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The impact of voids in proximity to buried utility pipes

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ABSTRACT: Deterioration of the burial conditions of water distribution pipes can occur through the migration of fines or localised erosion due to leakage from the pipe. The latter can generate significant voids in the proximity of the pipe leading to a loss of support that can alter the long-term pipe capacity that can lead to structural failure. The impact of voids on the performance of small diameter buried utility pipes is examined. Centrifuge experiments to model a 315mm diameter High Density Polyethylene (HDPE) prototype pipe, with and without the presence of voids, were conducted under vertical surface loading. Voids were modelled using a low stiffness compressible material that proved sufficient to maintain the void geometry and prevented internal soil collapse. Increased mobilisation of the pipe was found to be significant when the voids exceeded 1.5 times the pipe diameter and were located below the spring-line at the invert and haunch positions.

1 INTRODUCTION

Utility pipes are essential to daily life since they support contemporary civilization by not only distributing drinking water and collecting sewage, but also serving as networks for electricity and communication. A large portion of the UK's water distribution network was constructed during the beginning of the 20th century, during the industrial revolution, making it one of the oldest types of infrastructure (Bayton et al., 2018). Water shortage is a serious problem brought on by the availability of water resources, rising demand, and leaks from outdated distribution systems (Figure 1). According to DiscoverWater (2019), leaks in the UK result in the loss of over 3 billion litres of water per day, which amounts to a 22% reduction in the amount of drinkable water that reaches customers' taps in England and Wales (Laspidou, 2014).


Figure 1 Underground freshwater leakage image (Water matters UK2013).

The extreme climatic conditions in which buried infrastructure systems operate, such as external loads, ground movement, or extreme heat/freezing, make them susceptible to degradation throughout the course of their useful lives. In the UK, pipe networks are now functioning much past their intended design life and can be as old as 100 years. Since the pace of network renewal is significantly lower than what is necessary, it is critical to comprehend the causes of pipe deterioration to prevent additional failure (Industry, 2014).


Figure 2 Erosion and void formation around breached pipe (water matters UK.2013).

Pressurised water distribution pipe leaks can result in localised voids surrounding the pipe, as seen in Figure 2, as well as secondary consequences such as bed fluidization and soil material erosion. Balkaya et al. (2012) documented similar observations within the vicinity of excavated pipelines during repairs and maintenance. Axial thrust forces and traffic loads may cause extra bending stress in the pipe sections and joints if an unsupported scenario arises. This may lead to cyclic fatigue or local buckling that causes premature pipe failure if left undetected. It's also interesting to observe that, in cases of poor bedding areas with well-graded soil, the initial burial conditions of the pipe being laid in a pea-gravel trench are rarely observed around exhumed pipes. This suggests that fines/suffusion processes occur with groundwater flow, which may exacerbate the possibility of void formation (Elmrom, 2021).

Figure 3 summarises the complexity associated with underground utility pipelines and the difficulties caused by the influence of voids surrounding the pipe. This problem is poorly understood, and it affects the behaviour of pipes. Consequently, there is a strong incentive to comprehend the effects of shallow-depth voiding around pipes and the subsequent effects on pipe performance.

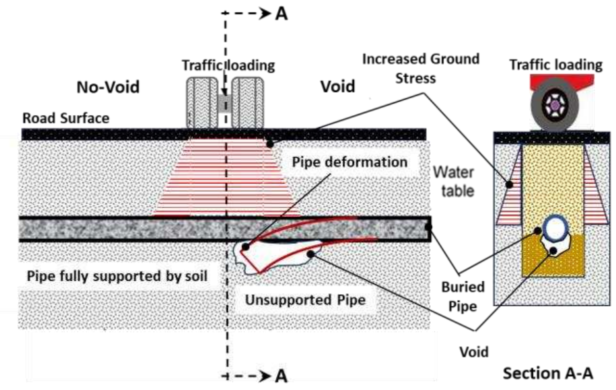

Figure 3 Buried pipe infrastructure and impact of support/void formation (Elmrom 2021).

It is impossible to observe or analyse the current underground pipe system, it is very difficult to forecast how void created underneath the pipe or any other area. Therefore, excavation work is necessary for pipe maintenance in the event of a pipe failure that causes water to leak, which will cause the earth to collapse and the void to vanish. Thus, the size and form of the void is unclear. Consequently, there is a strong incentive to comprehend the effects of shallow-depth voiding around pipes and the subsequent effects on pipe performance.

2 EXPERIMENTAL SET-UP DESIGN

2.1 Facility

A set of centrifuge model experiments was carried out utilising the 4 m diameter 50g-tonne geotechnical beam centrifuge at the University of Sheffield, with a centrifugal acceleration of 19.2 times Earth's gravity (19.2g). The full technical specification of Sheffield centrifuge is summarised in Table 1. The centrifuge enables the reproduction of prototype stress conditions in order to accurately capture the small-strain stiffness and dilatation responses related to the pipe-soil interaction issue (Elmrom, 2021).

Table 1 University of Sheffield centrifuge specification.

Description	Specification
Platform radius	2.0m
Effective radius	1.7m
Payload size	W=0.6m circumferential L=0.8m vertical in-flight H=0.9m Radial in-flight
Max Acceleration	500Kg at100g;330Kg at150g
In-flight balancing	From max of ±45kN to±1.5kN at 280RPM
Real experiment	275Kg at 19.2g

2.2 Soil properties

The employed material in this experiment is a fine E-Fraction of silica dry sand, commercially known as HST95 (see Table 2), which was pluviated into a strong box using an automatic point pluviator with three degrees of freedom to create uniform test beds and achieve a targeted relative density (Rd) of 80%. The model pipe and the attached system were previously fixed in their respective places inside the strong box which has inner dimensions of 600 mm (L), 400 mm (W), and 400 mm (H) and wall thickness of 30mm.

Table 2 Properties of HST95 silica sand (Elmrom2021).

property	Value
Particle size D_{10}	0.098mm
D_{50}	0.147mm
D_{60}	0.15mm
Specific gravity, *Gs*	2.56
Max void ratio ($e_{\max}$)	0.872
Min void ratio ($e_{\min}$)	0.514
Sand peak angle of shear	37.5°(at Rd=80%)
Sand-pipe peak angle of shear	19°(at Rd=80%)

2.3 Model pipe

The choice of the model pipe material was made to accurately mimic the properties of the prototype pipe in terms of Young's modulus (E). Therefore, applying the bending stiffness scaling law of $1{:}N^4$, the scaled bending stiffness of the model pipe accurately represents the prototype pipe, as long as it is within the same range of values. This ensures that the flexible behaviour is still accurately reproduced Figure 4 shows the scaling concept for the pipes.

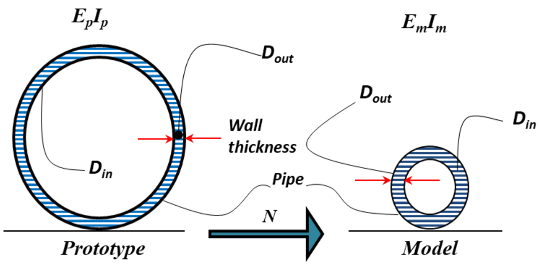

Figure 4 Scaling concept for plastic pipe.

Garnier et al. (2007), provided an in-depth review of centrifuge scaling laws, and the findings of the present study are succinctly presented in Table 3. The small-scale models were subjected to prototype stress conditions by providing an acceleration of 19.2g.

Table 3 Flexible pipes properties.

Description	Prototype Dimension	Model Dimension
Gravity(g)	1g	19.2g
Material	HDPE	PE100
Young's Modulus (E)	900MPa	885.6MPa
Diameter (D)	315mm	16mm
Thickness (t)	28.6mm	1.8mm
Flexural Stiffness (EI)	2.4e+11 Nmm^2	1.85e+06 Nmm^2
Scaling law for EI	1	$1/19.2^4$

2.4 Modelling of a void

Void formation in the fill material can arise due to many processes, such as the washing out of small particles through suffusion, fluctuations in the groundwater table causing moisture variations, infiltration at the surface, and movements of pipes. Regardless of the process via which a void may develop, its presence near a pipe will lead to a specific area losing its support. This will inevitably raise the risk of the pipe deforming when subjected to vertical surface pressure. Creating a "real-time" void in a centrifuge model using any of the procedures is a significant technical challenge. In tunnelling applications, Mair (1979) was the first to develop the technique of deflating a fluid-filled "bladder" or membrane to replicate the reduction of volume below the surface. A similar approach was adopted in this work, except that the material used to replicate the void was a sponge, which can simulate larger voids. This offered the ability to provide suitable support to hold back the sand material in a desired void geometry while providing a region of almost zero support in the proximity of the pipe. The sponge was cut into different spheres. Different types of void sizes were modelled in the experiment or increased in geometry according to the prototype void size. These sizes varied between $0.5D_p$, $1D_p$, and $2D_p$. Figure 5 shows sponge location, an example of a rectangular prism (rectangular cuboid) of sponge used to replicate voids in the model. Additional information is available in Elmrom (2021).

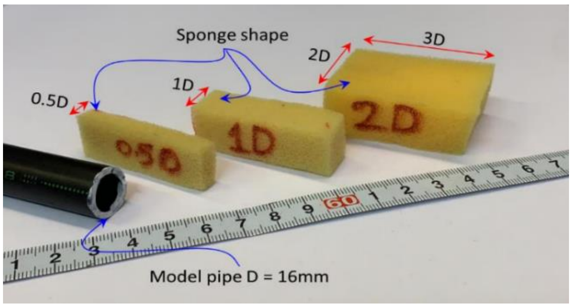

Figure 5 Rectangular sponge used to replicate voids in the mode (Elmrom 2021).

2.5 Model Preparation

Seven pairs of strain gauges in half-bridge configurations were positioned on the vertical axis (crown-invert) of the model pipe. This enabled the replication of the bending response at the midpoint, assuming that the load was applied at this location. Strain gauges were calibrated for bending moments in each 90-degree orientation (Sales et al., 2015). Additional scaling aspects considered were the sand-pipe particle interaction. Iglesia et al. (2011) stated that the scaling ratio, D (pipe diameter to soil particle size), should be greater than 30. The scaling ratio here, preserved, is in excess of 100 (D/D_{50}), thus there are no adverse interaction observations that should occur. The model pipe was placed at the centre of the strong box, at the required burial depth, with the attached sponge to represent the void (size/location). Subsequently, sand was pluviated all over until the desired cover above the respective pipe was achieved.

An aluminium frame was designed to hold in place the instruments that are used to simulate traffic loading and the LVDTs that measure pipe and footing displacement. Knowing that the footing dimension is 13 mm × 26 mm to represent a wheel contact area (0.25 m × 0.5 m at prototype scale), and due to the significant force exerted by the footing, it was vital to consider the impact of this force on the cross beam. Figure 6 displays the aluminium frame. In order to prevent the aluminium footing from penetrating the sand during the test, a piece of rubber mat was placed on the sand surface.

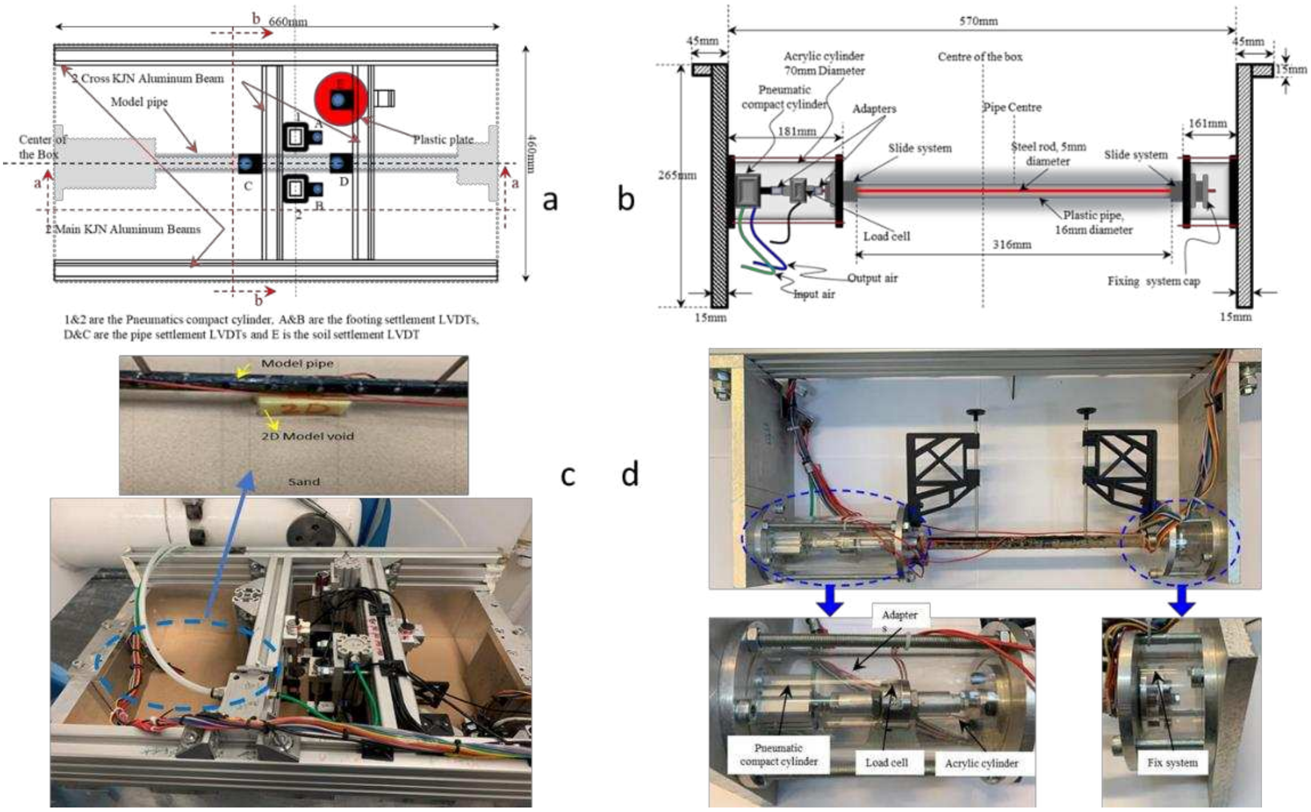

Figure 6 Test setup: schematic(a) plan view and;(b) elevation;(c) photo of pipe placement and;(d) side view.

2.6 Test configuration

A total of eight centrifuge tests were performed, encompassing scenarios both with and without a void. Two void locations were considered: at the midspan, beneath the invert (180°) and along the side of the pipe along the spring line (270°), Figure 7. Three void geometries of $0.5D_P$, $1D_P$, and $2D_P$ were assessed. The cover depth (Z_c) for the pipe crown was 1 metre.

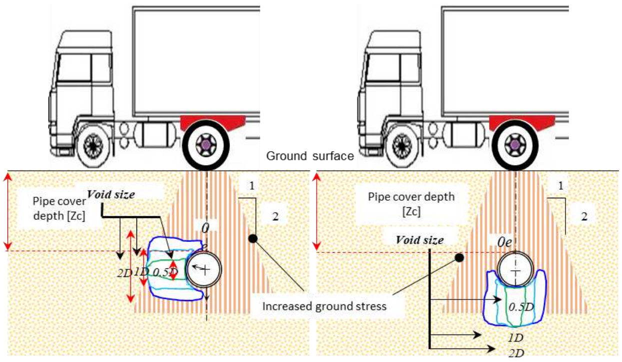

Figure 7 Void geometries size and locations.

The chosen magnitude of the model load accurately represents half of a wheel axle of a prototype-scale 44-ton articulated truck, which is equivalent to the maximum allowable load on roads in the UK. This is equivalent to a vertical load of 6 metric tonnes per wheelbase. This complies with the guidelines for monotonic and cyclic loads as outlined in (AASHTO, 2010). More details are shown in Table 4.

Table 4 test configuration.

Test No.	Cover depth	Load Magnitude	Void size	Void location	Load type
T1	1 m	6T-Single	None	-	Static
T2	1 m	6T-Single	$0.5D_p$	180°	Static
T3	1 m	6T-Single	$1D_p$	180°	Static
T4	1 m	6T-Single	$2D_p$	180°	Static
T5	1 m	6T-Single	None	-	Static
T6	1 m	6T-Single	$0.5D_p$	270°	Static
T7	1 m	6T-Single	$1D_p$	270°	Static
T8	1 m	6T-Single	$2D_p$	270°	Static

3 RESULT AND DISCUSSION

A suite of tests was undertaken to explore the aspect of pipe-soil-void interaction. Each test consisted of two phases: spin-up and monotonic loading. During the spin-up phase, the centrifuge speeds increased, starting at 1.3 g and increasing to 5 g until the required speed of 19.2 g. Figure 8 shows an example of pipe behaviour during ramp time. The bedding of the pipe caused a little background bending stress during this ramp period. Therefore, increased soil self-weight due to spin-up caused soil compression and 'flow' around the pipe. Meanwhile, fixing the pipe at either end caused bending stresses. A great bending moment was observed, especially at the midspan of the pipe. Hence, this data was checked during each spin-up to ensure pipe sensor functionality.

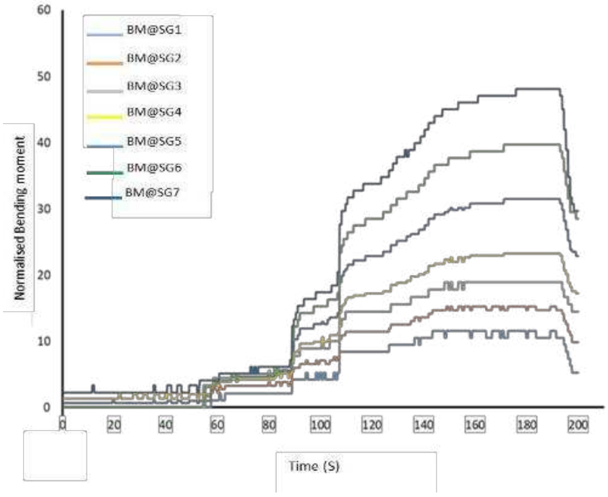

Figure 8 Spin-up stage and self-weight effect on pipe.

3.1 Effect of void located at pipe invert (180°)

The presence of voids was shown to have a substantial impact on the performance of the pipe in the monotonic scenario. The outcomes represented in Figure 9 highlight the consequences of monotonic loading when a void is present at the pipe invert (180°). It has been observed that bending moment increases at the pipe invert as the void size V (0.5Dp, 1Dp, and 2Dp) increases. For instance, when the void was just 0.5 times the diameter of the pipe (V = 0.5Dp), the bending moments and pipe deflection recorded at the major axis showed a fivefold increase compared to the no void scenario. Also, the relevant pipe deflection for voids bigger than that exceeds the permissible deflection criteria of 5% of the pipe diameter during the installation, whereas the allowable deflection of the buried pipe should not exceed 2% of the pipe diameter, resulting in significant sagging and hogging moments in the pipe at the point of inflection. The observations of surface settlement of the wheel loading also confirmed the loss of stiffness in the pipe-soil-void system with the introduction of the void and the increased mobility of the load area.

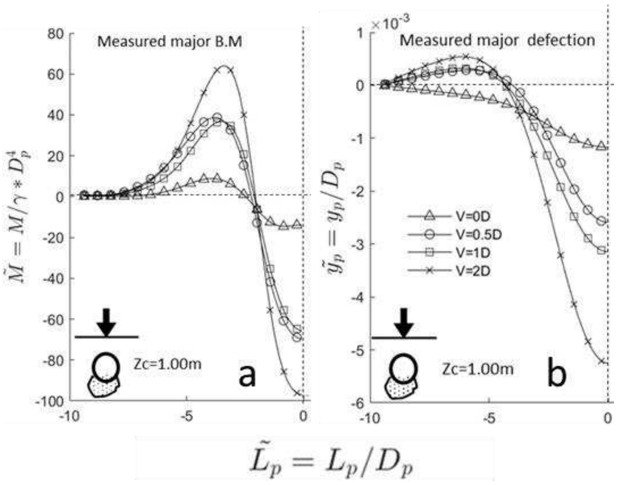

Figure 9 pipe monotonic response with presence of void (a) bending moment (b)pipe deflection.

All results presented in dimensionless terms where $\tilde{M}$ is the normalised bending moment, $\tilde{L}$ is the pipe length, M is the bending moment, ɣ is soil unit density D_p is the pipe diameter and L is the pipe length.

3.2 Effect of void located at pipe invert (270°)

The findings indicate that having a void at the spring line (270 degrees) with a load eccentricity of 2Dp and 1m depth leads to an increase in the bending moment and pipe deflection along the minor (horizontal) axis of the pipe. Nevertheless, it was observed that there was a marginal elevation in the bending moment magnitude in comparison to the test conducted without void (Figure 10). Therefore, it can be inferred that the size and position of the void both have a significant impact on the bending moment and pipe deflection, as seen in Figure 11.

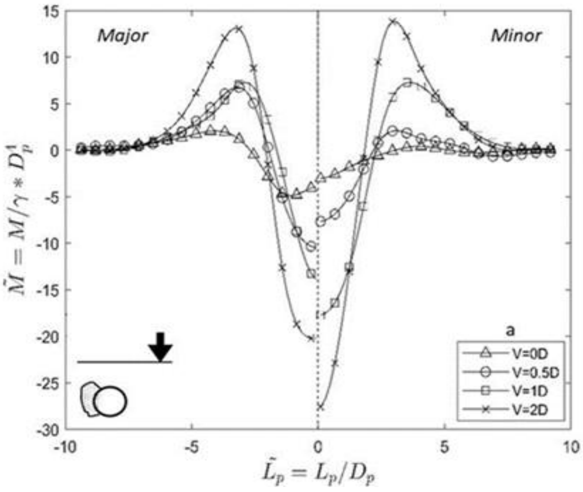

Figure 10 Void size and location effect at e=2 for Major and minor bending moment.

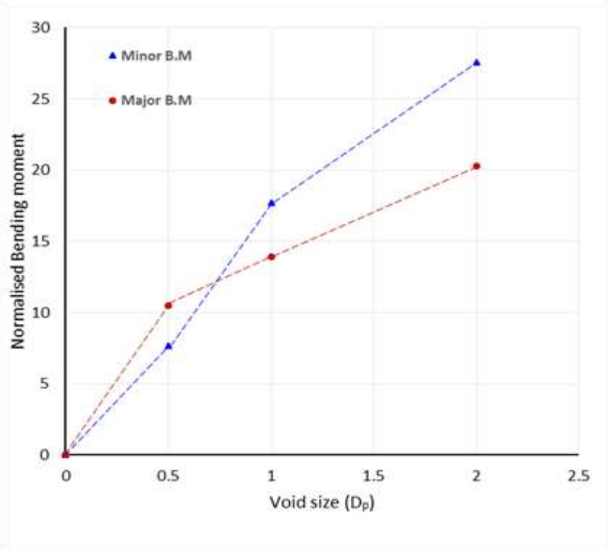

Figure 11 Void size effects located at pipe invert (180°).

CONCLUSIONS

An investigation was conducted to examine the influence of void size and location on buried pipe exposed to external loading. The investigation showed that the void size and location both have a significant influence on the bending moment and pipe deflection. For example, a bigger void size at the pipe invert (180°) causes the major bending moment to rise by about 25% compared to the non-void test result. Consequently, pipe deflection increased considerably with increasing void size, to the extent that it exceeded the allowable deflection criteria of 2% pipe diameter. The findings indicated a notable increase in the bending moment along the minor axis due to the presence of the void located at the springline (270°). Conversely, results indicated a decrease in the bending moment and deflection on the major axis. Those results were compared to the findings obtained when there was no void present. It is evident that the deflection of the pipe grows along the minor axis as the void size placed at the pipe springline increases.

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