Transportation Geotechnics 14 (2018) 117–125

Contents lists available at ScienceDirect

Transportation Geotechnics

journal homepage: www.elsevier.com/locate/trgeo

Experimental investigation of the earth pressure distribution on buried pipes backfilled with tire-derived aggregate

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ARTICLE INFO

Article history:
Received 3 June 2017
Revised 22 October 2017
Accepted 23 November 2017
Available online 24 November 2017

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

ABSTRACT

This paper presents the results of an experimental investigation that has been conducted to measure the earth pressure distribution on a rigid pipe buried in granular material and backfilled with tire-derived aggregate (TDA). An experimental 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. Tactile sensing technology is used in this study to measure the soil pressure acting on the pipe. This method allows for a continuous pressure profile to be recorded using flexible sheets that follow the cylindrical shape of the pipe. Two sets of experiments are performed in this study-one set with only granular backfill material (benchmark tests) and the second involved the introduction of a soft zone of tire-derived aggregate above the pipe. Results show that 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 as low as 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 zone.

Introduction

The rapid growth of the transportation industry around the world has resulted in an enormous amount of waste tires generated yearly, making safe disposal of this waste material a dire necessity and extreme challenge. Tire-derived aggregate (TDA) is an engineered product made by cutting waste tires into 25–305 mm pieces that can be used to replace natural aggregates in civil engineering applications [7]. Extensive research has been done over the past two decades (e.g. [3,5,29,26,20]) 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 [2]. Direct shear tests performed on Type-A TDA samples [8,31], suggested that the shear resistance of the material increased with the increase in normal load with no apparent peak value. The measured friction angle was found to be about 36°, which increased to about 39° for TDA-sand interface. Compression tests were also performed on different TDA materials [19,32], and the results indicated that the material compressibility is highly dependent on the initial unit weight and the applied stress level.

Another TDA application in civil engineering that utilizes the compressibility and lightweight characteristics of the material is in buried structures. It is known that the magnitude and distribution of earth pressures on buried pipes and culverts are highly dependent on the relative stiffness of the structure and the backfill material. To reduce earth loads on these rigid structures, the induced trench installation method has been proposed (e.g. [13,4]). In this method, the loads are redistributed around the structure by introducing a compressible material above the upper wall to promote positive arching. Expanded polystyrene (EPS) which has low stiffness and exhibits a desirable elastic-plastic behavior has been successfully used in these applications [30,14,15,18,16,17]. When an embankment is constructed over a buried conduit with compressible inclusion (see Fig. 1), the soft zone compresses more than its surrounding fill, and thus positive arching is induced above the conduit.

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https://doi.org/10.1016/j.trgeo.2017.11.007
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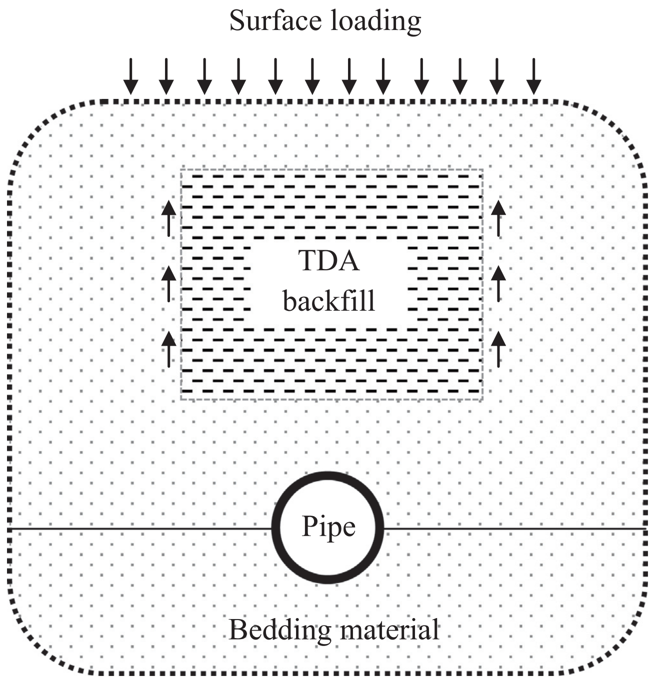


Fig. 1. Schematic of a buried pipe overlain by a layer of TDA backfill.

This method of installation dates back to the early 1900s. Researchers studied the relevant soil-structure interaction using experimental testing and field instrumentation (e.g. [24,12,28,21]), as well as numerical modelling [10,9,27], to help understand the method and to address uncertainties with this design approach.

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. [22,25,1]). A standard tactile sensor typically consists of an array of force-sensitive cells embedded between two flexible polymeric sheets to measure the normal pressure distribution. 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. [16,17] 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 [6]. 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. The results of each are compared at different locations on the circumference of the pipe.

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.

Test chamber

The test chamber used in the experiments is shown schematically in Fig. 2. The dimensions $(1.4\ \mathrm{m} \times 1.0\ \mathrm{m} \times 0.45\ \mathrm{m})$ 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 [11]. All steel wall surfaces are previously epoxy coated and covered with two plastic sheets. The first sheet is adhered directly to the walls of the box whereas the second is loosely placed in a manner that the two sheets are separated using a thin layer of grease. This layer aims to minimize friction between the backfill material and the rigid walls during soil placement and surface loading.

Instrumented pipe

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. TactArray distributed pressure measurement system [23] (Pressure Profile Systems, Los Angeles, CA, USA) – used in this study – consists of two sets of orthogonal electrodes separated using a flexible insulator that acts as a spring allowing for flexible pad designs. On applying normal load to the sensors, the distance between the electrodes changes, resulting in a change in capacitance; whereas, applying a tangential force changes the effective area between the electrodes. The capacitive sensors are thus capable of detecting pressures by sensing the applied forces. 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 as shown in Fig. 3a. Shim stocks made from the same pipe material are used to provide a similar contact surface condition onto the original pipe as well as to absorb the shear stresses developing at the soil-pipe interface.

It should be noted that, although the pipe has been chosen to perform such that no significant deformation develops during loading, two LVDTs are installed orthogonally inside the pipe to ensure the validity of this assumption. The maximum diameter change, at surface pressure of 100 kPa, was found to be less than 0.04 mm, which is considered insignificant.

Sensor calibration

In addition to the manufacturer calibration, a series of experiments has been conducted to study the effect of the protective layers on the measured pressure. A pneumatic system was used to apply vertical pressure directly over the sensing pad. The pressure was gradually increased up to a value comparable to that expected in the experiment. The response was compared before and after the addition of the protective layers (Fig. 3b). The data recorded by the sensing pad demonstrates scattered pressure readings,

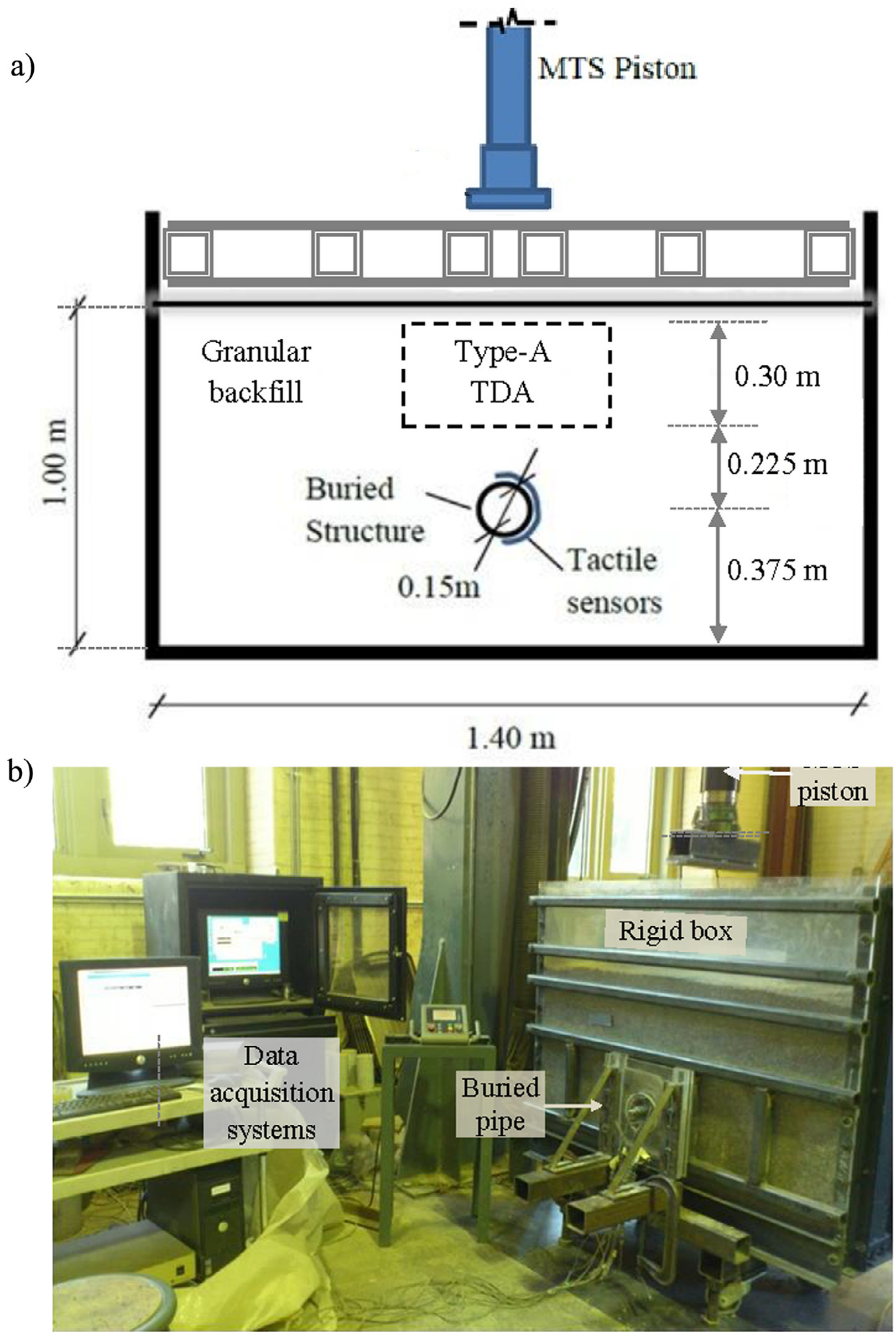


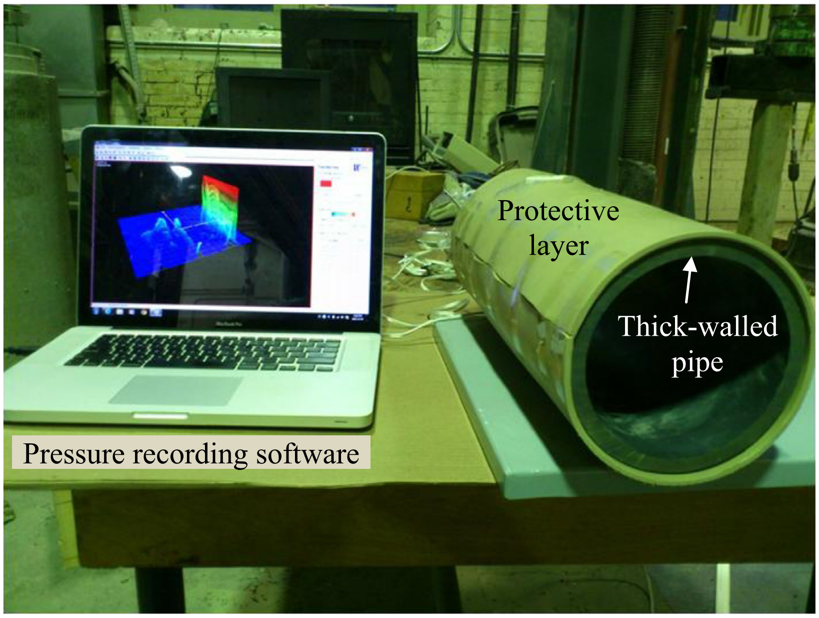
Fig. 2. The testing facility used in the experimental work (a) schematic of the test chamber and the buried pipe and (b) a photograph showing the details of the experimental setup.

where a compression of about 0.13 mm results at an applied load of 900 N. Insignificant increase in compression was recorded after adding the protective layer above the sensing pad. This indicates that the chosen protective material is sufficiently stiff; causing no additional compression under the loading level expected in the experiment.

Material properties and testing procedure

In this study, the soil placement procedure was applied to all tests to ensure consistent initial conditions. 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.

The dry sandy gravel backfill used is of 16.3 kN/m^3 average unit weight. 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 grain size distribution of the soil is shown in Fig. 4. The soil was placed and tamped in layers to form a dense base bedding material below the pipe. The instrumented pipe was then placed over a thin film of sand to improve the contact between the soils and the pipe. Backfill placement continued in a)



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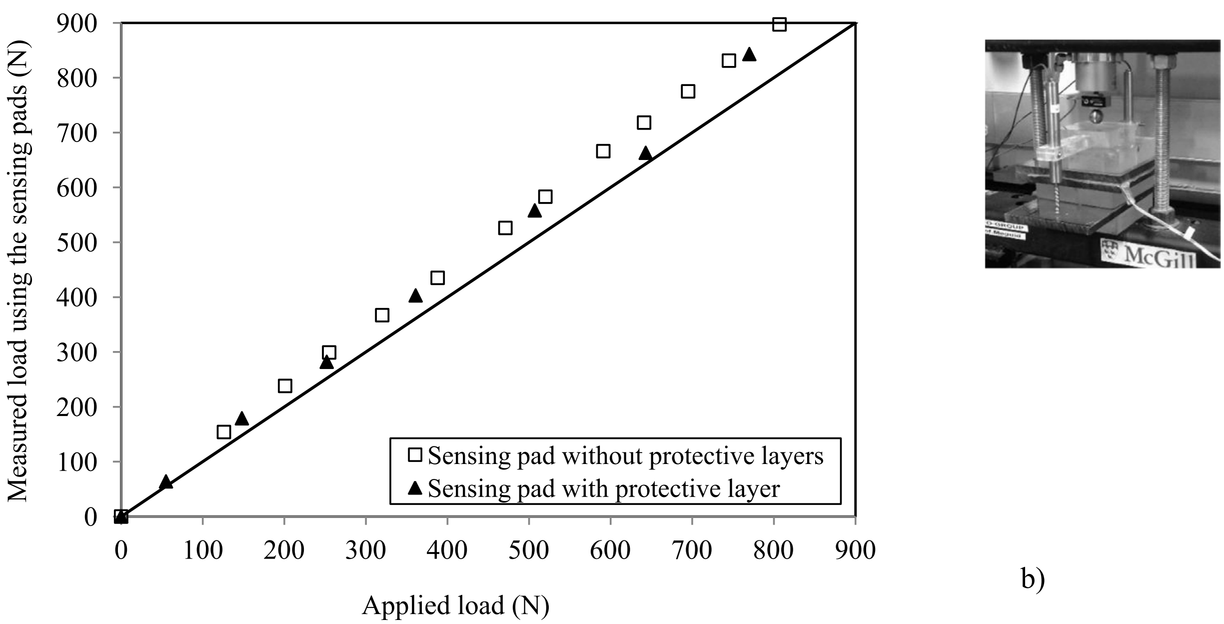

Fig. 3. (a) Instrumented pipe and (b) effect of protective layers on the measured pressure.

layers over and around the pipe up to the target soil height of 1.0 m. 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 properties of the granular backfill material are summarized in Table 1a.

The TDA material used in the experiments was obtained from a local tire-recycling centre in Montreal, Canada. The material is categorized as Type-A with pieces that range in size from 30 to 120 mm. The size distribution of the TDA material is shown in Fig. 4. 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). 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

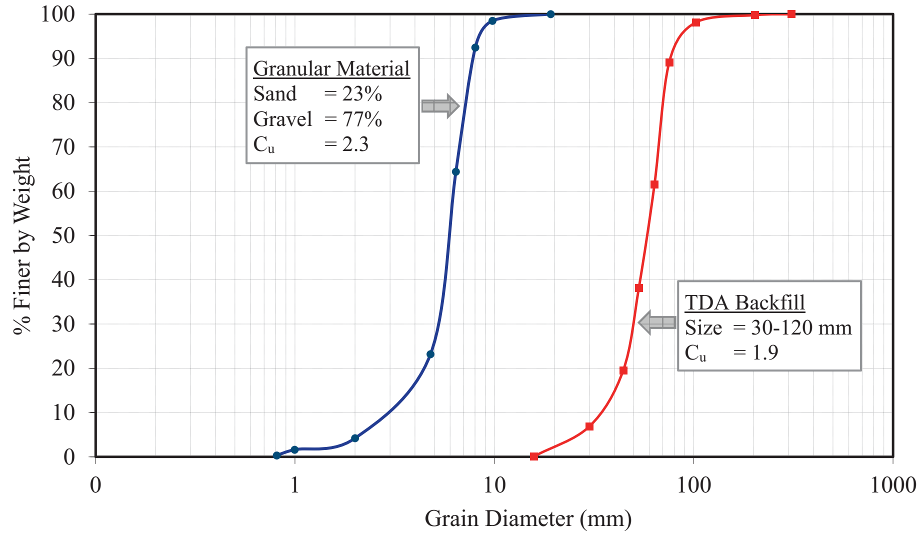

Fig. 4. Particle size distributions of the granular and TDA backfill materials.

Table 1
Properties of the backfill material.

(a) Granular material[a]	
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

[a] Meguid et al. [16,17].

setup was prepared for the next test. A sample of the radial pressure distribution – as recorded by the data acquisition software – is shown in Fig. 5.

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.

Initial condition

Hoeg [6] developed an analytical solution for the contact pressure acting on underground 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:

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

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, 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:

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

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

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

The above constants are functions of the compressibility and flexibility ratios that are defined as follows:

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

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

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.

The initial earth pressure calculated using Hoeg's solution is demonstrated in Fig. 6. 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 in Fig. 6, 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-

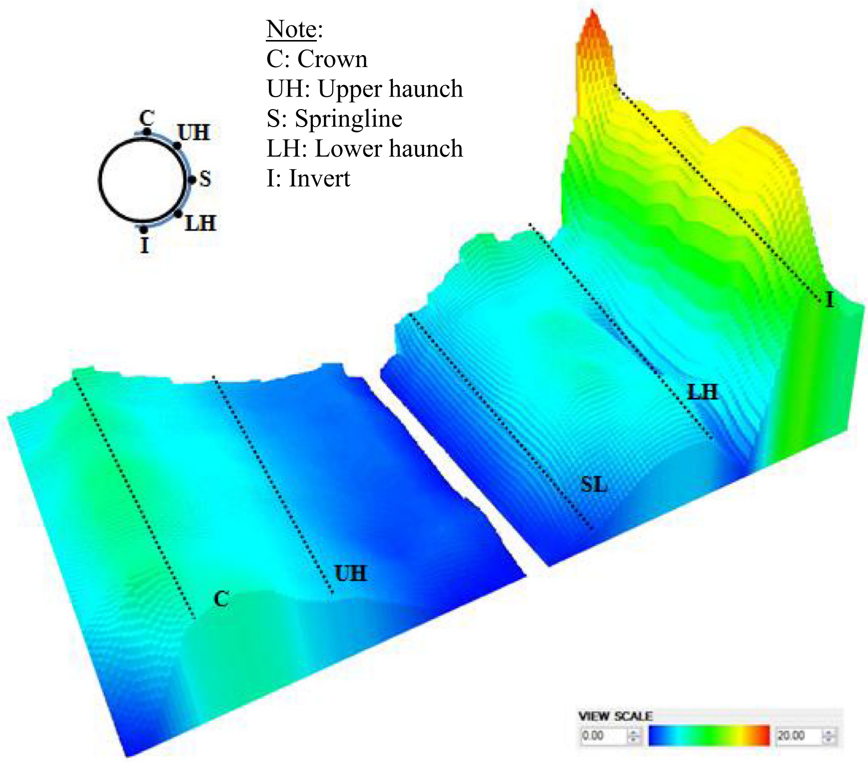

Fig. 5. A snapshot of the measured earth pressure distribution around the pipe.

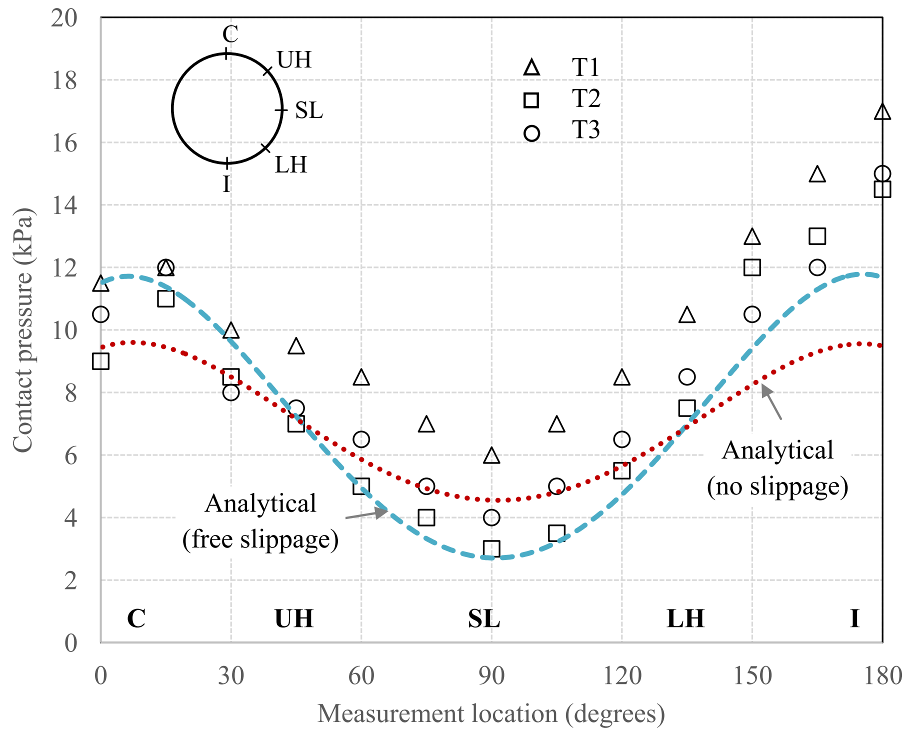

Fig. 6. Measured and calculated pressures on the pipe under initial loading condition.

situ pressure at a depth of 1*D* 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.

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 four selected locations, namely: crown (C), upper haunch (UH), springline (SL), and invert (I).

Fig. 7 illustrates the changes in contact pressure at the crown with the increase in applied load up to a maximum surface movement of 15 mm (applied pressure of about 50 kPa). The benchmark tests 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 as 18 kPa. This is attributed to the soil arching effect and load re-distribution around the pipe; ultimately a consequence of the soft-zone presence. These findings are consistent with the published experimental results for induced trench installation using geofoam inclusion. McGuigan and Valsangkar [15] reported a reduction of about 70% of the prism load above rigid culverts constructed using induced trench method. Meguid et al. [16,17] measured a reduction in pressure of more than 70% at the upper wall of a rigid box buried in granular material and overlain by EPS15 geofoam block.

The earth pressure at the upper haunch increased from 10 kPa to as high as 20 kPa in the benchmark tests as shown in Fig. 8. Although these pressures are much smaller in magnitude compared to those recorded at the crown, a reduction of more than 50% was measured at the upper haunch after the introduction of the TDA zone. A similar trend was found at the springline (Fig. 9) with contact pressure decreasing from 12 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. 10). 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. 11 for applied displacement of 15 mm. Although the distribution pattern is similar for the benchmark and the ITI construction with TDA, the magnitudes have drastically decreased, particularly at the crown and invert. This suggests that utilizing TDA above buried pipes can result in a significant reduction in earth load and consequently, an economic design. Another way of quantifying the changes in pressure is presented in Fig. 12. Compared to the conventional construction using granular

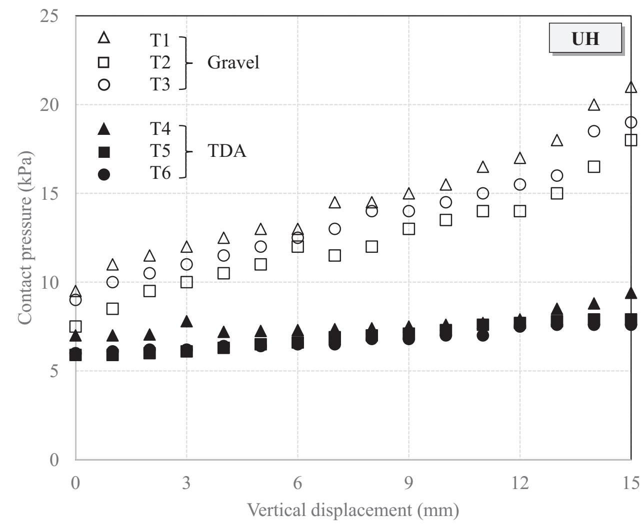

Fig. 8. Measured contact pressures at the upper haunch.

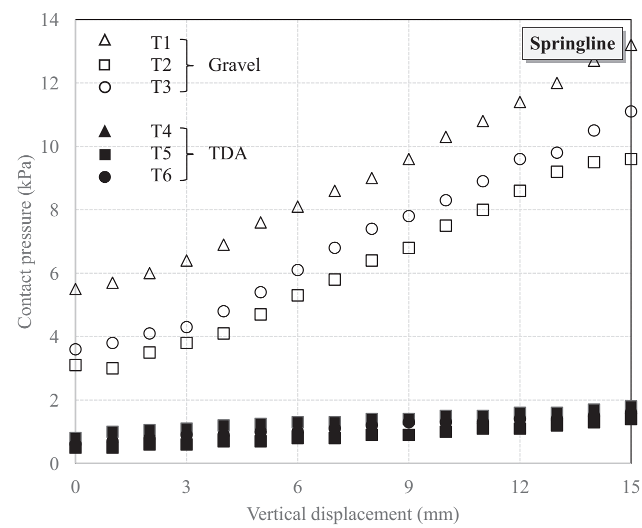

Fig. 9. Measured contact pressures at the springline.

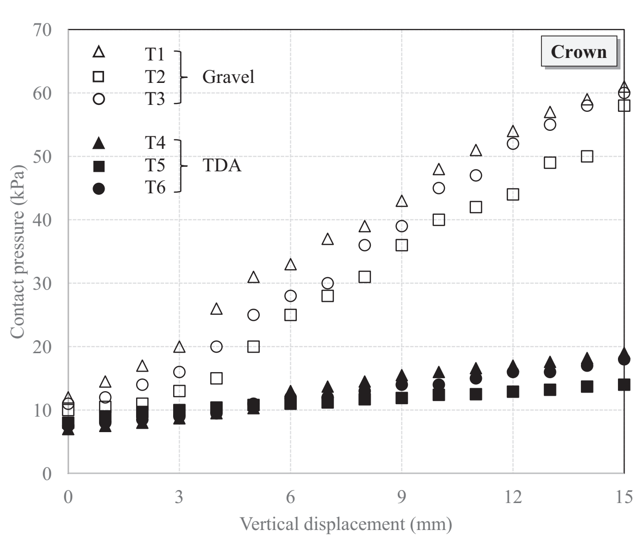

Fig. 7. Measured contact pressures at the crown.

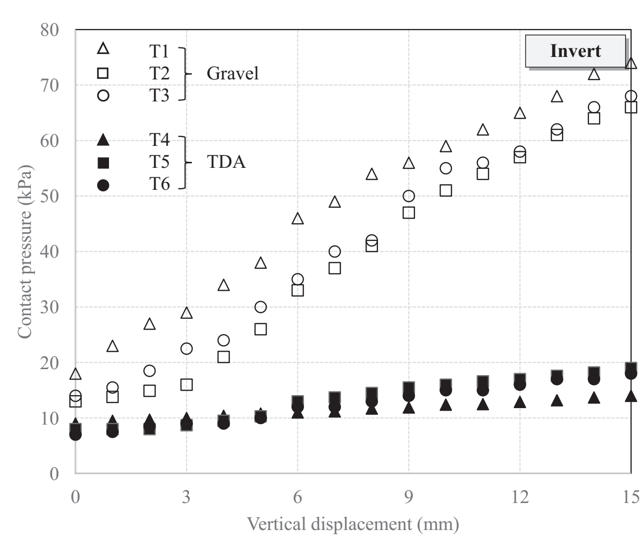

Fig. 10. Measured contact pressures at the invert.

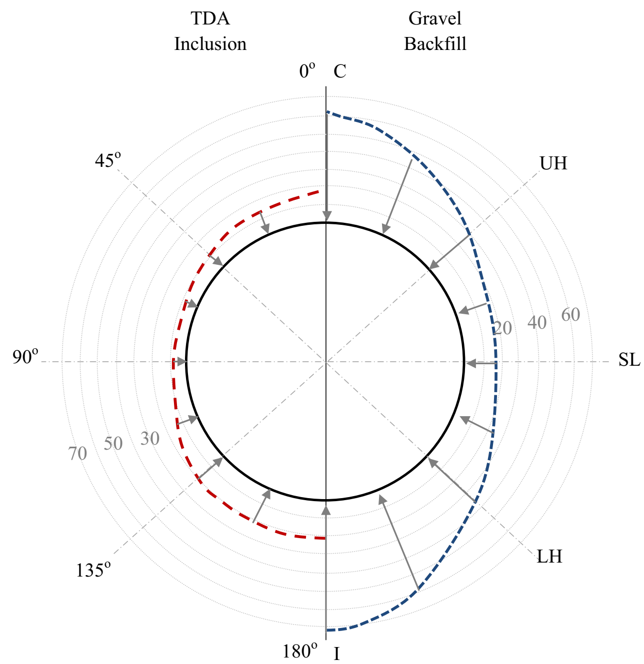

Fig. 11. Contact pressure distributions on the pipe (kPa) at maximum applied displacement.

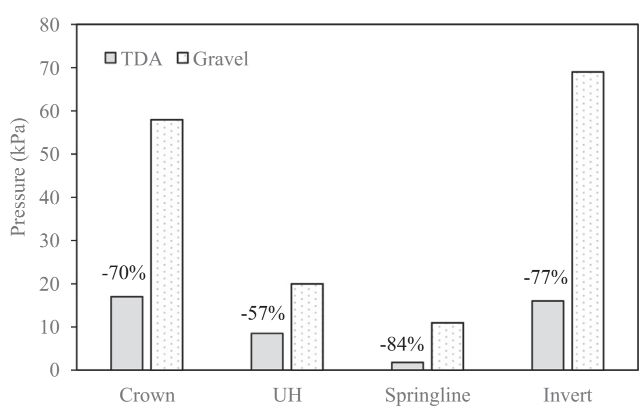

Fig. 12. Comparison between the average measured earth pressure at different locations.

backfill, the changes were found to be 70%, 57%, 84% and 77% at the crown, upper haunch, springline and invert, respectively.

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.

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 an environmentally sound alternative to gravel backfill and EPS geofoam. Further studies are needed to examine the role of the soft zone geometry and TDA properties on the pressure transferred to the pipe.

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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