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Project Summary Report 1805-S
Evaluation of the Extent of Backwater Effects of Bridge Piers
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PROJECT SUMMARY REPORT

BACKWATER EFFECTS OF BRIDGE PIERS IN SUBCRITICAL FLOW

Introduction...

The construction or renovation of bridges may require placement of bridge piers in the channel or floodplain of natural waterways. These piers will obstruct the flow and cause an increase in water levels upstream of the bridge for subcritical flows. The increase in the water level is called the backwater. The amount of backwater caused by piers depends mainly on their geometric shape, their position in the stream, the flow rate, and the amount of channel blockage. Investigation of how piers influence channel obstruction and hydraulic efficiency is an important issue in bridge design. Furthermore, it has been postulated that the hydraulic effects of the piers are localized and dissipate quickly in the upstream direction. Part of this project was to investigate this postulate.

For subcritical channel flow, which is the type of flow that exists in most rivers, the rise in the water level due to bridge piers and abutments is usually assumed to occur where the flow contraction begins upstream of the bridge. This distance upstream of the bridge is approximately equal to the average encroachment distance of the roadway embankment into the channel. The hydraulic effects of bridge piers on backwater profiles have traditionally been included in the overall backwater effects of a roadway crossing of a stream.

The National Flood Insurance Program, which is administered by the Federal Emergency Management Agency (FEMA), requires permits for channel improvements and floodway map revisions for any encroachment into a designated floodway. FEMA considers bridge piers in a floodway to be an encroachment, so regulations effectively allow no backwater due to the piers without a map revision. The map review, while both time-consuming and expensive, can also include the possibility of purchasing flood easements, yielding another construction-related cost.

This research project has attempted to evaluate the water level change due to bridge piers and to study the nature of the variation of the water surface upstream of the piers.

The following three objectives were addressed in this research:

1. Evaluate the drag coefficient of bridge piers to obtain a better understanding of scaling relationships between laboratory and prototype conditions;
2. Compare the experimental results to the results of previous studies and, where appropriate, develop relationships between the backwater and the Froude number (and possibly other factors); and
3. Study the nature of the water level variation upstream of the piers.

To accomplish these objectives, two series of experiments were performed using a large physical model. The first series evaluated the drag coefficient, while the second series focused on water level variation.

Only TxDOT's Type A (Yarnell's Type I) flows were considered in this project. Type A flows are those for which the water level is low enough that the flow does not impinge on the superstructure and remains subcritical in the contracted region.

Much research has been undertaken on backwater effects from channel obstructions, and a few studies related specifically to bridge piers. The earliest study that was found in the literature was published in 1852, so it is clear that the backwater effects of bridge piers have been a concern for at least 150 years. Subsequent studies were done in the early part of the 20th century. The results that are most widely used were published by Yarnell in 1936, namely

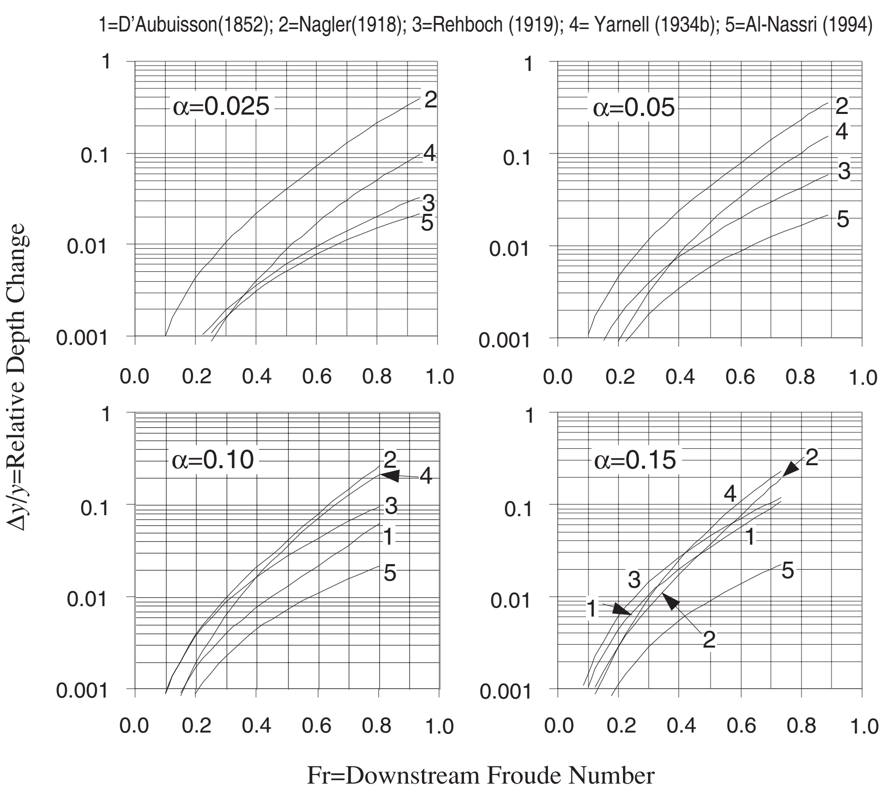
$$\frac{\Delta y}{y} = K\left(K + 5Fr^2 - 0.6\right)\left(\alpha + 15\alpha^4\right) Fr^2$$

where Δy = increase in water level caused by the piers, y = flow depth, K = coefficient depending on the pier shape, Fr = Froude number downstream of the pier, and α = ratio of the area of the submerged part of the piers to the total flow area. The Froude number is defined by $Fr=V/\sqrt{gy}$, where V = flow velocity and g = acceleration of gravity. Yarnell's equation is compared with other similar equations in Figure 1. There are no curves for one of the references for α = 0.025 and 0.05 since the equation gives negative values of Δy for these small α values.

In spite of the long history of concern with the problem of backwater from bridge piers, additional studies were needed for several reasons:

- Strangely, Yarnell's publication has no comparison of his commonly used prediction equation and the extensive data that he collected.
- Many bridge piers are now circular columns, but Yarnell did a relatively small percentage of his experiments for this shape.
- The relative amount of obstruction caused by the piers now is typically smaller than the conditions that Yarnell and other people investigated. Yarnell studied piers with α = 0.117 to 0.50, but piers now typically have α = 0.10 or smaller.
- There are significant differences between Yarnell's work and other studies, as illustrated in Figure 1.
- Immediately upstream of a pier, there is a two-dimensional mound of water with the water surface being higher in line with the pier and lower as one moves laterally. Farther upstream, the increase in the water level becomes one dimensional, i.e., the water level is the same across the full width of the channel. The backwater is defined as the maximum increase in water level after the water surface has only a one-dimensional increase. However, none of the previous publications gives any information on the extent of the two-dimensional variation of the water surface.

Figure 1: Various relationships for backwater



What We Did...

Two types of experiments with different objectives were performed. The first type was to measure the drag forces on piers, while the second measured the rise in water level upstream of bridge piers, i.e., the backwater. The measurements were made in a large laboratory channel constructed for this project. The channel is 5 ft (1.52 m) wide, 2.6 ft (0.81 m) deep, and 110 ft (33.5 m) long. Four pier configurations were used:

- 3.5 in. (8.9 cm) diameter.
- 6.5 in. (16.5 cm) diameter.
- Two 6.5 in. (8.9 cm) diameter piers with one behind the other.
- Rectangular pier with semi-circular nose and rectangular tail (diameter of the nose equal to 6.5 in. (16.5 cm) and length of the rectangle equal to 3 ft (91.4 cm)). This pier is a replica of one of the pier shapes used by Yarnell.

Only the single 3.5 in. (8.9 cm) pier was used for the drag force measurements. The drag forces were measured and the drag coefficients determined as an aid to the interpretation of the backwater measurements and to provide additional insight into scaling the model results to prototype conditions.

For the backwater measurements, the vertical position of the water surface was measured at four points in two cross sections downstream of the pier and at 20 points in eight cross sections upstream of the pier. At each cross section, measurements were made on each side of the channel. In addition, for the four cross sections immediately upstream of the pier, measurements were also made on the centerline of the channel (i.e., in line with the pier) to determine the extent of the mound of water in front of the piers.

What We Found...

Backwater Results

The measured backwaters are shown in Figure 2 through Figure 5. Yarnell's equation (Equation 1) is shown on each of the figures. The measured backwater values for all of the piers, including a replica of one of Yarnell's piers, were consistently lower than those predicted by Equation 1. Thus, a new equation, called the two-parameter equation, was fitted to the data. The new equation is

$$\frac{y}{y} = \beta K\left(K + \mu 5 Fr^2 - 0.6\right)\left(\alpha + 15\alpha^4\right) Fr^2$$

where β and μ are the two additional parameters. As can be seen by comparing Equations 1 and 2, the new equation is a modification of Yarnell's equation since his equation is widely used. For the three sets of experiments with circular piers, the best-fit values are β = 1.24 and μ = 0.40. For the Yarnell pier, the behavior of the data is different and the best values are β = 0.65 and μ = 0.69. Equation 2 with these best-fit values is shown in each of the same as given by Yarnell (0.9 for a single circular pier, 1.05 for two circular piers in line, and 0.9 for the Yarnell pier).

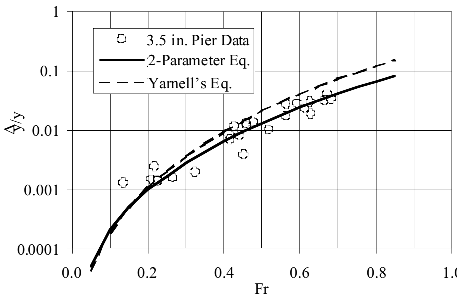


Figure 2: Backwater for the 3.5 in. (8.9 cm) diameter pier

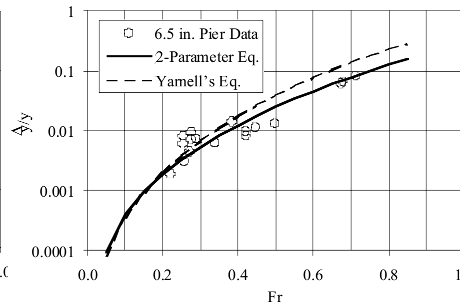


Figure 3: Backwater for the 6.5 in. (16.5 cm) diameter pier

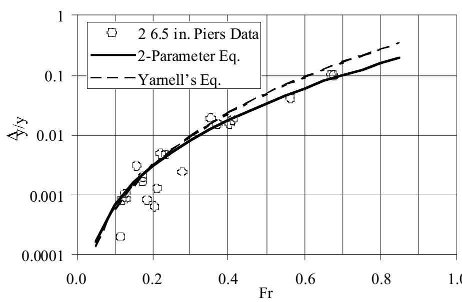


Figure 4: Backwater for the twin cylinder 6.5 in. (16.5 cm) diameter pier

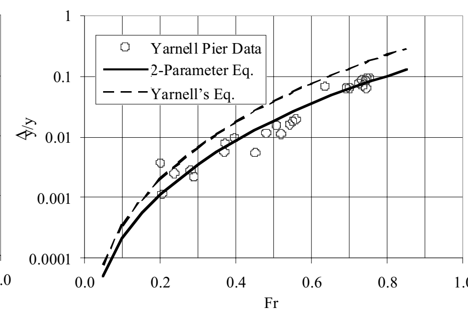


Figure 5: Backwater for Yarnell's pier

The measurements indicated that the length of the two-dimensional mound of water immediately upstream of a bridge pier (Figure 6, where WSL = water surface level) is no greater than the channel width. For an actual bridge with multiple lines of piers in the river flow direction, the equivalent condition is that the mound is no longer than the lateral distance between the lines of piers.

Increasing Manning's *n* To Calculate Backwater

Another objective was to evaluate the possibility of increasing Manning's n to account for the backwater effects of piers rather than using an expression such as Equation 1 or 2. For wide shallow flows where the hydraulic radius is approximately equal to the flow depth, the increase in Manning's *n* (Δn) can be estimated from

$$\frac{\Delta n}{n} = \sqrt{1 + \frac{\phi^2 K y^{4/3}}{g L n^2}\left(K + 5Fr^2 - 0.6\right)\left(\alpha + 15\alpha^4\right)} - 1$$

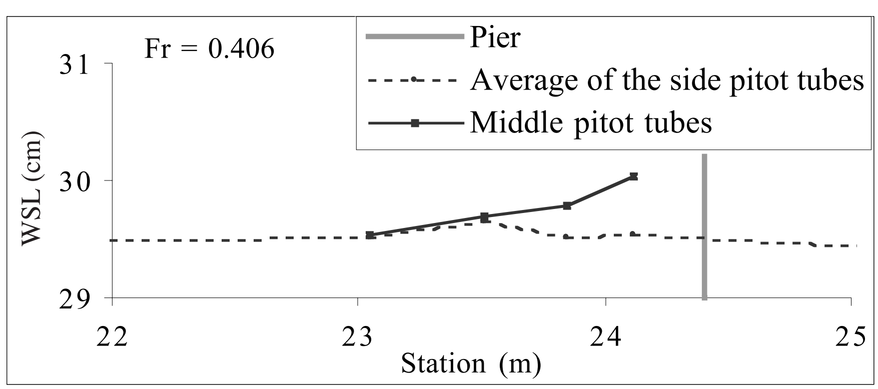
where L is the reach length (normally the flow length under the bridge) where the increased n is used and ϕ = 1.486 for English units and 1 for SI units. As Equation 3 shows, the appropriate increase in *n* depends on many factors so that it is not possible to develop simple guidelines for using this method. The amount of effort required to determine an appropriate Δn for any given set of conditions is as great as the effort to calculate Δy directly.

The Researchers Recommend...

Based on the work summarized above and presented in detail in the technical report, the recommendations from this project are as follows:

1) The backwater due to bridge piers for Type A flows should be calculated from Equation 2 with *b* = 1.24 and *m* = 0.40, not Equation 1.
2) Equation 3 can be used to determine the amount to increase Manning's *n* to account for the backwater of bridge piers rather than calculating Δy directly, but the amount of effort to get the correct increase in *n* is as great as calculating Δy.

Figure 6: Mound of water immediately upstream of a pier



For More Details...

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The research is documented in the following reports:

1805-1 *Backwater Effects of Piers in Subcritical Flow,* March 2002

To obtain copies of a report: CTR Library, Center for Transportation Research,
(512) 232-3138, email: ctrlib@uts.cc.utexas.edu

TxDOT Implementation Status January 2002

The research evaluated the impact of bridge piers on water surface elevations of flood flows upstream of a bridge. The research indicates that the increase in water surface elevations due to bridge piers is somewhat less than indicated by the standard formula. A new formula is proposed. The two-dimensional mound of water that exists immediately upstream of a pier rapidly dissipates in the upstream direction.

The results will be presented to the Federal Emergency Management Agency (FEMA) in order to demonstrate the impact of bridge piers relative to the compliance criteria of the National Flood Insurance Program(NFIP). The results of the research will be incorporated into the on-line Hydraulic Design Manual to enhance the project development process.

For more information, please contact Bill Knowles, P.E., RTI Research Engineer at (512) 465-7648 or email at wknowle@dot.state.tx.us.

Your Involvement Is Welcome!

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