamic simulation (solution of the Saint Venant equations) with a given set of constant boundary conditions that are extended over a prescribed time period.
4. Default calculation settings, as defined by the installation of the software and/or any user guide provided by the software, should in the first instance be used for undertaking the test. In addition, alternative calculations settings can tested and reported upon if deemed appropriate by the tester.

11 TEST 'J' - BRIDGES

11.1 Aim of Test

The aim of the test is to:

- assess the ability of each software package to model an Arch Bridge (Part A) and a US BPR Bridge (Part B) under steady boundary conditions; and
- assess water level results for low and high flows.

11.2 Test Configuration

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).

This test configuration consists of a 22m laboratory flume. The flume has a compound cross section containing a main channel and two flood plains on either side. For this test a smooth main channel and smooth floodplain are assumed. The bridge is placed 10m from the inlet.

Two types of bridge are to be modelled in this test and they are designated Part A and Part B:

- Part A - Arch Bridge: Figure 11.1 shows the dimensions for the multiple opening semi-circular arch bridge used in Part A of the test.
- Part B - USBPR Bridge: Figure 11.2 shows the dimensions for the deck-single opening straight deck bridge used in Part B of the test.

Figure 11.1: Multiple Opening Semi-Circular Arch Bridge (MOSC) Model (after Atabay and Knight, 2002)

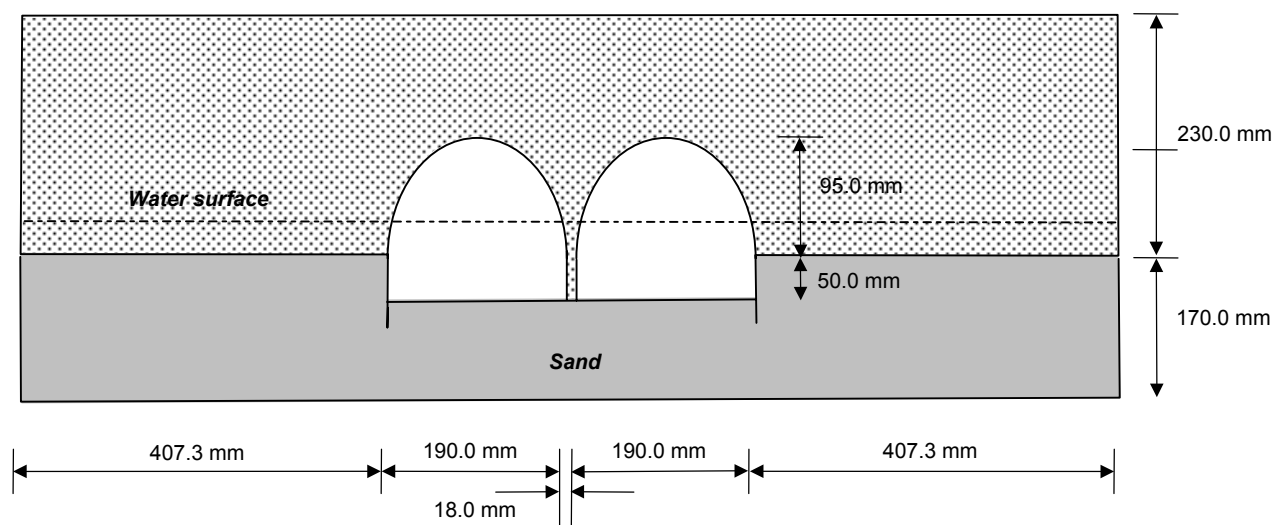
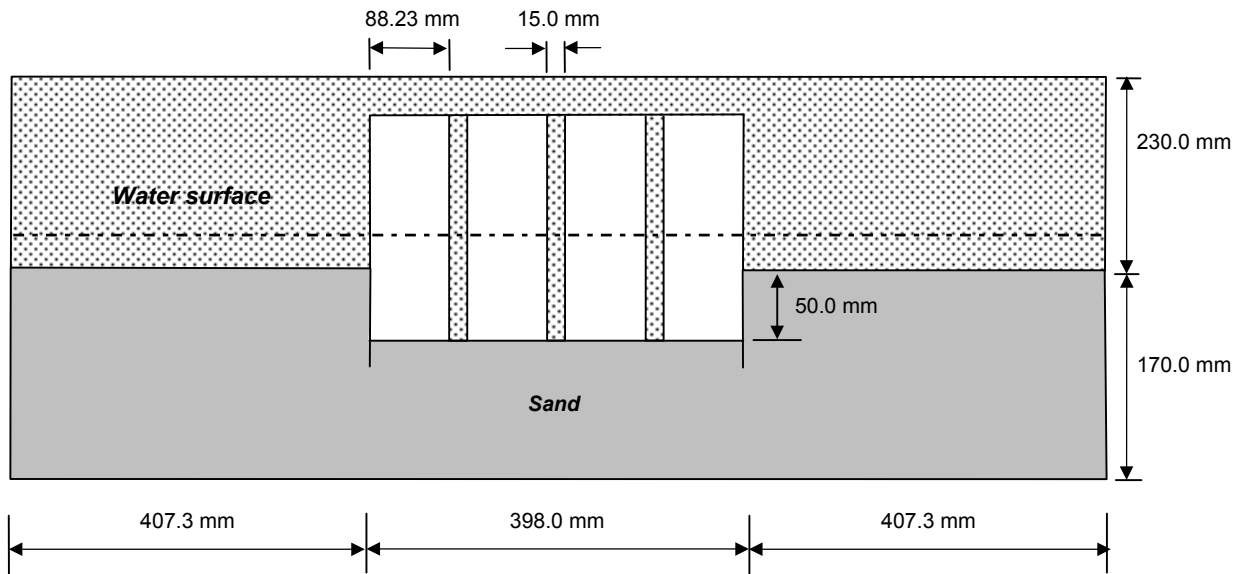


Figure 11.2: Deck-Single Opening Straight Deck Bridge Model (after Atabay and Knight, 2002)



The length of the bridge should be set at 0.12m.

For Part A, the upstream boundary is set as $0.02097\text{m}^3/\text{s}$ and $0.03443\text{m}^3/\text{s}$.

For Part B, the upstream boundary is set as $0.02098\text{m}^3/\text{s}$ and $0.03429\text{m}^3/\text{s}$.

Normal depth is to be used as the downstream boundary in all cases.

Interpolated cross-sections (Note 1 Section 11.5) should be used so as to improve model stability and/or provide velocity and water level results at the locations identified in Section 11.4.

The Manning's n for the flume is measured at 0.0091.

There is no stipulation on the time-step that should be used for the quasi-steady simulation; however, the software's default calculation settings should be used for both steady and quasi-steady simulations (Note 2 Section 11.5).

11.3 Dataset

The dataset is provided in the ISIS, HEC-RAS and MIKE 11 data formats as part of the benchmarking test data series. The dataset are available for download via the Environment Agency's website (<http://www.environment-agency.gov.uk/floodresearch>).

11.4 Reporting

The reporting of the results should follow the format and style of the Environment Agency Benchmarking Study (Crowder *et al*, 2004) results for Test J and should be in SI units.

The reporting should specifically cover the following:

- method and details of any cross-section interpolations;
- solution criteria/method at the bridge; and
- list of any notes, errors or warnings etc. that the software provides as part of the calculation process.

For the steady state simulations results for water level should be reported upon in tabular form for the cross-sections immediately upstream and downstream of the bridge.

11.5 Test Notes

1. Interpolated cross-sections can be used to improve model stability and/or provide results at a prescribed location in the model. The interpolated sections should take one of the following forms:

- a) Geometric cross-section data (i.e. x-y co-ordinates) that represent the physical form of a cross-section at the required location.

- b) Software specific routines/capabilities that provide interpolated section properties at the required location.

Alternative methods of interpolation can be tested and reported upon in addition to the above.

2. Default calculation settings, as defined by the installation of the software and/or any user guide provided by the software, should in the first instance be used for undertaking the test. In addition, alternative calculation settings can be tested and reported upon if deemed appropriate by the tester.

12 TEST 'K' - CULVERTS

12.1 Aim of Test

The aim of the test is to:

- assess the ability of the software package to model unsteady fluid flow in a circular culvert, such that the flow correctly changes from free surface open channel flow to fully pressurised pipe flow;
- test the performance of culverts with both mild (Part A) and steep (Part B) bed slopes, in order that the software can also be analysed for subcritical and supercritical flow respectively; 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.

12.2 Test Configuration

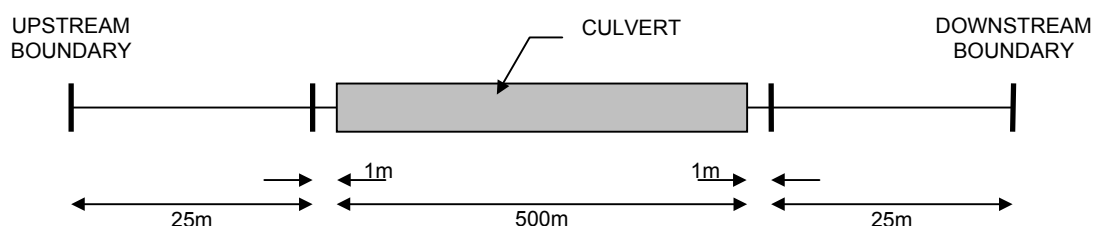
The test configuration for both Parts A and B is illustrated schematically in Figure 12.1. There is one reach that is to be defined with a minimum of four cross-sections as prescribed by the dataset (Section 12.3).

Interpolated cross-sections (Note 1 Section 12.5) should be used to improve model stability and provide velocity and water level results at the locations identified in Section 12.4.

A constant Manning's n value of 0.025 is to be used for the main channel.

For Part A of the test the bed slope is 0.0025 (mild) and for Part B 0.01 (steep).

Figure 12.1: TEST K - Schematic Illustration of Test Configuration

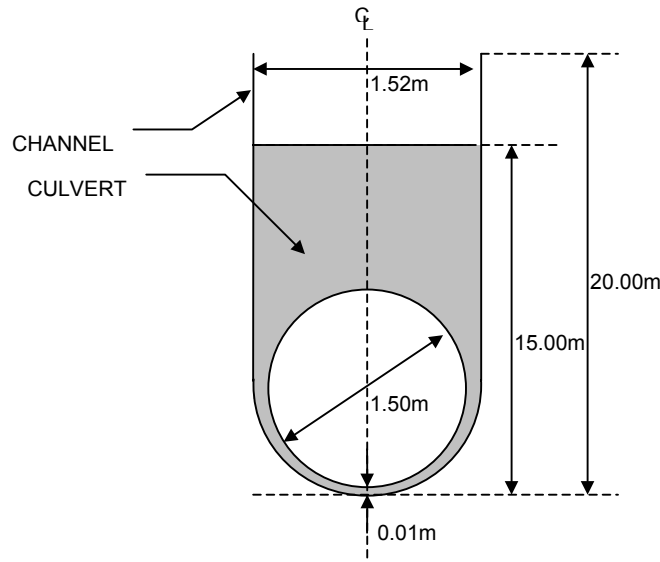


The culvert dimensions are the same for both Parts A and B and are illustrated schematically in Figure 12.2. The culvert diameter is 1.5m and a culvert Manning's roughness (n) of 0.025 is to be used. If a Manning's n value cannot be defined for the culvert roughness then a Colebrook-White K_s value of 0.075m can be used as an alternative, in accordance with the following relationship (Webber, 1971):

$$n = \frac{K_s^{1/6}}{26}$$

If a K_s value can be defined in addition to an n value then the model can be tested with a K_s value in addition if desired.

Figure 12.2: TEST K - Schematic Illustration of Culvert Dimensions



The ability of the software to consider culvert i) entry and exit losses (above those inherently included/required by the software), ii) overtopping, or iii) other specific features, is not a primary consideration. However, suitable representation of these, where appropriate, can be considered and reported upon if deemed appropriate.

For Parts A and B of the test separate unsteady flow boundary conditions are to be used.

For Part A, the upstream boundary is to be defined with a constant inflow of $0.75\text{m}^3/\text{s}$. The downstream water level boundary is initially to be set at 0.5mAD at 0.0hrs , and then linearly increased to 4.2mAD at 1.36hrs (82.0 min). The downstream boundary should then be fixed at this level through to 2.0hrs . A suitable data interval for the boundary condition should be used for all boundaries.

For Part B, the upstream boundary is to be defined with a constant inflow of $1.5\text{m}^3/\text{s}$. The downstream water level boundary is initially to be set at 0.5mAD at 0.0hrs , and then linearly increased to 9.7mAD at 1.36hrs (82.0 min). The downstream boundary should then be fixed at this level through to 2.0hrs . Boundary data should be defined at a 1 minute data interval to two decimal places, with linear interpolation between the data values given above.

There is no stipulation on the time-step that should be used for the unsteady simulation; however, the software's default calculation settings should be used (Note 2 Section 12.5).

A steady state flow simulation can be used to provide suitable initial conditions to the unsteady simulation.

12.3 Dataset

The dataset is provided in the ISIS, HEC-RAS and MIKE 11 data formats as part of the benchmarking test data series. The datasets are available for download via the Environment Agency's website (<http://www.environment-agency.gov.uk/floodresearch>).

12.4 Reporting

The reporting of the results should follow the format and style of the Environment Agency Benchmarking Study (Crowder *et al*, 2004) results for Test K and should be in SI units.

The reporting should specifically cover the following:

- method and details of any cross-section interpolations;
- solution method for the various flow regimes/controls through the culvert;
- the method of deriving any initial conditions for use in the unsteady simulation; and
- list of any notes, errors or warning etc. that the software provides as part of the calculation process.

For both Parts A and B of the unsteady simulations the following results should be presented and discussed:

- Stage verses Time at 0.0m, 25.0m, 527.0m and 552.0m from the downstream boundary;
- Velocity verses Time at 0.0m, 25.0m, 527.0m and 552.0m from the downstream boundary;
- Discharge verses Time at 0.0m, 25.0m, 527.0m and 552.0m from the downstream boundary;
- Froude Number verses Time at 0.0m, 25.0m, 527.0m and 552.0m from the downstream boundary; and
- Stage and Flow Velocity verses Time at the culvert inlet, mid culvert and culvert outlet (see Note 3). For the mid results the theoretical full culvert flow velocity of 0.424m/s for Part A and 0.949m/s for Part B should also be shown.

12.5 Test Notes

1. Interpolated cross-sections can be used to improve model stability and/or provide results at a prescribed location in the model. The interpolated sections should take one of the following forms:
 - a) Geometric cross-section data (i.e. x-y co-ordinates) that represent the physical form of a cross-section at the required location.
 - b) Software specific routines/capabilities that provide interpolated section properties at the required location.

Alternative methods of interpolation can tested and reported upon in addition to the above.

2. Default calculation settings, as defined by the installation of the software and/or any user guide provided by the software, should in the first instance be used for undertaking the test. In addition, alternative calculations settings can tested and reported upon if deemed appropriate by the tester.
3. It is recognised that some software packages may not be able to provide this information due to the method of solution or model configuration requirements. In such cases these results do not need to be presented; however, this limitation should be reported upon.

13 TEST ‘L’ – SURGE WAVE

13.1 Aim of Test

The aim of the test is to:

- assess the ability of the software packages to replicate the behaviour of a surge wave, caused by the sudden collapse of a large body of water, in a channel with a local constriction and expansion; and
- benchmark the numerical results with laboratory results obtained in the European Commission’s CADAM project (Frazao, 1999) – the European Concerted Action on Dam-Break Modelling.

13.2 The CADAM Project

The CADAM project was set up and funded by the European Commission in 1998, as a two year programme of work performed by participants from over ten different European countries, to further computational modelling techniques into dam-break analysis.

Due to the very irregular and unpredictable nature of dam-break surge flows, benchmark data was gathered based upon laboratory models designed to recreate a dam-break in simple channels. The physical models were used as a means by which to evaluate the quality of the hydraulic flow data generated using numerical methods and computational models.

Three test cases were proposed in the CADAM Report 3 (Frazao, 1999); Test Case 1 – L Shaped Channel; Test Case 2 – Local Constriction; Test Case 3 – Flood Plain. All three tests were performed in channels of uniform rectangular cross-section, and were designed to provide simplified results for a surge wave experiencing a change in direction downstream of the reservoir, a constriction in the flow, and an expansion of the flow area.

To enable the future comparison with numerical results, water levels, flow velocities, and discharge were measured using staging meters and pressure gauges at specific channel locations.

This test is only concerned with Test Case 2 for a Dam-Break in a channel with a local constriction.

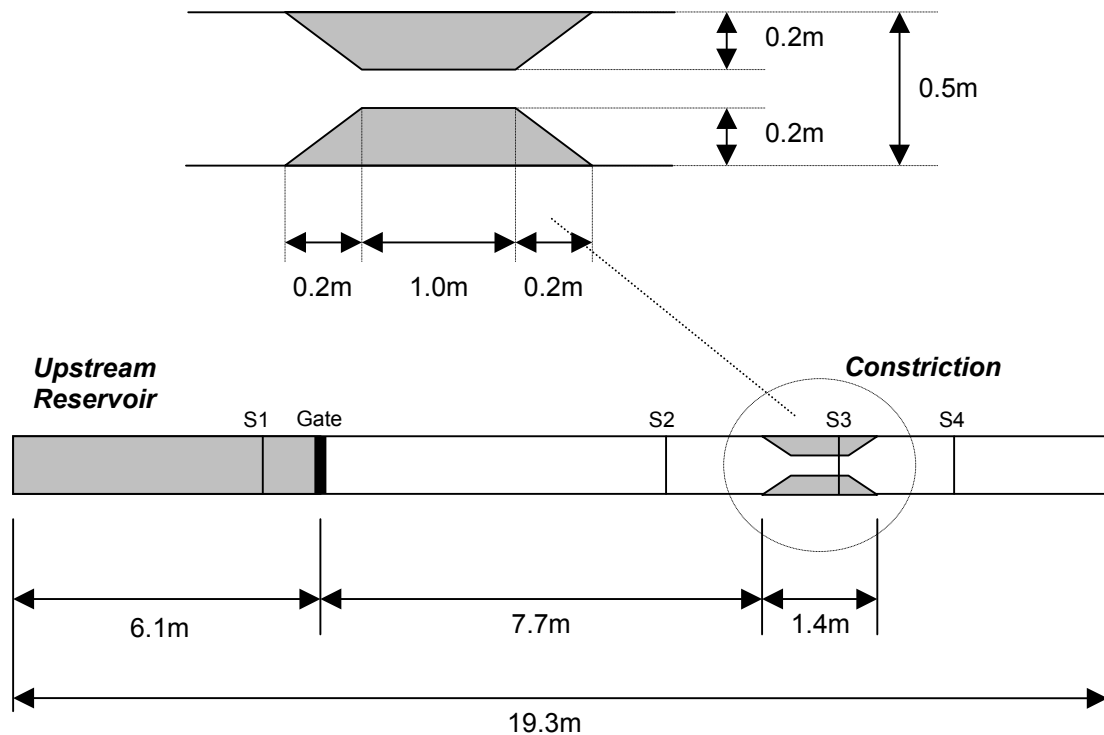
13.3 The CADAM Laboratory Configuration

The physical laboratory model for the ‘Dam-break in a channel with a local constriction’ was built, as illustrated in Appendix C, at the ‘Laboratório Nacional de Engenharia Civil’ in conjunction with the ‘Instituto Superior Técnico’ in Portugal¹. A schematic diagram of the channel is given in Figure 13.1.

The model comprises of a horizontal channel of uniform 0.5m wide rectangular cross-section. The overall length of the channel was set at 19.30m, with the first 6.10m of the channel at the

upstream end specified for the reservoir. A removable sluice gate was built into the channel to retain the water within the reservoir, the gate being removed in approximately 0.2 seconds to simulate the break of the dam. A constriction was located 7.70m downstream of the sluice gate, with an overall length of 1.4m, the first and last 0.2m of the constriction being tapered at 45 degree angles to the channel walls. The middle width of the constriction of 0.1m therefore remains uniform for 1.0m in length, as illustrated in Figure 13.1.

Figure 13.1: Schematic Diagram of Channel with Local Constriction (m)



The initial conditions for the test were set at 0.3m depth of water in the reservoir upstream of the gate, and 0.003m in the channel downstream of the gate. The experimental data for the test was obtained by removing the gate, and measuring the depth and velocity of flow at the benchmarking stations S1 to S4 (Figure 13.1). S1 is located 1.0m upstream of the dam gate, S2, 6.10m downstream of the dam gate, S3, 8.80m downstream of the dam gate, and S4, 10.50m downstream of the dam gate. The measurements were taken every 0.04 seconds, and recorded up to a simulation time of 10.00 seconds.

13.4 Laboratory Dataset

Laboratory water level results for locations S1, S2, S3 and S4 are provided in Appendix C at 4s intervals from 0s through to 10s.

13.5 Test Configuration

There is no prescribed test configuration for the test; however, the model should be set up such that the laboratory configuration is appropriately represented.

It is suggested that a suitable value for Manning's n throughout the modelled reach is 0.01. Cross-sections should be defined with a physical geometry and not interpolated cross-sections.

Suitable initial conditions should be developed so as to enable satisfactory completion of the simulation.

The software's default calculation settings should initially be used (Note 1 Section 13.7).

13.6 Reporting

The reporting of the results should follow the format and style of the Environment Agency Benchmarking Study (Crowder *et al*, 2004) results for Test L and should be in SI units.

Where appropriate numerical results should be benchmarked against laboratory results.

The reporting should specifically cover the following:

- test configuration;
- representation of boundary conditions;
- method of deriving any initial conditions;
- adjustments to default calculation settings (see Note 1); and
- Stage verses Time results at the defined locations.

13.7 Test Notes

1. Default calculation settings, as defined by the installation of the software and/or any user guide provided by the software, should in the first instance be used for undertaking the test. If the software is unable to perform the test, or provides unstable results as a consequence of the default settings, then alternative calculations settings can be used. This requirement must be reported upon.

14 TEST 'M' - SPECIFICATION

14.1 Comment

Due to technical constraints and revisions to the test specifications, Test M is not published within this report. It is possible that this test specification will be published on the Environment Agency's web site (<http://www.environment-agency.gov.uk/floodresearch>) in due course.

15 TEST 'N' - SPECIFICATION

15.1 Comment

Due to technical constraints and revisions to the test specifications, Test N is not published within this report. It is possible that this test specification will be published on the Environment Agency's web site (<http://www.environment-agency.gov.uk/floodresearch>) in due course.

16 TEST 'O' – TIDAL OUTFALL

16.1 Aim of Test

The aim of the test is to:

- assess the ability of each software package to model flapped outfalls that are influenced by both tidal and fluvial boundary conditions;
- 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.

16.2 Test Configuration

The test configuration is defined by the test dataset (Section 16.3) and is illustrated schematically in Figure 16.1. There is one main river designated Ri and three main tributaries designated Mi, Sa, and Do. Tributary Do has a further tributary designated Lo.

Inflow hydrographs are defined for each of the tributaries and at the upstream boundary of the model. In addition, two further inflow hydrographs are defined to incorporate flows from tributaries that are not being modelled.

A time dependant water level boundary is defined at the downstream limit of the model to simulate tidal conditions.

Interpolated cross-sections (Note 1 Section 16.5) may be used in order to improve model stability and/or provide velocity and water level results at the locations identified in Section 16.4.

At each cross-section Manning's n values are used to define channel roughness. A range of Manning's n values is used to define changes in roughness a) within a cross section, and b) along the length of the model.

Junctions are defined with a distance of 0.0m between bounding cross-sections or defined structures (i.e. tidal outfall).

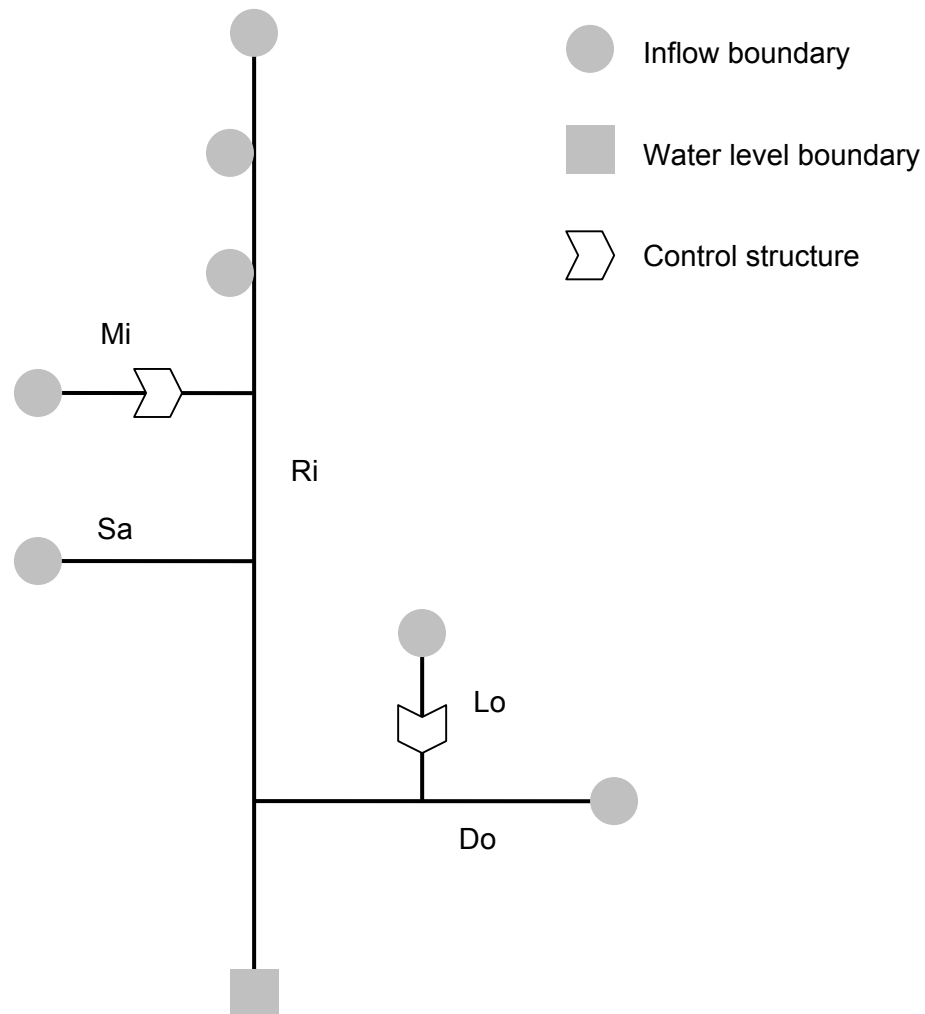
Two tidal outfalls are defined within the model. One is located on tributary Mi immediately upstream of the junction with the main river, Ri, the other being located on tributary, Lo immediately upstream of the junction with tributary, Do.

The tidal outfalls are to enable tide locking when the downstream water level is higher than the upstream water level. The dimensions of each outfall are defined by the test dataset (Section 16.3).

The software package is to be tested with unsteady flow and level boundary conditions as defined by the dataset (Section 16.3).

Results from a steady state flow simulation may be used as the initial conditions to the unsteady simulation. Alternatively, the modeller may choose to use results from a quasi-steady (Note 2 Section 16.5) or an additional unsteady simulation that provides suitable steady non-uniform flow conditions for commencing the unsteady simulation.

Figure 16.1: TEST O - Schematic Illustration of Test Configuration



When using an additional unsteady simulation to develop initial conditions for the unsteady simulation, the modeller should define his/her own boundary conditions so as to provide steady non-uniform flow conditions which are analogous to the unsteady flow boundary conditions at 0:00hrs.

There is no stipulation on the time-step that should be used for the unsteady simulation; however, the modeller should select a time-step that secures an adequate representation of the tidal curve.

The software's default calculation settings should initially be used (Note 3 Section 16.5). However, alternative settings may be tested in addition and reported upon if deemed appropriate.

16.3 Dataset

The dataset is provided in ISIS format as part of the benchmarking test data series. The dataset is available for download via the Environment Agency's website (<http://www.environment-agency.gov.uk/floodresearch>).

16.4 Reporting

The reporting of the results should follow the format and style of the Environment Agency Benchmarking results for Test O (Crowder *et al*, 2004) and should be in SI units.

Longitudinal plots should report values at each physical and interpolated cross-section. Tabular reporting of results may be presented in addition.

The reporting should specifically cover the following:

- method and details of any cross-section interpolations including their location;
- the method adopted for developing initial conditions for undertaking the unsteady simulation;
- maximum water level results in graphical or tabular format;
- longitudinal plot of maximum water levels for each channel;
- details of the hydraulic equations, parameters and methods used to calculate the flow through the outfall structure. Details of any additional capabilities/features of the software, which are specifically relevant to this test, may also be briefly reported upon;
- a plot of the discharge with respect to time at the most downstream cross-section of the main river, R_i ;
- a plot of the discharge with respect to time through each of the outfall structures; and
- a summary of any notes, errors or warning etc. that the software provides as part of the calculation process should be provided.

16.5 Test Notes

1. Interpolated cross-sections may be used to improve model stability and/or provide results at a prescribed location in the model. The interpolated sections should take one of the following forms:
 - a) Geometric cross-section data (i.e. x-y co-ordinates) that represent the physical form of a cross-section at the required location.
 - b) Software specific routines/capabilities that provide interpolated section properties at the required location.

Alternative methods of interpolation may be tested and reported upon in addition to the above.

3. Quasi-steady (QS) flow refers to the undertaking of a fully hydrodynamic simulation (solution of the Saint Venant equations) with a given set of constant boundary conditions that are extended over a prescribed time period.
4. Default calculation settings, as defined by the installation of the software and/or any user guide provided by the software, should in the first instance be used for undertaking the test. In addition, alternative calculations settings may be tested and reported upon if deemed appropriate by the tester. In that case justification for the alternative settings should be provided.

17 CONCLUSIONS AND RECOMMENDATIONS

The specifications provide range of different tests that cover a broad range of modelling scenarios. However, it is important to stress that these specifications may only assess a limited range of model capabilities.

The specifications could be applied to 1D, 2D and 3D software packages; however, it is acknowledged that for 2D and 3D models some judgement may be required in defining physical geometry and structures.

Similar specifications could be developed to benchmark software for modelling, sewer modelling, coastal and estuarine modelling, and groundwater modelling etc.

The specifications need to be enhanced and expanded in order to enable benchmarking of software as improvements and capabilities are made, and so as to consider more complex hydraulic issues and real-life modelling problems that are relevant to river management. This typically includes the following:

- hydraulic issues associated with planform (i.e. confluences, split flows and bends);
- use of hybrid 1D/2D, quasi-2D or 2D models (i.e. higher dimension models) for enhanced floodplain modelling (inundation modelling / flood spreading);
- Logical Rules (i.e. structure operation);
- hydrological boundaries (i.e. groundwater flow, evoptransportation, evaporation, FEH inputs etc.);
- use of XML as a language for common data format; and
- effectiveness of water quality and sediment transport modules in hydrodynamic models.

In order to achieve the above, suitable field data will be needed so as to enable qualitative and quantitative benchmarking.

From undertaking the benchmarking study a number of issues arose which were outside the scope of the project, but which the project team felt worthy further of investigation, in order to improve the accuracy of the hydrodynamic river modelling. These include the following:

- how packages handle interpolation – when it is needed, and what intervention by the modeller is required;
- whether the default weighting factors are acceptable, and under what circumstances they should be altered;
- use and relevance of the Courant number and appropriate time-step intervals;
- modelling of junctions. Two methods can be used (water level or energy level balance), but it is not clear which is the more appropriate in different junction configurations. It may be necessary to carry out model or field tests to provide clear guidance;
- incorporation of new conveyance formulations, such as that derived from the associated R&D Project ‘Reducing uncertainty in river flood conveyance’. This may also involve guidance on preparing and using conveyance tables; and
- incorporation of new afflux formulations, as derived from the associated R&D Project ‘Hydraulic performance of river bridges and other structures at high flows’.

18 REFERENCES

- Atabay, S., and Knight, D. W., (Jan. 2002), "Scoping Study into Hydraulic Performance of Bridges and other Structures, including Effects of Blockages, at High Flows (Bridge Afflux Experiments in Compound Channels)", Technical paper presented for JBA Consulting Engineers & Scientists and the Environment Agency
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APPENDIX A TEST A - ANALYTICAL SOLUTIONS

Chainage (m)	TEST A – Analytical Solutions				
	Part 1	Part 2	Part 3	Part 4	Part 5
100.00	1.32769	2.99080	2.16148	3.58583	2.60229
99.00	1.32416	2.97108	2.15406	3.58043	2.57995
98.00	1.32076	2.95103	2.14651	3.57492	2.55555
97.00	1.31748	2.93063	2.13885	3.56931	2.52903
96.00	1.31433	2.90990	2.13105	3.56358	2.50031
95.00	1.31129	2.88881	2.12313	3.55774	2.46933
94.00	1.30836	2.86736	2.11508	3.55178	2.43603
93.00	1.30553	2.84555	2.10690	3.54569	2.40036
92.00	1.30280	2.82336	2.09858	3.53946	2.36229
91.00	1.30016	2.80080	2.09013	3.53311	2.32182
90.00	1.29760	2.77785	2.08155	3.5266	2.27899
89.00	1.29512	2.75452	2.07283	3.51995	2.23387
88.00	1.29271	2.73080	2.06396	3.51315	2.18660
87.00	1.29036	2.70668	2.05496	3.50618	2.13741
86.00	1.28807	2.68217	2.04581	3.49904	2.08657
85.00	1.28583	2.65726	2.03652	3.49172	2.03449
84.00	1.28364	2.63196	2.02708	3.48422	1.98165
83.00	1.28149	2.60625	2.01749	3.47652	1.92862
82.00	1.27937	2.58016	2.00775	3.46862	1.87610
81.00	1.27728	2.55367	1.99786	3.46051	1.82484
80.00	1.27522	2.52680	1.98781	3.45217	1.77566
79.00	1.27317	2.49954	1.97761	3.44360	1.72944
78.00	1.27113	2.47192	1.96725	3.43478	1.68701
77.00	1.26910	2.44393	1.95673	3.42570	1.64917
76.00	1.26708	2.41558	1.94606	3.41635	1.61662
75.00	1.26505	2.38689	1.93521	3.40672	1.58991
74.00	1.26302	2.35787	1.92421	3.39678	1.56941
73.00	1.26098	2.32854	1.91304	3.38653	1.55528
72.00	1.25892	2.29891	1.90170	3.37594	1.54745
71.00	1.25684	2.26900	1.89020	3.3650	1.54566
70.00	1.25474	2.23883	1.87852	3.35369	1.54943
69.00	1.25261	2.20842	1.86667	3.34199	1.55815
68.00	1.25045	2.17780	1.85465	3.32987	1.57110
67.00	1.24825	2.14698	1.84246	3.31731	1.58749
66.00	1.24602	2.11600	1.83008	3.30428	1.82085
65.00	1.24375	2.08489	1.81753	3.29076	1.80938
64.00	1.24143	2.05366	1.80481	3.27672	1.79770
63.00	1.23907	2.02236	1.79190	3.26212	1.78581
62.00	1.23665	1.99100	1.77881	3.24692	1.77371
61.00	1.23418	1.95963	1.76554	3.23109	1.76139
60.00	1.23165	1.92828	1.75208	3.21459	1.74885
59.00	1.22906	1.89697	1.73844	3.19737	1.73609
58.00	1.22641	1.86574	1.72462	3.17938	1.72312
57.00	1.22369	1.83462	1.71061	3.16057	1.70992
56.00	1.22091	1.80365	1.69641	3.14088	1.69649
55.00	1.21805	1.77286	1.68202	3.12024	1.68284
54.00	1.21512	1.74227	1.66744	3.09859	1.66896
53.00	1.21211	1.71192	1.65268	3.07584	1.65486
52.00	1.20902	1.68185	1.63772	3.05192	1.64052
51.00	1.20585	1.65207	1.62258	3.02672	1.62596

50.00	1.20260	1.62262	1.60724	3.00015	1.61116
49.00	1.19925	1.59352	1.59171	2.97209	1.59613
48.00	1.19582	1.56479	1.57599	2.94241	1.58087
47.00	1.19229	1.53647	1.56007	2.91097	1.56538
46.00	1.18867	1.50856	1.54397	2.87762	1.54965
45.00	1.18495	1.48108	1.52767	2.84218	1.53369
44.00	1.18112	1.45407	1.51118	2.80445	1.51749
43.00	1.17720	1.42751	1.49450	2.76421	1.50107
42.00	1.17316	1.40144	1.47763	2.72121	1.48441
41.00	1.16902	1.37585	1.46057	2.67518	1.46752
40.00	1.16476	1.35076	1.44331	2.62578	1.45040
39.00	1.16039	1.32617	1.42587	2.57267	1.43305
38.00	1.15589	1.30209	1.40824	2.51542	1.41547
37.00	1.15128	1.27851	1.39042	2.45356	1.39767
36.00	1.14655	1.25544	1.37241	2.38654	1.37964
35.00	1.14169	1.23287	1.35421	2.31372	1.36139
34.00	1.13670	1.21080	1.33583	2.23439	1.34293
33.00	1.13158	1.18922	1.31727	2.75431	1.32424
32.00	1.12632	1.16812	1.29852	2.77961	1.30534
31.00	1.12093	1.14751	1.27960	2.79849	1.28623
30.00	1.11540	1.12736	1.26049	2.81295	1.26691
29.00	1.10973	1.10766	1.24121	2.82427	1.24738
28.00	1.10391	1.08841	1.22175	2.83329	1.22766
27.00	1.09795	1.06960	1.20212	2.84059	1.20774
26.00	1.09184	1.05120	1.18231	2.84658	1.18763
25.00	1.08558	1.03320	1.16234	2.85155	1.16733
24.00	1.07917	1.01560	1.14221	2.85571	1.14684
23.00	1.07260	0.99837	1.12191	2.85923	1.12619
22.00	1.06588	0.98150	1.10145	2.86221	1.10536
21.00	1.05900	0.96498	1.08083	2.86477	1.08436
20.00	1.05196	0.94879	1.06005	2.86696	1.06321
19.00	1.04477	0.93292	1.03913	2.86886	1.04190
18.00	1.03741	0.91734	1.01806	2.87050	1.02044
17.00	1.02989	0.90206	0.99684	2.87192	0.99885
16.00	1.02222	0.88704	0.97548	2.87315	0.97712
15.00	1.01438	0.87228	0.95399	2.87422	0.95527
14.00	1.00637	0.85777	0.93236	2.87515	0.93330
13.00	0.99821	0.84348	0.91060	2.87595	0.91121
12.00	0.98989	0.82942	0.88871	2.87665	0.88903
11.00	0.98141	0.81556	0.86671	2.87724	0.86675
10.00	0.97276	0.80189	0.84459	2.87774	0.84439
9.00	0.96396	0.78840	0.82235	2.87816	0.82195
8.00	0.95501	0.77508	0.80001	2.87850	0.79944
7.00	0.94590	0.76192	0.77757	2.87877	0.77687
6.00	0.93664	0.74891	0.75503	2.87898	0.75425
5.00	0.92723	0.73603	0.73239	2.87913	0.73159
4.00	0.91767	0.72328	0.70967	2.87922	0.70890
3.00	0.90797	0.71066	0.68687	2.87925	0.68619
2.00	0.89812	0.69814	0.66399	2.87923	0.66346
1.00	0.88814	0.68573	0.64103	2.87916	0.64074
0.00	0.87803	0.67341	0.61801	2.87904	0.61801

APPENDIX B TEST E - ANALYTICAL SOLUTIONS

Analytical Solution

Nomenclature

η = Tidal Elevation

u = velocity

x = Distance from closed end (negative, i.e. closed end $x = 0$, open end $x = -100000$)

a_o = input wave amplitude

μ = characteristic of channel, involving friction

σ = frequency, $2\pi / T$

κ = wave number characteristic of channel, involving friction

t = time

T = wave period

Equation for tidal elevation at any point measured in the negative direction from the closed end, at any time t . i.e. at the closed end $x = 0$ m, at the open end $x = -100000$ m.

$$\eta = a_o \left(e^{-\mu x} \cos(\sigma t + \kappa x) + e^{\mu x} \cos(\sigma t + \kappa x) \right) \quad \text{Equation 1}$$

[Ippen's equation 10.41]

Equation for velocity at any point, at anytime:

$$u = \frac{a}{h} \frac{\sigma}{\sqrt{\mu^2 + \kappa^2}} \left(e^{-\mu x} \cos(\sigma t - \kappa x + \alpha) - e^{\mu x} \cos(\sigma t + \kappa x + \alpha) \right) \quad \text{Equation 2}$$

[Which is very similar to Ippen's equation 10.48, (with the substitution for $\kappa_o = \sigma / C_o$ from equation 10.34), except that the second *cos* replaces a *sin* in Ippen's equation.]

The solution of these two equations gives us the analytic solutions which we compare with the model results. A spreadsheet has been prepared which will do the calculation, which accompanies the dataset for the test.

Below are the details of the solution, following Ippen.

We have the wave frequency,

$$\sigma = \frac{2\pi}{T} \quad \text{Equation 3}$$

where T is the period of the incoming wave, in seconds.

We must convert the Manning's n to a Chezy C by the formula,

$$C = \frac{h^{1/6}}{n} \quad \text{Equation 4}$$

where h is the mean depth of water in metres.

The friction factor, f ,

$$f = \frac{8g}{C^2} \quad \text{Equation 5}$$

[after Ippens equation 10.24],

Ippen's linear friction coefficient, M , is given from his equation 10.29,

$$M = \frac{f}{3\pi} \frac{u_{\max}}{gh} \quad \text{Equation 6}$$

where, u_{\max} , is some representative velocity in the channel.

Ippen derives the following equations that express the channel geometry and wave characteristics using two variables, κ , and μ :

$$\kappa_o^2 = \kappa - \mu^2 \quad \text{Equation 7}$$

[Ippen's equation 10.34]

$$\kappa_o = \frac{\sigma}{C_o} = \frac{\alpha}{\sqrt{gh}} \quad \text{Equation 8}$$

$$\frac{g}{\sigma} M = 2 \frac{\mu}{\kappa} \frac{1}{1 - (\mu/\kappa)^2} \quad \text{Equation 9}$$

[Ippen's equation 10.35a]

$$\tan \alpha = \frac{\mu}{\kappa} \quad \text{Equation 10}$$

We need to solve equations 7 a, 9 for κ , and μ . Equation 9 can be rearranged to

$$\frac{g}{\sigma} M = 2\mu \frac{\kappa}{\kappa_o^2} \quad \text{Equation 11}$$

Combining this with equation 7 to eliminate μ , gives

$$\kappa^4 - \kappa_o^2 \kappa - \frac{\kappa_o^2}{4} \left(\frac{gM}{\sigma} \right)^2 = 0 \quad \text{Equation 12}$$

This can be solved for κ^2 using the formula for quadratic equations [for $ax^2 + bx + c = 0$ then $x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$] to give

$$\kappa = \left[0.5 \left(\kappa_o^2 + \sqrt{\kappa_o^4 + \kappa_o^4 (gM / \sigma)^2} \right) \right]^{1/2} \quad \text{Equation 13}$$

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and from equation 11

$$\mu = \frac{gM}{\sigma} \frac{\kappa_o^2}{2\kappa} \quad \text{Equation 14}$$

and

$$\alpha = \tan^{-1}(\mu / \kappa) \quad \text{Equation 15}$$

APPENDIX C TEST L - LABORATORY CONFIGURATION AND EXPERIMENTAL DATASET

Time	S1	S2	S3	S4	Time	S1	S2	S3	S4
(s)	(m)	(m)	(m)	(m)	(s)	(m)	(m)	(m)	(m)
0.00	0.300	0.003	0.003	0.003	2.000	0.180	0.003	0.003	0.003
0.04	0.300	0.003	0.003	0.003	2.040	0.179	0.003	0.003	0.003
0.08	0.300	0.003	0.003	0.003	2.080	0.178	0.003	0.003	0.003
0.12	0.300	0.003	0.003	0.003	2.120	0.177	0.003	0.003	0.003
0.16	0.300	0.003	0.003	0.003	2.160	0.176	0.003	0.003	0.003
0.20	0.300	0.003	0.003	0.003	2.200	0.175	0.003	0.003	0.003
0.24	0.300	0.003	0.003	0.003	2.240	0.174	0.003	0.003	0.003
0.28	0.300	0.003	0.003	0.003	2.280	0.174	0.003	0.003	0.003
0.32	0.300	0.003	0.003	0.003	2.320	0.173	0.003	0.003	0.003
0.36	0.300	0.003	0.003	0.003	2.360	0.173	0.003	0.003	0.003
0.40	0.297	0.003	0.003	0.003	2.400	0.172	0.003	0.003	0.003
0.44	0.295	0.003	0.003	0.003	2.440	0.171	0.003	0.003	0.003
0.48	0.292	0.003	0.003	0.003	2.480	0.171	0.003	0.003	0.003
0.52	0.289	0.003	0.003	0.003	2.520	0.170	0.003	0.003	0.003
0.56	0.286	0.003	0.003	0.003	2.560	0.169	0.003	0.003	0.003
0.60	0.282	0.003	0.003	0.003	2.600	0.168	0.003	0.003	0.003
0.64	0.278	0.003	0.003	0.003	2.640	0.168	0.003	0.003	0.003
0.68	0.273	0.003	0.003	0.003	2.680	0.167	0.003	0.003	0.003
0.72	0.269	0.003	0.003	0.003	2.720	0.167	0.003	0.003	0.003
0.76	0.263	0.003	0.003	0.003	2.760	0.166	0.003	0.003	0.003
0.80	0.259	0.003	0.003	0.003	2.800	0.166	0.003	0.003	0.003
0.84	0.255	0.003	0.003	0.003	2.840	0.165	0.003	0.003	0.003
0.88	0.250	0.003	0.003	0.003	2.880	0.165	0.003	0.003	0.003
0.92	0.244	0.003	0.003	0.003	2.920	0.165	0.003	0.003	0.003
0.96	0.241	0.003	0.003	0.003	2.960	0.164	0.003	0.003	0.003
1.00	0.236	0.003	0.003	0.003	3.000	0.163	0.017	0.003	0.003
1.04	0.232	0.003	0.003	0.003	3.040	0.163	0.029	0.003	0.003
1.08	0.228	0.003	0.003	0.003	3.080	0.162	0.036	0.003	0.003
1.12	0.224	0.003	0.003	0.003	3.120	0.161	0.040	0.003	0.003
1.16	0.221	0.003	0.003	0.003	3.160	0.161	0.040	0.003	0.003
1.20	0.217	0.003	0.003	0.003	3.200	0.161	0.043	0.003	0.003
1.24	0.215	0.003	0.003	0.003	3.240	0.161	0.044	0.003	0.003
1.28	0.212	0.003	0.003	0.003	3.280	0.160	0.045	0.003	0.003
1.32	0.210	0.003	0.003	0.003	3.320	0.160	0.046	0.003	0.003
1.36	0.206	0.003	0.003	0.003	3.360	0.159	0.045	0.003	0.003
1.40	0.205	0.003	0.003	0.003	3.400	0.159	0.047	0.003	0.003
1.44	0.202	0.003	0.003	0.003	3.440	0.159	0.046	0.003	0.003
1.48	0.200	0.003	0.003	0.003	3.480	0.159	0.047	0.003	0.003
1.52	0.198	0.003	0.003	0.003	3.520	0.159	0.046	0.003	0.003
1.56	0.196	0.003	0.003	0.003	3.560	0.157	0.048	0.003	0.003
1.60	0.194	0.003	0.003	0.003	3.600	0.158	0.049	0.003	0.003
1.64	0.193	0.003	0.003	0.003	3.640	0.157	0.048	0.003	0.003
1.68	0.191	0.003	0.003	0.003	3.680	0.157	0.051	0.003	0.003
1.72	0.189	0.003	0.003	0.003	3.720	0.156	0.051	0.003	0.003
1.76	0.188	0.003	0.003	0.003	3.760	0.157	0.047	0.003	0.003
1.80	0.186	0.003	0.003	0.003	3.800	0.157	0.049	0.003	0.003
1.84	0.185	0.003	0.003	0.003	3.840	0.156	0.049	0.003	0.003
1.88	0.183	0.003	0.003	0.003	3.880	0.156	0.050	0.003	0.003
1.92	0.183	0.003	0.003	0.003	3.920	0.155	0.050	0.003	0.003
1.96	0.181	0.003	0.003	0.003	3.960	0.156	0.050	0.003	0.003

Time	S1	S2	S3	S4	Time	S1	S2	S3	S4
(s)	(m)	(m)	(m)	(m)	(s)	(m)	(m)	(m)	(m)
4.00	0.156	0.051	0.003	0.003	6.000	0.148	0.066	0.096	0.032
4.04	0.156	0.051	0.003	0.003	6.040	0.147	0.064	0.098	0.034
4.08	0.155	0.053	0.003	0.003	6.080	0.148	0.066	0.096	0.027
4.12	0.155	0.053	0.003	0.003	6.120	0.147	0.067	0.092	0.021
4.16	0.154	0.054	0.003	0.003	6.160	0.148	0.068	0.099	0.025
4.20	0.155	0.053	0.003	0.003	6.200	0.147	0.068	0.102	0.023
4.24	0.154	0.052	0.003	0.003	6.240	0.147	0.070	0.104	0.020
4.28	0.155	0.056	0.003	0.003	6.280	0.147	0.069	0.103	0.025
4.32	0.154	0.055	0.018	0.003	6.320	0.146	0.070	0.100	0.022
4.36	0.154	0.055	0.034	0.003	6.360	0.147	0.071	0.102	0.024
4.40	0.153	0.055	0.052	0.003	6.400	0.146	0.072	0.103	0.023
4.44	0.153	0.055	0.054	0.003	6.440	0.147	0.072	0.108	0.023
4.48	0.153	0.054	0.057	0.003	6.480	0.146	0.073	0.104	0.022
4.52	0.152	0.054	0.056	0.003	6.520	0.147	0.073	0.103	0.020
4.56	0.153	0.054	0.069	0.003	6.560	0.146	0.075	0.103	0.022
4.60	0.152	0.055	0.066	0.003	6.600	0.146	0.075	0.108	0.022
4.64	0.153	0.054	0.068	0.003	6.640	0.145	0.075	0.104	0.022
4.68	0.151	0.055	0.069	0.003	6.680	0.146	0.075	0.104	0.025
4.72	0.152	0.056	0.083	0.003	6.720	0.145	0.074	0.106	0.023
4.76	0.151	0.057	0.084	0.003	6.760	0.146	0.074	0.105	0.023
4.80	0.152	0.057	0.090	0.003	6.800	0.145	0.075	0.103	0.022
4.84	0.151	0.058	0.082	0.003	6.840	0.146	0.076	0.106	0.021
4.88	0.152	0.058	0.090	0.003	6.880	0.145	0.075	0.101	0.021
4.92	0.150	0.060	0.095	0.003	6.920	0.145	0.075	0.101	0.022
4.96	0.151	0.060	0.090	0.003	6.960	0.145	0.075	0.104	0.021
5.00	0.151	0.060	0.086	0.003	7.000	0.144	0.075	0.103	0.023
5.04	0.150	0.060	0.092	0.003	7.040	0.145	0.076	0.105	0.020
5.08	0.151	0.061	0.089	0.003	7.080	0.144	0.076	0.105	0.019
5.12	0.150	0.062	0.088	0.003	7.120	0.145	0.075	0.106	0.023
5.16	0.151	0.062	0.087	0.003	7.160	0.144	0.075	0.106	0.024
5.20	0.149	0.063	0.087	0.003	7.200	0.145	0.076	0.107	0.023
5.24	0.151	0.063	0.088	0.003	7.240	0.143	0.078	0.106	0.022
5.28	0.150	0.063	0.088	0.003	7.280	0.144	0.079	0.106	0.023
5.32	0.151	0.064	0.089	0.003	7.320	0.143	0.085	0.105	0.025
5.36	0.149	0.063	0.089	0.003	7.360	0.144	0.093	0.107	0.023
5.40	0.151	0.064	0.090	0.003	7.400	0.142	0.106	0.105	0.026
5.44	0.150	0.064	0.085	0.003	7.440	0.143	0.106	0.106	0.026
5.48	0.150	0.064	0.089	0.003	7.480	0.142	0.115	0.104	0.023
5.52	0.149	0.064	0.092	0.014	7.520	0.143	0.134	0.103	0.020
5.56	0.149	0.064	0.095	0.023	7.560	0.142	0.135	0.106	0.023
5.60	0.149	0.063	0.098	0.028	7.600	0.141	0.134	0.109	0.021
5.64	0.149	0.064	0.104	0.029	7.640	0.141	0.149	0.108	0.022
5.68	0.149	0.064	0.106	0.030	7.680	0.140	0.137	0.106	0.021
5.72	0.148	0.064	0.102	0.032	7.720	0.140	0.140	0.109	0.023
5.76	0.149	0.062	0.104	0.028	7.760	0.139	0.149	0.105	0.023
5.80	0.148	0.062	0.097	0.034	7.800	0.140	0.156	0.103	0.027
5.84	0.149	0.063	0.104	0.028	7.840	0.138	0.153	0.104	0.023
5.88	0.147	0.063	0.099	0.034	7.880	0.138	0.156	0.105	0.026
5.92	0.149	0.063	0.098	0.027	7.920	0.137	0.151	0.111	0.026
5.96	0.147	0.063	0.094	0.023	7.960	0.138	0.171	0.115	0.025

Time	S1	S2	S3	S4	Time	S1	S2	S3	S4
(s)	(m)	(m)	(m)	(m)	(s)	(m)	(m)	(m)	(m)
8.00	0.135	0.187	0.108	0.027	10.00	0.115	0.231	0.111	0.027
8.04	0.136	0.198	0.104	0.023					
8.08	0.134	0.196	0.101	0.026					
8.12	0.135	0.202	0.101	0.026					
8.16	0.134	0.206	0.103	0.024					
8.20	0.134	0.211	0.108	0.024					
8.24	0.132	0.214	0.104	0.022					
8.28	0.133	0.221	0.102	0.022					
8.32	0.133	0.220	0.108	0.025					
8.36	0.132	0.225	0.107	0.023					
8.40	0.132	0.225	0.106	0.021					
8.44	0.131	0.221	0.104	0.023					
8.48	0.131	0.218	0.106	0.023					
8.52	0.130	0.214	0.104	0.022					
8.56	0.130	0.205	0.107	0.023					
8.60	0.128	0.205	0.108	0.023					
8.64	0.129	0.214	0.108	0.025					
8.68	0.127	0.214	0.106	0.021					
8.72	0.128	0.219	0.110	0.024					
8.76	0.126	0.224	0.106	0.024					
8.80	0.127	0.231	0.106	0.023					
8.84	0.125	0.233	0.103	0.026					
8.88	0.125	0.235	0.104	0.023					
8.92	0.124	0.234	0.107	0.023					
8.96	0.124	0.229	0.105	0.025					
9.00	0.123	0.225	0.105	0.022					
9.04	0.123	0.224	0.108	0.022					
9.08	0.124	0.224	0.108	0.024					
9.12	0.122	0.226	0.106	0.024					
9.16	0.122	0.230	0.106	0.027					
9.20	0.121	0.229	0.106	0.024					
9.24	0.122	0.230	0.107	0.023					
9.28	0.120	0.231	0.106	0.025					
9.32	0.121	0.228	0.106	0.022					
9.36	0.119	0.223	0.104	0.022					
9.40	0.121	0.222	0.107	0.023					
9.44	0.119	0.223	0.105	0.023					
9.48	0.120	0.227	0.108	0.023					
9.52	0.118	0.232	0.108	0.024					
9.56	0.119	0.235	0.111	0.026					
9.60	0.118	0.233	0.109	0.025					
9.64	0.119	0.233	0.111	0.025					
9.68	0.118	0.233	0.113	0.022					
9.72	0.117	0.234	0.112	0.021					
9.76	0.117	0.229	0.111	0.023					
9.80	0.117	0.225	0.111	0.025					
9.84	0.116	0.231	0.112	0.024					
9.88	0.116	0.233	0.112	0.026					
9.92	0.116	0.231	0.111	0.025					

9.96	0.115	0.229	0.110	0.025					
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