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Innovative approach to determine the minimum wall thickness of flexible buried pipes

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Abstract. This paper uses a finite element based approach to provide a comprehensive understanding to the behaviour and the design performance of buried uPVC pipes with different diameters. It also investigates pipes with good and poor haunch support and proposes minimum safe wall thicknesses for these pipes. The results for pipes with good haunch support showed that the maximum pipe wall stress and deformation increase as the diameter increased. The results for pipes with poor haunch support showed an increase in the dependency of the developed vertical displacement on the haunch support as the diameter or the backfill height increased. Additionally, poor haunch support was found to increase the soil pressure, with the effect increasing as the diameter increased. The design of uPVC pipes for both poor and good haunch support was found to be governed by critical buckling. A key outcome is a new design chart for the minimum wall thickness, which enables the robust and economic design of buried uPVC pipes. Importantly, the methodology adopted in this study can also be applied to the design of flexible pipes manufactured from other materials, buried under different conditions and subjected to different loading arrangements.

Keywords: soil-structure interaction; underground structures; design; finite element method; failure; numerical analyses

1. Introduction

Flexible pipes are widely used for transporting potable water, storm water and waste water (Balkaya *et al.* 2012, Chaallal *et al.* 2015a, Mohamedzein and Al-Aghbari 2016). As a result, there have been many studies undertaken to investigate the behaviour of these pipes during installation, under soil weight and under traffic load. These studies investigated the response of flexible pipes using numerical modelling, laboratory tests and field tests. The laboratory and field tests were conducted under controlled conditions where good support was provided for the pipe in the haunch zone (Sargand *et al.* 2001, Sargand *et al.* 2005, Arockiasamy *et al.* 2006, Talesnick *et al.* 2011, Terzi *et al.* 2012, Mehrjardi *et al.* 2013, Kraus *et al.* 2014, Bildik and Laman 2015, Bryden *et al.* 2015, Chaallal *et al.* 2015b, Khatri *et al.* 2015, Lee *et al.* 2015, Terzi *et al.* 2015, Mohamedzein and Al-Aghbari 2016) and similar conditions were adopted for the previous numerical modelling studies (Katona 1990, Zhan and Rajani 1997, Yoo *et al.* 1999, Suleiman *et al.* 2003, Arockiasamy *et al.* 2006, Kang *et al.* 2007a, Trickey and Moore 2007, Kang *et al.* 2009, Petersen *et al.* 2010, Kang *et al.* 2013a, b, 2014, Kraus *et al.* 2014, Bryden *et al.* 2015, Chaallal *et al.* 2015a, Luo *et al.* 2015, Saadeldin *et al.* 2015, Alzabeebee *et al.* 2017a). However, all of these studies have neglected the effect of poor support in the full haunch area, although proper haunch support is difficult to achieve in practice (Boschert and Howard 2014, Turney *et al.* 2015). In addition, there is a lack of clear understanding on the combined effect of the pipe diameter and backfill height under the impact of backfill soil weight and traffic load for pipe with both good and poor haunch support. This is due to the fact that the previous studies focused either on the effect of the traffic load only (Petersen *et al.* 2010, Alzabeebee *et al.* 2017a) or considered the combined soil weight and traffic load, but with limited diameter and backfill height ranges as shown in Table 1. Furthermore, the previous studies have neglected the stringent loading conditions as has been shown by Alzabeebee *et al.* (2017a). More importantly, no study has been conducted on the required minimum wall thickness for a safe and economic design of buried flexible pipes.

Therefore, the present study focuses on improving the current state-of-the-art of buried flexible pipes by investigating the following aspects using robust three-dimensional finite element modelling:

1. The effect of pipe diameter, backfill height and traffic load on the behaviour of buried unplasticised polyvinyl chloride (uPVC) pipes with good haunch support. This type of pipe has been considered as it is a standard pipe used in UK for drainage and sewerage applications (BSI 2009).
2. The impact of the poor haunch support on the behaviour of uPVC pipes under traffic load.
3. Compare the results of both good and poor haunch support with the design limits specified in the British Standard (BS) (BSI 1997, BSI 2010) to investigate the performance of pipes according to the BS design standard, and hence make the results from this study useful in practice for designing buried flexible pipes.

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Table 1 Details of previous studies on the response of flexible pipe under combined soil weight and traffic load

No.	Reference	Type of study	Pipe material	D (m)	H (m)
1	Zhan and Rajani (1997)	2DFE	uPVC	0.2	1.20-2.20
2	Yoo *et al.* (1999)	2DFE	ST	1.0	1.00
3	Arockiasamy *et al.* (2006)	F, 2DFE and 3DFE	uPVC PE	0.9 1.2	0.50-1.80 0.60-2.40
4	Talesnick *et al.* (2011)	L(1-g)	HDPE	0.2	0.20
5	Mehrjardi *et al.* (2013)	L(1-g)	uPVC	0.2	0.16-0.24
6	Kraus *et al.* (2014)	L(1-g) and 3DFE	uPVC	0.5	0.30-0.90
7	Bryden *et al.* (2015)	L(C) and 3DFE	ST	3.0	1.50 and3.00
8	Chaallal *et al.* (2015a)	3DFE	uPVC PE	0.9 1.2	0.45-1.80 0.60-2.40
9	Chaallal *et al.* (2015b)	F	uPVC PE	0.9 1.2	0.45-1.80 0.60-2.40
10	Mohamedzein and Al-Aghbari (2016)	L(1-g)	uPVC	0.2	0.10-0.50

Note: D, inside diameter of the pipe; H, backfill height; F, Field test; 2DFE, two-dimensional finite element; 3DFE, three-dimensional finite element analysis; uPVC, unplasticised polyvinyl chloride; PE, polyethylene; L(c), laboratory centrifuge test; ST, steel; L(1-g), laboratory test; HDPE, high-density polyethylene.

4. Investigate the minimum required wall thickness for a safe and economic design of buried uPVC pipes under the effect of BS traffic loading requirements.

5. Improve the design methodology of the BS to account for the effect of poor haunch support to ensure more robust and safe designs.

2. Design criteria of the buried flexible pipes based on the British Standard

According to the British Standard (BS), buried flexible pipes are designed based on the following criteria:

1- Displacement:

The BS recommends calculating the vertical displacement of the pipe due to the combined backfill soil weight and traffic load. The displacement should not exceed 5.00-10.00% of the diameter of the pipe (BSI 2016). However, the pipe displacement limitation has been established based on serviceability requirements and does not represent the overall collapse condition of the pipe (Gumbel *et al.* 1982).

2- Critical buckling:

Buckling failure is an excessive inward pipe deformation and happens when the tangential compressive stress exceeds a limiting value (Tee *et al.* 2013). Exceeding the buckling limit means that the pipe cannot retain its original shape (Tee *et al.* 2013). Buckling is considered as a failure condition even if pipe material failure has not occurred (Gumbel *et al.* 1982). According to the BS (BSI 2010), the buckling of the pipe is evaluated based on the maximum soil pressure applied on the pipe. The critical buckling pressure is calculated using Eq. (1) for the supported pipe and Eq. (2) for the unsupported pipe. According to BSI (1997), the factor of safety should be ≥ 1.50 for unsupported pipes and ≥ 2.00 for supported pipes. However, the BS (BSI 2010) recommends using Eq. (2) to calculate the critical buckling pressure, and hence the factor of safety against buckling, to account for the loss of side support due to trench digging for the installation of future nearby utilities.

$$Pcr = 0.6\left(\frac{E_p I_p}{Dmean^3}\right)^{0.33}(E')^{0.67} \tag{1}$$

$$Pcr = 24\,\frac{E_p I_p}{Dmean^3} \tag{2}$$

where, Pcr is the critical buckling pressure, E_p is the modulus of elasticity of the pipe, I_p is the moment of inertial of the pipe, E' is the overall modulus of soil reaction and $Dmean$ is the mean diameter of the pipe.

3- Pipe Material failure:

The pipe fails if the pipe wall stress exceeds the yield stress of the pipe material. Therefore, the designer should pay attention to the stresses developed in the pipe wall and make sure that the pipe wall stresses are lower than the material strength with an appropriate factor of safety. The BS (BSI 1997, BSI 2010) recommends checking the maximum pipe wall stress. However, there is no mention to the appropriate factor of safety against pipe material failure.

These three criteria were considered in this paper to investigate the factor of safety of the buried pipe for both poor and good haunch support conditions, and to propose the minimum required wall thickness.

3. Details of the finite element modelling

Midas GTS/NX (2015), a commercial finite element software, was used in this study to develop a finite element model simulating the case of a buried uPVC pipe subjected to traffic loading. The developed model was validated by comparing the results of the displacement, bending moment and soil pressure with case studies available in the literature. The results of this validation can be found elsewhere (Alzabeebee *et al.* 2017a, 2018).

The developed model had a 15 m length, 12 m width and 10 m height. The pipe was modelled using three noded triangular shell elements and the soil (backfill soil and surrounding soil) was modelled using four noded tetrahedron solid elements. Fine mesh with an average element size of 0.15 m was used to model the buried pipe and the trench, while a coarse mesh was used for the surrounding soil with an average element size of 0.5 m. A full bound interface between the soil and the pipe has been considered in the analysis, as the slippage between the soil and the pipe has been shown to have an insignificant effect on the results (Dhar *et al.* 2004, Balkaya *et al.* 2013, Alzabeebee *et al.* 2017a). 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 directions.

The British Standard main road traffic load (BSI, 2010) has been considered in this study as this loading configuration is more stringent than the Canadian and AASHTO truck loading (Alzabeebee *et al.* 2017a). This loading configuration includes two axles with four wheels in each axle as shown in Fig. 1. The wheel load is equal to 112.5 kN. A wheel print area of 0.25×0.5 m was considered to model the tyre pressure (Petersen *et al.* 2010, Kang *et al.* 2013a, 2014). The truck is assumed to travel perpendicular to the direction of the pipeline with the first axle load being directly above the pipe as shown in Fig. 1. It was found from a previous study by the authors that this loading position simulates the worst-case scenario (Alzabeebee *et al.* 2017a).

A review of the literature showed that simulating the dependency of the modulus of elasticity of the soil on the stress level significantly improves the numerical modelling predication of the response of buried pipes (Katona 2017) and produces a very good match with the experimental and field data (Dhar *et al.* 2004, Kang *et al.* 2013a, b, Turan *et al.* 2013, Kang *et al.* 2014). Therefore, the behaviour of the soil has been simulated using the hyperbolic Duncan-Chang soil model (Duncan and Chang 1970) as this model can capture the stress dependency very well. The Duncan-Chang hyperbolic soil model is a non-linear elastic soil model (Duncan and Chang 1970). The model has five input parameters (modulus number (K), modulus exponent (n), failure ratio (Rf), cohesion of the soil (c') and angle of internal friction of the soil (ϕ') These parameters can be obtained from three triaxial tests with different confining pressures (Al-Shayea *et al.* 2003). These parameters are used to find the tangent modulus of elasticity of the soil depending on the applied stress using Eq. (3). In addition, the shear strength parameters of the soil (i.e., c' and ϕ') are used to investigate the failure condition of each soil element within the finite element mesh by comparing the stress level (S_1-S_3) of each soil element with the stress level at failure (S_1-S_3)$_f$, which is calculated using Eq. (4). In the hyperbolic soil model, the tangent modulus of elasticity of the soil element is reduced if the element reaches the stress level at failure. The percentage decrease in the tangent modulus of elasticity depends on the experience of the user. In MIDAS GTS/NX, the tangent modulus of elasticity at failure is calculated by considering a stress level of 10 kPa to account for the soil failure.

$$Et = \left[1 - \frac{Rf\ (1-\sin\phi')\ (S_1 - S_3)}{2c'\cos\phi' + 2S_3\sin\phi'}\right]^2 KP_a\left(\frac{S_3}{P_a}\right)^n \quad (3)$$

$$(S_1 - S_3)_f = \frac{2c'\cos\phi' + 2S_3\sin\phi'}{1-\sin\phi'} \quad (4)$$

where, Et is the tangent modulus of elasticity, S_1 is the major principal stress, S_3 is the minor principal stress and P_a is the atmospheric pressure.

A linear elastic model was used to model the pipe. This model was used because the previous studies showed that this model accurately simulates the behaviour of buried flexible pipes (Dhar *et al.* 2004, Kang *et al.* 2013a, b, 2014, Alzabeebee *et al.* 2017a). Fig. 2 shows the finite element model used in this study. The numerical analysis was conducted in steps to simulate the excavation and trench filling similar to previous studies (Petersen *et al.* 2010, El Naggar *et al.* 2015, Mehrjardi *et al.* 2015, Allard *et al.* 2016). The steps can be summarised as follows:

Step 1: The initial soil stresses of the *in-situ* soil were calculated using a coefficient of horizontal earth pressure of 1.0 (Brown and Selig 1991).

Step 2: Simulation of the trench excavation was conducted in stages. The trench width was calculated depending on the outside diameter of the pipe (D_{out}) using Eq. (5).

$$T_w = 1.5D_{out} + 0.3 \quad (5)$$

Step 3: The pipe and the backfill soil were then added in stages using a coefficient of horizontal earth pressure of 1.0 (Brown and Selig 1991). The horizontal earth pressure coefficient was increased to 1.0 for the backfill soil to simulate the compaction effect based on the methodology proposed by Taleb and Moore (1999).

Step 4: The BS traffic loading was then applied incrementally in 25 equal increments.

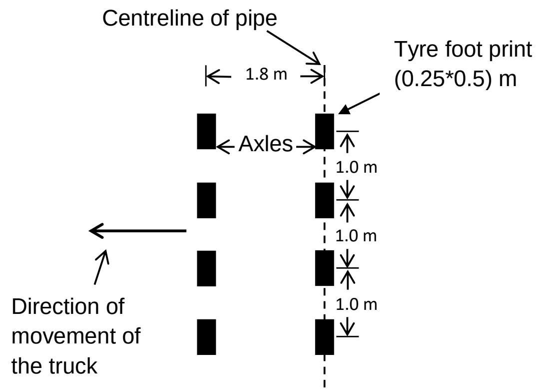


Fig. 1 The British Standard main highway ('main road') loading configuration (BSI, 2010, Alzabeebee *et al.* 2016)

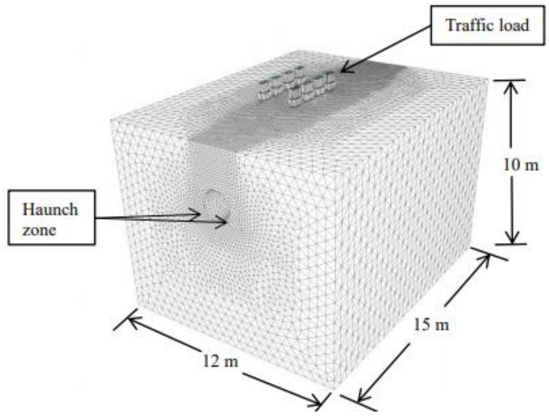


Fig. 2 The finite element mesh used in the analyses

4. Material properties of the soil and pipe and the pipes diameters

In this study, a well graded sand with a degree of compaction of 90% measured according to the standard Proctor test (SW90) was considered for the backfill, haunch zone (for the models with good haunch support) and bedding soils. This soil type was chosen to simulate a pipe buried in a good quality backfill material (Chaallal *et al.* 2015a, Alzabeebee *et al.* 2017b). The assumption of a stiff bedding layer was made to simulate the expected worst-case scenario where the pipeline is being laid directly on to a

Table 2 The material properties for the soils used in the parametric study

Property	SW90*	ML49*	Natural soil**
γ (kN/m^3)	20.99	10.40	21.00
υ	0.30	0.30	0.30
c' (kN/m^2)	0	1	30
ϕ' (°)	42	23	36
K	640	16	1500
Rf	0.75	0.55	0.90
n	0.43	0.95	0.65

*Adopted from Boscardin *et al.* (1990); ** adopted from Alzabeebee *et al.* (2017a, b)

Table 3 Pipes diameters and thicknesses used in this study

Inside diameter (D) (m)*	Wall thickness (t) (m)*	Critical buckling pressure (kPa)**	E_p (kPa)*	υ*	Yield stress (kPa)***
0.3	0.036	1,726	689,000	0.35	17,237
0.6	0.061	916			
0.9	0.070	588			
1.3	0.089	369			

*Adopted from Petersen *et al.* (2010); ** calculated using Eq. (2); *** adopted from AASHTO (2012)

native overconsolidated soil. This has been considered because excavating the bedding soil may increase the cost of the pipeline installation by 15% (Wong *et al.* 2006), hence it is expected that contractors may not excavate the native overconsolidated bedding soil. The poor haunch support has been simulated by using a sandy silt soil with a degree of compaction of 49% measured according to the standard Proctor test (ML49) in the haunch zone (refer to Fig. 2 for the location of the haunch zone). The material properties of the trench soils (SW90 and ML49) are taken from the literature (Boscardin *et al.* 1990), while the *in-situ* soil was assumed to be stronger than the backfill soil (Alzabeebee *et al.* 2017a, b). Table 2 shows the material properties of the bedding soil, backfill soil, haunch soil and natural soil.

The long-term material properties of the uPVC material were considered in this study as these properties represent the worst-case scenario (i.e., lower yield stress and critical buckling pressure). The uPVC material properties (modulus of elasticity (E_p), Position ratio (υ) and tensile yield stress), pipe diameters and pipe thicknesses were adopted from the literature (Petersen *et al.* 2010, AASHTO 2012) and are shown in Table 3. The tensile yield stress of the uPVC material (shown in Table 3) is usually considered as the yield stress for both tension and compression when calculating the factor of safety in the design practice of flexible pipes (Katona 1990, AASHTO 2012), although, the compressive strength of the uPVC material is higher (Ognedal *et al.* 2012, Mohamedzein and Al-Aghbari 2016). This consideration is accepted in the pipeline industry to add additional conservatism to the design of flexible pipes (Katona 1990). Therefore, in this paper the tensile yield stress has also been considered as the yield stress for both tension and compression. The critical buckling pressure for each pipe was calculated using Eq. (2) as recommended by the BS (i.e., assuming the condition of an unsupported pipe) and is also shown in Table 3.

5. Results of good haunch support

The behaviour of the pipe with good haunch support was considered first to understand the impact of the pipe diameter, backfill height and traffic load on the response of the PVC pipe, and hence provide a comprehensive understanding before studying the effect of the poor haunch

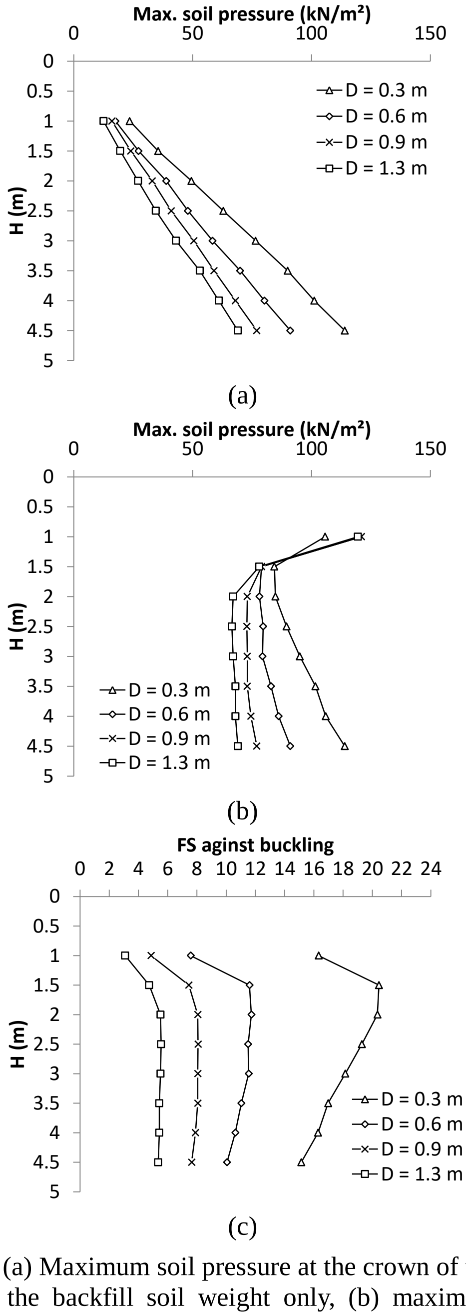


Fig. 3 (a) Maximum soil pressure at the crown of the pipe under the backfill soil weight only, (b) maximum soil pressure at the crown of the pipe under the total load and (c) factor of safety against buckling

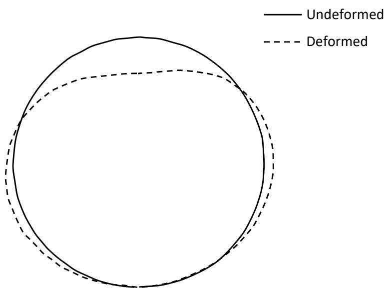


Fig. 4 Deformed shape of the pipe due to the total load (pipe with an inside diameter of 1.3 m and a backfill height of 1.00 m) (Note: the deformed shape is magnified by a factor of 47)

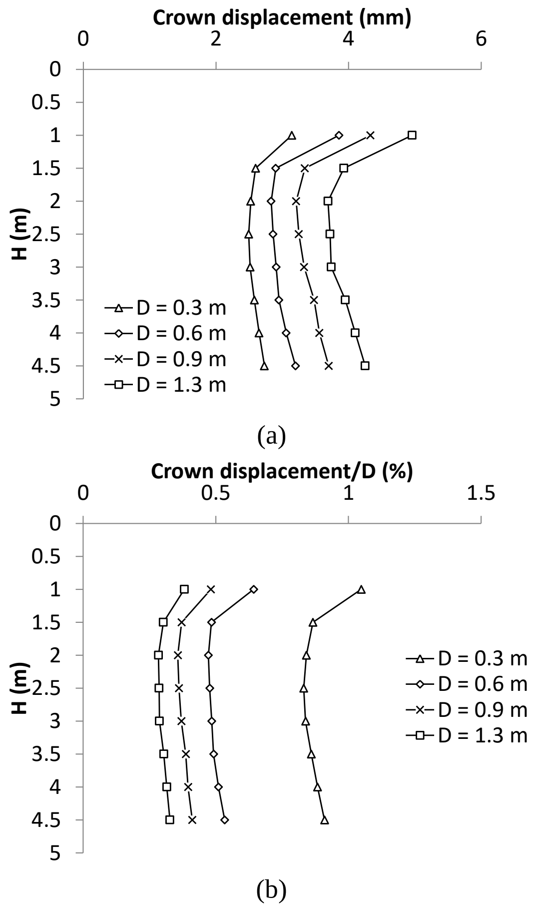


Fig. 5 (a) Crown displacement under the total load and (b) normalized displacement (crown displacement/D) under the total load

support. The backfill height used in this study ranged from 1.00 m to 4.50 m. A minimum backfill height of 1.00 m was considered as it is the minimum accepted backfill height for the buried pipes under the BS main road traffic loading condition (HA 2001), while a maximum backfill height of 4.50 m has been considered because the traffic load effect on the maximum soil pressure ends at this backfill height (Alzabeebee *et al.* 2017a).

The results of this section are divided into three sub-sections covering the maximum soil pressure, the pipe displacement and the pipe wall stress.

5.1 Maximum soil pressure

Fig. 3(a) and 3(b) shows the maximum vertical soil pressure applied at the pipe crown due to the backfill soil weight only (Fig. 3(a)) and combined backfill soil weight and traffic load (hereafter referred to as the total load) (Fig. 3(b)). It can be clearly seen from Fig. 3(a) that increasing the backfill height linearly increases the maximum soil pressure due to the increase of the soil weight above the pipe. It can also be observed that increasing the diameter of the pipe decreases the maximum soil pressure. This is due to the decrease in the pipe stiffness as the diameter of the pipe increases, which in turn reduces the percentage of load attracted by the pipe as a result of soil arching (Moore 2001, Kang *et al.* 2007b, Moradi *et al.* 2015).

Fig. 3(b) shows that the total maximum vertical soil pressure decreases nonlinearly then increases approximately linearly. This is because of the interaction of both the weight of the backfill above the pipe and the traffic load, where the traffic load significantly influences the maximum soil pressure. However, as the backfill height increases the influence of the traffic load significantly decreases, which in turn impacts the maximum soil pressure.

Fig. 3(c) shows the factor of safety against buckling obtained by dividing the critical buckling pressure (shown in Table 3) by the maximum soil pressure at the crown of the pipe obtained from the modelling (Fig. 3(b)). It can be seen that although the critical buckling pressure for the unsupported pipes were used, the factor of safety is very high for all the cases with a minimum value of 3.10. This indicates that the pipes are safe against buckling for the good haunch support conditions as the obtained factor of safety is higher than the BS minimum requirement (i.e., higher than 2.00).

5.2 Pipe displacement

Fig. 4 shows an example of the deformed shape of the pipe due to the application of the total load for the case of a pipe with an inside diameter of 1.3 m, buried with a backfill height of 1.00 m. It can be seen that the pipe is deformed with a heart shape. This heart shape has been formed due to the significant increase in the stress at the crown of the pipe due to the application of the traffic load. However, it can also be seen that the deformed shape is not symmetric. This is due to the non-uniformity of the traffic load applied on the surface, where the critical loading condition was used as mentioned earlier. This gives additional confidence in the validity of the numerical methodology adopted in this paper, where other experimental studies have also reported the same deform shape for the plastic pipes under the traffic load effect (Arockiasamy *et al.* 2006, Mehrjardi *et al.* 2013, Chaallal *et al.* 2015b).

Fig. 5(a) shows the crown vertical displacement for all of the considered cases due to the application of the total load. It can be seen that the pipe vertical displacement follows the same trend observed for the maximum soil pressure, where the vertical displacement decreases nonlinearly as the backfill height increases, and then increases. Again, this is due to the interaction effect of the backfill weight and traffic load and the decrease in the effect of the traffic load as the backfill height increases. It can also be noticed that increasing the diameter of the pipe increases the crown displacement. This is due to the significant decrease in the pipe stiffness as the diameter increases, where the pipe becomes more responsive to the applied load as the stiffness decreases. These results are in agreement with the experimental finding reported by Sargand *et al.* (2001), where they found that increasing the diameter of the flexible pipe increases the crown displacement.

Fig. 5(b) shows the normalized vertical displacement (i.e., ratio of the maximum pipe displacement to the pipe inside diameter) for all of the considered scenarios. It can be seen that the normalized vertical displacement is less than 5.00% for all of the considered cases, where the maximum normalized vertical displacement is 1.05% recorded for the smallest pipe diameter (D=0.3 m) with a backfill height of 1.00 m. This gives a minimum factor of safety of 4.76 (i.e., 5.00%/1.05%) for the pipe displacement limitation based on the minimum BS requirements (5.00%) for safe performance of buried flexible pipes.

5.3 Pipe wall stress

It is important to investigate the pipe wall stress to estimate the factor of safety of the pipe against material failure. Some studies have investigated the failure of the uPVC pipes using the maximum hoop stresses (Zhan and Rajani 1997, Kang *et al.* 2013a, b, 2014). However, Balkaya *et al.* (2012, 2013) mentioned that the principal wall stress represents the critical stress condition for uPVC pipes. Hence, they used the maximum principal stress to study the factor of safety of the pipe under the effect of erosion voids. Therefore, because of this difference of opinion in the literature, both the maximum hoop stresses and principal stresses have been investigated to find the critical stress condition. Fig. 6 shows a comparison of the hoop and principal stress around the pipe for the case of a pipe with an inside diameter of 0.9 m buried with a backfill height of 1.50 m under the effect of the total load. It can be clearly seen from the figure that both the maximum hoop and principal stresses occur at the pipe springline and on the compressive side. However, the maximum principal stress (977 kPa) is higher than the maximum hoop stress (722 kPa) with a percentage difference of 35%. This confirms the finding of Balkaya *et al.* (2012), (2013). Thus, the principal stress has been used to study the pipe wall stress and the factor of safety of the pipes against material failure.

Fig. 7 shows the maximum principal stress (compressive stress) for all of the considered pipes under the soil weight only (Fig. 7(a)) and for the total load (Fig. 7(b)). Fig. 7(a) shows that as expected increasing the backfill height linearly increases the maximum principal stress, which is due to the increase in the soil pressure. However, the figure shows that increasing the diameter of the pipe increases the wall stress. This is due to the increase of the stress applied at the pipe shoulders as the diameter increases and hence resulting in a higher stress at the springline.

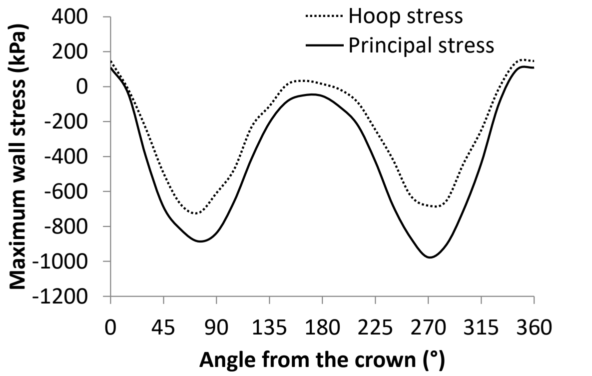


Fig. 6 Comparison of the hoop and principal wall stresses induced due to the application of the total load

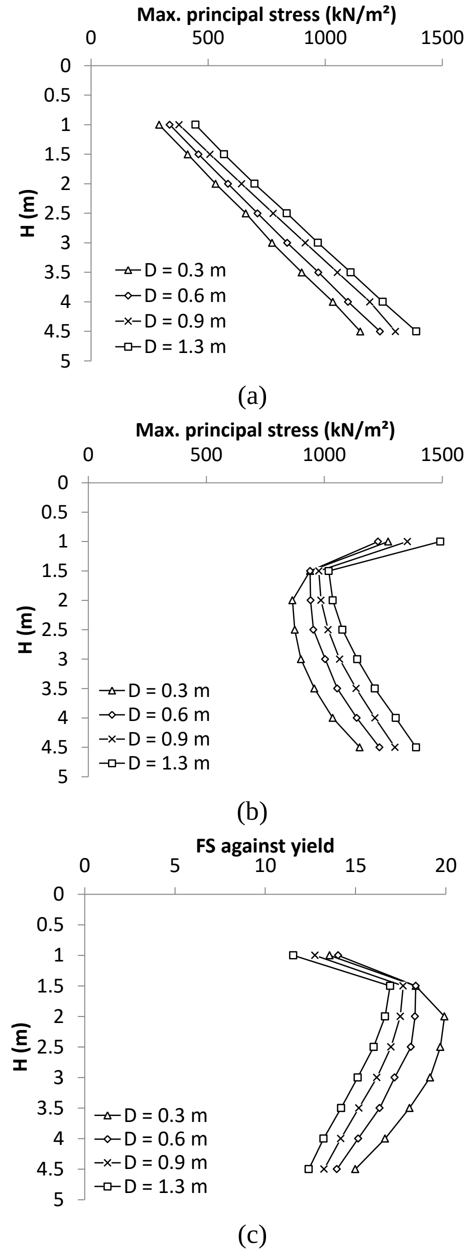


Fig. 7 (a) Maximum principal stress in the pipe wall under the backfill soil only, (b) maximum principal stress in the pipe wall under the total load and (c) factor of safety against material yield

Fig. 7(b) shows that the wall stress nonlinearly decreases for all of the diameters up to a backfill height of 1.50 m. After this the wall stress increases for the pipes with an inside diameter ranging from 0.6 m to 1.3 m, while the stress decreases for the smallest diameter pipe as the backfill height increases from 1.50 m to 2.00 m. This complex behaviour is due to the interaction of the effect of the backfill weight and traffic load as discussed earlier in section 5.1. It can also be seen that increasing the diameter of the pipe increases the maximum wall stress.

Fig. 7(c) shows the factor of safety against the pipe material failure for all of the considered cases. This factor of safety has been calculated by dividing the yield stress of the pipe material (Table 3) by the maximum wall stress (Fig. 7(b)). It can be clearly seen that the pipes are safe against failure with a minimum factor of safety of 11.55.

In summary, the results of the robust three-dimensional finite element modelling have shown that the uPVC pipes are safe based on the BS criteria if a good support has been provided for the pipe during the installation.

6. Results of poor haunch support

The results for the poor haunch support are presented in terms of ratios or percentage differences based on the results for the good haunch support. This has been considered to provide an in-depth understanding of the impact of poor haunch support in comparison with good haunch support. The following subsections present in detail the effect of poor haunch support on the maximum soil pressure, pipe displacement and pipe wall stress.

6.1 Maximum soil pressure

Fig. 8 shows a comparison between the maximum vertical soil pressure for a good haunch and a poor haunch support condition for a pipe with an inside diameter of 1.3 m and a backfill height of 1.00 m. It can be seen that the soil pressure significantly increases at the pipe invert due to the poor haunch support. This increase is due to the concentration of the reaction pressure in the invert zone. This means the soil in the invert zone has to react to most of the pressure developed above the pipe in order to satisfy equilibrium conditions (Alzabeebee *et al.* 2016, 2017c). This is due to the lack of mobilization of the haunch support. The figure also shows that the poor haunch support does not significantly affect the maximum soil pressure at the crown of the pipe, where the percentage difference is 2%. However, the soil pressure in the shoulders, springline and haunch zones significantly decreases due to the poor haunch support.

Fig. 9(a) shows the soil pressure ratio (the ratio of the maximum vertical soil pressure for the poor haunch support condition to the maximum soil pressure for the good haunch support condition) for all of the considered cases. It can be seen that the maximum soil pressure ratio significantly increases for all of the considered scenarios. It can also be seen that increasing the pipe diameter or backfill height increases the soil pressure ratio. This is due to the increase in the soil weight above the invert as the backfill height or

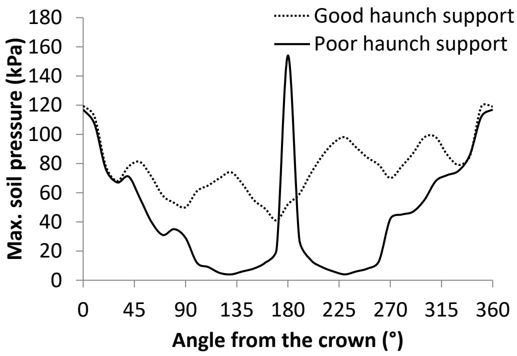
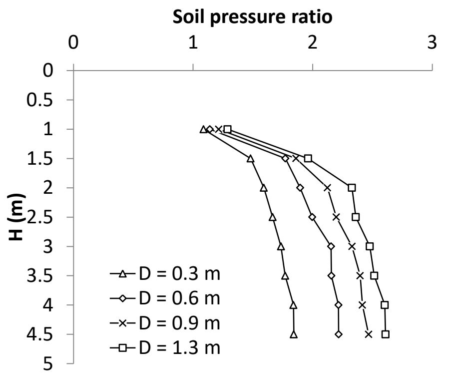
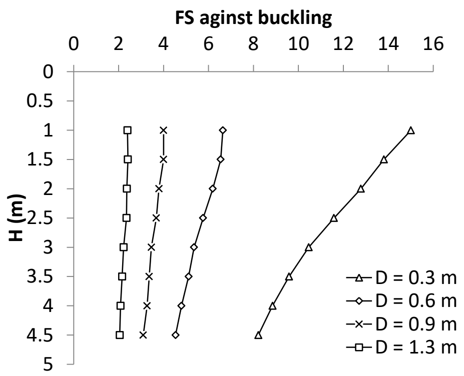


Fig. 8 Effect of poor haunch support on the developed vertical maximum soil pressure around a pipe with an inside diameter of 1.3 m and a backfill height of 1.00 m



(a)



(b)

Fig. 9 (a) Soil pressure ratio and (b) factor of safety against buckling

diameter increases. Hence, the reaction pressure at the invert will be increased due to the lack of support in the haunch zone. However, this increase is not linear, where the ratio approximately stabilizes after a backfill height of 3.00 m for all of the considered diameters. This behaviour is due to the significant decrease of the traffic load effect as the backfill increases.

Fig. 9(b) shows the factor of safety against buckling for the poor haunch supported condition calculated using the maximum soil pressure. It can be seen that the factor of safety for the pipes with an inside diameter of 1.3 m significantly decreases compared to the full haunch support, where the minimum factor of safety becomes 2.05 compared to a minimum value of 3.10 (Fig. 3(c)) for the good haunch support (a percentage decrease of 34%). However, comparing the factor of safety for all of the cases with the BS factor of safety requirement (i.e., 2.00) shows that the pipes are safe against buckling even with the increase in soil pressure due to lack of good support.

6.2 Pipe displacement

The effect of poor haunch support on the deformed shape and the maximum pipe vertical displacement has been investigated. Fig. 10 shows a comparison of the deformed shape of a buried pipe under the effect of the total load with both good and poor haunch support conditions. It can be seen that poor haunch support changes the deform shape of the pipe from a heart shape into an invert heart shape. This is due to the lack of good support at the haunch zone, which makes the pipe deflect more easily in this zone as a reaction to the applied load. This observation is consistent with that reported by Dhar *et al.* (2004) and the hypothesis proposed by Rogers (1988) for the behaviour of buried flexible pipes under applied loads. Furthermore, it can be seen that the crown vertical displacement is also increased due to the poor haunch support.

Fig. 11(a) shows the percentage increase in the crown vertical displacement calculated based on the good haunch support results for all of the considered cases. The figure shows that increasing the pipe diameter significantly increases the pipe vertical displacement indicating that increasing the pipe diameter increases the dependency of the developed vertical displacement on the haunch support. The percentage increase ranged from 6% to 62% depending on the pipe diameter and backfill height. The figure also shows that the percentage increase decreases nonlinearly as the backfill height increases followed by a nonlinear increase. This is due to the interaction of the soil weight and the traffic load and the dependency of the pipe vertical displacement on the haunch support and the applied load. Fig. 11(b) shows the normalized pipe vertical displacement with respect to the pipe inside diameter. It can be seen from the figure that, although there was a significant increase in the pipe vertical displacement due to the poor haunch support, the maximum displacement is lower than the 5.00% limitation with a minimum factor of safety of 4.24 (i.e., 5.00%/1.18%).

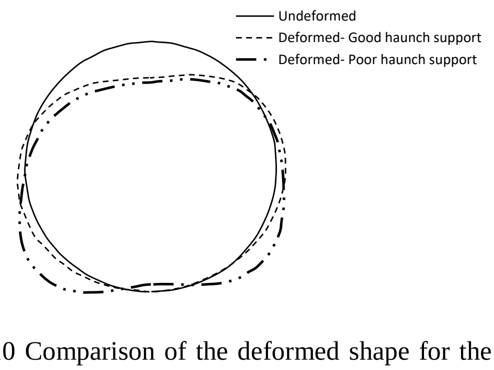


Fig. 10 Comparison of the deformed shape for the good and poor haunch support conditions for a pipe with an inside diameter of 1.3 m and a backfill height of 1.00 m (Note: the deformed shape is magnified by a factor of 47)

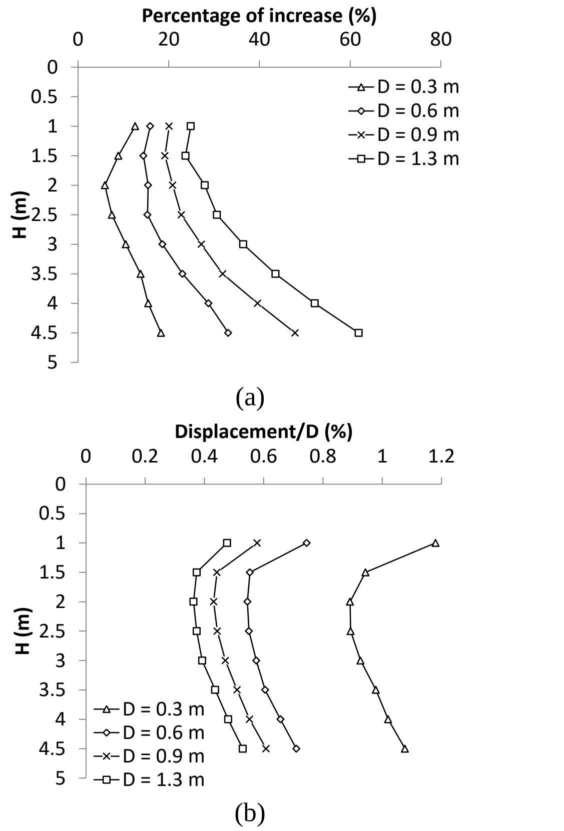


Fig. 11 (a) Percentage increase in the pipe displacement due to a poor haunch support and (b) normalized displacement (crown displacement/D) under the total load

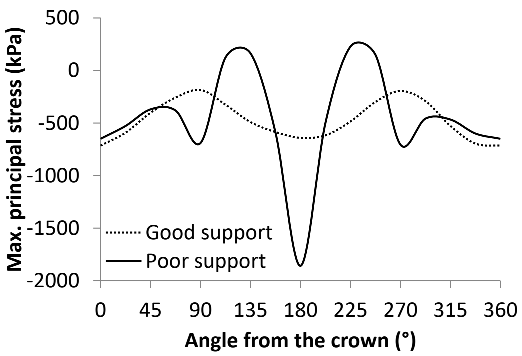


Fig. 12 Comparison of the principal wall stress for a good and poor haunch supported pipe under total load (pipe internal diameter of 0.6 m and backfill height of 2.00 m)

6.3 Pipe wall stress

Fig. 12 shows the effect of the poor haunch support on the developed principal stress in comparison with the good haunch support, for a pipe with an inside diameter of 0.6 m buried with a backfill height of 2.00 m under the effect of the total load. It can be seen that the zone of the maximum principal stress changes from the pipe crown to the pipe invert due to the poor haunch support. This is due to the significant increase in soil pressure at the pipe invert due to the poor haunch support as discussed in section 6.1.

To investigate the percentage increase in the maximum

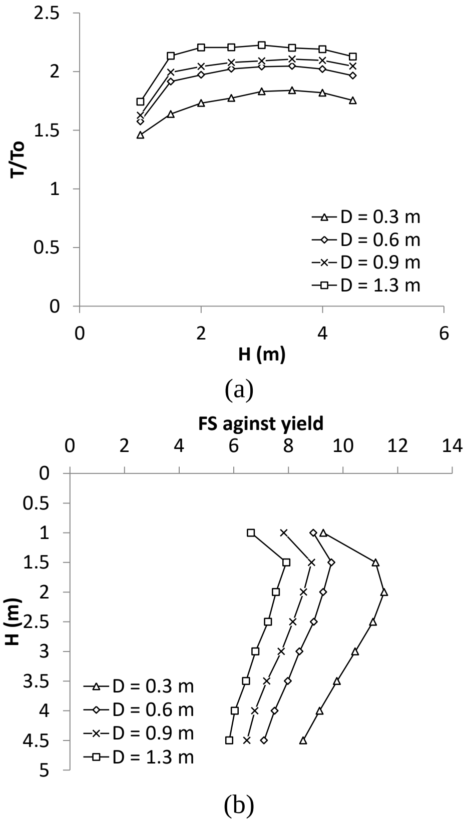


Fig. 13 (a) The ratio of maximum wall stress for the poor haunch support (T) to the maximum wall stress for the good haunch support (To) and (b) factor of safety against pipe material failure

pipe wall stress for all of the considered cases, the ratio of the maximum wall stress for the poor haunch support condition (T) to the maximum wall stress for the good haunch support condition (To) has been calculated and presented in Fig. 13(a). From this figure it can be seen that the maximum pipe wall stress significantly increases due to the poor haunch support, where the ratio ranges from 1.46 to 2.23. It can also be seen that the ratio increases as the diameter of the pipe increases due to the increase of the soil weight above the pipe invert as the diameter increases. Hence, the reaction pressure at the pipe invert significantly increases. Moreover, increasing the backfill height to 3.00 m increases the maximum wall stress ratio. Again, this is also due to the increase in the stress at the pipe invert as the backfill height increases. However, the increase in the invert stress is affected by the traffic load reduction as the backfill height increases. Hence, the ratio decreased slightly after a backfill height of 3.00 m.

Fig. 13(b) shows the factor of safety against pipe material failure obtained using the maximum pipe wall stress. It can be seen from this figure that although the pipe wall stress has significantly increased for all of the considered cases, the pipes are still far away from the failure condition, with a factor of safety ranging from 5.83 to 11.51. This means that the uPVC pipes are safe against material failure even with the poor haunch support condition.

In summary, the results for both poor and good haunch support conditions demonstrated that the design of buried uPVC pipes is governed by the critical buckling (Figs. 3(c) and 9(b)) as the pipe wall stress is far away from failure (Figs. 7(c) and 13(b)) and the pipe vertical displacement is also far away from the 5.00% limit (Figs. 5(b) and 11(b)). In addition, the results of the poor haunch support showed significant changes in the behaviour of the pipes due to poor haunch support. However, the comparisons with the BS limitations indicated that the uPVC pipes were performing very well even if poor haunch support is provided during installation. This indicates that the pipe wall thicknesses considered in this study (i.e., the wall thicknesses adopted from Petersen *et al.* 2010) provide a very conservative and uneconomic design. Hence, it is important to find the minimum pipe wall thickness which can be used safely for buried uPVC pipes under the most stringent conditions (i.e., under traffic loading and with poor haunch support) to achieve a robust and economic design. In addition, an update to the design methodology of the BS is required to account for the poor haunch support for other grades of uPVC pipe, as the current BS design methodology assumes a good haunch support (BSI 1997, BSI 2010). The next section therefore discusses the derivation of safe and economic wall thicknesses and an update of the BS methodology to account for the effect of poor haunch support.

7. Practical implications

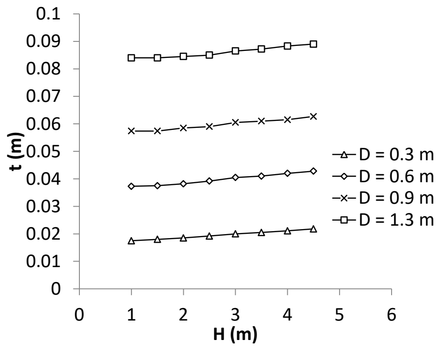
7.1 Minimum safe wall thickness

The minimum pipe wall thickness for all of the cases considered in this study was calculated using the following methodology:

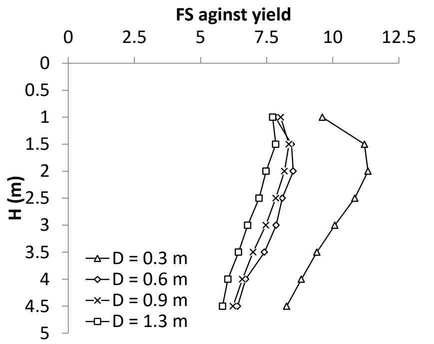
1- The results of the poor haunch support analyses showed that the buckling pressure governs the design of the buried uPVC pipes under the effect of traffic loading. Hence, the first step was to make sure that the proposed pipe wall thickness satisfies the limit for the critical buckling pressure. This has been done by calculating the critical buckling pressure for each case by multiplying the maximum soil pressure obtained from the poor haunch support analysis by two (the minimum factor of safety against buckling recommended in the BS (BSI 1997)). The calculated ultimate buckling pressure was then used in Eq. (2) to find the required minimum pipe wall thickness for each case by following a trial and error process.

2- The buried pipes with the new wall thicknesses (calculated in step 1) were then evaluated using the finite element model developed in this study to make sure that the pipe maximum displacement and pipe wall stress for the new minimum wall thicknesses did not exceed the limits specified in the BS (i.e., the maximum displacement is less than 5.00% and the pipe wall stress is less than the yield stress of the pipe material). The poor haunch support condition was considered in all of the finite element analyses to make sure that the new wall thicknesses accounted for the worst-case scenario expected in practice as discussed earlier.

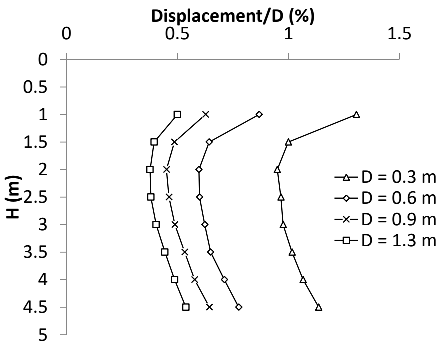
Fig. 14(a) shows the minimum wall thickness calculated



(a)



(b)



(c)

Fig. 14 (a) Minimum pipe wall thickness required for a safe performance of buried uPVC pipe with poor haunch support, (b) factor of safety against pipe material failure for pipes with the minimum wall thicknesses and (c) normalized vertical displacement (crown displacement/D) for pipes with minimum wall thicknesses

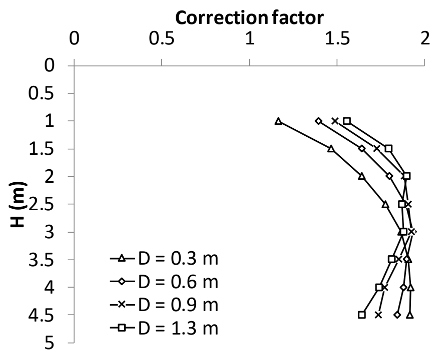


Fig. 15 Correction factor for the maximum soil pressure on the pipe under the total load for different backfill heights

in step 1 for all of the considered cases. Fig. 14 also shows the factor of safety against pipe material failure (Fig. 14(b)) and the normalised vertical displacement (Fig. 14(c)) obtained from the finite element analysis for the pipes with the proposed new wall thicknesses. It can be seen from these figures that, as expected, the pipes wall thickness calculated based on the critical buckling limit satisfy the BS limitations for both the yield stress and the maximum displacement ratio. Hence, the wall thicknesses shown in Fig. 14(a) can be used for an economic, safe and robust design of buried uPVC pipes under traffic load with poor haunch support, where only the pipe inside diameter and backfill height are required. Moreover, these wall thicknesses can also be used to produce more economic and sustainable buried pipes.

It should be noted these wall thicknesses were derived considering a good quality backfill material and a poor haunch support condition. Therefore, the use of this information is limited to these conditions. However, the methodology used in this research can be applied to other flexible pipes manufactured from different materials and installation conditions.

7.2 Update to the design methodology of the BS

The previous section discussed the derivation of safe minimum wall thicknesses for the uPVC pipes considered in this study. However, an intensive literature review conducted by the authors showed that the long-term modulus of elasticity of the uPVC material is significantly affected by the grade and ranges from 689,000 kPa to 1,089,372 kPa (Petersen *et al.* 2010, AASHTO, 2012, Kraus *et al.* 2014). In addition, the calculated pipe wall thickness is significantly affected by the pipe modulus of elasticity as the pipe design is governed by the critical buckling, which directly depends on the pipe modulus of elasticity as can be clearly seen in Eq. (2). This means that the use of the proposed wall thicknesses (Fig. 14(a)) is limited to pipes with a modulus of elasticity of 689,000 kPa. Hence, a more general solution that can be used for different grades of uPVC pipe is proposed in this section. The approach magnifies the calculated soil pressure using a correction factor to account for the significant effect of poor haunch support. This correction factor is obtained, for all of the cases considered in this study, by dividing the maximum soil pressure at the pipe invert for the poor haunch support condition (obtained from the finite element analysis) by the maximum soil pressure calculated based on the British Standard (Eq. (6)) (BSI 2010).

The correction factors are shown in Fig. 15 and these enable designers to incorporate the effect of poor haunch support in the design of uPVC pipes. Fig. 15 can cope with pipes of different moduli of elasticity, as it was found from the finite element analysis that the modulus of elasticity of the uPVC pipe does not significantly affect the calculated correction factor (the percentage different in the correction factor was less than 1% as the modulus of elasticity changed from 689,00 kPa to 1,089,372 kPa). The designer can use Fig. 15 to find the required correction factor depending on the inside diameter of the pipe and the backfill height, and then multiply this factor by the maximum soil pressure at the pipe crown obtained from the British Standard equation. (Eq. (6)), which assumes a good haunch support. The designer can then use Eq. (2) to find the minimum pipe wall thickness (i.e., design the pipe) to satisfy the critical buckling requirements as the authors demonstrated in step 1 in section 7.1. The calculated thickness already satisfies the displacement and wall stress requirements as has been demonstrated earlier in this paper. It is important to note that Fig. 15 can only be used for H and D values within the range presented in this graph. In addition, the conclusion of the critical buckling governing the design has been established based on the assumption of a compacted backfill soil with both good and poor haunch support. Hence, the use of Fig. 14a and Fig. 15 is only applicable to pipes with similar diameters, backfill heights and installation conditions. Any attempt to extrapolate the values of H and D or use the figs. for different installation conditions may lead to inaccurate design.

$$BS\ Max. soil\ pressure = \gamma H + \frac{54.5}{H} + \frac{42}{1.8^H} \qquad (6)$$

8. Conclusions

This paper has presented for the first time a robust comprehensive analysis studying the effect of pipe diameter, backfill height and poor haunch support on the behaviour of buried flexible pipes subjected to traffic loading. The results presented in this paper have provided details previously missing in the literature and provided an insight into the behaviour of flexible pipes with both good and poor haunch support. The key findings from this study are as follows:

1- Increasing the diameter of the pipe for both good and poor haunch support increases the pipe vertical displacement and pipe wall stress, although the maximum soil pressure generally decreased with an increase in the pipe diameter. This is due to a decrease in the pipe stiffness and an increase in the soil weight above the pipe shoulders as the diameter increases.

2- The maximum principal stress is higher than the hoop stress for both good and poor haunch support. Hence, future studies should consider the maximum principal stress to investigate the factor of safety against failure of the pipe material.

3- The poor haunch support significantly increases the pipe vertical displacement with the effect increasing as the diameter of the pipe increases. The percentage increase ranged from 6% to 62%, depending on the pipe diameter and backfill height.

4- Increasing the pipe diameter increases the dependency of the pipe crown displacement on the haunch support.

5- Poor haunch support changes the zone of the maximum pipe wall stress from the springline to the pipe invert, and significantly increases the maximum pipe wall stress with a percentage increase ranging from 46% to 123%, depending on the pipe diameter and backfill height. The percentage increase increases as the diameter or the backfill height increases.

6- The critical buckling governs the design of buried uPVC pipes under the effect of traffic loading for both good and poor haunch support.

7- A new design chart (Fig. 14(a)) has been proposed in this study to calculate the required minimum pipe wall thickness for a robust and economic design of buried uPVC pipes under the stringent BS traffic loading condition. The design chart accounts for the effect of poor haunch support and can be used easily by only knowing the pipe inside diameter and backfill height. In addition, this chart can be used by uPVC pipe manufacturers to produce more economic and sustainable buried pipes.

8- A new correction factor chart (Fig. 15) has been proposed in this study to incorporate the effect of poor haunch support in the design methodology of the British Standard. This chart can be used to correct the BS maximum soil pressure equation for uPVC pipes, and this is insensitive to the long-term modulus of elasticity for the pipe and so can be used for different grades of uPVC pipe. The design chart is easy to use as it only requires the pipe diameter and the backfill height.

9- Importantly, the methodology adopted in this study is not limited to uPVC pipes, and can be applied to the design of flexible pipes manufactured from other materials, buried under different conditions and with different loading arrangements.

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