CENTER FOR TRANSPORTATION RESEARCH
THE UNIVERSITY OF TEXAS AT AUSTIN

Project Summary Report 0-2109-S
Project 0-2109: Evaluate the Effects of Channel Improvement, Especially Channel Transitions, on Culverts and Bridges
Authors: Randall J. Charbeneau
February 2005

PROJECT SUMMARY REPORT

# Hydraulics of Low-Headwater Box Culverts

Low-headwater box culverts are used along highways in areas with low topographic relief where highway rise associated with roadway embankments over drainage channels is kept small, and the corresponding upstream headwater must also remain low to prevent water overtopping the roadway under design-flow conditions. For such conditions, the design headwater depth may be limited to the culvert rise, and the velocity head contribution to the headwater specific energy may be significant. Use of conventional methods for culvert design can result in use of multiple-barrel box culverts with upstream channel expansion leading to the culvert entrance.

Field experience documents that use of upstream channel expansions leading to multiple- barrel box culverts can result in poor hydraulic performance of the channel/culvert system with accumulation of sediment and debris in the outer culvert barrels. Issues associated with hydraulics of channel expansion sections and design requirements are addressed through this research program.

There have been many investigations of culvert hydraulics, at least since the 1920s. Under the sponsorship of the Bureau of Public Roads (now the Federal Highway Administration [FHWA]), the National Bureau of Standards (now the National Institute of Science and Technology [NIST]) conducted an extensive series of experiments to better define the performance of culverts with different configurations and with different operating conditions. This research was performed during the 1950s and 1960s, and forms the basis for many culvert design procedures and computer programs. While the FHWA equations remain the most widely used tools for culvert design and analysis, they are ambiguous in their description of the transition from unsubmerged to submerged inlet control conditions (the curves for unsubmerged and submerged conditions do not intersect), which are significant for low-headwater culverts.

Retrofit of existing culvert structures and design of new culverts often use safety end treatments (SETs) to protect vehicular traffic from the culvert structure. While there have been a few investigations of the effects of SETs on culvert performance, none of these consider the standard Texas Department of Transportation (TxDOT) design of SETs. There is a need to document the impacts that standard TxDOT SETs have on culvert hydraulic performance.

The following three primary objectives were addressed in this research:

1. Evaluate the hydraulic performance of a channel expansion from a trapezoidal (nonrectangular) channel leading to a multiple-barrel box culvert, including the distribution of flow and specific energy.
2. Determine the hydraulic performance curve for box culverts.
3. Determine the minor loss coefficient for safety end treatments at a culvert entrance.

## What We Did...

Three types of experiments with different objectives were performed using two different channels. One channel had an upstream section with trapezoidal cross section, an expansion section, and a downstream section containing a multiple-barrel box culvert with two, four, and six barrels open. The physical model of the multiple-barrel culvert system used a 1:10 scale model based on a prototype culvert barrel with a 10 ft span and a 6 ft rise. The second channel had a rectangular cross section and was used to investigate single-barrel culverts with different end configurations and with SETs.

The first type of experiment was to measure the velocity profile and depth at different cross sections upstream of a multiple-barrel box culvert. Velocities were measured using a SonTek Acoustic Doppler Velocity (ADV) meter and pitot tubes. These measurements were used to calculate the depth-average velocity and specific energy at different locations upstream of the culvert system, and to evaluate the flow characteristics through the expansion section leading to the culvert entrance. The second type of experiment was to measure the velocity and depth immediately upstream of each culvert barrel. These measurements were used to evaluate the performance curves for the culvert systems. The third type of experiment was to measure the depth and velocity upstream of a culvert model with and without the presence of SETs. These measurements were used to evaluate the minor loss coefficients associated with SETs for different culvert end configurations.

In addition to the physical modeling experiments, numerical modeling experiments were performed using the Finite Element Surface Water Modeling System (FESWMS) developed for the FHWA. The numerical model was first calibrated using the physical model experiment data, and then the calibrated model was used to simulate flow in different channel configurations and to evaluate potential remedies for existing culvert systems.

Finally, hydraulic principles were used to develop a consistent set of performance curve modeling equations for unsubmerged and submerged inlet control conditions. For unsubmerged conditions, the performance curve is written

$$\frac{HW}{D} = \frac{3}{2}\left(\frac{1}{C_b}\right)^{2/3}\left(\frac{Q}{BD\sqrt{gD}}\right)^{2/3}$$

In this equation HW = headwater (upstream specific energy measured from the base of the culvert entrance), D = culvert rise, $C_b$ = side contraction coefficient, Q = barrel discharge, B = culvert span, and g = gravitational acceleration. For submerged conditions, the performance equation is

$$\frac{HW}{D} = \frac{1}{2C_d^{\,2}}\left(\frac{Q}{BD\sqrt{gD}}\right)^2 + C_c$$

In this equation $C_d$ is the discharge coefficient and $C_c$ is the soffit (or ceiling) contraction coefficient. The three coefficients are related through $C_d = C_b\, C_c$. The transition from unsubmerged to submerged conditions occurs when

$$\frac{HW}{D} = \frac{3}{2}C_c$$

The transition between the curves is both continuous and smooth, providing a consistent model for analysis of box culvert hydraulics under both unsubmerged and submerged conditions.

## What We Found…

The upstream channel cross section shape is critical for understanding the hydraulics of flow through the channel expansion section. As water approaches the expansion, the water surface elevation drops. Because of the trapezoidal cross section shape, this drop in water surface elevation imparts an inward (centerline) component to the flow near the channel boundaries, resulting in a hydraulic jet that remains focused through the channel expansion section and downstream. A typical example is shown in Figure 1, where the longitudinal (distance upstream from the six-barrel culvert model) and transverse station locations are normalized by the culvert span, and E is the specific energy.

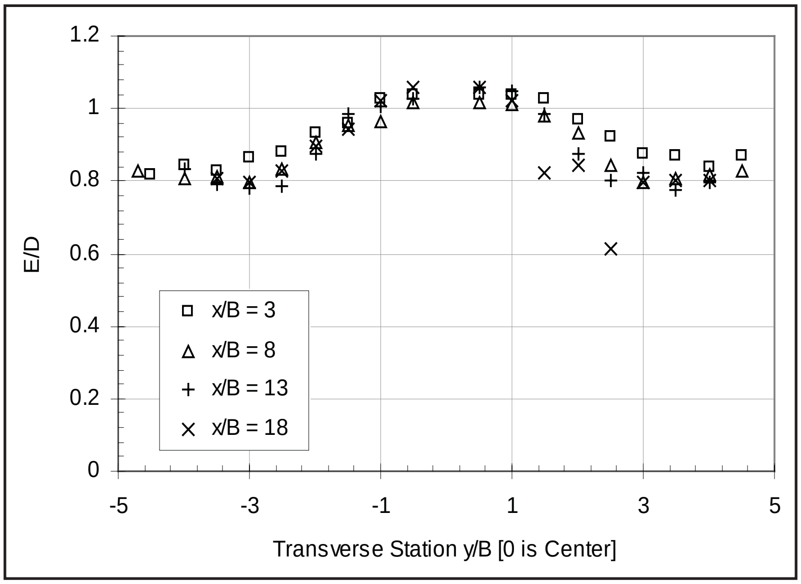


*Figure 1: Measured specific energy distribution at different cross section distances (x/B) upstream of the model culvert system*

The culvert system has a width 6B, and for this experiment the channel expansion is located a distance x/B = 20 upstream from the culvert model. While the experiments show that there is some spreading of the jet downstream from the expansion, it remains focused and results in greater specific energy for culvert barrels located near the channel centerline. The central barrels carry more discharge than the outer barrels, and this can result in accumulation of sediment and debris in the outer barrels, which is observed at field locations.

The performance curves measured through this experimental program differ significantly from the FHWA performance equations. An example of box culverts without wingwalls is shown in Figure 2. The data are for one-, two-, four-, and six-barrel culvert systems. For design of low-headwater box culverts, the headwater and discharge are fixed and the performance curve is used to estimate the required culvert size. This figure shows that the FHWA equations predict a larger culvert size than suggested by these experimental results. With use of a smaller culvert size (even with limited culvert rise), the apparent requirement of an upstream channel expansion can be avoided.

A number of different end configurations were evaluated during the experimental program. Most experiments were performed for a box culvert without wing-

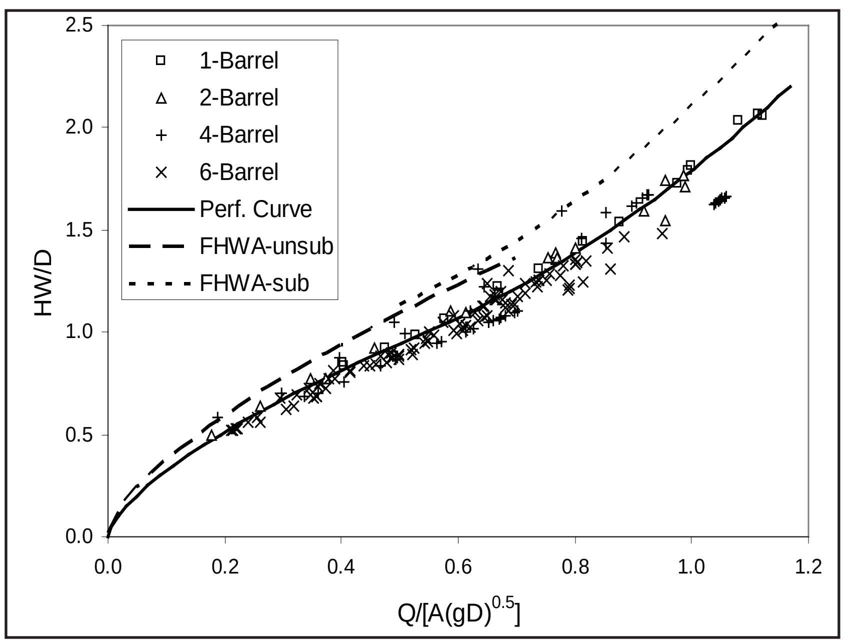


*Figure 2: Performance curves for a box culvert without wingwalls, comparing the FHWA equations with results from this experimental program*

Table 1: Representative parameter values for culvert performance

| | $C_b$ | $C_c$ | $C_d$ |
|---|---|---|---|
| Box culvert | 1.000 | 0.667 | 0.667 |
| Vertical headwall | 0.914 | 0.624 | 0.571 |
| 3:1 mitered | 0.898 | 0.569 | 0.511 |
| 6:1 mitered | 0.876 | 0.703 | 0.615 |
| 6:1 flared | 0.897 | 0.755 | 0.677 |
| 30-degree skew | 0.802 | 0.614 | 0.492 |

walls and a vertical headwall. Other configurations evaluated include a box culvert with 3:1 wingwalls (parallel) and a vertical headwall, 3:1 mitered wingwalls and headwall, 6:1 mitered wingwalls and headwall, 6:1 wingwalls with 15 degree flare, and 3:1 wingwalls with barrel at 30 degree skew. Representative performance parameters for these different configurations are provided in Table 1. If one considers culvert efficiency in terms of decreased size for a given headwater and discharge, then the box culvert is most efficient while the culvert with skew barrel is least efficient. Increasing the wingwall slope increases the culvert efficiency.

The SET minor loss coefficient is used to calculate the increase in headwater associated with the presence of SETs, based on the barrel velocity head. The relationship is

$$K = \frac{h_m}{v_b^2/2g}$$

In this equation, K is the minor loss coefficient, $h_m$ is the minor head loss, and $v_b$ is the barrel velocity. The experimental program shows that there is negligible correlation between the magnitude of the minor loss coefficient and either headwater or discharge. Furthermore, there is little difference in minor loss coefficient values associated with the different culvert end configurations. The data in Figure 3 suggest that a representative minor loss coefficient K = 0.021 may be used for all end configurations with standard TxDOT SETs. These data confirm that the effect of SETs on headwater is small.

In the evaluation of potential remedies for existing culverts, it was found that changing the expansion ratio had little effect on flow characteristics downstream of the expansion. The most effective remedy identified during the experimental and numerical modeling program was to place rock gabions upstream of the culvert entrance. These gabions disturb the jet issuing from the channel expansion and can result in a uniform headwater and flow across the culvert barrels, with minimal overall increase in headwater. Additionally, sediment accumulation will occur upstream of the gabions, at least making maintenance easier than removal of sediment from the culvert barrels.

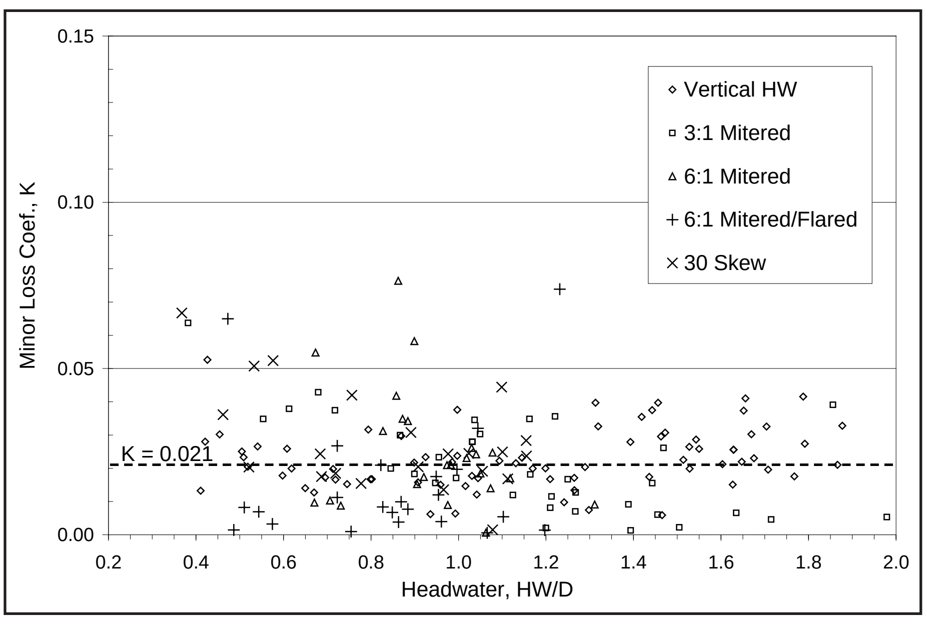


Figure 3: SET minor loss coefficient as a function of headwater for different culvert end configurations

## The Researchers Recommend…

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

1. For design of low-headwater box culverts, the headwater should include both the upstream flow depth plus the approach velocity head.
2. Natural upstream channel cross section shapes (trapezoidal) will strongly influence the flow distribution through channel expansion sections, and the 4:1 expansion ratio expected from the literature might not be observed, resulting in greater specific energy near the channel center than sides. Care should be used in assuming that all barrels in a multiple-barrel box culvert system will carry the same discharge.
3. The performance equations developed through this research program predict a smaller required culvert area for a fixed headwater and discharge than predicted by FHWA equations. These equations should be considered for use in design by TxDOT. Additional experiments are required to document performance of different end configuration systems.
4. The performance equations may be used with or without SETs present.
5. The minor loss coefficient K = 0.021 may be used for standard TxDOT SETs for all end configurations.
6. The SET minor loss coefficients do not vary with either headwater or discharge, and the overall impact of SETs on culvert performance is small.
7. The FESWMS model is applicable to the class of problems dealing with channel transitions near highway structures.

## For More Details...


Research Supervisor: Randall J. Charbeneau, Ph.D., P.E., (512) 471-2125
email: charbeneau@mail.utexas.edu

TxDOT Project Director: George R. Herrmann, (915) 947-9321
email: GHERRMA@dot.state.tx.us

TxDOT Research Engineer: Tom Yarbrough, P.E., Research and Technology Implementation Office,
(512) 465-7403
email: tyarbro@dot.state.tx.us


The research is documented in the following reports:

2109-1 *Hydraulics of Channel Expansions Leading to Low-Head Culverts*

2109-2 *Evaluation of Hydraulics Effects of Safety End Treatments*

To obtain copies of a report: CTR Library, Center for Transportation Research,
(512) 232-3126, email: ctrlib@uts.cc.utexas.edu

## Your Involvement Is Welcome!

## Disclaimer




CTR

The University of Texas at Austin
Center for Transportation Research Library
3208 Red River #115
Austin, TX 78705-2650