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Investigation of the structural performance of two flexible pipes set in one trench with a new placement method for separate sewer systems

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ABSTRACT

Substantial research has been conducted on single flexible pipes buried in a trench. In contrast, the objective of this study is to determine the structural performance of two buried flexible sewer pipes positioned one over the other in a single trench. An innovative configuration is designed, based around the use of an innovative manhole structure which can accommodate both foul and surface water, to solve the challenges associated with constructing separate sewer systems in narrow streets while providing additional space for other infrastructure services. The behaviours of the two flexible pipes were tested using a 3D finite element (FE) model validated with experimental data from a laboratory investigation. A modified Drucker–Prager cap soil constitutive model was used to simulate the elasto-plastic soil behaviour. The results show that this approach comprising the use of a large-diameter flexible pipe set above a small-diameter flexible pipe mitigates the strain on the smaller pipe and decreases the total deflections of both pipes and the soil.

1. Introduction

Pipe materials are typically categorised as either rigid pipes (e.g., concrete/cast iron) or flexible pipes, examples of which include high-density polyethylene (HDPE), polyvinyl chloride (PVC), and steel or glass fibre-reinforced plastics (GRP). Flexible pipes, which are defined as those capable of being deflected at least 2% without showing structural distress, have recently become more common during the installation of sewer systems to avoid the corrosion that affects rigid pipes (Bizier, 2007; Moser and Folkman, 2008). Flexible pipes behave differently than rigid pipes because buried flexible pipes are integrated into the soil as a single system. The pressure over the pipe is influenced by the vertical settlement ratio between the pipe and the adjacent soil column at a horizontal surface above the pipe. The stiffness of the soil provides support for the sides of a buried flexible pipe against horizontal deformation due to the positive arching action of flexible pipes allowing some of the vertical load to be transferred into the surrounding soil, thereby enhancing the resistance of the system to applied loads (Sargand and Masada, 2003). In contrast, rigid pipes resist an applied load only by the inherent strength of the pipe (Moser and Folkman, 2008). An important merit of the system composed of soil and buried flexible pipes is that its elasto-plastic behaviour responds differently to loads than the behaviours of linear elastic materials; this is worth noting because buried pipes must support external loads such as the soil overburden and traffic loads applied at the surface.

The structural performance of a single flexible or rigid pipe buried in soil has been investigated by many researchers (Mahmoodian and Aryai, 2017; Masada and Sargand, 2011; Stanić et al., 2016). Furthermore, many studies have used the finite element (FE) model to characterise a variety of factors that influence the behaviours of buried pipes (Chaallal et al., 2015; J. Kang et al., 2013; J. S. Kang et al., 2013; McGrath et al., 2009; Shou and Chen, 2017; Xu et al., 2017; Zhou et al., 2017).

The FE model was used by Law and Moore (2007) to explore the structural performance of a damaged rigid pipe lined with an HDPE. They used the laboratory physical model to validate the FE model, which produced results that only varied by 10%. Moreover, Hajali et al. (2016) studied the impact of variation of soil properties on the output of the FE model used to simulate soil-pipe interaction. Shou et al. (2010) and Yen and Shou (2015) utilised the FE model to explore the soil-pipe interface friction for estimating the required jacking force in sewer installation using a jacking method.

J. Kang et al., 2013; J. S. Kang et al., 2013b studied the maximum and minimum cover depths for laying plastic pipes under roadways using a 2D FE model (ABAQUS) to investigate the geometric nonlinearity of the soil-pipe system. They incorporated the nonlinear Duncan and Selig soil models to simulate the soil behaviour and identified

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the associated parameters. The pipes were composed of PVC and HDPE with diameters of 0.3, 0.6, 1.2 and 1.5 m, and the dimensions of the FE model were approximately three times the pipe diameter. Laboratory test data presented by McGrath et al. (2009) were used to calibrate and validate the above-mentioned FE model, and satisfactory agreement was reported between the FE results and the measured deflections for both the HDPE tests and the PVC tests. Their findings recommended maximum cover depths for corrugated HDPE and PVC pipes of 13 and 14 m, respectively, for pipe diameters less than 1.2 m and maximum cover depths of 6 and 8 m for pipe diameters greater than 1.2 m. The recommended minimum cover depth was 0.9 m; this value is used in this research.

Sargand et al. (2005) monitored the performance of flexible pipes (specifically, HDPE pipes) subjected to a backfill soil depth of 6 and 12 m for two years. The field results indicated that the flexible pipes performed satisfactorily. The FE model used to simulate this case incorporated a series of triaxial compression tests conducted in the laboratory to identify the soil properties. The study conclusion was that the FE results tended to overestimate the soil pressure acting against the pipe and to underestimate the pipe deflections.

McGrath et al. (2009) used a 2D FE model to develop design procedures for buried plastic pipes (HDPE and PVC). A laboratory test was conducted using the biaxial cell designed by Brachman et al. (2001), and the experimental results were compared with the FE model to evaluate the model's effectiveness at estimating the pipe behaviours during deep burial. It was found that the developed FE model could be used effectively and that the performance of the FE method is essential in selecting the appropriate constitutive model to characterise soil behaviours.

However, little research has been conducted on flexible buried pipes when they share one trench—the so-called one-over-one configuration. This configuration of accommodating the two flexible pipes of the sewer system in one trench vertically is not common in engineering practice here in the UK or in the EU. Nevertheless, widely it can find intersecting between a sanitary pipeline route and a storm pipeline route at different levels in traditional configurations consisting of separate sewer systems, specifically beneath street crossings.

Conventional separate sewer systems incorporate two parallel pipes set in two different trenches or in one large trench. The storm pipe is typically larger than the sanitary pipe and is set at a shallower depth. A minimum horizontal space is maintained between the two pipes in conventional systems. This minimum space is required to provide sufficient working space and maintain safe conditions for the workers installing the pipes using an open-cut method (ASTM, 2013; BS_EN 752:2008, 2013).

Streets are generally occupied by complex subterranean utilities such as potable water pipelines, gas lines, electrical cables and communication cables; therefore, finding a place to configure a conventional separate sewer system can be challenging (Broere, 2016; Hunt et al., 2014; Tait et al., 2008).

For example, the EPA implemented a project to provide an overview of many recent sewer systems; one of the resulting proposals was to employ a vacuum system for a sewage network ((United States Environmental Protection Agency, 2007)). In addition, the American Society of Civil Engineers (ASCE) implemented a project using small pressurised tubes to separate the sewage system from the storm network (Jones, 2006). Unfortunately, both solutions were relatively expensive and involved complex technical equipment.

The present research investigates a new method for installing a sep-arate sewer system by placing both pipes in one trench. The sani tary pipe, which is normally smaller, is located at the bottom, and the storm pipe, which is normally larger and set at shallower depths, is located on top. The proposed method is possible because of a patented manhole design (Abbas et al., 2018a) that addresses the challenges associated with constructing a separate sewer system in narrow streets while providing additional space for other infrastructure services (Broere, 2016). The structural performance of the new design has been investigated by Abbas et al., 2018b, 2018ab.

This paper investigates the structural performance of a new method for installing a separate sewer systems under narrow streets using one trench to accommodate two separate pipes in a one-over-one configuration. The structural integrity of the new method is tested through experimentation and FE modelling, and the results of laying two flexible pipes in a one-over-one configuration are compared with those in a traditional configuratio [illegible] rench.

2. Methodology

This new method of configuring a separate sewer system requires a test of the structural integrity of the system before it can be implemented in the field. This test, which is performed by the researchers in conjunction with the United Utilities water company, is designed to validate the proposed system in two respects: the road surface deflection and the structural performance of the pipes when buried in one trench, one over the other. However, data on the structural performance of flexible pipes configured one over the other within a single trench are scarce.

Therefore, to achieve this target, two steps are proposed. The first step includes establishing a physical model in the lab to test the performance of buried pipes under an applied load (specifically, a traffic load). The second step uses 3D FE models to simulate the buried pipes in the physical laboratory model for validation and to calibrate the material properties and boundary conditions. Two configurations of flexible pipes are tested. The first involves only the small pipe lying in the trench with exposure to live loads (corresponding to the conventional configuration of a sewer system). The second position involves two flexible pipes that are set in the trench, one over the other, under the same live loads and conditions as the first position.

The FE model upgrades into a full-scale model to explore the performances of sewer systems in new configurations by simulating the behaviours of two pipes buried in one trench in comparison with the traditional method (i.e., the behaviour of one pipe laid in the trench). Two ranges of pipe diameters are tested. The first set uses diameters of 200 mm for the sanitary pipe and 300 mm for the storm pipe, and the second set uses diameters of 500 mm for the sanitary pipe and 1000 mm for the storm pipe. The test was conducted with three different configurations. The first position involved only the sanitary pipe in the trench, the second position involved only the storm pipe in the trench, and the third position laid both pipes in one trench with the storm pipe lying over the sanitary pipe.

2.1. Physical modelling

As mentioned above, field data are lacking for the one-over-one configuration of pipes installed in one trench. It was therefore essential to build a physical model in the laboratory to carry out experimental tests and identify the mechanical properties and boundary conditions for the proposed system under applied loads.

A physical model was built in the laboratory to test the performances of two PVC pipes with diameters of 160 mm and 80 mm. A wood trench configured in a hydraulic steel rig was used to situate the two PVC pipes with the large pipe on top and the small pipe on the bottom. The physical model with dimensions of $2.5 \times 0.5 \times 1\,m^3$ was embedded in a hydraulic rig used to provide lateral support for the trench walls and to apply the live load. The maximum load was 10 tons. A normal composite soil (corresponding to the soil used within the UK to embed sewer systems) was used to bury the pipe system. The filling soil was added in 5–10 cm thick layers to achieve the required degree of compaction. The bedding layer was used to nestle two 160 mm diameter PVC pipe as the storm pipe, and an 80 mm pipe was used as the sanitary pipe (DEFRA, 2011).

An innovative method was used to measure the deflection in both buried pipes and the settlement in the soil underneath each pipe under the applied live load. GFRA-3-70 strain gauges, which are appropriate for measuring the strain of a plastic material, were fixed on the pipe surfaces to monitor the strains resulting from the filling soil and the compaction process. Steel beams were screwed to the top and bottom of each pipe to measure both the top pipe deflection and the bottom pipe deflection which represents the soil settlement underneath. These beams were housed in plastic tubes to allow them to move freely without any friction with the surrounding soil when buried in the soil and reflect the deflection of both the top and the bottom of the pipe. Linear vertical displacement transducers (LVDTs, Micro-Measurements HS 50) were positioned at the tops of the beams to measure the beam deflection representing the deformation of the top and bottom of the pipe.

Two sets of LVDTs were used for each pipe on two sides approximately 30 cm from the centre where the live load was applied to maintain the accuracy of measuring. The strain gauges and LVDTs were connected to a P3 strain indicator and recorder to continuously record the strain gauge motion from the filling and compaction process and the pipe deflections from the LVDTs when the live load was applied. A steel plate with dimensions of $0.5 \times 0.25\,m^2$ was used to simulate a truck tyre footprint (Kang et al., 2013) using a compression load cell located between the hydraulic load arm and the tyre footprint to synchronise the applied load with the measured displacement. Figs. 1a–1c shows the configuration of the physical model for two PVC pipes buried in soil accommodated by the trench.

2.2. FE model

The FE method has been found to provide more reliable results during the performance testing of buried pipes than traditional empirical

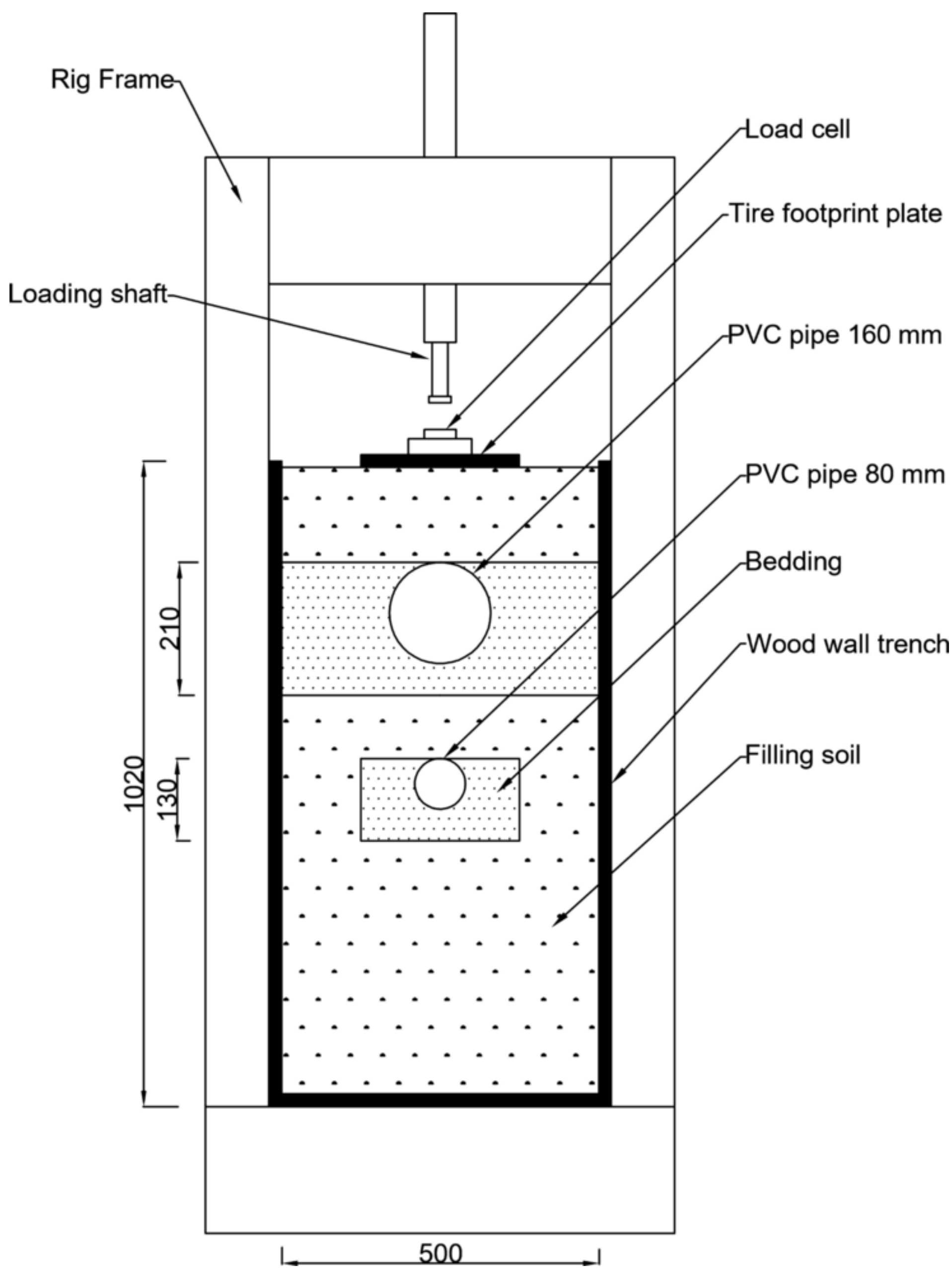

Fig. 1a. Setup of the trench in the hydraulic rig to test the performances of the buried structural pipes.

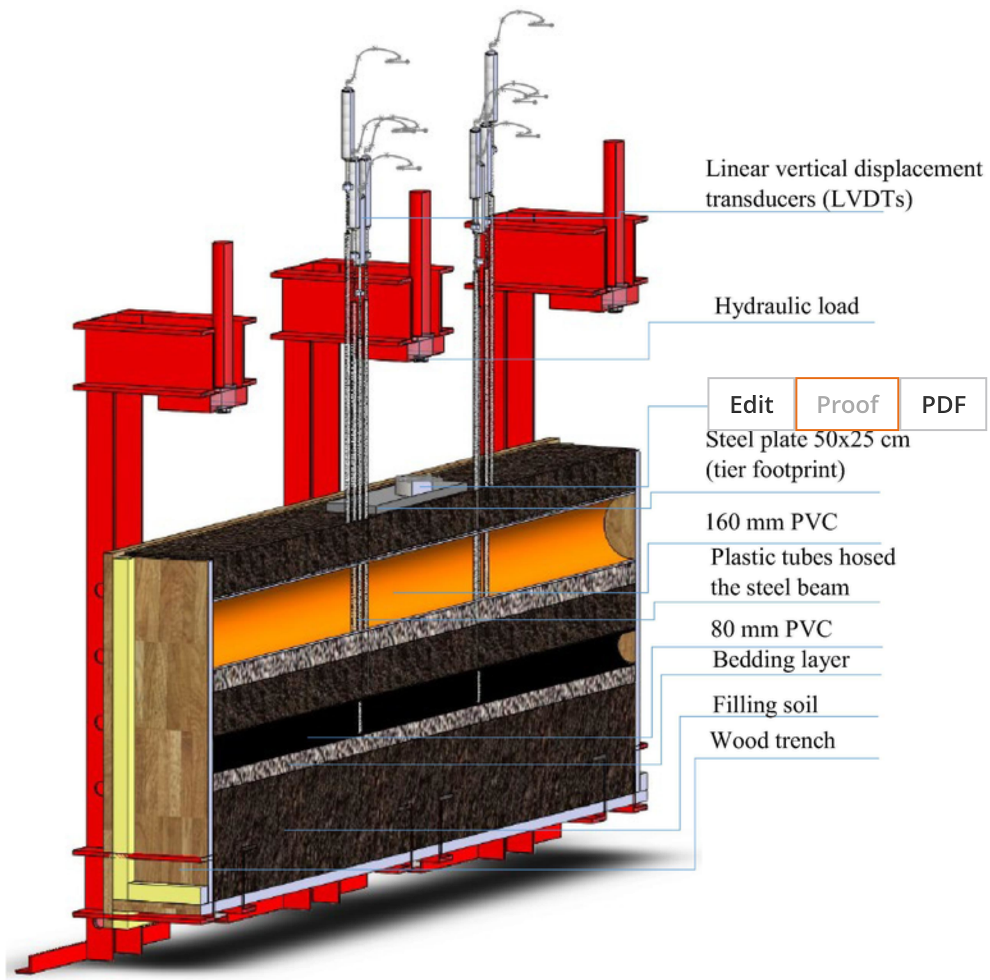

Fig. 1b. Configuration of the physical model in the laboratory equipped with measurement and recording devices.

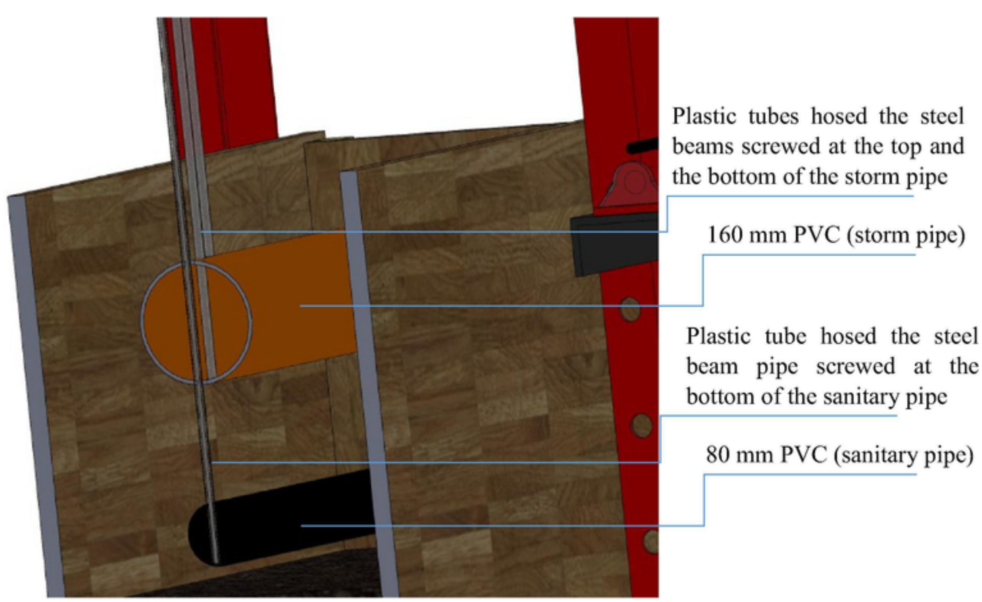

Fig. 1c. Setup of the beams, which were screwed at the top and the bottom of each pipe, inside plastic tubes.

approaches (Jung et al., 2014; Zhou et al., 2017). The FE method is convenient tools for studying the behaviours of buried flexible pipes and avoiding the substantial costs of field tests while inspecting many scenarios and testing a variety of factors that influence the behaviours of buried pipes (Tian et al., 2015; Tsai et al., 2014). However, the accuracy of the FE results depends on the selection of an appropriate constitutive model to simulate both the soil-pipe interactions and the calibrated material properties of the model (ABAQUS, 2012). Therefore, experiments are essential for validating the chosen model and material properties and for establishing correct input data to ensure an accurate simulation (Moser and Folkman, 2008).

FE models were established to simulate the laboratory physical model, including the plate of the tyre footprint, the load cell, the pipes, the bedding layers and the filling soil. The models have the same dimensions and boundary conditions as the physical model. The same series of loads applied in the physical model were used in the FE model.

2.2.1. Soil-pipe system interaction

The structural performance of a flexible pipeline is a function of both the soil strength and the pipe stiffness. Spangler (1941) discussed a phenomenon in which a flexible pipe receives support from the side soil against horizontal deflection and in which the stiffnesses of both the soil and the pipe control the overall performance. However, determining the stiffness of the filling soil-pipe system is a complex task for a pipeline designer, particularly because soil, which is a complex material that exhibits a wide range of elasto-plastic behaviours due to its varying texture, is difficult to model and predict (Orr, 2010). An elasto-plastic material is additively composed of both elastic and plastic strain increments. Accordingly, designers often encounter challenges when selecting the most appropriate constitutive soil model for a numerical model to establish the modelling parameters. The main factors that influence the model selection are the analysis type, the material and the range of pressures/stresses in addition to an in-depth understanding of the concepts of constitutive methods.

In this research, conventional classification laboratory tests were carried out on soil samples extracted from the physical model to identify the mechanical properties; subsequently, the soil was classified as a poorly graded sand with silt (SP-SM) in accordance with ASTM standards.

The modified Drucker–Prager cap constitutive model was selected to simulate the elasto-plastic behaviour of the soil, because this model has been widely used in FE analyses for a variety of geotechnical engineering applications. This model is appropriate for frictional materials, such as granular cohesive soils, that exhibit a pressure-dependent yield strength (i.e., the material becomes stronger as the pressure increases) in which the compressive yield strength is greater than the tensile yield strength (ABAQUS, 2012).

Three triaxial compression tests were conducted on undisturbed soil specimens obtained from the physical model after completing the compaction process. The results of these three triaxial tests under different confining pressures were used to calculate the modified Drucker–Prager cap constitutive model parameters (Lees, 2012). The FE software (ABAQUS package) then used these data to determine the material properties using a least-squares fitting method to minimise the relative error in the stress. The calibration of the yield parameters for the model was conducted by determining the point on each stress-strain curve corresponding to the initial deviation from the ultimate yield surface (i.e., the point on each stress-strain curve corresponding to the peak stress). The triaxial test results were also used to identify the soil angle of friction β and cohesion d for the Drucker–Prager model, which were extracted from the effective stress p plotted against the shear stress q. An isotropic consolidation test was used to identify the plastic strain of the soil through applied loading-unloading cycles and to calculate the volumetric elastic strain, which can be subtracted from the total volumetric strain (Helwany, 2007). Three isotropic consolidation tests were conducted on soil specimens extracted from the trench to establish the cap-hardening curve.

The compression index Cc and swelling index Cs obtained from the isotropic consolidation test were used to calculate the λ and κ slopes of the normal consolidation and loading-unloading lines in the e–ln(p) plane using Eqs. (1) and (2), respectively.

$$\lambda = \frac{Cc}{\ln 10} \quad (1)$$

$$\kappa = \frac{Cs}{\ln 10} \quad (2)$$

These two parameters were used to establish the cap hardening curve that describes the evolution of soil plastic volumetric strain has been presented in the Data in Brief. Accordingly, the plastic volumetric strain (ε_v^p) was calculated using Eq. (3).

$$\varepsilon_v^p = \frac{\lambda - \kappa}{1 + e0} \ln \frac{p'}{p} \quad (3)$$

where p = effective [illegible]ress, e_0 = void ratio, and λ and κ are the [illegible]lation and loading-unloading lines, respectively.

The elastic behaviour of soil is nonlinear and stress dependent (i.e., soil becomes stronger as the pressure increases), and FE analysis is an adequate method for simulating soil behaviours under loading because it presents elastic moduli in incremental form (Hügel et al., 2008). Eq. (4) shows the influence of the effective stress p′, Poisson ratio ν, void ratio e_0, and loading-unloading line slope κ on Young's modulus. Table 1 presents the soil parameters required for the modified Drucker–Prager cap constitutive model that were calculated during the above procedures.

$$E = \frac{3(1 - 2\nu)(1 + e0)p'}{\kappa} \quad (4)$$

2.3. Full-scale FE model

The 3D FE model, which was validated as discussed earlier, was developed at the actual model (i.e., laboratory) scale.

Conventional sewer systems typically use minimum diameters of 200 mm for sanitary networks and 300 mm for storm networks. The minimum cover depth used to provide protection for a sewer system network is 1 m for pipes with diameters of 200–1000 mm and 2 m for pipes with diameters of 1000 mm and above (Bizier, 2007; Read, 2004). These minimum sewer system design criteria were selected to test the structural integrity of the new installation method for a separate sewer system.

Table 1
Parameters of the modified Drucker–Prager cap constitutive model.

Items	Parameters	Value
Soil	Density	1685 kg/m^3
	E	16.943 MPa
	υ	0.295
	Drucker–Prager	
	β	55
	K	0.8
	ψ	15
	λ	0.044
	κ	0.0056
	e_0	0.48
Bedding	Density	1855 kg/m^3
	E	75 MPa
	ϕ	35
	C	0
	υ	0.35

The 3D FE model was applied with the real-scale dimensions of two sets of pipe diameters. The first set included two PVC pipes buried at a soil cover depth of 1 m: a 200 mm diameter sanitary pipe and a 300 mm diameter storm pipe. The second set also included two PVC pipes buried at a soil cover depth of 2 m: a 500 mm sanitary pipe and a 1000 mm storm. The same soil and bedding material properties identified and used in the laboratory for the physical model were also used for the 3D FE real-scale model; the homogenous soil properties were used along the cover depth and length of the trench. The width and height of the whole model were selected to measure the extent to which a live load can affect the native soil around the trench occupied by the pipes (Najafi and Sever, 2015). Therefore, the dimensions of the identified model were $10 \times 6 \times 5\,m^3$ for the first set of experiments and $10 \times 6 \times 10\,m^3$ for the second set. Two lanes representing two wheels of an H20 truck passing over the buried pipe section were established at the surface to apply the live load. Figs. 2a and 2b illustrates the model of the first set of pipes (200–300 mm) for the case consisting of the two pipes in one trench.

The ABAQUS 2017 package was used to implement the 3D FE model on the LJMU cluster, as the dimensions of the model required powerful high-performance computing.

3. Results and discussion

3.1. Physical model

Two configurations of pipes were tested in the physical model. The first corresponded to the conventional approach with one pipe in the trench. The 80 mm sanitary pipe was laid under 40 cm of cover soil. The second test configuration was implemented by locating the sanitary pipe in the same position and laying the storm pipe on top. The pipe strain was measured through the application of each layer of soil in each case, that is, both when the sanitary pipe was independent and when it was positioned near the storm pipe. The results show a fluctuation in the pipe deformation associated with compaction. There was no significant change in the strain to which the sanitary pipe was exposed. In both cases, the displacement was between 0.3 and 0.4 mm. The additional load originating from the addition of the storm pipe bedding layer, which has a higher density than the removed filling soil. This load was balanced by the decreased load resulting from adding the storm pipe on top and replacing the filling soil. This case was tested when the pipe was empty; however, flowing water (classified as a live load) can add a supplementary load.

Transducers were used to measure the deformations of both pipes under a series of applied live loads. The results of the deformation of the sanitary pipe are presented for each case, that is, both when the sanitary pipe is alone in the trench and when the storm pipe is above it. The results presented in Fig. 3 shows the behaviour of the sanitary pipe under the applied H20 live loads.

The results of the buried sanitary pipe indicate a reduction in the pipe displacement w[illegible]pe lying alone in the trench to one lying [illegible]lacement of the sanitary pipe was 2.92 mm when laid alone and 2.1 mm when laid below the storm pipe under an H20 load. These physical model experimental results were used to validate the FE model using the same dimensions, objects, boundary conditions and material properties. The validation process was necessary to increase the confidence in the results when transitioning from the FE model to the real-scale model (Moser and Folkman, 2008).

3.2. FE models

Two 3D FE models were established to simulate the new design. The first was built to simulate the laboratory physical model and was then used to extract and validate the model parameters and boundary conditions. The second used the full-scale dimensions of a separate sewer system with two different ranges of pipe diameters that are normally used in intermediate sewer system networks (i.e., sewer systems between the lateral sewers and trunk line). The second model was used to investigate the structural performance of the proposed separate sewer system configuration (two PVC pipes set in one trench) relative to conventional full-scale systems under an H20 traffic load to validate the structural integrity of the proposed method.

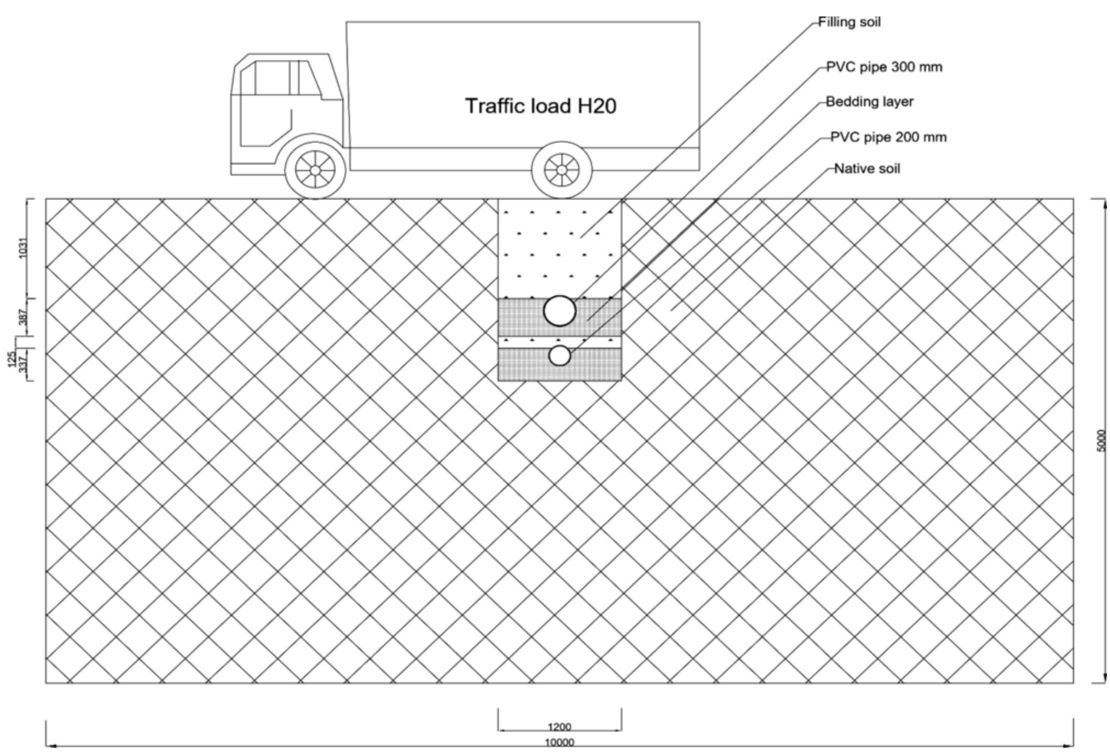

Fig. 2a. A section of the model of a 300 mm diameter storm pipe and 200 mm diameter sanitary pipe in one trench.

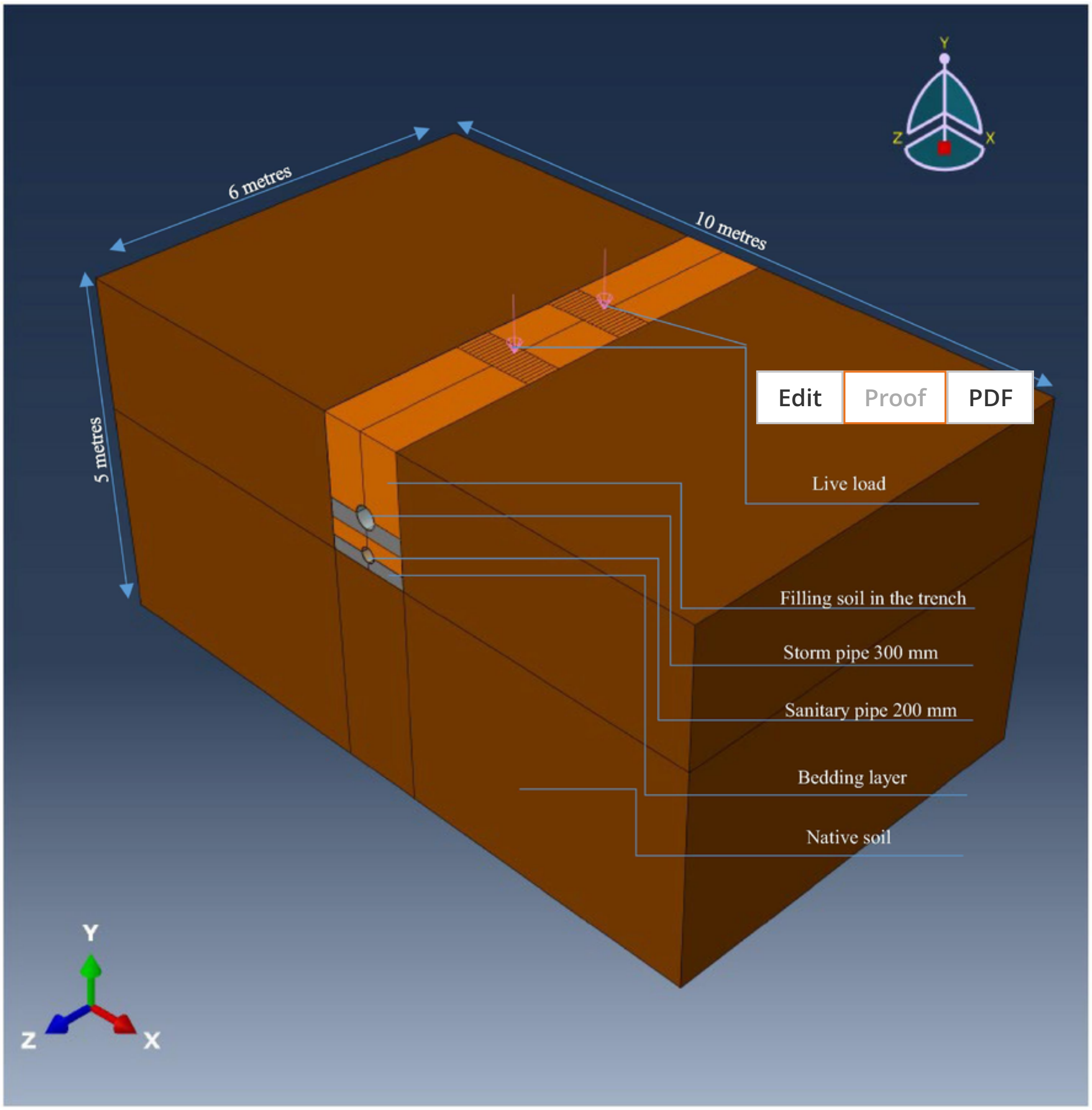

Fig. 2b. 3D FE model of a 300 mm (storm pipe) and 200 mm (sanitary pipe) in one trench.

3.2.1. FE model of the physical model

The boundary conditions and dimensions applied in the physical model were determined for the FE model. The material properties extracted from laboratory tests of each object were identified for the FE model using a modified Drucker–Prager cap constitutive model for both the physical FE model and the real-scale model to simulate the soil behaviour. A convergence study was conducted until an acceptable mesh was obtained (Brinkgreve, 2013). The same series of loads applied in the physical model was used in the FE model to explore the behaviours of the pipes and compare the physical and FE model results for validation.

The results of an applied series of loads in both cases of the FE model (i.e., for one and two pipes set in one trench) are presented in Fig. 3 for a system subjected to an applied H20 live load. These results are compared with the experimental results from the physical model, and they show acceptable consistency. Both model results demonstrate the mitigation of strain in the sanitary pipe when it is positioned below the storm pipe.

A comparison of the FE and experimental results for the deflection of the sanitary pipe shows an almost identical match for both cases under an H20 load. The displacements were 2.92 mm in the experiment and 2.87 mm in the FE analysis for the case of one pipe, and the displacements were 2.1 mm and 1.96 mm, respectively, for the case of two pipes.

3.2.2. Real-scale FE model

The 3D FE full-scale model was used to verify the structural integrity of the proposed system; two sets of pipe diameters were used in two different cases simulating the critical cases regarding the effects of the traffic load on the buried pipes. The traffic H20 live load was selected for application to the real-scale model. The first case involved a test of the system when a 300 mm diameter PVC pipe was used for the storm pipe and a 200 mm diameter PVC pipe was used for the sanitary pipe. In one configuration, both pipes are laid in one trench; in the other configurations, either the sanitary pipe or the storm pipe is lying alone in the trench. Fig. 4 demonstrates the deflection of the storm pipe in the two configurations. The first step (when only the static load of the soil column weight is applied) produced a displacement of 2.05 mm both pipes and a displacement of 2.28 mm for a single pipe in the trench. The displacements from the applied live load were 4.95 mm when the storm pipe was laid above the sanitary pipe in one trench and 5.52 mm when the storm pipe was laid alone. Fig. 5 presents the deflections of the sanitary pipe, which were 1.61 mm when both pipes

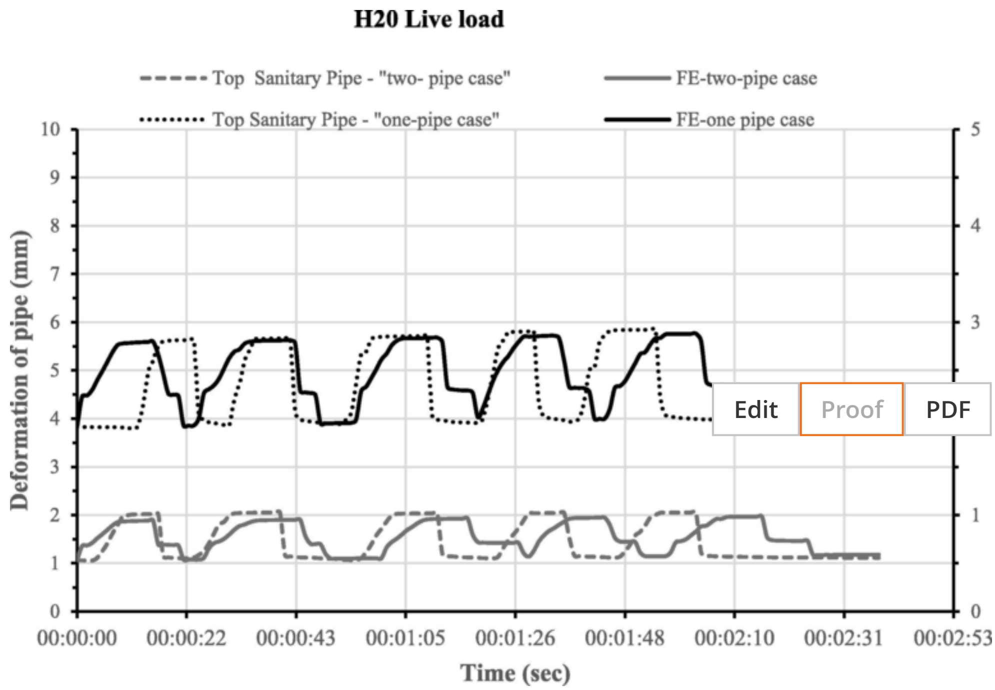

Fig. 3. Comparison of the experimental and FE results of the deflection of the small (sanitary) pipe when set alone in the trench with that when it is set below a storm pipe under an applied H20 live load.

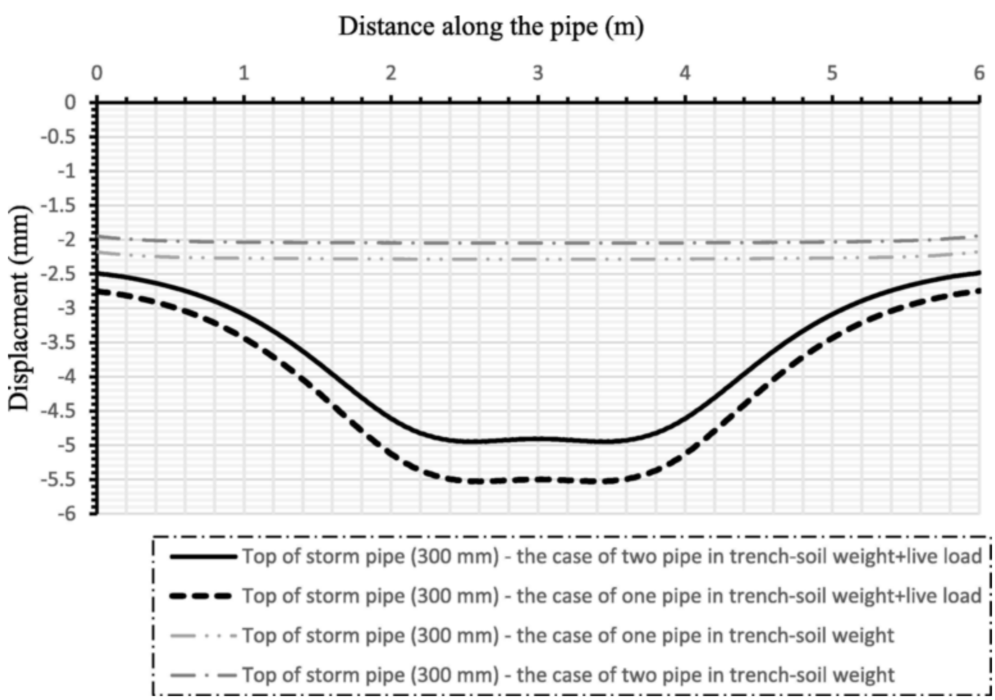

Fig. 4. Comparison between the deflections of a storm pipe (300 mm) when set alone and when set above a sanitary pipe in one trench.

were laid in the trench and 1.84 mm for the case of one pipe under a static load. The displacements were 3.49 mm when the sanitary pipe was set below the storm pipe and 4.75 mm when the sanitary pipe was set alone under a live load. The longitudinal shape deformations of both the storm pipe and the sanitary pipe exhibited the same pattern. The results show that the new configurations for setting two pipes in one trench reduce the deflections of both pipes. This result occurs because the contact area between the side systems (i.e., the two pipes and the side soil) increases, allowing an additional load to be transferred to the side soil, according to Spangler (1941).

The second case in the 3D FE real-scale model involved a 1000 mm diameter storm pipe and a 500 mm diameter sanitary pipe; this is the normal range of pipe diameters observed in a conventional separate system, because the storm pipe diameter rapidly grows larger than the sanitary pipe diameter downstream within the sewer network. The same series of pipe configurations used in the first case was used for the second case, but the cover depth increased from 1 m to 2 m.

Fig. 6 presents the results of the storm pipe (1000 mm) deflection when laid alone and when laid above the sanitary pipe (500 mm) in the first step when only the static load of the soil column weight is applied.

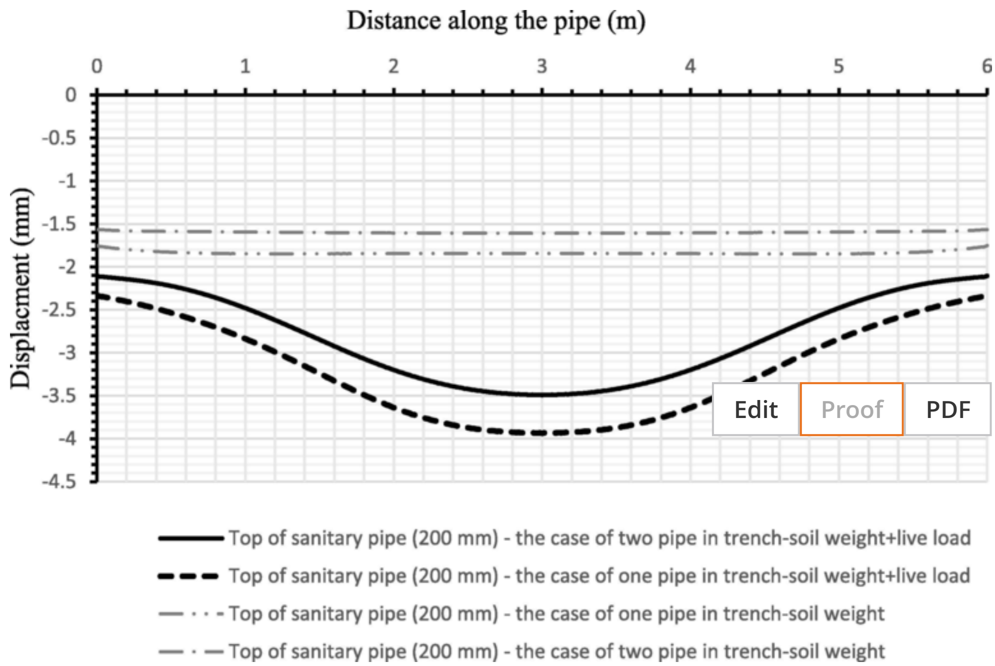

Fig. 5. Comparison between the deflections of a sanitary pipe (200 mm) when set alone and when set below a storm pipe in one trench.

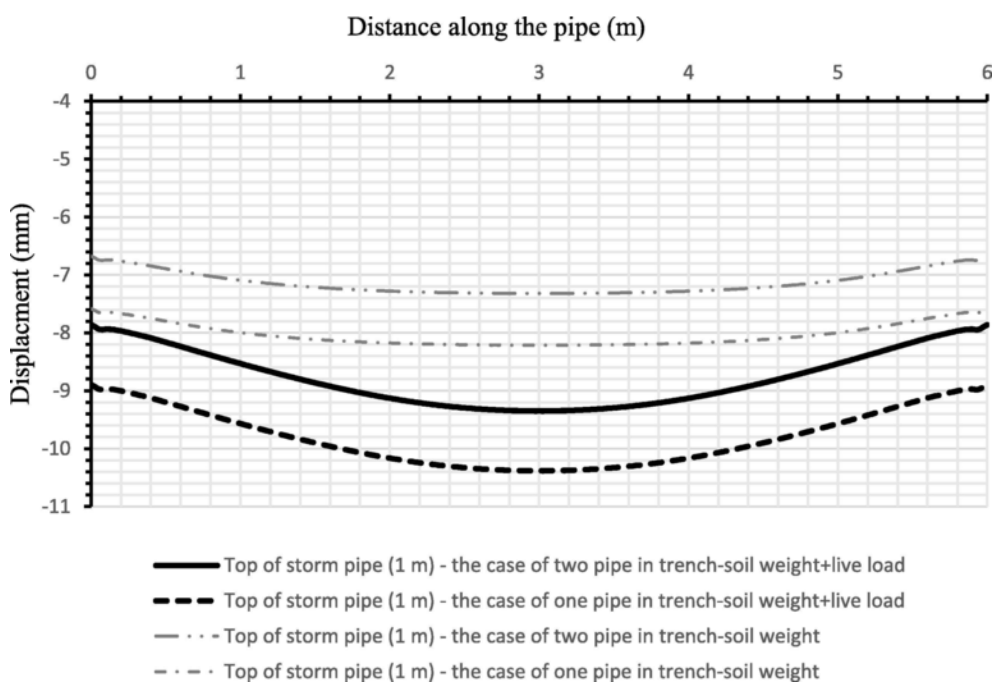

Fig. 6. Comparison between the deflections of the storm pipe (1000 mm) when set alone and when set above a sanitary pipe in one trench.

The displacements were 7.32 mm with two pipes in the trench and 8.21 mm with the storm pipe alone. The maximum displacements from the applied live load were located at the centre of the pipe, and they were 9.35 mm for two pipes and 10.38 mm for one pipe in the trench. The structural behaviours were the same as the deflections observed with two pipes in the trench and less than that with one pipe in the trench.

Fig. 7 shows the displacement of the sanitary pipe (500 mm) in two configurations, that is, when set alone and when set below the storm pipe (1000 mm). The deformations in the first step (when only the static load of the soil column weight is applied) were 4.94 mm in the first position (with the sanitary pipe below the storm pipe) and 5.84 mm in the second position (when only one pipe was in the trench). The location of maximum deformation was not at the centre of the pipe. The deflections from the applied live load were 6 mm for the case of two pipes in the trench and 7.17 mm at the centre of the pipe for the case of one pipe in the trench.

The longitudinal deformation differed between the two configurations of the sanitary pipe (i.e., when set alone and when set below the storm pipe). The displacement was less when the sanitary pipe was set below the storm pipe, because the large storm pipe transfers some load to the side soil generated by horizontal deformation and the load on the side of the sanitary pipe balances the load on top (Spangler, 1941; Watkins, 1957). Furthermore, the pipe diameter has a significant in-

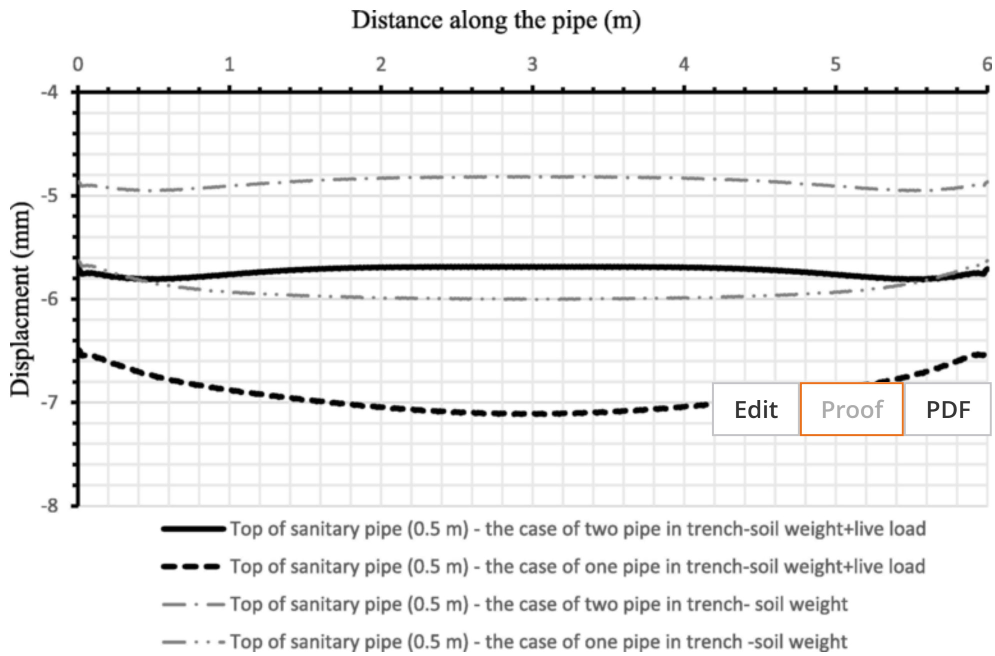

Fig. 7. Comparison between the deflections of the sanitary pipe (500 mm) when set alone and when set below a storm pipe (1000 mm) in one trench.

fluence on the generation of a lateral pressure on the side in addition to the effects of the soil type and compaction efficiency (Chakraborty, 2018; Elshimi Tamer and Moore Ian, 2013). There are two causes of this phenomenon, that is, the width of the trench and the ratio of the pipe diameters, as the storm pipe diameter is approximately twice the sanitary pipe diameter. This effect was not detected for the first set of pipes (200–300 mm) because the difference between the pipe diameters was not as large.

The surface soil deformation was also explored for all three configurations of the both pipe sets. Table 2 summarises the finding for pipe deflections and deformation of the soil surface using the different pipes placements in a trench. The soil surface deformations were reduced when two pipes laid in the one trench for the both sets. We conclude that applying two bedding layers to accommodate a two-pipe system in one trench partially increases the soil stiffness, thereby reducing the deflection of the soil surface under applied load. The depth of the trench with only one pipe affects the deformation of the surface, as the deformation in the case with only the sanitary pipe (at greater depth) was slightly larger than that in the case with only the storm pipe (at shallower depth). The soil settlement for the second set of pipes from the weight of the soil column was approximately 9 mm, which is more than the 6 mm of soil settlement for the first set. The larger pipe diameters of the second set required larger bedding layers for the 1000 mm and 500 mm diameter pipes, thereby increasing the soil column weight and trench width. These two criteria explain why the soil settlement resulting from the weight of the soil column was larger in the second case (Zhou et al., 2017).

Table 2
The summary of pipe deflection and surface soil for two sets of pipes and at three different positions of placing the pipes in the trench.

Set	Pipe Diameter	Deflection of the pipes and soil surface (mm)					
		Sanitary pipe in the trench		Storm pipe in the trench		Both pipes in the trench	
		Soil load	Soil and traffic load	Soil load	Soil and traffic load	Soil load	Soil and traffic load
1	200 mm	1.84	4.75	–	–	1.61	3.49
	300 mm	–	–	2.28	5.52	2.05	4.95
	Soil surface	2.55	19.86	2.54	18.36	2.3	17.82
2	500 mm	5.84	7.17	–	–	4.94	6
	1000 mm	–	–	8.21	10.38	7.32	9.35
	Soil surface	9.19	24.6	10	23.6	9.02	22.58

The results of both the physical model and the 3D FE models show that the pipe deformation decreases when two pipes share a trench in a one-over-one configuration (with the larger pipe on top). The flexible pipe stiffness and the side soil support stiffness play a significant role in decreasing the strain on both pipes. This relationship in shown clearly in the theory of Spangler (1941) and his student Watkins (1957) (i.e., the Iowa formula), which is used to calculate the flexible pipe deflection (ASTM-D2412, 2008).

$$\Delta x = \frac{D_L K W_c r^3}{EI + 0.061 M_s r^3} \quad (5)$$

where Δx = horizontal pipe deflection; D_L = deflection lag factor; K = bedding constant; W_c = Marston's load per unit length of pipe; r = mean radius of the pipe; E = modulus of elasticity of the pipe material; I = moment of inertia of the pipe wall; and Ms = modulus of soil reaction of the sidefill.

The proposed separate sewer system configuration increases the pipe elasticity in the denominator of Eq. (5) because the two pipes are set in one trench, where the static and live loads can both affect the system vertically. The contact area of the system (two flexible pipes) also increases, as represented by the mean pipe radius. This configuration allows for the side soil to exhibit a greater influence on the pipe sides; therefore, more applied load is transferred to the side soil than in the conventional case with one pipe set in the trench. It is clear that the range of pipe diameters and cover depth have an impact on the structural performance of the pipes; therefore, other different scenarios investigating the influence of these parameters on the behaviour of the buried pipes in the new positions have been presented in the Data in Brief. The first scenario was by increasing the storm pipe diameter from

300 mm to 500 mm for the first set. Increasing the cover depth for the second set to 4 m, constituted the second scenario. The results of both scenarios revealed an increase in the deflection of the pipe with an increase of the pipe diameter or the cover depth; the behaviour of the pipes' deflection was not different from the behaviour results from the pipes tested in a variety of positions for the original sets described above.

The deflections of the pipes were within the design requirement criteria for flexible pipe (less than 2%) in both cases (i.e., both the conventional configuration of a separate sewer system and the proposed configuration of two pipes in the same trench). The new method shows a slight reduction in the deflections of both pipes in the trench and in the soil surface deformation, confirming the structural integrity of the new system for the pipes and for the road surface.

4. Conclusion

This research explores the structural performance of two flexible pipes set in one trench, where the pipe with the larger diameter is situated above the smaller diameter pipe. This new, innovative method is particularly applicable in cases involving a separate sewer system beneath narrow streets, which are prevalent in UK and EU cities, and in cases where the installation of a conventional separate sewer system is challenging.

Multiple 3D FE models were utilised to test the behaviours of pipes in the proposed configuration and to compare them with the behaviours of pipes under conventional methods, in which one pipe is set alone in a trench. Experimental results produced from using a physical model in the lab were used to validate the FE models.

The material properties were identified through a series of laboratory tests for both the pipe and filling soil. The modified Drucker–Prager cap constitutive model was selected to simulate the soil behaviour. The validation process enabled the researchers to confidently upgrade the physical 3D FE model to a full-scale 3D FE model, which was used to test two sets of pipe diameters in the new configuration. The first set of pipes had diameters of 200 mm and 300 mm, and the second set had diameters of 500 mm and 1000 mm, which correspond to the range of pipe diameters typically used in conventional separate sewer systems. The system was tested under an H20 live load applied at the surface over the trench centre in two places to simulate a two-axle truck.

The deflections of the two pipes in the new configuration were compared with the individual deflections of the sanitary pipe and storm pipe when they were both set alone in a trench. The results show that the new configuration decreases the deflections in both pipes and the deformation of the surface soil relative to conventional methods in which a single pipe is placed in a trench.

For the first set of pipes (a 200 mm diameter sanitary pipe and a 300 mm diameter storm pipe), the decrease in the deformation of the storm pipe under the live load was approximately 10%. The reduction in the deformation of the sanitary pipe was approximately 26% when the pipe was set below the storm pipe relative to that when it was set alone in the trench.

For the second set of pipes (a 500 mm diameter sanitary pipe and a 1000 mm diameter storm pipe), the reductions in the deformation under the applied live load were 10% in the storm pipe and 15% in the sanitary pipe.

The Iowa formula was employed to explain the observed reductions in the pipe deformation in terms of an increase in the pipe elasticity and the contact area between the pipe sides and soil, which are used as parameters in the Iowa formula.

The results of both configurations showed that the effects of the applied live load were higher on the first set of pipes than on the second set, whereas the soil column weight had a larger effect on the second set than the first set, the reason for which is because the soil cover depth used in the second set (2 m) was larger than that used in the first set (1 m).

The surface soil deformation was explored for both sets of pipes, and it was found to slightly decrease between 3% and 10% when using two pipes in one trench compared with using one pipe. This finding can be explained in terms of the slightly increasing soil stiffness, as two bedding layers were used in the trench with one pipe.

In general, the proposed separate sewer system configuration showed slight reductions in the deflections of both pipes in the trench and in the soil surface deformation, confirming the structural integrity of the new method for sewer systems and road surfaces.

Uncited references

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Declaration of Competing Interest

The authors declare that there are no potential conflicts of interest associated with this research.

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Availability of data and materials

Raw data were generated at Liverpool John Moores University. The derived data supporting the findings of this study are available from the corresponding author (A. Abbas) on request.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.tust.2019.103019.

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