Earth Pressure Distribution on Rigid Pipes Overlain by TDA Inclusion

Mohamed A. Meguid(✉)

Civil Engineering and Applied Mechanics, McGill University, Montreal, Canada
mohamed.meguid@mcgill.ca

Abstract. Rigid pipes installed under high embankments are often installed using the induced trench technique by introducing a compressible zone above the pipe. A new application of tire-derived aggregate (TDA) for induced trench rigid pipes is evaluated in this study. An experimental investigation that has been conducted to measure the earth pressure distribution on a rigid pipe buried in granular material and backfilled with TDA is presented in this study. A setup has been designed and built to allow for the installation of an instrumented pipe in granular material and measuring the contact pressure acting on the pipe wall. Results show that the use of TDA as a compressible material can provide similar beneficial effects to rigid pipes compared to expanded polystyrene (EPS) geofoam and other commonly used soft inclusions. The earth pressure is found to decrease significantly all around the pipe compared to the conventional installation with aggregate backfill. The average measured earth pressure above the crown of the pipe was found to be as low as 30% of the overburden pressure for installations with granular backfill material. The pressure at the invert also decreased by about 75% with the introduction of the soft TDA zone above the pipe.

Keywords: Soil-structure interaction · Tire-derived aggregate
Buried pipes · Induced trench installation · Soil arching
Contact pressure measurement

1 Introduction

The construction of buried pipes and culverts under high embankment fills can impose significant earth loads on these structures depending on the installation condition. The vertical earth pressure on a rigid conduit installed under earth embankment is generally greater than the weight of the soil above the structure because of negative arching. To reduce the vertical earth pressure on rigid pipes and culverts, the induced trench installation (ITI) method introduced by Marston (1922, 1930) can be used. In this method, the loads are redistributed around the buried structure by introducing a compressible material above the top of the pipe to promote positive arching as depicted in Fig. 1.

H. El-Naggar et al. (Eds.): GeoMEast 2018, SUCI, pp. 1–13, 2019.
https://doi.org/10.1007/978-3-030-01902-0_1

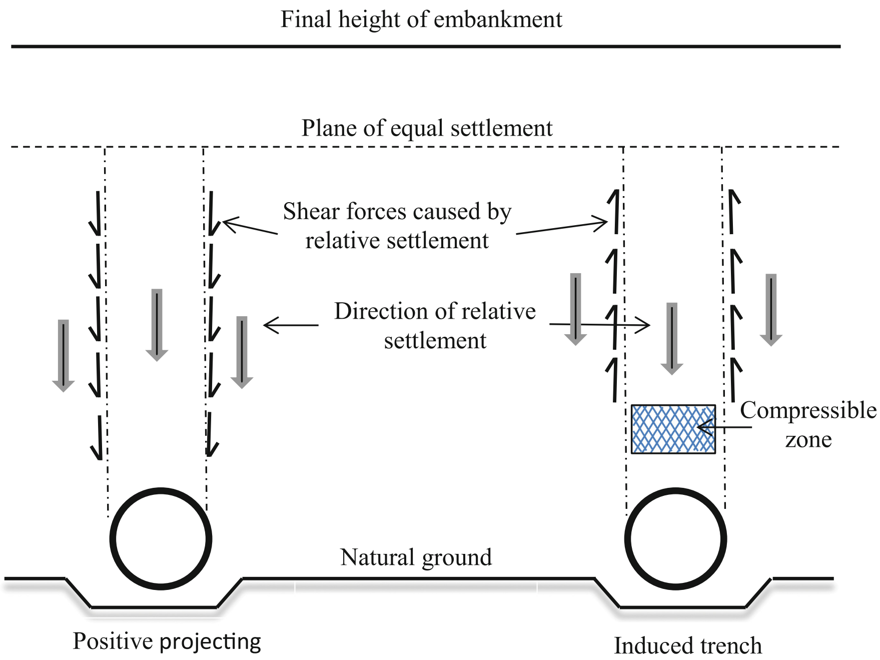

Fig. 1. Schematic of the induced trench method

The ITI installation method for rigid conduits buried under high embankments dates back to the early 1900s. Researchers studied the relevant soil-structure interaction using experimental testing and field instrumentation (e.g. Sladen and Oswell 1988; Vaslestad et al. 1993; Liedberg 1997; Sun et al. 2011; Oshati et al. 2012; Meguid et al. 2017a, b; Meguid and Youssef 2018) as well as numerical modelling (Kim and Yoo 2002; Kang et al. 2008; McGuigan and Valsangkar 2010; Meguid and Hussein 2017) to help understand the method and to address uncertainties associated with this design approach. The material used for the compressible zone mostly consisted of sawdust, wood chips, or EPS geofoam.

Tire-derived aggregate (TDA) is an engineered product made by cutting waste tires into small pieces (25–305 mm) that can be used to replace natural aggregates in civil engineering applications (Humphrey 2004). Extensive research has been done over the past two decades (e.g. Bosscher et al. 1992; Drescher and Newcomb 1994; Tweedie et al. 1998; Strenk et al. 2007; Mills and McGinn 2010) to examine the performance of TDA under different loading conditions. These studies demonstrated that TDA is a suitable fill material with engineering properties that are comparable to conventional aggregates. Applications include the construction of large embankments, bridge abutment backfill, retaining walls and pavement subgrade.

TDA is generally classified, based on size and gradation, into two types: Type-A, with a maximum particle size of 75 mm, and Type-B with a maximum particle size of 305 mm (ASTM D 6270). Direct shear tests performed on Type-A TDA samples

(Humphrey 2008; Xiao et al. 2015) suggested a friction angle that ranges from 36° to about 39° for TDA-sand interface.

In this study, an investigation into the contact pressure distribution on buried pipes is conducted using laboratory experiments. The experimental work involves a thick-walled PVC pipe that is instrumented with tactile pressure sensors and buried in granular material while a distributed load is applied at the surface. The tactile sensors used in this study are adapted from the robotics industry and have been successfully used in geotechnical engineering applications to measure the distribution of normal stresses in granular soils (e.g. Paikowsky et al. 2000; Springman et al. 2002; Ahmed et al. 2015). Due to their limited thickness, tactile sensors possess favourable characteristics with respect to aspect ratio and stiffness over the conventional load cells. In addition, being flexible enables shaping the sensing pads to cover curved surfaces, hence suitable for cylindrical shape structures. Meguid et al. (2017a, b) and Meguid and Youssef (2018) used tactile (TactArray) sensors to measure contact pressure distributions on both circular as well as square shaped structures.

The measured pressures are initially presented for a benchmark condition where only granular backfill material is used and the results are compared with Hoeg's analytical solutions (Hoeg 1968). A series of experiments are then performed by incrementally increasing the surface pressure for two backfill conditions: (1) the pipe is backfilled with only granular material; and (2) a layer of TDA is introduced above the pipe. The experimental setup and test procedure are presented in the next section, followed by the pressure results of the two-backfill conditions.

2 Experimental Setup

The experimental setup consists of a thick-walled pipe embedded in granular backfill material contained in a test chamber. The pipe is instrumented using tactile sensing pads - wrapped around its outer perimeter - covering the area near the middle third of the pipe length. A universal MTS testing machine with a capacity of 2650 kN is used to apply distributed load, utilizing a rigid steel platform. A detailed description of the experimental setup is given below.

2.1 Test Chamber

The test chamber used in the experiments is shown schematically in Fig. 2. The dimensions (1.4 m × 1.0 m × 0.45 m) are selected in order to represent a two-dimensional loading condition. The rigid walls are placed far from the pipe to minimize boundary effects; wherein the distance from the outer perimeter of the pipe to the sidewalls of the tank is more than 4 times the pipe diameter (Leonards and Roy 1976). All steel wall surfaces are epoxy coated and covered with two plastic sheets separated using a thin layer of grease to minimize friction between the backfill material and the rigid walls.

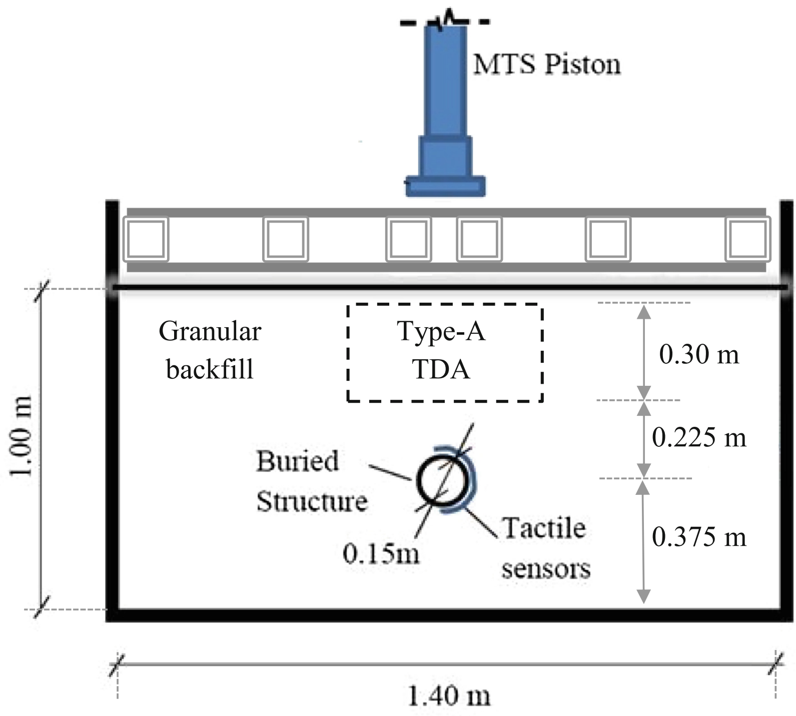

Fig. 2. Schematic of the test chamber

The pipe used for this study (15 cm in outer diameter and 1 cm in wall thickness) is instrumented using two custom-made sensing pads installed directly on the pipe wall. Each sensing pad contains 255 square-shaped sensors with pressure ranging from 0 to 140 kPa. The sensors are protected from backfill abrasion by covering the instrumented pipe with a thin layer of stiff rubber sheet.

Two LVDTs are installed orthogonally inside the pipe to confirm the rigid pipe assumption. The maximum diameter change, at surface pressure of 100 kPa, was found to be less than 0.04 mm, which is considered insignificant.

2.2 Material Properties and Testing Procedure

The dry sandy gravel backfill used in this study has an average unit weight of 16.3 kN/m^3. Sieve analysis, conducted on selected samples, indicated a coarse-grained material with 77% gravel and 23% sand. The friction angle of the backfill - determined using direct shear tests - is found to be 47°. The soil was placed and tamped in layers to form a dense base bedding material below the pipe. This was achieved by raining the sand from a constant height into the chamber in layers. From the base up to the pipe invert, the soil was placed in three layers 100 mm in height. Each layer was first graded to level the surface then tamped using a steel plate with a long handle to reach the base of the test chamber. The sand placement continued up to the pipe invert. Above the invert, the rained sand was gently pushed around the pipe up to the crown to ensure full contact between the sand and the pipe. Then, another layer of sand was added to cover the pipe. The remaining sand required to reach the height above the crown was placed and graded to minimize damage to the pressure sensors. The instrumented pipe was placed over a thin film of sand to improve the contact between the soil and the pipe. Density of the backfill was measured in the rigid box using density cups placed at different locations and collected after the completion of the tests.

The TDA material used in the experiments was obtained from a local tire-recycling centre in Montreal, Canada (Meguid and Youssef 2018). The material is categorized as Type-A with pieces that range in size from 30 to 120 mm. The properties of both the granular backfill and TDA material are summarized in Table 1.

Table 1. Properties of the backfill material

(a) Granular material*	
Specific gravity	2.65
Coefficient of uniformity (C_u)	2.3
Coefficient of curvature (C_c)	1.6
Minimum dry unit weight ($\gamma_{\min}$)	15.1 kN/m^3
Maximum dry unit weight ($\gamma_{\max}$)	17.3 kN/m^3
Experimental unit weight (γ_{d})	16.3 kN/m^3
Internal friction angle (ϕ)	47°
Cohesion (c)	0
Elastic Modulus (E)	150 MPa
Poisson's ration (υ)	0.3
(b) Tire-derived aggregate	
Maximum size	75 mm
Unit weight (γ)	6.2 kN/m^3
Uniformity coefficient (C_u)	1.9

*Meguid et al. (2017a, b)

A total of six experiments were conducted including three benchmark tests where the instrumented pipe is surrounded by dry sandy gravel backfill only. For the remaining tests, a layer of TDA is placed above the pipe. For the benchmark tests, the placement of the backfill continued up to a distance 0.45 m above the crown. For experiments involving TDA, the granular backfill was used to make a 15 cm cover above the pipe, followed by the addition of TDA within a zone that measures 45 cm in width and 30 cm in height. The thickness of the aggregate cover placed above the pipe has been chosen to ensure that the protruding steel wires in the TDA (up to 10 cm in length) do not damage the pressure sensors. These dimensions were chosen to represent a compressible layer that has a thickness of about two times the pipe diameter. Two wood planks were used to assist in shaping the TDA zone while the rest of backfill material was added. The surface was finished by adding 10 cm of granular material over the entire backfill and levelled in the test chamber.

Surface load was applied using a loading platform placed under the actuator of the MTS machine. The load was gradually applied under displacement control with a displacement rate of 1.0 mm/min. The test would be stopped when either a surface displacement of 15 mm is reached or the pressures on the tactile sensors exceeded their allowable capacity (140 kPa). These limiting values were chosen in this study to avoid excessive pressure that could damage the tactile sensors. After the completion of each test, the tank was emptied using a vacuum machine connected to a collection barrel. The pipe was then retrieved and the setup was prepared for the next test.

3 Results and Discussions

The measured radial earth pressures are summarized in this section and the results are compared for the two investigated cases: (1) conventional backfill (benchmark tests); and (2) induced trench method using TDA inclusion. To validate the measured pressures in the benchmark tests, the sensor readings recorded following the placement of the granular backfill material are compared to Hoeg's analytical solution. The changes in earth pressure at selected locations on the circumference of the pipe are then presented.

3.1 Initial Condition

Hoeg (1968) developed an analytical solution for the contact pressure acting on buried cylinders. The solution is expressed in terms of two stiffness ratios (the compressibility ratio and the flexibility ratio) and three constants derived for two different boundary conditions, namely, no slippage or free slippage condition. The radial pressure (σ_r) is expressed as follows:

$$\sigma_r = \frac{1}{2}p\left\{(1+K)\left[1 - a_1\left(\frac{R}{r}\right)^2\right] - (1-K)\left[1 - 3a_2\left(\frac{R}{r}\right)^4 - 4a_3\left(\frac{R}{r}\right)^2\right]\cos 2\theta\right\} \tag{1}$$

where R is the pipe radius, r is the distance from the pipe center to the soil element under analysis, K is the lateral earth pressure coefficient expressed in terms of Poisson's ratio ($\upsilon/1-\upsilon$), p is the soil vertical stress, θ is the angle of inclination from the springline and a_1, a_2 *and* a_3 are constants. The latter constants for the free slippage condition are given by:

$$a_1 = \frac{(1-2v)(C-1)}{(1-2v)C+1} \tag{2}$$

$$a_2 = \frac{2F + 1 - 2v}{2F + 5 - 6v} \tag{3}$$

$$a_3 = \frac{2F - 1}{2F + 5 - 6v} \tag{4}$$

The above constants are functions of the compressibility and flexibility ratios, which are measures of the extensional and flexural stiffnesses of the soil medium relative to the pipe. These rations are defined as follows:

$$C = \frac{1}{2}\frac{1}{1 - v}\frac{E_s}{\frac{E_p}{1-v_p^2}}\left(\frac{D}{t}\right) \tag{5}$$

$$F = \frac{1}{4}\frac{1 - 2v}{1 - v}\frac{E_s}{\frac{E_p}{1-v_p^2}}\left(\frac{D}{t}\right)^3 \tag{6}$$

where, E_s, v are the Elastic modulus and Poisson's ratio of the soil, respectively; E_p, v_p are the Elastic modulus and Poisson's ratio of the pipe, respectively; D is the average pipe diameter and t is the wall thickness. A soil-pipe system with both C and F of zero signifies a perfectly rigid embedded pipe.

The initial earth pressure calculated using Hoeg's analytical solution is demonstrated in Fig. 3. The pressure distribution is characterized by maximum values at the crown and invert which quasi-sinusoidal decrease towards the springline (SL). For the free and no slippage boundary conditions, the pressures at the crown and invert were found to be about 12 kPa and 9 kPa, respectively. These values decreased to 3 kPa and 5 kPa, respectively, at the springline. By superimposing the measured pressure values on the analytical solution, it is evident that the experimental results followed a similar pressure distribution pattern with an increase of about 2 kPa at the invert. This is consistent with additional in-situ pressure at a depth of 1D below the crown. This pressure difference is not usually captured by Hoeg's solution that assumes a deeply buried pipe with vertical pressure that is the same above and below the pipe. It should be noted that the contact pressure measured using the tactile sensors and reported in this study represents the radial earth pressure acting on the pipe.

3.2 Effect of TDA on Contact Pressure

To evaluate the effect of introducing the soft TDA zone on the distribution of earth pressure onto the pipe, a comparison is made between the recorded pressure readings at three selected locations, namely: crown (C), springline (SL), and invert (I).

Figure 4 illustrates the changes in contact pressure at the crown with the increase in applied load up to a maximum surface movement of 15 mm. The benchmark tests

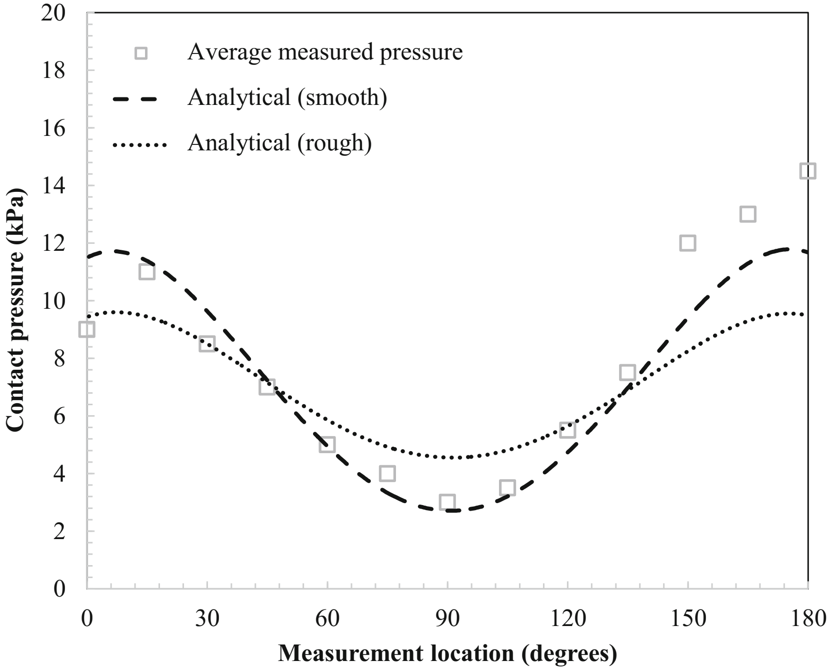

Fig. 3. Measured and calculated pressures on the pipe under initial loading condition

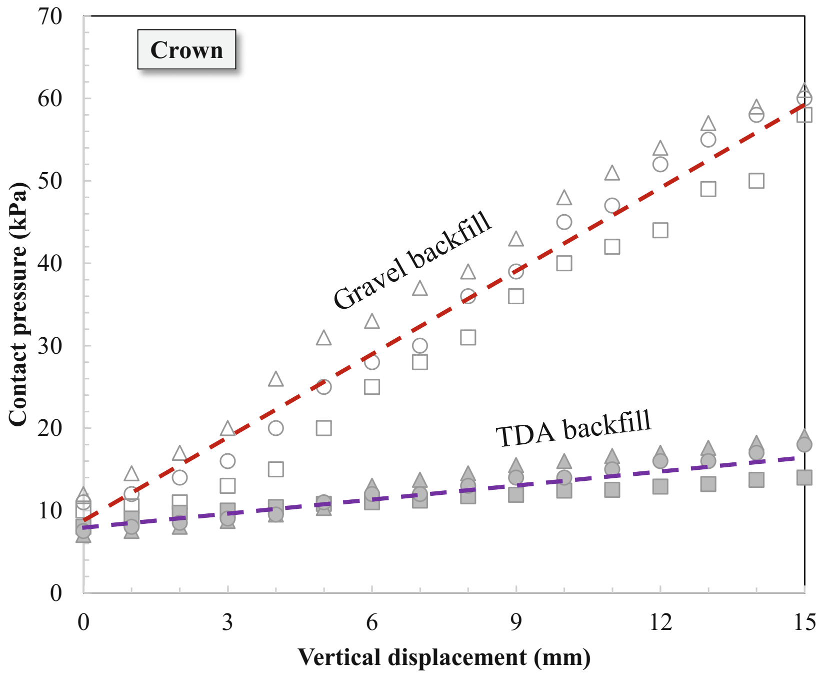

Fig. 4. Measured contact pressures at the crown

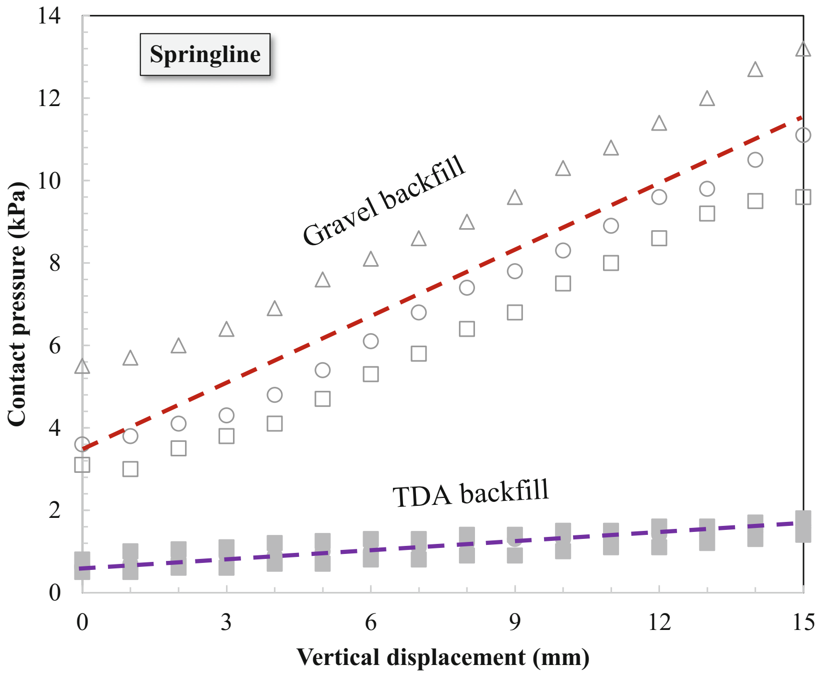

Fig. 5. Measured contact pressures at the springline

showed consistent increase in radial pressure from the initial condition (about 10 kPa) up to a maximum value of about 60 kPa. Tests involving the TDA inclusion above the pipe resulted in a significant decrease in radial pressure at the crown from 60 kPa to as low as18 kPa. This is attributed to the soil arching effect and load re-distribution around the pipe; ultimately a consequence of the soft-zone presence.

The earth pressure at the springline increased from 4 kPa to as high as 11 kPa in the benchmark tests as shown in Fig. 5. Contact pressure decreased from 11 kPa in the benchmark tests, at applied displacement of 15 mm, to less than 2 kPa, using the induced trench method with TDA inclusion.

The highest measured pressure was recorded at the invert of the pipe where pressure reached about 70 kPa when gravel backfill was used (see Fig. 6). This value decreased significantly to less than 20 kPa using TDA inclusion. The pressure distribution on the pipe at all investigated locations is summarized in Fig. 7. The contact pressure is normalized with respect to the benchmarks tests. It is found that contact pressures decreased at all locations as the surface displacement increased from 0 mm (initial condition) to 15 mm. The pressure ratio at the beginning of the test was found to

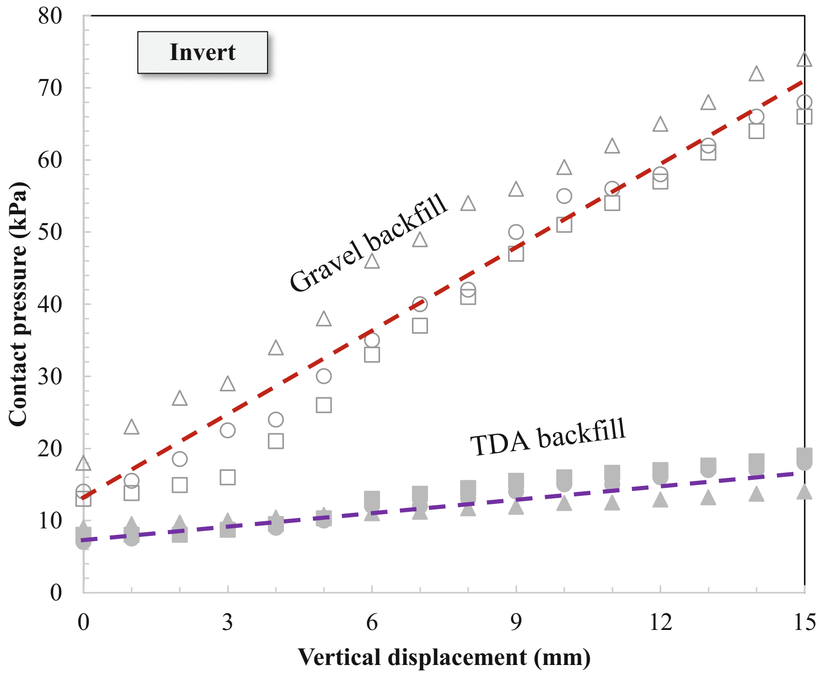

Fig. 6. Measured contact pressures at the invert

be 70%, 52% and 20% at the crown, invert and springline, respectively. As the load is applied and the induced trench took effect, the pressure ratio changed to 30%, 25% and 13% at the crown, invert and springline, respectively when the applied displacement reached 15 mm. This suggests that utilizing TDA above buried pipes can result in a significant reduction in earth load and consequently, an economic design.

Based on the above results, the effect of TDA in reducing radial earth pressure on the pipe is evident. In addition, the effect seems to become more pronounced at high surface loads where sufficient compression develops in the TDA zone and consequently more shear stresses are generated at the boundaries of the induced trench. Given the increasing amount of waste materials that may be disposed in landfills around the world, re-using scrap tires in buried structures seems to be a sound alternative both technically and environmentally.

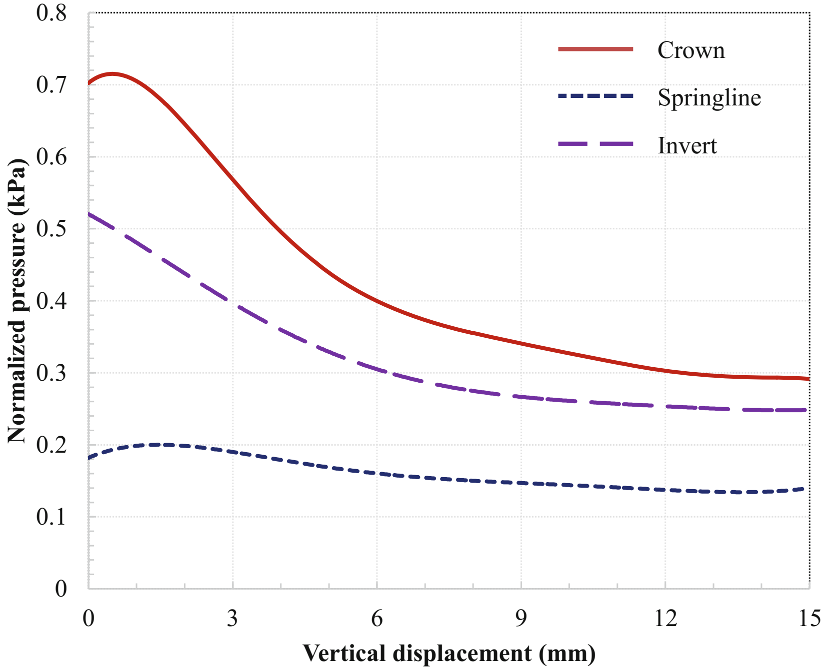

Fig. 7. Average normalized pressures for the case of TDA inclusion with respect to the measured values for gravel backfill

4 Summary and Conclusions

This study investigated the earth pressure distribution on a buried pipe installed using the induced trench method. The contact pressure distribution on the pipe was measured using the tactile sensing technology, which is able to provide a continuous pressure profile on the pipe wall. The effect of installing a soft zone of TDA on the radial pressure distribution on the pipe was examined.

The induced trench installation described in this study was successful in reducing the vertical loads on the buried pipe. The average measured earth pressure above the crown of the pipe was found to be about 30% of the overburden pressure for installations with granular backfill material. Significant reduction in radial pressure was also recorded at the invert with pressure reduction of about 77% with the introduction of the soft TDA inclusion.

This study suggests that using TDA in induced trench construction is both technically and environmentally sound alternative to gravel backfill and EPS geofoam.

Acknowledgements. This research is supported by a research grant from the Natural Sciences and Engineering Research Council of Canada (NSERC). The authors would like to acknowledge the support of Dr. W.D. Cook and Mr. J. Bartczak in conducting these experiments.

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