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

$$\Delta y = K \left( y + 5Fr^2 - 0.6 \right) \left( y + 15a^2 \right) Fr^2$$

where $\Delta y$ = increase in water level caused by the piers, $y$ = flow depth, $K$ = coefficient depending
on the pier shape, \( Fr = \text{Froude number} \) downstream of the pier, and \( \alpha = \text{ratio} \) of the area of the submerged part of the piers to the total flow area. The Froude number is defined by \( Fr = \frac{V}{\sqrt{gy}} \), where \( V = \text{flow velocity} \) and \( g = \text{acceleration of gravity} \). Yarnell’s equation is compared with other similar equations in Figure 1. There are no curves for one of the references for \( \alpha = 0.025 \) and 0.05 since the equation gives negative values of \( \Delta y \) for these small \( \alpha \) 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 \( \alpha = 0.117 \) to 0.50, but piers now typically have \( \alpha = 0.10 \) 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.

\textbf{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.

\textbf{What We Found...}

\textbf{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

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Various relationships for backwater}
\end{figure}
measured backwater values for all of
the piers, including a replica of one of
Yarnell’s piers, were consistently
lower than those predicted by Equa-
ton 1. Thus, a new equation, called
the two-parameter equation, was fit-
ted to the data. The new equation is

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

where \( \beta \) and \( \mu \) are the two additional
parameters. As can be seen by com-
paring 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 \( \beta = 1.24 \) and \( \mu = 0.40 \). For the
Yarnell pier, the behavior of the data
is different and the best values are
\( \beta = 0.65 \) and \( \mu = 0.69 \). 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).

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 condi-
tion 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 expres-
sion 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
\( n \) (\( \Delta n \)) can be estimated from

\[ \Delta n = \frac{\phi}{\pi} \left(\frac{K}{L}\right)^{1/2} \left(15\alpha^4\right) \left\{ 1 + 15\alpha^2 \left(K + 5Fr^2 - 0.6\right) \right\}^{-1} \]

where \( L \) is the reach length (norma-
ly the flow length under the bridge)
where the increased \( n \) is used and
\( \phi = 1.486 \) for English units and 1 for
SI units. As Equation 3 shows, the ap-
propriate 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 re-
quired to determine an appropriate \( \Delta n \)
for any given set of conditions is as
great as the effort to calculate \( \Delta y \)
directly.

**The Researchers Recommend...**

Based on the work summa-
rized above and presented in detail in
the technical report, the recommenda-
tions 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 deter-
mine the amount to increase
Manning’s \( n \) to account for the
backwater of bridge piers rather
than calculating \( \Delta y \) directly, but
the amount of effort to get the
correct increase in \( n \) is as great as
calculating \( \Delta y \).
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.

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Disclaimer

This research was performed in cooperation with the Texas Department of Transportation and the U. S. Department of Transportation, Federal Highway Administration. The content of this report reflects the views of the authors, who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the FHWA or TxDOT. This report does not constitute a standard, specification, or regulation, nor is it intended for construction, bidding, or permit purposes. Trade names were used solely for information and not for product endorsement. The engineer in charge was Edward R. Holley (Texas No. 51638).