# Behaviour of a deep-corrugated large-span box culvert during backfilling

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ABSTRACT
This paper presents results from a full-scale experiment of a 10-m-span deep-corrugated metal box culvert. The culvert was instrumented and backfilled with compacted Granular A material under controlled laboratory conditions to a cover depth of 1.5 m. Two and three-dimensional finite element analyses were performed to model its behaviour during backfilling. The effect of soil compaction on the culvert's response during backfilling was also considered in the model. The results showed that the maximum upward displacement during side backfilling of the structure to a height of 1.8 m was only 3.2 mm and the maximum deformation measured in a single lift occurred when the first lift of soil was placed over the crown. The three-dimensional finite element analysis was able to calculate central deflections and maximum bending moments within 5 and 6% of the measured values.

RÉSUMÉ
Cet article présente les résultats d'une expérimentation grandeur nature pour une durée de 10m dalot métallique profond ondulé. Le ponceau a été instrumenté et remblayé à l'aide un matériau granulaire dans des conditions contrôlées en laboratoire à une profondeur couvercle de 1,5 m. Deux et trois dimensions analyses par éléments finis ont été réalisées pour modéliser le comportement du ponceau durant le remblayage. L'effet du compactage du sol sur la réponse du ponceau au cours de remblayage ont été également pris en compte dans le modèle. Les résultats ont montré que le déplacement maximum à la hausse au cours de côté le remblayage de la structure d'une hauteur de 1,8 m n'était que de 3,2 mm et la déformation maximale mesurée dans un ascenseur unique s'est produite lors de la première levée de terre a été placé sur la couronne. L'analyse par éléments finis a été en mesure de calculer détournements centrale et le maximum des moments de flexion dans 5 et 6% des valeurs mesurées.

## 1 INTRODUCTION

Long-span metal box culverts can be used as an alternative to typical short-span concrete or steel stringer bridges. They have been gaining in popularity in recent years because of rapid construction and relatively low cost. The behaviour of long-span metal box culverts is significantly influenced by the backfill material. The structure gains strength from the interaction with the surrounding soil, and the steel and soil components form a composite structure. The behaviour of this kind of structure during backfilling warrants consideration. The vertical displacement at the crown due to placement of side fill (i.e. peaking) can be a major concern during backfilling long-span metal culverts assembled from conventional (shallow) corrugated plates (with a pitch of 152 mm and a depth of 51 mm). For long-span culverts with deep-corrugated plates, displacements during backfilling are expected to be smaller. For the same plate thickness, the deep corrugated plates have about nine times the bending stiffness and three times the bending capacity of shallow corrugated plates.

Most of the work reported in the literature for the behaviour of long-span culverts during backfilling focuses on culverts with conventional shallow corrugated plates (e.g., Katona, 1978; Duncan, 1979; Taleb and Moore, 1999). Some recent studies have examined the behaviour of long-span metal box culverts having deep corrugated plates (e.g., Choi et al., 2009; Flener, 2010). Choi et al. (2009) presented a two-dimensional analysis to examine the 2000 Canadian Highway Bridge Design Code (CHBDC) moment equation for long-span metal box culverts. However, the equation Choi et al. proposed is believed to be very conservative. For example, the earth load bending moment calculated using that equation for a 10.5 m span culvert with 1 m soil cover is 1.5 times the plastic moment of the deep-corrugated section, even though the measurements of Lougheed (2008) indicate that this structure has considerable reserve capacity at this burial level. Flener (2010) presented a two-dimensional finite element analysis for four long-span metal box culverts. However, the analysis underestimated the displacement and thrust forces during backfilling compared with the measured values.

The objectives of this paper are to: 1) report a set of experimental measurements of deflections, strains and structural resultants for a deep-corrugated large-span box culvert backfilled in controlled conditions using well-graded sand and gravel; and 2) present results from two and three-dimensional finite element analyses of the culvert using orthotropic shell theory to model the structure.

## 2 EXPERIMENTAL DETAILS

Figure 1 shows the layout and geometry of a long-span deep-corrugated box culvert backfilled to cover depth of 1.5 m, as measured from the bottom of the corrugation at the inside crown to the top ground surface. The particular culvert tested had a bottom span of 10 m, an inside rise of 2.4 m and a length of 6 m.

The circumferential direction ($\xi$) is defined in Figure 1 as the curve of the box culvert in the x-y plane along the neutral surface of the corrugation, starting at the crown, while the axial direction (z) is defined along the length of the culvert. Directions x and y are also defined in Figure 1, where a point beneath the centre of the box culvert at its bottom corresponds to x=0, y=0 and z=0. The culvert was fabricated from galvanized steel plates with a corrugation pitch (wavelength) of 400 mm, corrugation depth (amplitude) of 150 mm, and plate thickness of 6 mm. The crest and valley locations of the corrugation are shown in the inset of Figure 1a, while the crown and shoulder locations of the box culvert are shown in Figure 1b. The box culvert was backfilled with 21 layers of dense well-graded sand and gravel (denoted as granular A in Ontario) to a cover depth of 1.5 m, as shown in Figure 2.

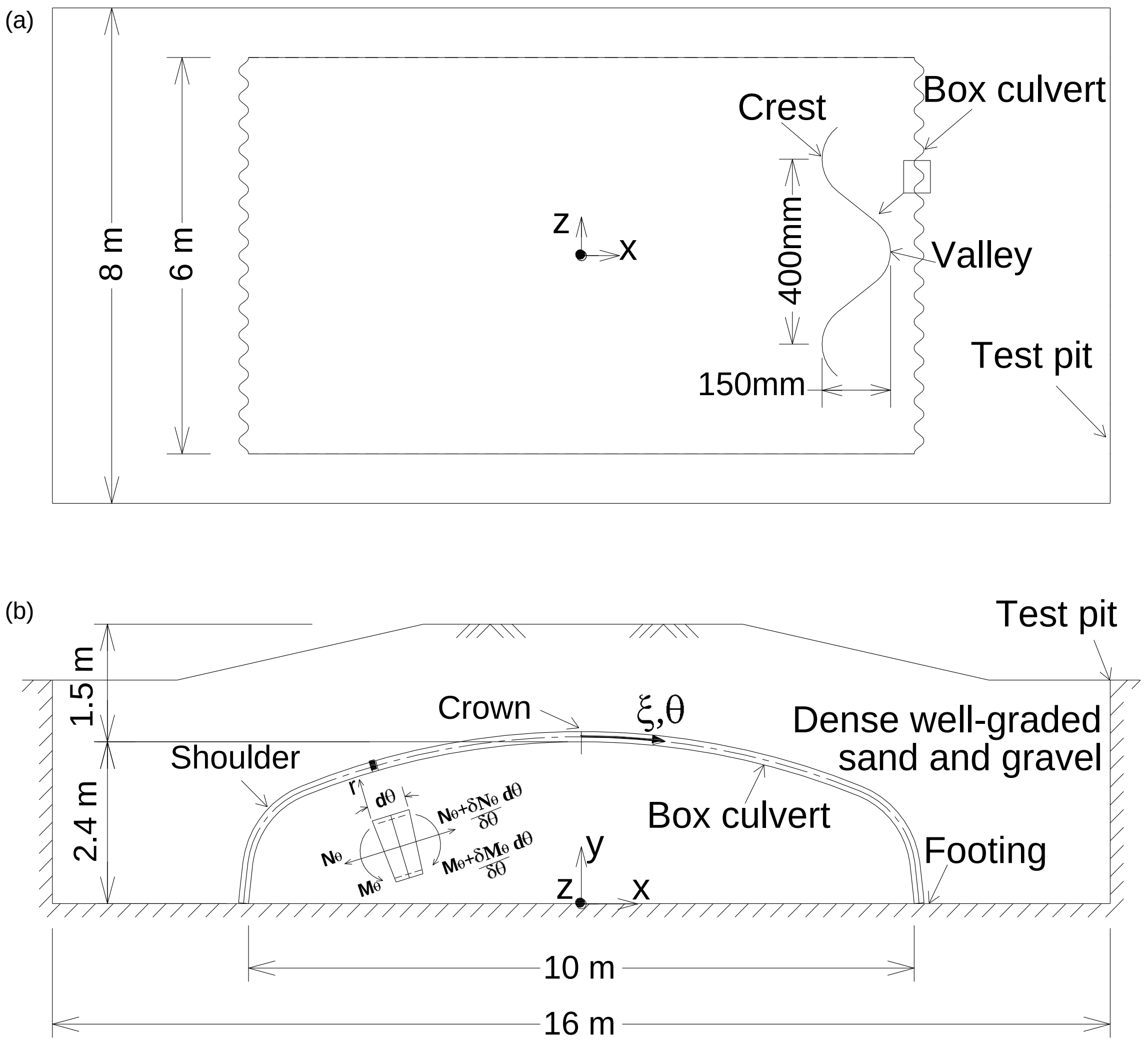


Figure 1. (a) Plan and (b) elevation views showing the layout and dimensions of the box culvert

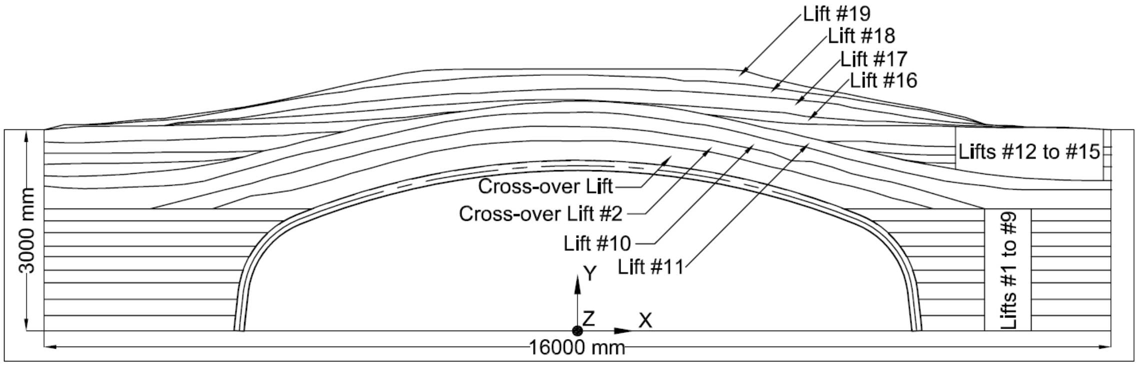


Figure 2. Soil layers (drawn to scale) as recorded by laser level during compaction

The backfill was compacted to just over 100% of the maximum dry density obtained using a standard Proctor test. The culvert was backfilled using light weight equipment and the soil was compacted using a light weight vibrating plate. It should be noted that use of other light weight construction equipment (e.g., like a D4 dozer) may be permitted by the manufacturer's specifications for backfilling in the field. Any effects of loading from such equipment during backfilling are not considered in this paper.

The structural response of the culvert (strains and deflections) was monitored using various instruments. Combinations of 5 mm 120 Ω uni-axial and 5 mm 120 Ω bi-axial strain gauges were used at selected circumferential and axial locations. Uni-axial gauges were used to measure either circumferential ($\varepsilon_\theta$) or axial ($\varepsilon_z$) strain, while bi-axial gauges were used to measure both $\varepsilon_\theta$ and $\varepsilon_z$ at selected locations. An electronic theodolite (Leica TCA2003 with TPS1000 system total station) was used to monitor the deflection of prisms attached to the underside of the culvert to ± 0.2 mm.

## 3 NUMERICAL DETAILS

The box culvert was modeled using two and three-dimensional finite element analysis using the program ABAQUS. In the two-dimensional analysis, the structure was modeled using a series of beam elements with equivalent modulus and thickness calculated as follows:

$$t' = \sqrt{\frac{12I}{A}} \qquad [1]$$

$$E' = \frac{12EI}{t'^3} \qquad [2]$$

where:

t′ = equivalent beam thickness,
I = second moment of area of the plate/unit length,
A = area of the plate/unit length,
E′ = equivalent modulus for the plate, and
E = modulus of steel.

This approach imposes the same stiffness in the circumferential and axial directions, despite the fact that this structure is much stiffer in the circumferential direction.

The culvert was also modeled using three-dimensional finite element analysis employing orthotropic shell theory (i.e. with different stiffnesses in the circumferential and axial directions). The analysis modelled the corrugation as a solid, prismatic section by using the four-noded shell elements along the neutral surface of the section using equivalent material parameters (see Moore and Taleb 1999 for calculations of orthotropic parameters). Table 1 provides the input parameters used for the shell elements in the three-dimensional analyses.

Table 1. Input parameters for shell elements for three-dimensional analysis

| Property | Value |
|---|---|
| Equivalent thickness t′ | 158 mm |
| Young's modulus in circumferential direction ($E_\theta$) | 12,000 MPa |
| Young's modulus in axial direction ($E_z$) | 10.9 MPa |
| Equivalent shear modulus in local element coordinates 1-2 and 1-3 | 2,170 MPa |
| Equivalent shear modulus in local element coordinates 2-3 | 5.6 MPa |
| Poisson's ratio, ν | 0 |
| Yield stress | 15.2 MPa |

A Mohr-Coulomb failure criterion was used to model shear failure in the soil and the resulting plasticity. The properties of granular material reported by Scott et al. (1977) were used in the analysis. Soil parameters used in the analysis are shown in Table 2. The interface between the soil and the structure was modelled as bonded, as shown to be reasonable for this sort of problem by Taleb and Moore (1999).

Figure 3 shows the finite element mesh used for three-dimensional finite element analysis. Only one-quarter of the test was modelled because of symmetry. In the two-dimensional analysis, the soil was modelled using 6-noded modified quadratic plane strain triangle elements, while it was modelled using 10-node modified quadratic tetrahedron solid elements in the three-dimensional analysis. The boundary conditions, where the box culvert was attached to the floor, were modeled by applying the displacement boundary conditions directly to the locations of the bolts, neglecting the deformations in the base angles which connected the structure to the base (the floor of the test pit). The boundaries of the test pit shown in Fig.1, where soil met concrete walls of test pit, were modeled with rough rigid boundaries.

Table 2. Properties of granular backfill material

| Property | Value |
|---|---|
| Density ($\gamma$) | 21.5 kN/m$^3$ |
| Secant modulus of elasticity (E) (at confining pressure of 50 kPa)* | 60 MPa |
| Poisson's ratio ($\nu$) | 0.30 |
| Peak secant friction angle* | 56$^o$ |
| Dilation angle ($\psi$) | 20$^o$ |
| Cohesion | 3 kPa |

* Scott et al. (1977)

The method introduced by Taleb and Moore (1999) was implemented here to model the compaction. The method provides information on the likely effects of soil compaction. The concept is to impose horizontal earth pressures that remain in the soil after compaction. This earth pressure is set equal to the passive earth pressure, since this will be an upper bound to the horizontal stresses expected in the soil. The response of flexible and rigid structures to earth pressures resulting from compaction is different. For flexible structures, the structure deforms under this horizontal pressure and much of the additional lateral earth pressure is released as the structure deforms. For rigid structures, the structure does not deform and the horizontal earth pressures remain, acting to change thrusts or moments (especially at the crown).

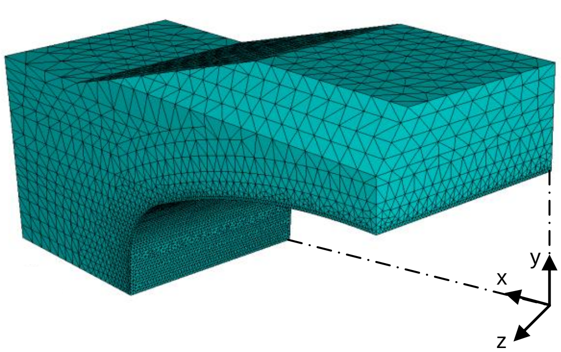


Figure 3. Finite element mesh for orthotropic analysis

## 4 RESULTS

### 4.1 Deformed Shape

Figures 4 to 6 show the global deformed shape of the box culvert at a soil cover of 0.45, 1 and 1.5 m, respectively. The deflections are magnified by a factor of 30 to illustrate the pattern of deformation. Vertical downward displacement was measured at the crown while upward and lateral displacement directed away from the centre of the culvert was measured at the shoulder.

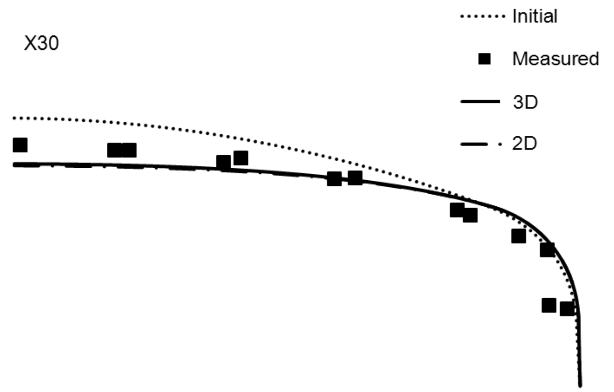


Figure 4. Global deformed shape at a soil cover of 0.45 m

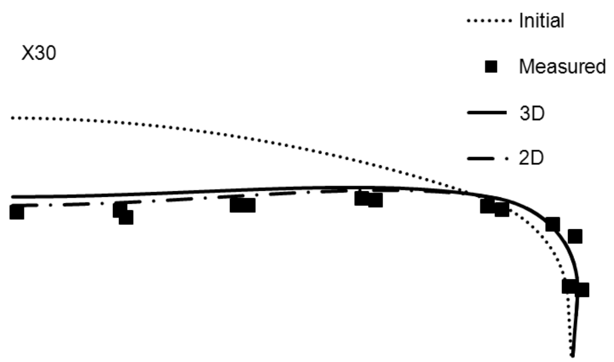


Figure 5. Global deformed shape at a soil cover of 1.0 m

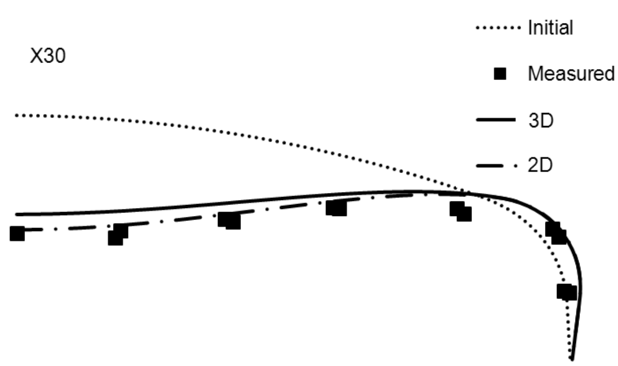


Figure 6. Global deformed shape at a soil cover of 1.5 m

Both two and three-dimensional analyses successfully captured the general pattern and the magnitude of the displacement at different heights of soil cover. At a soil cover of 1.5 m, the two-dimensional analysis calculated the displacement at the crown within 3% of the measured values, while the three-dimensional analysis calculated the displacement at the crown within 5%.

## 4.2 Moment

Circumferential bending moments were calculated using the measured circumferential strains, assuming a linear strain distribution as follows:

$$M_\theta = EI_\theta (\varepsilon_{Crest} - \varepsilon_{Valley}) / d \qquad [3]$$

where:

$I_\theta$ = second moment of area per unit length in the circumferential direction,

$\varepsilon_{Crest}$ = circumferential strain at the corrugation crest,

$\varepsilon_{Valley}$ = circumferential strain at the corrugation valley, and

d = depth of corrugation.

A few strain gages failed during testing, so mid-surface strain measurements were used instead. Figures 7 to 9 show the circumferential bending moment of the box culvert at a soil cover of 0.45, 1 and 1.5 m, respectively. The bending moment was calculated using finite element analysis and compared to the values calculated using the measured circumferential strains at z=0, 0.9 m, -0.9 m and 2 m (denoted as Rows 4, 3, 5 and 6, respectively).

The two-dimensional finite element analysis overestimated the maximum bending moment values at the shoulder of the box culvert (i.e., near $\xi$=5000 mm). At a soil cover of 1.5 m, the two-dimensional analysis calculated the bending moment at the crown ($\xi$=0) and the shoulder within 5 and 20% of the average values calculated using measured strains, respectively.

The three-dimensional analysis provided values closer to the measured values at the shoulder. At a soil cover of 1.5 m, the three-dimensional analysis calculated the bending moment at the crown and the shoulder within 13 and 6% of the average values calculated using measured strains, respectively.

The values of the thrust calculated were very small compared to the deep-corrugated section thrust capacity. The maximum thrust calculated using two and three-dimensional finite element analysis was less than 200kN/m, which is less than 10% of the thrust capacity of the deep-corrugated section (2200 kN/m). The average strains measured across the corrugated plates were very small, thus it was not possible to calculate reliable values of the thrusts for the test structure. As a result, the finite element thrust values have not been compared to any measurements.

## 4.3 Modelling Soil Compaction

The effect of compaction-induced locked in horizontal stresses on the behaviour of the box culvert was studied. Only two-dimensional analysis was performed to model the effects of soil compaction on the behaviour of the box culvert. Modelling the effects of soil compaction decreased the displacement of the box culvert at the crown. This is because the culvert was supported with high lateral stresses due to soil compaction which reduced the amount of vertical displacement at the crown. However, the decrease in the crown displacement due to compaction was less than 4% of the calculated displacement when the effects of compaction were not modelled. This is likely because the height of the box culvert sides subjected to additional lateral stress resulting from compaction is small compared to the culvert span.

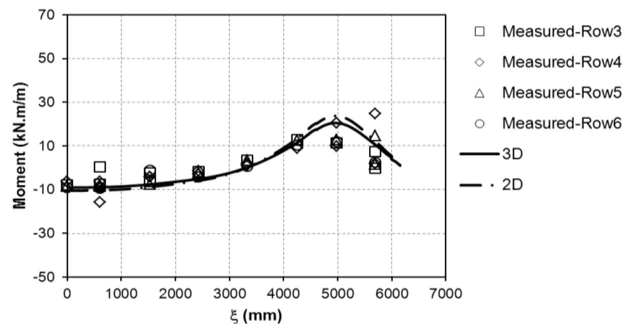


Figure 7. Bending moment at a soil cover of 0.45 m

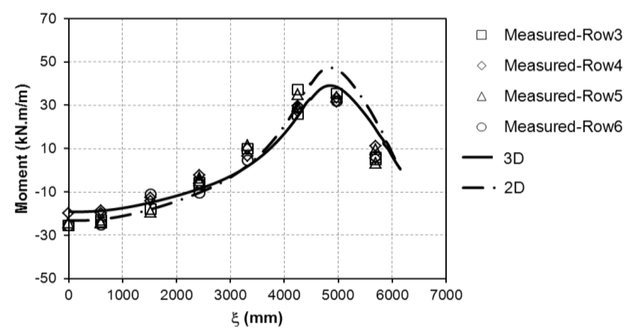


Figure 8. Bending moment at a soil cover of 1.0 m

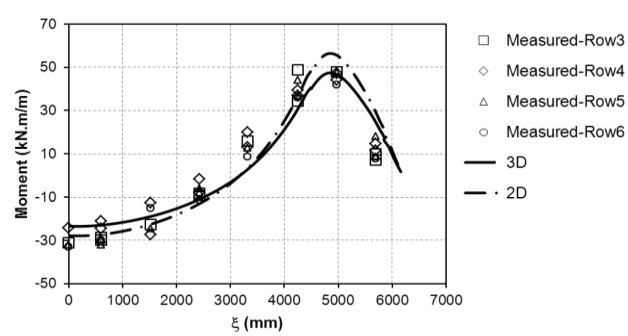


Figure 9. Bending moment at a soil cover of 1.5 m

Modelling the effects of soil compaction increased the circumferential bending moment of the box culvert at the crown and the shoulder. This is because the additional lateral stresses reduce the lateral deformations. This reduces the positive arching between the culvert and the surrounding soil which makes the stresses around the culvert less uniform and therefore increases the bending moment of the box culvert. However, the increase in the bending moment due to compaction was less than 7% of the moment calculated using analysis that neglects the effects of compaction.

## 5 DISCUSSION

Two and three-dimensional analyses were performed to model the behaviour of a long-span deep-corrugated metal culvert. Two-dimensional finite element analysis successfully calculated the deformed shape of the box culvert. The bending moment calculated using the two-dimensional analysis was reasonably close to the values calculated using measured strains from the large-scale laboratory experiment. The two-dimensional finite element analysis neglects the effect of low stiffness of the box culvert in the axial direction, while three-dimensional analysis considers the low stiffness of the culvert in the axial direction. This is why the two-dimensional analysis overestimated the bending moment of the box culvert especially at the shoulder.

Figure 10 shows a comparison between the bending moments calculated using the measured strains and the moments calculated using the CHBDC equations for earth load. It needs to be noted that the CHBDC indicates that their equations are not valid for box culverts having spans more than 8 m; however, in the absence of other equations, it is of interest to see how well these existing equations may or may not compare with the measured data for the 10-m-span box culvert. The CHBDC moment equations worked well at a soil cover of 0.45 m, while they overestimated the moment at deeper soil covers. At a soil cover of 1.5 m, the CHBDC moment equations overestimated the bending moment at the crown and the shoulder by about 73%. Current design equations in the CHBDC need to be modified to consider long-span metal culverts having spans more than 8 m. However, as previously mentioned, the design equations provided by Choi et al. (2009) are likely very conservative, predict unrealistically large values of bending moment and are not recommended for estimating moments from burial loads for long-span box culverts.

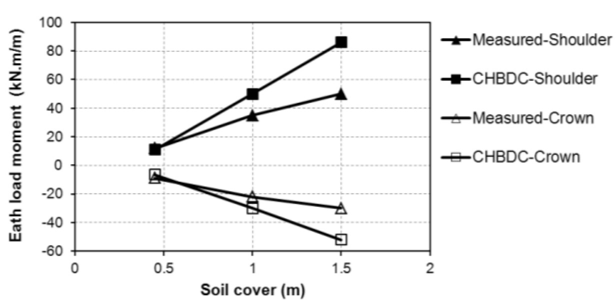


Figure 10. Comparison between the measured moments and the CHBDC moment equation

## 6 CONCLUSIONS

The behaviour of a 10-m span deep-corrugated metal box culvert measured in the laboratory during backfilling with well-graded sand and gravel was reported. The box culvert deformations and bending moments were calculated using two and three-dimensional finite element analysis and compared to the measured values. For the particular conditions examined, the following can be concluded:

1. The behaviour of the box culvert during backfilling was successfully predicted using the three-dimensional finite element analysis. Two-dimensional finite element analysis successfully predicted the deformed shape and overestimated the bending moment of the box culvert at the shoulder by about 20% of the average measured values.
2. Modelling the increase in lateral stresses due to soil compaction has a minor effect on the response of long-span deep-corrugated metal box culvert during backfilling. The change in the crown displacement due to compaction was less than 4% of the displacement calculated without modelling compaction. The changes in the bending moment values at the crown and the shoulder due to compaction were less than 7% of the moment calculated without modelling compaction effects on lateral stresses.
3. The CHBDC moment equation overestimates the moment of long-span metal box culverts especially for deep soil cover. At a soil cover of 1.5 m, The CHBDC moment equation for the 10 m span test culvert overestimated the measured moment by about 73%.

The results and conclusions are for the particular conditions, materials and construction methods examined. Since backfilling was conducted without using a light weight dozer as permitted by the manufacturer's specifications, the potential effects of loading from permitted construction equipment during backfilling should be considered.

## 7 ACKNOWLEDGEMENTS

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REFERENCES


CHBDC 2006. Canadian Highway Bridge Design Code. CAN/CSA-S6-06, Canadian Standards Association International, Mississauga, Ontario.

Choi, D., Kim, G. and Byrne, P. 2009. Evaluation of Moment Equation in the 2000 Canadian Highway Bridge Design Code for Soil-Metal Arch Structures. Canadian Journal of Civil Engineering, Vol. 31, No. 2: 281-291.

Duncan J. 1979. Behaviour and design of long-span metal culverts. Journal of the Geotechnical Engineering Division, Vol. 105, No. 3: 399-418.

Flener, E.B. 2010. Soil-Steel Interaction of Long-Span Box Culverts - Performance during Backfilling. Journal of Geotechnical and Geoenvironmental Engineering, Vol. 136, No. 6: 823-832

Girges Y., Abdel-Sayed G. 1995. Three-Dimensional Analysis of Soil-Steel Bridges, Canadian Journal of Civil Engineering, Vol. 22, No.6: 1155–1163.

Katona, M.G. 1978. Analysis of Long-Span Culverts by the Finite Element Method, Transportation Research Record, Transportation Research Board, Washington D.C., Vol. 678, pp. 59-66.

Lougheed, A.C. 2008. Limit States Testing of a Buried Deep Corrugated Large-Span Box Culvert. MSc Thesis, Department of Civil Engineering, Queen’s University.

Scott, J.D., Bauer, G.E., and Shields, D.H. 1977. Triaxial Testing on Granular A Aggregate. Ontario joint transportation and communications research program, Ont. Project O-1.

Taleb, B. and Moore, I.D. 1999. Metal Culvert Response to Earth Loading Performance of Two-Dimensional Analysis. Transportation Research Report No. 1656, Transportation Research Board, Washington, D.C.: 25-36