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Abstract (200 words)

The current design practice in the UK for estimating the soil pressure on a buried pipe under traffic loads is based on a simple equation derived using a Boussinesq solution. In order to test and verify this equation, and study the effect of pipe diameter and backfill height for rigid (concrete) and flexible (PVC) pipes, a study has been conducted using three-dimensional finite element modelling. It was found that increasing the diameter of the concrete pipe nonlinearly decreases the maximum vertical displacement, while the relationship between the concrete pipe diameter and the maximum thrust force was found to be dependent on the backfill height. Increasing the diameter of the PVC pipe linearly increases the displacement and the maximum thrust force. The effect of traffic live load on the maximum thrust force becomes insignificant for a cover depth larger than 2 m and 3 m for the concrete and PVC pipes, respectively. The results indicate that there are significant issues with the maximum soil pressure equation used in the British Standard. A new equation has been developed using numerical modelling results and using a regression analysis to predict the maximum soil pressure on a buried pipe based on backfill height.

Keywords: Pipes & pipelines; design methods & aids; research & development; codes of practice and standards

List of notation

F	is the field test
3DFE	is the three-dimensional finite element analysis
2DFE	is the two-dimensional finite element analysis
L (1-g)	is the laboratory test
L(C)	is the length of the laboratory centrifuge test
PE	is the polyethylene
PP	is the polypropylene
UPVC	is the unplasticized polyvinyl chloride
HDPE	is the high density polyethylene
PVC	is the polyvinyl chloride
AL	is the aluminium
ST	is the steel
CON	is the concrete
RC	is the reinforced concrete
C	is the calculated maximum soil pressure under traffic live load
H	is the backfill height
E	is the modulus of elasticity
υ	is the Poisson ratio

γ	is the unit weight of the soil
c'	is the cohesion of the soil
ϕ'	is the angle of internal friction of the soil
K, n, and R_f	is the hyperbolic soil model parameter
D	is the diameter of the pipe
Wt	is the trench width
USCS	is the unified soil classification system
CR	is the predicted maximum soil pressure due to the traffic live load using the regression equation

1. Introduction

Buried pipelines are widely used for drainage and sanitary applications as well as transporting products such as gas and water. These pipelines are usually buried beneath the highways. During their service life, pipelines should resist the external forces from soil overburden pressure and traffic live load if buried at a shallow depth (≤3 m). For these reasons, and to achieve a safe and economical design of pipelines, it is very important to correctly estimate the stresses and strains developed under external forces.

In order to fully understand the extent of previous studies in the area of buried pipes, a thorough literature review was conducted. The behaviour of pipes during installation (Arockiasamy *et al.,* 2006; Kawabata *et al.,* 2008; and Elshimi and Moore, 2013), under soil overburden pressure (Rogers, 1999; Dhar *et al.,* 2004; Sargand *et al.,* 2005; Chapman *et al.,* 2007; Abolmaali and Kararam, 2010; and Gallage *et al.*, 2012), and traffic live load has received significant attention from researchers in the literature. A lot of numerical, laboratory, and full-scale studies on the response of the pipes under these effects are available in literature. The traffic live load in these studies has been considered in a number of ways, e.g. as a uniform pressure (Yoo *et al*., 1999; Trickey and Moore, 2007; Bryden *et al.,* 2014; and Kraus *et al.,* 2014), single axle load (Fleming *et al.,* 1997; Kang *et al.,* 2013a; Kang *et al.,* 2014; Lay and Brachman, 2014; Mai *et al.,* 2014a; and García and Moore, 2015), and multiple axle loads (McGrath *et al.,* 2002; Arockiasamy *et al.,* 2006; Wong *et al.,* 2006; Kraus *et al.,* 2014; Rakitin and Xu, 2014; Chaallal *et al.,* 2014a; Chaallal *et al.,* 2014b; Sheldon *et al.,* 2014; and García and Moore, 2015). The details of the studies on the pipes with a single axle load or multiple axle loads are shown in Table 1. Most of these studies simulated the load configuration and the maximum tyre pressure of American Association of State Highway and Transportation Officials (AASHTO) standard design trucks (H-20, H-25, HS-20, and HS-25) (AASHTO, 1998) and a Canadian standard design truck (CL-625) (CSA, 2006). However, a review on the design guidelines for buried pipelines showed that the loading configuration recommended in the BS 9295 (2010) (two axles with a maximum axle load of 450 kN) is different from that of the H-20 and H-25 (one axle with a maximum nominal axle load of 178 kN) and CL-625 (one axle load with a nominal maximum axle load of 175 kN or a tandem axle with maximum nominal axle load of 240 kN). In addition, the current design practice in the UK for the maximum soil pressure on a pipe under traffic load is based on a simple equation derived using a Boussinesq solution as shown in Equation 1 (BS 9295 2010).

$$C = \left(\frac{54.5}{H} + \frac{42}{1.8^H}\right)$$

1.

Where C is the calculated maximum soil pressure under traffic load in kPa and H is the backfill height in m.

A review of the literature has shown that using the Boussinesq solution for estimating the forces in the pipe due to a surface live load is not accurate (Yoo *et al*., 1999). Therefore, in order to test, and potentially improve, this equation, rigorous numerical analysis results and/or field test results are required. However, due to the complex nature of the soil-pipe interaction under traffic live load and the nonlinearity of the soil, it is not possible to use the results and the recommendations from the previous studies to test and improve this equation. This is because of the difference in the loading configuration and the maximum axle load used in these previous studies. Furthermore, the literature lacks clear conclusions for the effect of pipe diameter and backfill height on the behaviour of the pipe, where most of the studies have focused on certain pipe types, certain pipe diameters, and certain backfill heights (refer to Table 1). Therefore, the present study aims to assess the effect of pipe diameter and backfill height on rigid (concrete) and flexible (PVC) pipes under the live loading configuration specified in BS 9295 (2010) using a validated nonlinear three-dimensional finite element model. In addition, the results of the maximum soil pressure on the pipe obtained from these analyses have been compared with the current design equation (Equation 1) recommended by BS 9295 (2010).

2. Model validation

Model validation in numerical analyses is very important to gain confidence in the approaches and models used. Therefore, two pipe related tests that are available in the literature have been considered for validating the finite element modelling techniques used in the present study (one field and one laboratory based). MIDAS GTS NX 2015 (v1.1), a commercial three-dimensional finite element package, has been used to create the numerical models. The field test was chosen to validate the numerical modelling because it is comparable in terms of scale to the present study, while the laboratory test has been considered to test the validity of the modelling to predict the response of pipes in more controlled laboratory conditions.

2.1 Validation Problem 1

A field test involving a corrugated HDPE pipe with a nominal diameter of 0.90 m has been modelled to validate and evaluate the predictions of the proposed numerical model (Arockiasamy *et al.,* 2006). The pipe was buried in a trench with a minimum width of 1.655 m. The backfill height was 0.45 m. Crushed limestone was used for the 0.152 m bedding layer and poorly graded sand with silt with a degree of compaction of 95 % of the Standard Proctor maximum dry density was used as the backfill material. The pipe was subjected to surface live loads from two axles of two trucks with a maximum axle load of 181 kN. The axle load value simulated an AASHTO HS-20 truck with an impact factor calculated using the equation from AASHTO (1998). The space between the two trucks was 0.91 m.

A numerical model was developed for this problem, with a length, width, and height of 15 m, 12 m, and 10 m, respectively. Four noded tetrahedron solid elements were used to model the surrounding soil and the trench, while three noded triangular shell elements were used to model the pipe. Sensitivity analyses were undertaken to evaluate the impact of the mesh size on the results and the best agreement was achieved when the average element size was 0.15 m for the pipe, 0.15 m for the trench, 0.25 m for the bedding layer, and 0.5 m for the surrounding soil. The finite element mesh is shown in Figure 1. The truck live load for each tyre was modelled as a surface pressure over a tyre foot print area of approximately 0.23 x 0.31 m (Arockiasamy *et al.,* 2006). A linear elastic model was used to model the pipe. The Duncan-Chang hyperbolic soil model (Duncan and Chang, 1970) was used to represent the behaviour of the soil. The Duncan-Chang hyperbolic soil model was chosen because it has the ability to model the effect of the stress level on the soil stiffness, which gives a better prediction for the behaviour of the pipe (Dhar *et al.,* 2004; Kim and Yoo, 2005; Kang *et al.,* 2007; Kang *et al.,* 2013a; Kang *et al.,* 2013b; and Kang *et al.,* 2014). The mechanical properties of the bedding soil, backfill soil, and natural soil were adopted from the literature (Boscardin *et al.,* 1990) and are shown in Table 2. The modulus of elasticity (E) and the Poisson ratio (υ) of the pipe were taken equal to be 760000 kPa and 0.4, respectively (Arockiasamy *et al.,* 2006).

As part of the modelling process, a full interface bond between the pipe and the soil has been assumed in the analysis as previous studies have shown that using a full bond gives a good prediction for the behaviour of the pipe (Taleb and Moore, 1999; Kim and Yoo, 2005; Kang *et al.* 2007; Meguid and Kamel, 2014; and Mai *et al.,* 2014b). The base of the model was restrained against movement in all directions, while the sides of the model were restrained against movement in the horizontal direction. Four steps were performed in the finite element analyses:

Step 1: The initial earth pressures for the in situ soil were calculated. The coefficient of the lateral earth pressure of the natural soil was taken equal to 1.

Step 2: The trench was excavated.

Step 3: The bedding soil, pipe and backfill soil were added to the model. The coefficient of the lateral earth pressure of the compacted backfill was taken as equal to 1 (Brown and Selig, 1991)

Step 4: The traffic live load was applied using 25 equal loading increments.

This field test has also been modelled in the literature using 2D and 3D elastic finite element (Arockiasamy *et al.,* 2006) and 2D nonlinear finite element model (Kang *et al.,* 2014).

Figure 2 compares the maximum vertical and horizontal displacement of the pipe obtained from the field results (Arockiasamy *et al.,* 2006), the present model, two- and three-dimensional finite element elastic models (Arockiasamy *et al.,* 2006), and a two-dimensional analysis using the Duncan-Selig hyperbolic soil model (Kang *et al.,* 2014). Figure 3 compares the results of the soil pressure around the pipe obtained from the field test and the same numerical studies. From Figure 2, it can be seen that the present model predicted the displacement of the pipe better than the previous models with a difference of 14.3 % for the vertical displacement (3.5 mm from the field test and 4 mm from the developed model) and 12 % for the horizontal displacement (1.5 mm from the field test and 1.32 mm from the developed model). Figure 3 shows that the present model predicted the soil pressure around the pipe reasonably well. It can be seen also that the two-dimensional model also predicted the soil pressure reasonably well. However, the decision to use a nonlinear three-dimensional model in this study was made to avoid using the spreading factor, which is an empirical factor used in the two-dimensional modelling to take into account the three-dimensional effect of traffic loads on pipes. It is worth noting that Kang *et al.* (2014) did not report the value of the spread factor which has been used in their analysis. The difference between the actual and predicted results can be justified by the complexity and variability of soil density pattern around the pipe and the difference between the real and the assumed soils properties. However, it can be concluded that the model is able to represent the soil-pipe interaction with an acceptable accuracy when compared with field results and previous numerical studies.

2.2 Validation Problem 2

The displacement of a PVC pipe with an external diameter of 0.47 m and a thickness of 0.013 m has been reported by Kraus *et al.* (2014). This pipe was tested in a laboratory test box with a length, width, and height of 3.05 m, 2.44 m, and 2.59 m, respectively. A surface load of 107 kN was applied over a plate area of 0.9x0.9 m. The backfill height in this test was 0.46 m. A gravelly soil with a degree of compaction of 95% of the Standard Proctor maximum dry density was used as the bedding material, and a sandy soil with a degree of compaction of 95% of the Standard Proctor maximum dry density was used as the backfill and the natural soil.

This test was modelled using 0.15 m size elements for the pipe and the soil. The same element types as for the Validation Problem 1 (section 2.1) were used. The length, width, and height of the numerical model were 3.05 m, 2.44 m, and 2.59 m, respectively. A linear elastic model has been used to model the pipe. The Duncan-Chang hyperbolic soil model (Duncan and Chang, 1970) was used to represent the behaviour of the soil. The material properties of the soils were adopted from the literature (Boscardin *et al.*, 1990) and are shown in Table 3. The modulus of elasticity (E) and the Poisson ratio (υ) of the pipe were taken as 689000 kPa and 0.35, respectively (Kraus *et al*., 2014). A full bond between the pipe and the soil was assumed in this analysis. The base of the model was restrained against movement in all directions, while the sides of the model were restrained against movement in the horizontal direction only. Three steps were performed to model the installation of the pipe and the loading:

Step 1: The initial earth pressures of the compacted soil beneath the pipe were calculated using a coefficient of lateral earth pressure of 1.0 (Brown and Selig, 1991).

Step 2: The bedding soil, pipe, and soil above the pipe were added, and the initial earth pressures were calculated using a coefficient of lateral earth pressure of 1.0 (Brown and Selig, 1991).

Step 3: The surface load was applied in 25 equal loading increments.

The predicted and recorded vertical displacement of the PVC pipe is shown in Figure 4. It can be seen that a good estimation is obtained from the numerical model, where the percentage difference between the maximum predicted and measured vertical displacement is equal to 7

%. It can be also be seen that the difference between the results is less than that for the field problem (Validation Problem 1), which is expected as the laboratory tests for small pipe diameters are usually more controlled, with less uncertainties regarding the compaction of the soil, the recorded results, and the uniformity of the support around the pipe. This validation problem, together with Validation Problem 1, gives confidence in the modelling technique being used.

3. Load configuration and critical load condition

As stated in the introduction, the aim of this study was to investigate the behaviour of buried pipes under the live load configuration recommended by BS 9295 (2010). In this standard, three loading configurations are recommended, eight tyres with a tyre load of 112.5 kN for 'main roads' (main highways), two tyres with a tyre load of 105 kN for 'light trafficked roads' (lightly trafficked highways) and two tyres with a tyre load of 60 kN for 'fields' (agricultural unpaved roads). In this study, the loading configuration for main highways (hereafter referred to as the MR-BSI live load) is considered since it represents the worst case scenario. This loading configuration is comprised of two axles with four wheels in each axle. The centre to centre spacing between the wheels is 1.0 m and the centre to centre spacing between the axles is 1.8 m. The total load of each wheel is 112.5 kN including a dynamic allowance factor of 1.3. This load is modelled as a surface pressure in the present analysis with a wheel foot print area of 0.5*0.25 m (Petersen *et al.,* 2010; Kang *et al.,* 2013a; and Kang *et al.,* 2014). To find the critical loading condition, the effect of the truck position with respect to the pipe has been investigated. The cases of a truck travelling parallel and perpendicular to the pipeline axis were investigated at different S values, where S is the horizontal distance between the centreline of the pipe and the first set of wheels for the truck travelling parallel to the pipe (Figure 5(a)) or the distance between the centreline of the pipe and the right hand truck axle for the case of truck travelling perpendicular to the pipe (Figure 5 (b)).

The material properties of the surrounding soil, bedding soil, backfill soil, and pipe, which are mentioned in the Validation Problem 1, are used in this analysis with a backfill height of 0.45 m. For each case the maximum thrust and maximum horizontal and vertical displacement of the pipe have been recorded.

Figure 6 shows the maximum horizontal and vertical displacement and maximum thrust of the pipe for different S values for the case of a truck moving parallel to the pipeline axis (Figure 5(a)). It can be seen that the maximum horizontal and vertical displacement are equal to 2.18 mm and 6.78 mm when S = 0 m, however the maximum thrust was obtained when S = 1.25 m and is equal to 45.76 kN/m.

Figure 7 shows the maximum horizontal and vertical displacement and the maximum thrust of the pipe for different S values for the case of a truck moving perpendicular to the pipeline axis.

From these Figures it can be seen that the maximum vertical displacement and thrust in the pipe were obtained when the centre of the right hand axle was above the crown (S = 0 m) and are equal to 10.1 mm and 47.5 kN/m respectively. However, the maximum horizontal displacement of 3.9 mm was recorded when the centre of the right hand axle was 0.25 m away from the crown of the pipe (S = 0.25 m).

It can be concluded from these Figures that the highest vertical and horizontal displacements in the pipe are obtained when the truck is moving perpendicular to the pipeline axis and the critical case is obtained when the centre of the right hand axle is above the crown of the pipe. This is because of the dependency of the pipe behaviour on the surrounding soil stiffness (Fleming *et al.*, 1997; Brachman and Krushelnitzky 2005; and Saadeldin *et al.*, 2015) and the dependency of the soil stiffness on the stress level. The confining pressure in the soil adjacent to the sides of the pipe is larger for the cases where the pipe is between the two axle loads because of an increase in the stress level, which increases the stiffness of the soil adjacent to the sides of the pipe. Increasing the soil stiffness increases the side support on the pipe, and hence the settlement and the thrust forces will be smaller. However, for the case where one axle is directly above the pipe, the stress level will not distribute equally around the pipe and the soil stiffness will be smaller. Furthermore, the stress level on the crown of the pipe will be larger when the axle load is directly above the pipe.

These results are in agreement with the findings from Chaallal *et al.* (2014a), who observed from a field test involving a flexible pipe under two axle loads that the worst case for the pipe was when one of the axles was directly above the pipe.

Comparing the results of the critical case of the MR-BSI live load and the case of the two axles of the two HS-20 design trucks (from the validation section) shows that the MR-BSI live load is much more stringent with the calculated horizontal and vertical displacements under the MR-BSI live load being 195% and 153% higher respectively.

4. Parametric study

A parametric study has been carried out to examine the performance of concrete and PVC pipes under the critical condition of the MR-BSI live load. The diameters and thicknesses of these pipes are adopted from the literature (Petersen *et al.,* 2010) and are shown in Table 4. The study investigated the effect of the pipe diameter and backfill height (0.5 m to 4.5 m) on the maximum soil pressure, the maximum vertical displacement of the pipe, and the maximum thrust force in the pipe. The boundary conditions, the elements types, the constitutive models for the soil and the pipe, and the elements sizes were the same as for the validation problems. A gravelly sand with a degree of compaction of 90% measured according to the maximum Standard Proctor dry density (SW in the unified soil classification system (USCS) (Das, 2010) (hereafter referred to as SW90)), and a sandy silt with a degree of compaction of 90% (ML in the USCS (hereafter referred to as ML90)) have been used in the analyses. The study focused on these soils because they are the most common soils to be used as a backfill material in practice (Chaallal *et al.,* 2014b). The thickness of the bedding layer is taken as equal to 0.10 m and modelled using a SW90 soil. The natural surrounding soil is assumed to be stiffer than the trench soil. The material properties of the soils used are shown in Table 5, and the material properties of the pipes are shown in Table 6. The trench width (W_t) has been calculated using Equation 2 (Arockiasamy *et al.,* 2006). The results of the parametric study are discussed in the next subsections.

$$W_t = 1.5\,D + 0.3$$

2.

4.1 Maximum soil pressure on pipes

In this section, the effect of backfill height on the maximum soil pressure acting on the pipes is discussed for concrete and PVC pipes. Figure 8 (a) and (b) shows the maximum soil pressure at the crown of the pipe due to the MR-BSI live load only for the case of the PVC pipes embedded in SW90 and ML90 soils, respectively. The predicted maximum soil pressure from the BS equation (Equation 1) is also shown in this figure. It can be seen that the maximum soil pressure due to the effect of traffic live load decreases nonlinearly as the backfill height increases for both soils. For the SW90 soil, the percentage decrease in the tyre stress (i.e. 900 kPa) for a backfill height of 1m is equal to 91%, 89%, and 88% for pipe diameters of 0.37 m, 0.76 m, and 1.47 m, respectively. This reveals that approximately 90% of the tyre stress is reduced at a backfill height of 1.0 m. For a backfill height of 3 m, the percentage decrease is equal to 99%, 98%, and 97% for pipe diameters of 0.37 m, 0.76 m, and 1.47 m, respectively. It can also be seen that increasing the diameter of the pipe increases the maximum soil pressure, which indicates that negative arching increases as the diameter of the pipe increases. The same trend in behaviour is also noticed for the ML soil.

Comparing the results of the SW and the ML soils shows that the maximum soil pressure for the models with the SW backfill is larger than that with the ML backfill for all of the considered diameters. This indicates that positive arching increases as the type of the backfill soil changes from SW90 to ML90. This is probably due to the fact that the SW soil is stiffer than the ML soil, which makes the ML backfill soil experience larger settlement under the same loading condition. This increases the positive arching effect as larger shearing forces are develop on the sides of the trench (Kang *et al.,* 2007, Kang *et al.,* 2013b).

Comparing the results of the SW90 and ML90 soils with Equation 1 shows, in general, that the equation underestimates the soil pressure at backfill heights of 0.5 m and 1.0 m, and overestimates the soil pressure at a backfill height equal to or greater than 2.0 m. The ratio between the soil pressure predicted from the numerical modelling (P) and the soil pressure calculated from Equation 1 (C) varies between 1.82 and 0.039 for the 0.37 m diameter pipe, 2.85 and 0.096 for the 0.76 m diameter pipe, and 2.9 and 0.19 for the 1.47 m diameter pipe.

Figure 9 (a) and (b) shows the predicted and calculated maximum soil pressure for the concrete pipes. It can be seen that the same behaviour as for the PVC pipes is recorded, where approximately 88% and 98% of the tyre stress is reduced at backfill heights of 1.0 m and 3.0 m, respectively. Similar observations were also found by Bian *et al.* (2012) from a full scale study on the effect of truck loads on an arch concrete culvert (width of 3.5 m and height of 2.5 m) buried in a poorly graded gravel with a backfill height ranging from 0.5 m to 3.5 m. Bian *et al.* (2012) noticed that the tyre stress decreased by 91 % at a depth of 1.0 m below the ground surface.

Comparing the results of the SW90 and ML90 soils with Equation 1 shows that in general the equation underestimates the maximum soil pressure at backfill heights ranging from 0.5 m to 2.5 m for the SW90 soil and from 0.5 m to 2.0 m for the ML90 soil. However, Equation 1 overestimates the soil pressure at a backfill height equal to or greater than 3.0 m for the SW90 soil and 2.5 m for the ML90 soil. The ratio between the predicted and calculated maximum soil pressure (P/C) varies between 2.29 and 0.05 for the 0.41 m diameter pipe, 2.84 and 0.08 for the 0.76 m diameter pipe, 2.91 and 0.33 for the 1.47 m diameter pipe, and 3.64 and 0.47 for the 2.89 m diameter pipe.

4.2 Pipe thrust

Figures 10 and 11 present the effect of PVC and concrete pipe diameter and backfill height on the maximum thrust force developed in the pipe under the MR-BSI live load only and buried in a SW90 soil. In Figure 10, it can be seen that increasing the diameter of the PVC pipe from 0.37 m to 1.47 m increases the maximum thrust force. As expected, increasing the backfill height decreases the maximum thrust force developed in the pipe under the live load effect.

Figure 11 shows that for backfill heights of 0.5 m and 1 m, there is a sharp increase in the thrust force when the diameter of the pipe changed from 0.41 m to 0.76 m. However, beyond 0.76 m diameter the thrust developed decreases as the diameter increases. For a backfill height of 1.5 m and 2 m, the thrust force continues to increase after the 0.76 m diameter, however the increase is small. This behaviour was due to the dependency of the developed thrust on the surrounding soil stiffness (which depends on the backfill height) and also on the change in the zone of maximum thrust from the invert to a region bounded by the crown and shoulder of the pipe as the diameter and the backfill height changes. It should be noted here that the effect of the traffic live load did not produce an increase in the maximum thrust forces in the PVC pipes after a backfill height of 3 m, and for the concrete pipes after a backfill height equal to or greater than 2.5 m. This is due to the significant reduction of the soil pressure due the effect of the backfill height as discussed in section 4.1. In addition, the small amount of stress which did reach the pipes after these backfill heights added additional support to the sides of the pipe, which in turn reduced the maximum thrust in the springline instead of increasing it. This happened in the concrete pipes at a depth smaller than for the

PVC pipes because of the tendency of the concrete pipes to attract more load than the PVC pipes due to their higher stiffness.

The trend in the behaviour of the PVC and concrete pipes is noticeably different. This is because of the changing maximum thrust zone for the concrete pipes, which depends on the pipe diameter and the backfill height. The maximum thrust zone changed from the invert to a region bounded by the crown and shoulder of the pipe. This is because of the stiffness of the pipe, which changed for each case due to the difference in the wall thickness and the diameter of the pipe, and the effect of the arching as the stiffness, diameter, and the backfill height changed. Peterson *et al.* (2010) also noticed that the maximum thrust changes as the backfill height and the diameter changes. However, for the PVC pipes, the maximum thrust force occurred in the shoulder zone for all of the cases, giving the trend in the results shown in Figure 10.

4.3 Pipe displacement

Figure 12 presents the effect of varying diameter and backfill height on the maximum vertical displacements of PVC pipes under the MR-BSI live load and buried in a SW90 soil. It can be seen that the maximum vertical displacement of the PVC pipe increases approximately linearly as the diameter of the pipe increases for all of the backfill heights. Furthermore, the displacement significantly decreases as the backfill height increases. This finding is consistent with the findings of past studies by Tricky and Moore (2007), Chaallal *et al.* (2014a), and Chaallal *et al.* (2014b), which also concluded that increasing backfill height significantly decreases the vertical displacement of pipes.

Figure 13 presents the effect of diameter and backfill height on the maximum vertical displacement of concrete pipes under the MR-BSI live load with a SW90 backfill. It can be seen that increasing the diameter of the concrete pipe causes the maximum vertical displacement to decrease nonlinearly for all of the backfill heights.

It should be noted that a direct comparison between the PVC and concrete pipe response cannot be made because of the differences in the modulus of elasticity and the wall thicknesses of the pipes being modelled.

Additional controlled experimental studies are required to support the findings from the present study as very limited field studies were found in the literature on the effect of pipe diameter on the soil pressure, thrust, and displacement developed in the pipe under live load. Wong *et al.* (2006) investigated the short and long term behaviour of concrete pipes under the effect of soil weight and traffic loads with a diameter range of 0.60-0.90 m. However, the burial depth, the trench geometry, the surrounding soil and the backfill soil were different for each pipe, which does not help in drawing a direct conclusion to support the findings from the current study. Sheldon *et al.* (2014) reported the vertical and horizontal displacement of corrugated metal and concrete pipes with two different diameters, however the backfill height was different for each diameter and hence no direct conclusion can be drawn to support the findings from the present study.

5. Practical implication

As shown in section 4.1, there are significant issues with Equation 1 as adopted in the British Standard for estimating the maximum soil pressure on the pipe under traffic live load. Therefore in this section, a new equation has been developed using regression analysis. Several trials have been made to find the best fit equation using linear and non-linear regression analyses. The best equation was chosen based on the maximum coefficient of determination. The maximum soil pressure from 112 data points obtained from the numerical modelling for the PVC and concrete pipes with backfill heights ranging from 1 m to 4.5 m were used in the derivation of the regression equation. The backfill height of 0.5 m was excluded from the regression analysis as from a practical point of view, the minimum allowed cover in the United Kingdom for the pipes under the main road loading requirement is approximately 1m (DTHT, 2001). The equation obtained from the regression analysis has a coefficient of correlation of 0.93 and is given by Equation 3. It should be noted here that this equation is valid for a backfill height of 1.0 m or higher.

$$\mathrm{CR} = 900(1 - (-0.01\ \mathrm{H}^2 + 0.0833\ \mathrm{H} + 0.8243))$$

3.

Where, CR is the predicted maximum soil pressure from the regression equation in kPa. H is the backfill height in m.

6. Conclusions

A validated three-dimensional finite element model has been developed and used to find the critical loading conditions for the British Standard traffic live load configuration for a buried pipe and a study of the behaviour of PVC (0.37-1.47 m) and concrete pipes (0.41 -2.89 m) under this critical loading condition has been conducted. A cover depth range of 0.5-4.5 m has been modelled in this study for both the PVC and concrete pipes. The following conclusions can be drawn from the present study:

1- The MR-BSI loading configuration imposes a higher stress and displacement on the pipe compared with two AASHTO HS-20 trucks, where the predicted horizontal and vertical displacements under the critical MR-BSI live load configuration are 195% and 153% higher than that predicted under two HS-20 design trucks with two axles.
2- The equation recommended by the British Standard (BS 9295, 2010) for estimating the maximum soil pressure on a buried pipe has been shown not to be accurate. A new regression equation has been proposed based on the results of an extensive numerical study. The proposed equation has a coefficient of determination of 0.93. This new

equation can be used to predict the maximum soil pressure under traffic live loads for a backfill height equal to or greater than 1.0 m.

3- The effect of traffic load on the maximum thrust force is negligible for a backfill height greater than 3 m for the PVC pipes and a backfill height of 2.5 m or higher for the concrete pipes analysed in this study. Greater backfill heights only cause redistribution of the thrust forces around the pipe without increasing the maximum thrust developed.

4- Increasing the diameter of the PVC pipe approximately linearly increases the maximum thrust forces in the pipe for all of the backfill heights considered. However, for the concrete pipes with backfill heights of 0.5 m and 1 m, the maximum thrust force increases when the diameter changes from 0.41 m to 0.76 m, following by a small decrease as the diameter increases from 0.76 m to 2.89 m. However, for a backfill height of 1.5 m and 2 m, increasing the diameter of the pipe continuously increases the maximum thrust force, but the increase is small.

5- Increasing the diameter of the pipe approximately linearly increases the vertical displacement in the PVC pipes and nonlinearly decreases the vertical displacement for the concrete pipe type.

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Figure captions

Figure 1 Finite element model of the selected problem

Figure 2 Comparison of the vertical and horizontal displacement of the HDPE pipe under live load

Figure 3 Comparison of the soil pressure around the HDPE pipe under live load

Figure 4 Predicted and measured vertical displacement of the PVC pipe

Figure 5 The load cases considered in the analysis (a) axles perpendicular to pipe, but the truck moving parallel to the pipe (b) axles parallel to the pipe, but truck moving perpendicular to the pipe

Figure 6 Results from the analysis of the pipe for the case of the MR-BSI live load travelling parallel to the pipeline axis with different S values (a) maximum vertical and horizontal displacement (b) maximum thrust. (Note: S = 0 when the first set of wheels are directly above the pipeline axis, as shown in Figure 5(a).)

Figure 7 Results from the analysis of the pipe for the case of the MR-BSI live load travelling perpendicular to the pipeline axis with different S values (a) maximum vertical and horizontal displacement (b) maximum thrust. (Note: As shown in Figure 5(b), S = -1 m when the right hand axle is 1 m to the left of the pipeline axis, S = 0 when the right hand truck axle is directly above the pipeline axis and the other axle is 1.8 m to the left of the pipeline axis, S = 1.8 m means the left hand truck axle is directly above the pipeline axis and the other axle is 1.8 m to the right of the pipeline axis.)

Figure 8 Calculated and predicted maximum soil pressure on PVC pipes under live load only (a) SW90 backfill (b) ML90 backfill

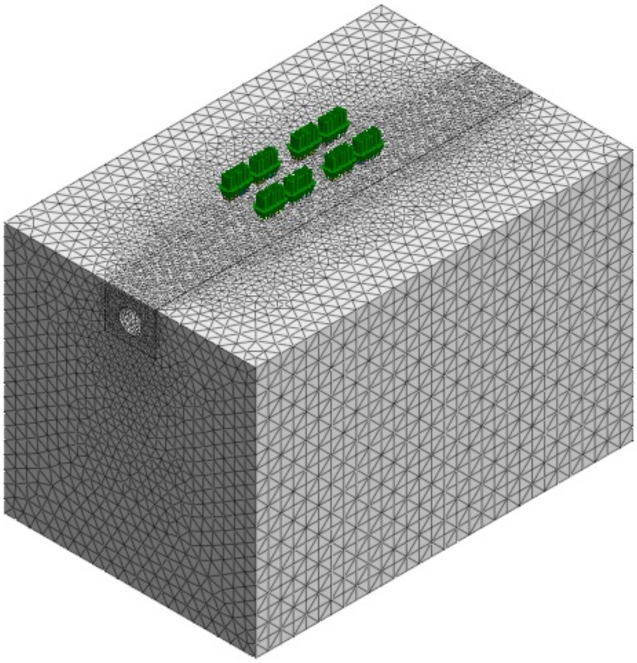
Figure 9 Calculated and predicted maximum soil pressure on concrete pipes under live load only (a) SW90 backfill (b) ML90 backfill

Figure 10 Maximum thrust developed in the PVC pipes under the MR-BSI live load only

Figure 11 Maximum thrust developed in the concrete pipes under the MR-BSI live load only

Figure 12 Maximum vertical displacement of PVC pipes developed under the MR-BSI live load only

Figure 13 Maximum vertical displacement of concrete pipes developed under the MR-BSI live load only



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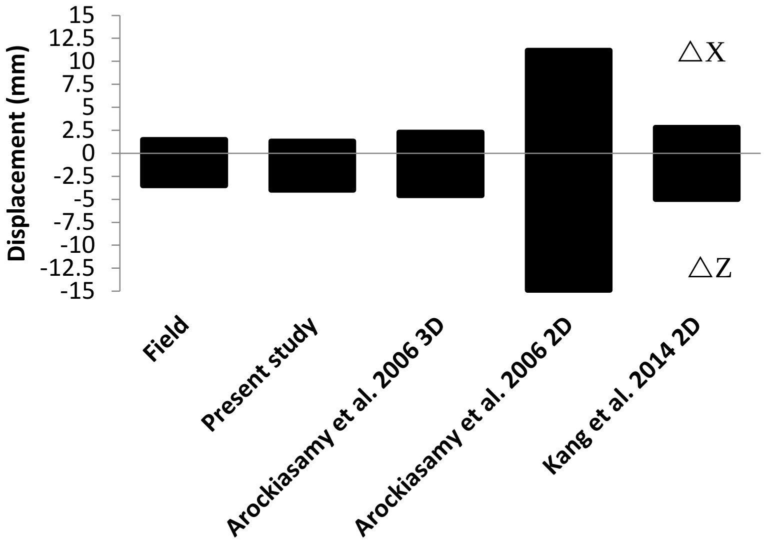

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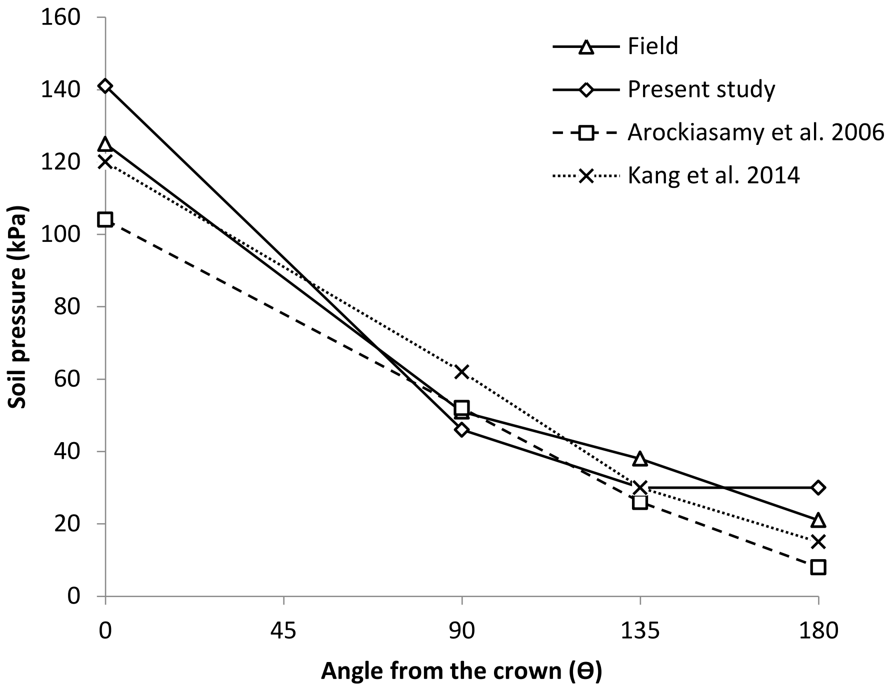

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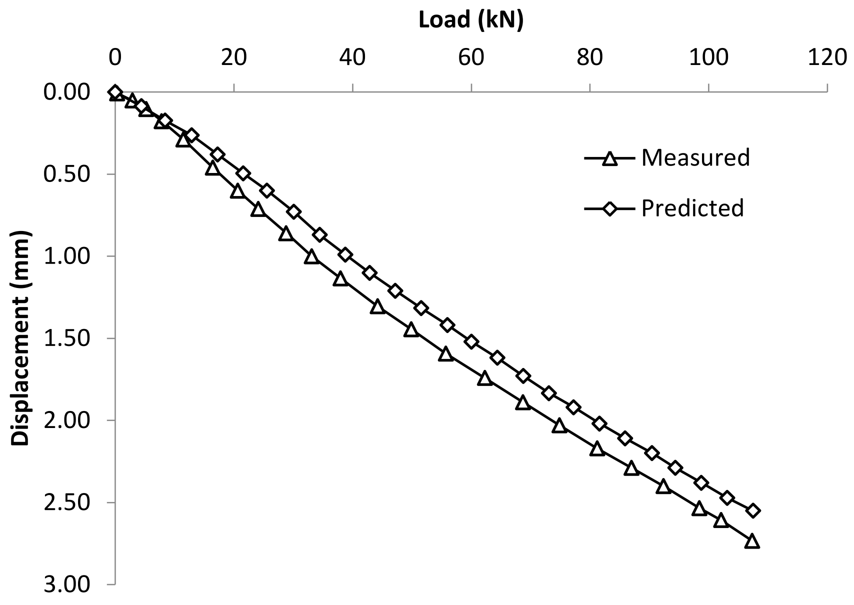

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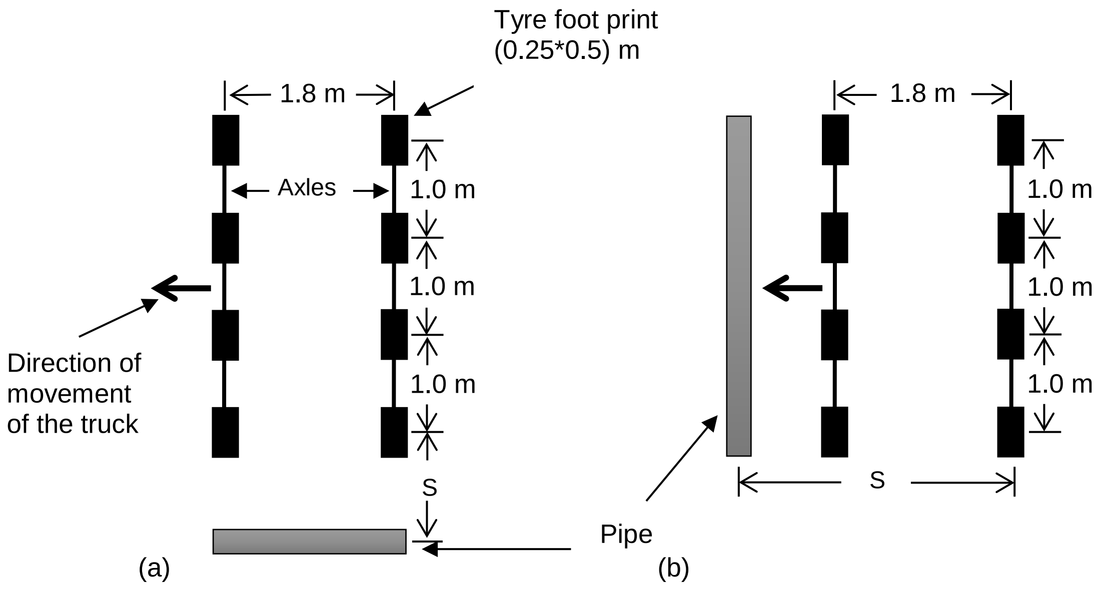

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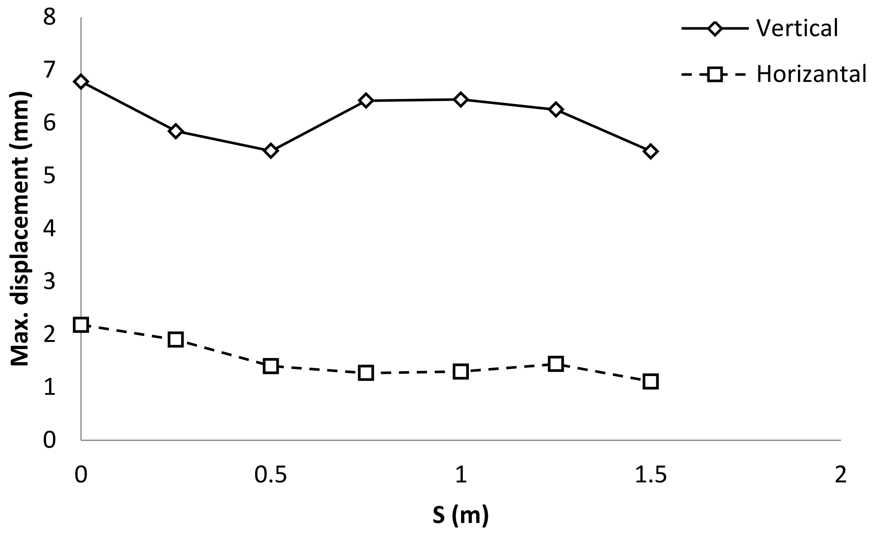

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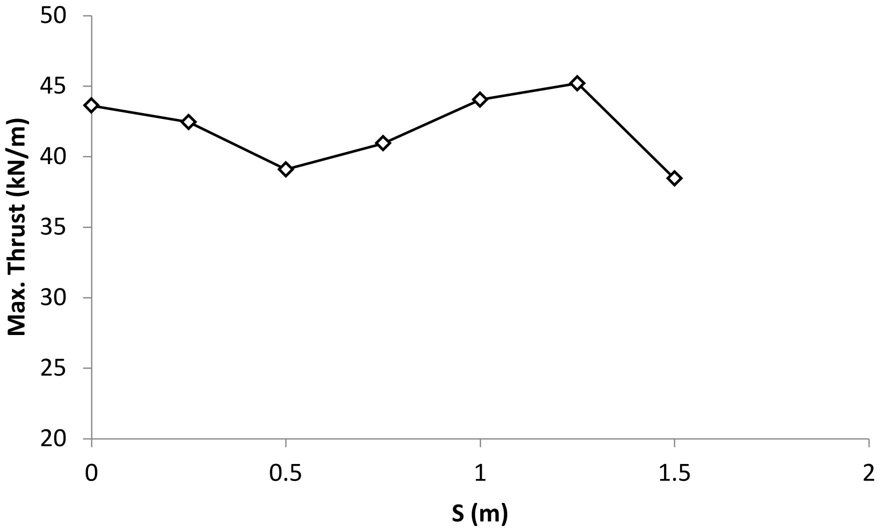
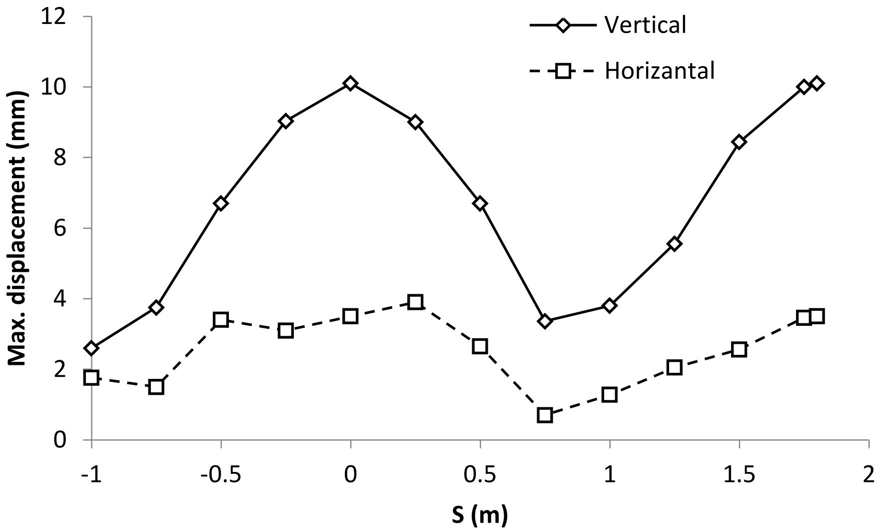


Figure 6b



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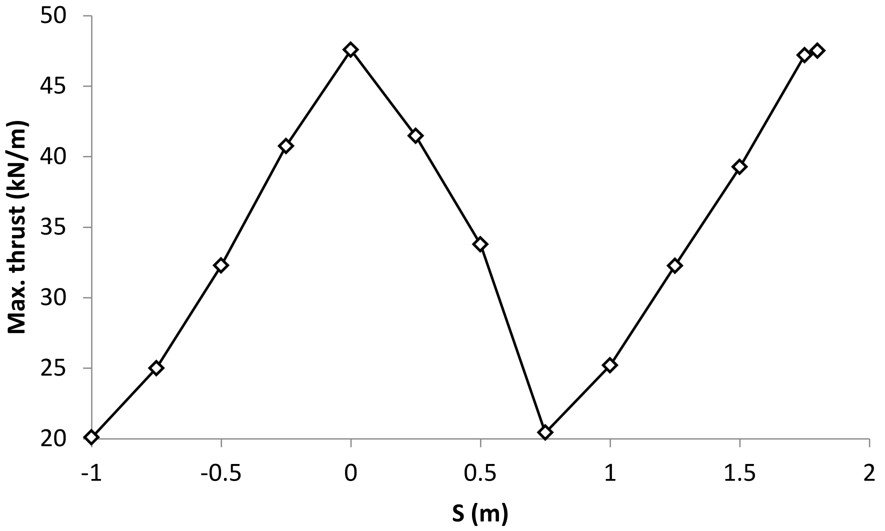

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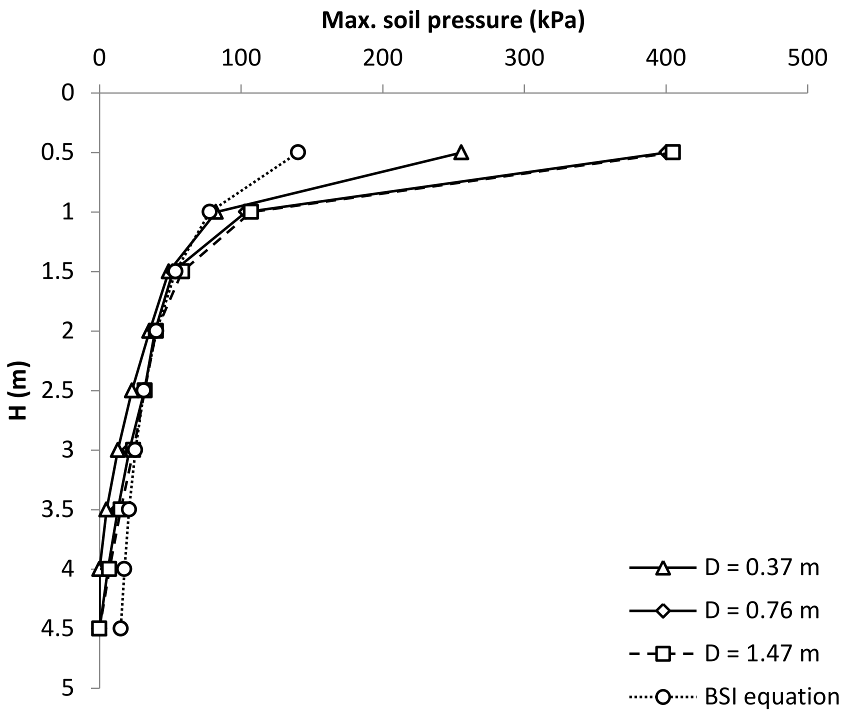

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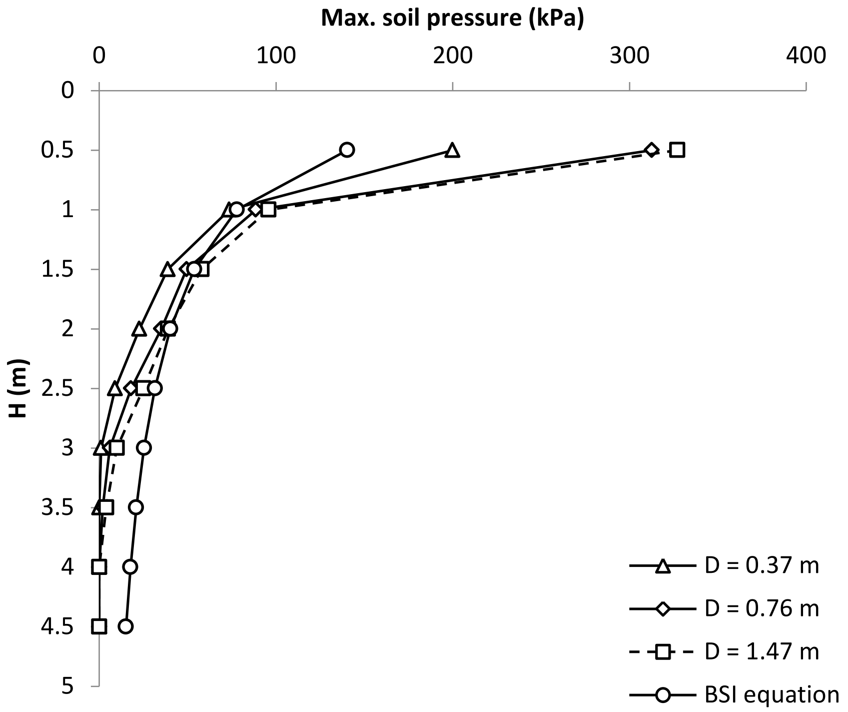

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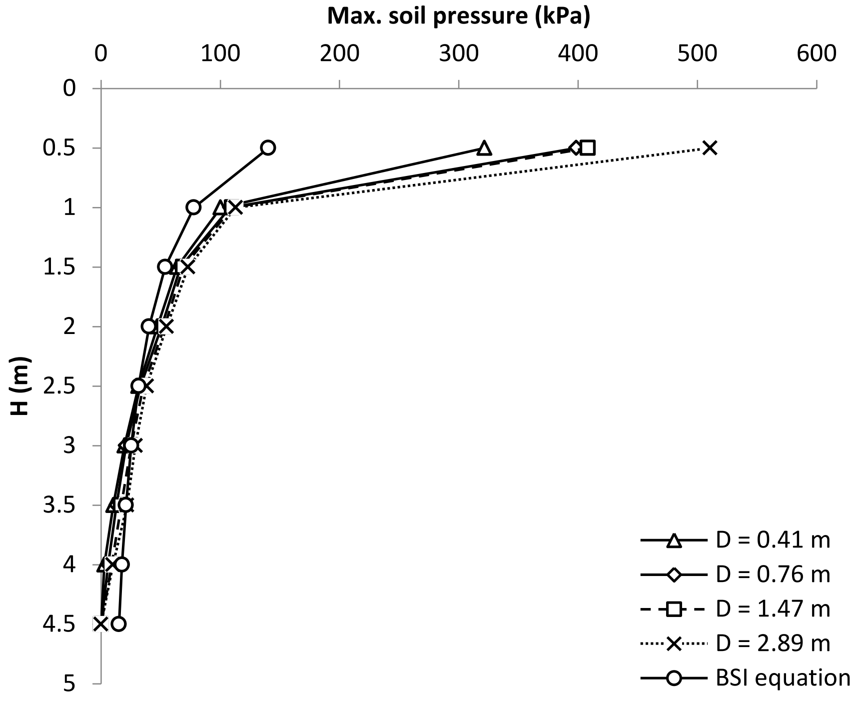
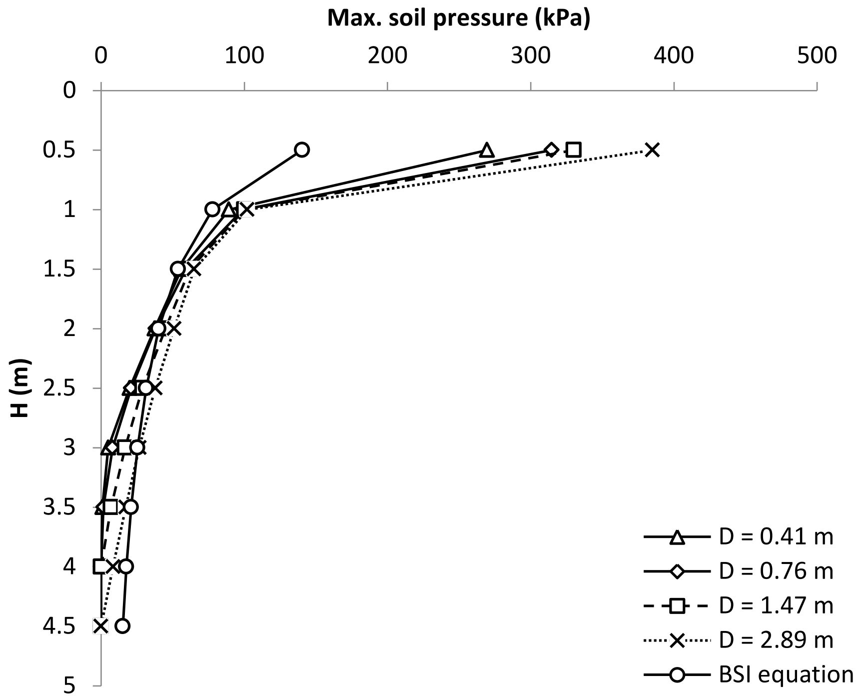


Figure 9a



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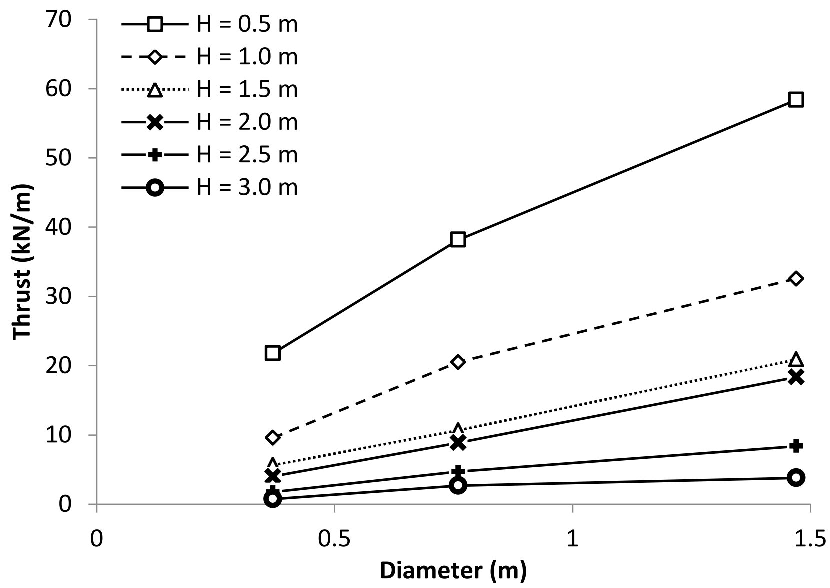

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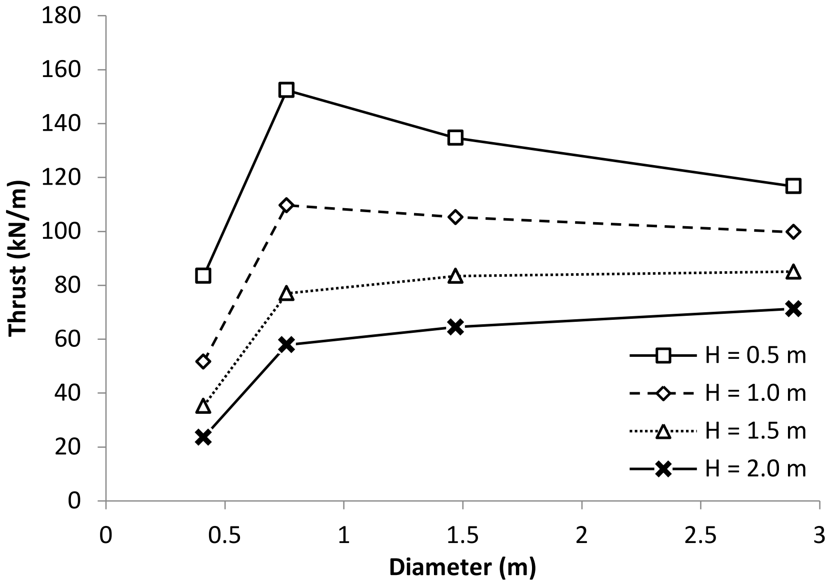

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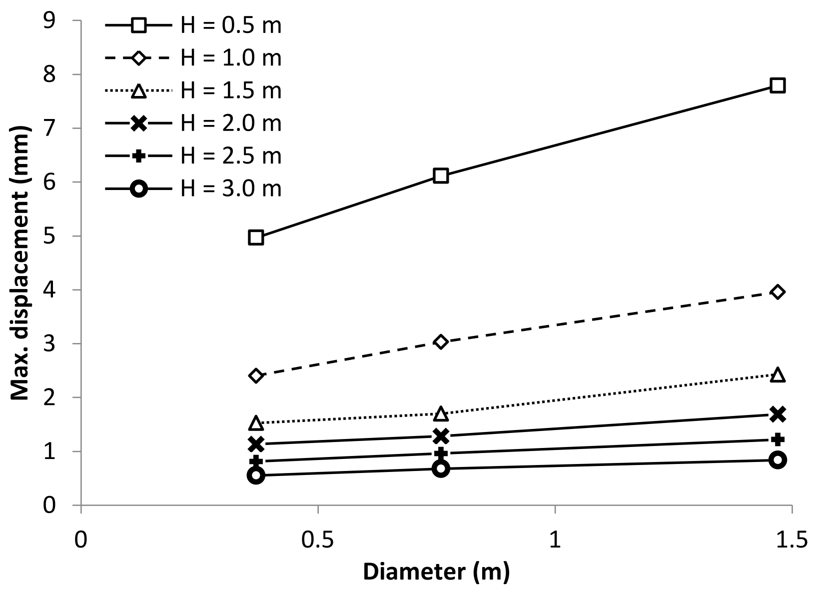

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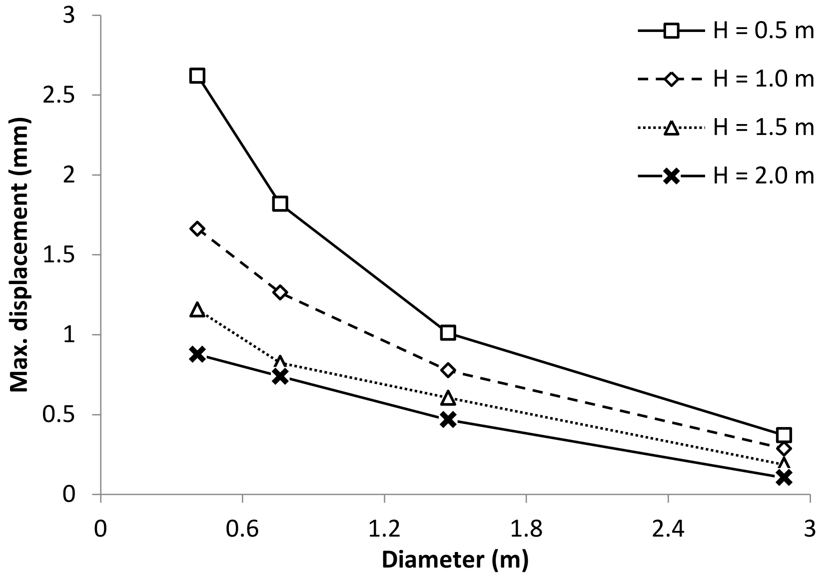

3
2.5
2
1.5
1
0.5
0
Max. displacement (mm)
0
0.6
1.2
1.8
2.4
3
Diameter (m)
H = 0.5 m
H = 1.0 m
H = 1.5 m
H = 2.0 m

Figure 13

Table 1 Summary of previous studies on buried pipes behaviour under live load effect

No.	Reference	Type of study	Pipe material	Nominal Pipe diameter (m)	Backfill height (m)	Truck type	Number of trucks	Number of axles per truck	Max. axle load (kN)	Max. Tyre pressure (kPa)
1	Fleming *et al.* (1997)	F	PE, PP, and UPVC	0.60	1.00	---*	1	1	108	---
2	McGrath *et al.* (2002)	F	PE, ST, and RC	1.50	0.30 and 0.60	---*	1	5	107	---
3	Arockiasamy *et al.* (2006)	F/3DFE	HDPE, PVC, ST, and AL	0.90	0.45-1.80	HS-20	2	2	181	635
		F/3DFE	HDPE	1.20	0.60-2.40	HS-20				
4	Wong *et al.* (2006)	F	CON	0.60-0.90	1.40-1.85	---*	---	---	141	---
5	Kang *et al.* (2013a)	2DFE	HDPE and PVC	0.30-1.50	0.10-2.80	HS-20 and H-25	2	1	178	712
6	Chaallal *et al.* (2014a)	F	HDPE, PVC, ST, and AL	0.90	0.45-1.80	HS-20	2	2	181	635
		F	HDPE	1.20	0.60-2.40	HS-20				
7	Chaallal *et al.* (2014b)	3DFE	HDPE, PVC, ST, and AL	0.90	0.45-1.80	HS-20	2	2	181	635
		3DFE	HDPE	1.20	0.60-2.40	HS-20				
8	Kang *et al.* (2014)	2DFE	HDPE and PVC	0.30-1.50	0.10-2.80	HS-20 and H-25	2	1	178	712
9	Kraus *et al.* (2014)	L(1-g)	PVC	0.45	0.46	HS-30	---	---	---	132
		L(1-g)	CON	0.50	0.46	HS-30				
9	Kraus *et al.* (2014)	2DFE and 3DFE	PVC	0.45	0.46	---*	---	3-19	445	448
		2DFE and 3DFE	CON	0.50	0.46	---*				
10	Lay and Brachman (2014)	L(1-g)	RC	0.60	0.30	HS-20	1	1	145	483
10	Lay and Brachman (2014)	L(1-g)	RC	0.60	0.30-0.90	CL-625	1	1	400	1333
11	Mai *et al.* (2014a)	L(1-g)	ST	1.80	0.60 and 0.90	CL-625	1	1	224	747

11	Mai *et al.* (2014a)	L(1-g)	ST	1.80	0.60 and 0.90	HS-20	1	1	182	607
12	Rakitin and Xu (2014)	L(C)	RC	1.40	1.00 and 2.00	---*	1**	3	95	283
12	Rakitin and Xu (2014)	L(C)	RC	1.40	1.00-4.00	---*	1**	2	567	468
13	García and Moore (2015)	L(1-g)	ST	1.20	1.20	CL-625	1	1	203	677
13	Becerril García and Moore (2015)	L(1-g)	ST	1.20	1.20 and 2.10	CL-625	1	2	325	542
14	Sheldon *et al.* (2014)	F	ST	0.90 and 1.20	0.54 and 0.77	---*	1	2	133	---
14	Sheldon *et al.* (2014)	F	CON	1.40 and 2.10	0.60 and 1.40	---*	1	2	127	---
		F	HDPE	0.90	1.40	---*				

* Not a standard truck.
** Half of the truck was simulated in the centrifuge model.

Table 2 The material properties of the soil for Validation Problem 1 (Boscardin *et al.,* 1990)

Property	Backfill	Bedding	Natural soil
γ (kN/m^3)	19.91	22.07	22.07
υ	0.3	0.3	0.3
c' (kPa)	28	0	0
ϕ' (°)	34	48	48
K	440	950	950
Rf	0.95	0.7	0.7
n	0.4	0.6	0.6

Table 3 The material properties of the soil for Validation Problem 2 (Boscardin *et al.,* 1990)

Property	Backfill, bedding and natural soil
γ (kN/m^3)	22.07
υ	0.3
c' (kPa)	0
ϕ' (°)	48
K	950
Rf	0.7
n	0.6

Table 4 Pipes diameters and wall thicknesses (Petersen *et al.,* 2010)

Pipe type	Nominal diameter (m)	Outer diameter (D) (m)	Wall thickness (m)
Concrete	0.3	0.41	0.051
	0.6	0.76	0.076
	1.2	1.47	0.127
	2.5	2.89	0.229
PVC	0.3	0.37	0.036
	0.6	0.76	0.061
	1.2	1.47	0.089

Table 5 The material properties for the soils used in the parametric study

Property	ML90*	SW90*	Natural soil**
γ (kN/m^3)	18.84	20.99	21.00
υ	0.30	0.30	0.30
c′ (kPa)	24	0	30
ϕ′(°)	32	42	36
K	200	640	1500
Rf	0.89	0.75	0.90
n	0.26	0.43	0.65

* adopted from Boscardin *et al.* (1990)

** assumed values

Table 6 Linear elastic properties of the concrete and PVC pipes (Petersen *et al.*, 2010)

Pipe type	E (kPa)	υ
Concrete	24856000	0.20
PVC	689000	0.35