Earth Pressures on Closely Spaced Twin Circular Culverts Backfilled with Controlled Low Strength Material within Narrow Space

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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. Very limited research is reported on earth pressure distribution on twin culverts backfilled with CLSM. To develop a better understanding of earth pressure distribution, a twin circular culvert installation was instrumented for this research project. 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. This paper presents the results of field monitoring and compares the data with the numerical analysis predictions for the constructed installation. The practical significance of the results obtained is discussed based on the results obtained.

RÉSUMÉ

Dans plusieurs cas, deux ponceaux doivent être placés très près l'un de l'autre. L'espace étroit entre les tuyaux ne permet pas de placer le matériel de remplissage (gravier) et compacter tel que requis. Dans ces situations, du matériel à force faible contrôlée (MFFC) peut être utilisé au lieu de remplir avec de la terre. Très peu d'information est disponible sur la distribution de la pression sur la terre dans le cas de doubles ponceaux remplis avec du MFFC. Pour obtenir une meilleure compréhension de la distribution des forces, des instruments furent placés sur une installation de doubles ponceaux. Un espacement entre les tuyaux de seulement 280mm au point le plus proche fut utilisé. Du MFFC fut utilisé pour remplir entre les tuyaux jusqu'à la moitié de la hauteur du tuyau. La hauteur totale de la colline est 7.4 m à l'élévation du couche de forme. Cet article présente les résultats obtenus sur le chantier en comparaison avec les prédictions obtenues par analyse numérique de l'installation. Les différence significatives entre les résultats obtenus sont discutées relatives aux résultats.

1 INTRODUCTION

Culverts are an essential part of any highway infrastructure. 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, a controlled low strength material (CLSM) can be used instead of conventional soil fill. CLSM is a self-compacting, self-levelling, 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, utility bedding, void filling and construction of bridge abutment approaches (Folliard et al. 2008).

Studies conducted 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 database, 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 placed in lifts and compacted with conventional compaction equipment 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 back-analyze the field results.

2 BACKGROUND

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) have 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).

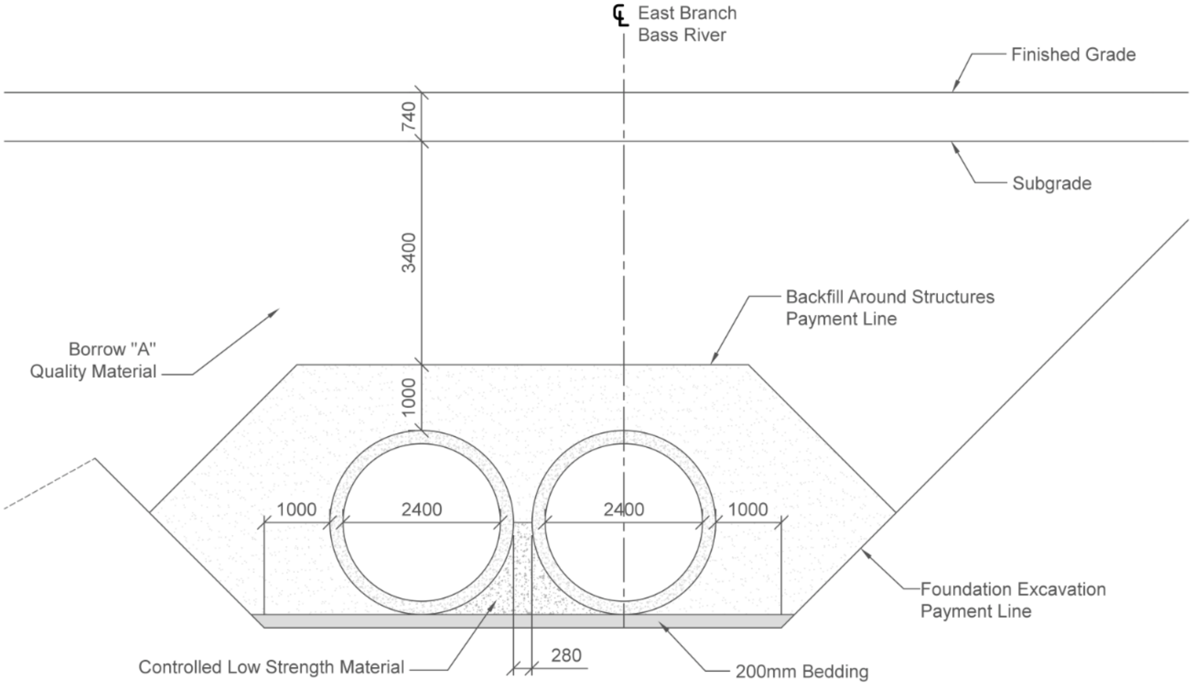

Figure 1. Design details of East Branch Bass River Culvert No. 1 (based on NBDTI 2013).

McGuigan and Valsangkar (2011*a*) investigated the effect of spacing on twin box culverts installed using both the positive projecting and induced trench method. Induced trench installations include a highly compressible zone of material above the culvert that causes positive soil arching in the fill above. Positive projecting installations do not contain this compressible zone, and are often subject to negative soil arching. 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 due to increased positive arching. Culvert spacing was varied from $0.5B_c$ to $1.5B_c$ (where B_c is the outside culvert diameter), and in all cases the pressures at the crown, springlines and base were lower for the twin culvert installation. The lowest pressures corresponded to the smallest culvert spacing. For the induced trench condition, the preferred geometry for the compressible zone consisting of width and thickness above the culverts resulting in the greatest reduction in earth pressures was determined for twin culverts spaced at $0.5B_c$, $1.0B_c$ and $1.5B_c$. For the first two spacings, a single compressible zone spanning both culverts was preferred, while two separate zones over each culvert were preferred for the $1.5B_c$ 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 due to variation in arching.

3 FIELD INSTRUMENTATION AND MONITORING

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 long 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 (2800 mm outside diameter). 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 1. The specified strength of the CLSM was 7 MPa ± 3 MPa.

Construction on this project began in August 2015 and was completed in October 2015. The final embankment height was 7.4 m up to the height of the sub-grade, which was the maximum height of the embankment before construction of the road structure.

3.1 Instrumentation Details

Sixteen sensors in total were installed at the site. Fourteen earth pressure sensors (Geokon 4800-1, Lebanon, New Hampshire) in the soil fill surrounding the culverts, and two NATM (New Austrian Tunneling Method) style (Geokon 4800-2, Lebanon, New Hampshire) embedded in the CLSM between the culverts.

The locations along the culvert alignment were chosen to coincide with the centre of the east and west-bound traffic lanes to ensure that the sensors would experience the loading from the maximum embankment height. The sensor location under the west-bound lane was located 18 m from the culvert outlet, while the sensor location under the east-bound lane was located 13.2 m from the culvert inlet. The crown, outside springlines, outside haunches and invert were all instrumented with earth pressure sensors. Each sensor was installed at the centre of the pipe section to reduce the influence the pipe joints might have on sensor readings.

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. 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 hot 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.

The operating capacities of the chosen cells were 70 kPa (NATM), 170 kPa (springlines) and 350 kPa (invert, haunches, crown) to ensure adequate sensitivity in readings for the expected loads 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.

3.1 Instrumentation Installation

The locations around the culverts where sensors were installed are presented in Figure 2**Error! Reference source not found.**. One earth pressure sensor was installed at each pipe invert. A 200 mm deep trench was excavated in the pipe foundation bedding. A piece of geofabric was placed in the trench to prevent erosion and migration of the finer material into the underlying foundation bedding. One hundred millimetres of bedding sand (ready-mix concrete sand obtained offsite by the contractor) was placed in the trench and compacted with a plate compactor. The sensor was then placed ensuring complete contact between the sensor face and the sand bed. The trench was then filled in with an additional 100 mm of bedding sand, matching the grade of the surrounding foundation soil. The soil above the sensor was 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, with the exception of the geofabric layer. Sensor leads were run to the side of the culvert and fed into 100 mm diameter PVC pipe attached to the culvert pipe above the shoulders with wire strapping. 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. 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 runs into the east pipe junction box.

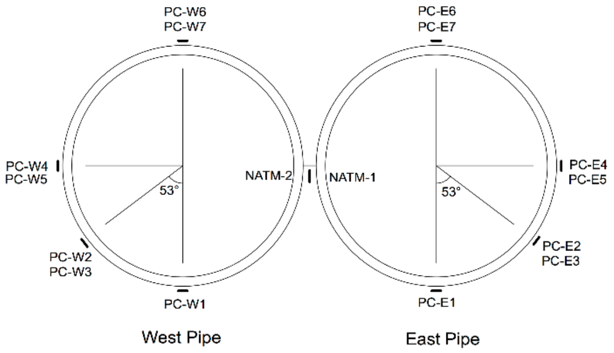

Figure 2. Placement of the earth pressure and NATM sensors around the culverts.

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 up 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. 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 (2011*b*) installed earth pressure sensors using this method based on observations by McGrath (2000) and obtained consistent data.

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. The concrete was placed at 6:00 PM on August 19th, 2015 and allowed to cure until 10:00 AM the next morning before backfilling continued above the CLSM. The pinch tubes for each cell were crimped at 9:30 AM.

3.2 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 bedding for each pipe section comprised 200 mm of crushed gravel (Fig. 1) 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. Well-graded gravel was then placed in 300 mm lifts up 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 inside springlines using an excavator bucket. Plywood sheets were supported against the pipe outlet to contain the CLSM in between the culverts. A steel panel from a trench box was placed at the other end of the culvert sections for the same reason. The contractor placed wooden blocks in between the culverts in order to maintain the space between them while backfilling was completed on the outside portion of the culverts up to the springlines. The blocks between the instrumented culvert sections (sections 8 and 10 when counting from the outlet) were removed; however, the block between section 6 was partially encased in CLSM, and could not be removed. The remaining blocks were either encased in the concrete or covered with soil when soil backfilling above CLSM resumed.

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. 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.

3.1 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, and the temperature was also noted. Using the manufacturer provided correction factors for temperature and barometric pressure, the digital output of the readout was then converted to a pressure. This process was repeated for each subsequent set of readings. Table 1 outlines the field readings taken once the embankment had reached the maximum height of 7.4 m, up to April 2016.

The theoretical contact length between the culvert and the bedding soil 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 centred at the invert of the pipe. McGuigan and Valsangkar (2011*a*) found that this 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.

Table 1. Summary of field measurements at embankment height of 7.4 m.

Location	Number of Cells	Measured radial pressure, kPa		
		Minimum	Maximum	Mean
Invert	2	278	330	305
Outside haunch	4	-4	45	23
Outside springline	4	-6	40	17
Crown	4	65	208	144
CLSM	2	n/a[a]	n/a[a]	n/a[a]

[a] NATM cells ceased functioning

The theoretical dead load of the culvert was 56 kN/m using the calculated contact length of 630 mm and the weight of the culvert section provided by the manufacturer. This 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 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.

Wilson (1985) found that by ensuring an uncompacted zone in the centre of the pipe bedding supporting the invert, the settlement of the pipe would increase the effectiveness of compactive 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 differential settlements along the alignment of the pipe.

Earth pressures measured at the invert during construction are presented in Figure 3. The pressures measured ranged from 278 kPa to 330 kPa and averaged 305 kPa. The average pressure corresponds to $1.6\gamma H$ when using the measured culvert dead loads. Kang (2008) found that base contact pressures for box culverts were greater than the theoretical height of soil and a 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; however, this was not noted in this installation. 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.

Four sensors were installed at the haunch locations (Figure 4). During construction, once the height of the embankment was approximately 1 m above the crown of the culvert, both sensors at the outside haunches on culvert section 10 (sections counted from culvert outlet) 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 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.

The sensors at the springlines all experienced a drop in pressure once the embankment reached the full height (Figure 5). 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 at rest factor of 0.3, or 0.3 γH which is in the range expected for this soil type. One possible explanation for the simultaneous drop in pressure of all 4 springline sensors, could be settlement of the surrounding soil fill causing the fine sand layer to arch around the sensors.

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 6). The mean corresponds to 1.6 γH.

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; no pressure reading was recorded. 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.

The two locations where sensors were installed were not backfilled uniformly due to the staged construction method used to reduce tree-clearing requirements. Sensors placed at section 10 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.

4 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 experienced 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*a, b*) and McAfee and Valsangkar (2008) reported good agreement between field measurements and those modelled using FLAC.

The culverts were modelled in FLAC using structural beam elements. A grid resolution of 70 mm was used for the model. Since a static analysis was used for the modelling, a fine mesh could still be used while maintaining reasonable model run times. The pipes were modelled as non-yielding, and 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 the type of interface (slip or no slip) did not have a significant impact on the earth pressures measured.

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. The limits of each zone were approximated based on the design drawings and field measurements to maintain a simplified grid. This modelling sequence is similar to that in Bryden et al. (2015) and Allard and El Naggar (2016).

Each soil type material was modelled using a Mohr-Coulomb constitutive model, except for the CLSM, which was modelled as a linear elastic material. The material zones and the parameters used for each soil type are presented in Table 2. Due to the difficulty in compacting soil fill below 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.

Table 2. Material properties used for modelling

Material	Young's modulus (MPa)	Poisson's ratio	Density (kg/m^3)	Friction angle (°)
CLSM	2400	0.20	2185	
Embankment Fill	15	0.3	2160	32
Backfill Soil	14	0.25	2100	40
Haunch Soil	3	0.25	1800	35
Bedding Sand	14	0.25	2030	40
Foundation Soil	20	0.25	2110	40

4.1. Analysis

Generally, good agreement was observed between field measurements and those calculated with FLAC, except for the invert. The dead load of the culvert was estimated in FLAC to be 56.7 kN/m using the procedure outlined in the Canadian Highway Bridge Design Code (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. 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 3 summarizes the field and calculated values.

Table 3. Summary of FLAC calculations and field measurements expressed as a function of theoretical overburden pressure at reference sensor location

Sensor Location	FLAC Simulation	Field Measurements
Crown	1.1	1.6
Springline	0.3	0.3
Haunch	0.4	0.3
Invert	1.0	1.6

The earth pressure calculated at the invert of the culvert with FLAC was outside of the 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 the mean measurement at the haunch in FLAC. The horizontal earth pressure calculated at the outside springline of the culverts was within the range of values measured (Table 1) in the field, though closer to the upper end of measured values. At the crown, the calculated earth pressure was 13% less than the mean earth pressure measured in the field, but still within the range of measured values.

5 CONCLUSION

Twin circular reinforced concrete culverts (2400mm ID) installed with 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.

FLAC software was used to model the field installation, and good agreement between the field readings and the numerical model estimates was obtained.

The benefits of CLSM are mainly from a constructability perspective when installing culverts with narrow space between them. Use of CLSM in a narrow space does not affect earth pressures exerted on the twin culverts when compared to using loosely placed soil backfill. CLSM can allow culverts to be installed with a narrow space in order to meet hydraulic and environmental constraints and still be practical for long-term stability and constructability. This case study once again demonstrates the significant influence of construction methodology and sequence on earth pressures exerted on rigid pipes.

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