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1 **Abstract**

2 Induced trench construction is commonly used to reduce earth pressures on rigid
3 circular and box culverts. Most of the reported literature pertains to the performance of
4 induced trench culverts during construction and shortly after construction. This paper
5 addresses the post construction performance of induced trench culverts. First, results of
6 field inspection reports are presented as an indirect assessment of performance of 90
7 induced trench culverts installed in New Brunswick which have been in service for up to
8 24 years. Second, earth pressure measurements are presented from three case studies
9 where prototype installations were monitored over periods ranging from 4 to 9 years. The
10 case studies presented include a single circular culvert, a cast-in-place double cell box
11 culvert, and a twin circular culvert installation. The fill heights above the instrumented
12 structures varied from 19 to 25 m. All the available data from both the field inspections
13 and earth pressure measurements indicate that the culverts installed in induced trenches
14 are performing in a satisfactory manner.

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19 *Key words:* induced trench, field instrumentation, soil-structure interaction, post
20 construction performance, long-term monitoring

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Introduction

The induced trench method has been used for several decades to reduce vertical earth pressures on rigid culverts buried under high embankments (typically fill heights > 10 m). In recent years, scepticism over the reliability of the method has grown because of pipe failures, uncertainties with design methods, questions regarding the long-term reliability of load reduction, and issues related to constructability (McGuigan and Valsangkar 2010). As a result, the induced trench installation option has been omitted from the last three editions of the *Concrete Pipe Design Manual* (e.g., ACPA 2000, 2011) and some jurisdictions in North America have discontinued its use. At the same time, however, other jurisdictions, such as the New Brunswick Department of Transportation and Infrastructure (NBDTI), continue to benefit from the successful use of induced trench construction (Hansen et al. 2007). The purpose of this paper is to report the post construction performance of several induced trench culverts installed in New Brunswick, both indirectly, through field inspection reports, and directly, through earth pressure measurements of instrumented structures.

Background

Induced trench installations include a zone of compressible material directly above rigid culverts installed beneath high embankments. As the prism of soil directly over the culvert settles relative to the adjacent embankment material, upward shear forces are mobilized that reduce the vertical load transferred to the top of the culvert (positive arching). In contrast, rigid culverts installed beneath embankments with no compressible zone (positive projecting) experience higher earth pressures than the theoretical

overburden because the prism of soil directly above the culvert settles less than the adjacent embankment material (negative arching). Fig. 1 shows the simplified mechanisms of the induced trench and positive projecting conditions.

The induced trench method of construction, along with its theoretical basis, was originally proposed by Marston (Marston and Anderson 1913; Marston 1930) and was later developed by Spangler (Spangler 1950; Spangler and Handy 1973). Since its development, several shortcomings with the theory have been discussed in the literature (e.g., Sladen and Oswell 1988; Scario 2003; Handy 2004). In addition to shortcomings related to the theoretical basis of induced trench method, questions of long-term performance beyond 2-3 years still remained unaddressed. Of the case studies reported in the literature, most deal only with performance up to the end of construction. In the few studies that deal with post construction performance, only 2-3 years of data has been presented. Vaslestad et al. (1993) instrumented and monitored three induced trench installations (two circular culverts and one box culvert) and observed no load increase for 2–3 years following the completion of construction of the embankments. McAfee and Valsangkar (2008) instrumented a circular induced trench culvert and observed no load increase 2 years after the embankment was constructed to its full height. Another case of good long-term performance is that of an uninstrumented twin culvert induced trench installation which has performed well for over 35 years (Spangler 1966; McAfee 2005).

Over 100 induced trench installations have been constructed in New Brunswick since 1991, most of which have been done under the supervision of NBDTI. Targeted field inspection programs were carried out by NBDTI in 2001 and 2007 to assess the structural integrity of several of these installations, the results of which are summarized

herein. This is considered to be an indirect assessment of post construction performance. Additionally, NBDTI, in partnership with the University of New Brunswick (UNB), has instrumented four induced trench culvert installations. Short-term performances of these structures have been reported in the literature by McAfee and Valsangkar (2008), Parker et al. (2008), McGuigan and Valsangkar (2011), and Oshati et al. (2012). These papers also compare the short term monitoring data with those calculated using the Marston-Spangler theory, where appropriate, as well as numerical and centrifuge modelling results. This paper reports the findings of field inspections and earth pressure measurements of three of these instrumented structures, which have been in service for 4 to 9 years. This is discussed below as a direct assessment of post construction performance.

Indirect assessment of performance: field inspections

Typical details of installations in New Brunswick

Over 100 induced trench culverts have been constructed in New Brunswick since 1991. This type of construction is typically used when fill heights above the top of the culvert exceeds 10 m. The typical construction detail used by NBDTI for a single circular culvert is shown in Fig.2. The methodology is also used for reducing stresses on twin circular and box culverts, although there is no standard detail. Table 1 presents the inventory of induced trench installations constructed in New Brunswick.

A targeted field inspection program was carried out by NBDTI in 2001 and 2007 to record the structural performance of the majority of the induced trench culvert installations. In addition to these targeted inspections, all the induced trench culverts

larger than 1.2 m in diameter are inspected on a routine basis at a typical frequency of 2 to 3 years to assess structural integrity.

Field inspections: 2001

A detailed inspection program of induced trench culverts was first carried out by NBDTI in 2001. The scope of this field work consisted of visually inspecting the interior of 50 induced trench culverts for signs of structural distress. Table 2 presents the salient details of the culverts inspected in 2001. For pipes smaller than 1.2 m in diameter, a remote controlled camera was used for inspection. Photographs of interior surfaces were taken to establish bench mark conditions for future assessments. All the cracking on the interior surfaces of pipes, sagging or distortion of pipes or any other visible damage was recorded. The results of this inspection program have been reported by Hansen et al. (2007).

The 50 installations that were inspected had embankment fill heights ranging from approximately 9 m to 32.5 m, and the inside pipe diameters ranged from 750 mm to 3000 mm. The height to outside diameter ratios varied from 3 to 13 and the period of service at the time of 2001 inspection varied from 2 years to 10 years. Of the 50 installations inspected, 49 comprised a single culvert. The thickness of the compressible layer varied from $0.5 B_c$ to $1.5 B_c$, where B_c is the outside width of the culvert. The width of compressible layer ranged from 1.0 to $1.3 B_c$ in all installations. The material used for the compressible zone mostly consisted of sawdust or wood chips. There was only one case of twin culverts, in which two 1800 mm diameter pipes were utilized. The spacing between these twin pipes was $1.6 B_c$ and the embankment height was 13.5 m. The twin

114 culverts were designed as two individual single induced trench culverts (two
115 compressible zones) without accounting for any interaction between the two culverts.

116 Radial cracking of the inlet and outlet headwalls was the most commonly
117 observed damage. Circumferential cracking near the pipe joints was also noted in a few
118 of the installations. The circumferential cracks at the joint locations ranged from 5-10 cm
119 long hairline cracks, to cracks which almost extended along the entire inside
120 circumference of the pipe. As this type of cracking was noted in the vicinity of joints, it
121 was concluded that this damage was most likely caused due to overstressing of pipe joints
122 during installations or due to post construction differential settlement of the pipe sections.
123 Longitudinal cracking was observed at the springline level in only two pipe installations.
124 In one instance the length of these longitudinal cracks varied from 1 to 3.3 m at four
125 different locations approximately at the mid-sections of the longitudinal axis of the pipe.
126 In the second case, similar cracking was observed near the end sections of the culvert
127 where the height of embankment was less than the maximum height and the subject area
128 of culvert was outside the influence of compressible layer. The cause for cracking beyond
129 the influence of the compressible zone near the pipe ends may be attributed to differential
130 settlement along the length of the pipe due to differential loading conditions.

131 The inspections revealed that the culverts which were installed under the two
132 highest fill heights of 32.4 m and 32.5 m did not have any circumferential or longitudinal
133 cracking.

134 An independent analysis for each of the field installations inspected in 2001 was
135 carried out to determine required class of pipe (MacLeod 2003). The procedure
136 recommended in the Concrete Pipe Handbook (ACPA 1998) was used to determine the

required pipe class. For every installation, pipe strengths greater than Class V (140-D) would have been required without the use of an induced trench. As pipe classes exceeding Class V (140-D) are not commercially available from pre-cast plants, either a cast-in-place pipe or a site specific pre-cast pipe would have been required for each site, resulting in increased costs. A comparison of the independent analysis by MacLeod (2003) with the NBDTI designs indicates that at many locations, a pipe of lesser strength than the field installed pipe could have been used. However, this difference in pipe class did not exceed more than the next pipe class. It was concluded from the independent analysis that the classes of pipes selected by NBDTI were conservative and thus may also explain, at least in part, why these have performed satisfactorily.

Field inspections: 2007

A second targeted inspection program was undertaken by NBDTI in 2007 in which thirty seven (37) induced trench culverts were inspected. The period of service at the time of 2007 inspection varied from <1 to 16 years. Twelve (12) of these culverts had been previously inspected in 2001. In this program culverts which were larger than 1.2 m in diameter/size were visually inspected. For culverts smaller in diameter than 1.2 m, a remote controlled camera was used. The salient features of the culverts inspected in 2007 are presented in Table 3.

The most common damage observed was radial cracks in the pipe headwalls at the inlet and outlet of most of the culverts. This observation is similar to the one noted in the 2001 inspections.

159 Circumferential cracks were found inside several of the inspected culverts. These
160 hairline types of cracks were generally in the order of 5 - 10 cm long. In a few instances,
161 the circumferential cracks extended along the entire internal surface of the pipe.
162 However, these cracks were found to be close to the joints between pipe sections, as
163 observed in 2001 inspections. It was therefore inferred that the cause is likely to be
164 overstressing of pipes during pipe installation or post construction differential settlement
165 of the pipe sections.

166 Longitudinal hairline cracking was also noted in several culverts, but these cracks
167 were localized in nature and in only a few instances occurred beyond the influence of the
168 induced trench (i.e., in areas of lesser fill height near the embankment toe).

169 The twelve (12) culverts which were inspected both in 2001 and 2007 showed no
170 additional damage or changes in the intervening years between inspections.

171 It was concluded from the 2007 inspections that there was no evidence of
172 structural damage, suggesting that the initial load reduction achieved by the induced
173 trenches has been sustained many years after the construction of these culverts. The fact
174 that the pipe designs were conservative may also have contributed to acceptable structural
175 performance of the pipes.

176

177 ***Routine inspections***

178 In addition to the targeted inspections summarized above, all the induced trench
179 culverts larger than 1.2 m in diameter/size are visually inspected at a typical frequency of
180 2 to 3 years to assess structural integrity. For the 3 instrumented culverts discussed in the

later part of this paper, the details of these inspections are presented in appropriate sub-sections.

The results of routine inspections once again indicate that there is no evidence of structural damage where induced trench construction was utilized to reduce earth pressures on the culverts.

Summary of field inspections

Targeted field inspections of 75 induced trench culvert installations out of a total 102 installations in the Province of New Brunswick along with the routine inspection of large diameter/size culverts (>1.2 m) indicates that all these structures have performed satisfactorily. The inspections included culverts whose inside diameters varied from 750 mm to 3600 mm with fill heights above the crown varying from 7.5 m to 35.0 m. Both single and twin culvert installations were inspected. The field inspections program included culverts varying in ages from 2 years to 24 years. The results of this performance appraisal confirm the suitability of induced trench culvert installations for fill heights in excess of 7.5 m.

Direct assessment of performance: instrumented culverts

Peter Smith Brook installation

Site description and instrumentation

The Peter Smith Brook culvert is an induced trench installation constructed as part of a highway upgrade near Longs Creek, New Brunswick. Work began on the Peter Smith Brook induced trench installation in the summer of 2005 and the final height of the embankment was reached approximately one year later. A 117 m long, 3000 mm inside diameter reinforced

concrete culvert was installed under 18.0 to 19.4 m of fill. The thickness of the compressible fill material was 2.75 m. Details of the installation are shown in Fig. 3, and are reported in detail by Parker et al. (2008).

There were a few unique aspects of this installation: part of the culvert was installed under a new embankment (eastbound lanes; fill height of $H = 19.4$ m) while part of the culvert was installed in a wide trench which was dug into an existing embankment (westbound lanes; $H = 18.0$ m); the compressible fill material was placed in two stages as the height of the embankment was raised; and when the height of soil cover was approximately 16 m above the pipe, a stockpile of 7 m height was inadvertently placed by the contractor above the pipe for few weeks. The effect of stockpile on the measured earth pressures is discussed in detail by Parker et al. (2008).

A total of 10 vibrating wire pressure cells (5 contact pressure cells and 5 earth pressure cells) along with 4 vibrating wire settlement plates were installed at the Peter Smith Brook induced trench installation. Contact pressure cells were installed on the culvert at the crown and springline and the earth pressure cells were installed within the embankment. In addition to contact and earth pressure cells, vibrating wire settlement plates were also installed at two different elevations within the embankment. The location of the instrumentation is shown in Fig. 4. Further details of instrumentation are reported in Parker et al. 2008.

Post construction monitoring results

Performance of the installation during and immediately after construction has been reported by Parker et al. (2008). Instrument readings are reported below for years 2006, 2011, 2013, and 2015.

As shown in Fig. 5, the measured vertical earth pressures on the crown of culvert have consistently decreased since the end of construction in December 2006 except for month 78 (June 2013) when they were recorded to be higher (discussed more below). The

measured vertical earth pressures at the crown at the end of embankment construction ranged from 61 kPa to 85 kPa, averaging 72 kPa, or $0.20gH$ (where gH represents the theoretical overburden pressure above the crown). At the end of 9 years, the vertical pressures at the crown ranged from 7 kPa to 23 kPa, averaging 16 kPa ($0.05gH$), representing an average reduction of 78% since the end of construction.

As shown in Fig. 6, the average measured lateral earth pressures at the culvert springline have also slightly decreased (by 3%) since the end of construction from 153 kPa ($0.39gH_s$) to 149 kPa ($0.38gH_s$), where H_s is the fill height above the springline. The calculated pressure line shown on Fig. 6 represents the theoretical overburden pressure at the springline multiplied by an assumed lateral earth pressure coefficient of 0.5. The average lateral earth pressure readings were significantly (17%) higher in June 2013 than at the end of construction. Since these increases pressures were also observed at the crown on this date (and also at the Manzer Brook site, which will be discussed in Section 4.2), it is likely that the readings taken on this day are not reliable and are therefore not included in the interpretation. One possible explanation for the higher observed lateral pressures in PC-11 than PC-3 and PC-4 is that PC-11 is installed under the west bound embankment which is 1.4 m higher than the east bound embankment.

The observed reduction in vertical earth pressures at the crown is also observed in earth pressure cell (PC 6) located just above the compressible layer at elevation 72 m (Fig. 7a), which has experienced a 90% reduction and is currently measuring only 4% of the theoretical overburden pressure. Thus, the observed data indicate additional arching is occurring after the end of construction. It is also possible that localized arching directly

252 above the contact pressure and earth pressure cells is contributing to the observed
253 reduction in vertical earth pressures.

254 The data from the earth pressure cells installed in the embankment at elevation 72
255 m are presented in Fig. 7a. These earth pressure cells show that vertical earth pressures
256 are decreasing immediately above the compressible layer (PC6), while increasing in the
257 embankment fill adjacent to the zone above compressible layer (PC7), thereby indicating
258 ongoing load transfer due to arching. The data from the earth pressure cells installed at
259 elevation 78 m are presented in Fig. 7b. The pressure cell located above the culvert
260 centreline (PC8) and the one offset 8 m from the culvert centreline (PC9) are recording
261 similar earth pressures, indicating that the plane of equal settlement must be between
262 elevations 72 and 78 m. The vertical pressure at elevation 78 m directly above the pipe is
263 increasing while the earth pressure in the adjacent soil is decreasing, indicating that there
264 is a reversal in settlement pattern above the plane of equal settlement. A possible reason
265 for the recorded earth pressures at elevation 78 m being greater than the overburden
266 pressure is reversal of the settlement pattern above the plane of equal settlement. Parker
267 et al. (2008) provide results of numerical modelling analysis showing that the vertical
268 stresses at the pressure cell locations at elevation 78 m were greater than the overburden
269 stress due to significant redistribution of stresses.

270 The data from the four settlement plates are presented in Table 4. In our
271 interpretation we have not included data from June 2013 as these readings are not
272 considered reliable (as with earth pressure measurements taken on that date). The overall
273 settlements have increased since 2006 by about 30 mm to 70 mm. The settlement plates
274 installed at elevation 72 m indicate the expected trend of more total settlement in the area

directly above the compressible layer when compared to the settlement plates located 8 m away from the centre of the compressible zone. The differential movement between the soil column above the induced trench and the adjacent soil was $125 \text{ mm} \pm$ at the end of construction and has remained virtually unchanged over the subsequent nine year period. However, the settlement plates located at elevation 78 m show that the soil over pipe has settled more relative to the soil 8 m outside.

Field inspections

Routine inspections of Peter Smith Brook culvert were carried out by NBDTI in 2006, 2008 and 2012. A damaged edge, 0.3 mm wide crack, possible spalling and installation damage at few locations, and several hairline cracks were observed during these inspections. The inspection reports rate the structural condition of the culvert to be excellent.

Manzer Brook installation

Site description and instrumentation

The Manzer Brook installation forms a portion of the Route 8 highway near Fredericton, New Brunswick. Two 3660 mm inside diameter reinforced concrete culverts were installed side by side under $H = 22.4 \text{ m}$ of fill. The specified pipe was a Class 140-D (Class V), with a wall thickness of approximately 410 mm, resulting in an outside pipe diameter, B_c , of 4480 mm.

Work on the induced trench installation began in June 2009, and by December 2009 the embankment had been constructed to subgrade level ($H = 21.7 \text{ m}$). The

298 pavement structure was added about a year later, resulting in a final fill height of
299 approximately 22.4 m above the pipes ($H/B_c = 5.0$).

300 The culverts were installed in an induced trench to reduce the earth loads on the
301 culverts, thereby allowing for the use of standard precast pipe sections. The details of the
302 induced trench installation are shown in Fig. 8 and are reported in more detail by
303 McGuigan and Valsangkar (2011). A single compressible zone of loosely placed
304 sawdust, approximately 14 m wide by 3 m thick was constructed above the culverts.

305 A total of 24 Geokon earth pressure cells were used to measure the earth pressures
306 in the soil immediately adjacent to the pipes at the crown, shoulder, springline, haunch,
307 and invert locations. The earth pressure cells were installed at two sections under the full
308 embankment height, 5 m apart along both pipes for redundancy. The location of the
309 pressure cells are given in Fig. 9.

311 *Post construction monitoring results*

312 Performance of the installation during and immediately after construction has
313 been reported by McGuigan and Valsangkar (2011). Earth pressure readings are reported
314 below for years 2009, 2010, 2013, and 2015.

315 The post construction vertical earth pressures measured at the crowns are shown
316 in Fig. 10. The average vertical earth pressures measured at the crown at the end of
317 construction was 305 kPa ($0.67gH$). After five years the average pressure on the crown
318 was 289 kPa ($0.61gH$), representing an average decrease of 8%. The addition of the
319 pavement structure is reflected in the overburden lines shown on Figs. 10 and 11. The
320 2013 readings were approximately 4% higher than at the end of construction. Higher than

expected readings were also recorded at the springlines and haunches in 2013. As discussed previously, the readings taken in 2013 are not considered to be reliable.

Fig. 11 shows the radial earth pressures measured at the shoulders since the end of construction. The earth pressures measured at the outside and inside shoulders at the end of construction were 369 kPa and 327 kPa, respectively. After five years both the outside and inside pressures have reduced by 11% to 340 kPa and 302 kPa, respectively. The higher pressures observed on the outside shoulders are likely due to the arching mechanism of the induced trench.

The lateral earth pressures observed at the culvert springlines since the end of construction are shown in Fig 12. At the outside springline (Fig. 12a) the average lateral earth pressures have remained virtually unchanged from the end of construction at 161 kPa. However, accounting for the increase in overburden due to the pavement structure, this represents a decrease of approximately 3% when normalized to the overburden pressures ($0.32gH_s$ to $0.31gH_s$). At the inside springline (Fig 12b) the average lateral earth pressures have increased by 4%, from 159 kPa ($0.32gH_s$) to 170 kPa ($0.33gH_s$). The calculated pressure lines shown on Fig. 12 represents the theoretical overburden pressure at the springline (gH_s) multiplied by an assumed at rest lateral earth pressure coefficient of 0.5.

Fig. 13 shows the post construction earth pressure measurements at the haunches. A net reduction of 8% was observed at the outside haunches, with the average pressures decreasing from 143 kPa to 132 kPa. A very significant pressure reduction of 77% was observed at the inside haunches, with average pressures decreasing from 76 kPa to 17 kPa. One likely explanation for this significant reduction is that space limitations between

the pipes made effective backfilling and compaction of the inside haunch areas difficult. The backfill in the inside haunch areas may be settling relative to the pipe, thereby causing the reduced recorded pressures.

No post construction data is available for the invert locations since they ceased to function during construction, presumably due to overloading (McGuigan and Valsangkar 2011).

With the exception of the inside springlines, which have experienced a slight (4%) pressure increase, the post construction monitoring results indicate an overall decrease in earth pressures acting on the Manzer Brook culverts. Temporary pressure increases as high as 17% were observed in the June 2013 readings, which are likely due to seasonal factors.

Field inspections

A routine field inspection of the Manzer Brook culverts was carried out by NBDTI in November 2014, four years after construction. The inspection report describes the culverts as being in good condition without any structural distress or significant cracking.

McBean Brook

Site description and instrumentation

The McBean Brook culvert is a 142 m long double cell rectangular cast-in-place reinforced concrete box culvert buried under 25.1 m of fill. The external height and width of the double cell culvert are 4.65 m and 6.75 m, respectively, and the 0.6 m thick base

slab is 7.35 m wide. The thickness of the roof, outside, and inside walls are 0.45 m, 0.55 m, and 0.45 m, respectively. A 2.5 m thick by 8.0 m wide compressible layer of hay was placed above the culvert to form the induce trench. Details of the installation procedure are provided by Oshati et al. (2012), and a cross section through the induced trench installation is shown in Fig. 14.

A total of thirty two Geokon earth pressure cells were installed around the culvert base, sidewalls, and roof at two separate locations under the full embankment height. The locations of the pressure cells are shown in Fig. 15.

Post construction monitoring results

Pressures measured on the culvert during and immediately after construction have been reported by Oshati et al. (2012). Since the completion of the embankment in July 2011, seven sets of measurements have been taken, the results of which are presented below. Since the completion of the embankment, the pavement structure was added, resulting in approximately 16 kPa of overburden pressure. However, since the exact timeline is not known, the overburden pressure ratios reported below do not reflect the addition of the pavement structure. Similarly, the overburden pressure lines in Figs. 16-18 do not reflect the increased overburden pressure.

The post construction vertical earth pressures measured on the culvert roof are presented in Fig. 16. The average roof pressures have reduced by 34%, from 223 kPa (0.42 gH) to 148 kPa (0.28 gH). As with the Peter Smith and Manzer Brook sites, measured earth pressures in early June (at 23 months and 35 months) were generally

389 higher than the observed trend, although these readings generally did not exceed the end
390 of construction measurements.

391 Figs. 17a & b show the post construction lateral earth pressures measured at the
392 north and south sidewalls, respectively. On average, the lateral pressures have increased
393 by 5% since the end of construction, from 230 kPa ($0.40gH_s$) to 242 kPa ($0.42gH_s$). The
394 maximum average lateral pressure that was recorded since the end of construction was
395 272 kPa ($0.47gH_s$) in June 2014, an 18% increase. The minimum recorded average lateral
396 pressure since the end of construction was 225 kPa ($0.39gH_s$), representing a 2%
397 decrease.

398 The post construction contact pressures measured at the base are shown in Fig.
399 18. Since the end of construction, the average base contact pressures have decreased by
400 14 % from 302 kPa to 259 kPa. At the end of construction, the average base contact
401 pressure was 19% higher than the average roof pressure plus the pressure due to the dead
402 load of the structure due to downward shear forces on the sidewalls (Oshati et al. 2012).
403 Four years later, the average contact pressures measured at the base are 45% higher than
404 the average roof pressure plus dead load pressure.

405 The post construction earth pressure measurements revealing a decrease in
406 average vertical pressures on the roof accompanied by an increase in average lateral
407 pressures on the sidewalls are generally indicative of ongoing positive arching.
408 Additionally, measurements have shown a decrease in contact pressures at the base,
409 although the pressure reduction observed at the roof is not fully transferred to the base.
410 The reason is likely due to the increase in lateral pressures adjacent to the culvert
411 resulting increased downdrag on the sidewalls.

412

413 *Field inspections*

414 The McBean Brook culvert was inspected in August 2015, 4 years after
415 construction. Significant hairline cracking extending from the ceiling down the side walls
416 of both cells was noted during this inspection. The length of hairline cracking in each cell
417 was approximately 20 to 30 linear meters (not continuous). In many instances, the
418 observed hairline cracking was in the proximity of construction joints. There was leakage
419 from the roof and sidewalls noted in both cells. Even though the cracking was not
420 considered to be significant, a program of epoxy injection in the observed cracks was
421 recommended. As the results of inspection were unexpected, a borehole investigation
422 program was undertaken to determine causes for the observed cracking and leakage. The
423 boreholes drilled from the road surface indicated that the groundwater table was above
424 the roof of the culvert partially explaining the observed leakage from the roof and side
425 walls. Piezometers have been installed to monitor long term variations in the groundwater
426 levels. As the measured earth pressures are less than the design earth pressures, the cause
427 of observed behavior is considered to be unrelated to high earth pressures due to loss of
428 positive arching. NBDTI is currently investigating to determine the causes for the
429 observed hairline cracking. One possible explanation may be differential settlement of the
430 culvert under the embankment, although this has not been verified. It is noted that this is
431 the only cast-in-place induced trench structure that has been installed in New Brunswick,
432 which may not accommodate differential settlement as well as jointed precast pipe
433 sections.

434

435 **Summary and conclusions**

436 Induced trench design of rigid culverts under high embankments has successfully
437 been used in the Province of New Brunswick since 1991, with a total of 102 culverts
438 having been constructed using this methodology. The internal pipe diameters/size have
439 varied from 750 mm to 3660 mm with embankment heights above the culverts varying
440 from 7.5 m to 35.0 m.

441 Targeted field inspections were undertaken by NBDTI in 2001 and 2007 in which
442 50 and 37 induced trench culverts were inspected, respectively. In addition, all the
443 induced trench culverts with an internal diameter greater than 1.2 are routinely inspected
444 at a frequency of 2 to 3 years. The data from these inspections indicate that except for
445 minor hairline cracking, all these culverts have performed satisfactorily. There is only
446 one exception to this general observation where a more recently constructed cast-in-place
447 double cell box culvert (i.e., the McBean Brook culvert) has developed more hair line
448 cracking than anticipated. The cause is still under investigation but early indications are
449 that it is not related to a loss of positive arching, since earth pressure measurements
450 actually indicate ongoing positive arching. Thus, inspection of close to 90 installations
451 show that the induced trench culverts have performed satisfactorily over a period ranging
452 from 5 to 24 years.

453 The data from an instrumented 3000 mm inside diameter culvert under 19.4 m of
454 fill at the Peter Smith Brook site indicate that positive arching continues to occur nine
455 years after completion of construction, resulting in reduction in vertical earth pressures at
456 the crown. In comparison, there are no noticeable changes in the horizontal earth
457 pressures at the springline. As can be expected, additional settlement has been observed

of the soil column directly above the pipe relative to the adjacent soil on either side of the pipe. The measured earth pressures on the culvert after a period of 9 years are noted to be below design earth pressures calculated accounting for the positive arching induced by compressible layer.

Post construction monitoring of the twin 3660 mm inside diameter induced trench culverts at the Manzer Brook site generally show an overall reduction of earth pressure on the pipes. With the exception of the inside springlines, which have experienced a net increase of 4%, the average earth pressures elsewhere have decreased by 3 to 11%. Major pressure reductions of 77% measured at the inside haunches are thought to be due to settlement of the haunch backfill relative to the haunches and not related to the soil arching mechanism.

Post construction earth pressure measurements at the cast-in-place double cell box culvert at the McBean Brook site reveal a decrease in average vertical pressures on the roof accompanied by an increase in average lateral pressures on the sidewalls. This behaviour is indicative of ongoing positive arching. Average contact pressures at the base have also been observed, although the pressure reduction observed at the roof is not fully transferred to the base. This is likely due to increased lateral pressures and associated downdrag along the culvert sidewalls.

For future monitoring programs, consideration should be given to a data logger set-up, rather than periodic readings with a read-out unit. The additional data obtained by such a system may better help explain the long term pressures and settlements, and may better identify and quantify seasonal variations in the readings.

480 In summary, the field inspection of 90 induced trench culverts with service life
481 varying from 3 to 24 years, all show that these structures have performed satisfactorily
482 without showing any signs of structural distress. Monitoring data from three instrumented
483 sites confirm sustained load reduction due to positive arching 4-9 year after construction.
484 The data reported thus confirms that induced trench construction is a valid installation
485 method for rigid culverts buried under high embankments.

486

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Figure captions

Fig. 1. Simplified arching mechanism of positive projecting and induced trench culverts. B_c , outside diameter of culvert; H , height of embankment above top of culvert (McGuigan and Valsangkar 2011).

Fig. 2. Typical induced trench detail used by the New Brunswick Department of Transportation and Infrastructure.

Fig. 3. Cross section through Peter Smith Brook induced trench installation (Parker et al. 2008).

Fig. 4. Location of instrumentation for the Peter Smith Brook induced trench installation (Parker et al. 2008).

Fig. 5. Post construction vertical earth pressure measurements at the crown at the Peter Smith Brook site.

Fig. 6. Post construction lateral earth pressure measurements at the springline at the Peter Smith Brook site.

Fig. 7. Post construction vertical earth pressures measured within the embankment at the Peter Smith Brook site: (a) Elevation 72 m; (b) Elevation 78 m. For reference, the culvert crown is at elevation 68.4 m and the maximum fill height is at elevation 86.4 m.

Fig. 8. Cross section through the Manzer Brook induced trench installation (McGuigan and Valsangkar 2011).

Fig. 9. Locations of earth pressure cells at the Manzer Brook site (McGuigan and Valsangkar 2011).

Fig. 10. Post construction vertical earth pressure measurements at the crown at the Manzer Brook site.

Fig. 11. Post construction earth pressure measurements at the shoulders at the Manzer Brook site.

Fig. 12. Post construction lateral earth pressure measurements at the springlines at the Manzer Brook site: (a) outside springlines; (b) inside springlines.

Fig. 13. Post construction earth pressure measurements at the haunches at the Manzer Brook site: (a) outside haunches; (b) inside haunches.

Fig. 14. Cross section through McBean Brook induced trench installation (Oshati et al. 2012).

Fig. 15. Locations of earth pressure cells at the McBean Brook site (Oshati et al. 2012).

Fig. 16. Post construction vertical earth pressure measurements at the roof at the McBean Brook site.

Fig. 17. Post construction lateral earth pressure measurements at the sidewalls at the McBean Brook site: (a) north sidewall; (b) south sidewall.

Fig. 18. Post construction contact pressure measurements at the base at the McBean Brook site.

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Table 1: Inventory of induced trench culverts in New Brunswick

Type	Shape	Diameter/size range (mm)	Fill height range (m)	Years in service range	Number of culverts
Precast	Circular	750-3600	7.5-35.0	6-24	88
Precast	Box	2400-3600	13.2-32.0	9-11	6
Precast	Twin Circular	1200-3660	11.5-21.5	5-11	6
Precast	Twin Box	3600 x3600	20.0	9	1
Cast-in Place	Double cell box	2600x3600(H)	25.1	3	1

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Table 2: 2001 Culvert inspections by NBDTI

Inside diameter (mm)	Fill height (m)	Year built	Thickness of compressible layer (mm)
750	12	1991	1000
1200	10.8	1991	1500
1200	9.5	1995	1500
1200	11.4	1995	1500
1200	11.8	1995	1500
1200	12	1995	1500
1200	14.4	1995	1450
1370	18.5	1995	2745
1500	9.5	1995	915
1500	10.2	1995	1850
1500	10.9	1995	915
1500	11	1995	1800
1500	12.3	1995	1800
1800	10	1995	1100
1800	11.8	1995	2200
1800	22.8	1995	2000
1800*	13.5	1995	2200
1500	12.3	1996	925
1500	13.6	1996	925
1500	21.2	1996	2800
750	8.9	1997	475
750	11.9	1997	475
900	13.5	1997	1200
900	16.2	1997	1200
1050	10.1	1997	1300
1050	10.4	1997	650
1050	11.2	1997	1300
1050	11.8	1997	650
1050	12	1997	1300
1200	9	1997	1500
1200	10.2	1997	1500
1200	32.5	1997	2200
1500	16.1	1997	1500
1800	11.8	1997	2200
2100	12.6	1997	1250
2100	15.4	1997	1250
2100	22.5	1997	2600
2400	15.9	1997	2950
2400	16.6	1997	3000
2400	32.4	1997	1800
1050	12.7	1999	650
1500	11.2	1999	925
2100	9.5	1999	2500
2100	11.4	1999	1300
2100	13.5	1999	2600
2100	15.1	1999	2600
2100	15.4	1999	2600
3000	13.5	1999	1800
3000	16.1	1999	1800
3000	19.1	1999	3600

Note: *Twin culvert

Table 3: 2007 Culvert inspections by NBDTI

Inside diameter (mm)	Fill height (m)	Year built	Thickness of compressible layer (mm)
1370	18.5	1995	2745
1800	22.8	1995	2000
1500	21.1	1996	2800
1200	32.5	1997	2200
1500	16.1	1997	1500
2100	22.5	1997	2600
2400	15.9	1997	2950
2400	16.6	1997	3000
2400	32.5	1997	1800
2100	11.4	1999	1300
3000	13.5	1999	2600
3000	16.1	1999	1800
750	10.3	2002	2000
900	11.8	2002	580
1800	9.3	2002	900
1800	11.8	2002	1150
1800	11.8	2002	1100
2100	13	2002	1300
1200	12	2003	1200
750	10	2004	500
1050	22	2004	1500
1200	9.3	2004	750
1200	10	2004	1500
1200	12	2004	1500
1500	10.8	2004	1350
1500	10.8	2004	1350
2100	11.3	2004	1200
2100	15.3	2004	1200
3000	17.3	2004	2000
1200	14.8	2005	1500
2100	15.8	2005	1200
3000	19.3	2005	2750
3600	12	2005	1500
1500	9.5	2006	1000
3000	17.3	2006	2250
3000	9.8	2007	1500
3600	12	2007	2160

Table 4: Summary of measured settlements at the McBean Brook site

Instrument	Location	Height of fill (m)	Total settlement (mm)			
			Dec-06	Nov-11	Jun-13*	Oct-15
SP-1	At Elev. 72 m, above induced trench	14.8	426	479	449	495
SP-2	At Elev. 72 m, at 8 m away from induced trench centreline	14.9	301	354	349	373
SP-3	At Elev. 78 m, above induced trench	9.1	186	240	238	--
SP-4	At Elev. 78 m, at 8 m away from induced trench centreline	9.0	253	271	273	282

* Jun-13 readings are not considered to be reliable and are not included in the authors' interpretation of the data.

Fig. 1. Simplified arching mechanism of positive projecting and induced trench culverts. B_c , outside diameter of culvert; H , height of embankment above top of culvert (McGuigan and Valsangkar 2011).

The diagram illustrates a cross-section of a Class 'A' backfill structure. A central circular structure is surrounded by a layer of Class 'A' backfill, which has a width of $3 \times B_c$ and a height of d . Above this, there is a layer of sand or other compressible material, with a width of $5 \times B_c$ and a height of $1.3 \times B_c$. The entire structure is supported by a base of lightly compacted backfill, which has a width of $3 \times B_c$ and a height of 300 . The structure is labeled 'BORROW 'A'' and 'CLASS 'A' BACKFILL AROUND STRUCTURES'.

Fig. 3. Cross section through Peter Smith Brook induced trench installation (Parker et al. 2008).

Fig. 4. Location of instrumentation for the Peter Smith Brook induced trench installation (Parker et al. 2008).

Fig. 5. Post construction vertical earth pressure measurements at the crown at the Peter Smith Brook site.

Fig. 6. Post construction lateral earth pressure measurements at the springline at the Peter Smith Brook site.

(a)

(b)

Fig. 7. Post-construction vertical earth pressures measured within the embankment at the Peter Smith Brook site: (a) Elevation 72 m; (b) Elevation 78 m.

Fig. 8. Cross section through the Manzer Brook induced trench installation (McGuigan and Valsangkar 2011).
155x122mm (300 x 300 DPI)

Fig. 9. Locations of earth pressure cells at the Manzer Brook site (McGuigan and Valsangkar 2011).

68x32mm (300 x 300 DPI)

Fig. 10. Post construction vertical earth pressure measurements at the crown at the Manzer Brook Site.

Fig. 11. Post construction earth pressure measurements at the shoulders at the Manzer Brook site.

Fig. 12. Post-construction lateral earth pressure measurements at the springlines at the Manzer Brook site: (a) outside springlines; (b) inside springlines.

Fig. 13. Post-construction earth pressure measurements at the haunches at the Manzer Brook site: (a) outside haunches; (b) inside haunches.

The diagram illustrates a cross-section of a proposed drainage structure. The structure is a rectangular box with a width of 16.750 and a height of 2.60 by 3.60. It is surrounded by Class 'A' Backfill, which is 0.500 thick on the sides and 0.500 thick on the top. The structure is set within a larger rectangular area of 35.00 width and 25.10 height. The top of the structure is at the same level as the existing ground, which is indicated by a dashed line. The structure is labeled 'BORROW 'A' MATERIAL' and 'CLASS 'A' BACKFILL'. The existing ground is labeled 'EXISTING GROUND'. The structure is labeled '2.60 by 3.60'.

Fig. 15. Locations of earth pressure cells at the McBean Brook site (Oshati et al. 2012).

Fig. 16. Post construction vertical earth pressure measurements at the roof at the McBean Brook site.

Fig. 17. Post-construction lateral earth pressure measurements at the sidewalls at the McBean Brook site: (a) north sidewall; (b) south sidewall.

Fig. 18. Post construction contact pressure measurements at the base at the McBean Brook site.