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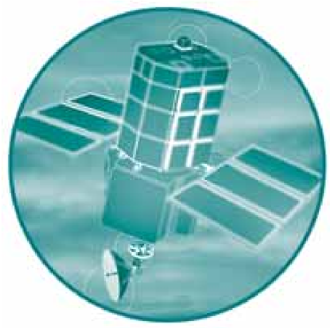

Afflux at bridges and culverts

Review of current knowledge and practice

Annex 6:
Bridge Afflux Experiments in Compound Channels

R&D Project Record W5A-061/PR6

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AFFLUX AT BRIDGES AND CULVERTS

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Bridge Afflux Experiments in Compound Channels

R&D Project Record W5A-061/PR6

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Tel: 01454 624400 Fax: 01454 624409 Website: www.environment-agency.gov.uk

 June 2004

ISBN 1 8443 2291 2

Dissemination Status
Internal: Released Internally
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Statement of Use
This Technical Report contains the results of the first phase of a study to improve the estimation of afflux at river structures in high flows. The information in this document will be used in developing improved software and guidance for flood defence and land drainage practitioners, and is made available for reference and use.

Keywords
Afflux, backwater, blockage, bridges, culverts, channel structures.

Research Contractor
This document was produced under R&D Project W5A-061 by Serter Atabay and Donald W Knight, School of Civil Engineering, The University of Birmingham. The research contractor was JBA Consulting – Engineers & Scientists, South Barn, Broughton Hall, Skipton, North Yorkshire, BD23 3AE.
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Environment Agency's Project Manager
The Environment Agency's Project Manager for Project W5A-061 was: Andrew Pepper, External Advisor, Engineering Theme.
Further copies of this report are available from the Environment Agency's science dissemination service

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1 INTRODUCTION

This report contains the results of some experiments on bridge afflux undertaken in 1999 at the University of Birmingham using a 22 m long research flume with a compound cross-section. The aim of the experiments was to explore the general behaviour of bridge afflux, prior to making an application to the Engineering and Physical Sciences Research Council (EPSRC) for funding to examine this phenomenon in some detail. However, an application has not yet been made since the EPSRC is likely to require significant financial support from the Environment Agency and others, as well as detailed modelling studies, to accompany any such experimental work.

This report should be read in conjunction with an accompanying CD-Rom that gives all the data and graphs in directories that correspond to the different types of bridge tested. Some ancillary experiments were performed in the channel with varying floodplain roughness, and these stage-discharge data are also included in the CD-Rom.

Experiments with the different types of bridge models have been collated in a directory called ***BRIDGE***, as illustrated in **Figure 1**.

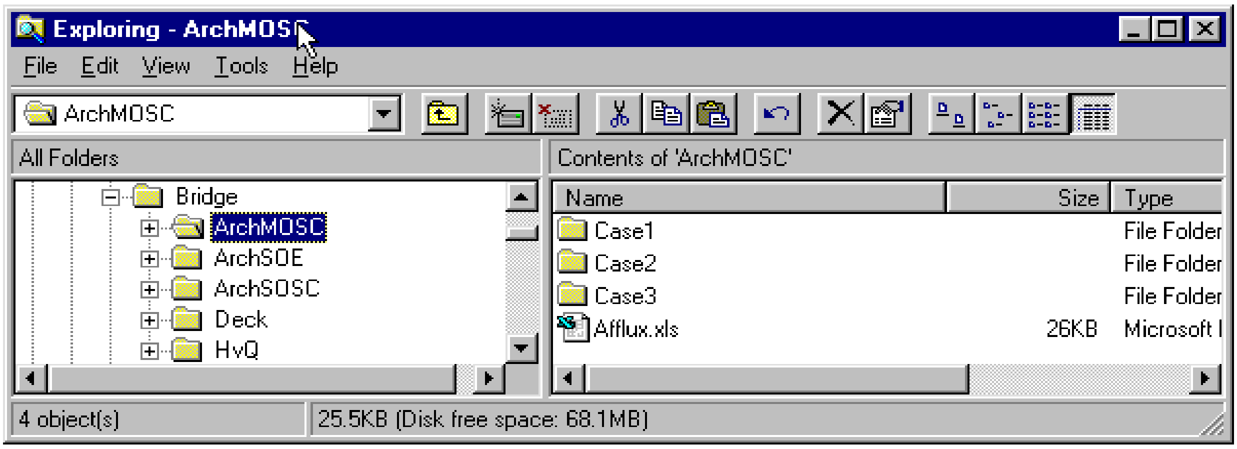


Figure 1: Organization of experimental work with different types of bridge models

2 THE EXPERIMENTAL DATA ON BRIDGE MODELS AND THE ASSOCIATED CD-ROM

2.1 Bridge models

Four different types of bridge models were examined in a two-stage channel with five different roughness configurations. The experimental data have been organised into five directories, representing four different types of bridge models and all the stage-discharge relationships for the different roughness cases. The naming convention is as follows:

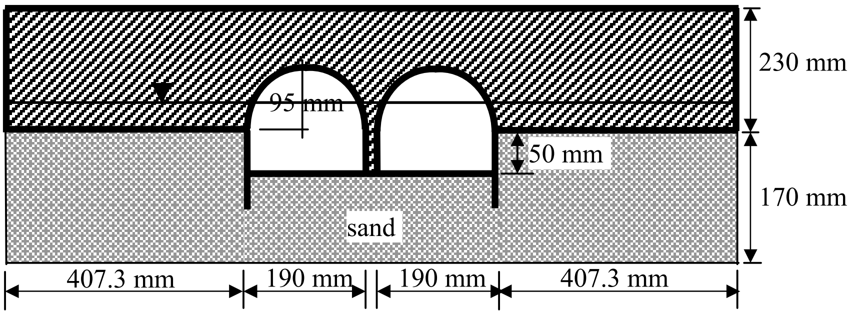
ArchMOSC This directory represents all the experiments with the **M**ultiple **O**pening **S**emi **C**ircular **Arch** bridge model (See **Figure 2a**).

ArchSOE This directory represents all the experiments with the **S**ingle **O**pening **E**lliptic **Arch** bridge model (See **Figure 2b**).

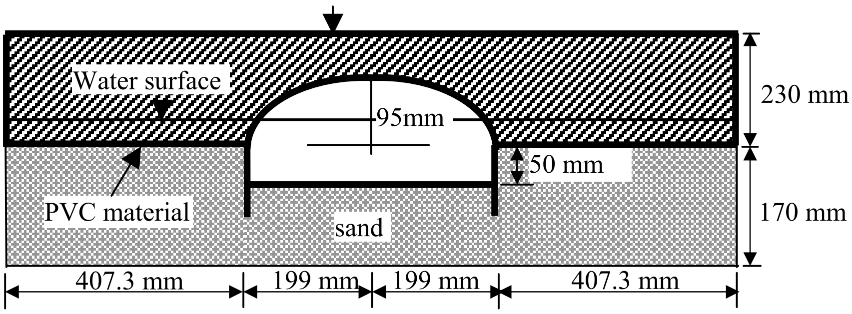
ArchSOSC This directory represents all the experiments with the **S**ingle **O**pening **S**emi **C**ircular **Arch** bridge model (See **Figure 2c**).

Deck This directory represents all the experiments with the **S**ingle **O**pening **S**traight **Deck** bridge model with or without piers (See **Figure 2d**).

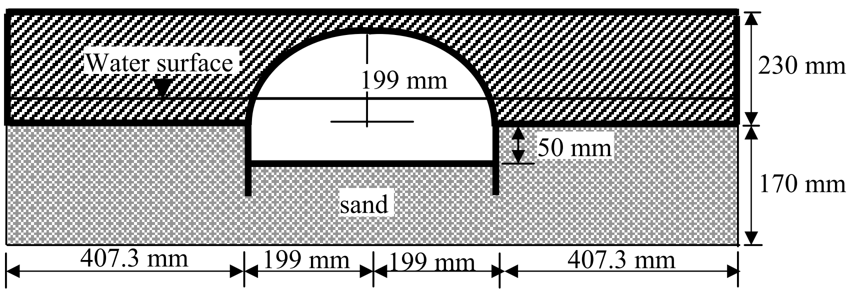
HvQ This directory represents all the experiments performed in order to obtain the uniform flow depth for a particular discharge. In this **HvQ** directory there are five different directories each representing different roughness configurations as shown in **Figure 3**.



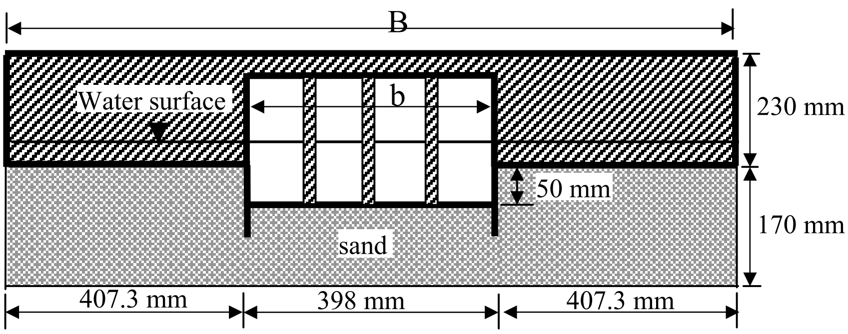
(a) ArchMOSC-Multiple opening semi-circular arch bridge model



(b) ArchSOE-single opening elliptic arch bridge model



(c) ArchSOSC-single opening semi-circular arch bridge model



d) Deck-single opening straight deck bridge model

Figure 2: The Four different types of bridge models examined in this study

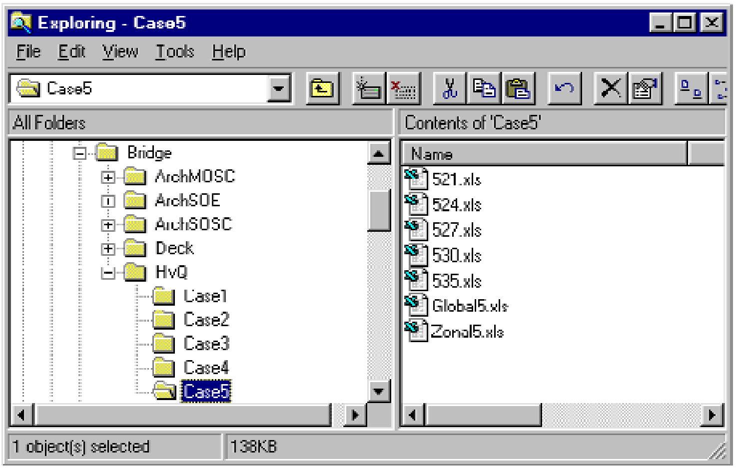


Figure 3: Organization of experimental work for stage-discharge relationships

2.2 Roughness

The roughness was varied on the floodplain by adding triangular A-frame elements, made up of open wire mesh, at different spacing intervals, λ. The various roughness cases are defined as follows:

CASE 1: Smooth main channel and smooth floodplain
CASE 2: Smooth main channel and rough floodplain (λ=0.5m)
CASE 3: Rough main channel (λ=2.0m) and rough floodplain (λ=0.5m)
CASE 4: Rough main channel (λ=3.0m) and rough floodplain (λ=0.25m)
CASE 5: Rough main channel (λ=4.0m) and rough floodplain (λ=0.125m)

2.3 Ancillary experiments

In order to obtain the stage discharge relationships, a number of ancillary experiments were performed over a range of discharges for each channel roughness, as shown in **Table 1**.

Table 1: Ancillary stage-discharge experiments

Case No	Nmber of experiments	Q (m^3/s) varied between
Case1	13	0.010 & 0.055
Case2	9	0.015 & 0.050
Case3	8	0.015 & 0.035
Case4	8	0.015 & 0.040
Case5	5	0.021 & 0.035

In the 'case' directories (**Case 1 – Case 5**) there are several experimental files for uniform flow depths and two results files. These result files are named as **Global.xls**, in which analysis was made using the single channel method, and **Zonal.xls**, in which analysis was made using the divided channel method. There is a single number after these files that represents the Case number. For example as seen from **Figure 3,** for Case 5 these file are named as **Global5** and **Zonal5**. In **Figure 3** there are five experimental files, which are named as 521.xls, 524.xls, 527.xls, 530.xls and 535.xls. The first number refers to the Case No. (which is Case 5 here) and the last two numbers refer to the discharge value. For example, the experiments with the same discharge values for Case2 are named as 221.xls, 224.xls, 227.xls, 230.xls and 235.xls.

It should be noted that all these ancillary experiments were performed without any bridge model in the flume. The results were later compared with the experimental results performed with the bridge models in place, in order to find the precise backwater effect for a particular discharge value and channel roughness. In Cases 3-5, the main channel was also roughened, as well as the floodplains, in order to obtain results that were comparable with real conditions in rivers, and to get away from performing experiments only in smooth channels.

2.4 Experimental cases

As seen from **Figure 4**, ArchMOSC and ArchSOE bridge models were examined for the roughness configurations Case 1, Case 2 and Case 3, and the ArchSOSC bridge model was examined for Cases 1-4. The deck bridge model, with or without piers, was examined for Case 1, Case 3, Case 4 and Case 5. For each type of bridge model and roughness case, a total of 5 experiments were generally carried out. In all, some 145 experiments were undertaken in this study.

As seen on the right hand side of **Figure 4**, for single opening semi-circular arch bridge model (**ArchSOSC**), the experiments were named as ASOSC121-ASOSC135. The first letter, A, refers to the type of bridge, i.e. arch bridge, and SOSC refers to ‘single opening semi circular’. The same procedure that was used for the experiments investigating the stage-discharge relationships (see directory HvQ) was also adopted here for the experiments with the bridge models. The first number refers to the Case No., and the last two numbers refer to the value of the discharge. For example, AMOSC230 means that an Arch bridge-multiple opening semi-circular type, with Case 2 type roughness, was examined with a discharge value of 30 l/s.

Deck bridge models were examined for different width ratios (b/B) by changing the value of b, as shown in **Figure 2d**, from 0.398m to 0.498m and 0.598m. The experiments for the Deck bridge model were therefore divided into three different directories according to the values of b (b=0.398, b=0.498 and b=0.598), as illustrated in **Figure 5.** These three directories were also divided into two further directories, Nopiers and Piers, according to the whether the bridge model was examined with or without piers.

As seen on the right hand side of **Figure 5,** the experiments were named as D598321P-D598335P. The first letter, D, refers to the Deck bridge model, the first three numbers refer to the value of b, which is 598mm in this case, and the rest refer to the case number and discharge values, as explained earlier. The last letter, P, means that the bridge model was examined with piers. If there is no letter after the discharge value, this means that the bridge model was examined without piers. For example, if the deck bridge experiment without piers was carried out for Case 3, with a discharge value of 30 l/s and b=0.398m, then the experiment was named as D398330. If piers were used then the experiment name was D398330P.

There is a results file, Afflux in each main directory, which shows the backwater effect for each type of bridge model and roughness case.

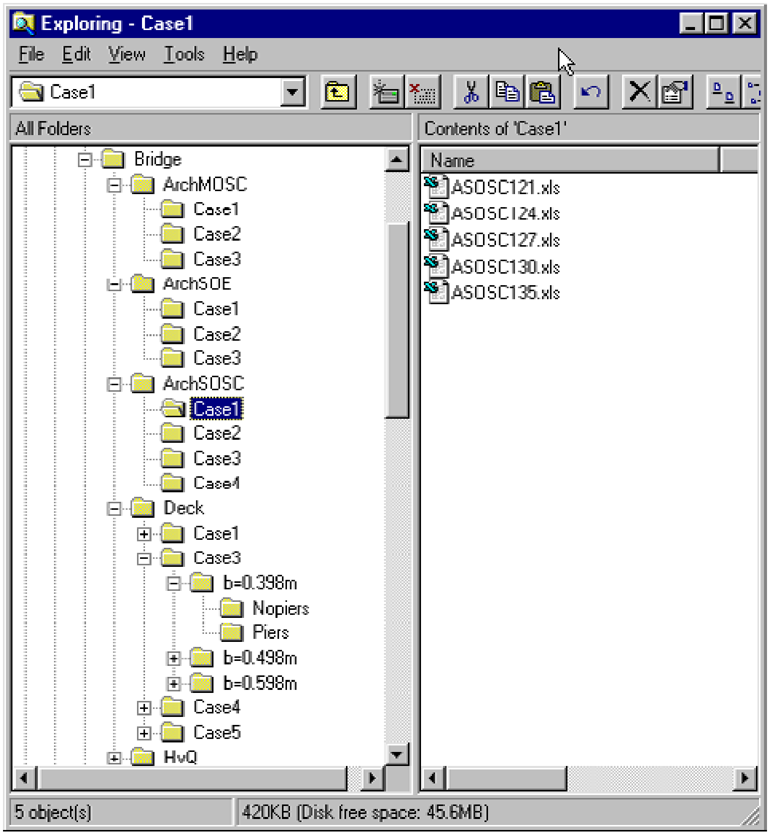


Figure 4: Name of experiments for the arch bridge models

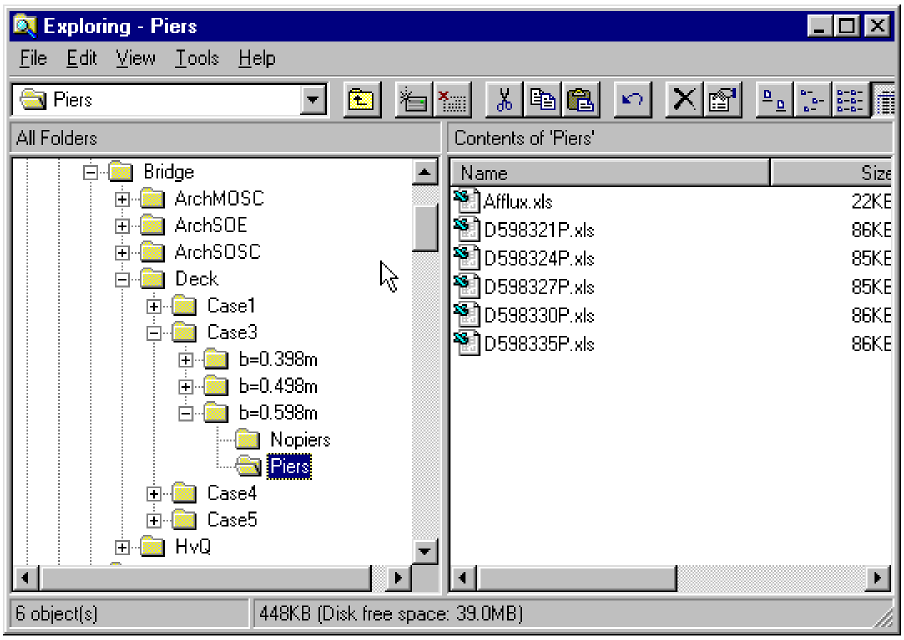


Figure 5: Name of experiments for the deck bridge models

3 STAGE-DISCHARGE AND RESISTANCE RESULTS

In this section the results concerning the stage-discharge and resistance relationships are presented. The results relate to compound channels, comprising one rectangular main channel and two symmetrically disposed floodplains, as illustrated in Fig. 2.

One of the most important procedures before any detailed measurements were taken was to obtain uniform flow for a particular discharge. In order to achieve uniform flow, the tailgate/s was/were adjusted to give several M1 and M2 profiles. The mean water surface slopes and related depths were then plotted versus tailgate position in a computer program and the tailgate setting that gave a mean water surface slope equal to the floodplain bed slope of 2.024×10^{-3} was interpolated from the graphs. The depth related to this tailgate setting was then accepted as the normal depth. This procedure was repeated for every single experiment in order to obtain accurate stage-discharge relationships for the symmetric compound channels.

In this study, after the experiments were carried out in the smooth compound channel, the differential roughness between the main channel and floodplain was simulated using 'A-frames' of aluminium wire grids. These were placed at different longitudinal intervals, λ, along the channel, for both the floodplain and main channel, as shown in **Table 2**. The experimental programme for the overbank flow cases is also shown in **Table 2.**

Table 2: Experimental programme

	No. of Experiments	Flow	Main channel	Floodplain	Dr
Case 1	13	Overbank	Smooth	Smooth	0.20~0.50
Case 2	9	Overbank	Smooth	Rough (λ=0.5m)	0.23~0.70
Case 3	8	Overbank	Rough (λ=2.0m)	Rough (λ=0.5m)	0.30~0.70
Case 4	8	Overbank	Rough (λ=3.0m)	Rough (λ=0.25m)	0.30~0.75
Case 5	5	Overbank	Rough (λ=4.0m)	Rough (λ=0.125m)	0.55~0.75

In order to analyse the data for the smooth and roughened compound channels, two different methods were adopted, treating the channel either as a single section, or dividing the channel into a number of sub-sections or zones. The results for the single channel and divided channel methods are given in the results files, Global and Zonal, respectively.

Using the equations of best fit through the experimental data, shown graphically in the CD-Rom**,** the stage-discharge relationship was obtained mathematically in the form of a power function for Case 1, and in the form of a second order polynomial function for Cases 2-5, as given by Equations 1 & 2,

$$H=\alpha Q^{\beta} \qquad \text{.......(1)}$$

$$H=\alpha Q^{2}+\beta Q+c \qquad \text{........(2)}$$

in which α, β and c are constants for each experimental configuration, H is the flow depth in m and Q is the discharge in m^3/s.

CASE 1: Smooth main channel and floodplain

$$H=0.2708Q^{0.3615} \qquad \text{…….(3)}$$

CASE 2: Smooth main channel and rough floodplain (λ=0.5m)

$$H=7.7522Q^2+2.4687Q+0.0253 \qquad \text{…..…(4)}$$

CASE 3: Rough main channel (λ=2.0m) and rough floodplain (λ=0.5m)

$$H=9.7506Q^2+3.3628Q+0.0358 \qquad \text{……..(5)}$$

CASE 4: Rough main channel (λ=3.0m) and rough floodplain (λ=0.25m)

$$H=3.6087Q^2+4.0631Q+0.028 \qquad \text{…..…(6)}$$

CASE 5: Rough main channel (λ=4.0m) and rough floodplain (λ=0.125m)

$$H=-82.101Q^2 + 10.304Q - 0.0621 \qquad \text{…..…(7)}$$

The correlation coefficients for Cases 1-5 are 0.9966, 0.9988, 0.9993, 0.9987 and 0.9991 respectively. All the stage-discharge relationships were used to find the precise flow depth for a given discharge when the experiments were carried out with the different bridge models.

The overall and zonal Manning's roughness coefficients, n, and friction factors, f were calculated using standard hydraulic resistance laws. Using the equations of best fit through the experimental data, again shown graphically in the CD-Rom, the stage-resistance relationships in terms of Manning's n and flow depth in m, were also obtained mathematically as shown in **Table 3.** Further details about the stage-resistance relationships for all cases are available elsewhere (Atabay, 2001).

Table 3: Stage-overall and zonal Manning's n relationships

(a) Single section method-overall Manning's n - stage relationships	
	$n_{overall}$
Case 1	0.0091
Case 2	$n= 5.0633H^3 - 2.4023H^2 + 0.5599H - 0.0176$
Case 3	$n= 12.464H^3 – 5.1099H^2 + 0.925H - 0.024$
Case 4	$n= 9.8061H^3 – 4.7253H^2 + 0.9798H - 0.0295$
Case 5	$n=5.232H^3 - 4.0069*H^2 + 1.1959H - 0.0565$

(b) Divided channel method-zonal Manning's n - stage relationships		
	$n_{main\ channel}$	$n_{floodplain}$
Case 1	~0.010	~0.0090
Case 2	$n_{mc}=0.0925H^{0.7591}$	$n_{mc}=0.2788H^{0.9382}$
Case 3	$n_{mc}=0.100H^{0.5825}$	$n_{mc}=0.22381H^{0.7114}$
Case 4	$n_{mc}=0.104H^{0.6255}$	$n_{mc}=0.3211H^{0.7418}$
Case 5	$n_{mc}=0.113H^{0.671}$	$n_{mc}=0.2440H^{0.5954}$

4 BACKWATER EFFECTS AND AFFLUX AT BRIDGES

In the previous section the stage-discharge relationships for the compound channel with five different roughness configurations (Cases 1-5) were presented. Four different types of bridge model, given below, were examined in this channel with the same roughness configurations.

- Single opening semi-circular arch bridge model
- Multiple opening semi-circular arch bridge model
- Single opening elliptic arch bridge model
- Single opening straight deck bridge model with & without piers

For a given roughness condition, each bridge model were placed at a cross section 10m from the flume inlet, named X=59m along the channel, as shown in **Figure A6**. After placing each bridge model in the channel, experiments were performed over a range of discharges and measurements taken. An attempt was made to subject each bridge to the same discharge values in order to aid direct comparisons. Water surface levels were taken at 1m intervals down the entire length of the flume and at 10 cm intervals in the immediate vicinity of the bridge model, on both upstream and downstream sides (i.e. sections X=58m-60m). These measurements were later used to find the afflux and backwater effect of the various bridges over a range of flows.

The full results are on the CD-Rom, and Appendix 1 contains a small sample of selected results to illustrate the afflux relationships. It is essential to refer to the CD-Rom to see the resistance relationships, the stage-discharge relationships and the afflux results for every channel roughness and bridge type. A brief description of the 5 cases in Appendix 1 is now given, with the Table and Figure numbers referring to those in Appendix 1.

Table A1 (Appendix 1) shows one set of water levels for ASOE218, with and without the single opening elliptic arch bridge model. **Figure A1 (Appendix 1)** shows the corresponding water surface levels for this particular bridge for a discharge of 18 l/s. These water surface levels are those recorded in Columns 3 and 4 of **Table A1.** The values of these water surface levels for uniform flow were smoothed using trendline equation through these data (see Column 7 of **Table A1**). **Figure A1** thus shows a direct comparison between those water levels with the bridge in place, and those without the bridge (i.e. the corresponding uniform flow case). It should be noted that for uniform flow, the water surface levels between sections 58m-60m, at 10 cm intervals, were interpolated using the best trendline through the water surface level data at 1.0 m interval along the channel. The best trendlines through the water surface level data are given for each corresponding uniform flow data file in the HvQ directory.

In order to calculate the backwater effects (afflux) water surface levels for uniform flow (Column 7) were subtracted from those measured with the bridge model in place (Column 8) of **Table A1.** A summary of the maximum afflux for arch bridges is given in **Table A2**, and those for deck bridges in **Tables A3-A5**. The corresponding afflux-discharge relationships are shown in **Figure A2** for arch bridges and in **Figs A3-A5** for deck bridges. The best fit polynomial equations are shown in each Table and Figure for ease of reference. The CD-Rom contains further details, as well as best fit linear equations through the same data.

5 CONCLUSIONS

These preliminary experiments indicate that there is a strong relationship between afflux and discharge for the four types of bridge opening tested in this investigation. They have been obtained for bridges in a compound channel, with varying degrees of roughness, thus being typical of idealised conditions in an actual river. These data are useful in so far as the vast majority of other experimental studies have generally been undertaken in channels with a simple rectangular cross-section, which is untypical of most rivers channels. A thorough analysis of these data is required, together with simulations using commercial 1-D and 2-D software. Further experimental studies should also be undertaken, extending the range of flows to include orifice-type flow, and to cover the many issues highlighted in the related report by Knight (2002).

The simple empirical relationships between bridge afflux and discharge obtained in this study for the four model bridge types, and presented in Appendix A and in the accompanying CD-Rom, make a small contribution to the sum of knowledge concerning afflux. It appears that such knowledge is gained slowly through a combination of small-scale laboratory studies, field measurements and numerical studies.

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Atabay, S., 2001, Stage-discharge, resistance, and sediment transport relationships for flow in straight compound channels, *PhD Thesis*, The University of Birmingham, England, UK

Knight, D.W., 2001, Conveyance in 1-D river models, *Report for HR Wallingford and the Environment Agency*, March, 1-29 [part of: Scoping study on reducing uncertainty in river flood conveyance, HR Wallingford, May 2001].

Knight, D.W., 2002, A review of current knowledge on bridge afflux, *Report for JBA and the Environment Agency*, December, 1-34 [part of: Scoping study into hydraulic performance of bridges and other structures, including the effects of blockage, at high flows, JBA, December, 2001].

APPENDIX A

EXPERIMENTAL RESULTS

EXPERIMENT NAME	ASOE218	Q = 18.03 l/s
EXPERIMENT DATE	12.03.1999	H = 72.3 mm

EXPERIMENTAL RESULTS
(according to measured WS and Bed Slope)

Chainage X (m) (1)	Bed Elevation (mm) (measured) (2)	WSE (mm) without bridge (measured) (3)	WSE (mm) with bridge (measured) (4)	Chainage X (m) (5)	Bed Elevation (mm) (smooth) (6)	WSE (mm) without bridge (smooth) (7)	WSE (mm) with bridge (smooth) (8)
52.00	**130.90**	**202.50**	**212.00**	**52.00**	**130.06**	**200.77**	**212.00**
53.00	**128.20**	**200.40**	**210.00**	**53.00**	**128.05**	**198.76**	**210.00**
54.00	**125.30**	**197.20**	**208.00**	**54.00**	**126.03**	**196.75**	**208.00**
55.00	**122.90**	**195.20**	**206.80**	**55.00**	**124.02**	**194.74**	**206.80**
56.00	**122.90**	**193.20**	**205.40**	**56.00**	**122.01**	**192.72**	**205.40**
57.00	**120.20**	**189.70**	**203.50**	**57.00**	**119.99**	**190.71**	**203.50**
58.00	**117.40**	**186.50**	**202.60**	**58.00**	**117.98**	**188.70**	**202.60**
58.30	117.01	185.75	201.60	58.30	**117.38**	**188.09**	201.60
58.40	116.88	185.50	201.30	58.40	**117.17**	**187.89**	201.30
58.50	116.75	185.25	201.50	58.50	**116.97**	**187.69**	201.50
58.60	116.62	185.00	200.60	58.60	**116.77**	**187.49**	200.60
58.70	116.49	184.75	200.50	58.70	**116.57**	**187.29**	200.50
58.80	116.36	184.50	199.50	58.80	**116.37**	**187.09**	199.50
58.90	116.23	184.25	196.20	58.90	**116.17**	**186.89**	196.20
58.965	**116.10**	**184.00**	**191.60**	**58.97**	**116.04**	**186.76**	**191.60**
59.085	115.81	183.71	182.50	59.09	**115.80**	**186.51**	182.50
59.20	115.54	183.68	178.00	59.20	**115.56**	**186.28**	178.00
59.30	115.30	183.65	186.00	59.30	**115.36**	**186.08**	186.00
59.40	115.06	183.61	182.30	59.40	**115.16**	**185.88**	182.30
59.50	114.82	183.58	179.00	59.50	**114.96**	**185.68**	179.00
59.60	114.58	183.55	183.50	59.60	**114.76**	**185.48**	183.50
59.70	114.34	183.51	187.10	59.70	**114.56**	**185.28**	187.10
60.00	**113.70**	**183.70**	**180.70**	**60.00**	**113.95**	**184.67**	**180.70**
60.20	113.32	183.30	181.00	60.20	**113.55**	**184.27**	181.00
61.00	**111.80**	**181.70**	**180.00**	**61.00**	**111.94**	**182.66**	**180.00**
62.00	**110.60**	**180.50**	**176.00**	**62.00**	**109.93**	**180.65**	**176.00**
63.00	**107.90**	**177.30**	**177.60**	**63.00**	**107.91**	**178.63**	**177.60**
64.00	**106.80**	**176.80**	**176.00**	**64.00**	**105.90**	**176.62**	**176.00**
65.00	**104.00**	**176.20**	**174.80**	**65.00**	**103.89**	**174.61**	**174.80**
66.00	**102.00**	**173.70**	**173.00**	**66.00**	**101.88**	**172.60**	**173.00**
67.00	**99.70**	**172.30**	**172.00**	**67.00**	**99.86**	**170.58**	**172.00**

Position of max. afflux

Max Afflux(mm)

Table A2: Arch bridge results

Type of bridge	Case no	Experimental name	Discharge (l/s)	Flow depth (mm)	Afflux (mm)	Afflux-discharge relationships
Arch Bridge-Multiple Opening Semi-Circular (AMOSC) *SOFFIT level=145mm*	1	AMOSC121	20.97	66.97	34.82	Afflux= 0.0257Q^2 + 1.1559Q
		AMOSC124	24.02	70.35	42.83	
		AMOSC127	27.04	73.42	50.75	
		AMOSC130	29.98	76.21	57.67	
		AMOSC135	34.43	80.12	69.97	
	2	AMOSC218	18.03	72.33	17.51	Afflux= -0.0063Q^2 + 1.0688Q
		AMOSC221	20.99	80.53	20.06	
		AMOSC224	24.08	89.24	21.90	
		AMOSC230	29.97	106.26	25.13	
		AMOSC235	34.28	119.02	29.99	
	3	AMOSC315	14.97	88.33	6.99	Afflux= 0.0097Q^2 +0.3347Q
		AMOSC318	18.00	99.48	8.95	
		AMOSC321	20.89	110.32	12.08	
		AMOSC324	24.04	122.28	13.21	
		AMOSC327	26.82	133.01	16.02	
Arch Bridge-Single Opening Elliptic (ASOE) *SOFFIT level=145mm*	1	ASOE121	20.97	66.97	30.92	Afflux= 0.0251Q^2 +0.9879Q
		ASOE124	24.02	70.35	38.33	
		ASOE127	27.04	73.42	46.05	
		ASOE130	29.98	76.21	52.17	
		ASOE135	34.43	80.12	63.37	
	2	ASOE218	18.03	72.33	13.90	Afflux= -0.0077Q^2 +0.8978Q
		ASOE221	20.99	80.53	16.06	
		ASOE224	24.08	89.24	16.80	
		ASOE230	29.97	106.26	18.73	
		ASOE235	34.28	119.02	22.49	
	3	ASOE315	14.97	88.33	5.79	Afflux= 0.0129Q^2 +0.1878Q
		ASOE318	18.00	99.48	7.45	
		ASOE321	20.89	110.32	9.78	
		ASOE324	24.04	122.28	11.61	
		ASOE327	26.82	133.01	14.52	
Arch Bridge-Single Opening Semi-Circular (ASOSC) *SOFFIT level=249mm*	1	ASOSC121	20.97	66.97	30.52	Afflux= 0.0201Q^2 +1.0754Q
		ASOSC124	24.02	70.35	37.13	
		ASOSC127	27.04	73.42	45.25	
		ASOSC130	29.98	76.21	50.67	
		ASOSC135	34.43	80.12	60.26	
	2	ASOSC218	18.03	72.33	14.21	Afflux= -0.0117Q^2 +0.9897Q
		ASOSC221	20.99	0.08	16.15	
		ASOSC224	24.08	0.09	16.50	
		ASOSC230	29.97	0.11	18.53	
		ASOSC235	34.28	0.12	20.59	
	3	ASOSC315	14.97	88.33	5.99	Afflux= 0.0032Q^2 +0.3445Q
		ASOSC318	18.00	99.48	7.14	
		ASOSC321	20.88	110.26	8.38	
		ASOSC324	24.05	122.30	10.40	
		ASOSC327	26.79	132.91	11.42	
	4	ASOSC415	15.15	90.36	4.40	Afflux= 0.0095Q^2 +0.0948Q
		ASOSC421	20.92	114.58	5.30	
		ASOSC424	23.86	127.02	7.71	
		ASOSC427	26.81	139.51	9.37	
		ASOSC435	34.30	171.63	14.58	

Table A3: Deck bridge results (part I)

Type of bridge	Case no	Experimental name	Discharge (l/s)	Flow depth (mm)	Afflux (mm)	Afflux-discharge relationships
Deck Bridge-Single Opening **S**trait **Deck** (Deck) *SOFFIT level=280mm*	1 b=398 with piers	D398121P	20.98	66.98	31.93	Afflux= $0.0212Q^2 + 1.1188Q$
		D398124P	23.98	70.30	38.73	
		D398127P	26.95	73.33	46.56	
		D398130P	30.02	76.25	53.46	
		D398135P	34.29	80.00	62.47	
	3 b=398mm no piers	D398321	20.88	110.26	8.88	Afflux= $-0.0021Q^2 + 0.4792Q$
		D398324	24.05	122.30	10.40	
		D398327	26.79	132.91	11.42	
		D398330	29.84	144.81	12.73	
		D398335	34.32	162.69	13.84	
	3 b=398mm with piers	D398321P	20.88	110.26	10.48	Afflux= $-0.0067Q^2 + 0.6576Q$
		D398324P	24.05	122.30	12.39	
		D398327P	26.79	132.91	12.52	
		D398330P	29.84	144.81	13.76	
		D398335P	34.32	162.69	14.55	
	3 b=498mm no piers	D498321	20.88	110.26	9.08	Afflux= $-0.0091Q^2 + 0.6074Q$
		D498324	24.05	122.30	9.00	
		D498327	26.79	132.91	9.32	
		D498330	29.84	144.81	10.43	
		D498335	34.32	162.69	10.05	
	3 b=498mm with piers	D498321P	20.88	110.26	9.38	Afflux= $-0.0092Q^2 + 0.6367Q$
		D498324P	24.05	122.30	10.01	
		D498327P	26.79	132.91	10.22	
		D498330P	29.84	144.81	10.93	
		D498335P	34.32	162.69	11.03	
	3 b=598mm no piers	D598321	20.88	110.26	5.58	Afflux= $-0.0059Q^2 + 0.3987Q$
		D598324	24.05	122.30	6.21	
		D598327	26.79	132.91	6.62	
		D598330	29.84	144.81	6.81	
		D598335	34.32	162.69	6.65	
	3 b=598mm with piers	D598321P	20.88	110.26	6.78	Afflux= $-0.0077Q^2 + 0.4922Q$
		D598324P	24.05	122.30	7.61	
		D598327P	26.79	132.91	7.62	
		D598330P	29.84	144.81	7.73	
		D598335P	34.32	162.69	7.84	

Table A4: Deck bridge results (part II)

Type of bridge		Case no	Experimental name	Discharge (l/s)	Flow depth (mm)	Afflux (mm)	
Deck Bridge-Single Opening Strait Deck (Deck)	*SOFFIT level=280mm*	4 b=398mm no piers	D398415	15.15	90.39	3.71	Afflux= $0.0058Q^2 + 0.1678Q$
			D398421	21.03	115.03	6.30	
			D398424	23.84	126.92	7.41	
			D398427	26.83	139.59	8.38	
			D398435	34.30	171.61	12.57	
		4 b=398mm with piers	D398415P	15.15	90.39	5.01	Afflux= $0.0022Q^2 + 0.3144Q$
			D398421P	21.03	115.03	8.10	
			D398424P	23.84	126.92	8.91	
			D398427P	26.83	139.59	9.47	
			D398435P	34.30	171.61	13.49	
		4 b=498mm no piers	D498415	15.14	90.33	3.31	Afflux= $0.0025Q^2 + 0.1815Q$
			D498421	21.00	114.91	5.10	
			D498424	23.74	126.50	5.51	
			D498427	26.80	139.49	6.67	
			D498435	34.30	171.60	9.19	
		4 b=498mm with piers	D498415P	15.14	90.33	4.01	Afflux= $0.0008Q^2 + 0.2624Q$
			D498421P	21.00	114.91	6.30	
			D498424P	23.74	126.50	6.51	
			D498427P	26.80	139.49	7.37	
			D498435P	34.30	171.60	9.99	
		4 b=598mm no piers	D598415	15.14	90.34	1.91	Afflux=$0.0032Q^2 + 0.0739Q$
			D598421	21.03	115.04	3.10	
			D598424	23.83	126.88	3.60	
			D598427	26.81	139.51	3.88	
			D598435	34.30	171.62	6.38	
		4 b=598mm with piers	D598415P	15.14	90.34	3.21	Afflux= $0.0016Q^2 + 0.1545Q$
			D598421P	21.03	115.04	3.50	
			D598424P	23.83	126.88	4.81	
			D598427P	26.81	139.51	4.97	
			D598435P	34.30	171.62	7.39	

Table A5: Deck bridge results (part III)

Type of bridge	Case no	Experimental name	Discharge (l/s)	Flow depth (mm)	Afflux (mm)	
Deck Bridge-Single Opening Strait Deck (Deck) *SOFFIT level=280mm*	5 b=398mm no piers	D398521	21.03	118.32	4.08	Afflux= $-0.0042Q^2 + 0.2705Q$
		D398524	23.96	137.63	3.89	
		D398527	26.98	156.16	4.12	
		D398530	29.99	173.06	4.34	
		D398535	34.33	194.86	4.40	
	5 b=398mm with piers	D398521P	21.03	118.32	6.78	Afflux= $-0.0041Q^2 + 0.3856Q$
		D398524P	23.96	137.63	6.69	
		D398527P	26.98	156.16	6.82	
		D398530P	29.99	173.06	8.04	
		D398535P	34.33	194.86	8.50	
	5 b=498mm no piers	D498521	21.03	118.32	3.07	Afflux= $-0.003Q^2 + 0.2059Q$
		D498524	23.96	137.63	3.29	
		D498527	26.98	156.16	3.02	
		D498530	29.99	173.06	3.74	
		D498535	34.33	194.86	3.50	
	5 b=498mm with piers	D498415P	15.14	90.33	4.01	Afflux= $0.0008Q^2 + 0.2624Q$
		D498421P	21.00	114.91	6.30	
		D498424P	23.74	126.50	6.51	
		D498427P	26.80	139.49	7.37	
		D498435P	34.30	171.60	9.99	
	5 b=598mm no piers	D598521	21.03	118.32	2.27	Afflux= $-0.0019Q^2 + 0.145Q$
		D598524	23.96	137.63	2.59	
		D598527	26.98	156.16	2.12	
		D598530	29.99	173.06	2.64	
		D598535	34.33	194.86	2.80	
	5 b=598mm with piers	D598521P	21.03	118.32	3.47	Afflux= $-0.0018Q^2 + 0.1859Q$
		D598524P	23.96	137.63	3.39	
		D598527P	26.98	156.16	3.22	
		D598530P	29.99	173.06	4.14	
		D598535P	34.33	194.86	4.40	

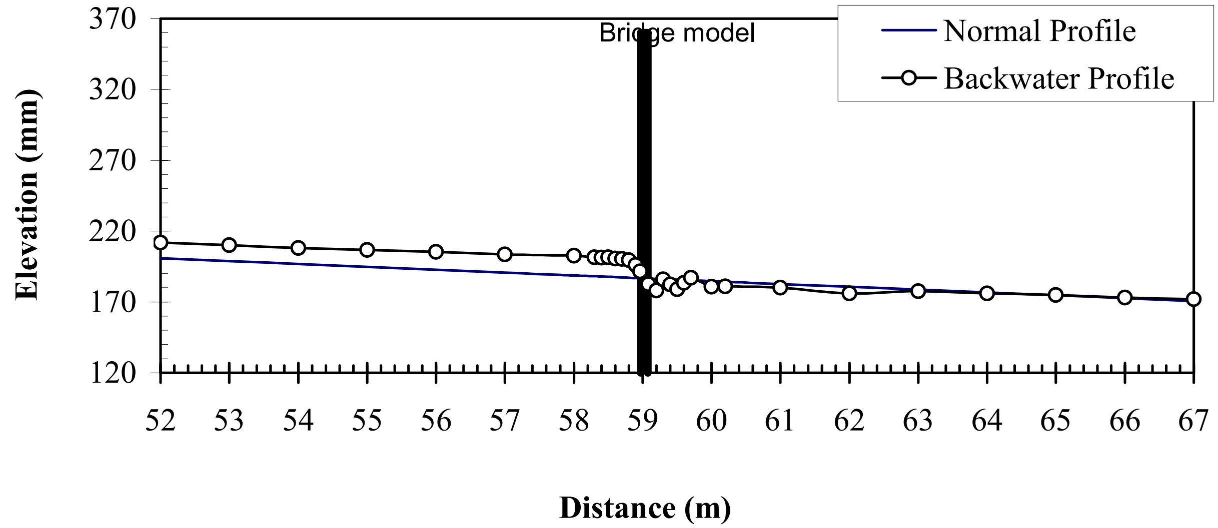
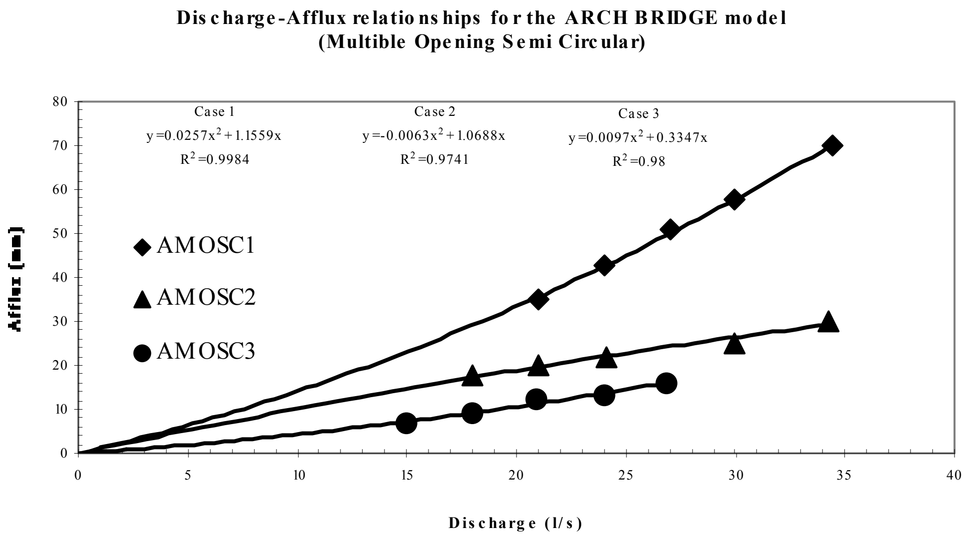
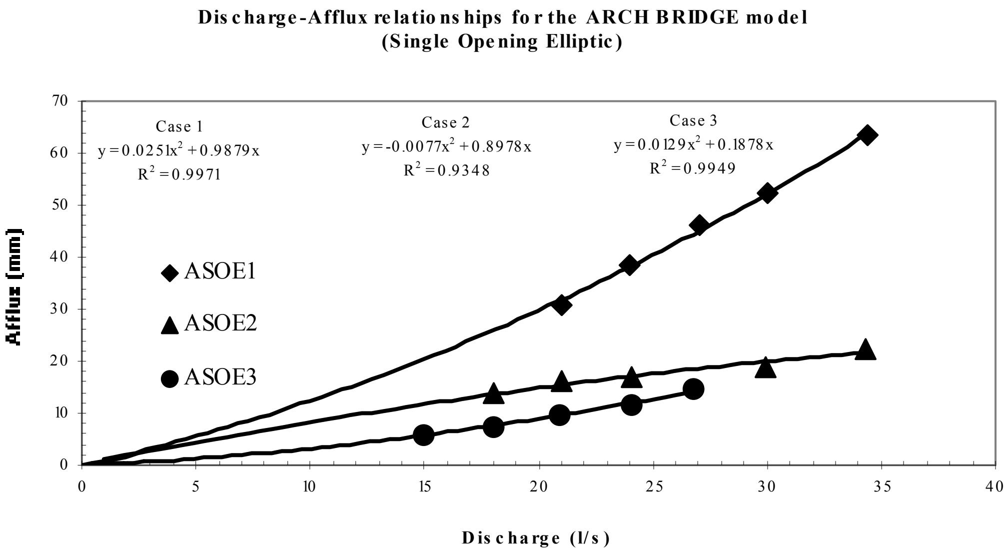


Figure A1: Comparison of water levels with and without bridge model





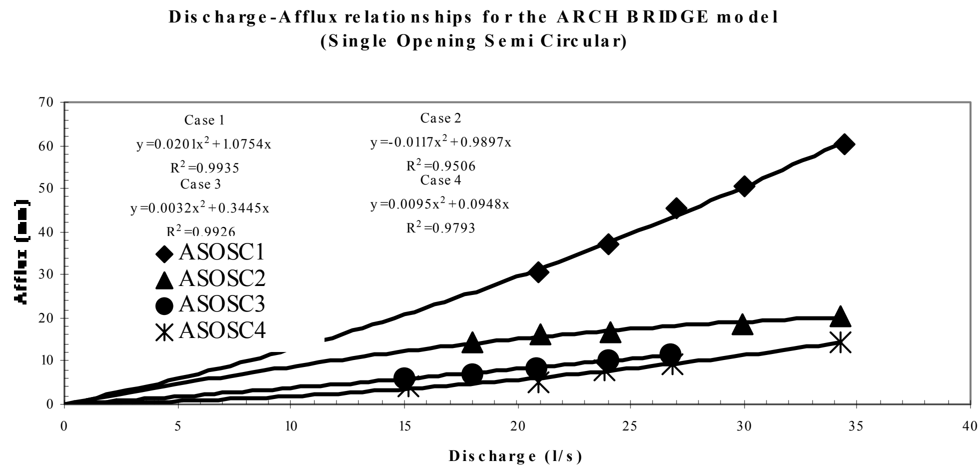
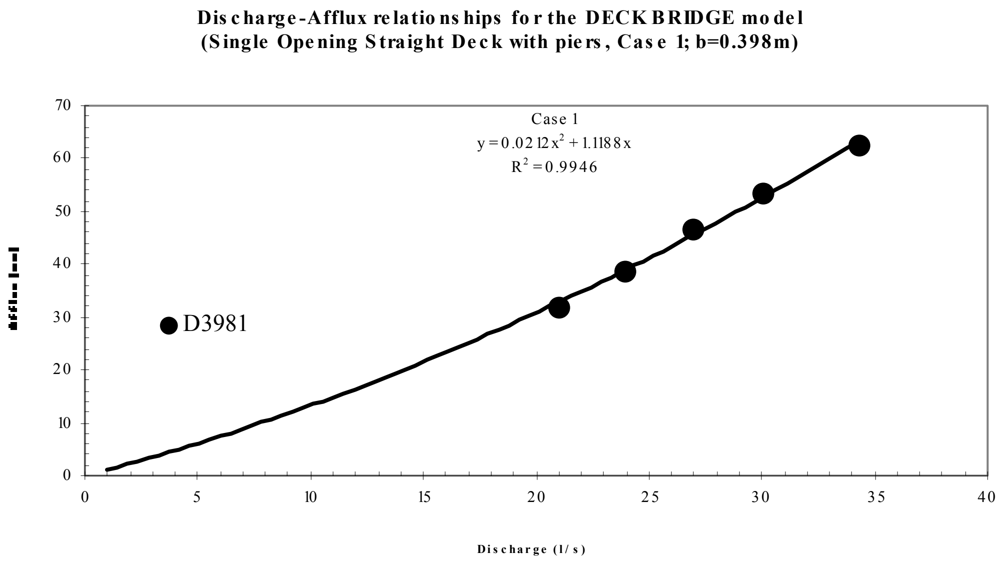
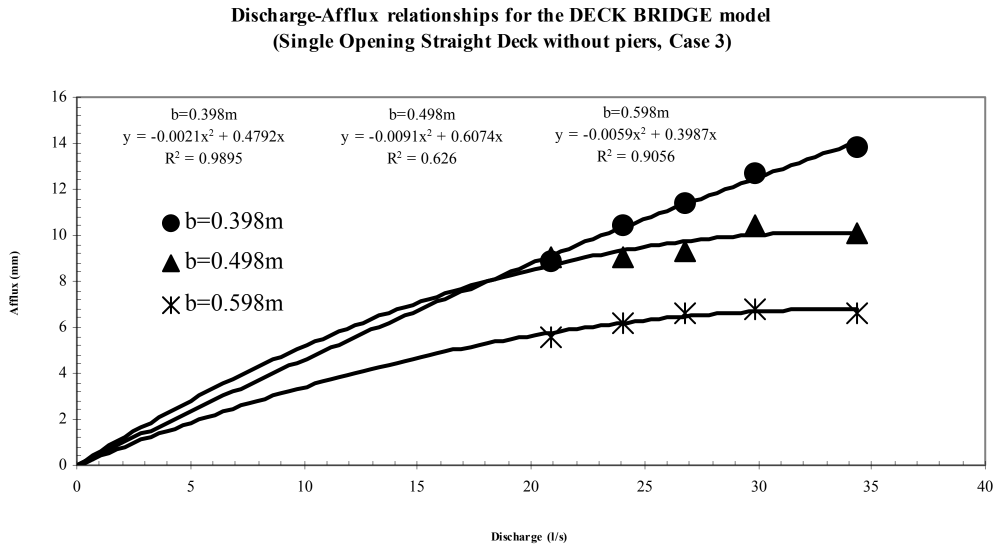


Figure A2: Afflux-discharge relationships for arch bridges





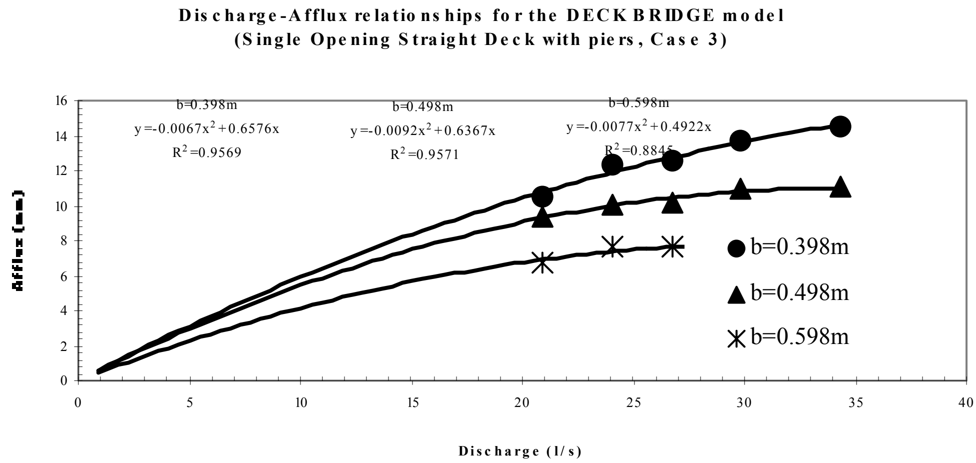
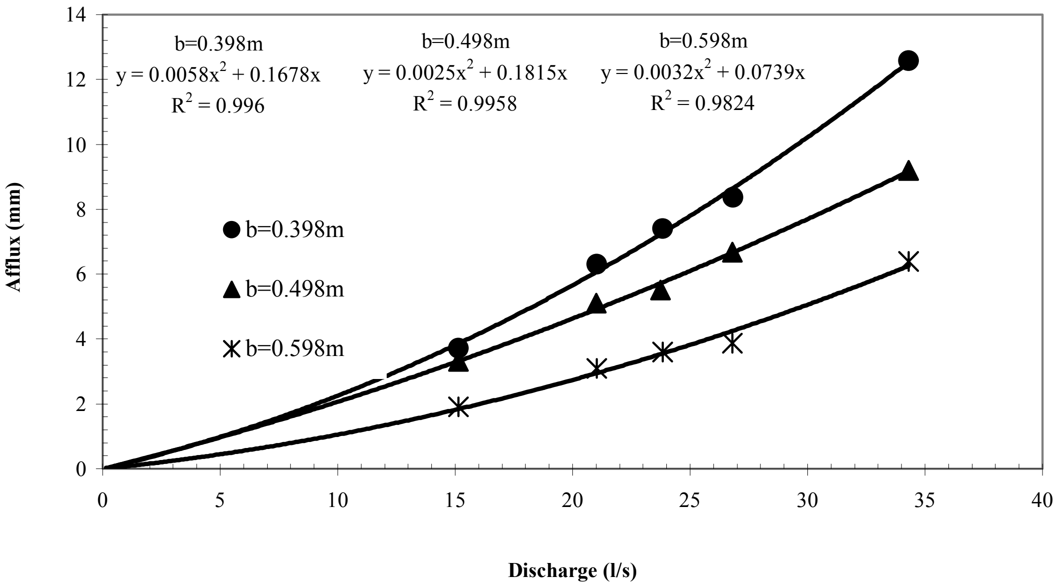


Figure A3: Afflux-discharge relationships for deck bridges

Discharge-Afflux relationships for the DECK BRIDGE model
(Single Opening Straight Deck without piers, Case 4)



Discharge-Afflux relationships for the DECK BRIDGE model
(Single Opening Straight Deck with piers, Case 4)

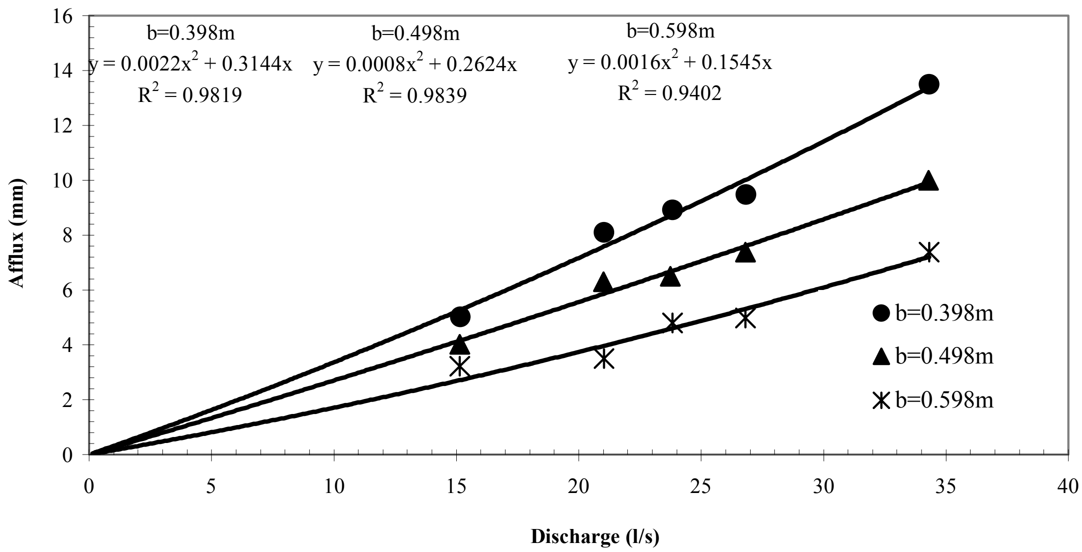
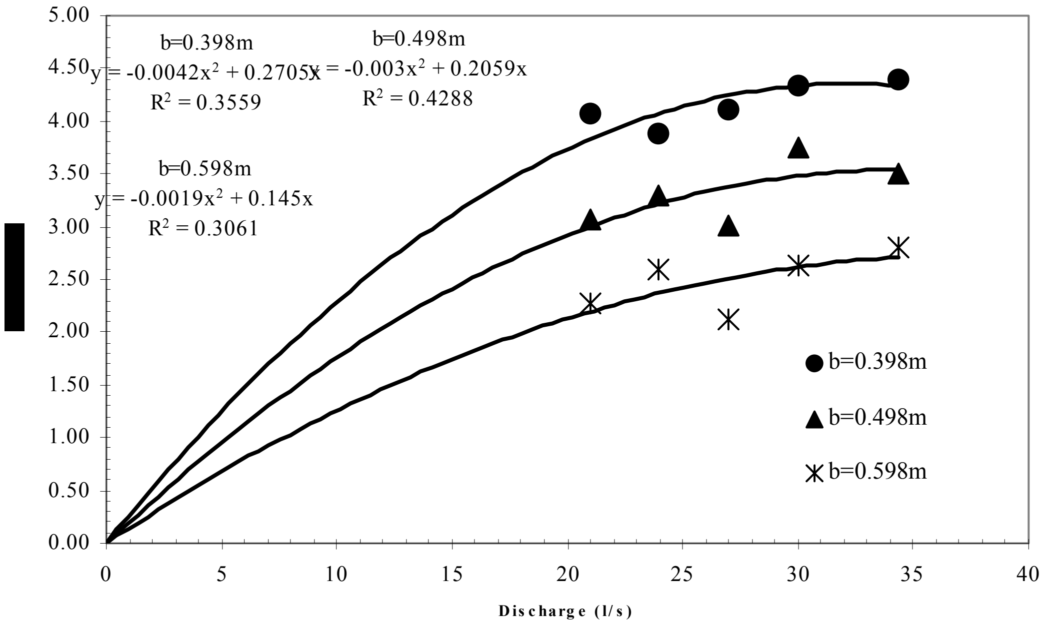


Figure A4: Afflux-discharge relationships for deck bridge (Case 4)

Discharge-Afflux relationships for the DECK BRIDGE model
(Single Opening Straight Deck without piers, Case 5)



Discharge-Afflux relationships for the DECK BRIDGE model
(Single Opening Straight Deck with piers, Case 5)

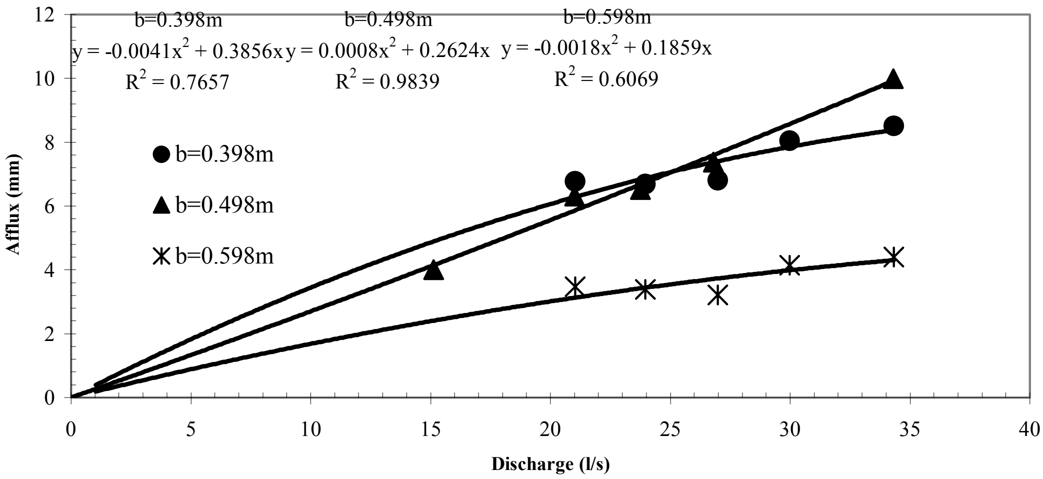


Figure A5: Afflux-discharge relationships for deck bridge (Case 5)

LONGITUDINAL WATER SURFACE PROFILE MEASUREMENTS

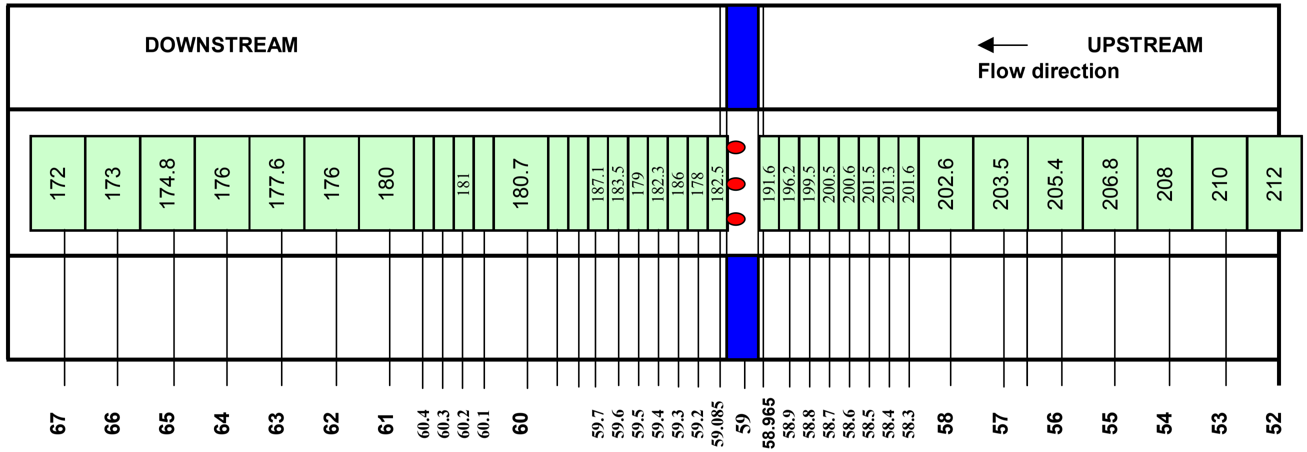


Figure A6: Water surface measurement positions along flume for single elliptic arch bridge model (Q=18 l/s)