EARTH PRESSURES ON TWIN CIRCULAR CULVERTS BACKFILLED WITH CONTROLLED LOW STRENGTH MATERIAL

by

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ABSTRACT

In many instances, twin rigid culverts need to be constructed at a very close spacing. The narrow spacing between culverts does not permit placement of granular fill in lifts and achieve the required degree of compaction. In these situations, controlled low strength material (CLSM) can be used instead of soil fill. CLSM is a self-compacting, self-leveling, cementitious material that goes by many names: flowable fill, lean-mix concrete, and controlled density fill to name a few. Even though CLSM has been used in rigid pipe construction, very limited research is reported on earth pressure distribution on twin culverts backfilled with CLSM. To develop better understanding of earth pressure distribution, a twin circular culvert installation was instrumented for this research project. The specified pipes were 140D (2400 mm ID) with a wall thickness of 200 mm, bringing the outside diameter ($B_c$) to 2800 mm. A spacing of only 280 mm was specified at the inside springlines of the two culverts. CLSM was used as fill in between culverts up to the height of the springlines instead of soil fill. The final embankment height was 7.4 m up to the sub-grade elevation. Sixteen sensors in total were installed at the site. Fourteen earth pressure sensors and two NATM (New Austrian Tunneling Method) type sensors were selected for this study. The earth pressure sensors were installed in the surrounding soil fill around two culvert sections of each pipe, while NATM cells were installed in CLSM. This thesis presents the results of field monitoring and compares the data with the numerical analysis predictions for the constructed installation. Practical significance of the results obtained are discussed. The use of CLSM as opposed to uncompacted soil fill did not significantly affect earth pressures on culverts, and the main benefits were found to be from a constructability perspective.
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<tr>
<td>--------</td>
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<td></td>
</tr>
<tr>
<td>ACI</td>
<td>American Concrete Institute</td>
<td></td>
</tr>
<tr>
<td>ACPA</td>
<td>American Concrete Pipe Association</td>
<td></td>
</tr>
<tr>
<td>ANSI</td>
<td>American National Standards Institute</td>
<td></td>
</tr>
<tr>
<td>Bc</td>
<td>Outside diameter of culvert</td>
<td></td>
</tr>
<tr>
<td>CHBDC</td>
<td>Canadian Highway Bridge Design Code</td>
<td></td>
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<tr>
<td>CLSM</td>
<td>Controlled low strength material</td>
<td></td>
</tr>
<tr>
<td>CSA</td>
<td>Canadian Standards Association</td>
<td></td>
</tr>
<tr>
<td>DL</td>
<td>Dead load of culvert</td>
<td></td>
</tr>
<tr>
<td>FLAC</td>
<td>Fast Lagrangian Analysis of Continua</td>
<td></td>
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<td></td>
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</tr>
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<td>ID</td>
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</tr>
<tr>
<td>ITI</td>
<td>Induced trench installation</td>
<td></td>
</tr>
<tr>
<td>NATM</td>
<td>New Austrian Tunneling Method</td>
<td></td>
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<tr>
<td>NBDOT</td>
<td>New Brunswick Department of Transportation</td>
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<td>NBDTI</td>
<td>New Brunswick Department of Transportation and Infrastructure</td>
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<tr>
<td>NCHRP</td>
<td>National Cooperative Highway Research Program</td>
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<tr>
<td>NIST</td>
<td>National Institute of Standards and Technology</td>
<td></td>
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<tr>
<td>PCA</td>
<td>Portland Cement Association</td>
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<tr>
<td>PPI</td>
<td>Positive projecting installation</td>
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</tr>
<tr>
<td>SIDD</td>
<td>Standard installation direct design</td>
<td></td>
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<tr>
<td>γ</td>
<td>Unit weight of soil</td>
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1.0 INTRODUCTION

Culverts are an essential part of any highway infrastructure. They provide a conduit for water passage through these structures, and a lower-cost alternative to bridge construction. In many instances twin culverts are used to meet the hydraulic design criteria. When field conditions require twin circular culverts to be installed with very narrow space between them, compaction of soil fill between culverts cannot be achieved as compaction equipment cannot be used in such a narrow space. In these situations, controlled low strength material (CLSM) can be used instead of soil fill. CLSM is a self-compacting, self-leveling, cementitious material that goes by many names: flowable fill, lean-mix concrete, and controlled density fill, to name a few. Its main applications are as a structural fill, utility bedding, void filling, and in construction of bridge abutment approaches (Folliard et al. 2008).

Studies on CLSM have been primarily focused on the properties and optimal mix designs of CLSM (Sama, 2015). In comparison, few studies have been conducted into the effects backfilling with CLSM has on soil structure interaction of culverts. To the author’s knowledge, no studies have been completed on concrete, precast twin circular culverts with CLSM backfilled in the narrow space between them. In view of lack of the noted data base, a 36 m long, 2400 mm inside diameter twin culvert under a 7.4 m embankment was instrumented to measure earth pressures at the invert, outside haunches, outside springlines, and crown of the culverts. CLSM was used as backfill between the culverts from the inverts up to the springlines; soil fill was used for rest of the backfill. Sensors
were embedded in the CLSM to measure induced stresses during subsequent soil backfilling operations. Numerical modelling using FLAC software was used to analyze field results and conduct a parametric study.

1.1. Objectives

The objective of this research was to identify and characterize the effects CLSM has on soil structure interactions when used as backfill between twin circular rigid culverts. A parametric study was carried out using numerical modelling to supplement and compare field results.

Objectives for this study are as follows:

1. Determine any differences in how earth pressures are exerted on twin culverts backfilled with CLSM compared to those backfilled with soil fill in between.

2. Determine which parameters have the greatest impact on soil structure response.

3. Determine validity and viability of construction method using CLSM in case of twin culverts with narrow spacing between them.

1.2. Scope of Work

This project only examines soil-structure interaction of twin circular culverts. The structural response of the culverts was not analyzed.
2.0 BACKGROUND & LITERATURE REVIEW

This chapter summarizes current culvert construction procedures, case studies of soil structure interactions in rigid culverts, and an overview of CLSM and its use in culvert construction. Considering the scope of work of this research, the literature review only focuses on case studies pertaining to earth pressures on rigid culverts.

2.1. Research on Buried Culverts

For the last two decades, the University of New Brunswick in conjunction with the New Brunswick Department of Transportation and Infrastructure (formerly the New Brunswick Department of Transportation) has been conducting research into the soil-structure interaction of buried pipes installed using both the Induced Trench Installation (ITI) method and the Positive Projection Installation (PPI) method (McGuigan & Valsangkar 2011a, 2011b; McGuigan et al. 2016; Oshati et al. 2012a, 2012b; McAfee & Valsangkar 2008). Figure 2.1 illustrates the soil arching mechanisms for these two types of installations.

McGuigan and Valsangkar (2011a) investigated the effect of culvert spacing on earth pressures for twin box culverts installed using both the positive projecting and induced trench method. Numerical modelling and centrifuge testing were conducted on twin box culverts to estimate earth pressures at the crown, as well as lateral pressures on the side walls. Results indicated that for the positive projecting condition, pressures were lower on twin culverts when compared to a single culvert installation. Culvert spacing was
varied from 0.5Bc to 1.5Bc, and in all cases the pressures at the crown, springlines and base were lower for the twin culvert installation, where Bc is the width of the box culvert. The lowest pressures corresponded to the smallest culvert spacing. For the induced trench condition, the preferred geometry for the compressible zone above the culverts was determined for twin culverts spaced at 0.5Bc, 1.0Bc and 1.5Bc. For the first two spacings, a single compressive zone was found to be most effective, while two separate zones were found to be optimal for the 1.5Bc spacing. When compared to a single induced trench culvert, it was found that in general, the twin culvert configurations resulted in higher earth pressures at the crown, and lower lateral pressures at the sidewalls. Similar contact pressures at the base were found between both twin and single induced trench culverts.

McGuigan and Valsangkar (2011b) instrumented twin circular 3660 mm diameter culverts installed using the induced trench method under 21.7 m of fill. The earth pressures at the invert of the culverts were much higher than expected, due to poor compaction in the haunch regions of the culverts and the stiff bedding material used. FLAC 2D was used to compare the twin induced trench condition to a single induced trench and twin positive projecting conditions. It was found that the vertical earth loads on the twin culverts installed in the induced condition were 6% higher than the single culvert installed in induced trench condition, and 30% lower than the twin positive projecting condition. McGuigan and Valsangkar (2011b) also concluded that vertical earth loads on the culverts cannot be determined solely from the radial pressures measured by the sensors in the field; shear forces—unaccounted for by the pressure sensors—contributed to 14% of the vertical load on the twin culverts. The results indicate
Figure 2.1. Simplified arching mechanisms for circular culverts of positive projection and induced trench culvert installation methods (from McGuigan and Valsangkar 2011b). $B_c$, outside culvert width; $H$, embankment height above the top.
that the induced trench condition is a viable installation option for large diameter twin pipes.

With the adoption of the standard installation direct design (SIDD) method in many North American design standards (ACPA 2007; CSA 2006), most jurisdictions have moved away from indirect design methods based on A, B, C and D bedding classes for positive projecting embankment installations. However, for induced trench culverts, the indirect design approach proposed by Marston (1930) and later refined by Spangler (Spangler 1950; Spangler and Handy 1973) remains the standard method for induced trench culverts. Many successful induced trench culvert installations have been completed, especially in New Brunswick, Canada (Hansen et al. 2007), although issues with the design theory have been identified by several researchers (Sladen and Oswell 1988; Handy 2004). While McGuigan and Valsangkar (2011ab) and other researchers at UNB (Oshati 2012ab, McAfee 2008) have demonstrated the induced trench method to be a viable construction method for reducing the vertical earth pressures on buried culverts, the induced trench method was omitted from the Concrete Pipe Design Manual (ACPA 2000) and some North American jurisdictions no longer consider induced trench as a design option.

The standard installation direct design (SIDD) prediction method was developed by the American Concrete Pipe Association (ACPA) in the 1970s to establish guidelines for estimating the resulting earth pressures using four standard installation types. The guidelines also defined the maximum utilization of native soils for each installation type.
The re-use of native soils (especially where favorable in-situ conditions exist) provides substantial cost savings by reducing the need for importing material for pipe bedding (American Concrete Pipe Association, 2011). Several full-scale research studies have been conducted focusing on evaluating each of the SIDD installation types.

Hill et al. (1999) instrumented a test installation consisting of two single reinforced concrete culverts to compare SIDD Type II and III installations with the standard installations performed by the Minnesota Department of Transportation (MnDOT). The two SIDD installations were compared to three standard MnDOT bedding conditions (clay, sand and flowable fill) for a total of five test beds. The results of the study indicated that soil stiffness plays a more significant role in the pipe performance than the density of the soil, which is the parameter that engineers and contractors typically focus on. The SIDD installations have produced consistent, reproducible results. While the MnDOT installations performed adequately, their performance was not uniformly predictable.

Zhao and Daigle (2001) conducted full-scale field monitoring of two of the SIDD installation conditions, Type II and Type III. A 1350 mm diameter reinforced concrete pipe was instrumented with earth pressure sensors in two locations, each prepared according to SIDD installation method. Strain gauges were embedded in two of the pipe sections when cast to measure strains in the pipe walls. The performance was measured over a three-year period and reported by Smeltzer and Daigle (2005). It was observed that the measured earth pressures corresponded well to those calculated using the SIDD
method, and that pressures calculated using Marston-Spangler theory were conservative. By designing with SIDD, the pipe strength requirements were reduced, and resulted in savings in both backfill material and pipe material. The authors also highlighted the common belief among contractors that more bedding compaction leads to better culvert performance; however, this is in contradiction to SIDD theory where uncompacted bedding is recommended to facilitate the transfer of pipe load to the haunch region.

Wong et al. (2006) conducted full scale field monitoring of four SIDD Type IV installations, measuring stresses around the test beds for a period of 20 months. In general, an increase in stress with time was observed in the field measurements over the long-term. This increase ranged between 20-45% at the crown, 20-40% for the vertical stress at the springlines, 20-30% for the horizontal stress at the springlines, and up to 50% for the invert. When compared to the field measurements, the SIDD method tended to over-estimate the stress at the crown and underestimate the lateral stress at the springlines; however, the study concluded overall that the SIDD method is a reasonable predictor of the stress envelope around a buried culvert installed using the cut-and-cover method. Measurements also indicated that the horizontal arching factor currently recommended in the SIDD method is overly conservative and can be increased while still maintaining an appropriate amount of conservatism in design.

### 2.2. Controlled Low Strength Material & Buried Pipes

The American Concrete Institute (ACI) defines CLSM as “a self-compacting, cementitious material used primarily as an alternative to compacted fill” (ACI 1994). It
has primarily been used as a structural fill for bridge abutment approaches, void filling, and utility trench bedding (Vahid 2014). The low strength and flowability of CLSM enable it to behave more like a soil than concrete. These unique properties of CLSM allow it to be used as a fill material in a variety of situations where traditional soil fill placement is not feasible.

The first recorded use of CLSM as pipe bedding was in the early 1960s (Adaska 1997). The United States Bureau of Reclamation used CLSM as bedding for 380 mm to 2400 mm diameter concrete pipes as part of the Canadian River Aqueduct Project from Amarillo to Lubbock, Texas. Centralized portable batching plants were established and moved every 16 km along the alignment of the pipeline as work progressed. It is estimated that this procedure saved 40% of the bedding costs by not having to import structural soil fill. Materials were sourced locally along the alignment for the CLSM and delivered by ready-mix concrete trucks.

In the 1970s, a power plant looking for a use for its fly ash, and a cement company looking to make more use of its ready-mix concrete trucks entered into a partnership. The aim was to develop an alternative to conventional soil backfill materials with fly ash as a substantial component. There was interest in developing a backfill material that did not suffer from the same problems as conventional soil fill (requirement of compaction, placement in lifts, settlement problems associated with poor compaction etc.). This partnership lead to the development of K-Krete,® which became a nation-wide name by
the mid-1970s. The success and interest in K-Krete® led to the development of many similar products (Hitch 1998).

The American Concrete Institute established Committee 229 (Controlled Low-Strength Material) in 1984 with the goal of standardizing the available information on the material referred to by many different names, including flowable fill, controlled density fill, soil-cement slurry, and unshrinkable fill. ACI Committee 229 reported on “Controlled Low Strength Materials” in 1994, summarizing much of the research that had been conducted on CLSM over the previous 15 years. The name was chosen as a general term to refer to a wide variety of fill materials. The report focused on applications, material properties, mix proportioning and quality control and quality assurance procedures (Brewer 1990). Table 2.1 summarizes the cited advantages to using CLSM in construction. Since the publication of ACI Report 229 in 1994, several ASTM standards have been developed specifically for CLSM to aid in the consistency of CLSM use across North America.

One of the most significant benefits of CLSM is the ability to use locally available materials. The incorporation of by-products such as fly-ash, bottom ash and foundry sand allow the cost of CLSM to be reduced, in addition to lending to the sustainability of CLSM by decreasing the number of by-products deposited in landfills (Trejo et al. 2004). A wider variety of fly ash types and sources can be incorporated into CLSM compared to traditional Portland cement concrete, due to the lower strength and density requirements.
Several disadvantages of CLSM have been also reported in the literature (Schmitz et al. 2004):

- Requirement of forms in some applications
- Segregation and bleeding
- Lateral pressure during its fluid state
- Potential leaching of constituent materials
- Durability of CLSM subjected to freezing and thawing cycles
- Higher-strength mixtures may not allow subsequent excavation
- Pipe buoyancy when in fluid state

Folliard et al. (2008) conducted extensive testing of CLSM as part of the National Cooperative Highway Research Program (NCHRP) Report 597, “Development of a Recommended Practice for Use of Controlled Low-Strength Material in Highway Construction.” A recommended practice was developed through a series of full-scale laboratory and field experiments that defined the properties of CLSM necessary for applications in utility trench bedding, void-filling, backfill and bridge abutments as well as test methods/performance criteria for CLSM in each of these applications. It was found that CLSM is an effective construction material if used in conjunction with an appropriate quality control and quality assurance program, as well as a familiarity with the unique properties of the material. Potential problems described include excessive long-term strength gain associated with fly-ash use as a supplementary cementitious material, and corrosion of metallic pipes when fully encased. Mitigation measures for both these issues are described in the NCHRP Report 597.
Table 2.1. Summary of CLSM advantages (from ACI 1994).

<table>
<thead>
<tr>
<th>Advantage</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>Readily available</td>
<td>Using locally available materials, ready-mixed concrete suppliers can produce CLSM to meet most project specifications.</td>
</tr>
<tr>
<td>Easy to deliver</td>
<td>Truck mixers can deliver specified quantities of CLSM to job site whenever material is needed.</td>
</tr>
<tr>
<td>Easy to place</td>
<td>Depending on type and location of void to be filled, CLSM can be placed by chute, conveyor, pump, or bucket. Because CLSM is self-leveling, it needs little or no spreading or compacting. This speeds construction and reduces labor requirements.</td>
</tr>
<tr>
<td>Versatile</td>
<td>CLSM mixtures can be adjusted to meet specific fill requirements. Mixes can be adjusted to improve flowability. More cement or fly ash can be added to increase strength. Admixtures can be added to adjust setting times and other performance characteristics. Adding foaming agents to CLSM produces lightweight, insulating fill.</td>
</tr>
<tr>
<td>Strong and durable</td>
<td>Load-carrying capacities of CLSM are typically higher than those of compacted soil or granular fill. CLSM is also less permeable, thus more resistant to erosion. For use as permanent structural fill, CLSM can be designed to achieve 28-day compressive strength as high as 8.3 MPa (1200 psi).</td>
</tr>
<tr>
<td>Allows fast return to traffic</td>
<td>Because many CLSMs can be placed quickly and support traffic loads within several hours, downtime for pavement repairs is minimal.</td>
</tr>
<tr>
<td>Will not settle</td>
<td>CLSM does not form voids during placement and will not settle or rut under loading. This advantage is especially significant if backfill is to be covered by pavement patch. Soil or granular fill, if not consolidated properly, may settle after a pavement patch is placed and forms cracks or dips in the road.</td>
</tr>
<tr>
<td>Reduces excavation costs</td>
<td>CLSM allows narrower trenches because it eliminates having to widen trenches to accommodate compaction equipment.</td>
</tr>
<tr>
<td>Improves worker safety</td>
<td>Workers can place CLSM in a trench without entering the trench, reducing their exposure to possible cave-ins.</td>
</tr>
<tr>
<td>Allows all-weather construction</td>
<td>CLSM will typically displace any standing water left in a trench from rain or melting snow, reducing need for dewatering pumps. To place CLSM in cold weather, materials can be heated using same methods for heating ready-mixed concrete.</td>
</tr>
<tr>
<td>Can be excavated</td>
<td>CLSM having compressive strengths of 0.3 to 0.7 MPa (50 to 100 psi) is easily excavated with conventional digging equipment, yet is strong enough for most backfilling needs.</td>
</tr>
<tr>
<td>Requires less inspection</td>
<td>During placement, soil backfill must be tested after each lift for sufficient compaction. CLSM self-compacts consistently and does not need this extensive field testing.</td>
</tr>
<tr>
<td>Makes use of coal combustion product</td>
<td>Fly ash is by-product produced by power plants that burn coal to generate electricity. CLSM containing fly ash benefits environment by making use of this industrial product material.</td>
</tr>
</tbody>
</table>
While many recent studies have focused on the laboratory characterization and optimal mix design of CLSM (Qian et al. 2015; Blanco et al. 2014), less research has been focused on the soil-structure interaction of CLSM after it has been placed. CLSM has become especially popular as a backfill alternative for vitrified clay pipes (VCP) (National Clay Pipe Institute 2015). Ease of placement, increased productivity, increased strength over granular soil and decreased cost are all cited advantages that lend to CLSM being used as a bedding and backfill material alongside VCP installations.

The increased use of CLSM as a pipe bedding has led to research on refining current design standards to account for the incompressibility, and increased support at haunches and invert that is provided by CLSM as a bedding material. Boschert and Butler (2013) demonstrated that Spangler’s modified version of the Marston equation could be used to predict loads experienced by vitrified clay pipes that were backfilled with CLSM. While still conservative, the modified version of the equation accounts for the support that CLSM provides to the haunches of the pipe. The original Marston equation presumes an inability of the sidefills in the haunch region to carry any significant load due to the difficulty in achieving proper compaction. As CLSM neither compacts nor settles, it provides much greater support than soil fill in the haunch region, rendering the Marston equation overly conservative for pipes bedded in CLSM.

Current design procedures assume granular soil for bedding and backfill (e.g. CSA 2006; AASHTO 2014). Sama et al. (2015) found that vertical pressures were significantly higher for CLSM used as backfill than for granular backfill estimated using Marston
equation when no positive arching was developed in the CLSM. A vitrified clay pipe (VCP) was instrumented with earth pressure sensors to measure the pressures experienced by the VCP when encased in CLSM. The Marston equation assumes positive arching in the soil prism above the top of the buried pipe. When this positive arching is not developed, the equation significantly underestimates the vertical pressures experienced by the pipe. In this study, a loss of positive arching occurred when the trench plates keeping the excavation open were removed. The pressures on the VCP increased by as much as 65% with the removal of the trench plates. Subsequently, it was recommended that the frictional forces between the CLSM and trench walls are estimated keeping in mind the possibility of losing positive arching through the trench box removal.

Many researches have reported several economic and technical advantages to using CLSM as backfill over soil fill, as stated earlier in this chapter; however, Kaneshiro et al. (2001) found that the reported economic advantages of CLSM may be overstated. Many cost analyses tend to omit the costs associated with disposing of excavated material, as well as the cost for quality control. For smaller projects, the increased unit cost of CLSM over soil fill, in addition to the above-mentioned costs, can make it a much more expensive alternative to conventional backfill. It is recommended that the designer should closely examine if the specific characteristics of CLSM are critical to the project when considering using it as a backfill alternative.
3.0 FIELD INSTRUMENTATION AND MONITORING

3.1. East Branch Bass River Twin Culverts

The East Branch Bass River Culvert No. 1 project, part of infrastructure upgrading near the parish of Allardville, New Brunswick is located on Route 360. A twin circular culvert installation was instrumented for this research project. Twin precast reinforced concrete pipes (36 m long, installed as 15, 2.4 m sections) were placed side by side and backfilled in between with CLSM. A spacing of only 280 mm was specified at the inside springlines of the culverts. The specified pipe was 140D (2400 mm ID) with a wall thickness of 200 mm, with an outside diameter (Bc) of 2800 mm. Because of the tight space specified at the springlines, CLSM was used as fill in between culverts up to the height of the springlines instead of soil fill. This negated the need for compaction equipment to stabilize interior soil fill and allowed a smaller area of the river to be disturbed. The details of the concrete fill and culvert construction are presented in Figure 3.1. The specified strength of the CLSM was 7 MPa ± 3 MPa.

The 2002 design DFO fish passage criteria were used in designing this culvert as the East Branch Bass River is an important route for fish spawning in this area. Several culvert sections contain baffles to improve hydraulic conditions that encourage fish passage. A notch width of 500 mm and height of 250 mm was specified for the baffles. This section of Route 360 also must support heavy truck traffic due to the Nepisiguit-Chaleur Regional Solid Waste Commission landfill located along the road, the proximity of Brunswick Mines at the West end of Route 360, and logging operations in the region.
**Figure 3.1.** Design details of the East Branch Bass River culverts (all dimensions are in mm, adapted from NBDTI 2013).
Construction on this project began in August 2015 and the embankment up to the sub-grade was completed in October 2015. The final embankment height was 7.4 m up to the top of the sub-grade, which was the maximum height of the embankment before construction of the road structure. As of April 2016, when the site was last visited, the site still had not been paved.

3.2. Instrumentation Details

Sixteen sensors in total were installed at the site. Fourteen earth pressure sensors (Geokon 4800-1, Lebanon, New Hampshire) were installed in the soil fill around the culverts, and two NATM (New Austrian Tunneling Method) style (Geokon 4800-2, Lebanon, New Hampshire) were embedded in the CLSM. The two NATM-style sensors embedded in the CLSM did not function as intended, and no results from these sensors are presented in subsequent sections. The earth pressure sensors were installed in the surrounding soil fill around two culvert sections of each pipe. Parker et al. (2008) found negligible differences in results between earth pressure sensors installed in the adjacent soil fill and contact pressure cells. Using earth pressure cells as opposed to contact pressure cells allowed for them to be protected by 100 mm of sand during the placement and subsequent backfilling of the culvert sections they were placed beneath. The sand cover reduces the chance that the sensor’s shape will be altered by the weight of the culvert sections, causing erroneous measurements from resulting stress concentrations of the deformed sensor. This was especially important at the inverts of the culverts, where the sensors were placed in the bedding soil before the pipes were placed on the bed and positioned with an excavator.
Two locations, 4.8 m apart were instrumented for redundancy. The locations were chosen to coincide with the centre of the east- and west-bound traffic lanes to ensure that the sensors would experience loading from the maximum embankment height. The crown, outside springlines, outside haunches and invert were all instrumented with earth pressure sensors. The locations for the cells was chosen based on the SIDD pressure distribution for positive projecting pipes. Each sensor was installed at the centre of the pipe section, to reduce the influence the pipe joints might have on readings.

Each earth pressure cell consists of two stainless steel plates welded together with a de-aired hydraulic fluid sealed between them. The diameter of the steel plates is 230 mm with a total sensor thickness of 6 mm. Vibrating wire technology is used to convert the fluid pressure to digital form.

After consulting with the manufacturer as to the type of sensor that would be most appropriate to encase in the CLSM, NATM-style pressure sensors were recommended (presented in Figure 3.2). These cells are similar in construction to the earth pressure sensors, with the addition of a “pinch tube” filled with de-aired hydraulic fluid; one end is attached to the fluid filled space between the sensor plates, and the other end is capped. The fresh-placed warm CLSM can cause the sensor to expand, allowing a void to develop between the CLSM and the sensor as it cools back to ambient temperatures. When the tube is pinched, hydraulic fluid is forced into the sensor, causing it to expand. This sensor expansion ensures complete contact between the sensor plates and the surrounding CLSM allowing all stress fluctuations to be measured. The NATM-style cells are rectangular, with dimensions 100 mm x 200 mm. Two NATM-style shotcrete sensors
Figure 3.2. NATM-style sensor after calibration.
(Geokon 4800-2) were placed inside the CLSM in between the culverts in line with the locations of the other sensors installed in the soil fill.

The operating capacities of the selected cells were 70 kPa (NATM), 170 kPa (springlines) and 350 kPa (invert, haunches, crown) to ensure adequate sensitivity in readings for the expected earth pressures at each location. Each cell is accurate to ±0.1% of the operating capacity (0.35 kPa or less for all sensors). Ultimate capacity for each cell is 150% of the operating capacity, allowing for readings up to 105 kPa, 255 kPa and 525 kPa for each type of cell. A summary of the sensors used is presented in Table 3.1.

**Table 3.1.** Description and placement of sensors.

<table>
<thead>
<tr>
<th>Location</th>
<th>East Pipe</th>
<th>West Pipe</th>
<th>Type</th>
<th>Capacity (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crown</td>
<td>PC-E6</td>
<td>PC-E7</td>
<td>PC-W6</td>
<td>PC-W7</td>
</tr>
<tr>
<td></td>
<td>PC-E4</td>
<td>PC-E5</td>
<td>PC-W4</td>
<td>PC-W5</td>
</tr>
<tr>
<td>Outside springlines</td>
<td>PC-E2</td>
<td>PC-E3</td>
<td>PC-W2</td>
<td>PC-W3</td>
</tr>
<tr>
<td>Outside Haunches</td>
<td>PC-E1</td>
<td>n/a</td>
<td>n/a</td>
<td>PC-W1</td>
</tr>
<tr>
<td>Invert</td>
<td>PC-E1</td>
<td>n/a</td>
<td>n/a</td>
<td>NATM-2*</td>
</tr>
<tr>
<td>CLSM</td>
<td>NATM-1*</td>
<td>n/a</td>
<td>n/a</td>
<td>NATM-2*</td>
</tr>
</tbody>
</table>

Note: Pipe sections counted from culvert outlet.  
*NATM-style cells were placed in CLSM between East and West pipes at section noted.

Verification calibration of each earth pressure sensor was completed in the UNB Civil Engineering Laboratory. A bed of sand was prepared in a steel strong box and each sensor was placed ensuring complete contact between the sensor surface and the sand bed, shown in Figure 3.3. The strong box was then filled to the top in three approximately
100 mm lightly compacted lifts. An inflatable rubber bladder was then placed on top of the sand. The strong box top was secured with 32 bolts torqued to 54 N·m each. An air hose and regulator were then attached to the bladder through an access point in the box. The bladder was inflated to 50 psi for 20 seconds to ensure the sensor was seated correctly. Once the sensor was seated, the pressure was backed off to 0 psi, and then inflated in 5 or 10 psi increments with pressure readings taken at each increment.

The readings from the sensor were then converted from Geokon Digital Units from the handheld readout unit to kPa and compared to the psi reading for that increment to verify the factory calibration factor. Good agreement between the applied load and factory calibration factors was achieved by several other graduate students at UNB (McGuigan and Valsangkar 2011a, Oshati and Valsangkar 2012a) using the same apparatus; however, the first few calibrations performed did not produce data that supported the factory calibration factors. The sensors were consistently under registering the applied pressure by the bladder as much as 60% in some cases. After correcting the testing procedure, the calibration factors provided by the manufacturer gave results closer to the applied pressure by the bladder, but one sensor’s readings were still as much as 35% off the applied pressure; however, the majority of readings—with the exception of the one sensor—were within 3-9% of the applied load.

The difference of 3% to 9% when compared to manufacturer’s calibration is typical and within acceptable limits considering differences in the testing apparatus and testing procedures. It is also worth noting that all of the readings obtained from the sensors in
Figure 3.3. Strong box apparatus used for the verification calibration of each cell, with earth pressures sensor prior to calibration.
UNB testing program were below the applied load indicated by the dial gauge on the air pressure regulator. There are a few possible explanations for this: it is unknown whether the dial gauge on the air pressure regulator had been calibrated prior to testing. It is possible that the dial gauge was showing a higher pressure than what was actually being applied to the bladder. Care was taken when preparing the sand bed to evenly compact each lift, fill the box to the same height each time, and strike off the top lift of the sand bed level to provide an even surface for the bladder to rest on. Over-compaction or uneven compaction could have resulted in the sand arching around the sensor, which would cause the sensor to register less than the full applied load. If frictional forces developed between the sand and the sidewalls of the strong box, this also could have resulted in a reduction in the load experienced by the cell. Finally, the handheld readout unit that was connected to each cell during testing had not been calibrated recently. If the calibration of the handheld unit was incorrect, it could also explain the difference in results. In light of these possible sources of error, the calibration factors provided by the manufacturer were used for interpretation of field measured data.

The manufacturer’s calibration procedure used standards traceable to the National Institute of Standards and Technology (NIST) and in compliance with the American National Standards Institute Standard Z540-1 Requirements for the calibration of measuring and testing equipment, which is more rigorous than what was done to confirm the calibration in the lab. Furthermore, the results from the sensors tested at UNB were linear, indicating that the sensors were functioning as intended. Figure 3.4 shows the data obtained from verification calibration done at UNB.
3.3. **Instrumentation Installation**

The locations where sensors were installed are presented in Figure 3.5. One sensor was installed at the invert of each pipe. One sensor was placed on the underside of the west pipe and one on the east pipe. A piece of geofabric was placed underneath the bedding sand to prevent erosion and migration of the finer material into the underlying foundation bedding. A layer of bedding sand 100 mm thick (ready mix concrete sand obtained offsite by the contractor) was placed in a shallow trench for each sensor. A diesel plate compactor was used to compact this bed. The sensor was placed ensuring complete contact between the sensor face and the sand bed. The trench was then filled in with 100 mm of bedding sand, matching the grade of the surrounding foundation soil then hand compacted with a 10-inch by 10-inch steel tamper to avoid damaging the sensor and cables. Sensors installed at the crown of the culvert were installed using this same procedure, apart from the geofabric layer.

Sensor leads were run up the side of the culvert and fed into 100 mm diameter PVC pipe attached above the culvert shoulders. The PVC pipe was run along the shoulder to the outlet of the pipes where the instrument cables were housed in a waterproof junction box. The junction boxes were mounted on a 4-inch by 4-inch piece of pressure treated lumber founded in a 6-foot sonotube filled with concrete. All sensors were run along their respective pipes (sensors on the west pipe were routed to the west junction box etc.) except for the NATM cell leads were both run into the east pipe junction box.
**Figure 3.4.** Verification calibration chart showing applied pressure vs. registered pressure for each sensor
Figure 3.5. Placement of the earth pressure and NATM sensors around the culverts.
Sensors installed at the haunch and springlines were installed by digging a trench approximately 250 mm wide and 300 mm deep into the already compacted backfill. Bedding sand was compacted in small lifts to the full depth of the trench, and then a 100 mm wide trench was dug into the compacted sand where the sensor was then installed as shown in Figure 3.6. Care was taken to ensure full contact between the sensor face and sand bed. Sand was placed in lifts and compacted using a custom-made steel compaction hand tool. McGuigan and Valsangkar (2011b) installed earth pressure sensors at similar locations using this method based on observations by McGrath (2000) and achieved success. The cells at the haunch were installed 53 degrees from the inverts. Cables were run up the side of the culvert into the PVC pipe and run down to the junction boxes.

The NATM cells were installed as soon as the CLSM was placed. A wooden frame was constructed to bridge across the culverts to allow the NATM sensors to be hung vertically down into the CLSM until it cured enough to support the sensors. Wooden blocks were placed in between the culverts by the contractor to maintain the space between them while backfilling was completed on the outside portion of the culverts up to the springlines. An attempt was made to remove these blocks adjacent to the location of the NATM cells; however, only the immediate two wooden blocks were able to be removed. Figure 3.7 shows the culverts shortly after CLSM placement, where the wooden spacer
Figure 3.6. Sensor installation at the springline of the culvert
Figure 3.7. Culverts after CLSM placement. Wooden spacer blocks visible between pipes
blocks are visible along with the wooden frame used to suspend the NATM cells. The concrete was placed at 6:00 PM on August 19th, 2015 and allowed to cure until 10:00AM the next morning before backfilling continued above the concrete. Figure 3.8 shows one of the NATM sensors encased in concrete with the pinch tube visible above the concrete. The pinch tubes for each cell were crimped at 9:30 AM.

3.4. Construction Details

Culvert construction was completed in two stages. Traffic on Route 360 was diverted along a temporary road constructed adjacent to the existing road to allow for the excavation of the embankment and existing culvert. Starting at the outlet, ten sections of the culvert were installed and backfilled close to grade. The temporary road was then diverted over the completed section of the embankment, allowing the five remaining culvert sections to be placed. This staged construction reduced the amount of brush clearing required for the job, as well as the length of the temporary road required to bypass the active part of the construction site. The specification originally called for the temporary pipe installed to divert the river around the site to be removed; however, the contractor was having difficulty removing the pipe, and opted to fill it with concrete instead. The design drawings depicting the project are shown in Appendix A.

The bedding for each pipe section comprised 200 mm of crushed gravel compacted to 100% standard proctor with a diesel plate compactor. A nuclear density gauge was used at each stage of backfill to ensure the material was compacted to specification. Wooden
Figure 3.8. Pinch tube sticking up out of concrete just prior to crimping.
blocks were placed between each pipe section as spacers to stabilize the sections while backfilling was conducted on the outside portion of the culverts. Well-graded gravel was then placed in 300 mm lifts to the springlines of the culverts and compacted using a plate compactor.

Once the backfilling of soil fill reached the outside springlines, CLSM was placed up to the springlines using an excavator bucket. Plywood sheets were supported against the pipe outlet to contain the CLSM in between the culverts to the springlines. A steel panel from a trench box was placed at the other end of the culvert sections for the same reason. The wooden spacers holding the culverts apart were not removed during concrete placement due to the need for them to keep the culvert sections apart during CLSM placement and curing. The spacers were either encased in the concrete or covered with soil when backfilling above CLSM resumed. The concrete fill strength results are summarized in Table 3.2.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 3.2. Concrete placement parameters and strength results</td>
<td></td>
</tr>
<tr>
<td>Average Slump</td>
<td>125 mm</td>
</tr>
<tr>
<td>Average Air</td>
<td>8.3 %</td>
</tr>
<tr>
<td>Average 7-day Strength</td>
<td>5.3 MPa</td>
</tr>
<tr>
<td>Average 28-day Strength</td>
<td>8.8 MPa</td>
</tr>
</tbody>
</table>
A second culvert installation 800 m down the road was completed by the contractor a week before CLSM placement at the East Branch Bass River project. The CLSM used on that job had a slump of 250+ mm. This resulted in the concrete running down grade and pooling at the outlet end of the site. For the East Branch River project, the CLSM ordered was less flowable and less workable than the other site. Table 3.3 provides details of mix proportions. The CLSM had an average slump of 125 mm and did not have the same problems with flowing down grade as the other site, but remained flowable enough to fill the area between the culverts. This change resulted in a material that was closer to the upper end of the unconfined compressive strength for CLSM by definition. Though some of the concrete cylinders cast from the site broke above the 8.3 MPa maximum strength definition for CLSM, the average was only 0.5 MPa higher at 8.8 MPa; furthermore, in this study the technical strength definition of CLSM is not as important, as it was the flowable qualities of the weak concrete, and its incompressibility relative to soil fill that was of importance to the design.

Backfilling of the well-graded gravel was resumed approximately 16 hours after CLSM placement. As soon as backfilling was 0.5 m above the crown of the culverts, a roller-compactor was used to compact subsequent lifts as presented in Figure 3.9. Pit run gravel till was used as fill once backfilling was 1 m above the culvert crown up to the maximum height of 7.4 m for the embankment construction. Figure 3.10 shows the completed embankment.
Table 3.3. Mix design for the controlled low strength material used at the East Branch Bass River site

<table>
<thead>
<tr>
<th>Material</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>8%</td>
</tr>
<tr>
<td>Fly Ash</td>
<td>11%</td>
</tr>
<tr>
<td>Water</td>
<td>16%</td>
</tr>
<tr>
<td>Sand</td>
<td>65%</td>
</tr>
<tr>
<td>Specified Air</td>
<td>11%</td>
</tr>
</tbody>
</table>
Figure 3.9. A roller (pictured in background) was used for compaction once 0.5 m of fill had been placed above the crown of the culvert.
Figure 3.10. Completed embankment looking toward the outlet. Mounted junction boxes housing sensor cable leads are visible adjacent to culvert sections.
3.5. Field Monitoring

Instrument readings were taken several times during the construction phase, and after backfilling was completed to the maximum height of the embankment. After each sensor was placed, an initial reading from the handheld readout unit was taken. Barometric pressure for the day, and temperature were also noted. Using the manufacturer provided correction factors for temperature and barometric pressure, the digital unit output of the readout was then converted to a pressure. This process was repeated for each subsequent set of readings. Table 3.4 includes readings taken up to April 2016, once the embankment had reached a fill height of 7.4 m.

Table 3.4. Summary of field measurements at fill height of 7.4 m.

<table>
<thead>
<tr>
<th>Location</th>
<th>Number of Cells</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Invert</td>
<td>2</td>
<td>278</td>
<td>330</td>
<td>305</td>
</tr>
<tr>
<td>Outside haunch</td>
<td>4</td>
<td>-4</td>
<td>45</td>
<td>23</td>
</tr>
<tr>
<td>Outside springline</td>
<td>4</td>
<td>-6</td>
<td>40</td>
<td>17</td>
</tr>
<tr>
<td>Crown</td>
<td>4</td>
<td>65</td>
<td>208</td>
<td>144</td>
</tr>
<tr>
<td>CLSM</td>
<td>2</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>

aNATM cells failed to function properly after installation
Readings were obtained from the invert of the culverts at two locations. Figure 3.11 shows the variation in earth pressures over the course of the embankment construction. The calculated dead load of the culvert of 56 kN/m corresponded to a theoretical earth pressure of 89 kPa. The measured earth pressure under the west pipe was 104 kPa, and 119 kPa under the east pipe, 17% and 34% greater than the calculated pressure, respectively. The theoretical contact length along the circumference between the culvert and the bedding soil of 630 mm was found using the procedure outlined in the Canadian Highway Bridge Design Code (CSA 2006). The CHBDC assumes a sinusoidal pressure distribution along the arc length defined by a 30° angle centered at the invert of the pipe.

McGuigan and Valsangkar (2011) found that the CHBDC procedure tended to overestimate the actual contact length of the pipe in the field for large diameter pipes. The contact length calculated assumes uncompacted middle bedding soil (as specified in SIDD Type 1-3 installations), which results in greater settlements of the placed pipe into the bedding. Wilson (1985) found that by ensuring an uncompacted zone in the middle bedding, the settlement of the pipe would increase the effectiveness of compaction efforts in the haunch region through the settlement of the pipe. This settlement spreads the load evenly across the invert and haunch area, limiting the possibility of a stress concentration at the invert of the pipe. In practice, laying large pipes on uncompacted soil could lead to excessive settlements that could damage pipes under large loads, or even cause differential settlements along the alignment of the pipe. The actual contact length measured in the field was closer to 460 mm, which corresponds to a dead load intensity of 121 kPa, which is within 14% of both measured values, or 7% of the mean.
Figure 3.11. Vertical earth pressures measured at the culvert invert
Table 3.4 outlines the field readings taken at the invert once the embankment had reached the maximum height of 7.4 m. The measured pressures ranged from 278 kPa to 330 kPa and averaged 305 kPa. The average pressure corresponds to \(1.6\gamma H + DL\), kPa (where \(H\) is the height of fill above the culvert crown, \(\gamma\) is the unit weight of the soil and \(DL\) is the measured culvert dead load). Kang (2008) found that base contact pressures for box culverts were greater than the theoretical height of soil and dead load of culvert due to downward frictional forces on the sides of the structures; McGuigan and Valsangkar (2011b) measured similar downward forces on twin circular culverts. For the positive projecting condition, measured earth pressures are expected to be greater than the weight of the soil fill above the sensor due to negative arching developing in the soil fill. This negative arching can explain why the measured invert pressures are 21% to 45% greater than the theoretical pressures calculated at the maximum height of the embankment.

The pressures measured at the outside haunches during construction are shown in Figure 3.12. Four sensors were installed at the haunch locations. During construction, once the height of the embankment was approximately 1 m above the crown of the culvert (corresponding to an embankment height of 4 m), both sensors at the outside haunches on culvert Section 10 registered a pressure lower than the initial pressure reading from when the sensors were installed. Neither sensor on culvert pipe section 8 registered this drop in pressure. It is not known why this drop in reading occurred; one possible explanation is that pipe section 10 shifted slightly once the larger compaction equipment was used for compaction of the soil lifts. The difficulty in achieving compaction in the haunch zone could also be a contributing factor to the variation in measurements noted. At the
Figure 3.12. Earth pressures measured at the haunches.
maximum height of the embankment, the minimum pressure measured by a haunch sensor was 4 kPa below the initial zero reading of the sensor when it was installed; the maximum pressure measured was 45 kPa.

Pressure variations in the springline sensors during culvert construction are shown in Figure 3.13. The earth pressures ranged from 6 kPa below the initial pressure measured by the sensor, to 40 kPa. The maximum measured earth pressure of 40 kPa corresponds to a lateral earth pressure coefficient of 0.3, or 0.3 $\gamma H_1$ kPa, (where $H_1$ is the height of fill above the springline, and $\gamma$ is the unit weight of the soil) which is in the range expected for this soil type. One possible explanation for the nearly constant response of sensors at the springline when the embankment was raised from 4m to 7 m could be settlement of the surrounding soil fill causing the fine sand layer to arch around the sensors resulting in recording reduced earth pressures.

Earth pressures measured at the crown ranged from 65 kPa to 208 kPa, with an average of 144 kPa once the embankment reached maximum height. Figure 3.14 shows the variation in earth pressures during the course of construction. The mean corresponds to $1.6 \gamma H$, kPa (where $H$ is the height of fill above the culvert crown and $\gamma$ is the unit weight of the soil). This increase above the overburden stress is due to negative arching induced above crown. The initial data collected from the NATM sensors were contradictory to what was expected. The day after installation one cell was not functioning. It was only registering a temperature reading and no pressure reading.
Figure 3.13. Earth pressures measured at the culvert outside springlines
Figure 3.14. Vertical earth pressures measured at the culvert crowns
The other cell was reading a negative pressure in relation to the initial pressure measured immediately after crimping the pinch tubes.

Two possible explanations for the negative pressure readings exist: the concrete was still workable when the tubes were crimped inflating the plate sensor, resulting in the concrete deforming to accommodate the expanding plate after the initial reading was taken. Then, as the concrete continued to cure, shrinkage could have caused a space to develop between the plates and the concrete. Second, if the concrete had not set a sufficient amount to allow maximum shrinkage to take place before crimping the sensors, the concrete would have shrunk after the plates were inflated, resulting in a negative pressure compared to the initial reading. Due to time constraints with the contractor, backfilling above the CLSM had to continue only 16 hours after placement, at which point the pinch tubes had to be crimped. The second NATM sensor may have had its lead damaged during backfilling or concrete placement operations, causing it to cease functioning properly. For future research projects where the concrete is not able to cure fully before backfilling must continue, sensor options that are not limited by the need for a pinch tube to counter the effects of concrete shrinkage should be explored.

Several inconsistent data points were recorded in the springline and haunch sensors. These data points were removed from the final figures presented. There are a few possible explanations for these readings: the construction sequence for this installation could have impacted the sensors: To support the culverts from being pushed apart by the weight and buoyant force of the liquid CLSM, backfilling was done up to the springlines.
outside the culverts. Wooden blocks were placed between the culverts to maintain the specified 280 mm spacing. This necessitated the installation of the haunch and springline sensors prior to the placement of CLSM between the culverts. After the CLSM had cured for 16 hours, backfilling was continued.

The two locations along the culvert alignment where sensors were installed were not backfilled uniformly. To reduce the amount of tree clearing required to complete this project, the contractor opted to construct the culvert in two phases: twenty culvert sections were placed initially (ten for each pipe) and backfilled almost up to grade. Then, traffic was re-directed over the completed section. The temporary road was then excavated, and the remaining 10 sections were placed and backfilled to grade. Sensors placed at the second location coincided with the last two culvert pipes placed during the first phase of construction. This change meant that the second location was located under the slope of the temporary road embankment until phase two of construction was completed and the entire length of the culvert was backfilled up to grade. It is likely that this unconventional construction methodology would have resulted in localized arching of sand around some of the sensors resulting in inconsistent responses. The ranges in values recorded at each sensor location are reasonable given the construction methodology and inherent variations in the soil fill used, as well as variations in compaction and soil stiffness between sensor locations.
4.0 NUMERICAL MODELLING

Numerical modelling of the field installation was undertaken to compliment the earth pressure readings measured in the field and allow for the modelling of conditions other than those in the field. FLAC 2D 7.0 (Itasca, 2015), a finite difference analysis program, was utilized for this purpose as it has been successfully used on other research projects analyzing earth pressures on buried culverts; McGuigan and Valsangkar (2011\textit{ab}) and McAfee and Valsangkar (2008) reported good agreement between field measurements and those modelled using FLAC.

The first condition that was modelled was the field condition, consisting of twin, circular culverts 280 mm apart with CLSM in between. The culverts were modelled in FLAC using structural beam elements. A grid resolution of 70 mm was used for the model presented in Figure 4.1. Since a static analysis was used for the modelling, a fine mesh could still be used while maintaining reasonable model run times. The structural response of the culverts was not analyzed as part of this research. The outer diameter of the culverts was used for the model pipes (2800 mm), with a Young’s modulus of 33.4 GPa for reinforced concrete. A Mohr-Coulomb interface was modelled between the structural beam elements and the surrounding materials to allow for movement along the culvert surface. The interface between the CLSM and culvert was modelled as bonded; however, it was found that neither interface had a significant impact on the earth pressures calculated.
Figure 4.1. FLAC model of initial problem geometry showing extent of material zones (both axes are in metres)
Once the problem geometry was set up in FLAC, the model was brought to equilibrium in several stages, adding a lift of soil in each run. This simulated the staged construction process used in the field. Figure 4.1 shows the limits of each material zone, as well as the lifts used. The limits of each zone were approximated based on the design drawings and field measurements to maintain a simplified grid. Table 4.1 presents the material properties used for modelling.

Table 4.1. Material properties used in modelling procedure

<table>
<thead>
<tr>
<th>Material</th>
<th>Young’s modulus (MPa)</th>
<th>Poissons ratio</th>
<th>Density (kg/m³)</th>
<th>Friction angle (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLSM</td>
<td>2400</td>
<td>0.20</td>
<td>2185</td>
<td></td>
</tr>
<tr>
<td>Embankment fill</td>
<td>15</td>
<td>0.3</td>
<td>2160</td>
<td>32</td>
</tr>
<tr>
<td>Backfill soil around pipes</td>
<td>14</td>
<td>0.25</td>
<td>2100</td>
<td>40</td>
</tr>
<tr>
<td>Backfill in haunch area</td>
<td>3</td>
<td>0.25</td>
<td>1800</td>
<td>35</td>
</tr>
<tr>
<td>Bedding Sand</td>
<td>14</td>
<td>0.25</td>
<td>2030</td>
<td>40</td>
</tr>
<tr>
<td>Foundation Soil (Till)</td>
<td>20</td>
<td>0.25</td>
<td>2110</td>
<td>40</td>
</tr>
</tbody>
</table>

Note: All soil densities except for haunch soil are averages of readings taken in the field with nuclear density gauge. CLSM density is average density of cylinders cast for compressive strength testing.

Each soil type material was modelled using a Mohr-Coulomb constitutive model, except for the CLSM, which was modelled as elastic. The estimated soil parameters were based on previous testing done on similar materials used in culvert construction. For the CLSM Young’s modulus, the American Concrete Institute (ACI) provides an empirical equation.
to calculate a value based on density and 28-day compressive strength. An average value of 9000 MPa based on the compressive strength test reports of the CLSM was calculated using the ACI method. Due to the low strength of CLSM compared to regular concrete, and the lack of literature supporting the use of the ACI empirical equation on low-strength concrete, a lower Young’s modulus of 2400 MPa was chosen based on lab experiments done by Shah (2012) deriving CLSM material properties; however, a sensitivity analysis comparing results using both values in FLAC found that the difference in earth pressures was negligible between them.

Due to the difficulty in compacting soil fill in the haunches of the culverts, a zone of poorly compacted material was included at the outside haunches of the culverts. The model geometry was built based on the construction drawings provided by the New Brunswick Department of Transportation and Infrastructure, and measurements made in the field. Once the model was built up to the final grade and brought to equilibrium, earth pressures were obtained from FLAC at the same points where sensors were installed in the field. Earth pressures obtained in the field were then compared to those modelled in FLAC.

4.1. Analysis

Generally, good agreement was observed between field measurements and those calculated with FLAC. The dead load of the culvert was estimated to be 56.7 kN/m using the procedure outlined in the Canadian Bridge Construction Manual (CSA 2006), using
the contact length between culvert and bedding sand measured in the field. In the field the
dead load was measured to be 56.9 kN/m under the west pipe, and 59.0 kN/m under the
east pipe. The vertical stresses are contoured in Figure 4.2. At the full height of the
embankment, values calculated with FLAC generally fell inside the range of measured
pressures for the locations that earth pressure cells were installed. Table 4.2 summarizes
the field and calculated values.

**Table 4.2.** Summary of radial earth pressures calculated with FLAC.

<table>
<thead>
<tr>
<th>Location</th>
<th>Range of measured values (kPa)</th>
<th>FLAC Calculated values (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Invert</td>
<td>278-330</td>
<td>201.7</td>
</tr>
<tr>
<td>Outside Haunch</td>
<td>0-45</td>
<td>49</td>
</tr>
<tr>
<td>Outside Springline</td>
<td>0-40</td>
<td>35.5</td>
</tr>
<tr>
<td>Crown</td>
<td>65-208</td>
<td>119</td>
</tr>
</tbody>
</table>

The earth pressure calculated at the invert of the culvert with FLAC was outside of the
range of measured pressures in the field. FLAC tended to underestimate the pressure at
the invert of the culvert. The average earth pressure measured at the invert was 304 kPa, a
40% increase over the pressure calculated with FLAC. The pressure measured at the
outside haunch was 18% less than FLAC analysis. The horizontal earth pressure
calculated at the outside springline of the culverts was within the range of values
measured in the field, though closer to the upper end of the measured values. At the
crown, the calculated earth pressure was within the range of measured values, 13% less
than the mean earth pressure measured. Table 4.3 presents the ratios of earth pressures
measured in the field and estimated with FLAC to the theoretical overburden stresses.
Figure 4.2. Contoured plot of vertical stresses calculated for the East Branch Bass River, NB site with FLAC (units for stress are in Pa and both axes are in metres).
Table 4.3. Summary of FLAC calculations compared to field measurements expressed as a function of overburden pressure ($\sigma_v$) at reference sensor location.

<table>
<thead>
<tr>
<th>Sensor Location</th>
<th>FLAC Simulation</th>
<th>Field Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crown</td>
<td>1.1</td>
<td>1.6</td>
</tr>
<tr>
<td>Springline</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Haunch</td>
<td>0.4</td>
<td>0.3</td>
</tr>
<tr>
<td>Invert</td>
<td>1.0</td>
<td>1.6</td>
</tr>
</tbody>
</table>

Several assumptions inherent to numerical modelling can explain the variation noted in Table 4.3. FLAC assumes a homogeneous soil layer with uniform compaction, which is often not the case in the field. The difficulty with achieving sufficient compaction in the haunch areas of the culverts has been documented in several studies. Variation in compaction, lift thickness and the unavoidable anisotropy of the soil material can all affect the values measured in the field. A few of the sensors in the field registered contradictory readings due to unconventional construction methods used compared to what was predicted in the field and one sensor ceased to function shortly after installation. This highlights the importance of redundancy when designing a geotechnical instrumentation program.

4.2. Parametric Study

After the initial problem geometry was modelled in FLAC and compared to the field readings, a parametric study was undertaken to further explore the development of earth pressures around the twin culverts backfilled with CLSM. The parameters that were
focused on in this study were the spacing between the culverts and the density of the material placed between the culverts. Two different spacings were modelled, comparing the earth pressures around the culverts when backfilled in between with CLSM to loose sand and gravel. The spacings chosen corresponds to 0.1Bc (initial condition) and 0.5Bc.

4.2.1. 280 mm Spacing (0.1Bc)

The first condition modelled was replacing the CLSM with a loose sand and gravel to assess the effectiveness of using CLSM versus filling the narrow space between the culverts with an uncompacted sand and gravel material. The earth pressures at the invert and haunch increased slightly, by 5% and 2% respectively. The earth pressures at the springline increased by 5% and the crown pressure remained essentially unchanged. FLAC assumes a homogeneous, evenly distributed material between the culverts, which in reality would be difficult to achieve with a loose sand and gravel. The narrow space in between the culverts would make it difficult to spread the fill evenly under the haunch area. The analysis was re-run with the addition of a small void in the inside haunch, which would be the most difficult place to spread fill with this culvert spacing. The earth pressures at the invert and haunch increased by 16% and 5% respectively, while the crown and springlines remained unchanged. Therefore, even though the earth pressures were not drastically different between the two initial conditions, the constructability of each geometry should be considered. The ease of placement of CLSM and the increased support that it provides to the haunches is more beneficial to the design when the loose fill cannot be placed with consistency in the field due to space constraints.
4.2.2. **1400 mm Spacing (0.5Bc)**

The distance between the culverts was increased from 280 mm to 1400 mm (corresponding to 0.5Bc) and modelled in FLAC with CLSM in between, presented in Figure 4.3. Compared to a spacing of 0.1Bc, the earth pressure at the crown increased 8%, the springline increased 26% and the invert increased 2%. A corresponding stress increase at the interface between the culvert and CLSM at the inside springline was determined. The earth pressures at the outside haunch were reduced by 30%. The redistribution of the load around the culvert increased the lateral load at the mid-line of the culvert, which in turn reduced the load experienced at the outside haunch. An increase in earth pressure at the crown as the culverts spacing increases is also expected, as the earth loads are redistributed from the culvert shoulders.

Modelling the 0.5Bc condition with loose sand and gravel in between resulted in an earth pressure increase of 8% at the crown, 12% at the spring lines and 1% at the invert compared to 0.1Bc. The haunch earth pressure was reduced by 15%. There was an increase in lateral load to a lesser extent compared to the same geometry with CLSM in between, which resulted in less of a reduction in pressure at the outside haunches. The stiffness of the CLSM compared to loose sand and gravel allows it to support a greater earth pressure without yielding or deforming to support the load.

Once the culvert spacing is beyond 1 m, it is possible a plate tamper or similar, smaller compaction equipment could be used in the space between the culverts. The model was
Figure 4.3. FLAC model after increasing space between culverts to 1400 mm showing extent of material zones (both axes are in metres)
run again using the same compacted backfill material from outside the culverts in place of the sand and gravel.

A poorly compacted zone of fill was included at the inside haunch, mirroring the same poorly compacted area at the outside haunch. Compared to the loose sand and gravel condition, the earth pressures at the crown and haunch decreased by 2% and 9% respectively, while the earth pressures at the invert and springline increased by 10% and 12% respectively. The compacted backfill in between the culverts restricts the degree the poorly compacted soil at the haunches can distribute the earth pressure, increasing the stress concentration at the invert of the culvert.

4.3. Discussion

The use of CLSM between culverts at close spacing instead of loose granular fill does not drastically impact the earth pressures experienced by the culverts; however, substituting CLSM for loose fill may be more practical for constructability. With such little space between culverts, it would be difficult to ensure that the fill is evenly distributed under the inside culvert haunches. The Canadian Highway Bridge Design Code recognizes the difficulty with achieving sufficient compaction and soil distribution in the haunch region of circular culverts. This becomes exponentially more difficult when the space between culverts is small enough that it is difficult to even spread the material once it has been placed.
Loose fill is also susceptible to erosion from rain during construction, and water inflow after culvert completion. Over the life of the culvert, it would be difficult to ensure that loose fill would not erode or migrate unless additional protection measures were put in place. The numerical modelling performed as part of this project assumed complete contact with the loose fill along the haunch of the culvert which may not always be the case in the field, depending on the degree to which the fill in between the culvert is able to be placed during construction. If voids are present, it could cause an uneven pressure distribution along the inside haunch which could lead to asymmetric settlement of the culvert, or bending loads not accounted for in the initial design. The increased support and stability provided by CLSM in the haunch area, combined with the time savings of not having to spread the fill in the enclosed space make it an attractive alternative to granular fill.

As the spacing of the culverts increases, there are less benefits of using CLSM over a soil fill. Once the spacing between the culverts is great enough that compaction equipment can be used, it becomes much more expeditious from a constructability perspective to use soil fill in between the culverts. This eliminates the need for formwork, scheduling around a concrete pour, waiting for curing and paying for concrete testing. There is also a reduction in vertical earth pressure at the crown of the culverts the closer they are together, though this does not always translate into a reduction of earth pressure at the invert of the culvert.
Several factors should be taken into account when considering CLSM aside from the benefits discussed thus far. The increased cost of CLSM over granular fill, testing requirements and proximity of the project site to a ready-mix facility can all greatly impact whether using CLSM as fill is ultimately beneficial to the project. Each project where it is considered should evaluate whether the characteristics of CLSM can help the project despite the stated disadvantages.
5.0 CONCLUSION

Twin circular reinforced concrete culverts (2400 mm ID) installed with a narrow space between them and backfilled with controlled low-strength material in between were instrumented with earth pressure sensors. The final embankment height during measurements was 7.4 m. Sensors were located at the crowns, outside springlines, outside haunches and inverts of the culverts, positioned to experience the maximum height of the embankment. Earth pressures at the crown and invert corresponded to 1.6 times the theoretical vertical overburden pressure. Pressures at the haunch and springlines both corresponded to 0.3 times the theoretical vertical overburden pressure. Negative soil arching (resulting in greater than theoretical pressures on the culverts) in a positive projecting installation is expected due to the greater relative settlements of the soil outside the soil prism above the culverts. Difficulty in compacting the soil in the outside haunches, combined with the compaction of the pipe bedding soil also contributes to the stress concentration at the inverts of the culverts.

FLAC was used to model the field installation, and reasonable agreement between the field readings and the numerical model were obtained. The earth pressure at the crown calculated with FLAC corresponded to $1.1\gamma H$. Two culvert spacings were evaluated, modelling each with either CLSM as fill in between or soil fill corresponding to $0.1B_c$ (field condition) and $0.5B_c$. For $0.1B_c$, the earth pressures around the culvert did not change dramatically between the CLSM and loose sand and gravel condition, though a
5% reduction in pressure at the invert was calculated for the CLSM condition. In general, as the culvert spacing increased, the earth pressures at the crown and invert did as well.

Ultimately, the earth pressures did not vary significantly at the invert (which normally governs design) between cases modelled. As the space between the culverts is increased, the benefits to using CLSM as fill become less obvious. The benefits of CLSM are greatest from a constructability perspective when installing culverts with narrow space between them. CLSM can allow culverts to be installed with a narrow space to meet hydraulic and environmental constraints and still be practical for long term stability and constructability. If the designer considers all the additional costs associated with using CLSM on a project, it is a viable alternative to soil fill when site conditions constrain the use of compaction equipment.
6.0 REFERENCES


American Concrete Institute. (1994). Controlled Low Strength Materials (CLSM). ACI 229 R-13, ACI Committee 229. Detroit, MI.


Fisheries and Oceans Canada. Guidelines for the Protection of Fish and Fish Habitat. (2002). Guidelines for the Protection of Fish and Fish Habitat (pp. 1–101). Fisheries and Oceans Canada.


Appendix A – Construction Design Drawings
Back Elevation of Weir

Plan of Weir

Steel Weir Insert - Front Isometric

Steel Weir Insert - Back Isometric

NOTES:
1. See particular specifications item No.143 for proper painting and installation procedures for steel weir inserts.
2. Steel weirs shall be sealed on site using osmium and cedar shingle wedges.

8 weir inserts required

For Viewing Purposes Only

DEPARTMENT OF TRANSPORTATION AND INFRASTRUCTURE

EAST BRANCH BASS RIVER CULVERT No. 1

SCALE: As Shown
Curriculum Vitae

Candidate’s full name: Gregory James Healy

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Conference Presentations: none