SURFACE LOAD TESTING OF NEW CIRCULAR AND ELLIPTICAL METAL CULVERTS AT SHALLOW COVER

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Tests conducted in the GeoEngineering laboratory at Queen’s examined the ultimate strength of buried circular and elliptical metal culverts under shallow cover. A circular culvert of 0.9 m diameter at cover depth of 0.45 m responding to a single wheel pair load at the ground surface over the crown was found to have strength controlled by full plastic moments developing at the shoulders and crown. This failure mechanism is different to that addressed in the AASTHO standards (which examines springline thrusts), and it occurred at loads lower than the required load capacity.

Testing of a horizontal ellipse of 1.6 m span and 1.35 m rise was also conducted at 0.45 m of cover, but under simulated tandem axle loading. This structure also had strength controlled by bending at the shoulders and crown.

Comparisons of experimental thrusts were made to estimates based on AASTHO design equations. These demonstrated that the maximum live load thrusts observed in the culverts at 0.45 m of cover were 136% and 197% of the AASHTO design estimates (for the circular and elliptical structures, respectively), while design estimates of thrust for cover of 0.9 m were reasonable and conservative compared to the experimental observations at that greater depth. Further study is recommended with the aim of either defining minimum burial depths for which AASHTO design can be employed, or changing the design equations for estimating thrust demand and introducing consideration of flexural limit states for small span corrugated steel pipes at shallow cover.

Key words: small size metal culverts, surface load response, flexural strength limits, laboratory testing, AASHTO design procedures

1. INTRODUCTION

Since late in the 19th Century, corrugated metal culverts have been extensively used as highway culverts given their low cost, light weight, and the ease of construction. Design procedures developed in the 20th Century have performed

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well, including those employed by the American Association of State Highway and Transportation Officials (AASHTO). Like other pipe design methods, the standards employ simple models that consider demands (e.g. springline thrust) resulting from earth and vehicle loads, and simple resistance models (e.g. thrust capacity). To the authors’ knowledge, there is no perception that the design procedures have been performing poorly, or leading to unsafe structures.

However, the development at Queen’s University of the world’s first laboratory facility designed to enable service load and ultimate limit state testing of shallow buried culverts under simulated vehicle loads (Moore and Brachman, 2012) presents a valuable opportunity for many important new studies. For example, research projects are investigating ‘how much deterioration is too much deterioration’ (e.g. Mai et al., 2014; Regier et al., 2017), and studying the performance of rehabilitation methods like grouted slip liners (e.g. Smith et al., 2015; Tetreault et al., 2017), spray-on-cementious liners (Becerril García & Moore, 2015; Moore & Becerril García, 2015) and paved inverts (Tetreault et al., 2017) have been conducted. These include ‘control’ tests, where the performance of new (uncorroded) steel culverts is measured prior to examining the deteriorated structures.

This paper discusses the results of two ‘control’ tests – one on a 0.9 m diameter circular pipe (corrugation amplitude 67.7 mm and depth of 12.7 mm, with plate thickness 1.6 mm), and another on a new elliptical structure of 1.6 m span and 1.35 m rise (amplitude 25.4 mm, period 76.2 mm, and thickness 1.82 mm). The testing conditions and measurements associated with those experiments are outlined, and then comparisons made to the AASHTO LRFD design procedures. The differences between measured responses and the AASHTO calculations and their implications for engineering design are then presented and discussed.

2. CONFIGURATIONS FOR THE CONTROL TESTS

Figure 1 shows drawings of the two pipe testing configurations being examined. Pipes were buried in the 8 m by 8 m by 3 m deep West test pit at the laboratory.

![Diagram](image)

Figure 1. Test configurations for two corrugated steel pipes at 0.45 m burial (modified from Regier et al., 2017 and Regier et al., 2016, respectively).
Both pipes were tested at two burial depths and under different loadings:
1. At burial depth of 0.9 m, loads were applied up to full AASHTO (2012) and Canadian Highway Bridge Design Code (CSA, 2014) service loads; CHDBC load geometries were employed; the circular pipe was tested under a steel plate of length 0.6 m and width 0.25 m, representing a wheel-pair; the elliptical structure was tested under two steel ‘axle’ beams representing a tandem axle load configuration with four wheel-pairs;
2. Burial depth was reduced to 0.45 m, and the structures reloaded up to full AASHTO service loads for the same CHDBC load geometries;
3. For the ellipse at 0.45 m, load plates for the wheel pairs were increased to 370 mm x 950 mm to delay bearing failure of the unpaved ground surface; loads were then increased to produce the ultimate limit state (ULS).

Figure 2a shows the circular pipe instrumented with optical fibres (under the black wrappings used for their protection) during burial in sandy gravel backfill. Figure 2b shows burial of the ellipse in the same backfill. Figure 3 shows the single wheel pair load pad used over the circular pipe and the tandem axle loads over the ellipse, the latter with the larger ULS test load-pads. Details of the compaction and density are given by Regier et al. (2016, 2017).

Figures 4 and 5 show sample data illustrating the effect of surface loading on the culvert thrusts and moments. In each case, the circumferential distributions of thrust calculated from average strain and moments calculated from curvatures are presented. For the circular pipe, thrusts and moments are close to zero around most of the bottom half of the structure, increasing noticeably above zero only at the East springline. Zones of significant compressive thrust occur at the shoulders and the crown, and bending moments of opposite sign develop in the shoulders and the crown. Yield moments are also shown on Figure 4b, revealing that at the service load of 71.2 kN on the wheel pair, the magnitude of the nega-
tive moment at the crown reaches the yield moment, and the positive moment at the shoulder reaches 75% of yield moment. In comparison, the thrust reaches less than 15% of the value calculated to produce crushing. There is evidence, however, that for this structure, backfilling in low density, low modulus material exacerbated the bending behaviour (see Regier et al., 2017).

Experimental bending moments in the ellipse are shown in Figure 5 for tandem axle load of 624 kN, which corresponds to wheel pair loads of more than double those used to generate the circular pipe data given in Figure 4. Since the ellipse was fabricated from flexurally stiffer and stronger corrugated plate, maximum measured bending moments remain below the yield moments for this much stronger corrugated plate, Figure 5b. Failure ultimately occurred as a result of plastic moments developing, producing the plastic hinge shown in Figure 6.

![Figure 3. Loading geometries for service and ultimate strength tests](image-url)
Figure 4. Stress resultants in circular pipe under 71.2 kN wheel-pair (from Regier et al., 2017)

a. Thrusts

b. Moments
Figure 5. Stress resultants in elliptical pipe under 623.8 kN tandem axle load

a. Thrusts

b. Moments
4. COMPARISON TO AASHTO DESIGN CALCULATIONS

AASHTO (2012) features thrust calculated for corrugated steel pipes as half of the total vertical pressure at the top of the pipe due to earth and vehicle loads $P_F$ multiplied by culvert span $S$:

$$T_L = \frac{P_F S}{2}$$

Vertical pressure

$$P_F = H \gamma_s + \frac{F_L\min. \ (W_0 + LLDF\cdot H\cdot OD)}{(L_0 + LLDF\cdot H)(W_0 + LLDF\cdot H)}$$

for burial depth to the crown $H$, soil unit weight $\gamma_s$, vehicle load on the ground surface $F_L$, surface contact length (parallel to the pipe axis) $L_0$, surface contact width $W_0$ (parallel to the pipe span) and live load distribution factor $LLDF$ (=1.15 for coarse grained backfills like the GP-SP test soil used at Queen’s).

Table 1 presents a comparison between test measurements and calculations using AASHTO (2012). Since the AASHTO procedures focus on design to resist thrust, the experimental and design code calculations for thrust are compared (even though measured strength at shallow cover was controlled by bending). Results are presented at the two burial depths used, 0.45 m and 0.9 m. The comparisons indicate that:

a. Thrusts measured at springlines were consistently lower than the AASHTO design model estimates;

b. Peak thrusts were actually observed at the crown or shoulder;

c. The design model estimates of thrust for both structures at 0.9 m were reasonable and conservative compared to the experimental values (measurements that were 73% and 88% of the design calculations); and

d. The design model estimates of thrust for both structures at 0.45 m were unacceptably unsafe relative to the experimental values (measurements that were 135% and 197% of the design calculations).
Testing reported by Mai et al. (2014) for a corroded steel culvert also revealed some shortcomings of the AASHTO design models for corrugated steel culverts.

All the measurements and design calculations are for unpaved roads, and the presence of a flexible or rigid pavement at the ground surface can be expected to lead to substantial reductions in the live load responses (as calculated for long span, deeply corrugated structures by Elshimi et al., 2014). Furthermore, the calculations presented here focus on vehicle load effects alone, and performance of the design procedures at very shallow cover may be better when earth loads are taken into consideration. Nevertheless, culvert design in North America purposely neglects the benefits of any pavement, because culverts need to maintain stability when a truck pulls over onto an unpaved shoulder and when pavements are absent during construction or reconstruction. Therefore, based on these test results, it is recommended that further study be undertaken to either

a. identify a minimum cover condition below which the AASHTO design procedure for small span corrugated metal culverts cannot be employed, and/or
b. establish design models to estimate bending moments in small span metal culverts, and require design of those structures considering flexure, and/or
c. modify fill height tables or other design guidance to address flexural design for very shallow cover based on more sophisticated analyses, like 3D finite element methods (e.g. Moore & Taleb, 1999; Elshimi et al., 2014).

Table 1. Thrust calculations based on AASHTO versus test measurements

<table>
<thead>
<tr>
<th>Applied load kN</th>
<th>Cover depth m</th>
<th>AASHTO thrust kN/m</th>
<th>Test thrust kN/m</th>
<th>location of maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Springline</td>
<td>Maximum</td>
</tr>
<tr>
<td>wheel pair load over 0.9 m circular pipe</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>71.2</td>
<td>0.45</td>
<td>40.4</td>
<td>10 (25%)</td>
<td>55 (136%)</td>
</tr>
<tr>
<td>50</td>
<td>0.9</td>
<td>16</td>
<td>4.8 (30%)</td>
<td>11.8 (73%)</td>
</tr>
<tr>
<td>tandem axle load over 1.6 m span ellipse</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>367</td>
<td>0.45</td>
<td>52.3</td>
<td>52.5 (100%)</td>
<td>103 (197%)</td>
</tr>
<tr>
<td>342</td>
<td>0.9</td>
<td>34.9</td>
<td>26.7 (76%)</td>
<td>31 (88%)</td>
</tr>
</tbody>
</table>