

MEASURED RESPONSE OF A DEEPLY CORRUGATED BOX CULVERT TO THREE DIMENSIONAL SURFACE LOADS

By

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ABSTRACT

Metal box culverts constructed from 400mm by 150mm plate resist applied loads largely in flexure and design predominantly focuses on bending moments rather than the thrusts considered for conventional corrugated plate. Moment distributions, deformations and thrusts have been measured during tests conducted on a deep corrugated metal box culvert (span of 10m, rise of 2.4m) and are reported for a truck of total load 240kN placed at eight locations across the culvert, with cover of 1.04m. Loading under the dump truck demonstrates the changing pattern of circumferential bending, with peaks moving across the culvert under the tandem axles at the rear of the truck. Bending for a truck weight of 240kN has a peak value less than 12 kN.m/m, which is less than 15% of the yield moment for the steel structure. Measurements at different axial locations from the culvert and truck centerline to 3m away demonstrate different levels of axial spreading for deflection, thrust and moment. Deflections are relatively uniform, moments decrease to about half of their peak values 3m away, and crown thrust actually becomes tensile at that 3m distance. The highly three dimensional nature of the response to vehicle load indicates that conventional design using two dimensional finite element analysis is very conservative.

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1. INTRODUCTION

The strength and stiffness of metal culvert structures depends on the composite behaviour of both the metal and soil components, e.g. [1-3]. While considerable work has been performed to understand the nature of load-sharing at normal operating loads e.g. [3-5] (the earth and vehicle loads expected in service), little is known about behaviour at load levels approaching collapse, how the different components of the composite system reach their strength limits, and how loads are redistributed from components in distress to others that still have reserve capacity. Since it has not been possible to conduct experiments that bring these structures up to and beyond their fully factored design loads (due to their size, the difficulty of finding trucks capable of carrying these loads, and the dangers associated with testing to ultimate limit states using weights on test vehicles), it has not been possible to observe this nonlinear response and model it confidently on the computer. Current theories of metal culvert strength therefore assume that load sharing between the components at collapse is identical to load sharing at service loads. Furthermore, deeply corrugated metal box culverts are an important culvert type that deserves further study to develop and assess design equations for use in Canadian [6] and US culvert design standards [7].

A Bridge PlateTM deep corrugated structural plate box culvert with a 10-m-span and 2.4-m-rise has recently been tested under controlled laboratory conditions using service loading applied using a truck. The experiments were conducted in the large scale buried infrastructure test facility at Queen's University. Objectives of this research program include:

- a. Upgrading the test facility to enable testing of large span culverts to their ultimate limit states
- b. Development of an experimental database for deep corrugated box culverts to support design methods developed for bridge design standards

- c. Acquisition of experimental data for use in developing or evaluating the performance of two dimensional and three dimensional computer models
- d. Measurement of the ultimate limit state for a large span metal culvert, to determine the reserve capacity and the possibility that strength assessments could be upgraded without compromising other aspects of the culvert performance (such as deflections under service loads)

The three dimensional structural response to 24 tonne tandem axle vehicle loading is reported here. Culvert response to fully factored loads will be documented in subsequent publications

2. TEST STRUCTURE, BACKFILLING, AND INSTRUMENTATION

The geometry of the test structure is illustrated in Figure 1. The structure has radius of 11.285 m at the sides, radius of 1.325 m at the shoulders, and radius of 11.285 m across the crown. The culvert was constructed on footings cast into the floor of the test pit, resting on granular fill below. The corrugated plate has wavelength 400mm, depth 150mm, second moment of area I of $23154 \text{ mm}^4/\text{mm}$, cross-sectional area A of $8.26 \text{ mm}^2/\text{mm}$, and thickness of 6.1 mm.

The culvert was erected in the large test pit in the GeoEngineering Laboratory at Queen's University (plan dimensions of 16m by 8m, and depth of 3m), Figure 2a. The culvert was then backfilled with well-graded gravel-and-sand backfill (Unified Soil Classification System: SW; AASHTO Classification: A-1-a), Figure 2b. It was placed in 0.2-m-thick lifts and compacted to a minimum of 95% of its Standard Proctor Maximum Dry Density using vibratory plate compaction

The deflection of the culvert was captured by an electronic theodolite ("total station") that monitors three directions of movement of prism targets fixed to the culvert, to a fraction of a millimeter, Figure 3. All results presented here are for the central circumferential section

of the culvert, Figure 3a. Deformations were also monitored using digital cameras and string potentiometers, though due to space restrictions these readings will be presented elsewhere.

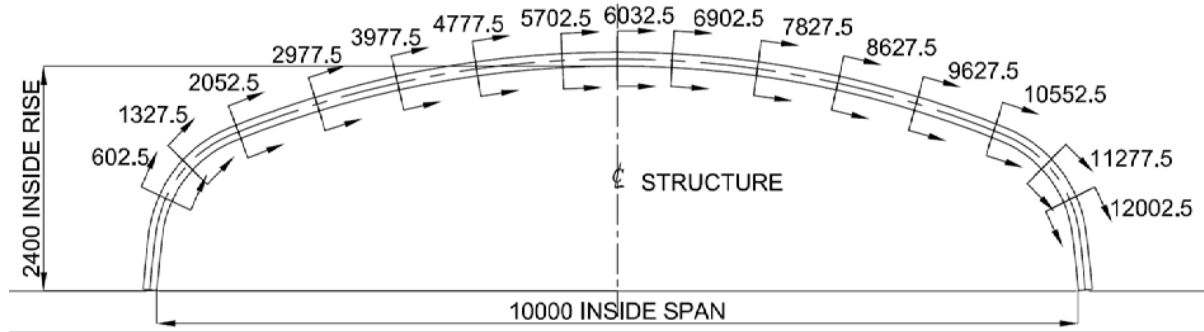
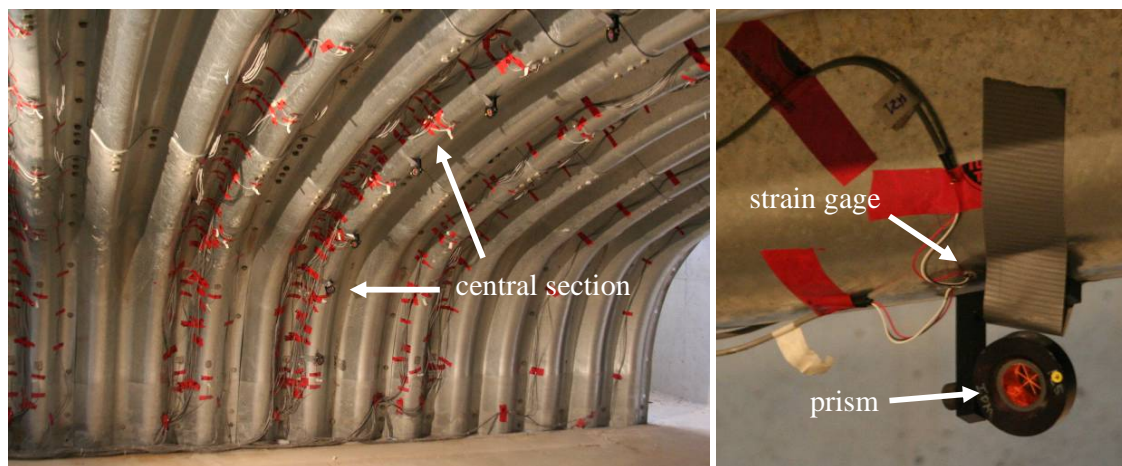


Figure 1. Box culvert geometry with locations of strain gages shown.



Figure 2. Culvert erection and backfilling.



a. Prisms and strain gaging

b. Detail of prism and strain gage

Figure 3. Instrumentation on the culvert (inside view).

Strain gauges were affixed to the culvert at several circumferential and axial locations (circumferential locations are shown in Figure 1; axial locations are illustrated in Figure 3a). Biaxial gages were used to measure circumferential and transverse strains. Circumferential strain measurements were used to calculate values of curvature κ_{θ} :

$$\kappa_{\theta} = \frac{\varepsilon_1 - \varepsilon_2}{h_1 - h_2}$$

for circumferential strains ε_1 and ε_2 measured at two locations with height (distance) relative to the neutral axis of the corrugated plate, h_1 and h_2 (one position is above the neutral axis with positive value of h , and one is below the neutral axis with negative value of h). In this paper, bending in the culvert is plotted as values of $EI\kappa_{\theta}$, where E is the elastic modulus of steel (2×10^5 MPa). For cases of elastic steel response (when strain values ε_1 and ε_2 are less than the yield strain), the value of $EI\kappa_{\theta}$ corresponds to the circumferential bending moment. For cases where the strain values exceed the yield strain, the value of $EI\kappa_{\theta}$ is greater than the bending moment in the corrugated plate. The $EI\kappa_{\theta}$ values are plotted in this article are for the central circumferential section along the unfolded length of the culvert. Values of strain at the corrugation mid-surface ε_c were also calculated and used to infer thrust, $EA\varepsilon_c$.

3. LOADING

Table 1 summarizes all load tests performed on the structure. Tests were performed:

- a. prior to backfilling (denoted A1 and A2)
- b. using a heavily loaded dump truck (denoted B1 to B8) at cover depth of 1.046m (illustrated in Figures 4 and 5)
- c. using an actuator and an axle loading frame, for culvert backfilled to three different cover depths (from ground surface to the lowest part of the corrugation) of 1.507m, 1.00m, and 0.45m

The actuator tests were performed with a high capacity steel frame designed to simulate either the standard single or tandem axle AASHTO HS20 loading patterns, but to much higher loads (a maximum of 2000kN). The tandem axle configuration is detailed in Figures 6 and 7. The actuator is held below the reaction frame shown in Figure 7, featuring four columns anchored into the limestone bedrock located below the base of the test pit. The frame permits the actuator to be located in different longitudinal positions. Two locations were used for this test program: one where the actuator was located centrally in the pit, and one with a 2m offset. Results presented later in this article are for tests B1 to B8.

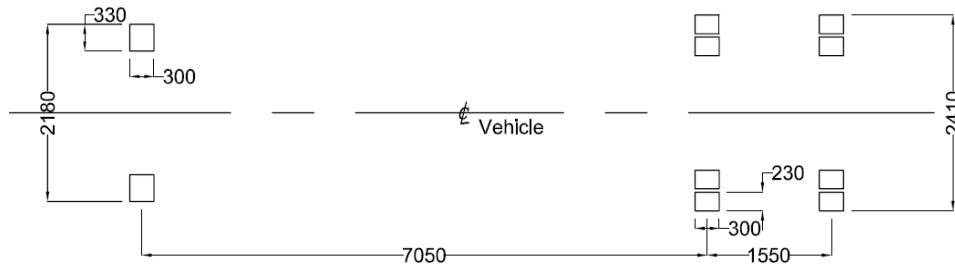
Table 1 Summary of all tests (results for B1 to B8 and E5 are reported later in this article).

Test	Cover ⁴ (mm)	Loading	Axle offset to culvert centre (m)	Maximum applied force (kN)
A1 ⁵	No soil	Single axle	0	30
A2 ⁶	No soil	Single axle	0	40
B1	1046	Tandem axle dump truck	6	240
B2	1046	Tandem axle dump truck	5	240
B3	1046	Tandem axle dump truck	4	240
B4	1046	Tandem axle dump truck	3	240
B5	1046	Tandem axle dump truck	2	240
B6	1046	Tandem axle dump truck	1	240
B7	1046	Tandem axle dump truck	0	240
B8	1046	Tandem axle dump truck	-1	240
C1	1507	Single axle	0	197.8
C2	1507	Tandem axle	0	275
D1	1000	Single axle	0	215.3
D2	1000	Tandem axle	0	328.4
D3	1000	Single axle	2	215.3
D4	1000	Tandem axle	2	328.4
E1	450	Single axle	0	234.5
E2	450	Tandem axle	0	351.4
E3	450	Single axle	2	234.5
E4	450	Tandem axle	2	351.4
E5a	450	Tandem axle	0	800
E5b	450	Tandem axle	0	1200

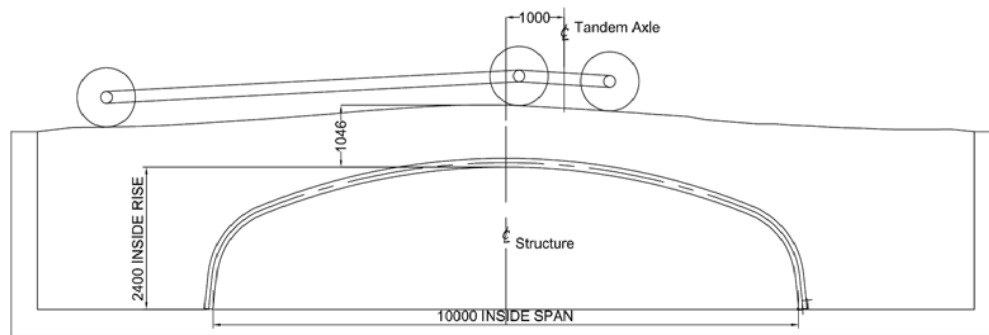
⁴ Distance from the lowest part of corrugation at the interior crown to the top of the soil at culvert centre.

⁵ Without headwalls and soil.

⁶ With headwalls and without soil.



a. Plan view



b. Elevation illustrating the last truck position and the backfill profile.

Figure 4. Geometry of the dump truck.



Figure 5. Truck over the culvert during testing.

4. CULVERT DEFLECTIONS

Figure 8 provides details of the incremental deflections of the middle circumferential ring of the structure. These are magnified by a factor of 200. Peak deflection under the truck load of 240kN was 9.5mm.

The deflection patterns appear entirely logical. The eccentricity of movement of the structure under the dump truck decreased steadily as the tandem axle at the rear of the truck approaches centre-span. However, with the two axles symmetrically placed on either side of the culvert crown in Test B7, there is still noticeable eccentricity in deformation, with the peak movement located a meter or so to the left of the centerline. This is likely the effect of either loads applied by the front axle of the truck, and/or the residual effect of vehicle approach from one side.

Perhaps most surprising is the magnitude of the residual deformations that remained immediately after the dump truck was driven off the structure (about two thirds of the maximum deflection), though much of this deformation decreased over the next 24 hours.

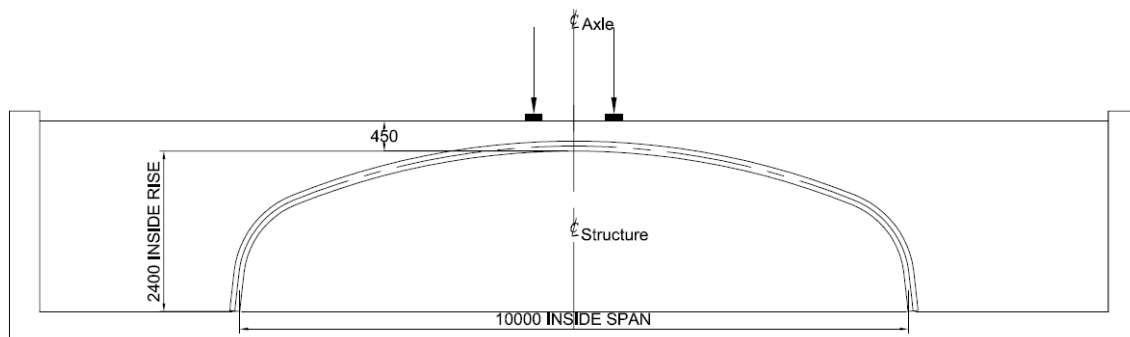


Figure 6. Location of the axle loads and the backfill profile for the ultimate limit state test.



a. Close-up of load frame

b. Overall view of test in the large scale test pit.

Figure 7. Reaction frame, actuator and axle frame during testing for fully factored axle loads.

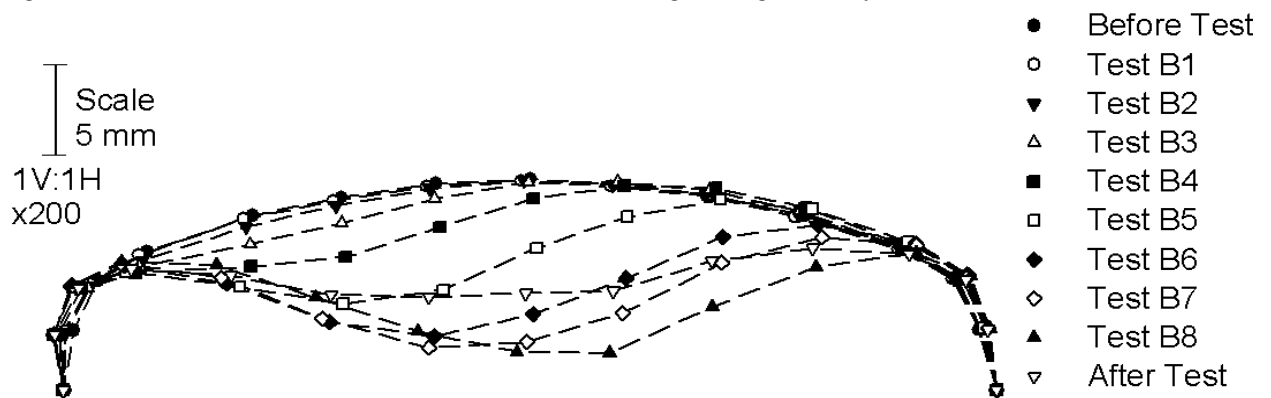


Figure 8. Culvert deflections for different truck locations (magnified by 200).

5. CULVERT BENDING

Figure 9 shows the pattern of incremental bending that developed in the structure during Tests B1 to B7. Figure 10 shows how bending moments during Test B7 varied in the axial direction. The regular, logical patterns of bending imply that the instrumentation worked successfully, and that curvature measurements are effective. Peak magnitude of $EI\kappa$ at the centerline of the structure was less than 12kN.m/m under the vehicle load of 240kN (a negative moment just left of the crown associated with inward movements at this location). This is well short of the value needed to induce yield (over 90 kN.m/m for yield stress of the steel of 300MPa). Of course, this incremental bending does not include the bending induced

by earth loads and construction operations, though it is significantly below yield moment and it is clear the structure is well short of its ultimate limit state.

Peak positive moment was similar in magnitude to the peak negative moment. This occurred at the left hand shoulder for the center of the tandem axles 2m to the left of the culvert crown. A positive moment of similar magnitude occurred about 3m to the right of the culvert crown during Test B7.

Bending directly under the wheel pads (at an offset of 900mm) was only slightly higher (peak of 13 kN.m/m), Figure 10. Moments degraded to about half their peak values at an axial distance of 3m.

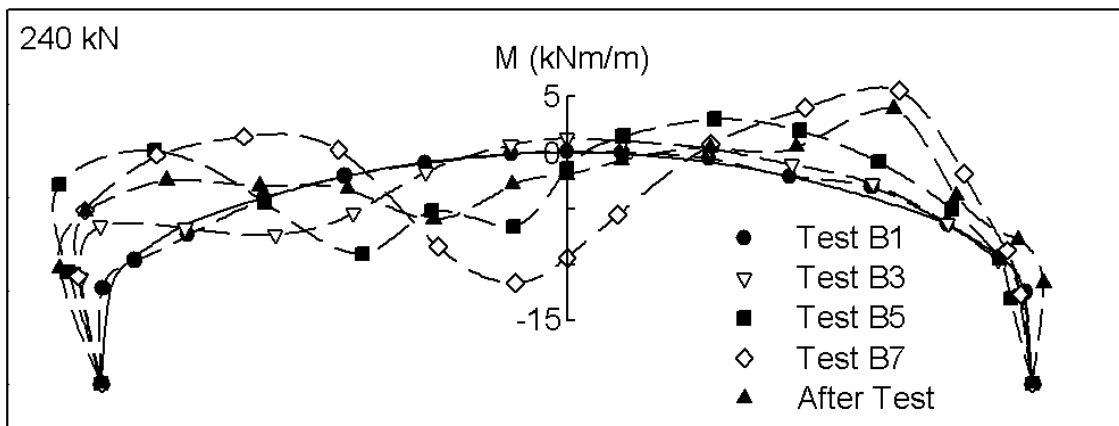


Figure 9. Incremental $EI\kappa_{\theta}$ distributions along the centerline ($z=0$) for different truck locations.

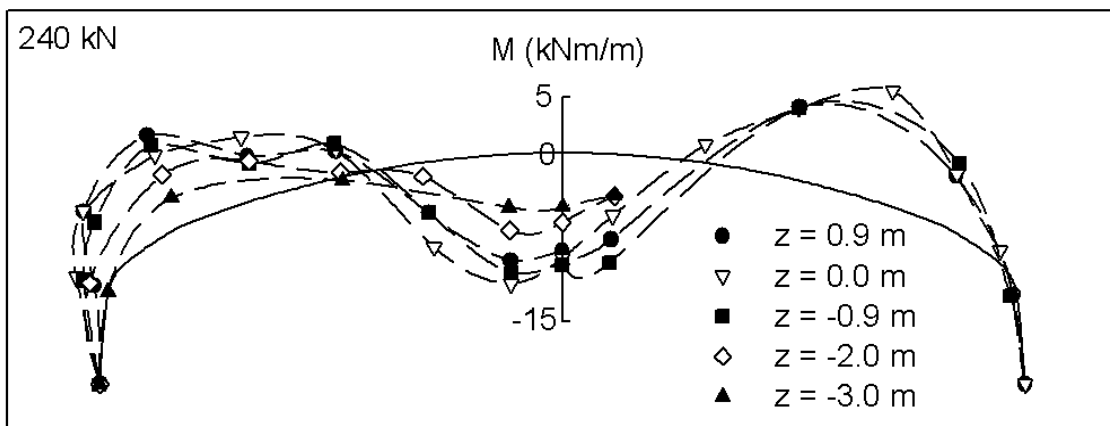


Figure 10. Incremental $EI\kappa_{\theta}$ distributions at different axial locations (Test B7).

6. CULVERT THRUST

Figure 11 shows the patterns of incremental thrust for tests B1 to B7. The peak thrust of 95 kN/m is far below the crushing force for this deep corrugated plate (over 2400 kN/m for yield stress of 300 MPa). The importance of moments as opposed to thrusts for these structures is clear. A qualitative assessment of Figure 11 indicates that the patterns of thrust are not as smooth as those seen for bending. This is likely a result of values of average strain ε_c that are much lower than bending strains that develop at the extreme fibers, so they are more sensitive to measurement errors. The patterns are, however, logical, and imply that strain measurements during the tests are able to provide good (though not excellent) experimental values of thrust.

Variations in thrust in the longitudinal direction are illustrated in Figure 12, and these show considerable three dimensional effects. First, measurements taken near the crown directly under the wheels (at axial locations $z=\pm 0.9\text{m}$) are almost double those taken at the culvert and truck centerline ($z=0$). Further attenuation occurs in the axial direction, and incremental crown thrust is almost zero at axial location of $z=2\text{m}$, and positive (tensile) at $z=3\text{m}$. It is clear that three dimensional effects influence thrust distributions considerably more than the moments. This suggests that conclusions about relationships between 2D and 3D surface loading resulting from the three dimensional studies on conventional large span metal culverts reported by Moore and Taleb (1999) and McGrath et al. (2002) have may also be relevant to deeply corrugated box culverts.

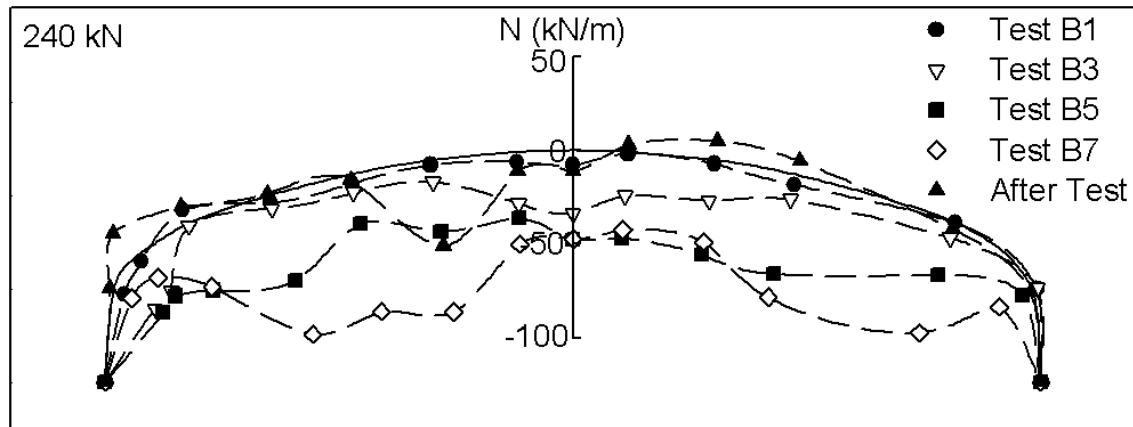


Figure 11. Incremental thrust (kN/m) along the centerline ($z=0$) for different truck locations.

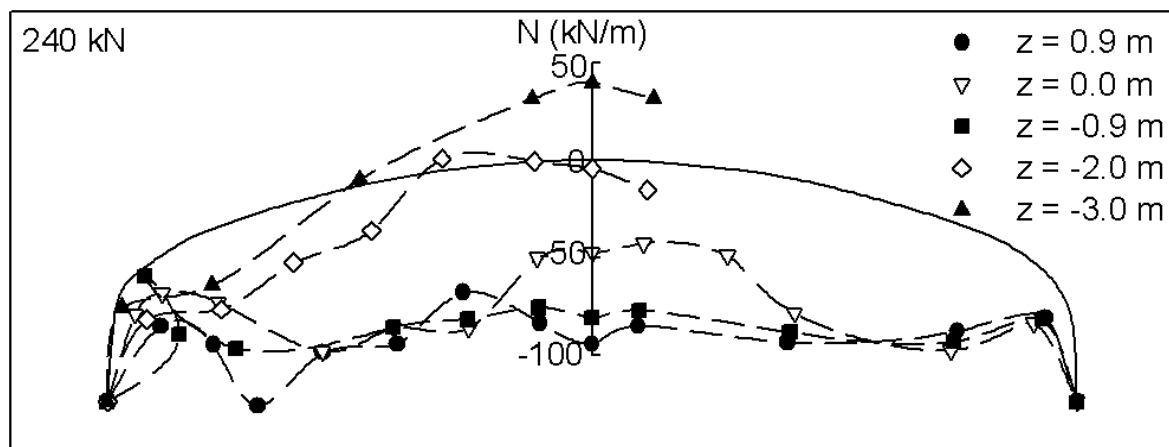


Figure 12. Incremental thrust (kN/m) distributions at different axial locations for Test B7.

7. DISCUSSION AND CONCLUSIONS

A deep corrugated metal box culvert was constructed in a large scale test pit upgraded to permit loading from real trucks and also using standard single and tandem axle design loads applied with a servo-controlled test system. The experiment produced effective measurements of the three dimensional patterns of deformation and strain, with those strain measurements permitting the culvert moments and thrusts to be calculated.

For the tests conducted using a dump truck with a tandem axle load of 240 kN, the maximum deflection was 9.5mm. The maximum moments and thrusts were 13 kN.m/m and 95 kN/m, respectively. These resulted in incremental circumferential stresses that were well below yield for this structure.

Subsequently, the actuator system was used to load the structure to an ultimate limit state of approximately 1100 kN onto a tandem axle, at cover depth of 450mm. This produced failure by local yield close to locations beneath the applied load. This is 2 times larger than that of the fully factored CHBDC and AASHTO tandem axle loads.

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