Physical investigation into the significance of ground conditions on dynamic leakage behaviour

Sam Fox, Richard Collins and Joby Boxall

ABSTRACT

Effective leakage models are crucial for leakage assessment and control strategies to improve the sustainability of vital water distribution, and other pipeline, infrastructure. This paper evaluates the interdependence of leak hydraulics, structural dynamics and soil hydraulics, particularly considering the significance of the soil conditions external to longitudinal slits in viscoelastic pipe. Initial numerical exploration and unique physical experimental results are presented exploring this complex physical phenomenon. The existence of an idealised fully restrained porous medium was shown to significantly increase the pressure- and time-dependent leak opening area whilst reducing the leak flow-rate, compared to a leak into water only. The research highlights the limitation of existing dynamic leakage modelling approaches which greatly simplify or neglect the influence of the soil conditions. Incorporation of this understanding into leakage modelling will enable more accurate estimation of leakage rates and hence the effects of management and control strategies.

Key words | leakage, leakage modelling, porous media, structural dynamics

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INTRODUCTION

The capacity to numerically represent physical phenomena is dependent on our ability to determine all the significant causative factors for a given scenario and incorporate these within a verifiable model. Leakage models play a pivotal role in assessing and controlling the total real losses from water distribution systems, forming the fundamental development platforms for leakage management approaches including leakage assessment and pressure management. The definition of the sensitivity of leaks to changes in pressure, specifically the pressure dependence of the leak area, has been identified as a key research topic aimed at improving current leakage modelling practice. Select investigations explore idealised model parameters where the pipe is not buried in a soil or other porous media, contrary to the typical conditions found for this typically buried infrastructure. Consequently the significance of the interdependence of the soil and leak hydraulics with the pipe and soil structural behaviour are generally omitted from developed leakage models. Understanding the influence of a representative porous media on the structural loading conditions and subsequent leakage magnitude will have a direct impact on improving leakage management applications and hence the overall sustainability of water distribution systems and other buried pipe infrastructure.

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BACKGROUND

Leakage studies often consider the relationship between pressure and flow-rate from individual failure apertures, with leaks in typical water distribution pipes shown to exhibit orifice type flow which may theoretically be characterised using the Orifice Equation (Greyvenstein & van Zyl 2006). However, the observed sensitivity of different leaks in operational systems to changes in pressure has led to the adoption and application of the Generalised Orifice Equation which accounts for the dynamic nature of many leaks (Schwaller & van Zyl 2014). Leakage behaviour is then quantified based on the knowledge and understanding of structural dynamics and leak hydraulics. When evaluating the performance of system leakage at District Metered Area level, the temporal water demand must also be considered (Clayton & van Zyl 2007). However, the impact of soil hydraulics are not commonly considered.

Recent studies have concluded that pipe structural behaviour, specifically the pressure-dependent leak area, is the primary causative factor for the marked leakage sensitivity observed in the field requiring the use of extreme values in the generalised Orifice Equation. Generally, leaks behave in two distinct manners dependent on the inherent pipe material properties. Failures in linear elastic materials such as cast iron and steel, display a simple pressure-dependent leakage response, whereas equivalent leaks in viscoelastic materials such as polyethylene, display a more complex time and pressure-dependent response (Ferrante 2012). Fox *et al.* (2014) confirmed qualitatively and quantitatively that the leak area is indeed the main influencing factor on the observed dynamic leakage for longitudinal slits in viscoelastic pipe. The study infers that a modified form of the Orifice Equation may therefore be used by incorporating the measured or modelled leak area. However, physical and numerical studies such as those presented by Fox *et al.* (2014) and Cassa & van Zyl (2011) neglect the effect of external ground conditions and the influence of soil hydraulics on the observed dynamic leak behaviour.

The association between structural performance and leak hydraulics has a significant influence on the net leakage behaviour of failures in pressurised pipes. In most cases numerical and physical studies simplify the analysis of leakage behaviour by eliminating the influence of porous media external to a pipe. Clayton & van Zyl (2007) emphasised the complexity of integrating the non-linear coupled soil and orifice hydraulics into leakage models. The consideration of soil hydraulics offers the potential to further our understanding of the physical mechanisms controlling leaks in buried pipes. Walski *et al.* (2006) derived and validated the theoretical Orifice Soil (OS) number to define the dominant head loss components for leaks in buried pipes using the energy equation. Small circular orifices were used for the experimental work, which are relatively insensitive to changes in pressure and therefore allow for the assumption of a constant leak area. Experimental results demonstrated the effectiveness of the OS number as a tool for defining the orifice or soil matrix head losses as the dominant factor defining the pressure-leakage relationship. However, the investigation results are limited to Darcy soil flow (no mobilisation of the soil) and laminar flow conditions due to the use of the Bernoulli equation, thereby assuming negligible turbulent hydraulic effects in the soil. Lambert (2001) highlighted the sensitivity and variability of the leakage exponent for small leaks in the laminar region, therefore hindering the conclusion drawn by Walski *et al.* (2006) that the static soil matrix head losses are solely dominant at low flow rates without consideration of the coupled dynamic orifice hydraulics. Noack & Ulanicki (2006) presented a numerical study for fixed area leaks, verified with physical observations, highlighting the relationship between the soil permeability and the leakage exponent. As the permeability of the soil matrix increases, the theoretical leakage exponent tends to unity, reflecting the significant change in characteristic leakage behaviour.

Fluidisation, or the mobilisation of soil particulate, results in a distinct hydraulic behaviour that differs from idealised Darcy flow explored by Walski *et al.* (2006). Initial experimental results presented by van Zyl *et al.* (2013) showed that the majority of measured head loss may be accounted for by fluidised zones, not the static zones, when considering leaks into unconstrained porous media. The fluidised soil behaved as an energy dissipation mechanism but had only a small effect on the pressure-leakage relationship observed, primarily due to the increased external pressure. Theoretically though, less mobile soils compared to the spherical ballotini used by van Zyl *et al.* (2013) may result in occlusion of the leak aperture directly affecting the hydraulic and structural loading of the leak orifice. The characteristics of porous media, namely the soil matrix composition/rigidity and the hydraulic conductivity (permeability), and the coupled effect with the leak hydraulics can therefore directly influence the observed leakage performance. This effect may be theoretically modelled using a modified Orifice Equation, accounting for both soil and orifice losses assuming a fixed orifice area and no soil fluidisation (Collins & Boxall 2013).

The coupled effects of structural behaviour and leak hydraulics, as well as the soil and leak hydraulics, have been examined within the available literature. The interdependence of all three of these fundamental principles remains an important but relatively unexplored area of research. The effect of the soil matrix external to a leaking pipe on the net head losses have been investigated to varying degrees of detail. The impact this has on the loading state of a pressurised pipe, in particular the head loss across the orifice length in the direction of the leak flow, has not been quantified. The effectiveness of numerical studies aimed at defining the structural behaviour of dynamic leaks in pressurised pipes using finite element analyses (e.g. Rahman *et al.* (1998), Cassa & van Zyl (2011) and De Miranda *et al.* (2012)) are dependent on the accuracy of modelled boundary and loading conditions. For hydraulic pipelines, the primary loading component is the pressure applied to the internal pipe face from the fluid. For highly sensitive leaks such as slits in the circumferential or longitudinal direction, the slit face loading is an additional component that has a significant influence on the scale of deformation of the leak (Lewis & Wang 2008). This is of particular significance for pipes defined as thick-walled, where the ratio of pipe diameter to wall thickness is less than 20. Such localised pressures are commonly excluded from analyses due to uncertainty in the definition of the true pressure distribution (Takahashi 2002), with authors stating that detailed fluid and thermal analyses are required before accurate definition (Kim *et al.* 2002). It may be inferred that the magnitude of the slit face pressure distribution is dependent on the external conditions surrounding the leak and the orifice flow, therefore necessitating a detailed understanding of the soil and leak hydraulics. Existing leak area models excluding the effect of slit face loading may therefore be seen as conservative. Without considering the interdependence of the leak and soil hydraulics and the structural behaviour of dynamic leaks, models may over- (i.e. ignoring soil resistance effects) or under- (i.e. ignoring slit face loading effects) predict the true leakage behaviour of individual leaks.

AIM AND HYPOTHESIS

The aim of the research was to investigate the influence of an idealised (invariable) external porous media on the dynamic leakage behaviour of longitudinal slits in polyethylene pipe, through some initial numerical studies and then a series of novel physical experiments. Three fundamental, interacting, principles were investigated; structural behaviour and leak and soil hydraulics, as summarised in Figure 1.

From considering the interdependence of leak and soil hydraulics, it may be expected that the existence of a fully constrained/consolidated porous media external to a leaking pipe will result in a distinct pressure-leakage relationship, less than that of an equivalent leak into air or

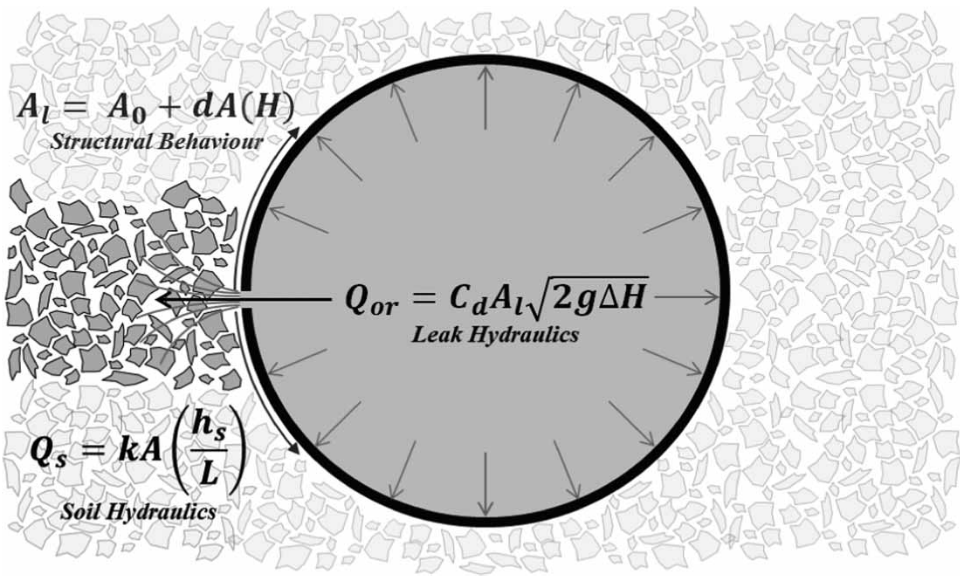

Figure 1 | Three fundamental governing principles for characterising the behaviour of dynamic leaks.

water. This is primarily due to the hydraulic resistance (permeability) of the porous media. However, this same resistance would significantly increase the slit face loading of a longitudinal failure opening. Consequently, consideration of the leak hydraulics and structural performance, particularly for highly sensitive leaks (longitudinal slits) in thick walled pipes, leads to the expectation of increased magnitude of deformation of the pressure-dependent leak area, increasing leakage. Thus the effects are interactive, producing combined, complex and currently uncertain behaviour and net effect.

CFD ANALYSIS

A preliminary program of computational fluid dynamics (CFD) simulations were run to qualitatively assess the null hypothesis that the existence of porous media external to a leaking orifice has negligible influence on leak hydraulics, with particular attention to the pressure distribution across the longitudinal slit face. A single model was developed for a fixed 60×1 mm longitudinal slit (constant area) in 50 mm nominal diameter pipe (wall thickness equal to 6.5 mm) contained within a 0.45 m^3 capacity box based on the dimensions of the physical investigation conducted by Fox *et al.* (2012). A 3D tetrahedral mesh, consisting of the pipe fluid volume and the surrounding box volume, was produced with a refined mesh of 0.25 mm across the slit face. The box volume allowed for the definition of two test cases; a water (fluid) cell zone and a porous media cell zone representative of the compact gravel utilised by Collins & Boxall (2013) external to the leaking pipe. For each test case a constant pipe inlet pressure head of 20 m (196,200 Pa) and zero pipe outlet velocity (system flow equal to leak flow-rate) was used and solved using a standard k–ε viscous model with enhanced wall functions. The k–ε viscous model provides an efficient and effective solver for near wall treatment and turbulent flow simulations (Oon *et al.* 2013). Figures 2 and 3 show the results of the simulations, focussing on the leak jet formation and the slit face pressure distribution.

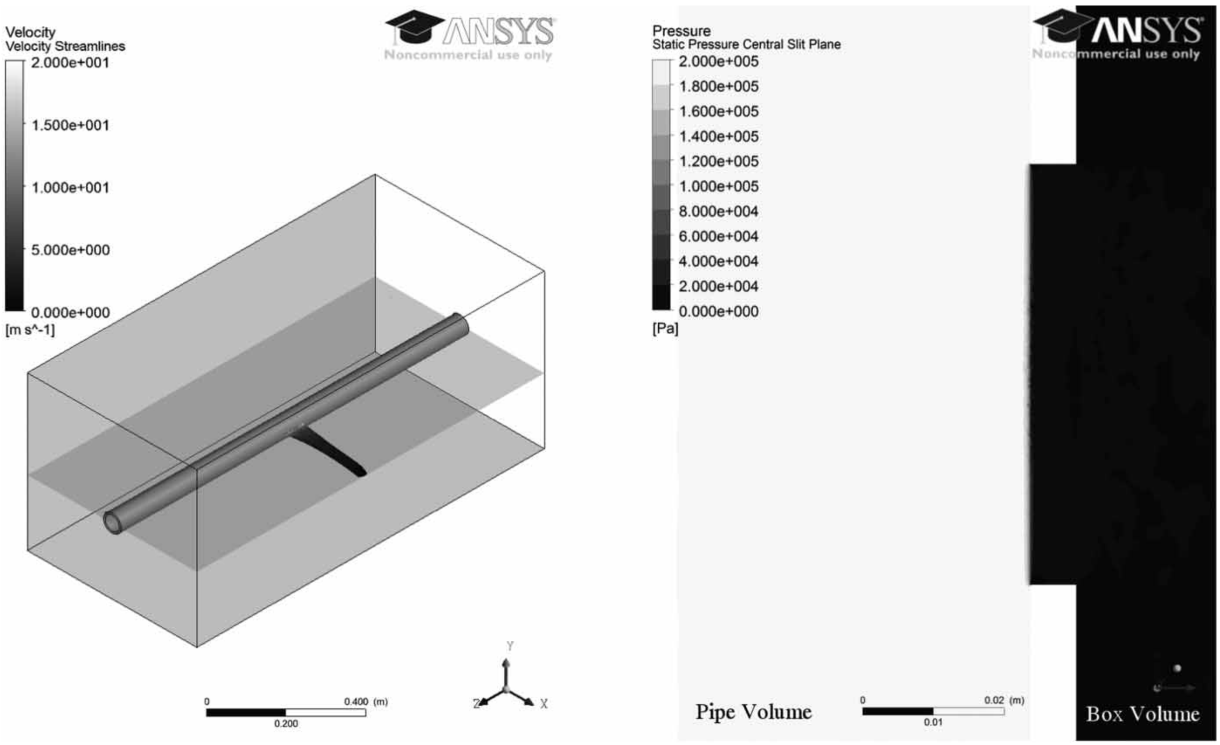

Figure 2 | CFD simulation results for leak into water, from a 60×1 mm longitudinal slit leaking into a fully submerged test section box. Velocity streamlines (left) and static pressure contour on central slit plane (right). Plane of interest shown as transparent surface on velocity streamline plot.

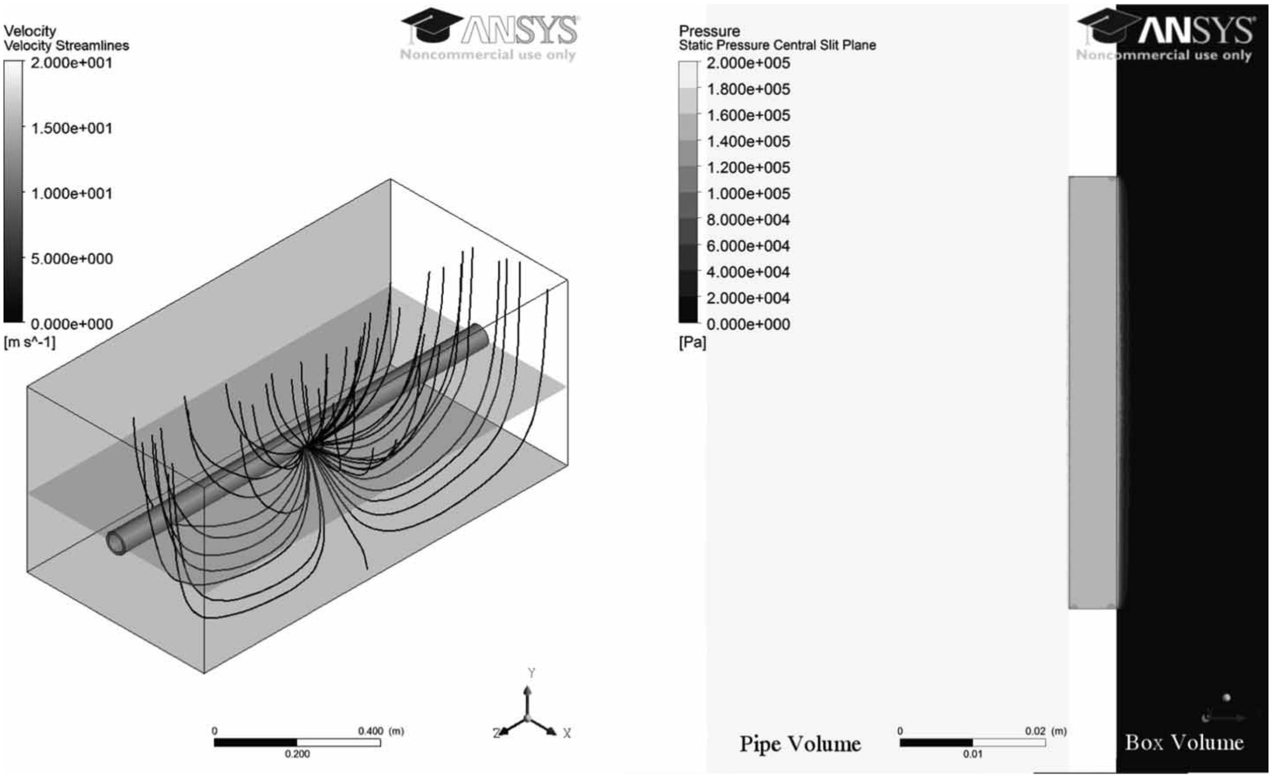

Figure 3 | CFD simulation results for leak into porous media representative of gravel, from a 60 × 1 mm longitudinal slit leaking into a fully submerged test section box. Velocity streamlines (left) and static pressure contour on central slit plane (right). Plane of interest shown as transparent surface on velocity streamline plot.

A clear distinction between the leak jet dispersion is evident from the simulation results of the velocity streamlines, with a reduced flow-rate of 0.43 L/s evaluated for the leak into gravel compared to 0.87 L/s for the equivalent flow into water. Crucially, there is also a quantifiable difference in the simulated slit face loading conditions. A horizontal plane through the centre of the slit, parallel to the longitudinal axis, was used to evaluate the slit face pressure. The mean slit face pressure for the water case was 4,710 Pa (equivalent to 0.48 m pressure head) and 147,150 Pa (equivalent to 15 m pressure head) for the compact gravel case. The findings of the qualitative CFD analysis therefore rejects the null hypothesis and support the theory that the existence of an idealised porous media external to a leak significantly increases the slit face loading (greater than one order of magnitude) and reduces the magnitude of the leak flow-rate due to the hydraulic resistance of the media. However, these CFD simulations assumed a constant leak area thereby isolating the leak and soil hydraulics from the structural dynamics for the analysis. In order to determine whether the results of these idealised numerical simulations reflect the real physical phenomena experienced by leaks in buried pipes, a series of physical experiments were designed and implemented in order to explore the complex interacting behaviour fully.

EXPERIMENTAL SETUP

A series of experiments were undertaken which recorded the synchronous pressure head, leak flow-rate, leak area and material strain under quasi steady-state conditions (slowly-changing) for an engineered longitudinal slit in medium density polyethylene (MDPE) pipe leaking into water and a porous medium.

Laboratory facility

The laboratory investigation utilised a 141 m length recirculating pipe loop facility at the University of Sheffield. The facility consists of 50 mm nominal diameter 12 bar rated MDPE pipe with water fed from an upstream holding reservoir (volume of 0.95 m^3) through a 3.5 kW Wilo MVIE variable speed pump. A 0.8 m removable section of pipe, 62 m downstream of the system pump, allows for the inclusion of different test sections housed within a 0.45 m^3 capacity box containing a single side viewing window. The flow-rate and pressure head data were recorded using a single Arkon Flow System Mag-900 Electromagnetic Flow Meter located immediately downstream from the system pump and a series of Gems 2200 Pressure Sensors, with data acquired at 100 Hz using a National Instruments (NI) USB-6009 Data Acquisition device (DAQ) and a Measurement Computing PMD1820 DAQ, respectively. Isolation of different sections of the pipe loop was achieved through the use of quarter-turn butterfly valves located at intervals along the pipe, including either side of the test section box.

A single test section was used for the experimental investigation consisting of a 0.8 m length of the same specification pipe as the main section but containing a 60×1 mm engineered longitudinal slit (Fox *et al.* 2014). The localised axial strain was measured using a TML GFLA-3-50 Strain Gauge attached using CN Cyanoacrylate adhesive parallel to the slit length and 0.531^c (radians) in the circumferential direction from the centre of the slit. Axial strain data were acquired at 10 Hz using NI 9944 Quarter-Bridge Completion Accessories connected by RJ50 leads to a NI 9237 4-Channel Module housed within a NI CompactDAQ Chassis. The leak area was measured using a non-intrusive image processing technique presented by Fox *et al.* (2012). Images of the visible leak during pressurisation and de-pressurisation were recorded at 3 fps by a GigaView SVSI High-Speed Camera through the side viewing window in the test section box, see Figure 4. The images were then analysed using an automated pixel count to quantify the leak area with a maximum associated error of approximately ± 3.82 mm^2. Based on the findings of Fox *et al.* (2014) and preliminary water-only experiments reported here, the axial strain can be used as a predictor of the synchronous leak area. By calibrating a linear relationship between strain and area, the dynamic leak area may be evaluated when it is not possible to visually quantify.

A repeatable methodology was established to compare the response of a leak into water and a fully constrained porous media at three discrete pressures. Test case A, leak direct into water, replicated the setup used by Fox *et al.* (2014). Test case B, leak into a fully constrained porous media, utilised a geotextile fabric (STABLEMASS 115)

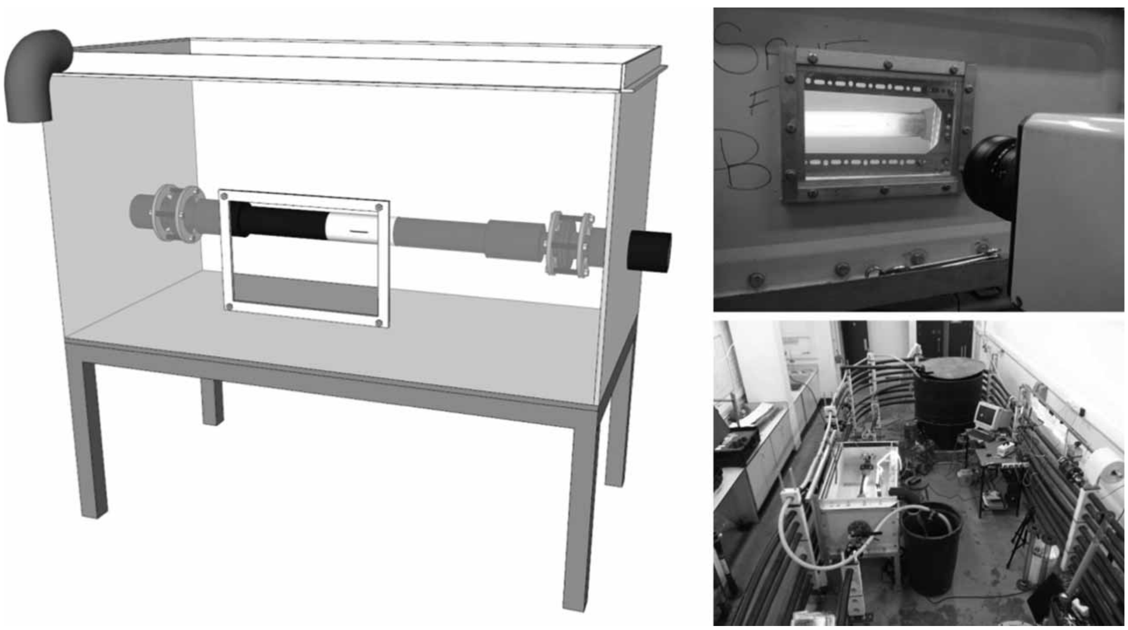

Figure 4 | Laboratory facility at the University of Sheffield.

with a permeability of 110 L/m^2/s. A 125 mm wide strip of fabric was wrapped three times around the pipe (approximately 5 mm total thickness), centred about the longitudinal slit, with negligible load or deformation transferred to the pipe, confirmed by the active strain gauge recordings during preliminary testing. The fabric was self-securing due to the inherent material texture. The use of geotextile fabric provides a consistent and fully constrained boundary condition (porous media), mitigating the occurrence of complex physical phenomena such as soil consolidation and fluidisation. Three discrete test section pressures of approximately 10, 20 and 26 m (actual initial pressurisation values listed in Table 1), set by constant pump speeds, were defined during preliminary testing. The chosen values provided a feasible range of test pressure heads based on the maximum capacity of the available equipment (e.g. size of pump). Each test case followed a pre-defined sequential loading sequence; pressurisation phase to 10 m head for 1 h, de-pressurisation phase (zero pressure) for 2 h and then repeated for 20 and 26 m pressure heads. A third set of experiments was also run to explore the effects of actual ground media external to the pipe/leak.

Table 1 | Summary table of results from 60 × 1 mm slit at three discrete pressures leaking into water and geotextile fabric. Net leakage refers to volume of leakage flow over 1 h pressurisation phase

Water			Geotextile fabric		
Initial pressure (m)	Net leakage (m³)	Mean C_d	Initial pressure (m)	Net leakage (m³)	Mean C_d
10.81	2.31	0.75	10.79	2.19	0.66
20.48	4.45	0.74	20.52	4.31	0.66
26.19	5.70	0.72	26.14	5.59	0.64

EXPERIMENTAL RESULTS

The response of the leak (longitudinal slit) into (A) water and a (B) porous media (geotextile fabric) were compared using measurements of the pressure head, leak flow-rate and axial strain. The initial pressurisations for each discrete pressure test are listed in the summary of results (Table 1). A pressure drop during the 1 h pressurisation phase resulted from the proportional increase in leak area and the constant input pump speed, with a maximum observed pressure drop of approximately 1.6 m for the 26 m initial pressurisation test case.

The results of the measured leak flow-rates for the two test cases are presented in Figure 5 where the data have been adjusted to $t = 0$ s for the start of each discrete pressure test case. The total measured volumes of flow (net leakage) through the leak were quantified by integrating the time

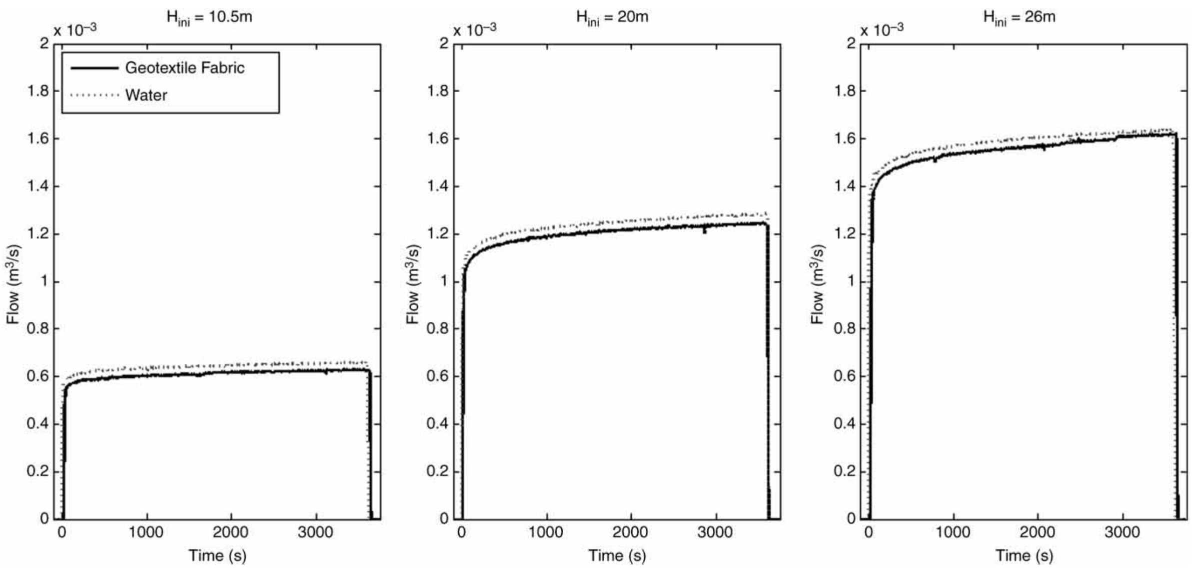

Figure 5 | Leak flow-rate through a 60 × 1 mm longitudinal slit at three discrete pressure heads into water (dotted line) and geotexile fabric (solid line).

series flow-rate for the 1 h pressurisation phase, with the results listed in Table 1. It was observed that the flow-rate through the geotextile was noticeably less than equivalent leak into water, greater than the instrumental flow-rate measurement error (<1%).

Alongside the measurements of fluid pressure and leak flow-rate, the synchronous structural behaviour of the leak opening was quantified. Axial strain measurements were recorded for both the water and geotextile fabric test cases, with leak area also recorded for the water case only. A fitting procedure between the measured leak area (mm^2) and material strain produced the linear relationship shown in Equation (1), assumed to be the same for both the water and geotextile test cases:

$$A_L = 16105\varepsilon_{ax} + 34.8 \quad (1)$$

The results of the recorded axial strain for both test cases are shown in Figure 6, which may therefore be considered as representative of the actual change of leak area due to the established linear association.

Axial strain measurements at the lowest pressure head displayed a very close correlation for both test cases. This is in contrast to the subsequent pressure head tests which resulted in a clear distinction between the structural response of the leak into water and geotextile fabric. Significantly higher strain values were measured for both the short (<10 s) and long term (>10 s) responses. Comparison of the geotextile fabric case to the water-only case showed a 9.3% increase in instantaneous axial strain response and 12.9% increase in ultimate axial strain response for the 26 m initial pressurisation test.

The results confirm that the existence of a fully constrained porous media, represented by the three-layer geotextile fabric, external to a longitudinal slit type leak results in a distinct pressure-leakage relationship due to the resistance of the porous media and the increase in time- and pressure-dependent leak area. In order to quantify the difference between the two test cases, the measurements of pressure head, leak flow-rate and the recorded and evaluated leak areas were input into the Orifice Equation to calculate the theoretical discharge coefficient, C_d (summarised in Table 1). The results of this analysis are presented in Figure 7 for both the geotextile fabric and water test cases.

The visible data spike at $t = 3{,}600$ s in Figure 7 is due to the small discrepancy in data acquisition time stamping between the flow, pressure and leak area data (less than ± 0.05 s). The mean discharge coefficient values for each test case and discrete pressure tests are summarised in Table 1.

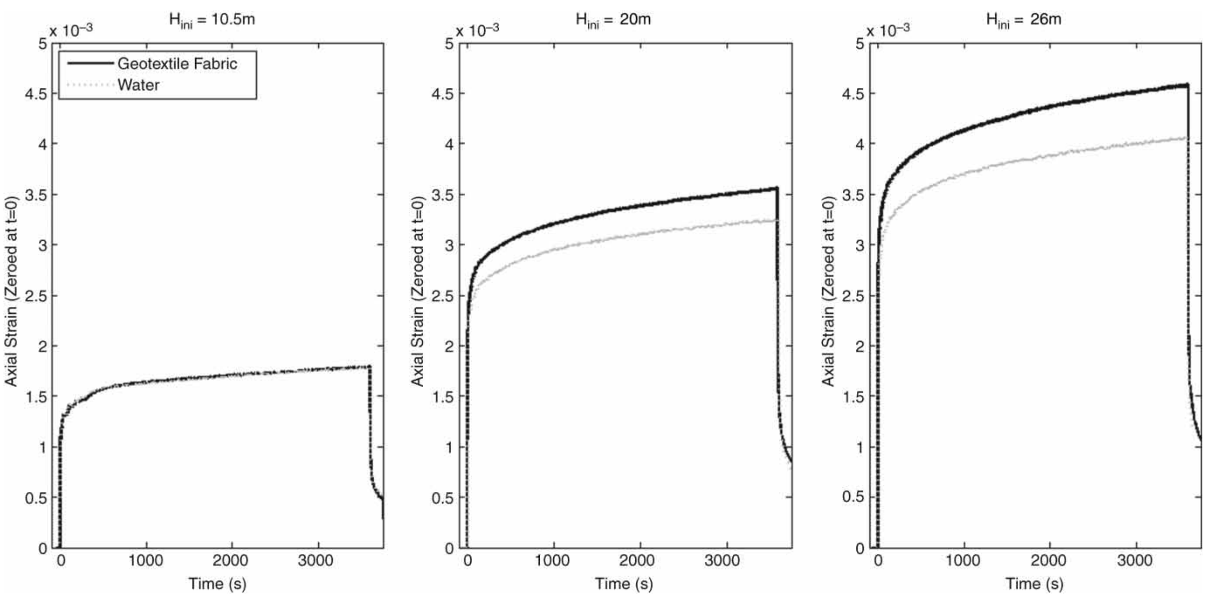

Figure 6 | Axial strain measured parallel to a 60 × 1 mm longitudinal slit in MDPE pipe at three discrete pressure heads for test cases into water (dotted line) and geotextile fabric (solid line).

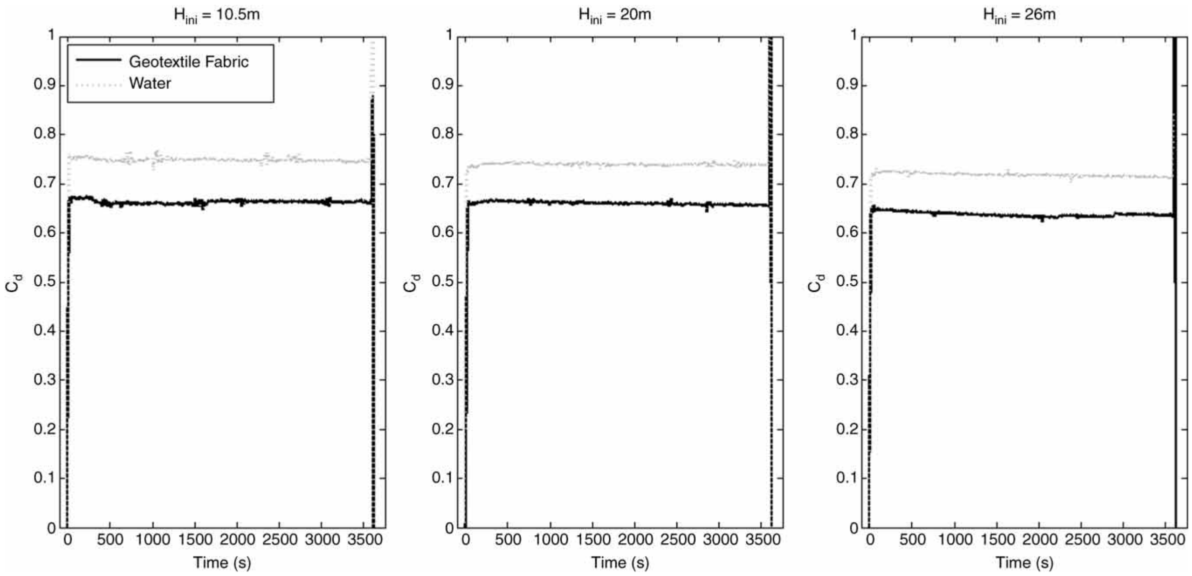

Figure 7 | Time series of evaluated discharge coefficients (C_d) for 60 × 1 mm longitudinal slit in MDPE pipe at three discrete pressure heads for test cases into water (dotted line) and geotextile fabric (solid line).

Additionally, the total standard deviation for the three pressure tests were evaluated as 0.0131 for the water test case and 0.0121 for the geotextile fabric test case, respectively. The results support the assumption that the application of a tailored constant C_d value (mean value ±2.5%) for different longitudinal slits is a valid approximation, despite the dynamic nature of the observed structural behaviour. A mean decrease of 11.3% for the geotextile fabric discharge coefficient relative to the equivalent C_d value for the water case was evaluated, emanating from the coupled influence of the dynamic leak area and the fabric permeability.

Finally, a qualitative physical assessment of the influence of a porous media more representative of those found in practice was conducted by burying the same test section in mixed gravel. An identical test procedure as utilised for the water and geotextile fabric cases was conducted, however, the results of the final pressurisation test only are presented in this paper as the leak became partially blocked during the first and second pressure tests. The test section was buried under 0.45 m depth of mixed grade pea gravel (approximately 5–12 mm diameter) consistent with the British Standard for backfill material for plastic pipework (BSI 1973). The initial pressure head was recorded as 26.15 m with an observed total head loss of 1.53 m over the 1 h pressurisation phase. The results for the measured change of axial strain and leak flow-rate are shown in Figures 8 and 9, respectively. The change of axial strain was utilised to account for the initial strain applied by the mixed gravel during burial, considering the effects of both compression loading and tensile bending.

Figure 8 indicates that there was an observable difference between the measured axial strain, and hence the leak area, for all three test cases with the leak into water displaying the smallest total structural deformation. From Figure 9 it can be seen that the leak flow-rates for the geotextile fabric and mixed gravel correlate well together, taking account of the step increase in flow-rate for the mixed gravel case at approximately $t = 1{,}100$ s, which is surmised to be due to the expulsion of a partial blockage within the cross-section of the leak opening. This correlation is considered to be due to the coupled effect of the porous media permeability and relative change of leak area for both test cases. These qualitative results support the hypothesis that a porous media external to a leak orifice will significantly influence both the hydraulics and the structural behavioural response of the leak, increasing the relative magnitude of change of leak area and simultaneously reducing the leak flow-rate due to the soil hydraulic resistance.

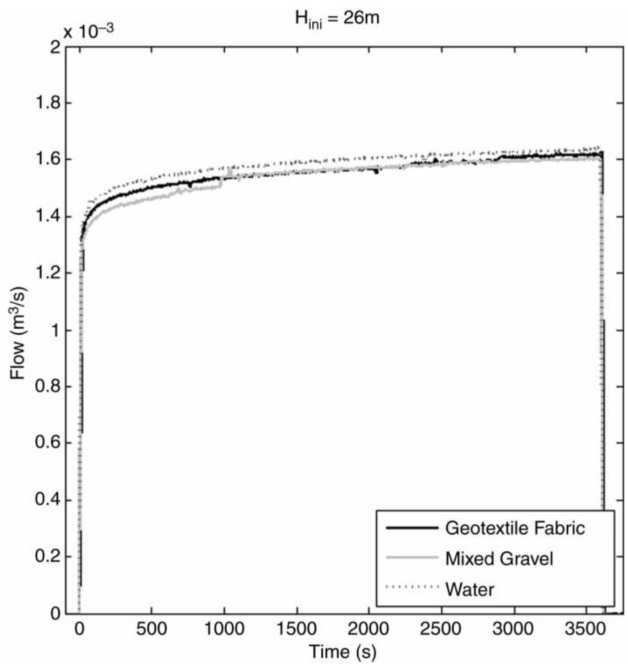

Figure 8 | Axial strain (change of strain) for a 60 × 1 mm longitudinal slit in MDPE pipe at 26 m pressure head for test cases into water (dotted line), geotextile fabric (solid black line) and mixed gravel (light grey line).

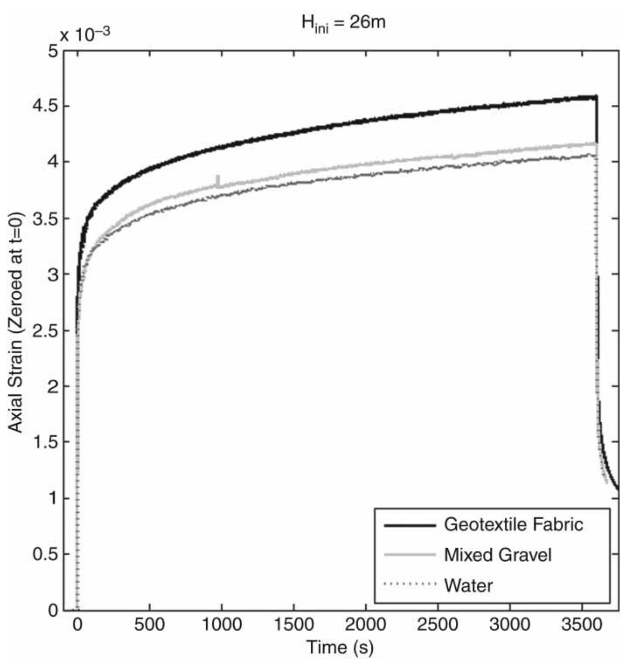

Figure 9 | Leakage flow rate for a 60 × 1 mm longitudinal slit in MDPE pipe at 25 m pressure head for test cases into water (dotted line), geotextile fabric (solid black line) and mixed gravel (light grey line).

DISCUSSION

The results of both the qualitative CFD simulations and the experimental investigation confirm that the existence of a porous media external to a longitudinal slit in a pressurised water pipe significantly influences the leak hydraulics, i.e. the magnitude of the leak flow-rate. Compact gravel was simulated within the CFD model and resulted in a constant slit face loading over 30 times larger than the equivalent loading for the simulated leak into water, and 75% of the pipe fluid pressure. Whilst the CFD simulations isolated the influence of the leak and soil hydraulics from the structural dynamics, the magnitude of the quantified slit face loading implied that this load case would result in a substantial increase in the relative total leak area.

The experimental work replicated the static soil zone using a geotextile fabric which allowed for the assessment of the leak and soil hydraulics as well as the structural dynamics. This idealised porous media resulted in a significant increase in leak area due to slit face loading, as demonstrated by the recorded material strain (compared to the leak into water case). However, the effect of this (to increase the flow-rate) was countered by the hydraulic resistance of the porous medium, resulting in lower overall leakage. It was shown that the observed leakage behaviour may be described using a modified form of the Orifice Equation, considering the measured time-dependent leak area, with a constant discharge coefficient. A theoretical constant C_d is applicable despite the dynamic structural nature of longitudinal slits in viscoelastic pipes, and includes the influence of the external soil hydraulics. The discharge coefficient may therefore be defined based on the explicit soil properties, providing the soil matrix structure remains the same, and the leak opening characteristics. Further work to determine whether this is also true for fluidised soil conditions is still required.

Walski *et al.* (2006) stated that in the real world, orifice head losses will dominate over the soil matrix head losses, thus dictating the leakage behaviour. Based on the results presented in this paper it is not feasible to confirm this statement as Walski *et al.* (2006) did not consider the effect ground conditions have on the dynamic leak area. The complex interdependence of the leak and soil hydraulics with the structural dynamics means that it is not trivial to assign a primary head loss component. By way of illustration, as the pressure in a buried pipe increases the leak area will increase due to the radial pressure distribution. The soil hydraulic resistance will therefore alter as the area of flow increases (based on assumption of Darcy flow), thus changing the resulting leak hydraulics. This resistance will then result in increased slit face loading, further increasing the dynamic leak area. Thus the effects are heavily coupled. Hypothetically, this coupling may result in equivalent leaks into water and porous media having the same magnitude leakage flow-rate at a given pressure, but distinctly different leak areas. The complex interdependence of the three parameters described is therefore critical in defining the leakage behaviour of buried leaks.

The magnitude of the influence a porous media external to a leaking orifice has on the observed leakage behaviour is dependent on the explicit permeability and resistance to fluidisation. The static geotextile fabric used within the experimental work represented an extreme no media movement or fluidisation case, highlighting the significance of the leak jet resistance on the structural loading due to occlusion as mentioned by van Zyl *et al.* (2013). The observed difference in the strain and flow rate measurements presented in Figures 8 and 9 for the quantitative water and geotextile fabric test cases and the qualitative results from the gravel test case show the variability in the influence of different porous media on the leakage behaviour. The relatively close correlation between the strain measurements for the water and gravel test cases at 26 m pressure head are surmised to be as a result of void formation or fluidisation of the mixed gravel immediately surrounding the leak, where the soil pore pressure exceeded the soil effective stress. This would result in a reduced slit face loading as the fluidised zone acts as a means of dissipating the energy, reducing the structural deformation relative to the non-fluidised geotextile fabric case. To fully quantify this effect, the structural influence of the gravel loading on the external surface of the pipe would need to be determined. However, the results do provide an initial insight into the influence of conservative and extreme external conditions on dynamic leakage behaviour whilst providing a platform for further work to consider the effects of different permeability media and leak sizes. Neglecting the existence of porous media surrounding buried pipes may therefore result in inaccurate estimations of the true leakage behaviour.

The presented work shows the importance of including slit face loading within the assessment of structural dynamics for deformable leaks. The CFD simulations of idealised compact gravel and the experimental results for the leak into a geotextile fabric present the worst case scenario regarding the magnitude of the slit face loading. In reality, the complex nature of soil structure and potential for void formation or fluidisation as a result of the presence of a leak jet may lead to more conservative slit face loading values. The axial strain measurements provided a unique opportunity to quantify the leak area of the longitudinal slits when the pipe is buried or wrapped in a geotextile fabric. The demonstrated effectiveness of this methodology therefore presents a potential tool for live asset monitoring in water distribution systems. Although it is not feasible to utilise strain gauges to measure leak areas in buried pipes, it may be possible to utilise them as a means of monitoring the structural integrity of pipelines by recording the magnitude of strain changes. For example, extreme changes in recorded strain may indicate the formation of a failure aperture within the vicinity of the strain gauge. Realistically though, the relationship between axial strain and leak area and the effectiveness of using strain gauges for assessment of the leak behaviour of buried pipes is more appropriate for further academic investigations of structural behaviour.

The Generalised Orifice Equation is commonly applied to define the pressure-leakage relationship for leaks within a District Metered Area (DMA). Results from field tests in several countries have highlighted the greater sensitivity of DMA leakage to pressure than described by the traditional Orifice Equation (Lambert 2001). The influence of different soil conditions, by location, on this relationship is possibly an important further area of research. Additionally, well constrained and consolidated soils reduce the relative leakage magnitude due to the inherent hydraulic resistance of the soil. However, the increased structural loading and subsequent increased deformation may lead to an increased risk of structural integrity failure. A detailed understanding of the influence of different soils on the pressure-leakage relationship of individual leaks may therefore advance the accuracy of the interpretation of DMA leakage assessments and subsequent application of leakage management strategies. Current leakage models describing the behaviour of individual leaks based on idealised conditions (neglecting the existence of an external porous media) may under- or over-predict the net leakage volume dependent on the specific soil properties (permeability, consolidation, degree of constraint and temperature) and interaction of this with leak hydraulics and structural behaviour of the pipe.

CONCLUSION

The results of novel physical experimental studies into leakage are reported, exploring the interdependence of leak hydraulics, structural behaviour of the pipe and the soil hydraulics. A novel synchronous data set is presented demonstrating the use of strain measurement as a direct proxy for leak area, enabling the measurement of dynamic leak area in buried conditions. The results showed that the existence of an idealised, fully constrained representative porous media (geotextile fabric) external to a longitudinal slit in a thick walled pipe, directly affects the pressure-leakage relationship. There was a measured increase in the time- and pressure-dependent change of leak area (measured strain). The increased deformation of the leak area was concluded as being a direct result of the increased magnitude of the slit face loading (supported by numerical simulation) which is dependent on the fluid pressure within the pipe and the external boundary conditions (porous media) affecting the head loss through the orifice. However, the overall leak rate was only increased by around 5%, as the increased leak area effect was counteracted by the hydraulic resistance of the media. Conversely, experimental results using mixed gravel media external to the pipe showed only a marginal increase in axial strain, and hence leak area compared to a water case, but overall leak flow rate approximated to the gravel case. This lack of dynamic leak area change is assumed to be due to the formation of a small void or fluidised zone immediately external to the leak, and the pressure dissipation effects provided by this providing significant pressure loss through the orifice. However, the media further from the leak still provide substantial overall hydraulic resistance. Further research is required into media effects, in particular void and fluidisation effects local to leak orifices using representative media. Overall, the research reported here shows that in order to accurately model and capture the leakage behaviour of dynamic leaks in buried pipes, the interacting effects of porous media permeability and slit face loading should be considered.

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