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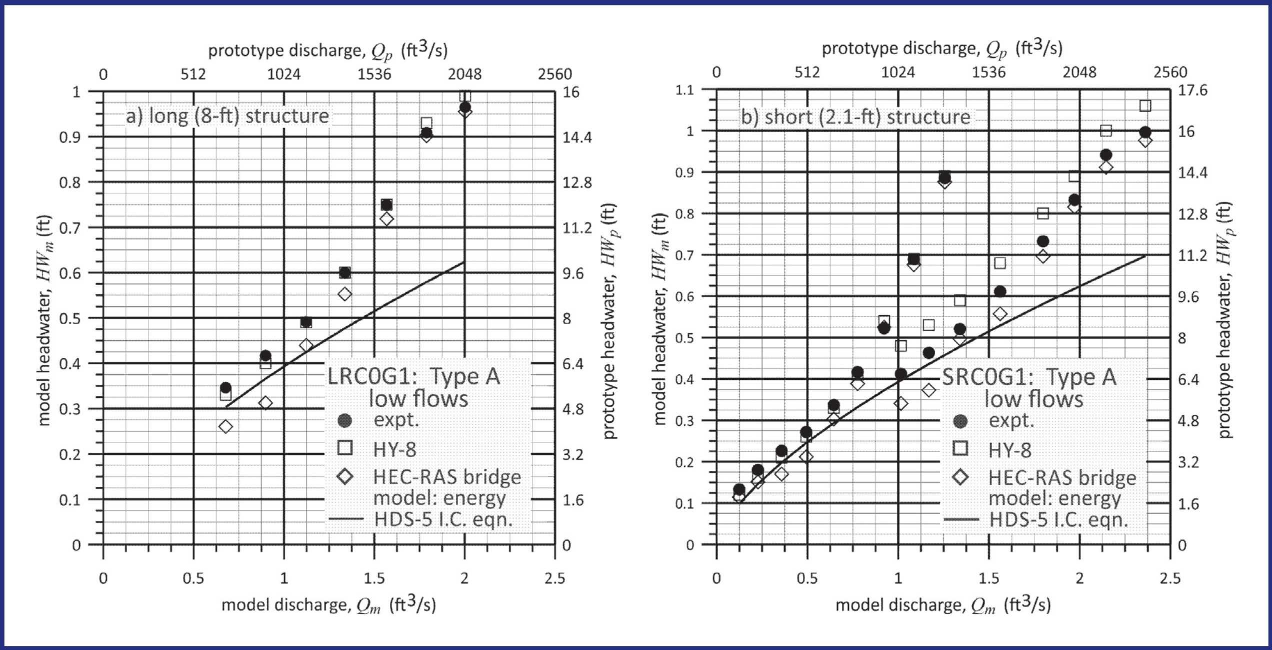
Assessment of HY-8 and HEC-RAS Bridge Models for Large-Span Water-Encapsulating Structures



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16. Abstract
Current INDOT policy requires that culvert-like structures with spans greater than 20 ft be treated for purposes of hydraulic analysis as a bridge, and hence mandates the use of software such as HEC-RAS for predicting the headwater, rather than the culvert-specific software, HY-8. In this context, culvert-like structures are assumed to have a standard inlet geometry (e.g., such as those already modeled in HY-8) and a constant barrel geometry. The present study examines the technical basis of this policy, and whether the policy could be revised to allow the application of simpler culvert-hydraulics analysis and HY-8 to culvert-like structures with spans greater than 20 ft. Laboratory experiments were performed with model box culverts of span 1.5 ft and two streamwise lengths, 2.1 ft and 8 ft, and performance curves describing the variation of headwater with discharge were obtained. The effects of bed roughness, the presence or absence of a cover (if present, the rise was 0.5 ft), and a range of tailwater levels, were investigated. The laboratory observa-tions were compared with predictions by HY-8 and HEC-RAS models, and the model performance assessed. In general, HY-8 predictions were found to be as good as, and in some cases superior to, the HEC-RAS predictions, for both long and short culvert-like structures. This was attributed to the empirical information in HY-8 being more tailored to the specific standardized geometry of culvert-like structures, and the automatic inclusion of roughness effects, whereas HEC-RAS, at least when used with default coefficients and settings, relied on generic coefficients and neglected roughness effects. It was therefore recommended that a change in INDOT policy allowing large-span culvert-like structures to be analyzed using conventional culvert hydraulics would be technically justified for problems where the structure could be considered in isolation and accurate input data are available.

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EXECUTIVE SUMMARY

ASSESSMENT OF HY-8 AND HEC-RAS BRIDGE MODELS FOR LARGE-SPAN WATER-ENCAPSULATING STRUCTURES

Introduction

Current INDOT policy requires that culvert-like structures with spans greater than 20 feet be treated for purposes of hydraulic analysis as a bridge, and hence mandates the use of software such as HEC-RAS for predicting the headwater, rather than the culvert-specific software, HY-8. In this context, culvert-like structures are assumed to have a standard inlet geometry (e.g., such as those already modeled in HY-8) and a constant barrel geometry. As larger-span culverts with spans greater than 20 feet have become more readily available, they may provide a cost-effective alternative to traditional bridges, and the technical basis of the current INDOT policy needs to be re-examined, and more flexibility in allowing conventional culvert hydraulic analysis to be applied to structures with spans larger than 20 feet may be warranted.

The main aim of the present study was a comparative assessment of conventional culvert hydraulics, specifically as implemented in HY-8, and bridge-hydraulics modeling, as implemented in the HEC-RAS bridge models, in applications where the water-encapsulating structure has a large span relative to its streamwise length. Laboratory experiments were performed with model box culverts of span 1.5 feet and two streamwise lengths, 2.1 feet and 8 feet, and performance curves describing the variation of headwater with discharge were obtained. The effects of bed roughness, the presence or absence of a cover (if present, the rise was 0.5 feet), and a range of tailwater levels were investigated. The laboratory observations were compared with predictions by HY-8 and HEC-RAS models, and the model performance was assessed.

Findings

In general, HY-8 predictions were found to be as good as, and in some cases superior to, the HEC-RAS predictions, for both long and short structures. With notable exceptions, the HY-8 predictions also tended to be more conservative in predicting higher headwater values than the HEC-RAS bridge predictions, which exhibited a pronounced tendency to underestimate the headwater.

The generally good performance of the HY-8 model was attributed to the empirical information in HY-8 being more tailored to the specific standardized geometry of culvert-like structures, and the automatic inclusion of roughness effects, whereas HEC-RAS, at least when used with default coefficients and settings, relied on generic coefficients and under certain conditions neglected roughness effects. Discrepancies between HY-8 predictions and observations (for both longer and shorter structures) are not necessarily due solely to inadequacies of culvert modeling as such, but are in part rather due to the specific HY-8 modeling choices, such as the polynomial approximation for the inlet control (I.C.) model, and to the strategy of choosing the higher of the inlet-control and the outlet-control estimates, which does however lead to the already noted more conservative HY-8 predictions.

Despite the good performance of the HY-8 model in predicting the study cases, its limitations should be recognized. It is restricted to culvert-like structures with standard inlet and constant barrel geometries, and making good predictions requires accurate input data. HY-8 models a structure in isolation, and if other nearby structures or stream features affect markedly the water surface elevations, which may become more likely for larger streams for which larger-span culverts come under consideration, then accurate specification of tailwater may become problematic. The more comprehensive HEC-RAS is capable of modeling a more complex stream system, in which the culvert being examined is only one model element among several, adding to the robustness of predictions. Note that in such a case, the culvert-like structure might still be modeled as a culvert, so that the important distinction is not necessarily between culvert and bridge models, but between modeling a structure in isolation or modeling it as part of a system. Similarly, there may be other issues such as those stemming from debris or stream instability, which might arise more frequently for larger streams, for which neither HY-8 nor HEC-RAS bridge models has distinct advantages, but which may receive greater attention within a bridge-hydraulic design context than in the traditional culvert-hydraulic design context. Thus, a preference for HEC-RAS modeling for larger-span larger-stream situations may be based on concerns that are not narrowly hydraulic in nature, but this should be more explicitly acknowledged rather than, as is often done, making dubious claims regarding the limitations of culvert hydraulics.

Based on the results of the study, it was concluded that the culvert-hydraulic analysis of large-span (>20 feet) culvert-like structures can be technically justified where the structure could be considered in isolation and accurate input and other empirical data, such as inlet control coefficients, are available and appropriate. It was therefore recommended that INDOT hydraulic design policy adopt a more flexible stance, allowing large-span culvert-like structures to be analyzed using conventional culvert hydraulic models, such as HY-8. No limit on span was determined in the study, but it was suggested that prudence dictate an initial phase during which the largest span permitted to be analyzed by HY-8 be limited to, for example, 36 feet. If practical experience in this initial phase did not reveal any serious unintended shortcomings, then the permissible largest span could be increased further if this was deemed desirable.

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1. INTRODUCTION, PROBLEM STATEMENT, APPROACH, AND SCOPE

Culverts and bridges are both water-encapsulating structures, and share some basic similarities. Traditionally, culverts have been viewed as a small-stream (ditches) solution, while bridges are associated with larger crossings, and therefore of larger scale. This makes understandable the current INDOT policy (INDOT, 2013; Sec. 203-3, to be referred to as INDOT2013-203) regarding the hydraulic design of both types of structures which requires that any structure with span larger than 20 ft be treated from a hydraulic analysis point of view as a bridge, and to be analyzed using the HEC-RAS software. The technical basis for this policy is however somewhat obscure. The most recent edition of the standard FHWA culvert manual (Schall Thompson, Zerges, Kilgore, & Morris, 2012; to be referred to as HDS-5-2012) notes that "culverts exceeding a 20 ft (6.1 m) span width (either as a single barrel or the total width of a multiple barrel crossing) are considered bridges in the National Bridge Inspection Standards (NBIS) and therefore subject to routine inspection according to NBIS requirements." Thus, the somewhat arbitrary value of 20 ft may have originated at least in part from an administrative or regulatory rather than a purely technical hydraulic distinction.

Nevertheless, HDS-5-2012 ultimately recommends that "large culverts with free surface flow through the structure (i.e., no headwater) are typically better analyzed based on the gradually varied open channel flow concepts used in bridge analysis than the calculation procedures detailed in this publication." and that "Based on NBIS regulations, as well as hydraulic issues, a reasonable guideline is to use bridge based modeling for a single culvert with a span of 20 ft (6.1 m) or more, given that such structures will typically operate with free surface flow." It should be pointed out that the original HDS-5 (Normann, Houghtalen, & Johnson, 1985; to be referred to as HDS-5-1985) did *not* give any specific recommendation regarding a maximum span appropriate for a culvert hydraulic analysis.

The practice in different U.S. states is not uniform. In the New York Highway Design Manual (NYSDOT, 2011), "It is recommended that for culverts with spans over 3.65 m (12 ft) a HEC-RAS analysis or an equally sophisticated backwater analysis be used to determine the size and shape of the culvert. For smaller culverts, an approximate analysis such as HY8 may be used with the criteria outlined in Chapter 8 of this manual." Other states do not base the bridge-culvert distinction solely on span size, but may include other criteria. The South Dakota Dept. of Transportation (SDDOT, 2013) Drainage Manual Chapter 14 states that "Any structure designed hydraulically to operate in free surface flow at the design event is treated as a bridge in this Chapter, regardless of actual length." Similarly, the Kentucky Dept. of Transportation (KYTC, 2010) Drainage Manual, Section D605-13 states that "for large structures with small length to width ratios, culvert analysis procedures become inaccurate. For these situations, a more appropriate analysis can be conducted using water surface profile calculations commonly used in bridge design. Generally speaking large culverts with spans over 20 ft or culverts that have drainage areas in excess of one square mile will be analyzed with water surface profile analyses."

A typical culvert may be distinguished from a bridge through several characteristics that may have implications for the hydraulic analysis:

- standardized inlet geometry,
- a comparatively larger streamwise length relative to some opening dimension such as the span or rise (due to a preference for earthen embankment cover),
- a uniform barrel geometry all along the length of the barrel, and
- an absence of piers (or similar structures) at least for single-barrel culverts.

In the following, the term "culvert-like structures" is applied to water-encapsulating structures with the above characteristics, except possibly for the feature of large streamwise length. While culverts are most commonly available with spans of less than 20 ft, current culvert technology allows spans exceeding 50 ft. Non-hydraulic issues, such as structural or geotechnical, were already discussed in the NCHRP report 473 (McGrath et al., 2002). Particularly with the interest in three-sided or bottomless culverts, and in larger culverts for aquatic organism passage, larger-span culverts are likely to gain in appeal as a cost-effective alternative to bridges.

Although culverts are more often than bridges designed to operate with their barrels partially or wholly full at design flow, this does not imply that the conventional hydraulic analysis of culvert does not consider or model inaccurately free-surface flow due solely to the effect of a large span. Despite the statements in HDS-5-2012 and in the KYDOT (2010) Drainage manual, the conventional hydraulic analysis of culverts as described in either HDS-5-2012 or HDS-5-1985 is in part based on gradually varied open channel flow concepts, and in some respects involves an even more detailed free-surface hydraulic analysis than is performed in current "routine" bridge hydraulic analysis. The question may then be raised whether there is a sound technical basis for the recommended limit on the culvert span for a culvert hydraulic analysis to be reliable. This project addresses this question by a laboratory study complemented by model computations using standard software. Laboratory flows in culvert-like structures are modeled as a culvert and separately as a bridge, and the degree of agreement between experimental observations and model predictions was taken to indicate the applicability of the different models.

The experiments were performed in a relatively large channel ($\approx$3.6 ft wide) with a model rectangular (box) culvert of span 1.5 ft. Of the differences between bridge and culvert structures, of primary concern was the effect of streamwise length. A central concept in the traditional hydraulic analysis of culverts is the distinction between inlet and outlet control. For a short (in the streamwise direction) structure, as is usually the case for a bridge, the distinction becomes less meaningful, and hence does not arise explicitly in discussions of bridge hydraulics, e.g., in the recent FHWA HDS-7 (Zevenbergen, Arneson, Hunt, & Miller, 2012). The experimental study therefore investigated both a "short" and a "long" structure, essentially with the same geometry but differing in the relative streamwise length.

The types of flows were varied from those where the flow was everywhere subcritical to those where the flow was critical within the structure, from those where neither inlet nor outlet was submerged, i.e., free-surface flow throughout, to the case where only the inlet was submerged, and the case where both inlet and outlet were submerged. Also as large-span structures often have a natural bed with larger flow resistance, the effect of flow resistance was studied through experiments with a relatively smooth bed to a bed with significant though artificial roughness. The observations were compared with the predictions of the standard culvert analysis software (HY-8) and the standard bridge-hydraulics software (HEC-RAS) for the model-scale flow configuration. If extraneous scale effects are assumed negligible, this comparison should provide some indication as to the extent that a culvert or a bridge model is more appropriate or possibly equally appropriate.

The theoretical bases of the standard bridge model, specifically those implemented in the HEC-RAS bridge modeling software, and the standard culvert model, as implemented in the HY-8 software, are compared in Chapter 2. Details regarding the experimental study, including the equipment, experimental design, and procedure are given in Chapter 3. The experimental results mainly in the form of culvert performance curves are then compared with predictions of HY-8 and HEC-RAS bridge models in Chapter 4, while study conclusions are summarized in Chapter 5.

2. COMPUTER MODELS (HY-8 AND HEC-RAS)

2.1 HEC-RAS Bridge Modeling Approach for Application to Culvert-Like Structures

The recent FHWA HDS-7 manual (Zevenbergen et al., 2012) provides a comprehensive overview of the hydraulic design of bridges in the U.S. Its discussion of traditional one-dimensional steady-flow approach focused on the use of the HEC-RAS model, which includes a bridge modeling component. Current practice at INDOT (INDOT2013-203, and by extension, in Indiana) as well as in other states is now based almost exclusively on the use of HEC-RAS, and this study will be restricted to this approach to bridge modeling.

Beyond the actual HEC-RAS bridge model, the HEC-RAS classification of bridge flows provides a convenient framework for organizing the work of the current study. The analysis of bridge hydraulics in HEC-RAS distinguishes between two types of flows based on whether the water surface reaches the bridge low chord (high flow) or is everywhere under the bridge an open channel flow (low flow). The low-flow definition is especially relevant in the present context, because as was seen in Chapter 1, a bridge is sometimes implicitly or explicitly distinguished from a culvert in operating at low flows as defined here under design conditions. A schematic is shown in Figure 2.1. For low-flow problems, various models may be chosen (energy, momentum, Yarnell, and WSPRO, with the energy only model being the default), while for high-flow problems, two approaches (energy only and pressure + weir flow, with the energy only being the default) are available. The actual HEC-RAS bridge modeling approach menu is shown in Figure 2.2. The default options shown selected in Figure 2.2 will be important in this study in that the results using these options will be reported in Chapter 4 in comparison with experimental observations.

Guidance for the choice of models is framed in terms of different flow types. For low flows, three types are distinguished:

i. type A, where the flow is subcritical everywhere (upstream of, within, and downstream of the structure),
ii. type B, where the flow becomes critical within the structure, so that the flow is subcritical upstream of the structure, but supercritical downstream, and
iii. type C, where the flow is supercritical everywhere (which will not be considered in the present work as it is considered unusual in the Indiana context).

The flow type is determined in HEC-RAS by a "momentum" comparison of the specific force at critical depth within the structure with an "effective" specific force at the downstream (respectively upstream) section for a subcritical (respectively, supercritical) profile. Except for a type B flow, the default energy only model would seem the most generally applicable for the present case where piers play no role. It also is the simplest as it does not require any additional input data. The momentum model is also recommended as generally applicable, though Brunner (2016; to be referred to hereafter as the HEC-RAS manual) points out that the approximation of the weight force assuming an average bed slope might be questionable for natural cross-sections. For the laboratory model, this should not be of concern. For all of the HEC-RAS bridge-model simulations in this study, the default energy only method for low flows was specified.

HEC-RAS treats type B flows somewhat differently in detail in that an approximate momentum model is *automatically* used to compute a subcritical upstream flow and a supercritical downstream flow. If this momentum model "fails to converge on an answer," then HEC-RAS will automatically switch to an energy model. As will be noted in Chapter 4.3, at least for certain examples, HEC-RAS does report unphysical momentum-based results where energy increases in the downstream direction, even when the default energy method is specified. For type B flows, a mixed-flow regime should be chosen so that both subcritical and

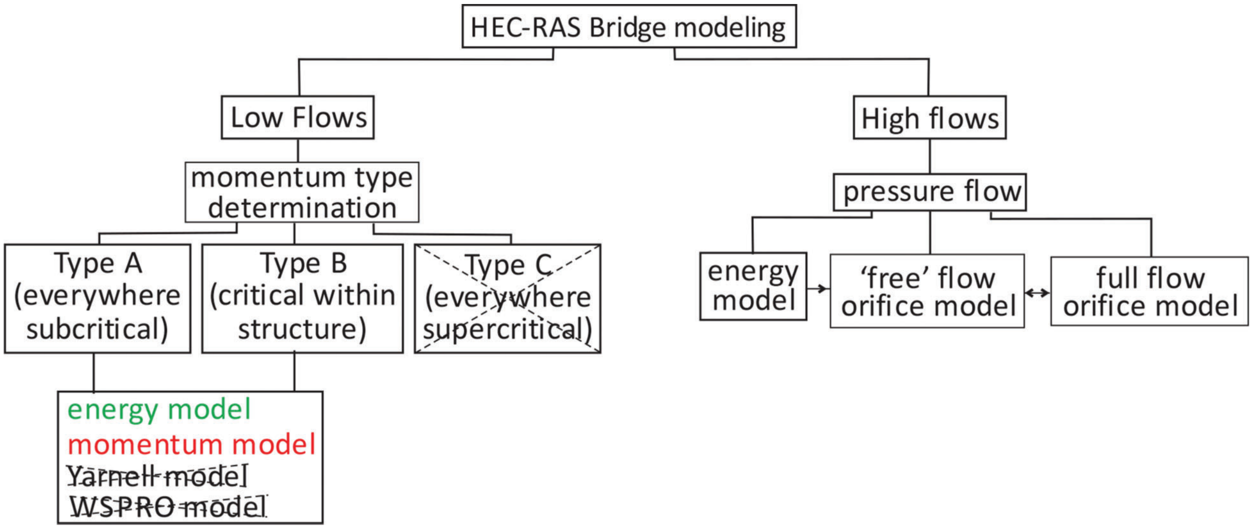


Figure 2.1 Schematic of HEC-RAS bridge modeling approach (the present study did not consider the flows and models that are crossed out).

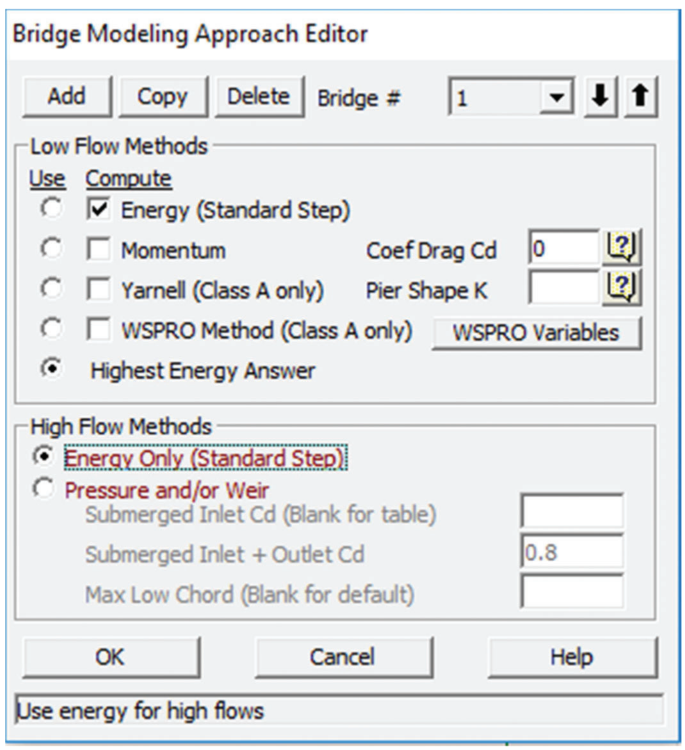


Figure 2.2 HEC-RAS menu for bridge modeling approach with default options selected.

supercritical flow in different flow reaches can be accommodated.

For dealing with high flows, HEC-RAS provides two approaches (see Figure 2.2), an indirect energy model and a more direct pressure-flow/weir model. The default energy approach treats the flow as entirely open channel, despite the free surface reaching the bridge low chord, by essentially determining the hydraulic grade line for that portion of the structure that flows full. The pressure-flow and/or weir model refers to the use of a gate or orifice (free-flow or full-flow) model, and for an overtopping flow, a weir model. The equations of the gated free-flow model involve only the sections immediately upstream (and possibly downstream) of the structure, and so do not include any effects within the structure (so essentially an inlet-control solution). The choice of model is left entirely to the user, and there is no option to choose the higher energy solution as there is in the low-flow solution. The guidance given recommends the pressure-flow/weir model if the inlet but not the outlet is substantially submerged, including possibly overtopping the structure, and the energy approach otherwise. The pressure-flow model does automatically switch to an energy solution if the latter gives a higher headwater. A full-flow orifice model is also automatically invoked if both inlet and outlet are submerged. The present study will not consider the problem of overtopping, but could cover a range of flows where the guidance would lead to the use of both models.

An aspect of HEC-RAS modeling of bridges that differs from HY-8 and that may be relevant in any difference in results when applied to culverts is the consideration of only two sections within the structure, one near the inlet and the other near the outlet. An energy (or momentum) equation applied within the structure uses only these sections independent of the streamwise length of the structure. The HEC-RAS practice of placing sections just upstream and just downstream of the structure implies that the energy and momentum balances between the structure and the sections may depend somewhat on another HEC-RAS practice, namely the definition of ineffective flow areas.

2.2 HY-8 Culvert Model

The standard software tool, HY-8, implements the conventional culvert analysis procedure outlined in HDS-5-2012 (or its earlier editions), though with specific choices. Because there are various versions of both HY-8 and HDS-5, it should be specified that the following is based on the documentation for HY-8 v. 7.3 and HDS-5-2012. For the present purposes, these should differ very little if at all from earlier versions.

The concept of hydraulic control plays a central role in culvert analysis. The location of control, which for the present purposes will be either at the inlet or at the outlet, may be considered where the bottleneck restricting the flow occurs. If there is inlet (respectively outlet) control, then small changes in the flow (or culvert) characteristics at the outlet (respectively, inlet) will have no effect on the headwater. The FHWA HDS-5 scheme generally makes two estimates of headwater, one assuming inlet control, and another assuming outlet control, and the higher estimate is taken to reflect the location of control and hence the actual (true) headwater. As the HEC-RAS manual points out, this is not necessarily true, but should give a conservative final headwater estimate. A practical distinction should be made between the original inlet-control equations of HDS-5 (and given later in Chapter 4), and the equations as implemented in HY-8, which are best-fit fifth-order polynomial models to these equations. If the flow within the structure is entirely or partially free surface, the outlet control estimate is obtained through a direct-step computation of water surface starting from a known or estimated water surface elevation (or total head) at the outlet to where the water surface reaches the culvert crown or to the inlet otherwise. This outlet-control estimate does model gradually varied free-surface flow within the culvert barrel, and is arguably more accurate than the analogous HEC-RAS computation that is based on only two sections, despite the statements to the contrary in HDS-5-2012 and the KYDOT 2010 Drainage manual. An inaccuracy can however arise if the conservative strategy of taking the higher headwater estimate as correct is in fact incorrect.

The concept of hydraulic control could also be applied to the bridge hydraulics, but as noted before discussions of bridge modeling rarely make use of the concept. This is presumably due to the relatively short streamwise extent of bridges compared to culverts, so that the distinction between inlet and outlet, and hence the distinction between inlet and outlet control become irrelevant. It may be noted however that, in the HEC-RAS manual, the term, “controlling section,” is repeatedly used in the discussion of determining the low-flow type.

2.3 Differences Between the HEC-RAS Bridge Model Applied to Culvert-Like Structures and the HY-8 Culvert Model

For the present work, a culvert-like structure is being assumed to the extent that it is prismatic (the geometry does not change within the structure) and its slope is constant (or at least piece-wise constant, as in broken-back culverts). It is also assumed that the inlet and barrel geometry are either standard or correspond closely to a standard inlet geometry. Here, the differences in the treatment of such a structure by the HEC-RAS bridge model and by HY-8 are examined. The HEC-RAS bridge model does offer some flexibility in choosing coefficients and settings, but in the following, unless otherwise specified, it is assumed that default coefficients and settings are used when referring to the HEC-RAS bridge model.

2.3.1 Inlet Control

Due to the geometry of a bridge inlet section being generally non-standard and possibly at least in part rather irregular, the HEC-RAS modeling of inlet control flows, such as Type B low flows, must rely on energy balances with generic inlet loss coefficients (low flows) or discharge coefficients (high flows). In contrast, if the structure inlet is standard, then the inlet control equations of HY-8 may be viewed as incorporating coefficients that are more tailored to the individual standard geometry. This may be particularly relevant when common inlet features such as wingwalls may affect the flow. Differences between a HEC-RAS bridge and a HY-8 culvert model of such a structure may be expected when the flow is inlet-controlled, with larger differences occurring when the implicit “tailored” coefficients of HY-8 differ significantly from the generic (default) and often constant coefficients of the HEC-RAS bridge model that may need to be inputted before a simulation.

2.3.2 Outlet Control

At least three effects may contribute to differences between HEC-RAS and HY-8 headwater predictions applied to culvert-type structures under outlet-controlled conditions. The first effect arises when the flow becomes critical at (or near) the outlet section. If the inlet and the outlet geometries of a structure are exactly the same as assumed here, then if critical flow is found to occur *within* the structure, then the default HEC-RAS bridge model automatically assumes that it occurs at the inlet section. There is an option to set *beforehand* the critical section if found at the outlet for all Type B flows, but unlike HY8, HEC-RAS does not determine from hydraulic conditions the location of control. The second effect arises because the HEC-RAS bridge model uses only two sections to evaluate the friction loss within the structure, while HY-8 evaluates this loss using a generally more accurate direct-step computation that however assumes a prismatic (constant) barrel geometry. A third effect lies, as in the inlet-control cases, in the use of generic coefficients. For example, in the case where both inlet and outlet are submerged, the HEC-RAS bridge model uses an orifice (full-flow) equation where a discharge coefficient must be specified beforehand and which does not model frictional losses within the culvert barrel. For a sufficiently short structure, whether the control is located at the inlet or outlet is likely irrelevant from a practical point of view, and so such an assumption should not affect much the headwater prediction. Differences between the two models would be expected to increase for longer and "rougher" structures where the water surface elevations change substantially within the structure. For such a case, the HY-8 would evaluate a more appropriate effective flow-dependent discharge coefficient. The HY-8 computation is limited not due to the free-surface nature of the flow through the barrel, but by the assumption that the barrel geometry does not change.

2.3.3 Other Comments

Culvert hydraulics is complicated in involving numerous scenarios, and it may not be possible to formulate simple but generally valid rules for the conditions under which the predictions of HY-8 and HEC-RAS will differ significantly. HY-8 emphasizes the distinction between inlet and outlet control and the HEC-RAS bridge model does not. In many cases, the HY-8 estimates for inlet and outlet control differ only slightly, but even in such cases, the final HY-8 and the HEC-RAS bridge model predictions may still differ. When water surface (or hydraulic grade) slopes within and outside the structure are not large, then significant differences between the two modeling approaches would be expected to be least likely. Thus, results for Type A low flows, where the flow is everywhere decidedly subcritical, are less likely to show large differences than a Type B low flow, where the flow becomes critical within the structure. A Type B low flow by itself however does not necessarily ensure a large difference. The HY-8 approach is more detailed and more tailored to a standard geometry, and so might be expected to be more reliable. Its assumption that the higher energy solution controls is however not necessarily correct, though should be conservative. HY-8 does also neglect velocity heads in the upstream and downstream channels, which might lead to differences in headwater predictions, but in typical design situations, these differences are expected to be small, often yielding again conservative estimates.

The distinction between inlet and outlet control for culverts is not accounted for in the HEC-RAS bridge model, but this may not be relevant for "short" structures. This raises the question as to what constitutes a short structure. If the inlet flow directly affects the flow at the outlet, then this condition would provide a working definition of a short structure. This can be interpreted as the inlet flow not being fully expanded before the outlet is reached, and therefore the length of a short structure might be expressed in terms of a small multiple of the critical depth or the culvert rise or the culvert span. Even for such short structures, differences may still be found in the predictions of HY-8 and the HEC-RAS bridge model if default generic coefficients are used in the latter rather than the coefficients tailored to standard geometries in the former. On the other hand, for such short structures, differences may be minimal for certain types of flows, e.g., Type A low flows.

There may also be flow features in short structures that are not modeled well or at all by *either* HY-8 or HEC-RAS. If the inlet flow strongly influences the outlet flow because the flow has not yet fully expanded at the outlet, then the flow within the structure should be considered as rapidly varied, and neither HY-8 nor HEC-RAS, both of which assume gradually varied flow in their computation, is capable of dealing directly with rapidly varying flows. In such models, these features are typically handled by rating curves (e.g., the inlet control equations in HY-8 or the gated-flow model in HEC-RAS, to be specified in Chapter 4.2), involving empirical coefficients, which are more tailored in HY-8 and more generic in HEC-RAS.

In this work, HY-8 and conventional culvert hydraulics will be for the most part used interchangeably. It should however be kept in mind that HY-8 is only one specific model, which makes some specific choices, and other culvert hydraulics models could make other choices that might require more effort but could also result in better headwater predictions. An example of such a choice is the use of polynomial model for inlet-control conditions, which makes for practical convenience and conservative estimates, but may not always give the closest agreement with observations.

2.4 Summary

The elements of the conventional culvert hydraulics model, especially but not solely as implemented in the

HY-8 software, and the bridge hydraulics model, as implemented in HEC-RAS, have been presented. The similarities and the differences between the two types of models have been highlighted, and it has been argued that, while for general problems with non-standard irregular geometries HEC-RAS does possess advantages, for problems with culvert-like geometries (standard inlet and constant barrel geometry), culvert hydraulics and HY-8 can provide simpler solutions that may be equally reliable for headwater prediction as HEC-RAS.

3. EXPERIMENTAL CONSIDERATIONS

3.1 Scaling and Similitude

While the aim of the study was not to simulate a specific structure in the field, it is helpful to consider the scaling of the laboratory model with respect to what might be expected in the field. Because the hydraulic problem mainly concerns the prediction of the headwater, *HW*, which involves the free surface, it is argued that the appropriate scaling is the Froude model law. Thus, the Froude number, *Fr*, should be the same in the model and the prototype, or

$$Fr_m = Fr_p,\ \text{i.e.,} \frac{V_m}{\sqrt{gL_m}} = \frac{V_p}{\sqrt{gL_p}} \qquad (3.1)$$

where V denotes a velocity scale, L a length scale, g the acceleration due to gravity, and the subscripts, m and p, refer to model and prototype quantities respectively. This leads to a relationship between the velocity-scale ratio, $V_r = V_p/V_m$, and the length-scale ratio, $L_r = L_p/L_m$, that must be satisfied for dynamic similitude, namely,

$$V_r = \frac{V_p}{V_m} = \sqrt{\frac{L_p}{L_m}} = \sqrt{L_r} \qquad (3.2)$$

As an example, if L_r is chosen as 16 (the laboratory model has a geometry that is 1/16 in scale of the field dimensions), then $V_r = \sqrt{16} = 4$, so that to ensure the same *Fr* in both model and prototype, velocities in the model should be 1/4 of the field velocities.

In the same manner, the appropriate discharge-scale ratio can be found as

$$Q_r = \frac{Q_p}{Q_m} = \frac{V_p A_p}{V_m A_m} = \frac{V_p L_p^2}{V_m L_m^2} = \sqrt{\frac{L_p}{L_m}} \frac{L_p^2}{L_m^2} = \left(\frac{L_p}{L_m}\right)^{5/2} \qquad (3.3)$$

so that a choice of $L_r = 16$ corresponds to $Q_r = 16^{5/2} = 1024$, i.e., a flow of 1 cfs in the laboratory corresponds to a flow of 1024 cfs in the field. Similarly, if a Manning's flow-resistance model is suitable, then a Manning's n scale ratio can also be determined as

$$n_r = \frac{n_p}{n_m} = \frac{\left(R_h^{2/3} S_f^{1/2}/V\right)_p}{\left(R_h^{2/3} S_f^{1/2}/V\right)_m} = L_r^{2/3}(1)^{1/2} L_r^{-1/2} = L_r^{1/6} \qquad (3.4)$$

For $L_r = 16$, the Manning's n in the field would be $16^{1/6} \approx 1.6$ times that in the laboratory.

The above scaling relationships may be illustrated by obtaining culvert performance curves (using e.g., HY-8) at the model scale and at the prototype scale, and then relating the two curves via scaling relationships. The results of two HY-8 simulations, at the prototype scale (box culvert with span, 24 ft; rise, 8 ft; slope, 0.0004; and Manning's n, 0.018) and at the model scale (span, 1.5 ft; rise, 0.5 ft; slope, 0.0004; and Manning's n of 0.011), are shown in Figure 3.1, assuming uniform flow in rectangular tailwater channel of width (58 ft prototype, 3.6 ft model), over a range of discharges from 0 to 3072 cfs (prototype) or 0 to 3 cfs (model). The scale ratio is $L_r = 16$. These values correspond to "target" values for the experimental study (see following section). By making use of the above scaling relationships, the results for the model scale are seen to agree with the results of the prototype scale. It is notable that over the range of discharges the HY-8 results at both scales switched from being outlet-controlled and open-channel flow throughout at low discharges to inlet-controlled and full flow at high discharges. Thus, the scaling relationships apply despite qualitative changes in the type of culvert flow. The above does not necessarily imply that the results of the laboratory experiments will scale in exactly the same manner, but, if performed at sufficiently large scale so that scale effects are secondary or negligible, it would be expected that the scaling also applies to the experiments.

3.2 Experimental Issues, Design, and Equipment

3.2.1 Design and Specification of Laboratory Channel

The scale of a laboratory model is generally chosen to be the largest that is practically feasible, i.e., within the constraints imposed by space and cost, so as to alleviate concerns about scale effects. Particularly for a study of culvert-bridge models, which presumably focuses on large-span structures (with spans greater than 20 ft), it was desired to perform the experiments at a larger scale than what was available at the beginning of the project (a channel of total width 1.33 ft). A larger scale channel however requires larger components (such as pipes, pump, and flow meter) that are more expensive and increase the ultimate cost of the system.

A sketch of the laboratory channel with the "long" culvert-like structure is given in Figure 3.2. A total channel width 3.6 ft was decided on as a practical compromise. This could readily accommodate a target model span of 1.5 ft, with a reasonably realistic contraction (in width) ratio of 2.4. Though other length-scale ratios could have been chosen, the design of the laboratory channel used a ratio of $L_r = 16$ as a general guideline. For $L_r = 16$, the corresponding prototype dimensions would be a channel width of ≈ 58 ft and a structure span of 24 ft, which would be in the range that according to current INDOT policy would be modeled as a bridge rather than as a culvert. For comparison, in the laboratory experiments of French (1966), on which were based the original box culvert coefficients and

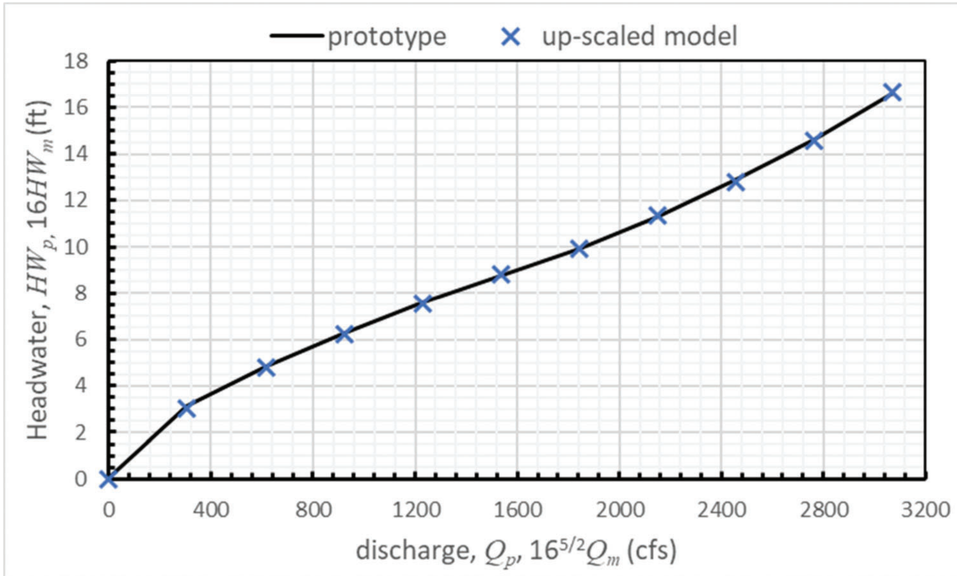


Figure 3.1 Computational results using HY-8 for the culvert performance curve at the prototype scale (full line) and at the model scale (crosses), with a scaling ratio of L_r=16.

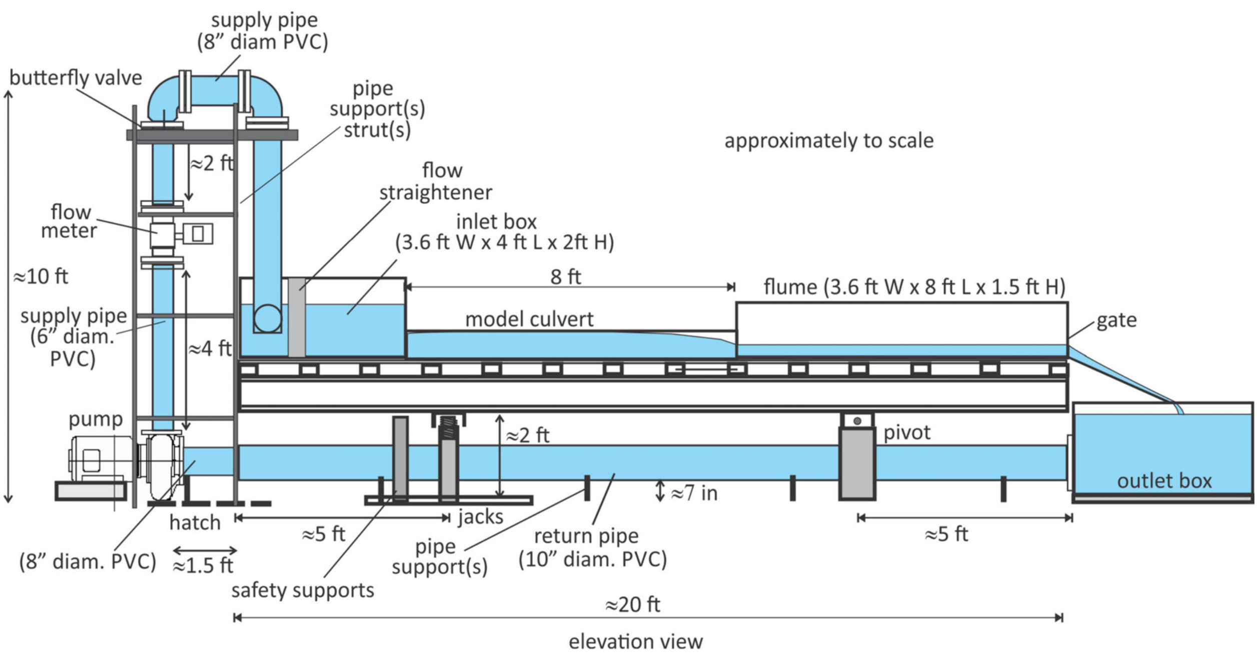


Figure 3.2 Sketch of laboratory channel (with the "long" structure): elevation view.

exponents in HDS-5-1985, the largest span was 1 ft, in a 12-ft wide channel, while in the more recent study of Jones, Kerenyi, and Stein (2007) on inlet geometry effects on box culverts, the largest span was 2 ft, in an 8-ft wide channel.

The channel was constructed on a platform consisting of a pair of 20-ft-long W10 × 30 wide-flange I-beams, supported by a downstream pivot point, and a pair of worm gear machine screw jacks, each rated for 2-ton capacity. The pivot + jack system allows the channel to be tilted so that a streamwise slope can be simulated. Although the jacking system is in place, it is not fully operational due to concerns that, without any external constraints, the load would not travel in a vertical plane, resulting in undue stresses on the jacks. An external stabilizer was originally designed to align the travel, but due to time constraints and a greater priority placed on low-slope applications, has not yet been implemented.

With the base of length 20 ft, it was decided to have the channel of approximately the same total length. For the study of the "long" structure, this was divided into an 8-ft-long downstream channel, an 8-ft-long culvert section, and an ≈3.5-ft-long upstream channel/reservoir. With a rise of $D=0.5$ ft, this implied a length to rise ratio of 16, which was considered reasonable. For comparison, the basic study of French (1966) had a rise up to 1 ft and length of 46.5 ft, while Jones et al. (2006) had a rise of 0.5 ft with a culvert length of 10.2 ft. For a scale ratio of $L_r=16$, the long structure would correspond to a 128-ft-long downstream channel and culvert section, and a 64-ft-long upstream reach. The upstream reservoir also contains the possibly submerged supply pipe as well as a short flow straightening section consisting of stacked 10-in long 1.25-in diameter thin-walled pipes, such that the distance from the end of the flow-straightening pipes to the culvert entrance is $\approx$1.3 ft. An additional outlet box also acts as a reservoir of volume of $\approx$500 gal to maintain an appropriate supply to the pump. A fast-drain facility was incorporated into the outlet box to allow increasing the total volume of water in the system that may be necessary at high discharges. The T-slot framing system used for the channel also served as linear railings, along which carriages with measurement equipment could be conveniently positioned. A vertical tailgate could be used to control the downstream flow, allowing the tailwater elevation to be varied.

Except for the sides of the culvert, which were made of transparent clear polycarbonate to allow viewing of the culvert flow, the channel (including base and sides) was fabricated of 3/4-in thick opaque high-density polyethylene (HDPE), commercially known as Seaboard. This material was chosen because its moisture absorption is very low, and so unlike plywood it does not delaminate or rot or warp under prolonged exposure to water. Somewhat more costly than marine plywood, but less costly than clear polycarbonate, it can be worked in much the way as wood except that special measures and sealants were necessary at all joints to prevent leaks. The Seaboard surface is not as smooth as Plexiglas, but rather has a slight roughness. A discussion of the value of the Manning coefficient, i.e., the Manning's *n,* for this surface is given in Appendix A, where an estimate, $n=0.011$, was obtained for the Seaboard surface. For some experiments, roughness was added artificially by placing on the channel bed an aluminum open-celled expanded metal grate-like sheet (see Figure A.3), with a total thickness of 0.3-in. The Manning's n with the roughened bed was found to vary with depth, but an intermediate value of $n=0.018$ was used in modeling the flows with the roughness in place. These estimates of n have substantial uncertainty, perhaps as much as 15%, associated with them, being based on a limited number of data points and small differences in water surface elevation.

3.2.2 Flow System Components

Based on preliminary estimates from HY-8 modeling of the laboratory model with a channel width of 3.6 ft and culvert span of 1.5 ft, it was decided that a range of laboratory discharges of 0 to 3 cfs would be adequate for the purposes of the study. If $L_r=16$ is assumed, then this would imply a discharge-scale ratio of $Q_r = L_r^{5/2} = 16^{5/2} = 1024$, so that the discharge range in the field would be 0 to $\approx$3000 cfs. Although the upper limit of 3000 cfs may be uncommon for typical culvert applications, sites with estimated bankfull widths of $\approx$60 ft and 50-year discharges in excess of 3000 cfs can be found in Indiana. Whether such sites would be suitable for large-culvert applications may be debated, but that such sites do exist does motivate the range of flows to be studied.

A practical constraint on the choice of pump was that the power draw at design flow was required be less than 20 hp in order for avoid costly electrical upgrades. A pump (PACO 60951LC) rated at 1500 gpm (3.34 cfs) at a head of 36.4 ft with a required power of 19.5 hp was ultimately selected. This pump had an 8-in inlet diameter and a 6-in outlet diameter, and so a combination of 8-in and 10-in diameter piping was used in the inlet piping, and a combination of 6-in and 8-in diameter piping was used in the outlet piping. From experience in operating the flow system, it is believed that the maximum discharge in the channel could exceed 1800 gpm ($\approx$4 cfs), but other factors such as the total storage volume might place a limit on achievable discharge. To control the discharge, the pump was paired with a programmable variable frequency drive (Baldor ACB530-U1-075A), by means of which the pump frequency and hence its discharge could be varied precisely.

Due to the mainly vertical pipe layout and also to pipe sizing, it was observed that the pump performance needed to be described by two curves. With the valve fully open, from startup, the pump discharge at low flow rates ($<$900 rpm pump frequency which resulted in a flow $\approx$750 gpm or $\approx$1.6 cfs), the outlet pipe system was not flowing full. The pump was therefore simply lifting the water in the vertical pipe to an elevation from which it flowed into the channel due to gravity. When the pipe does flow full, discharges could increase quite dramatically for small changes in pump frequency, with flow rates exceeding 1000 gpm (2.2 cfs) at pump frequency of 950 rpm. Hysteresis in the pump performance was also observed in that the pump head-discharge relationship differed depending on whether the pump frequency is being increased from startup or being decreased from a level associated with full flow.

An electromagnetic flow meter (Badger, M2000), installed $\approx$4 ft downstream of the pump outlet in the 6-in diameter pipe (see Figure 3.2), was used to measure discharge. It has a manufacturer specified accuracy of 0.25% of rate for measured velocities greater than 1.6 ft/s (i.e., discharges greater than 0.3 cfs). For the present applications, which are restricted to steady flows, small instantaneous fluctuations in discharge are not relevant, and so the flow meter time constant (damping factor in the flow meter manual) was set to 10 seconds, thus averaging out very-short-term flow rate fluctuations.

Aside from the discharge, the main measurement to be made was the water surface elevation, and specifically the headwater. This was performed with a digital point (depth) gage (Mahr Federal, MARCAL 30 EWR 4126702), with a manufacturer-specified resolution of 0.0005-in and accuracy of 0.002-in. In practice, in the presence of surface waves under flow conditions, the measurement error or uncertainty is determined more by the measurement process of determining an average water surface elevation. In some cases, measurements were taken directly in the flow, and the average water surface at a point was identified for the purposes of determining the water surface elevation as being located where the tip of the point gage was visually submerged for approximately half of the time. At some points, this was very difficult to determine with any precision. This was the case with the headwater at higher discharges. When this was noted, three taps were installed on the channel bed, and were attached via tubing to stilling wells, so that a more reliable estimate of the mean water surface elevation could be obtained. One tap, approximately 1.25 ft upstream from the culvert inlet, was used for the headwater, and the other two allowed monitoring of the water surface in the long culvert when the culvert cover was in place. At the highest headwater levels, the range of the digital point gage was exceeded, and so the stilling well levels were in those situations measured with a simple rule.

3.3 Design of Experiments

The primary results desired of the laboratory experiments were (steady-state) performance curves of the model structure corresponding to the various flow types described in Chapter 2.1, as these were to be compared with predictions of the culvert model HY-8 and the bridge model in HEC-RAS. The performance curve relates the headwater, HW, to the discharge, Q, for a given structure in a given channel. There are several common standard culvert geometries, but it was considered sufficient to study a single geometry, namely a rectangular or box culvert, of span, B_c=1.5 ft, in order to answer the basic question of whether a culvert model (such as HY-8) can successfully predict the performance curve of a relatively short structure or whether in such cases a bridge model (such as in HEC-RAS) is needed. For this reason, the effect of common inlet geometry features such as corner fillets, chamfers, bevels, or wingwalls were not studied; only a single 90° square headwall inlet was considered. Further, only a single rise, D=0.5 ft, was used, but low flows (where the culvert top plays no role) were studied with a culvert top absent.

The experiments were designed to investigate four effects:

- *structure length*—this is the primary aspect of interest, because the relative streamwise length is in some accounts given as the technical basis for conventional culvert hydraulics not being applicable to large-span structures
- *flow resistance or roughness*—large-span structures often take the form of three-sided or bottomless culverts with a natural and therefore rougher bottom, so the effect of roughness on headwater prediction becomes relevant
- *the presence or absence of culvert cover or crown*—while large-span structures may not always be designed to operate under partially or wholly full-flow conditions at design flow, the prediction of the headwater under such conditions remains an important aspect of any model
- *tailwater level*—in the most commonly occurring situation where large-span or more bridge-like structures might be considered, the flow within and upstream of the structure will be influenced by the tailwater level, which therefore needs study

To cover these four effects, sixteen (=2^4) series of experiments were performed, each effect being studied with at least two examples (e.g., a long and a short structure, a smooth and a rough bed, etc.). For each series, the performance curve was obtained by varying the discharge and measuring the corresponding headwater. It was also desired to cover the range of different flow regimes discussed in Chapter 2.1, namely the Types A and B low flows, and the gated-flow and orifice-flow high flows. The low-flow regime where a free-surface flow prevailed through the channel-structure system was mainly generated with the culvert cover absent, but some series with the culvert cover in place also had low-flow cases at smaller discharges. Most Type A flows occurred when the downstream gate was set sufficiently low as to generate a sufficiently high tailwater level, while most Type B flows occurred with the downstream gate set high enough that it exerted no control, such that the tailwater was low and had negligible influence on the flow within the structure and the headwater. The high flows were obtained with the culvert cover in place, with the gated flow resulting from a high gate (hence with low tailwater), and the orifice flow from a low gate (hence with high tailwater).

A main choice was the structure length, L_c. The length of the "long" structure was largely dictated by the overall size of the experimental facility. The span, B_c, was chosen so that, for the long structure, the flow at the structure outlet was not strongly or directly influenced by the flow at the structure inlet, i.e., the flow had expanded fully and become relatively uniform over the outlet cross-section. The length to rise ratio, L_c/D=16, and the length to span ratio, L_c/B_c=5.3, suggest that vertical uniformity is likely achieved, but lateral uniformity may be marginal. Some water-surface-profile and velocity measurements at the outlet did support the flow at the outlet of the long structure being relatively uniform. The length of the "short" structure was chosen to be reasonably realistic at the target prototype scale, and to be such that L_c/D and L_c/B_c were small enough that the outlet flow was definitely influenced by the inlet flow, over most of the discharge range. The chosen "short" length of L_c=2.1 ft yielded a prototype length of 33 ft (assuming a scale ratio of 16), and L_c/D=4.2 and L_c/B_c=1.4 should ensure that the inlet flow had not yet recovered fully at the outlet. For experiments with the "short" structure, the location of

TABLE 3.1
Range of experimental parameters

L_c / B_c	L_c / D	n	HW / D	HW / y_{cc}	y_t / y_{cc}	y_t / D
1.4, 5.3	4.2, 16	0.011, 0.018	0.5–2.5	1.6–5.6	0.5–3.1	0.2–2

the inlet was retained as for the "long" structure, so that the length of the downstream channel increased to ≈14 ft.

The range of experimental conditions covered in the study is summarized in Table 3.1 (where y_t is the tailwater depth, and y_{cc} is the critical depth in the structure). The extreme values in Table 3.1 for some parameters may be rare in typical practice, but were nevertheless included in the study as tests of model capability.

3.4 Experimental Procedure

The common experimental procedure involved:

- The downstream storage tank or outlet box was filled, and if necessary, the pump casing was bled to remove air pockets that might adversely affect the pump performance.
- The pump was started, and the pump speed slowly increased until a desired starting discharge, read from the flow meter, was achieved. Some time period was necessary before a suitably steady flow was obtained. Even at "steady" flow, a variation of ±1% to 2% in discharge was observed.
- Water-surface level measurements were then taken. These could be directly in the channel and/or culvert, or could also be in the stilling-well tubes. In limited cases, these might be more extensive profiles, but most often, measurements were obtained only at the headwater stilling well. Most level measurements were taken with the Mahr electronic depth gage, but if this could be not used due to scale limitations, then a simple rule was used. For cases, in which the tailwater played an important role, the tailwater depth needed to be measured and was taken at a distance of ≈4 ft from the culvert outlet (also approximately the same distance to the end of the downstream channel).
- The process was repeated until the entire range of desired discharges was covered. Two cautionary points should be noted:
  - At the higher discharges, attention to the water level in the downstream storage tank was needed to ensure that it was sufficiently above the inlet to the supply pipe to the pump. If the level was considered too low, the level in the tank was "topped" up by filling with additional water as needed. If such topping up was performed, then care should be exercised that water would be appropriately drained when the discharge was reduced in order to avoid the tank storage capacity being exceeded.
  - As noted before in Chapter 3.2.2, due to the pipe system not always flowing full, pump discharge can change quite dramatically in certain discharge ranges in the transition to full-pipe flow. In these ranges, care needs to be exercised in increasing or decreasing pump speed to avoid undesirable effects.

3.5 Summary

In this chapter, the Froude number model law was stated, and the modeling implications outlined. The experimental facility, which was built with this study in mind, was then described. The scope of the study and the consequent range of experimental conditions covered were then presented, followed by details of the experimental procedure.

4. EXPERIMENTAL AND COMPUTATIONAL RESULTS

4.1 Organization of Results

The experimental results are presented in this chapter together with the computational results using HY-8 and the HEC-RAS bridge models. Because the main issue of concern is the effect of structure length on modeling predictions, the results of the different cases are considered in pairs, with each pair characterized by the same conditions and differing only in the structure length. Eight pairs of experiment series, examining in turn, the effects of bed roughness, the constraint of a culvert top or cover, and the presence of high tailwater, will be discussed. For convenience in referencing, each experiment series is designated by a six-character label, with the first letter indicating a long (L) or short (S) structure, the second letter a smooth (S) or a rough (R) bed, the next two characters the absence (C0) or presence (C1) of a culvert cover, and the final two characters the absence (G0) or presence (G1) of a tailwater (i.e., downstream gate) effect. For example, the series LRC0G1 refers to experiments with the long (8-ft) structure, with a rough bed, no culvert cover (C0), and a downstream gate (G1) low enough as to cause tailwater effects under most conditions. For certain cases (Type A low flows according to the HEC-RAS bridge-flow classification), more than one series of experiments were conducted; in such cases, an alphabetic suffix (e.g., A and B) is added. After presentation of individual performance curves with a comparison of model predictions and observations in Section 4.3, the statistics of model performance are discussed in Section 4.4.

4.2 Computational Model Assumptions

The results to be presented are comparisons of the experimental culvert performance curves with HY-8 and HEC-RAS predictions. Except where noted, in the HEC-RAS bridge modeling, default options and values of coefficients were used. In the HEC-RAS results, the total head, i.e., including the velocity head, is used in all comparisons of headwater, and this was taken at an upstream section where the flow is assumed to be fully expanded. Default options and coefficient values were taken for the HEC-RAS bridge models. Ineffective flow areas were applied according to manual (Brunner, 2016) guidelines, with contraction coefficient just upstream of the structure and expansion coefficient just downstream of the structure taken to be 0.3 and 0.5. The main *non*-default HEC-RAS option taken was the specification of the internal bridge sections to be the same as the culvert span and rise, such that the barrel geometry is the same as the inlet and outlet geometry. Each series of experiments are discussed in turn. For the HY-8 simulations, a concrete box culvert with a Manning's n of 0.011 or 0.018 (as in the HEC-RAS simulations) was specified. In cases where the tailwater had no effect on the upstream flow, a very small constant tailwater was specified; otherwise, the *measured* tailwater (at a section ≈4 ft downstream of the structure outlet) was specified. All HY-8 computations were performed with version 7.5, but checks with version 7.3 showed no difference in results. HEC-RAS computations were all performed with version 4.1, using a mixed-flow regime (critical flow or specified downstream-depth boundary condition) in order to permit supercritical solutions.

In addition to the predictions from HY-8, curves corresponding to the traditional HDS-5 inlet-control equations for unsubmerged and submerged conditions will also be used as reference. For the case of a box culvert, the standard inlet geometry most closely corresponding to the laboratory model is that with a 90° headwall and ¾-in chamfers (Chart #10, Nomograph scale 1), though the model was not chamfered. Under the unsubmerged-inlet condition, the weir (or critical-flow) equation for the headwater, HW_{ICc}, is related to the discharge, Q, (in U.S. customary units) by

$$HW_{ICc} = 0.515(Q/B_c)^{2/3} \tag{4.1}$$

where B_c=1.5 ft is the structure span. For the submerged-inlet condition, the gated-flow equation for the headwater, HW_{ICg}, is given in U.S. customary units by

$$HW_{ICg} = 0.0375\left(\frac{Q}{B_c D}\right)^2 + 0.79D, \tag{4.2}$$

where the slope term has been neglected, and D is the culvert rise. For comparison with the HEC-RAS gated-flow, it is convenient to cast Eq. 4.2 in terms of a gated-flow discharge coefficient, $C_{d,gate}$, equivalent to that in HEC-RAS. This is found to be (in U.S. customary units)

$$C_{d,gate} = \sqrt{\frac{HW - 0.79D}{0.0375(2g)(HW - 0.5D)}} \tag{4.3}$$

For cases of high tailwater, with both inlet and outlet submerged, HEC-RAS applies an orifice model with a different discharge coefficient, $C_{d,or}$, such that

$$Q = C_{d,or} A_c \sqrt{2g\Delta H} \tag{4.4}$$

where A_c=$B_c D$ is the full structure area, and ΔH is the difference in total heads between the inlet and the outlet. In the following, ΔH=HW–y_t, as the channel slope is negligible (y_t being the tailwater depth). In terms of conventional culvert analysis, $C_{d,or}$, can be expressed as

$$C_{d,ori} = \sqrt{\frac{1}{K_{L,ent} + K_{L,exit} + K_{L,c}}} \tag{4.5}$$

$K_{L,ent}$ and $K_{L,exit}$ are local loss coefficients (with values of 0.5 and 1 assumed for the present cases) and $K_{L,c} = (n_c/c_M)^2 2g\left(L_c/R_{hc}^{4/3}\right)$ represents continuous losses due to boundary friction within the culvert (here n_c, L_c, and $R_{h,c}$ are the Manning's n, the length, and the hydraulic radius of the full-flow culvert, and c_M is the Manning's conversion constant, 1.49 in U.S. customary units). The default HEC-RAS value of 0.8 for $C_{d,or}$ may be viewed as neglecting $K_{L,c}$ in which case $C_{d,or} \approx \sqrt{1/1.5} = 0.82$.

4.3 Performance Curves

In the following, the culvert performance curves are plotted, with the actual measured values of headwater, HW_m, given on the left axis, while a prototype headwater, HW_p, assuming a scale ratio of 16, is given on the right axis. Similarly, the corresponding measured model discharges, Q_m, are given on the lower axis, while the scaled prototype discharges, Q_p, are given on the upper axis.

4.3.1 LSC0G0 and SSC0G0: Type B Low Flows (Smooth Bed, No Cover, and Gate High)

This pair of experiment series was performed without a culvert cover, and thus simulated flow conditions where the water surface within the structure does not reach the culvert crown (in the HEC-RAS classification, low flows). Further, the flow occurred with the gate high, without any downstream control, such that, despite the almost zero slope, the flow in the downstream channel was supercritical for all discharges. In the HEC-RAS bridge modeling classification, all flows in this series were Type B low flows. Figure 4.1 directly compares HW_m for the long and the short structures, and these are seen to align very well. For these conditions, the effects of length are negligible, which is also be interpreted as an unsubmerged inlet control prevailing, such that structure features downstream of the inlet have negligible effect on HW_m. While flow resistance may eventually become relevant for much longer or much rougher-bed structures, it seems justified to infer that the HW_m for even shorter structures under similar conditions would vary as in Figure 4.1. Thus, a model that predicts well the HW_m for the longer structure should also predict well for much shorter structures.

In Figure 4.2, each of the series is plotted with the model predictions of HY-8 and HEC-RAS, together with a curve representing the traditional HDS-5

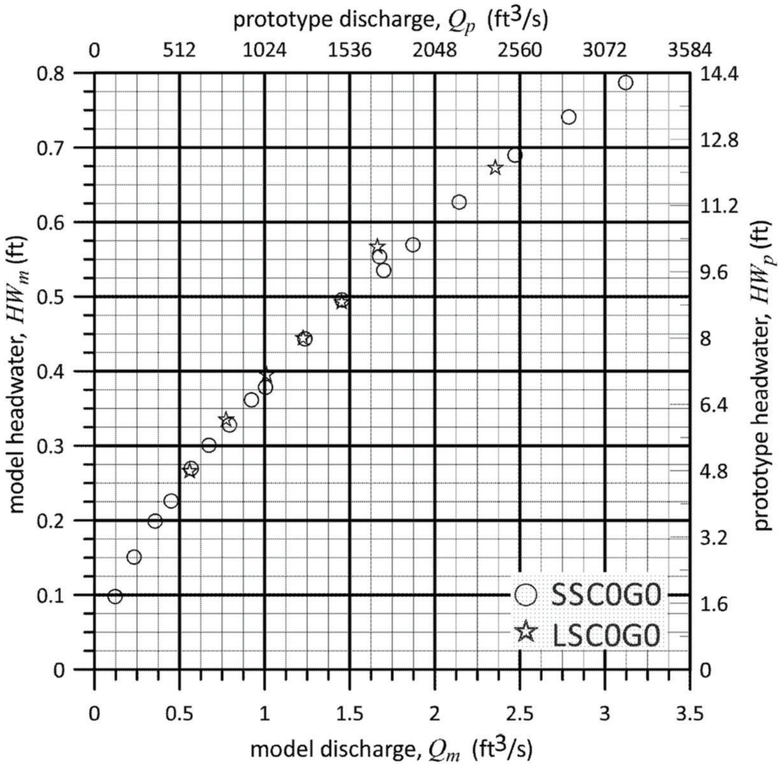


Figure 4.1 Comparison of measured headwater for long and short structures over smooth beds, no cover, and gate high.

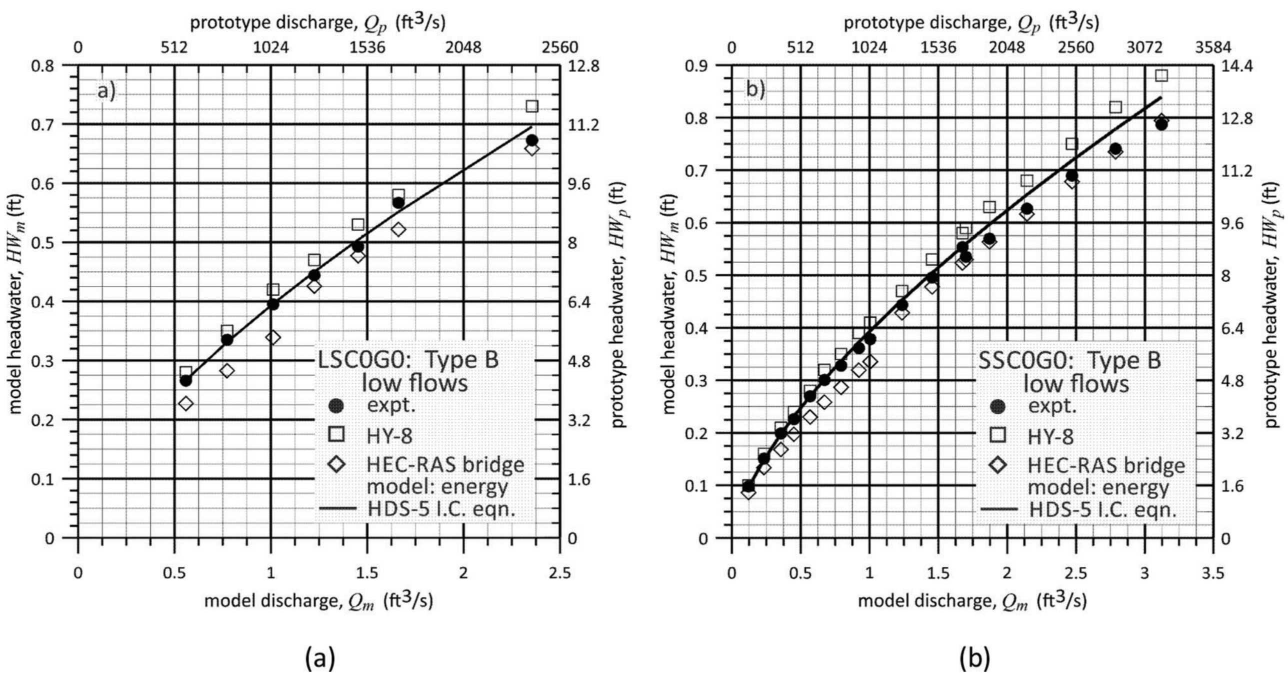


Figure 4.2 Comparison of measurements and predictions of different models (HY-8, HEC-RAS bridge, and HDS-5 inlet-control equations) for smooth-bed, no-cover, gate-high conditions, (a) long structure, (b) short structure.

(unsubmerged) inlet-control equation, i.e, Eq. 4.1. The observations are situated between the HY-8 and the HEC-RAS predictions. At lower discharges, the prediction of HY-8 agree better with the measurements than those of HEC-RAS, but at higher discharges the opposite is the case. Much of the discrepancy between the HY-8 predictions and the measurements seems to be due to the polynomial model fit adopted in HY-8, as the agreement is noticeably better, especially at higher discharges, with the reference curve for the traditional

HDS-5 weir equation than with the HY-8 predictions. Thus, discrepancies with HY-8 should not be interpreted as stemming necessarily from culvert modeling in general, but rather from a specific culvert model. The better agreement with HEC-RAS at higher discharges may also be explained from this perspective. For a Type B flow, HEC-RAS, by default, assumes critical flow at the inlet, and, like Eq. 4.1 but unlike the polynomial fit of HY-8, does not involve the culvert rise.

4.3.2 LRC0G0 and SRC0G0: Type B Low Flows (Rough Bed, No Cover, and Gate High)

These two series of experiments are similar to the preceding, except that a roughened bed was installed, both inside and outside of the structure. A direct comparison between the results for the long and the short structures in Figure 4.3 indicates only a slight though consistent effect of roughness on the culvert performance. The longer structure exhibits a slight increase in HW_m as might be expected due to the increased flow resistance. The slight effect of the increased roughness does suggest that, especially for the higher discharges, when frictional losses become more important, the hydraulic control has passed from the inlet as in the preceding series to the outlet.

The predictions of the different models are plotted in Figure 4.4. The effect of the rough bed is clearly seen in that both the HY-8 predictions and the measurements of HW_m tend to lie above the reference inlet-control curve (Eq. 4.1), which might be taken as more applicable to the smooth-bed case, as was seen in Section 4.3.1. The difference from the reference curve is also greater in the case of the longer structure due to the greater effect of flow resistance. Thus, although there is a small effect of flow resistance within the short structure and hence is outlet-controlled, the resulting HW_m in that case differs little from inlet-control reference curve. HEC-RAS consistently underpredicts HW_m, even for the short structure (compare the short-structure results in Figure 4.2b and Figure 4.4b). As was noted above, for Type B flows, HEC-RAS does not distinguish inlet and outlet control, and by default assumes inlet control with critical flow at the inlet, and thus does not take into account flow resistance within the structure. HY-8 does include flow resistance, and hence provides superior predictions, with the agreement improving with the longer structure.

4.3.3 LSC1G0 and SSC1G0: High Flows (Smooth Bed, with Cover, and Gate High)

According to the HEC-RAS classification of bridge flows, high flows refer to conditions where the water surface touches the structure low chord. In these two series of experiments, the smaller discharges are strictly speaking not high flows in the HEC-RAS sense, but they were performed to provide a context for the high flows. Further, the two series were also characterized by a supercritical downstream flow, and so the hydraulic control was always located within the structure.

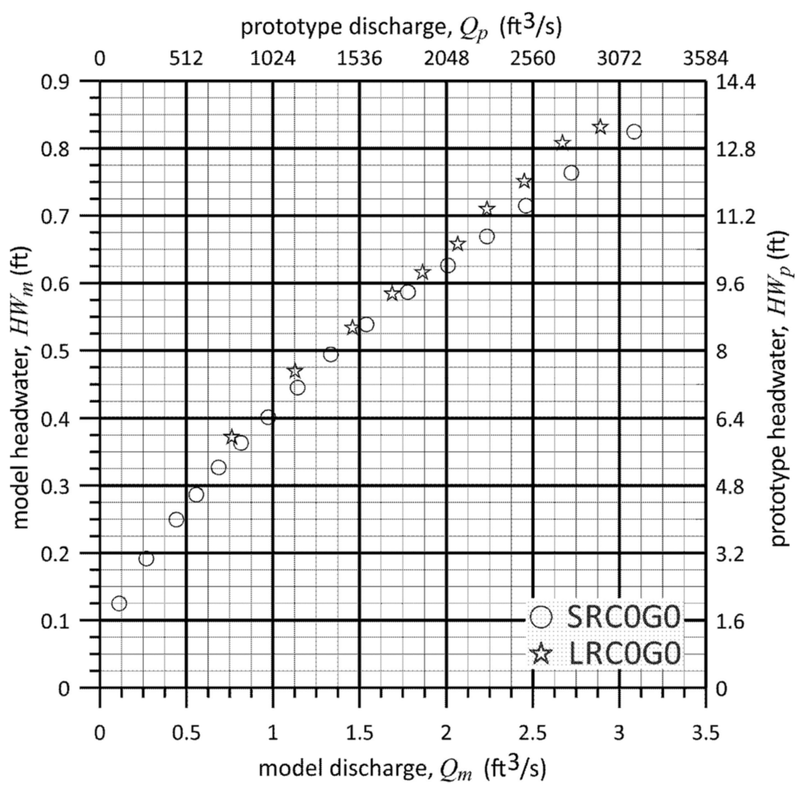
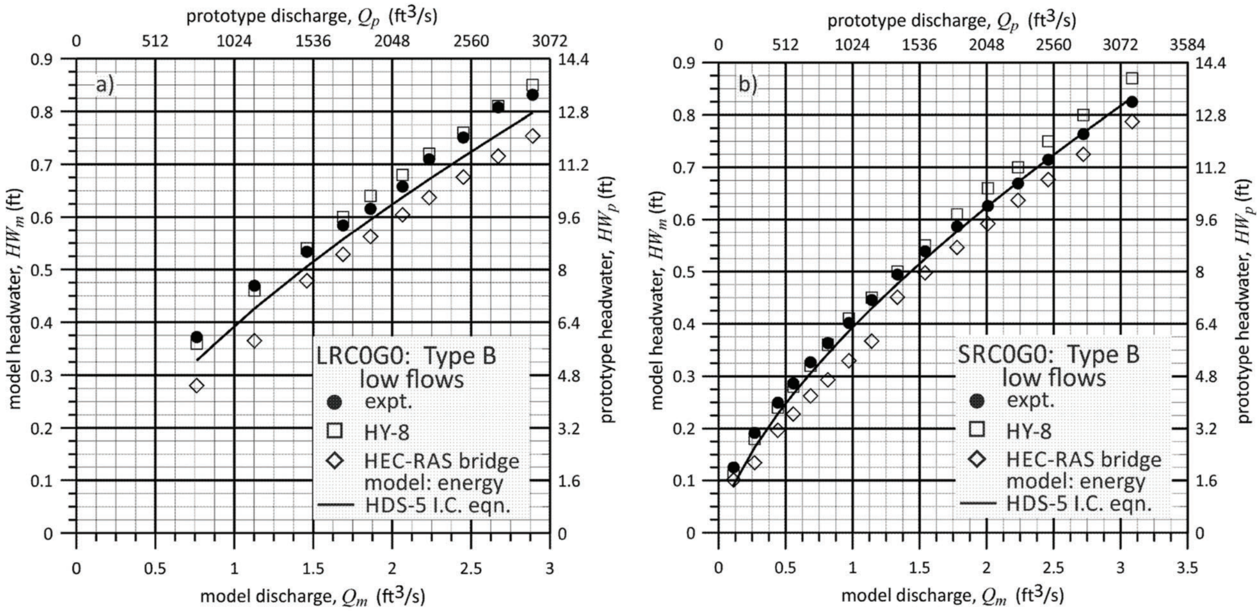


Figure 4.3 Comparison of measured headwater for long and short structures over rough beds, no cover, and gate high.



(a) (b)

Figure 4.4 Comparison of measurements and predictions of different models (HY-8, HEC-RAS bridge, and HDS-5 inlet-control equations) for rough-bed, no-cover, gate-high conditions, (a) long structure, (b) short structure.

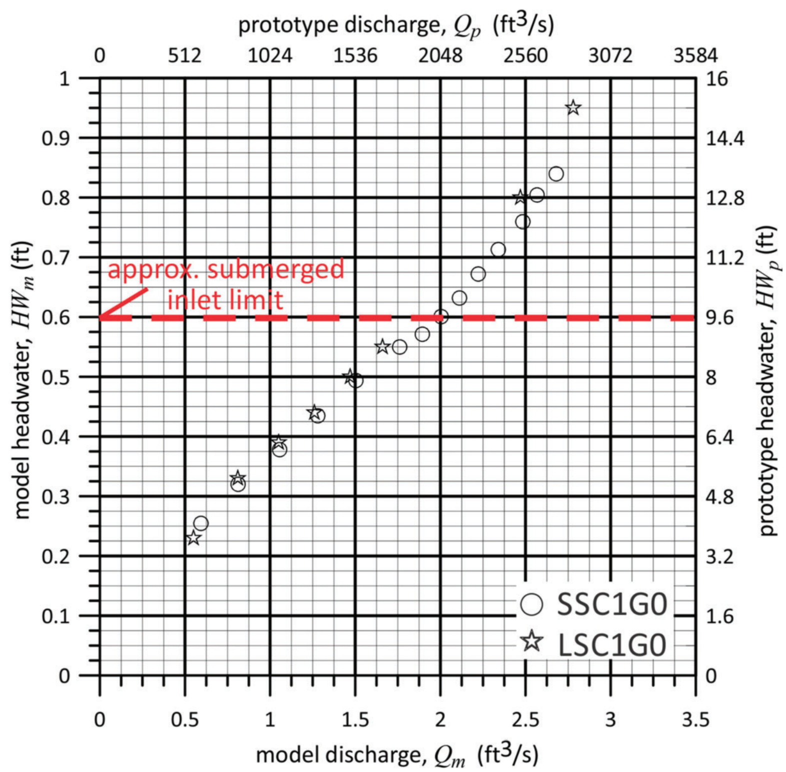


Figure 4.5 Comparison of measured headwater for long and short structures over smooth beds, with cover, and gate high.

The limited results of Figure 4.5 do not give a definitive picture of the effect of length on high flows, as only two points for the long structure actually submerged the inlet. The available high-flow data do not support a strong effect of structure length, and hence would be consistent with inlet control, which under submerged conditions would imply gated flow. For the smaller (unsubmerged-inlet) discharges, the results are consistent

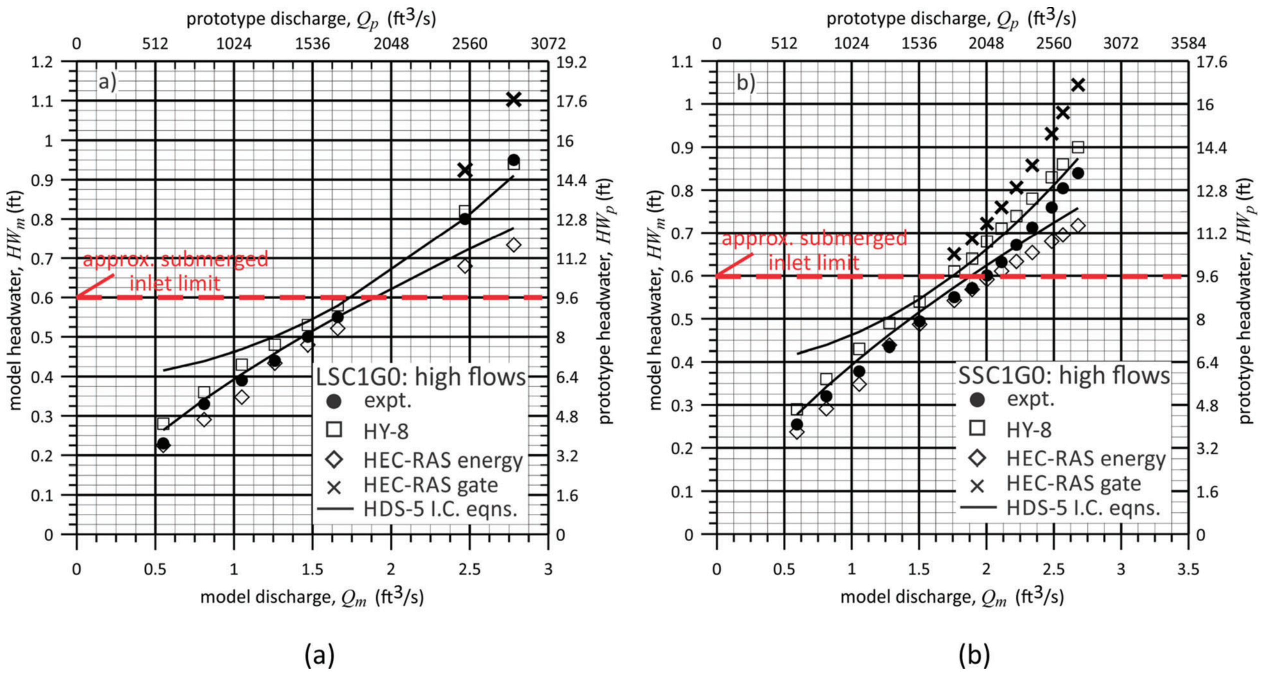


Figure 4.6 Comparison of measurements and predictions of different models (HY-8, HEC-RAS energy and gate, and HDS-5 inlet-control equations—the bottom curve is the unsubmerged-inlet model, Eq. 4.1, while the top curve is the submerged-inlet model, Eq. 4.2) for smooth-bed, with-cover, gate-high conditions, (a) long structure, (b) short structure.

with those previously seen for Type B flows that are inlet controlled (see the comparisons in Figure 4.6 with the reference inlet-control curves).

Model predictions are compared in Figure 4.6. Two predictions are given for the HEC-RAS bridge model, namely the default approach based on the energy equation, and the optional pressure-flow approach based on a gated-flow equation with a discharge coefficient, $C_{d,gate}$, internally determined by default. While the HEC-RAS predictions for low flows are adequate if underestimated, those for high flows are dubious since substantial disagreement with the measurements is seen for both energy- and pressure-based predictions. The default HEC-RAS energy-equation model still predicts HW_m close to (actually below) the critical-flow values more appropriate for the critical-flow case without a cover. The overestimating behavior of the HEC-RAS pressure model is traced to a low value internally determined for $C_{d,gate}$. The HEC-RAS manual (Brunner, 2016) shows $C_{d,gate}$ asymptoting to a maximum value of 0.5, but the corresponding HY-8 coefficient (derived from Eq. 4.2 and evaluated as Eq. 4.3) has a value of 0.58 for $HW/D=2$. As measurements indicate that the actual HW_m for the short structure are even lower than the HY-8 predictions, this suggests that the actual $C_{d,gate}$ is larger still than the HY-8 $C_{d,gate}$. It should nevertheless be noted that $HW/D=2$ would be extreme and rather rare in the usual bridge context, but may not be as rare in the usual culvert context. It must also be highlighted that the HEC-RAS bridge model does not determine which of the two solutions is to chosen, and the engineer must select the non-default option to obtain the alternate estimate.

In marked contrast, the HY-8 predictions track the measurement over the entire range of low and high flows, as HY-8 is capable of changing from outlet-control to inlet control, or from unsubmerged-inlet to submerged-inlet conditions. The agreement with measurements is however noticeably better for the longer structure. Some of the discrepancy, especially for the short structure, is attributed as earlier noted to the polynomial transition model as the traditional critical-flow Eq. 4.1 yields better agreement. For the short structure, the data in Figure 4.6 also suggest Eq. 4.1 may be applicable at least for smooth beds, to higher values of $Q/(A_c D^{1/2})$, $A_c=B_c D$ being the full culvert area, e.g., 4.5 (in U.S. customary units) than the value 3.5 usually recommended (HDS-5-2012).

4.3.4 LRC1G0 and SRC1G0: High Flows (Rough Bed, with Cover, and Gate High)

These two cases differ from the preceding two only in that a rough bed was installed. The results of Figure 4.7 for the high flows (with inlet submerged) support the inference made earlier based on the more limited data of Figure 4.5 that the effect of structure length on HW_m in a gated-flow situation is negligible. Moreover, the effect of roughness is slight but consistent particularly at the smaller discharges. Under high-flow conditions, the results for long and short structures with rough beds are indistinguishable. Thus, in such a case, if a model predicts HW_m well for the long structure, it should perform equally well for the short structure.

The qualitative behavior of the various model predictions, compared in Figure 4.8, is the same as seen

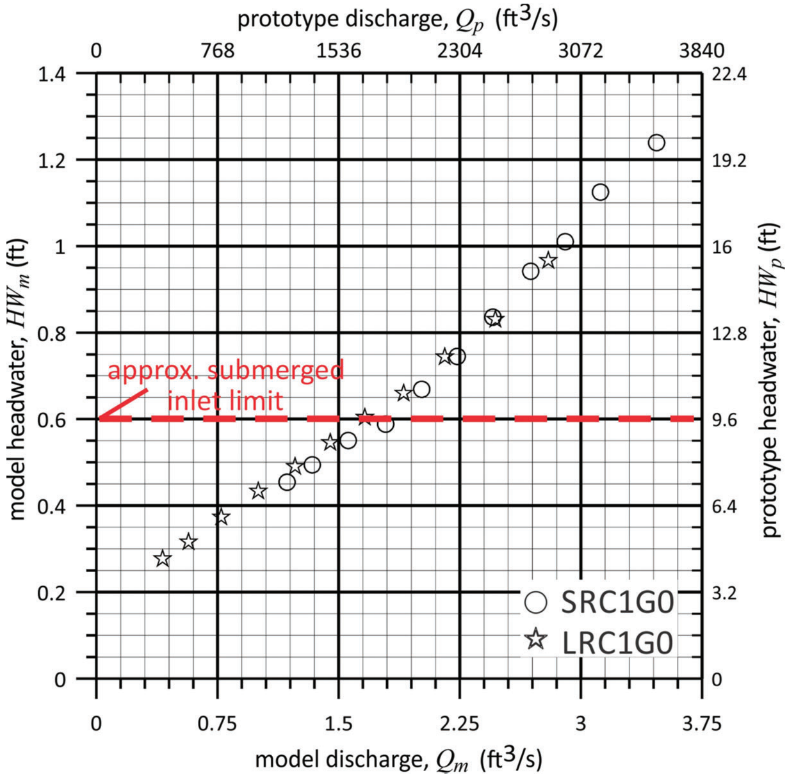


Figure 4.7 Comparison of measured headwater for long and short structures over rough beds, with cover, and gate high.

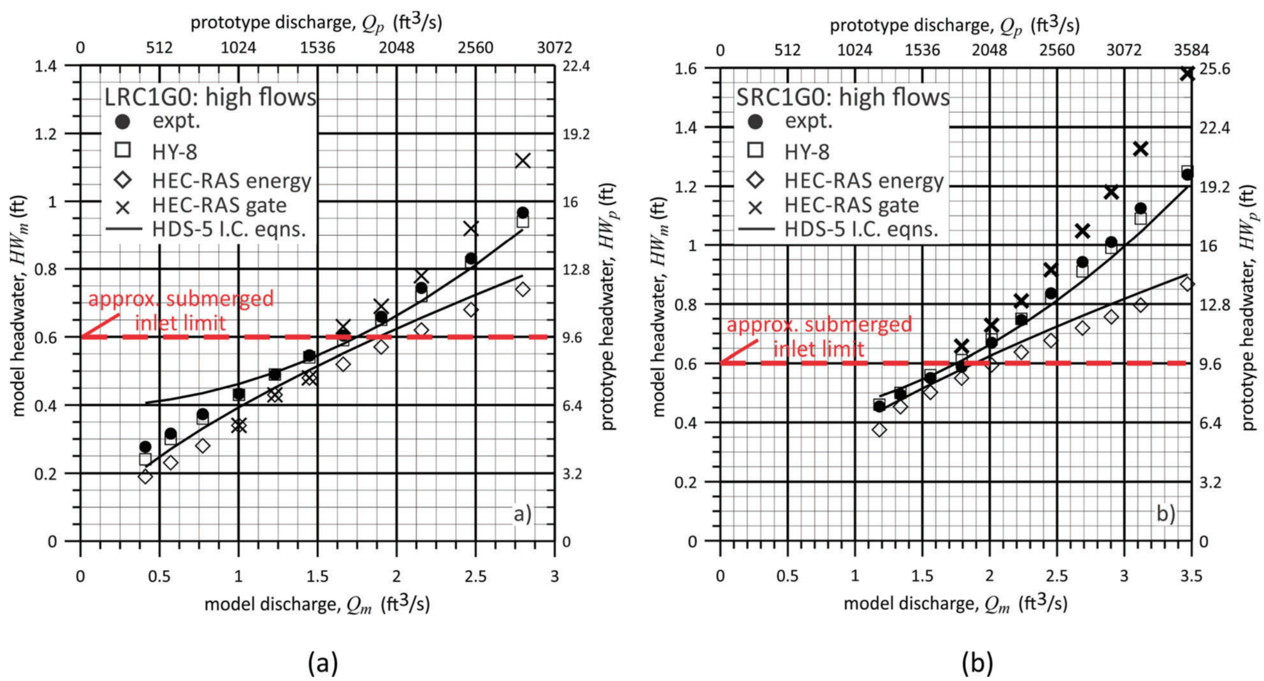


Figure 4.8 Comparison of measurements and predictions of different models (HY-8, HEC-RAS energy and gate, and HDS-5 inlet-control equations—the bottom curve is the unsubmerged-inlet model, Eq. 4.1, while the top curve is the submerged-inlet model, Eq. 4.2) for rough-bed, with-cover, gate-high conditions, (a) long structure, (b) short structure.

previously in Figure 4.6 for the comparable smooth-bed case. A consistent effect of roughness is however seen in that the observed HW_m are generally higher than reference curves (Eq. 4.1 and Eq. 4.2). It is noted that, for the short structure, HY-8 determines for all discharges an outlet control, with however predictions of HW_m identical to those assuming inlet control. On the other hand, for the long structure, HY-8 predicts outlet control for the lower discharges, but inlet control for the higher discharges. Unlike the comparable smooth-bed case (SSC1G0), the applicability of Eq. 4.1 seems more restricted.

4.3.5 LSC0G1 and SSC0G1: Type A Low Flows (Smooth Bed, No Cover, and Gate Low)

According to the HEC-RAS classification of bridge flows, Type A low flows refer to conditions where the flow is everywhere (upstream, within, and downstream the structure), and, to distinguish it from Type B low flows, the tailwater downstream of the structure is assumed to exert hydraulic control. In the following series of experiments, the imposed tailwater was generally (i.e., all except possibly the lowest discharges) high, which is meant here as a level exceeding the critical depth in the culvert, and hence was expected to influence the resulting headwater. A high tailwater in this sense does not by itself guarantee tailwater control of HW_m.

A comparison of two series of experiments involving the short structure with a single series involving the long structure is shown in Figure 4.9a in dimensional form as previously done, but also in dimensionless form in Figure 4.9b. The reference inlet-control curve from Eq. 4.1 has also been included in Figure 4.9a. The two series involving the short structure were performed with the downstream gate at two different positions, thereby generating two different tailwater conditions. At sufficiently low tailwater conditions, even if the tailwater was high in the sense of exceeding the critical depth in the culvert, all of the observations are seen to start from the inlet-control state (represented by the reference curve), and deviate from this state only for sufficiently high tailwater. This is more clearly seen in the dimensionless representation (Figure 4.9b), which plots the headwater normalized by its inlet control value against the ratio of the tailwater to the culvert critical depth, i.e., y_t/y_c. In the latter coordinates, the long-structure results are represented essentially by a single point, while the short-structure results, which plot as two distinct curves in Figure 4.9a, plot as a single curve in Figure 4.9b. The straight-line in Figure 4.9b ensures that a change in the tailwater y_t implies an equal change in HW_m for large y_t/y_c. For $y_t/y_c \lesssim 1.6$, Figure 4.9b indicates that $HW_m/HW_{ICc} \approx 1$ or HW_m retains it inlet-control value despite the high tailwater level.

The predictions of the various models are compared in Figure 4.10. In the absence of a cover, only a single prediction is given for the HEC-RAS bridge model. For the long structure, the HEC-RAS predictions are closer to the measurements than the HY-8 predictions. The problematic HY-8 performance stems primarily from the incorrect conclusion that outlet control prevails. The measurements in fact agree very well with the inlet-control reference curve. Indeed, the rather unexpected situation arises that HY-8 performs *better* for the short structure than for the long structure, even though for both long and short structures HY-8 predicts outlet control. This may be explained by the decreased effect of flow resistance on the HY-8 predictions for the short structure.

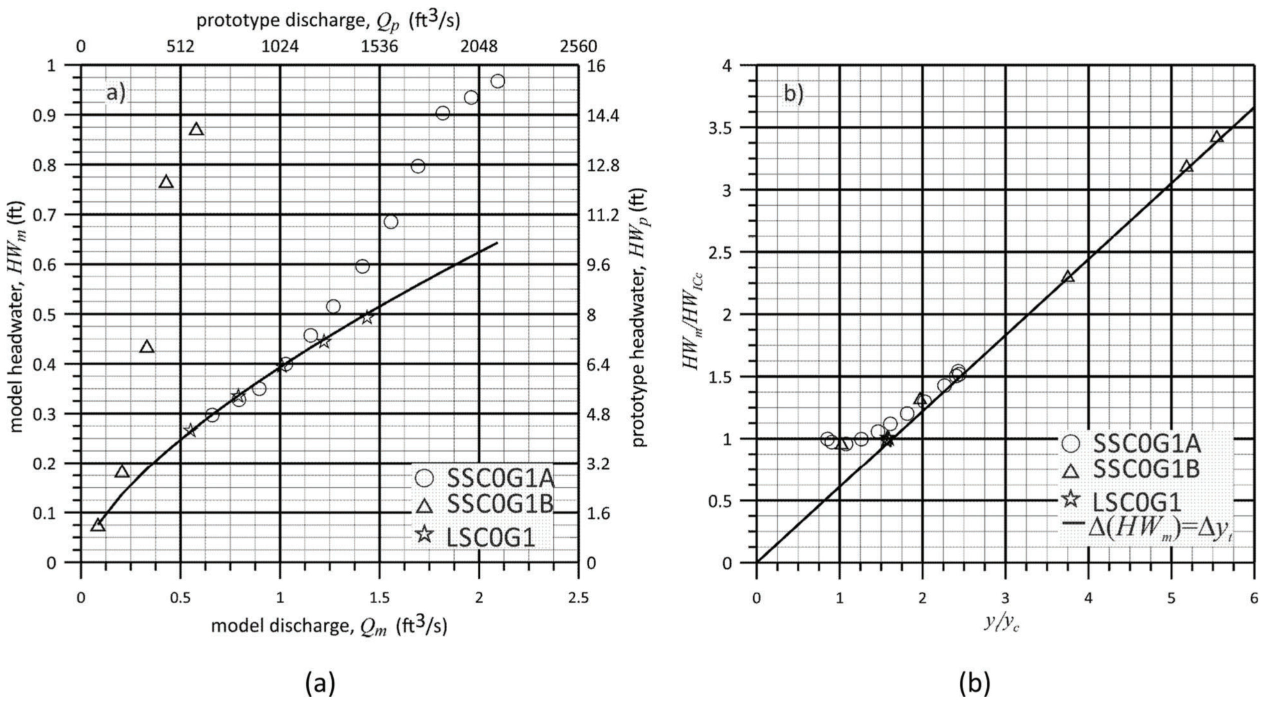
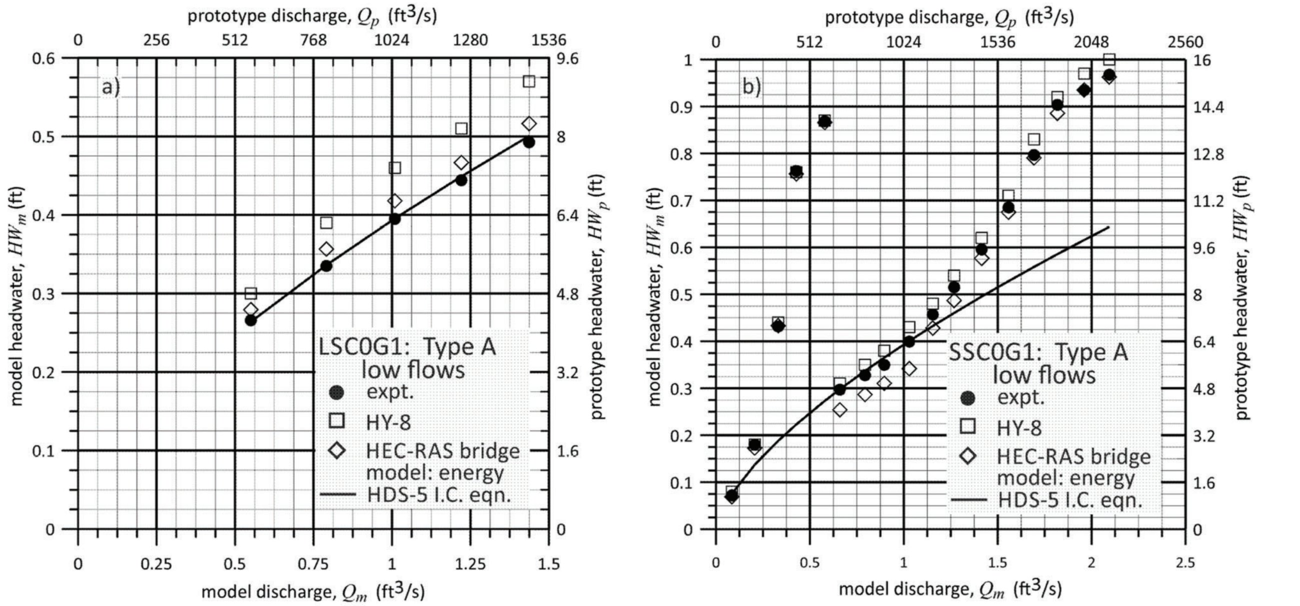


Figure 4.9 Comparison of measured headwater for a single series involving a long structure and two series involving the short structures over smooth beds, no cover, and gate low enough to generate mostly high tailwater conditions, in (a) dimensional, and (b) dimensionless coordinates.



(a) (b)

Figure 4.10 Comparison of measurements and predictions of different models (HY-8, HEC-RAS energy, and HDS-5 inlet-control equations Eq. 4.1) for smooth-bed, no-cover, gate-low conditions, (a) long structure, (b) short structure.

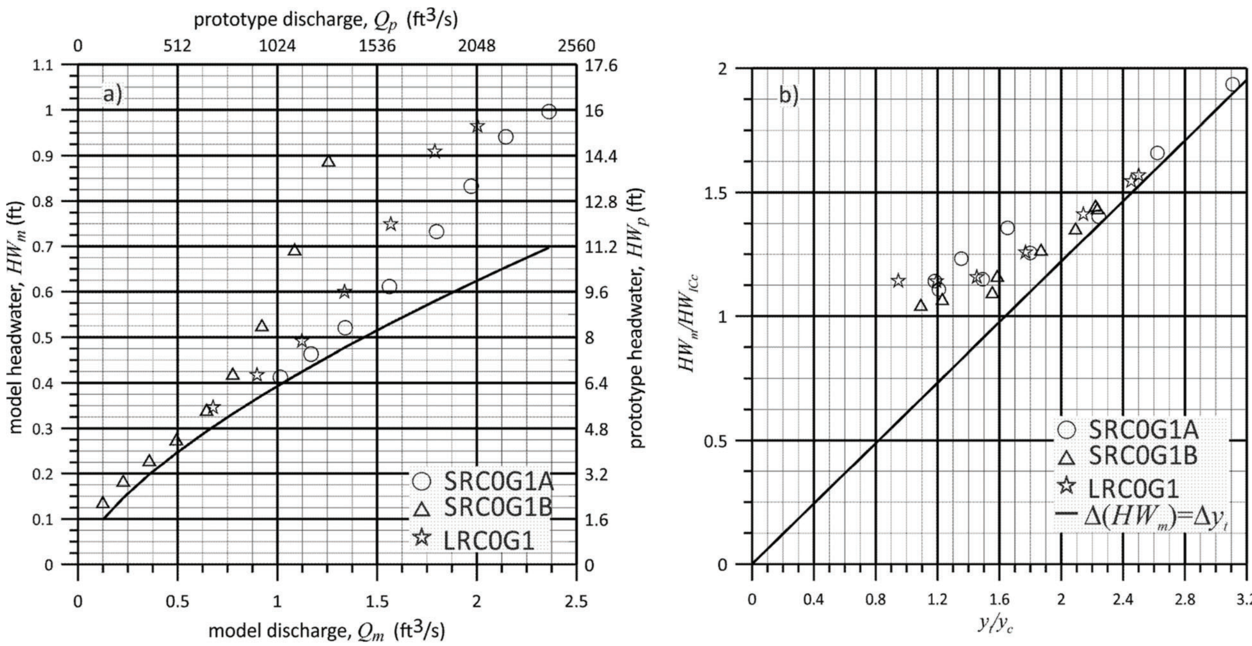
4.3.6 LRC0G1 and SRC0G1: Type A Low Flows (Rough Bed, No Cover, and Gate Low)

These two cases differ from the preceding two only in that a rough bed was installed, and the results are hence presented in Figure 4.11 and Figure 4.12 in the same manner. The general qualitative behavior is similar to that seen previously for the corresponding smooth-bed case (see Figure 4.9 and Figure 4.10), with the effect of roughness appearing mainly in a slight upward shift of HW_m due to the increased flow resistance, especially noticeable at smaller discharges. As seen in previous figures, at the smallest discharges, when the effect of the tailwater is small, the effect of a rough bed favors HY-8, especially for the long structure. At larger discharges as the tailwater effect dominates over the roughness effect, the superiority of HY-8 diminishes, and particularly for the short structure, measured HW_m agrees more closely with the HEC-RAS predictions.

4.3.7 LSC1G1 and SSC1G1: High Submerged-Outlet Flows (Smooth Bed, with Cover, and Gate Low)

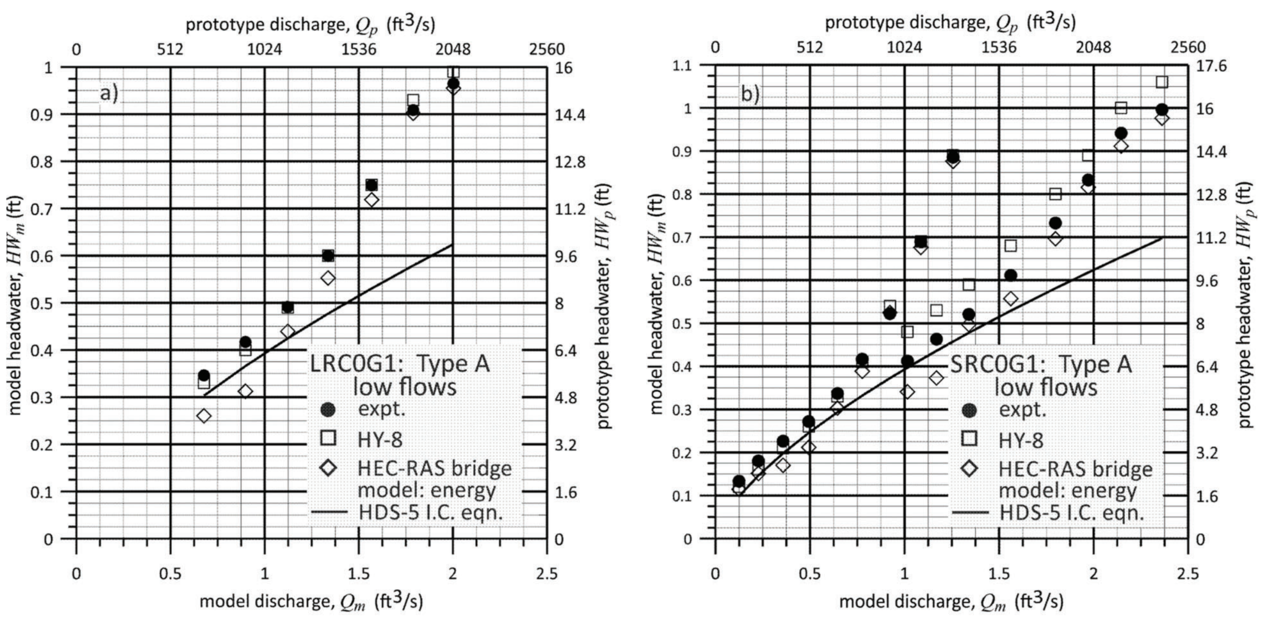
In these cases, the downstream gate was set low so that there was in general a strong tailwater effect, and, with a cover in place, at the largest discharges, both structure inlet and outlet were submerged. A comparison of HW_m for the long and the short structures over the range of discharges is given in Figure 4.13a. A difficulty in this plot is that it gives no indication of the tailwater conditions, and while the results seem to match, this is because the tailwater conditions were similar. More insight is obtained in a dimensionless representation in which an "orifice" discharge coefficient, $C_{d,or}$, evaluated from Eq. 4.4, is plotted against the relative tailwater depth, y_t/D, as in Figure 4.13b, so that when the outlet is submerged, $y_t/D>1$, is immediately evident. For $y_t/D>1$, corresponding to $Q_m \gtrsim 1.4$ cfs in Figure 4.13a, for both long and short structures, Figure 4.13b shows $C_{d,ori}$ becoming approximately constant at the same value of 0.8 as the HEC-RAS default value for the long structure, but consistently above that value for the short structure. The additional line, $C_{d,or}=y_t/D$, describes an ideal case without losses, and so provides an upper bound, that is especially useful for interpreting the results in the unsubmerged-outlet range, $y_t/D<1$.

Model predictions are shown in Figure 4.14. For the discharges with outlet submerged, the predictions of both HY-8 and the HEC-RAS orifice model are virtually indistinguishable. This is expected as the initial discussion of $C_{d,or}$ makes clear that the HEC-RAS orifice model with its default value of $C_{d,or}$ is equivalent to the HY-8 model when the effects of boundary friction within the structure is small or negligible, as they are for the short structure (with a smooth bed). For the long structure, a slight divergence of the predictions of HY-8 and HEC-RAS is seen, attributable to the greater losses within the long structure. Both models however perform well for submerged-outlet conditions, with the HEC-RAS orifice model doing especially well in the case of the *long* structure, though this may be somewhat fortuitous as the losses were such that, as seen in Figure 4.13b, $C_{d,or} \approx 0.8$, the default value of the HEC-RAS orifice model. It should be emphasized that the default energy model significantly underestimates HW_m for submerged-outlet conditions.



(a) (b)

Figure 4.11 Comparison of measured headwater for a single series involving a long structure and two series involving the short structures over rough beds, no cover, and gate low enough to generate mostly high tailwater conditions, in (a) dimensional, and (b) dimensionless coordinates.



(a) (b)

Figure 4.12 Comparison of measurements and predictions of different models (HY-8, HEC-RAS energy, and HDS-5 inlet-control equation, Eq. 4.1) for rough-bed, no-cover, gate-low conditions, (a) long structure, (b) short structure.

4.3.8 LRC1G1 and SRC1G1: High Submerged-Outlet Flows (Rough Bed, with Cover, and Gate Low)

These series differed from the preceding only in that a rough bed was installed, and so the main focus concerns the effect of roughness on submerged-outlet behavior. An additional series with the short structure was performed to illustrate the effect of differing tailwater conditions (through setting the downstream gate at different levels). Thus, in Figure 4.15a, the two series for the same short structure but with differing tailwater condition are clearly distinct; for the A series,

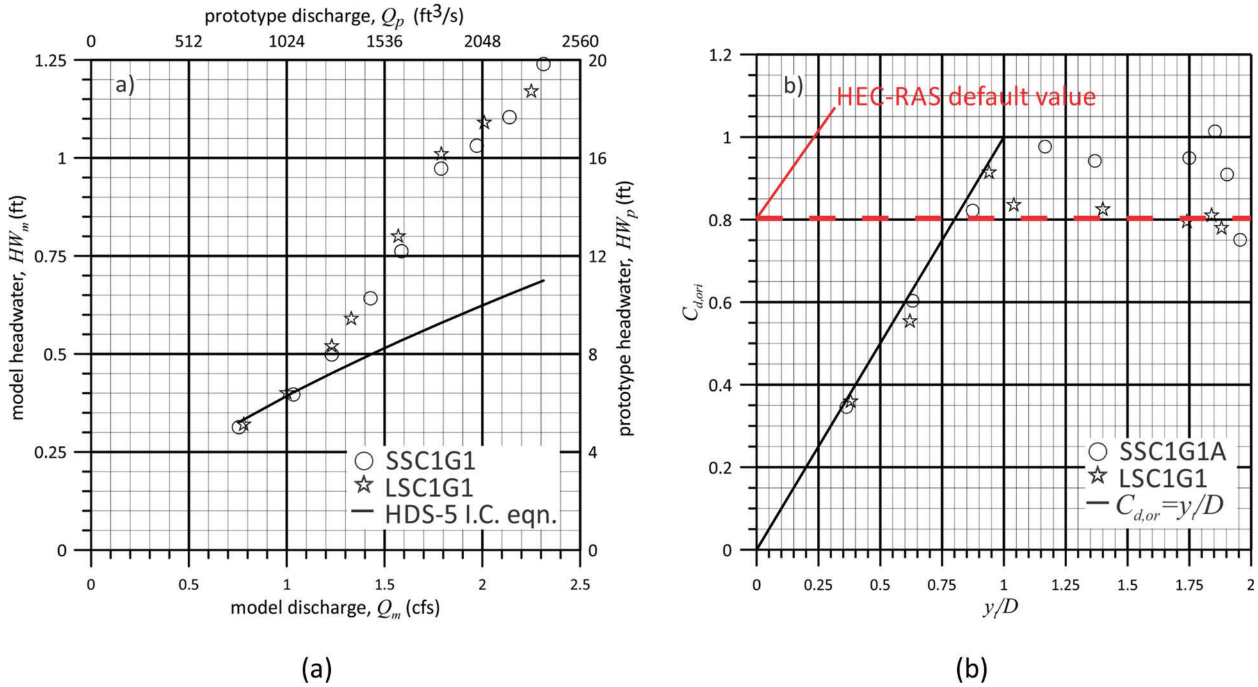


Figure 4.13 Comparison of measured headwater for a long structure and for a short structure over smooth beds, with a cover, and gate low enough to generate high tailwater conditions, in (a) dimensional, and (b) dimensionless coordinates.

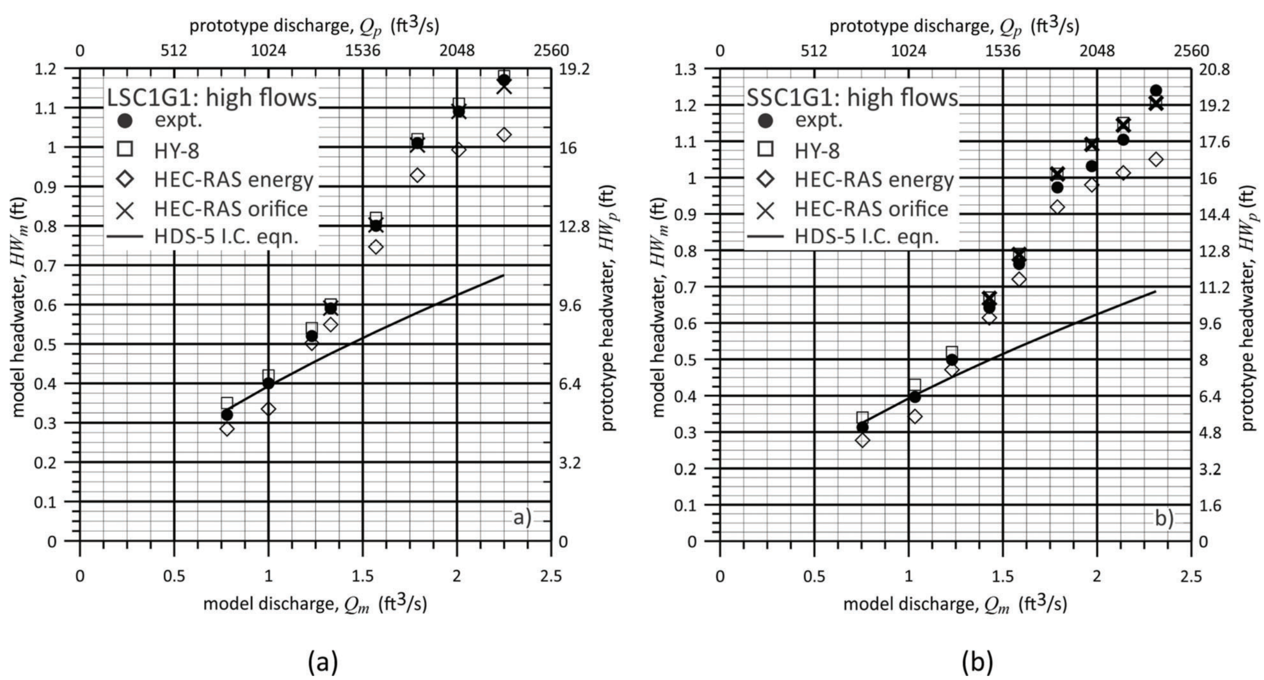


Figure 4.14 Comparison of measurements and predictions of different models (HY-8, HEC-RAS energy, and HDS-5 inlet-control equation, Eq. 4.1) for smooth-bed, with-cover, gate-low conditions, (a) long structure, (b) short structure.

the outlet is submerged for $Q_m \gtrsim 1$ cfs, while for the B series, the outlet is submerged for $Q_m \gtrsim 1.6$ cfs. Again, the dimensionless plot of $C_{d,or}$ vs y_t/D is more useful, as, in these coordinates, the results for the two series with the short structure collapse onto arguably a single curve. Whereas in the preceding smooth-bed case, the value of $C_{d,or}$ for the short structure was ≈ 1 under submerged-outlet conditions ($y_t/D > 1$), for the rough-bed short-structure case, the increased losses has reduced $C_{d,or}$ to ≈ 0.8, which is the default value in the HEC-RAS orifice model. On the other hand, for the rough-bed long-structure case, for the same reason, $C_{d,or}$ is further reduced to ≈ 0.7.

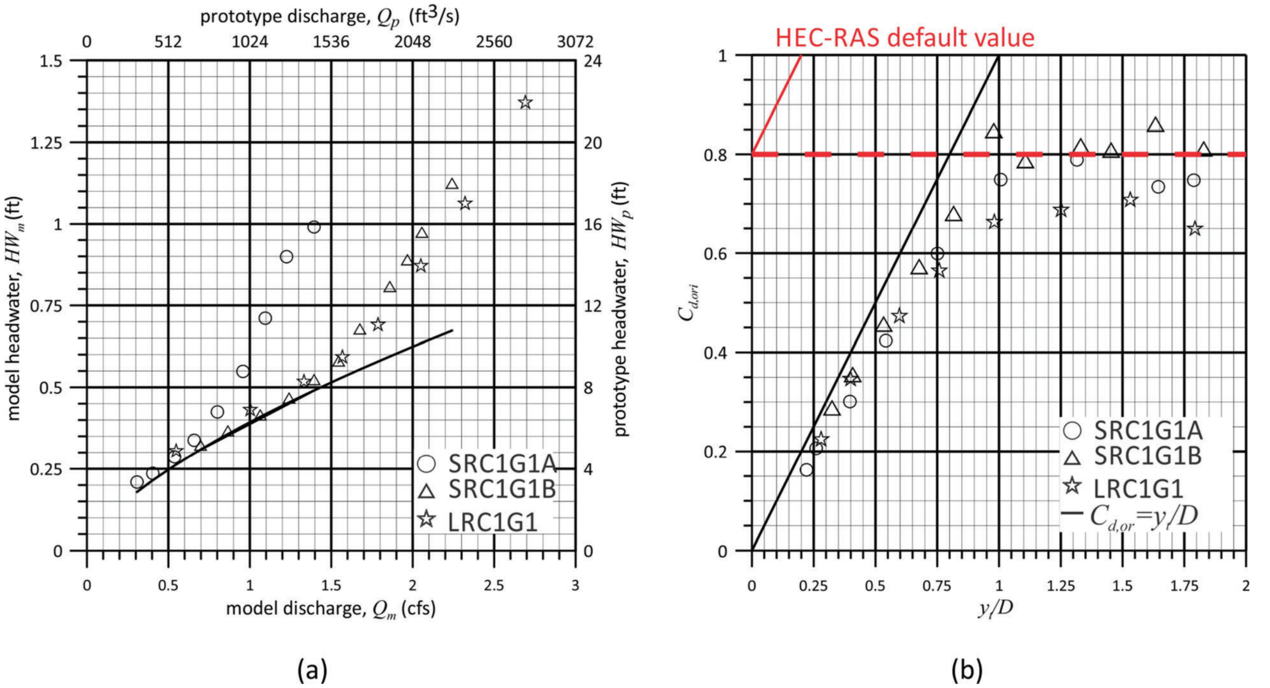


Figure 4.15 Comparison of measured headwater for a single series involving the long structure and for two series involving the short structure over rough beds, with a cover, and gate low enough to generate high tailwater conditions, in (a) dimensional, and (b) dimensionless coordinates.

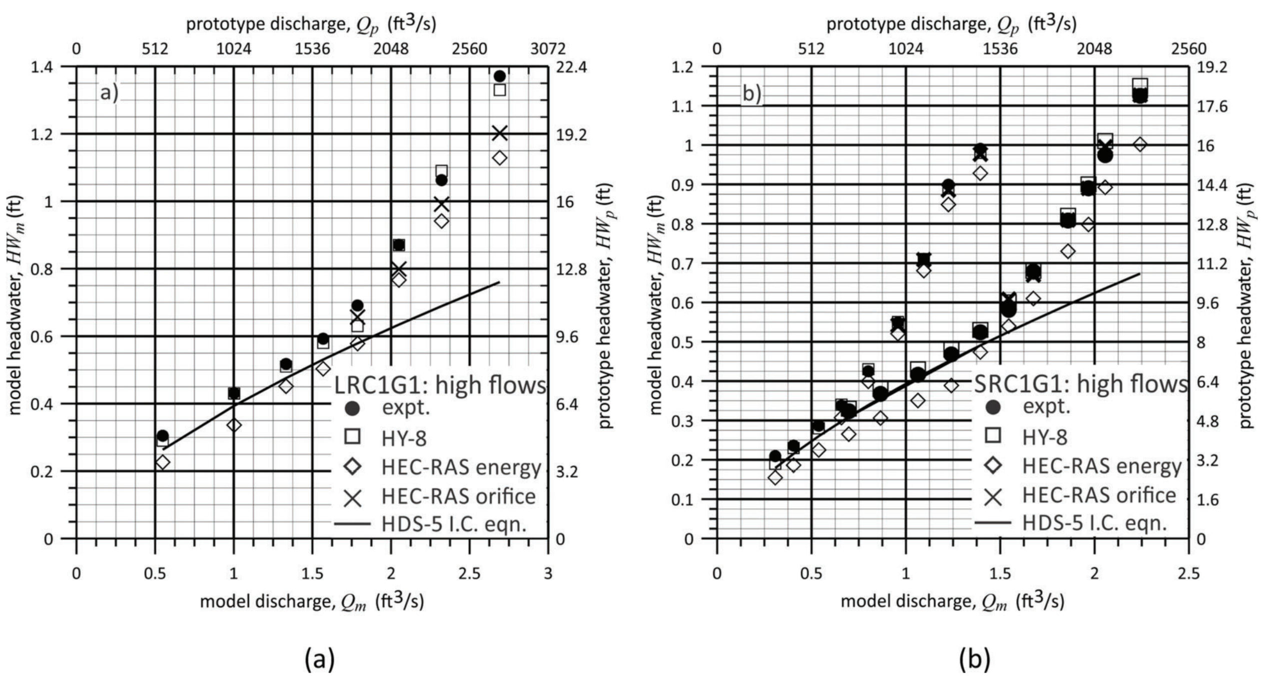


Figure 4.16 Comparison of measurements and predictions of different models (HY-8, HEC-RAS energy, and HDS-5 inlet-control equation, Eq. 4.1) for rough-bed, with-cover, gate-low conditions, (a) long structure, (b) short structure.

As might be inferred from the values of $C_{d,or}$ in Figure 4.15b, both the HY-8 and the HEC-RAS orifice models, and to a lesser extent, the HEC-RAS energy model, perform well for the two rough-bed short-structure series (Figure 4.16b). On the other hand, that the value of $C_{d,or}$ asymptotes to a value of $\approx$0.7 rather than 0.8 for the rough-bed long-structure case implies that the performance of the HEC-RAS orifice model deteriorates noticeably (Figure 4.16a) and the HEC-RAS energy model even more so, but the HY-8 predictions by contrast still agree quite well with the measurements as they account better for the losses within the structure.

4.4 Model Performance Statistics

In the preceding section, the results of the individual series were presented, and the performance of the different models in predicting the headwater, HW_m, was assessed for each series. In this section, an overall assessment of model performance is made. A single overall figure of merit would however be too simplistic as it would lump together quite different flow regimes. It is preferred therefore to examine the performance of the models for different broad classes of flows. The chosen classes correspond approximately, but are not necessarily identical, to the HEC-RAS classification, and hence are labeled differently. They are defined as

- low flows: those cases with no cover or in cases where a cover was in place where neither the inlet nor the outlet was submerged
  - Type A*: those low-flow cases with a high tailwater, i.e., a tailwater depth exceeding critical depth within the structure ($y_t/y_{cc}>1$)
  - Type B*: those low-flow cases with a low tailwater ($y_t/y_{cc}<1$) and hence where hydraulic control was exerted by the structure
- high flows: those cases with a cover in place, and where either the inlet or both inlet and outlet were submerged
  - gated flows (labeled as G): those high-flow cases with the inlet submerged, but with low-tailwater ($y_t/y_{cc}<1$) conditions (and hence unsubmerged outlet)
  - orifice flows (labeled as O): those high-flow cases with both inlet and outlet submerged

Each series as discussed in the preceding section may have more than one flow class. For example, a Type B* flow might have occurred at small discharges, while gated flows might have occurred at large discharges. Further the above classes do not necessarily correspond exactly to the HEC-RAS classes, because in HEC-RAS, more detailed criteria are applied, such as a check on the momentum, to refine the identification of classes. For example, a Type A* flow as defined here could potentially be determined to be a Type B HEC-RAS flow. For that reason, they have been designated here as A* and B* rather than A and B. A prefix (S or L) is used to distinguish between the short and the long structure.

The three basic models discussed previously in Section 4.3 are assessed, namely HY-8, the default HEC-RAS energy model, labeled as HR-E, and the non-default HEC-RAS pressure-weir (labeled as HR-P) model. As discussed in greater detail above, the two HEC-RAS models give identical or nearly identical results for low flows, but differ only in the treatment of high flows. The performance metric is based on the quantity, denoted as F, and defined as the ratio of the model prediction to the observed value of HW_m. The mean, $\overline{F}$, and standard deviation, S_F, are evaluated for each model for each flow class. The closer $\overline{F}$ is to 1 and the smaller S_F is, the better the model performance. In addition, the fraction of points within a certain band was also evaluated. Thus, $f_{<0.9}$ will denote the fraction of points with $F<0.9$, $f_{<9,1.15>}$ the fraction of points with $0.9<F<1.15$, and $f_{>1.15}$, the fraction of points with $F>1.15$. The closer $f_{<0.9,1.15>}$ is to 1 the better. The asymmetric definition of the "acceptable" interval (0.9, 1.15) reflects a preference for a more conservative, i.e., better an overestimate than an underestimate, prediction.

The performance statistics are summarized in Table 4.1, with the best model performance in each flow class being highlighted. It is apparent that, for most flow classes, even for the short structure, the predictions of the HY-8 model agree most closely with the observations. Somewhat surprisingly, only for a flow class with the *long* structure, L-A*, i.e., low flow Type A*, did the HEC-RAS models (recall that both should give the same or very similar results for low flows) prove markedly superior to HY-8, due to HY-8 exhibiting a pronounced tendency to overestimate HW_m (though on average only by 7%). As discussed in Section 4.3.5, this is mainly attributed to a conservative misidentification by HY-8 of the location of hydraulic control—outlet control is determined based on the high tailwater, but in reality inlet control prevailed (the observations agreed with the HDS-5 inlet control model). Thus the relatively poor performance of HY-8 is not necessarily related to a culvert analysis not being applicable (after all, this is applied to the long structure), but rather specifically to the HY-8 conservative strategy of choosing the higher tailwater estimate as correct. A more refined criterion for the location of control under these conditions, possibly incorporating a check on momentum as in HEC-RAS, would likely improve the performance of the HY-8 model. A related issue involves the polynomial model to deal with inlet-control cases, and the transition from unsubmerged- to submerged-inlet cases, as this also tends to lead to notable overestimation for some conditions.

The HEC-RAS bridge models, particularly the default HEC-RAS energy, generally underpredicted HW_m, with a large fraction (over 30%) with $F<0.9$ for several classes. This is of some concern, since more conservative estimates, implying higher HW_m, are usually preferred for design purposes. It is surprising that even for the more bridge-like short structure the HEC-RAS bridge models still underperformed relative to HY-8. This may be explained for the Type B low flows and gated high flows in i) the HY-8 inlet control equations being better suited to the standard inlet geometry than the more generic equations used in HEC-RAS, and ii) the better modeling of effects of roughness. For Type O high flows, the HEC-RAS orifice model performs as well as (or very slightly better than) HY-8 for the short structure. The reason for the relatively poor performance of the HEC-RAS model for Type A* low flows is less clear, but in many cases where HW_m is grossly underestimated for this flow class the tailwater level is relatively low (though still above the critical depth

TABLE 4.1
Performance statistics for the prediction of HW_m by the HY-8, the default HEC-RAS energy (HR-E), and the HEC-RAS pressure (HR-P) models for different flow classes (the best model in each category is shown in red)

Flow class		No. of points	HY-8 $\overline{F}$ (S_F)	HR-E $\overline{F}$ (S_F)	HR-P $\overline{F}$ (S_F)	HY-8 $f_{(0.9,1.15)}(f_{<0.9},f_{>1.15})$	HR-E $f_{(0.9,1.15)}(f_{<0.9},f_{>1.15})$	HR-P $f_{(0.9,1.15)}(f_{<0.9},f_{>1.15})$
Short structure	S-A*	42	1.030 (0.061)	0.918 (0.075)	0.921 (0.078)	0.952 (0.024,0.024)	0.667 (0.333,0)	0.667 (0.333,0)
	S-B*	51	1.050 (0.052)	0.903 (0.072)	0.912 (0.095)	0.980 (0.02,0)	0.529 (0.471,0)	0.490 (0.471,0.039)
	S-G	14	1.044 (0.060)	0.850 (0.093)	1.179 (0.060)	1.000 (0,0)	0.286 (0.714,0)	0.286 (0,0.714)
	S-O	15	1.018 (0.024)	0.924 (0.031)	1.010 (0.026)	1.000 (0,0)	0.733 (0.267,0)	1.000 (0,0)
	S	122	1.038 (0.055)	0.904 (0.074)	0.958 (0.117)	0.975 (0.016,0.008)	0.574 (0.426,0)	0.590 (0.312,0.098)
Long structure	L-A*	11	1.070 (0.081)	0.980 (0.096)	0.980 (0.096)	0.727 (0,0.273)	0.818 (0.182,0)	0.818 (0.182,0)
	L-B*	33	1.027 (0.062)	0.868 (0.083)	0.874 (0.094)	0.939 (0.030,0.030)	0.394 (0.606,0)	0.394 (0.606,0)
	L-G	7	0.986 (0.019)	0.824 (0.041)	1.103 (0.056)	1.000 (0,0)	0.000 (1,0)	0.571 (0,0.429)
	L-O	13	1.003 (0.036)	0.887 (0.043)	0.960 (0.070)	1.000 (0,0)	0.385 (0.615,0)	0.769 (0.231,0)
	L	64	1.025 (0.063)	0.886 (0.087)	0.935 (0.113)	0.922 (0.016,0.063)	0.422 (0.578,0)	0.563 (0.391,0.047)
Overall		186	1.034 (0.058)	0.898 (0.079)	0.950 (0.116)	0.957 (0.016,0.027)	0.522 (0.478,0)	0.581 (0.339,0.081)

in the culvert). This suggests that the flow is being misidentified as a Type B flow, and a critical-flow equation is being applied, when it should not be applied. As Type A* flows are likely the most commonly occurring case, it does raise the broader question whether for actual bridge flows the HEC-RAS bridge model may actually tend to underestimate the upstream water surface elevation.

More detailed analysis could be undertaken, such as separating out the effect of roughness. HY-8 tends to perform better in cases with roughness, as it automatically incorporates flow resistance in its modeling, while the HEC-RAS bridge model is quite limited in this regard. Considering only smooth-bed flows for both short and long structures shows HY-8 performing comparably to HR-E, but somewhat worse than HR-P, but both HR-E and HR-P perform comparatively poorly for rough-bed cases, leading to the overall better performance of HY-8.

Some qualifications in the interpretation of the above statistics should be made, particularly the overall statistics. The study covered a wide range of discharges, not all of which are necessarily relevant to routine design. The smallest (and possibly the largest) discharges at prototype scale might be considered rare, and unlikely to occur in practice. Similarly, some flow conditions such as the Type B* low flows may have been given more weight than is warranted by their frequency of occurrence under typical design conditions.

Despite these qualifications, the results of Table 4.1 support the conclusion that conventional culvert hydraulics as modeled in HY-8 can predict the headwater of culvert-like structures, whether short or long, at least as reliably and perhaps even better than the HEC-RAS bridge models when default coefficients and settings are used in the latter. It may be possible to improve the performance of the HEC-RAS bridge models by judicious selection of non-default coefficients and settings, but this would require greater effort/experience on the part of the engineer. A further consideration that was not addressed in the current study, but may be practically relevant is the effect of common inlet geometry details, such as wingwalls. These would not be directly modeled in HEC-RAS, but would be, at least for inlet-control conditions, in HY-8. Just as the performance of HEC-RAS can be improved, the predictions of HY-8 could also be improved, e.g., by identifying more reliably the location of control, or by more accurately treating the transition between unsubmerged- and submerged-inlet control conditions.

The good performance of HY-8 for both long *and* short structures also calls into question the notion implicit in HDS-5-2012 and other sources that the HEC-RAS bridge model by itself is inherently more capable of dealing with large-span short water-encapsulating structures where the flow is entirely in the free-surface regime, i.e., unsubmerged at both inlet and outlet. The HEC-RAS bridge model does have some broader flexibility in dealing with a wide range of non-standard non-prismatic geometries that may characterize a typical bridge context. Where the tailwater plays an important role, the good performance of HY-8 relies on reasonable specification of the tailwater level. Approximations such as a "uniform"-flow depth may be convenient, but may not yield accurate results. HEC-RAS has the decided advantage of being able to handle complex systems, e.g., multiple structures in close proximity, so that difficulties in setting the tailwater level can be lessened. If however only a culvert-like structure, i.e., with standard inlet and constant barrel geometries, is being considered in isolation, then with reliable input data, HY-8 can arguably give superior results. The larger scale associated with large-span structures may however be accompanied by other concerns, such as stream instability or debris, that cannot be dealt with by *either* HY-8 or HEC-RAS, but may receive greater attention in a more comprehensive bridge-modeling analysis than in a typical culvert-modeling effort.

4.5 Summary

Before an examination of the results of each experimental series, some details of the computations were given, together with reference curves or equations that play a role in the presentation of the experimental results. The eight pairs of experiments, comparing the effects for the long and the short structure, were then considered in turn. Finally, the predictions of HY-8 and the HEC-RAS bridge models were assessed by comparison with the experimental results.

5. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

A laboratory study of the headwater associated with two types of water-encapsulating structures was carried out in order to investigate whether the culvert hydraulic analysis could be justifiably applied to large-span culvert-like structures, namely relatively those with large spans but relatively short streamwise length. Two structures with a standard rectangular (box) geometry of the same span (1.5 ft) and rise (0.5 ft), hence with the same span-to-rise ratio of 3, but of different lengths, 2.1 ft and 8 ft, hence with length-to-span ratios of 1.4 and 5.3, were considered. In addition, experiments without a culvert cover were also conducted to examine so-called low-flow cases, in which the water surface does not reach the culvert crown, and which might be expected to occur more commonly for larger-span structures. The range of flow conditions led to a range of regimes, including that with the critical flow occurring either at the structure inlet or outlet, gated flow at the inlet, orifice-like flow with both structure inlet and outlet submerged, and the simple case where the flow throughout the system was everywhere subcritical (so with hydraulic control downstream of the structure). The effect of roughness was also studied by installing artificial roughness on the bed of both the structure and the model channel.

A key aspect of the research was an assessment of the standard software tools used in the hydraulic analysis of culverts (HY-8) and of bridges (HEC-RAS bridge) in their ability to predict reliably headwater, over the entire range of imposed conditions. Two versions of the HEC-RAS bridge model differing mainly in their treatment of high flows (when the water surface or total head reaches the structure low chord or crown) were tested, the default applying the usual energy equation, and the non-default applying a gated-flow or an orifice-flow model with appropriate default discharge coefficients.

The main conclusions from the study are:

- With accurate input data, conventional culvert hydraulics can predict well the behavior of the headwater for large-span structures that are relatively short in the streamwise direction under a wide range of flow conditions.
    - This success can be attributed to the standard inlet geometry of culvert-like structures that allows for a more customized inlet-control model, and a more flexible treatment of roughness or flow resistance within the structure. The restriction to structures of constant barrel geometry and the reliance on good input data, specifically tailwater conditions, should however be noted.
- The performance of the standard culvert hydraulics software tool, HY-8, was found to be consistently as good and for some flow classes superior to that of either the default HEC-RAS energy-based model, or the non-default HEC-RAS bridge model using the pressure-weir option for high flows, when default choices of discharge and other coefficients were accepted for the HEC-RAS models.
    - With default coefficients and setting, the HEC-RAS bridge models exhibited a pronounced tendency (especially the default HEC-RAS energy approach) to underpredict the headwater.

On the basis of the results of the study, the following recommendations may be made to the INDOT Hydraulics group:

- The current policy restricting the use of conventional culvert hydraulics analysis and HY-8 to structures with span less than 20 ft can be justifiably revised to permit their application to larger-span structures.
    - Neither the current experimental study nor the conventional theory of culvert hydraulics gives an upper limit above which HY-8 may *not* be justified when applied to a single culvert-like structure in isolation. The practical limits of HY-8 are likely to be determined by other issues that could become more relevant as the structure span and the project scale are increased. These may include issues that can be better handled by HEC-RAS such as a complex stream system with multiple structures, making problematic the treatment of any single structure in isolation, or issues that neither HY-8 nor HEC-RAS can directly

handle, such as stream instability, or debris. For the latter type of problems, while a HEC-RAS analysis does not necessarily offer any evident advantage, a bridge-hydraulics design procedure that is more comprehensive than the typical culvert-hydraulics procedure may be warranted.

– A policy wherein the upper limit on allowable structure span is gradually increased over phases, e.g., first to 36 ft for an initial 3 or 4 years, and then even larger if this initial phase is judged successful, is recommended as a prudent option.

6. ACKNOWLEDGMENTS

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APPENDIX. ESTIMATION OF CHANNEL CHARACTERISTICS

A.1 Channel Slope

The streams of Indiana are generally characterized by small slopes, and so it was decided to perform experiments with a small slope. Because the channel's jack system was not completely operational, experiments were performed with only a single slope. A small slope was set and then determined by measuring the bed surface elevation at several sections and then comparing these elevations with that of a still water surface. The results are shown in Figure A.1. It should be mentioned that the channel bed is made from three sheets of Seaboard (2 sheets of length 8 ft, and 1 sheet of length 4 ft) joined end to end, with the ends at $x \approx 0$ in and $x \approx$-96 in, and so some of the scatter in the data may be due to each sheet being of slightly different slope. The average slope was estimated from a linear regression to all of the data points, and was found to be 0.0004 ± 0.00015; the best-fit line in Figure A.1 corresponds to a slope of 0.0004. Although this slope is quite small, it was retained, as supercritical flow conditions in the downstream channel could still be achieved by lifting the tailgate completely. Thus, this slope would permit modeling of Types A and B low flows as well as the different high-flow types. Type C low flows, where the flow is everywhere supercritical could not be simulated but is expected to be rare at design flows in Indiana, and so was excluded from the study.

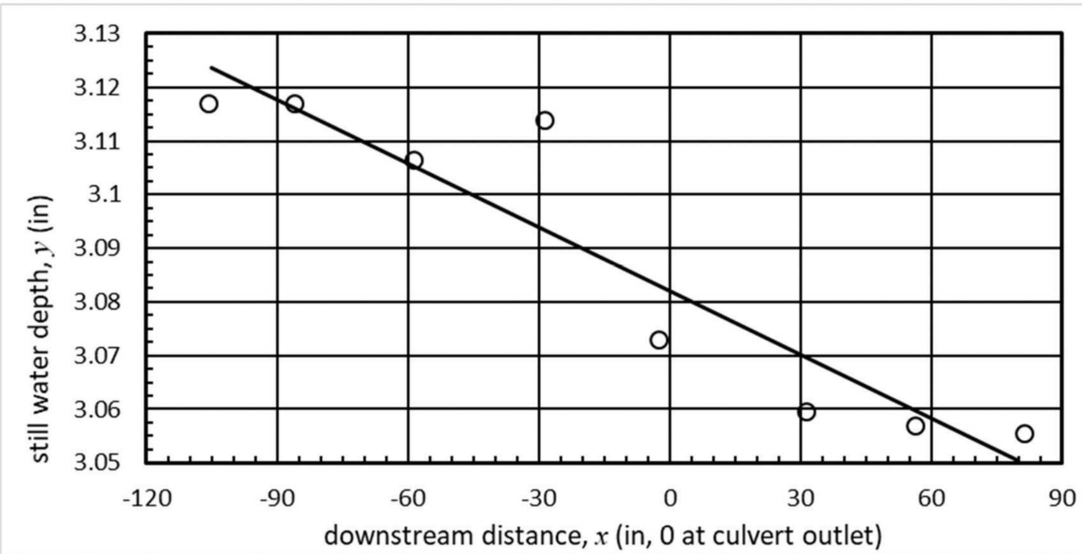

Figure A.1 Measurements of still-water depths used to estimate channel slope.

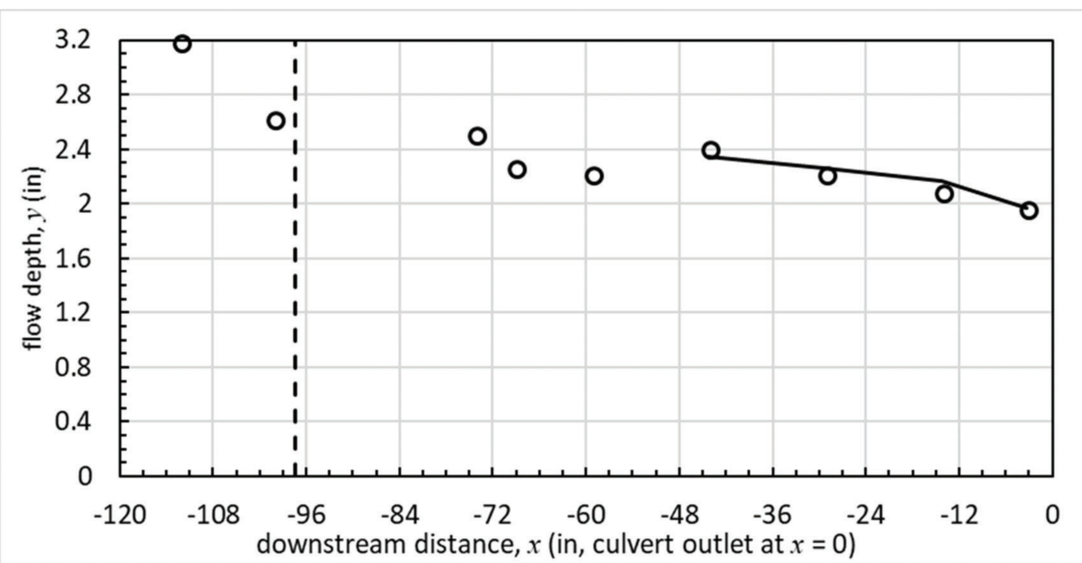

Figure A.2 Water surface profile measurements for flow over a smooth (bare) bed and the best-fit computed profile obtained in estimating Manning's n (=0.011); dashed line indicates location of culvert inlet.

A.2 Channel Roughness

The surface of the Seaboard sheets forming the bed and the sides of the channel was not perfectly smooth, and for model simulations with HY-8 and HEC-RAS the flow resistance coefficient (the Manning's n) needed to be estimated. The water surface profile within the 8-ft-long culvert barrel was measured, and then fitted to a computed profile, assuming a channel slope of $S_0=0.0004$. The flow chosen for the profile fitting was critical at the culvert outlet, so that a simple theoretical check and constraint on the profile was available, and at the same time varied sufficiently that a best-fit estimate would give a meaningful result. Results are shown in Figure A.2 for the chosen profile (discharge, $Q=0.56$ cfs, so that critical depth, $y_c=0.163$ ft), where the culvert inlet is located at $x=-97.5$ in and the outlet at $x=0$. Note that the nonlinear fitting was performed only for the four points in the downstream half of the culvert where the flow was gradually varied; the points in the upstream half of the culvert were observed to be strongly influenced by the rapidly varied inlet flow, which made the computational assumptions questionable. The best-fit estimate for Manning's n was 0.011, indicating the surface to be quite smooth. Due to the small number of points on which this estimate is based, the uncertainty is quite large (the standard error is ≈ 0.0014). At the prototype scale, the corresponding Manning's n assuming a scale factor of 16 would be ≈ 1.6 times the Manning's n at the laboratory scale, so that $n_p \approx 1.6 \times 0.011 = 0.018$, which would be significantly rougher than what would normally be assumed for a concrete culvert (the default value for a concrete box culvert in HY-8 is 0.012).

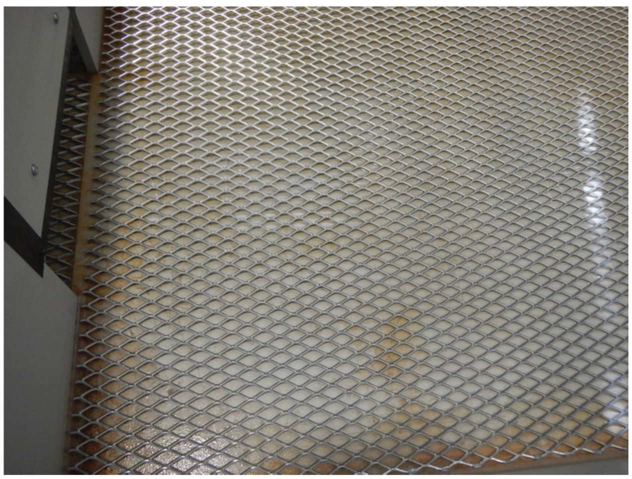

Figure A.3 Expanded-metal grating installed on the channel (and culvert) bed as artificial roughness (the region shown is the channel near the culvert outlet).

The effect of roughness or increased flow resistance was studied by installing artificial roughness elements in the form of a sheet of expanded-metal grating (see Figure A.3). The Manning's n for the roughened channel was estimated in a similar manner as for the bare channel. A complete water surface profile from the downstream end of the channel to a section upstream of the culvert inlet is shown in Figure A.4 for a discharge of 1.13 cfs. Although the downstream gate was high, so that it had no influence on the downstream flow, the added roughness was sufficient to cause a subcritical downstream flow and hence tailwater (in the absence of the roughness, the downstream flow would have been supercritical). Included in Figure A.4 is the best-fit profile (shown as a curve) obtained with a Manning's n of 0.020 (with a standard error of 0.0014) by again fitting over the measured profile in the downstream half of the culvert. The noticeable dips in

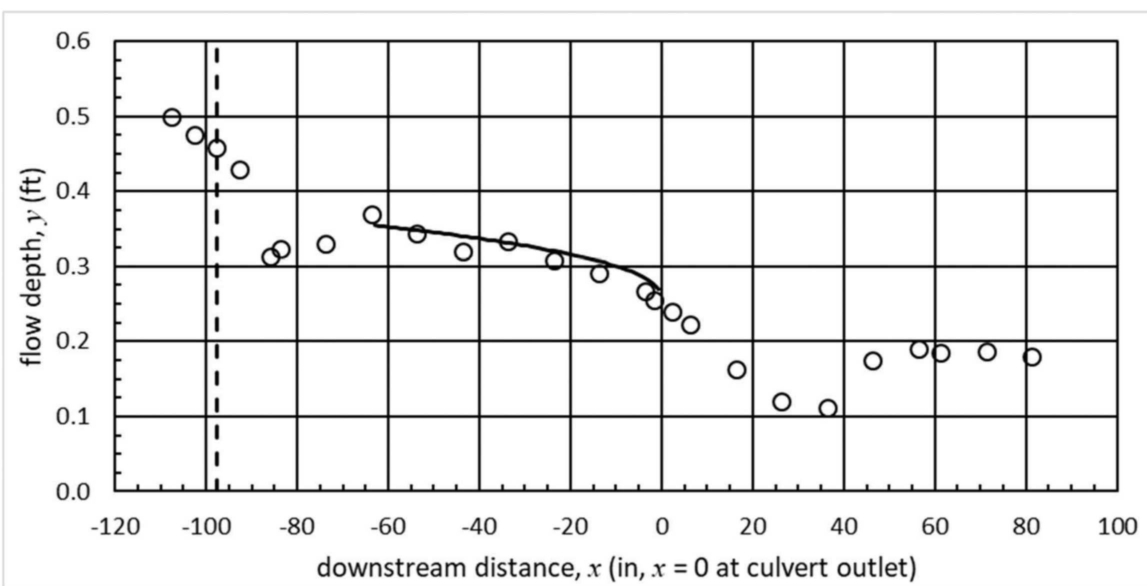

Figure A.4 Water surface profile measurements over the bed (with expanded-metal grating installed on bed as artificial roughness) and the best-fit computed profile obtained in estimating Manning's n (=0.020); dashed line indicates the location of the culvert inlet.

the water surface profile, indicative of rapidly varied flow in the vicinity of the culvert inlet and outlet should be pointed out. Subsequent estimates of Manning's n for other flow conditions based on two-point measurements downstream of the culvert suggested that n varied with flow depth, possibly exceeding 0.04 at the smallest depth (0.095 ft, which may be compared with the 0.025 ft thickness of the expanded-metal elements) to values of 0.015 at larger depths. These later estimates are even more uncertain being based on measurements at only two sections. A further consideration stems from the non-uniform roughness, with a relatively high roughness on the bed and a low roughness on the walls (and perhaps culvert top). In view of these different estimates of n, and effects due to non-uniform roughness, it was decided to use an intermediate value of 0.018 as a common value of n in the model computations.

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On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,600 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

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