National Cooperative Highway Research Program

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Structural Design of Pipe Culverts

An NCHRP staff digest of the essential findings from the final report on NCHRP Project 15-3, "Rational Structural Analysis and Design of Pipe Culverts," by R. J. Krizek, R. A. Parmelee, J. N. Kay, and H. A. Elnaggar, Northwestern University.

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THE PROBLEM AND ITS SOLUTION

Generally accepted methods for the structural design of pipe culverts require determination of the magnitude and distribution of loading and selection of a readily available rigid (concrete) or flexible (corrugated metal) culvert compatible with the loading. Although the Marston-Spangler concepts and the more recently developed ring compression theories are currently being used as a basis for determining the loads, a great deal of engineering judgment is involved in applying these load determination procedures, particularly in the case of rigid culverts. In addition, durability and handling problems, which are frequently critical in the case of flexible culverts, require the exercise of considerable engineering judgment.

One of the major uncertainties faced by the present-day designer is associated with the appropriate consideration of construction practices. This problem, together with the difficulty of specifying a generally acceptable failure criterion, makes the selection of a suitable safety factor extremely complicated. Perhaps the most important reasons which dictate the need for an evaluation of current design practices for both rigid and flexible culverts are the following:

1. There is serious concern about the extrapolation of currently used empirical relationships and field experience to the larger diameter pipes and higher fills coming into use.
2. With culvert-size highway drainage structures resulting in an expenditure of about $500,000,000 annually, the possibility of overconservatism in culvert design should be explored.
3. Current methods used in the design of pipe culverts fail to reflect in a rational way many of the factors that influence behavior in the field; for example, a better understanding of soil-pipe interaction is needed to further the development of intermediate-stiffness pipes made of different materials, such as plastics.

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In view of the expressed purpose of the study to "survey and evaluate existing information and current research" and to "develop a rational design procedure for both flexible and rigid culverts based on the evaluation," a thorough review of literature pertaining to previous and current culvert research was first conducted. Information on engineering practice with regard to design of culverts and practical field problems encountered during their installation was collected. Although a large amount of information is available for evaluation, its applicability to the development of rational design procedures is limited. In addition, the validity of many of the procedures used is strongly dependent on the assumptions underlying the theoretical considerations.

The objectives of the study were partially accomplished in terms of a thorough review of research, design procedures, construction practices, and field performance related to pipe culverts. However, it was determined that information is not available at the present time for the development of completely new and more rational design procedures. Emphasis was placed on (a) identification of conditions for which currently used design procedures, with modifications and improvements, are satisfactory for continued judicious use; (b) improvements to methods for selecting some of the more important material properties used in existing design methods; (c) determination of conditions for which different approaches should be developed; and (d) recommendation of long-range research needs.

FINDINGS

Based on the review and evaluation of all available information, the findings of the investigation are summarized by the following general observations pertaining to the structural design of pipe culverts:

1. Present-day culvert design practice, based largely on work conducted in the 1920's at Iowa State University, has withstood the critical test of time and cannot be readily discounted.
2. Despite the measure of success realized by use of these practices, they are empirical in nature, depend on experience and the exercise of engineering judgment, and several of the assumptions underlying their formulation are subject to question.
3. Although the mechanical properties of culvert materials can be specified within reasonably small tolerances, the mechanical properties of the surrounding and underlying soils present a more formidable challenge.
4. Notwithstanding all efforts to the contrary, there exists an uncomfortably large gap between the design of a culvert and installation practices.
5. In view of the scarcity of failures attributable to design shortcomings, and the fact that failures do not normally entail loss of life, it appears that current design procedures are extremely conservative. However, durability, handling, and construction considerations often control the design, particularly in the case of small pipes.
6. There is an obvious lack of reliable, well-documented field data that can be used to validate new or existing theories.
7. Current safety factor concepts for both rigid and flexible pipes are confusing and ambiguous, generally inconsistent, and sometimes theoretically ill-founded. Some of this misunderstanding arises from the inability to define "failure" in a completely acceptable manner.
8. Most current analysis and design procedures do not take full advantage of the greatly increased reservoir of analytical tools that are available. In this regard, it appears that the chances for achieving substantial long-range improvements lie in applying these analytical tools to the over-all soil-culvert interaction problem and not in modifying some parameters associated with existing methods.

APPLICATIONS

Although the findings listed in the foregoing are quite general in nature, they do provide the background for several specific short-term recommendations for which there is felt to be sufficient research and field experience to justify immediate implementation in the majority of cases. Undoubtedly there are special situations wherein their applicability may be questionable and good engineering judgment must continue to be exercised.

Small-Diameter Pipes Under Shallow to Moderate Fills

The Bureau of Public Roads manuals, "Reinforced Concrete Pipe Culverts: Criteria for Structural Design and Installation," and "Corrugated Metal Pipe Culverts: Structural Design Criteria and Recommended Installation Practices" -- both prepared by Merrill Townsend -- are widely used and generally satisfactory for this category of installation. Design procedures in the rigid pipe manual are based almost entirely on methods developed by Marston and Spangler in the 1920's, whereas the manual for flexible pipe depends largely on the various works of Spangler, Watkins, and White. Both manuals contain charts and tables to facilitate design and construction recommendations.

In the case of shallow fill heights, such factors as handling during construction, durability, and pipe availability are much more significant than structural design considerations, and further refinements of empirical parameters are not justified at this time. In view of current conservatism in culvert design and improvements in backfill placement techniques, some modification of current procedures should be considered when small pipes (up to 5-ft diameter) are to be placed under moderate fill heights, particularly when an occasional failure will not be considered catastrophic. When other factors, such as durability and availability, do not control the design, a value of 1,400 psi should be used for the modulus of soil reaction (E') in the design of flexible culverts, and a value of 0.5 is recommended for the lateral earth pressure coefficient (K) when designing rigid culverts.

Large-Diameter Pipes Under Shallow Fills

There is a vital need for extensive research in this important area. In such cases the significance of live loading and the complexity of load distribution usually dictate a high degree of conservatism. Massive sections are generally required for rigid structures when using conventional design methods. A flexible culvert design procedure that utilizes advantageously the interaction of the soil-structure composite system has recently been developed by Meyerhof, and highly economical structures have been constructed in Canada on this basis.

Large-Diameter Pipes Under Deep Fills

For this condition a decision must be made between the extrapolation of existing design methods and the application of closed-form analytic procedures or numerical techniques, such as the finite element approach. Conventional procedures result in extremely conservative designs from a structural standpoint. The numerical procedures are still in the preliminary development stage and have not been fully verified by field experience. When designing culverts for placement under high fills, full advantage should be taken of the potential supporting capacity of the surrounding soil by use of well-compacted, highly incompressible side-fill material. However, nonlinearity of the soil modulus must be considered under these conditions. Consideration also should be given to flexible conduits of corrugated steel or thin-walled reinforced concrete, rather than massive rigid structures. In design of flexible culverts under these conditions buckling stability also must be considered. The "imperfect trench" method and tunneling through a completed embankment are construction techniques that should be considered in the design process.

Construction Practices

Both good bedding and good backfilling adjacent to the pipe are important to the performance of both flexible and rigid pipes; these requirements become even more significant as the pipe diameter and height of fill increase to the point where structural considerations outweigh handling and durability considerations. For the more critical installations involving high fills, if the stiffness of the natural soil underlying a culvert varies substantially from that of the backfill material, such soils should be overexcavated to perhaps one-half the pipe diameter and replaced with compacted backfill material. For very stiff natural soils or rock, this requirement should be extended to about one pipe diameter. In light of currently available construction equipment, the following construction procedures may expedite the actual installation of a culvert, while at same time improving the reliability with which the loads acting on a culvert may be determined. As one possibility, consider placing the fill without the pipe to a level a few feet above the proposed crown of the pipe; then excavate a relatively narrow trench to receive the pipe, and properly place granular material around the sides of the pipe. Alternatively, consider completing the placement of the fill and installing the pipe by boring or tunneling through the compacted embankment; although this procedure is probably not economically feasible at the present time, except for unusual situations, its effectiveness should increase rapidly in the next few years.

Durability Considerations

No reliable means exist for accurately predicting the performance of a culvert in a given environment. On the basis of an evaluation of available information, the following considerations appear compatible with the present state-of-knowledge:

1. Where the peak flow velocity is excessive and the water contains significant amounts of sediment, allowance should be made for abrasion.
2. Where the normal water pH is less than 4.5, concrete culverts should generally be used. Although asbestos-bonded and bituminous-coated steel and stainless steel have been known to show high resistance to corrosion, further field experience is necessary before their use can be recommended.
3. Where the water pH exceeds 4.5, it may be desirable to provide an additional metal thickness to allow for corrosion. In the absence of local information, the method described in "Durability of Corrugated Metal Culverts," by J. E. Haviland, P. I. Belliar, and V. D. Morrell, Department of Transportation, State of New York (1967) is recommended.
4. Although long-term results are not available, short-term results indicate that aluminum culverts are suitable within the pH range of 4.5 to 9.
5. When concrete culverts are to be exposed to chlorides (deicing salts) and sulfates (coal mine drainage), special considerations should be observed during pipe production, such as the use of air-entrained concrete and sulfate-resistant cement, respectively.

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