Verification of ODOT’s Load Rating Analysis Programs for Metal Pipe and Arch Culverts

Problem

ODOT maintains a large population of Corrugated Metal Pipe (CMP) and metal arch culverts under highways. In order to evaluate the structural capacities of these culverts, ODOT currently uses an in-house spreadsheet program, CMP-Excel. The program considers culvert geometry, design strengths, and load ratings, which are typically calculated following the procedures recommended in AASHTO specifications and NCSPA guidelines. Culverts are generally evaluated based on a load rating factor, which is the ratio of actual live load capacity to the required live load capacity. The load rating procedure includes the load rating factor based on wall strength (RFW) and the load rating factor based on minimum cover (RFC). The lower of these two factors controls the culvert design and capacity. RFW is calculated from the capacity of wall thrust. For deep culverts or lightly loaded culverts, the rating factor based on wall (RFW) is significantly large. If the thrust due to live load plus impact is close to zero, RFW will be close to infinite. RFC is determined from the backfill height over the culvert. However, the culvert material properties are not considered in the load rating. RFC is independent from the thickness of corrugated metal plate as well as internal or external loads. Consequently, current load rating method needs to be revised to develop a more accurate method. To ensure successful performance over the design life, corrugated metal culverts must be designed and evaluated using an improved load rating method.
Objectives

The overall objective of this study is to develop a new load rating method, and to suggest recommendations for improving current load rating methods for corrugated metal culverts. The main goals of this research were to:

- Review ODOT’s culvert database and previous field experiments conducted for ODOT as well as other available sources to decide on a test matrix for testing and analysis of a wide range of CMP and metal arch culverts in Ohio.

- Conduct analyses of typical culverts by taking into consideration all factors involved, such as geometry, loading, backfill depth, soil-structure interaction, and corrugated steel behavior. These analyses were carried out using standard ODOT methods with CMP-Excel. The culverts were also analyzed using available theoretical methods (e.g., ring compression theory), simplified procedures (e.g., AASHTO Specifications), and interaction analysis programs (e.g., CANDE). These analyses helped identify critical test parameters affecting the culvert response.

- Perform field testing of metal pipe and arch structures with different backfill heights, damage and loading conditions, age, and geometry. A test matrix was designed to investigate the effect of certain parameters such as backfill height on the response of existing culverts.

- Compare the field test results with solutions obtained from numerical and analytical methods and tools used by ODOT, and determine for each loading condition and backfill height if the experimental results were expected. To achieve this objective, the calculated structural responses, including displacements, strains, moments and thrust forces, were compared with those obtained from field testing.

- Modify and improve the current load rating programs or develop new methods, if necessary, to analyze CMP and metal arch culverts. Develop recommendations based on evaluation of observed and predicted responses by providing new analysis methods or refinements to the existing programs and tools used by ODOT.

Description

In order to evaluate and improve the current load rating methods for metal culverts, a comprehensive experimental research including field testing of 39 culverts was conducted. The details of the experimental research are presented in this report. The test results are then compared with the response predicted from numerical simulations and theoretical methods. Each component of the load rating procedures is carefully evaluated and detailed analyses are conducted to investigate the accuracy of ODOT’s current load rating procedures. Finally, recommendations are provided to improve the current load rating procedures.

The experimental program was conducted to investigate the influence of several parameters on the field performance of culverts in Ohio. These parameters included backfill height, various static and dynamic load applications, and existing condition, size, shape, and other properties of...
culverts. A large number of test culverts were analyzed using a two-dimensional finite element program, CANDE. Predicted structural responses for the culverts are compared with those obtained from experimental tests. Experimental evidence and available theoretical methods were used to evaluate the load rating procedures adapted by ODOT. Pros and cons of current load rating procedures are extensively reviewed to suggest a better and advanced load rating method. Several recommendations are made to improve the current ODOT load rating procedures. The load rating method proposed in this study removes some of deficiencies of the current load rating procedures.

Conclusions & Recommendations

- Maximum deflections measured in test culverts decreased nonlinearly with increasing backfill height. Maximum deflections were nearly zero for deep culverts with backfill heights greater than 13 ft (4 m). Under both static and dynamic loading, culvert deflections and strains increased significantly when the backfill height was less than about 6.5 ft (2.0 m).
- Maximum deflections measured during dynamic truck loading were approximately 10 to 30% less than corresponding maximum deflections for static truck loading. Experimental data suggest that developing and calibrating culvert design methodologies using static deflection data is more conservative, and it eliminates the need to perform more sensitive dynamic load tests.
- There was no significant direct relationship between the maximum deflections and total truck weight for the culverts tested. However, a more reasonable relationship was obtained between the maximum deflections and AASHTO equivalent line load, $q$, which is a function of backfill height. Additional scatter is observed in the data for $q \geq 1.7$ kips/ft (25 kN/m). This indicates that culvert behavior is more difficult to predict when backfill heights are shallower because other factors, such as soil type and culvert age and condition, likely play a significant role. Culvert deflections decreased with improved culvert condition (i.e., by increased general appraisal number).
- Deflections predicted by the computer program CANDE for both the silty sand (SM) and silty clayey sand (SC) and theoretical methods were larger than experimental results. However, experimental thrust forces are similar to predicted and theoretical thrust forces. Thrust forces for two different soils (SM and SC) are similar. This result suggests that the effect of soil type on thrust forces is negligible. As supported by this conclusion, generally, soil type is not considered in load rating methods.
- ODOT’s current load rating procedures have some deficiencies. First, engineering judgment can influence the load rating significantly. Two similar culverts may have the same general appraisal numbers and similar damage, but may have quite different load ratings depending on the engineer who rates the culverts. Second, the rating factor based on minimum cover (RFC) is only a function of backfill depth, AASHTO minimum cover and span length. Culvert material properties, magnitude of applied loads or severe damage in culvert do not affect RFC. Finally, for deep culverts or lightly loaded
culverts, the rating factor based on wall (RFW) is significantly larger. If the thrust due to live load plus impact is close to zero (no live load pressure on the crown) RFW will be equal to infinity.

- Rating factors (RF) are calculated for the 39 test culverts assuming that all culverts are severely damaged and they are in worst possible condition. Most of the calculated RF values were larger than 1.0 indicating that most culverts would be safe even if they are severely damaged. This suggests that the current load rating procedures need to be revised as they seem to be unconservative and generally ineffective in identifying possible unsafe culverts.

- Several recommendations are made to improve the current ODOT load rating procedures. First, the proposed procedure does not include rating factor for cover depth, RFC. However, the cover depth must be checked during the initial design stage to ensure structural stability. Formulations to calculate the thrust capacity are the same. However, new reduction factors are introduced to reduce the design seam strength and wall area to reflect the current condition of the culvert reported during annual inspections. The usage of the buckling factor is extended to three cases to consider different culvert conditions including excessive crown deflection and local buckling. Finally, two load-rating procedures are proposed depending on the magnitude of the thrust produced by external live loads. The first one is for culverts subjected to very small live load stress, or for deep culverts, where the thrust due to live load is less than 1.0 k/ft (14.6 kN/m). It is recommended that the effect of live load be neglected in load rating evaluation of deep culverts, and inventory load rating is not necessary. When the thrust due to live load is larger than 1.0 k/ft (14.6 kN/m), the operating and inventory rating factors need to be calculated.

- Our analysis showed that the AASHTO minimum cover requirements might not apply to some large-span culverts constructed with relatively thin corrugated steel plates. In addition, the AASHTO minimum cover may not be applicable to damaged structures, for example due to steel corrosion, because the requirement is not related to structural properties. The proposed minimum cover requirement is related to cover, span length, and structural properties.

- In this study, it is recommended to use separate appraisal numbers for wall and seam conditions because the condition of wall and seam are not always the same. New reduction factors are introduced to account for damage and deterioration of seam and wall of the culvert using the appraisal numbers reported during regular inspections.

- The thrust capacity of wall calculated using the current ODOT procedure is very similar to the one proposed in this study. However, the wall thrust capacity calculated from the proposed procedure is typically smaller because the wall, seam and buckling strengths are reduced more by the proposed new reduction factors.

- We recommend a new load rating method for culverts subjected to very small live load stresses. Generally, these are deep culverts because the effect of external live load over the culvert is reduced as the cover depth increases.
The rating factors are very large for these culverts if the current ODOT procedure is used. In the proposed method, the effect of live load stress is ignored if the cover depth is larger than 6.5 ft (2.0 m) or the thrust due to live load is less than 1.0 k/ft (14.6 kN/m).

- For the worst possible culvert condition (i.e., the reduction factors have the minimum possible values for each culvert), proposed rating factors (RF) are smaller than ODOT’s RFs and are also less than 1.0 for most culverts. This suggests that the proposed load rating procedure is less conservative and more effective in evaluation of existing culverts.

- Some culverts with very thick plates (number 5 or smaller gauge number) are strong enough to have a RF larger than 1.0 even for the worst culvert condition. One of the objectives of the proposed procedure was to identify culverts if they become unsafe (when RF < 1.0). No matter how bad the condition of the culvert is, some of the culverts tested in this study will always have a RF larger than 1.0. In other words, these culverts will always be safe unless excessive deflections (i.e., deflection ratio at crown ≥ 10%), extreme local buckling or other specified severe damage conditions are reported.

- The design method for bridges has recently been changed from AASHTO Standard Specifications to AASHTO LRFD Bridge Design Specifications (2006). Although the load rating procedure and resistance factors are not changed, the method for live load application has changed. Based on the results of our load rating analysis using the AASHTO LRFD Specifications, we recommend to use AASHTO LRFD Specifications for live load application, which is more complicated than the method included in the AASHTO Standard Specifications.

**Implementation Potential**

The researchers suggest the following implementation plans as a result of this study:

- The researchers recommend implementation of the proposed load rating procedures, which should be relatively easy for ODOT. The current in-house load rating program, CMP-Excel can be updated quickly by adding some new factors and changing several formulations, as recommended.

- The proposed load rating method is recommended to eliminate engineering judgment that can influence the load rating significantly. Two similar culverts may have the same general appraisal number and similar damage, but may have quite different load ratings depending on the engineer who rates the culverts.

- Regarding RFC, the proposed minimum cover can ensure the structural stability because the proposed minimum cover is related to cover, span length, and structural properties. Although the AASHTO minimum cover requirements is used in the culvert design, the AASHTO minimum cover may not be applicable to large-span culverts and damaged structures because the requirement is not related to structural properties.

- We recommend separate appraisal and reports for wall and seam conditions during regular culvert inspections. In this study, use of separate
appraisal numbers for wall and seam is recommended because the condition of wall and seam is not always the same. New reduction factors are introduced to account for damage and deterioration of seam and wall of the culvert using the appraisal numbers reported during field inspections.

- The recommended separate appraisal numbers for wall and seam conditions is useful to manage and monitor culvert damage and deterioration. Also, separate reduction factors corresponding to the appraisal numbers is more effective to obtain more accurate load ratings.

- The proposed load rating method is effective, especially for deep culverts. The rating factors for these culverts calculated from the current ODOT procedure are almost always very large. In the proposed method, the effect of live load stress is ignored if the thrust due to live load is less than 1.0 k/ft (14.6 kN/m).

- Although the load rating procedure and resistance factors are not changed in the AASHTO LRFD Bridge Design Specifications, the method for live load application has changed. It is recommended using AASHTO LRFD Specifications for live load application, which is more complicated than the current standard method, and creates more critical culvert response.

- It is recommended to change the current in-house load rating program, CMP-Excel to implement the proposed load rating procedures or live load application for AASHTO LRFD Specifications.