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16. Abstract
This research program addresses issues associated with the hydraulic effects of bridge rails on floodwater levels upstream of bridge structures. The hydraulics of bridge rails and traffic barrier systems are not well understood, especially with regard to rail/barrier systems in series and the submergence of structures. The hydraulics of bridge rails is an important issue for TxDOT bridge rehabilitation projects with potentially significant cost implications. This research project is designed to address issues associated with the hydraulic performance of bridge rails and traffic barriers, and to provide guidance on how different rail/barrier systems can be included in floodplain hydraulics models.

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FEASIBILITY REPORT AND PLAN OF ACTION FOR DEVELOPMENT OF A NEW, HYDRAULICALLY EFFICIENT BRIDGE RAIL

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Hydraulic Performance of Bridge Rails based on Rating Curves and Submergence Effects, Joshua Brandon Klenzendorf, M.S. in Engineering, The University of Texas at Austin, May 2007.

Effects of Bridge Deck Submergence on Backwater, Michael V. Konieczki, M.S. in Engineering, The University of Texas at Austin, May 2007.

Hydraulic Analysis of Bridge Rails in Series: Rating Curves and Submergence Effects, Tyler J. McEwen, M.S. in Engineering, The University of Texas at Austin, May 2008.

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1.1 Background

In 1986, the Federal Highway Administration (FHWA) specified in the National Cooperative Highway Research Program Report 350 that all highway bridges on the National Highway System and the Interstate Highway System must use successfully crash tested bridge railing. Texas Department of Transportation (TxDOT) policy requires the use of successfully crash tested bridge rails on all new bridge construction as well as existing bridges scheduled for safety rehabilitation. In general, crash tested bridge rails have greater height and less open space when compared to bridge rails that have failed crash testing. The requirement to use successfully crash tested rails poses a concern with respect to floodplain analysis. In the event that existing bridge rails are upgraded to crash tested rails, the possible additional rail height and decreased open space may adversely impact the surrounding floodplain elevation. Construction or modification of bridge structures in communities that participate in the National Flood Insurance Program must meet regulatory requirements for surrounding floodplains mapped by the Federal Emergency Management Agency (FEMA). Construction of new structures or modification of existing structures, as in the case of safety rehabilitation, may result in an increase of the water surface profile for the one percent annual chance (100-year) flood event. The use of crash tested bridge rails with a greater height and less open space, especially in the safety rehabilitation of bridges, can cause issues with FEMA compliance due to poor hydraulic performance. Therefore, to prevent such setbacks, it is important to understand the hydraulic performance of various bridge rail types in order to determine the impact of different rails on the surrounding floodplains.

1.2 What the Researchers Did

The hydraulic performance of different bridge rails were evaluated through physical model studies. Rating curves, which describe the relationship between the upstream specific energy (depth) and flow rate passing through and over the rail, were measured for each rail type. Six different standard TxDOT rails were tested: T101, T203, T221, T411, T501, and SSTR. The T221, T501, and SSTR are solid rails with a small scupper drain at the bottom but have different cross sectional geometries. The T101 and T203 have more open space. The T411 has an intermediate amount of open space. (The T411 rail also has a crash-test rating TL-2, and NCHRP Report 350 says the rail must have a test rating of TL-3 or greater. All other rails tested do meet this requirement.) In addition, the T101 rail was also tested as if on the downstream side of the bridge, labeled as T101D, due to its nonsymmetrical geometry. A solid weir type rail was tested (weir rail), and a two-tube steel railing used in Wyoming (Wyoming rail) was tested due to its large amount of open space. Testing was also done with selected rails in series, representing rails on both the upstream and downstream sides of a bridge, and the T203 rail was tested at a skew angle orientation to check orientation effects on the model parameters and rail performance. The model rail dimensions are shown in Table 1. In this table h_r is the total rail height, h_{rL} is the height of the open space based within the rail face, b_p is the width of the bridge rail post that is attached to the bridge deck, and F_o is the fraction of open space within the rail face.

Table 1.1: Model Rail Dimensions

Rail Type	h_r (inch)	h_{rL} (inch)	b_p (inch)	F_o (%)
T203	13.75	7.25	30.0	26.4
T101	13.5	7.5	4.5	51.4
T101D	13.5	7.5	4.5	51.4
T501	16.0	1.5	45.25	2.3
SSTR	18.0	1.5	45.5	2.0
T221	16.0	1.5	45.0	2.3
T411	16.0	8.625	35.5	22.0
Wyoming	13.625	5.0 10.75	1.5	72.5
Weir Rail	17.0	0.0	60.0	0.0

Measurements were calibrated to a three-parameter model that allows for the prediction of the hydraulic performance of bridge rail systems over a range of flow conditions. Three different flow regimes were identified based on the height of the upstream specific energy (water surface) at the bridge rail and open-space geometry within the rail face. Type 1 flow corresponds to the lowest flow rates and the rail open space is not submerged. Type 2 flows occur when the upstream water surface submerges the open space and orifice-type flow occurs. Type 3 flows occur when the upstream specific energy (water depth) is greater than the total height of the rail and both orifice-type flow through the rail open space and weir-type flow over the top of the rail occurs. The rating curve model for Type 3 flow is as follows:

$$\frac{q}{\sqrt{g h_r^{3}}} = C_b C_c F_o \sqrt{2\left(\frac{e_u}{h_r} - C_c \frac{h_{rL}}{h_r}\right)} + C_d \left(\frac{2}{3}\right)^{1.5} \left(\frac{e_u}{h_r} - 1\right)^{1.5} \qquad (1)$$

In Equation (1) q is the unit flow rate (ft^3/s per ft of rail length), g is the gravitational constant, C_b and C_c are lateral and vertical contraction coefficients (model parameters), e_u is the upstream specific energy measured from the elevation of the bridge decking surface (approximately equal to the height of the upstream water surface above the bridge decking surface), and C_d is the discharge coefficient for weir-type flow (model parameter). The first term on the right side corresponds to orifice-type flow through the bridge-rail open space (this is the Type 2 flow model) while the second term corresponds to weir-type flow over the top of the bridge rail. C_b, C_c, and C_d are model coefficients that were evaluated through the physical model studies. One of the objectives of this study was to determine how these coefficient values depend on rail geometry characteristics, and thus determine whether one might identify bridge rail geometric characteristics that would result in improved bridge rail hydraulic performance. The most significant variables in characterizing the hydraulic performance of different bridge rail systems are the fraction of open space, F_o, and for low-flow conditions, the width of the bridge rail post, b_p. Thus it is of interest to determine how the individual model coefficients vary with F_o, and based on Equation (1), how the combination $C_bC_cF_o$ varies with F_o.

1.3 What They Found

The hydraulic performance of different bridge rail systems varies widely, primarily as a function of rail height and the amount of open space within the rail face. Figure 1 shows the rating curves for the different bridge rail types on a common scale. A hydraulically efficient bridge rail will allow a larger flow rate at smaller specific energy. Thus, the 'lower' the rating curve, the more hydraulically efficient the rail. Three groups of hydraulic performance can be identified through Figure 1. The solid (T501, SSTR, T221) and weir rails are least hydraulically efficient. Of intermediate efficiency are the T203 and T411 bridge rails. The most efficient rails are the T101 and Wyoming two-tube rails. The resulting model coefficients are listed in Table 2.

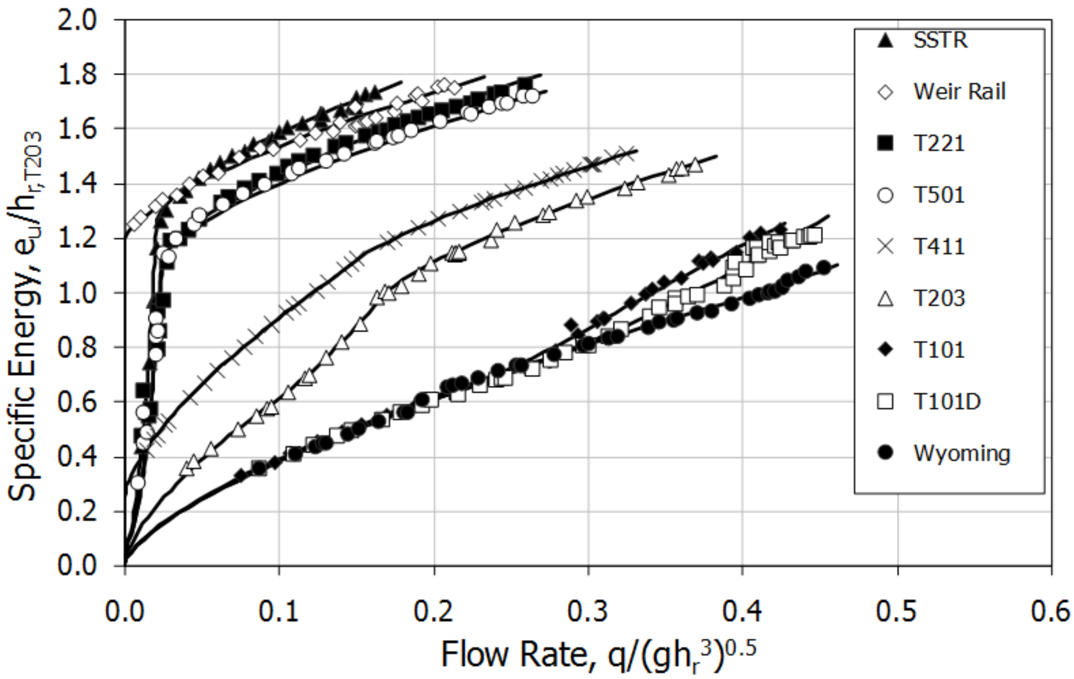

Figure 1.1: Rating curves for different bridge rails tested

Table 1.2: Rating Curve Coefficient Values

Rail Type	C_b	C_c	C_d
T203	0.806	0.718	0.802
T101	0.876	0.658	0.308
T101D	0.889	0.706	0.336
T501	0.891	0.862	1.082
SSTR	0.891	0.892	1.105
T221	0.786	1.0	0.945
T411	1.0	1.0	0.794
Wyoming	0.800	0.786	0.000
Weir Rail	0.000	0.000	1.225

There is no clear relationship between the fraction of open space and the magnitude of the contraction coefficients C_b and C_c. This is shown in Figure 2. A representative value of just over 0.8 appears appropriate, regardless of the bridge rail type (except for the weir rail with zero open space).

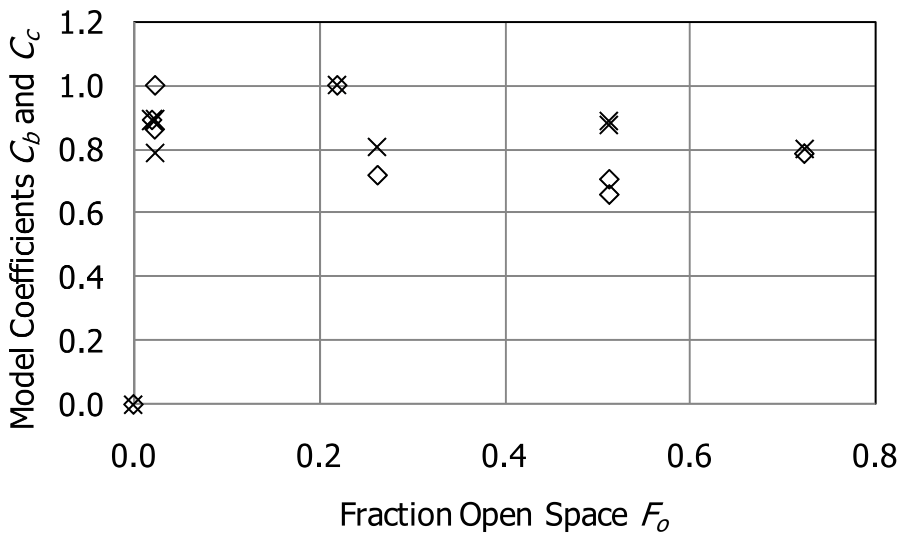

Figure 1.2: Contraction coefficient values C_b (cross) and C_c (diamond) as a function of fraction open space for different bridge rails

The product $C_bC_cF_o$ represents the fraction of effective open space in each rail (F_o is the actual fraction of open space and the coefficients C_b and C_c are lateral and vertical contraction coefficients). As might be inferred from Figure 2, the effective open space fraction is directly correlated with fraction open space, as shown in Figure 3. The linear correlation shown in the figure has slope 0.63, which corresponds to the average value of the orifice contraction coefficient $C_o = C_bC_c$. This value is similar to the theoretical value for a circular orifice: $C_o = \pi/(\pi + 2) = 0.611$. The exceptional behavior (data point significantly above the dashed line) occurs for the T411 rail, for which $C_o = 1.0$ (with $F_o = 0.220$). Such behavior is explained by the rounding of the entrance to open space in the T411 rail, so the tendency for streamline separation is small. From Figure 3 it is concluded that the magnitude of the leading coefficient in the orifice-type flow term in Equation (1) increases directly with fraction of open space.

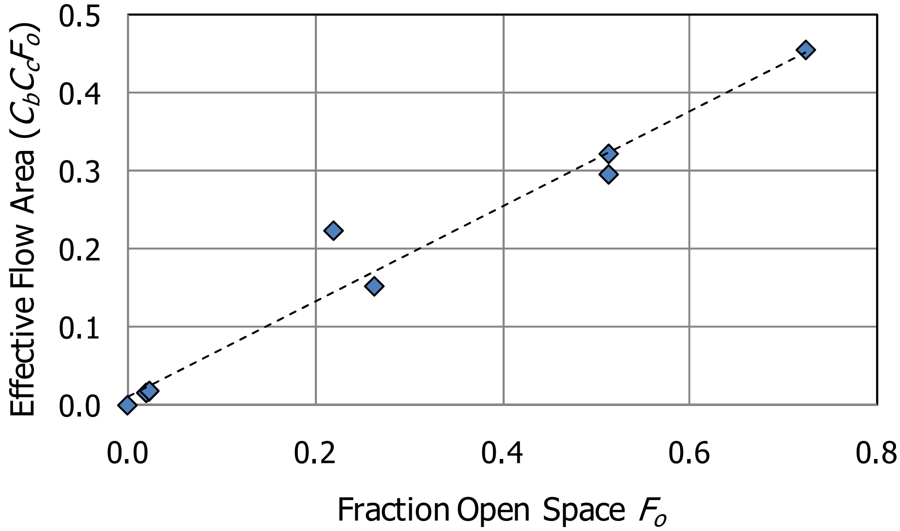

Figure 1.3: Effective flow area as a function of open space for different bridge rails

Corresponding to an increase in orifice-type flow with increasing flow area is a decrease in weir-type flow. This is shown in Figure 4.

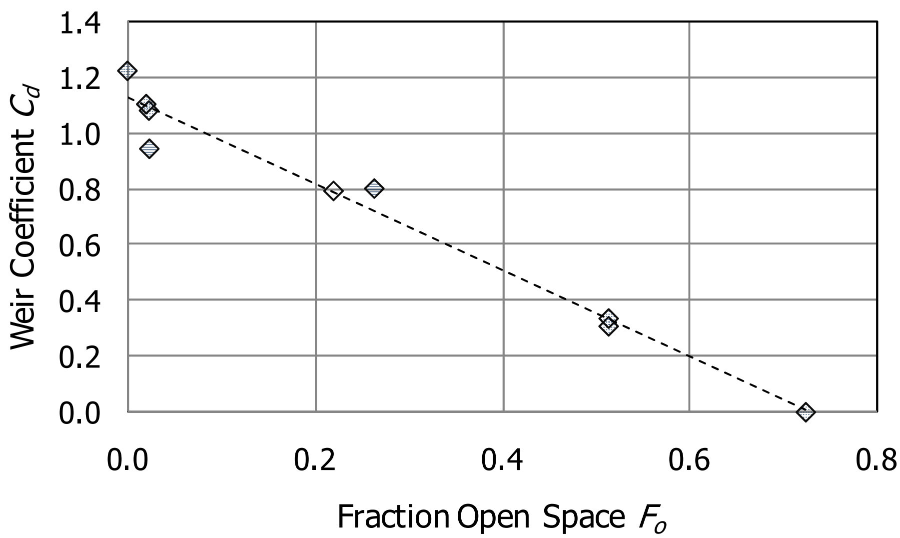

Figure 1.4: Weir-type discharge coefficient C_d as a function of fraction open space

1.4 What This Means

The hydraulic efficiency of different crash-tested bridge rails can be inferred from Figure 1. The T101 and Wyoming rails have the greatest efficiency, as shown by their larger discharge for a given upstream specific energy. The hydraulic efficiency of the T101 and Wyoming bridge rails for small flow rates is associated with the small rail post size and large open space. At larger flow rates the improved efficiency of the Wyoming rail over the T101 rail is associated with its larger effective flow area. Not surprisingly, the features that promote hydraulic efficiency are 1) small rail post size, 2) large fraction of open space in the rail face, and 3) rounding of the bridge structure elements to help control streamline separation.

One of the original objectives of this research program was to assess the feasibility for development of a crash-tested bridge rail with improved hydraulic efficiency, and to propose path forward towards its development. However, the results from this research suggest that the marginal gains from such an effort would be limited. Figure 4 shows that for the Wyoming rail, the effective weir-type flow has been eliminated (C_d = 0). There is no suggestion of improved hydraulic performance by increase the fraction of open space. This rail also has an orifice coefficient corresponding to the theoretical value for a sharp-edged orifice (see Figure 3 and the discussion of this figure). One option for improved hydraulic performance would be to make the tubes of the Wyoming rail more elliptical in cross-section, though it appears that such a change would have limited hydraulic effect, and the structural effects (crash-test response) are unknown.

For greatest hydraulic efficiency, it is recommended that TxDOT consider use of the Wyoming two-tube bridge rail.