Backwater Effects Caused by Bridges

Sarah Kingston
27/08/06

Backwater Effects Caused by Bridges

Contents: **Page:**

Backwater Effects Caused by Bridges

Introduction

The construction of bridges over watercourses is a practice that is vital to provide communication links between population areas – these communication links may be in the form of footpaths, roads, railways, or simply service crossings. In order to ensure the safety and efficient design of these water crossings, it is important to understand the hydraulics, hydrology and geomorphology of the watercourse, and how these factors will affect and be affected by the bridge structure.

In a study of the causes of failure of 143 bridges worldwide, it was found that 70 failed due to flood events (Martín Vide, 2002). This highlights the importance of understanding the interaction of water flow with bridge structures, rather than considering the bridge structure in isolation. However, it is not just the effects that flooding has on bridge structures that must be considered; the bridge structure itself affects the pattern of flow in the watercourse. In this report, backwater effects caused by bridges are considered.

Backwater Effects

As described above, bridges have an effect on the flow of the watercourse over which they are located. This is because part of the bridge structure is usually located within the channel of the river or stream, and causes an obstruction of water flow. Bridges which cross a river in more than one span have piers located in the watercourse, which force water to flow around them. The abutments of bridges also generally protrude into the watercourse, causing obstacles at either side of the channel. Even if under normal flow conditions no part of the bridge is obstructing flow, in flood conditions, where the water level is significantly raised, parts of the bridge superstructure may cause an obstruction to flow.

As water flowing in the channel approaches a bridge structure that restricts its flow area, the flow is forced to contract, in order to pass through the bridge, before expanding once again to the full channel width. As the constricted flow passes through the obstruction of the bridge, it accelerates, causing a depression in level of water surface. As the flow expands once more to the full channel width, so the water level recovers, to its downstream boundary condition level. This successive contraction and expansion results in a local head loss, which is compensated by an increase in water level upstream of the bridge. This phenomenon is known as afflux, or the backwater effect. Water levels upstream are raised by Δy with respect to downstream levels, (see figure 1 below), where Δy is equal to the head loss caused by the contraction and expansion of flow at the bridge.

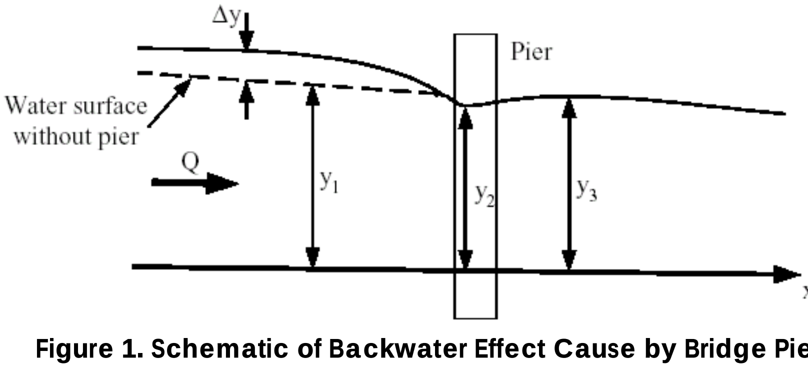

Figure 1. Schematic of Backwater Effect Cause by Bridge Pier (after Charbenau & Holley, 2001)

Modelling of Backwater Effects with HEC-RAS

HEC-RAS can be used to model the effects of a bridge crossing a watercourse, and to examine backwater effects. Below, an example project supplied with the HEC-RAS software is used to illustrate backwater effects caused by a single bridge crossing a river reach.

Geometric Data – River Reach, Cross Sections and Bridge Crossing

The bridge crossing modelled is of typical geometry, crossing the channel perpendicular to flow. The river is Beaver Creek, near Kentwood, Louisiana, U.S.A. Figure 2 below shows a schematic of the river reach, showing the cross-sections used and the location of the bridge crossing at mile 5.4.

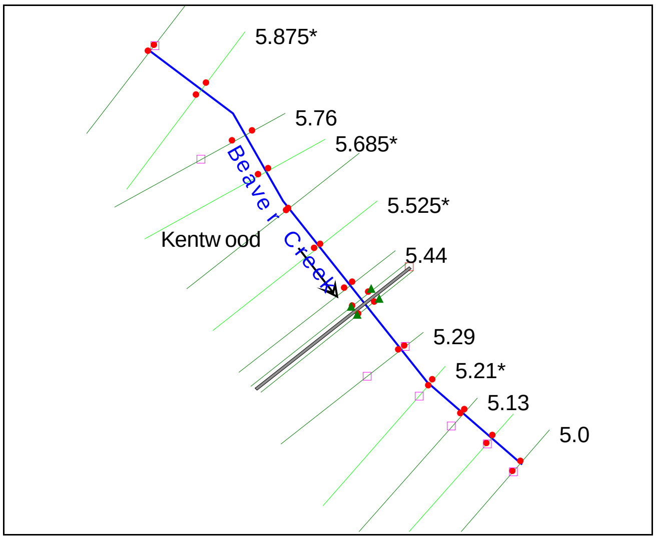

Figure 2. Schematic of Beaver Creek Showing Bridge Location

The lines perpendicular to the flow of Beaver Creek represent cross-sections for which data was entered, in the form of X-Y coordinates. The cross-section at mile 5.0 is the furthest downstream in this reach, and represents the downstream boundary condition for the model. Cross-sections marked with an asterisk indicated sections where channel geometry has been interpolated from neighbouring cross-sections.

In order to model the bridge crossing accurately, four cross-sections are required in the vicinity of the bridge. From downstream to upstream, these are as follows:

- 1st Cross-Section: Must be sufficiently far downstream for flow to have fully expanded after the bridge constriction. In this example, field data were used to provide the location of full expansion during a high flow event. Cross-section 5.29 was used.
- 2nd Cross-Section: Located immediately downstream of the bridge – located at toe of embankment slope downstream of bridge: Cross-section 5.39.
- 3rd Cross-Section: Located immediately upstream of the bridge, at toe of embankment slope upstream: Cross-section 5.41.
- 4th Cross-Section: Located where flow lines are still parallel, just before contraction begins upstream of the bridge: Cross-section 5.44.

Cross-section 5.39, immediately downstream of the bridge, is shown below:

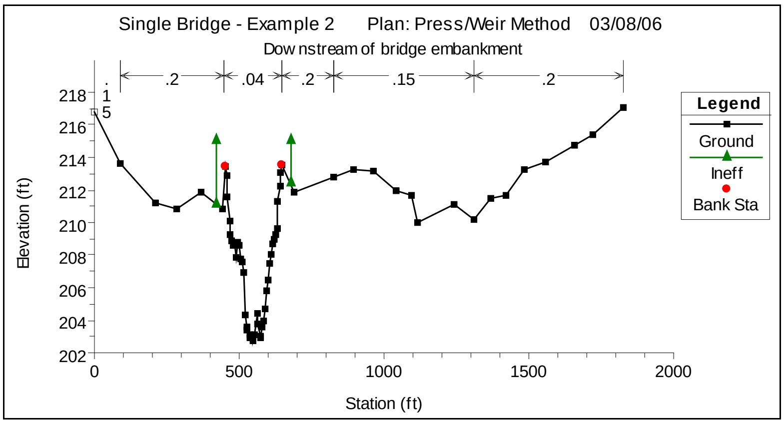

Figure 3. Cross-Section Geometry Downstream of Bridge

The red dots on either side of the main channel indicate the bank stations, and the vertical green lines to either side indicate ineffective flow areas. These ineffective flow areas are due to the presence of the bridge embankments on either side of the channel, immediately upstream of this cross-section. The geometry of the bridge structure itself is shown in figure 4 below:

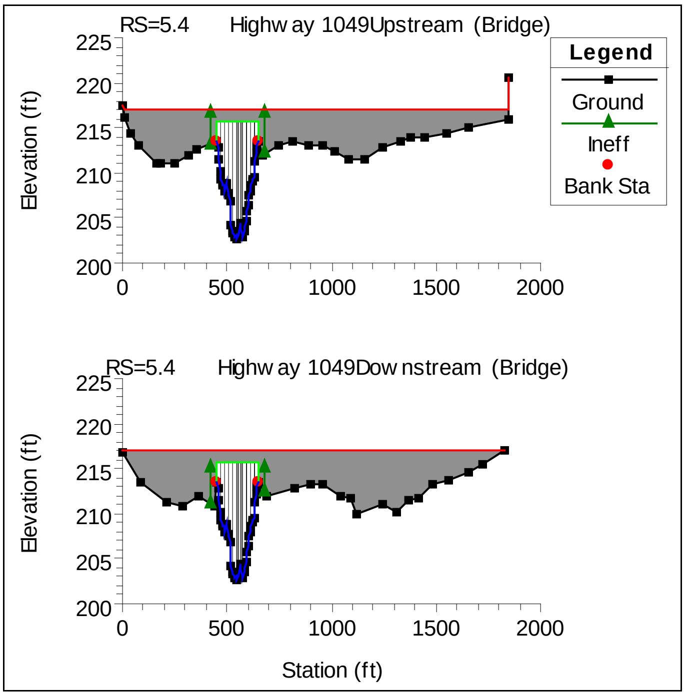

Figure 4. Geometry of Bridge Structure

The grey areas indicate the bridge deck structure and embankments on either side of the channel. The bridge piers can be seen as vertical lines within the channel area. Ineffective flow areas at either side of the bridge are again marked.

Modelling Approach

In HEC-RAS, various modelling approaches can be selected for the modelling of flow through a bridge structure. For low flow, where water flows under the bridge and does not reach the minimum level of the bridge deck, three modelling methods were computed, with the results of the highest energy loss used. These three methods are: the Yarnell equation (for subcritical, low flow), Momentum Balance and Energy Equation. For the Yarnell equation method, a pier shape factor of K=1.25 was used, representing rectangular piers. For high flow, where the upstream water level is greater than the lowest level of the bridge deck, the pressure and/or weir flow option was selected.

Steady Flow Data

Steady flow data were entered for the 25 year return period and 100 year return period events, with flows of 5000 and 10000 cfs, respectively. Data from the May 1974 flood were also used, as a high flow scenario, 14000 cfs. Boundary conditions were set for all three flow profiles as downstream water levels.

Steady Flow Analysis

A steady flow analysis was run using all the entered data. Results of the analysis were viewed as a profile plot, shown in figure 5, below.

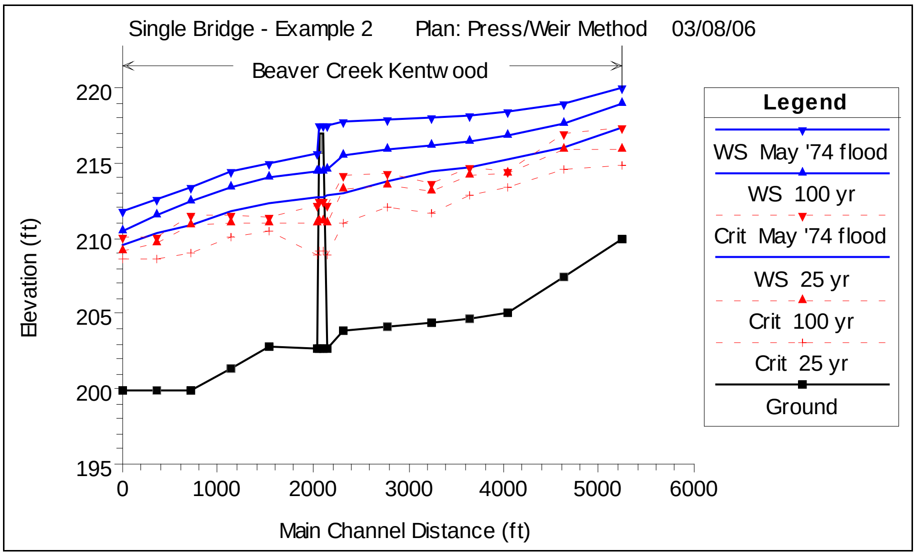

Figure 5. Profile Plot for Steady Flow Analysis

The critical depths for the three flow profiles are shown on the plot – all three calculated water surface profiles are above their respective critical depths, confirming that flow remained subcritical for each of the flow profiles. The 25 year and 100 year events were considered low flow events, as the upstream water elevation did not reach the bridge deck. The May 1974 flood, however, was a high flow event, with both pressure flow and weir flow over the top of the bridge occurring.

Observed Backwater Effects

The backwater effects of the bridge are not noticeable for the 25 year flood event; however, for the 100 year event and the May 1974 flood event, a clear increase in water level is seen upstream of the bridge, showing that backwater effects occur. Figure 6, below shows the same profile plot without the critical depth lines, for greater clarity:

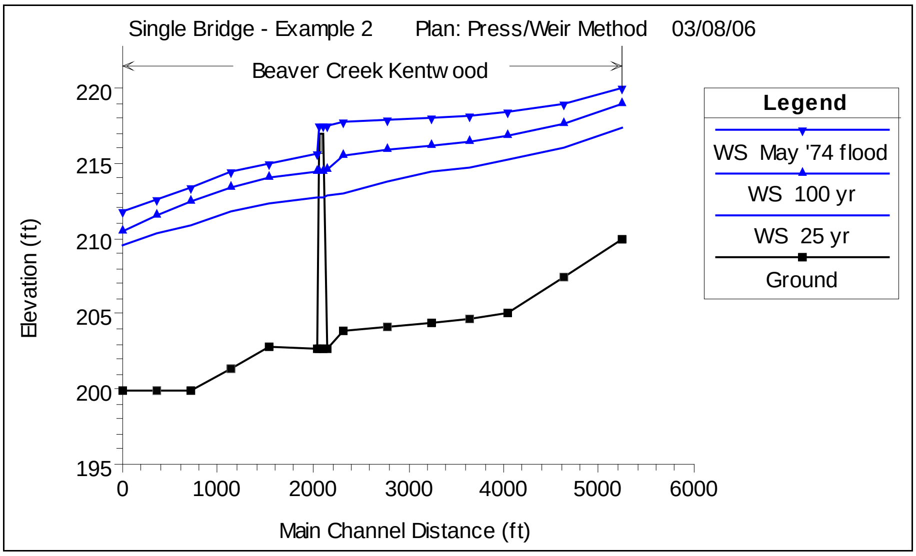

Figure 6. Profile Plot – Water Surface Only

Effect of Pier Width on Backwater Effect

In order to investigate further the backwater effect caused by the bridge, the pier widths of the modelled bridge were altered. The HEC-RAS model with altered pier widths can be opened via the following filepath: Hidráulica fluvial\HEC files\bridge.prj

In the original example project in HEC-RAS (shown above), the bridge had 9 piers, each of which was 1.25 ft wide. The total channel width at the location of the bridge was 197 ft. The piers therefore caused a 6% obstruction of the channel width.

The HEC-RAS model was re-run with a series of different bridge pier widths, as shown in Table A below:

Pier Width (ft)	Channel Width (ft)	% Obstruction of Channel
1.25	197	6
2.50	197	11
3.75	197	17
5.00	197	23
10.00	197	46

Table A. Pier Widths Used in Flow Simulations

The same steady flow data were used for the analysis; i.e., the 25 year, 100 year and May '74 Flood events.

Results of Pier Width Variation

Figure 7 below shows a plot of Δy values compared to the percentage channel obstruction, for the three flow scenarios. It can be seen that the backwater effect increased with the degree of channel obstruction by bridge piers for all flow scenarios, as would be expected. However, the more surprising outcome is that highest flow scenario, the flood of May '74, did not result in the greatest backwater effects: As soon as the initial pier width of 1.25 ft was increased to 2.5 ft, a greater backwater effect was seen for the 100 year event (see figure 7 and Table B, below).

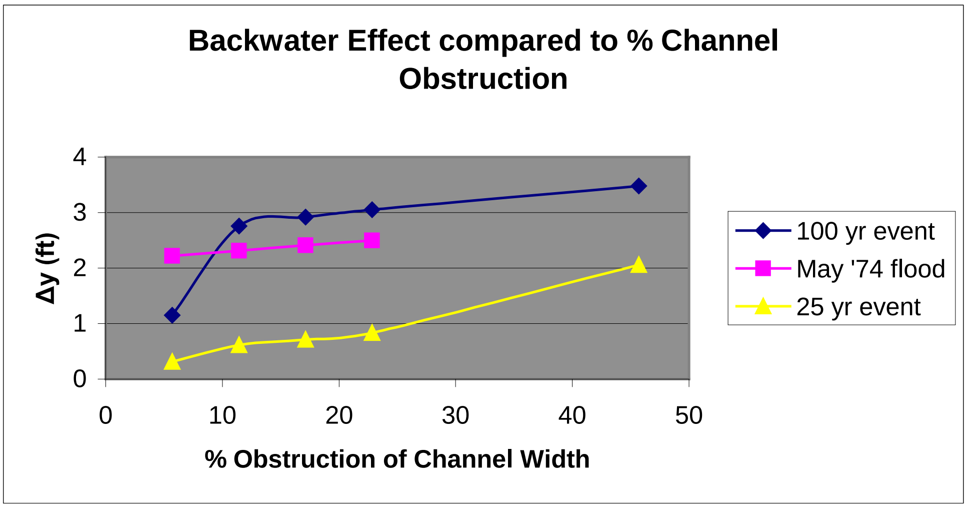

Figure 7. Effect of Channel Obstruction on Δy

Pier Width (ft)	% Obstruction of Channel	Δy (ft) 25 yr	Δy (ft) 100 yr	Δy (ft) May '74
1.25	6	0.31	1.15	2.22
2.50	11	0.61	2.76	2.31
3.75	17	0.71	2.92	2.41
5.00	23	0.83	3.05	2.5
10.00	46	2.06	3.48	n/a

Table B. Backwater Effects caused by Variation of Pier Width

Examination of the HEC-RAS Bridge Only Profile Output Table for the 2.5 ft pier width simulation shows that for this pier width, pressure and weir flow occurred for both the 100 year event and the May '74 event. Under the original bridge design conditions, pressure and weir flow only occurred during the May '74 event. This explains the apparent sudden increase in backwater effect seen in the 100 year event flow scenario. With pier sizes greater than 2.5 ft, the backwater effect for this flow scenario continues to increase, but to a lesser degree, as water is already flowing over the bridge deck. The Bridge Only Profile Output Table for the 2.5 ft pier width simulation is presented as Table C, below:

HEC-RAS Plan: 2.5 River: Beaver Creek Reach: Kentwood

River Sta	Profile	E.G. US.	Min El Prs	Prs O WS	Q Total	Min El Weir Flow	Q Weir	Delta EG
		(ft)	(ft)	(ft)	(cfs)	(ft)	(cfs)	(ft)
5.4	25 yr	213.38	215.7		5000	216.94		0.34
5.4	100 yr	217.09	215.7	217.32	10000	216.94	297.02	1.97
5.4	May '74 flood	217.77	215.7	223.17	14000	216.94	3727.04	1.76

Table C. Bridge Only Profile Output Talbe – Pier Width 2.5 ft

It can be seen in this table, that the upstream energy grade value for the May '74 Flood and the 100 year event exceeded the minimum elevations required for both pressure flow and weir flow; whilst low flow conditions remained for the 25 year event.

Figures 8, 9, 10 and 11 below show the water surface profile plots for pier widths of 2.5 ft, 3.75 ft, 5 ft and 10 ft, respectively. It should be noted in Figure 11, that the critical depth exceeded the water depth shown for the May '74 flood. For this reason, data from this scenario were discounted, and are not included in the results shown in Figure 7 and Table B, above.

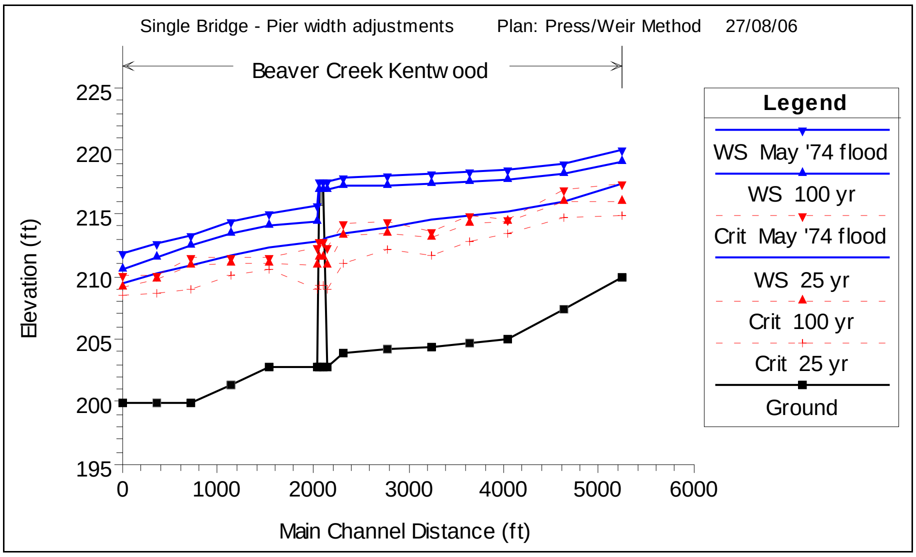

Figure 8. Profile Plot for 2.5 ft Pier Width

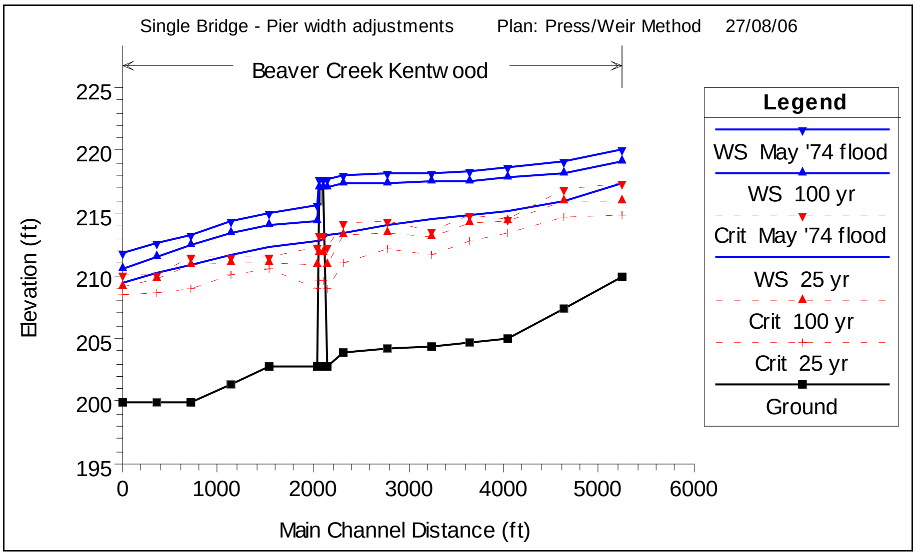

Figure 9. Profile Plot for 3.75 ft Pier Width

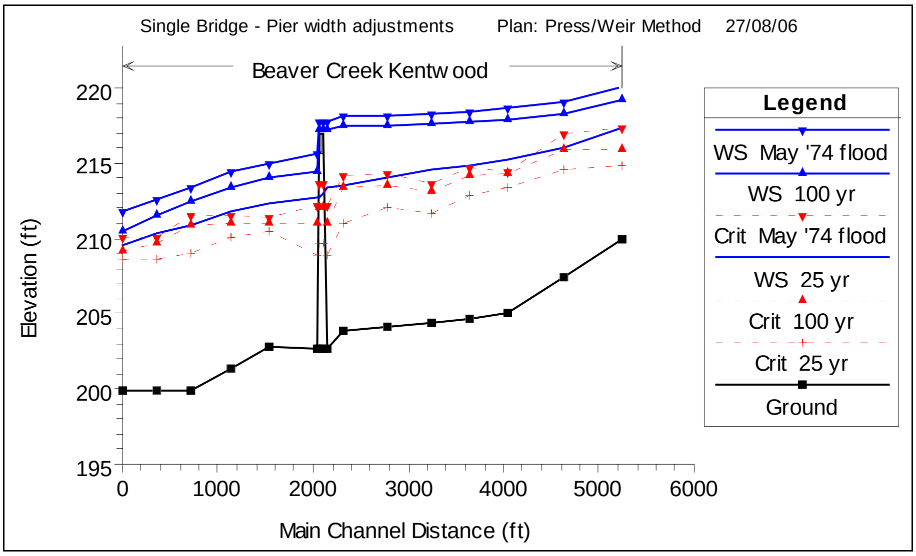

Figure 10. Profile Plot for 5 ft Pier Width

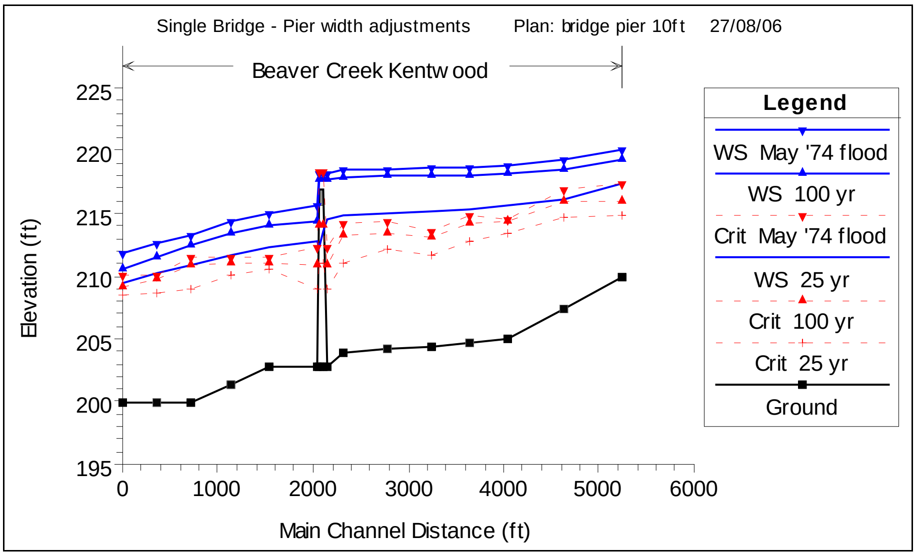

Figure 11. Profile Plot for 10 ft Pier Width

Discussion of Pier Width Variation Results

The results described above show clearly that backwater effects increase with bridge pier size. This is not surprising, since, as described earlier in this report, backwater effects are caused by the need to overcome the head loss caused by the sudden contraction and subsequent expansion of flow at the bridge structure. The greater the pier size, the greater the degree of obstruction, and the greater the contraction and expansion of flow required. Greater contraction and expansion of flow results in greater head loss, which in turn results in a greater Δy value, in order to overcome this head loss.

It should be noted that in this report, only a basic study of the effects of pier size on backwater effects has been undertaken. In the HEC-RAS model, the only condition to be altered was the pier size, in order to demonstrate the general effect of increased channel obstruction. In order to investigate these effects more accurately and in further detail, additional cross-sections would be required, in order to minimise errors in the HEC-RAS calculations. Real data from the field should also be collected, in order to calibrate the model – in this case, field data cannot be calculated for different pier sizes; however, a physical, scaled model of the bridge could be constructed, and tests run in the laboratory, in order to provide accurate results for the analysis of the effects of pier size increase.

Below, an example of an investigation of backwater effects using such a physical scaled model is described.

Study of Backwater Effects Caused by Semicircular Arch Bridges

Juan Pedro Martín Vide and Josep Maria Prió (Martín Vide & Prió, 2005), conducted a series of experiments to investigate the backwater effects (or "afflux") in semicircular arch bridges, such as are found throughout Spain, dating from the Roman and Medieval eras. They used a physical, scaled model of such a bridge, and conducted series of tests, successively lowering the bridge for each test, so that for the last test in each series, the arches and bridge deck were partially submerged with water. For four of the test series, the flow conditions of flow depth and discharge (and thus also Froude number) were varied, but a fixed horizontal base was used for the river bed. In the final series, the same flow conditions as for the first series were used, but a mobile river bed comprising sand was used in the vicinity of the bridge structure.

Martín Vide and Prió compared their experimental results to theoretical methods of Yarnell, Kindsvater and Bradley, as well as HEC-RAS. The conclusions drawn were that for a fixed bed, the degree of afflux (or backwater effect) depends principally on the degree of obstruction, calculated as the obstructed area divided by the flow area. For a mobile river bed, the degree of obstruction was less important; backwater effects were more or less constant with increasing obstruction. This is because the greater the obstruction, the greater the local bed erosion produced, thus compensating for the obstructed area, and reducing the need for an increase in upstream water level.

With regard to the comparison of experimental results with the theoretical methods, it was concluded that the Bradley and Yarnell methods overestimated backwater effects, although Yarnell's method compared well in pressure flow scenarios. The U.S. Geological Survey (Kindsvater) method gave lower results, and was considered suitable for low flow and pressure flow scenarios. It also allowed bed erosion to be satisfactorily taken into account. HEC-RAS also gave results which compared well to the experimental data.

Conclusions

Bridges crossings across waterways provide vital communications for society. Careful design is required in order to ensure that bridges over watercourses are not destabilised or destroyed by flood events. The effects of a bridge structure on the hydraulics of a water course must not be overlooked: due to head losses which occur in the vicinity of the bridge due to contraction and expansion of flow, an increased water level is caused upstream of the bridge – this is the backwater effect.

In this report, a simple example of a HEC-RAS model of a river reach containing a bridge has been reproduced, showing the backwater effects of the bridge on flood flows. Pier sizes of the bridge were increased, showing that greater backwater effects are observed with increased channel obstruction. Experimental work by professors of the Polytechnic University of Catalonia has also been examined, which confirms that backwater effects depend on the degree of obstruction of the channel, as well as on localised erosion effects.

Backwater effects should be considered in any new bridge design or bridge alteration work, as an increased obstruction to flow is likely to lead to increased water levels upstream, which could in turn present a flood risk to surrounding land users, as well as to the bridge itself.

References

Charbeneau & Holley, 2001	Charbeneau, R.J. & Holley, E.R. Backwater Effects of Piers in Subcritical Flow. *Texas Department of Transportation*. 2001
Martín Vide, 2002	Martín Vide, J.P. Ingeniería de Ríos. *Ediciones UPC*. 2002
Martín Vide & Prió, 2005	Martín Vide, J.P. & Prío, J.M. Sobreelevación causada por puentes de arcos de medio punto (Afflux caused by circular arch bridges). *Ingeniería hidráulica en México,* vol. XX, núm. 2, pp.49-59, 2005.