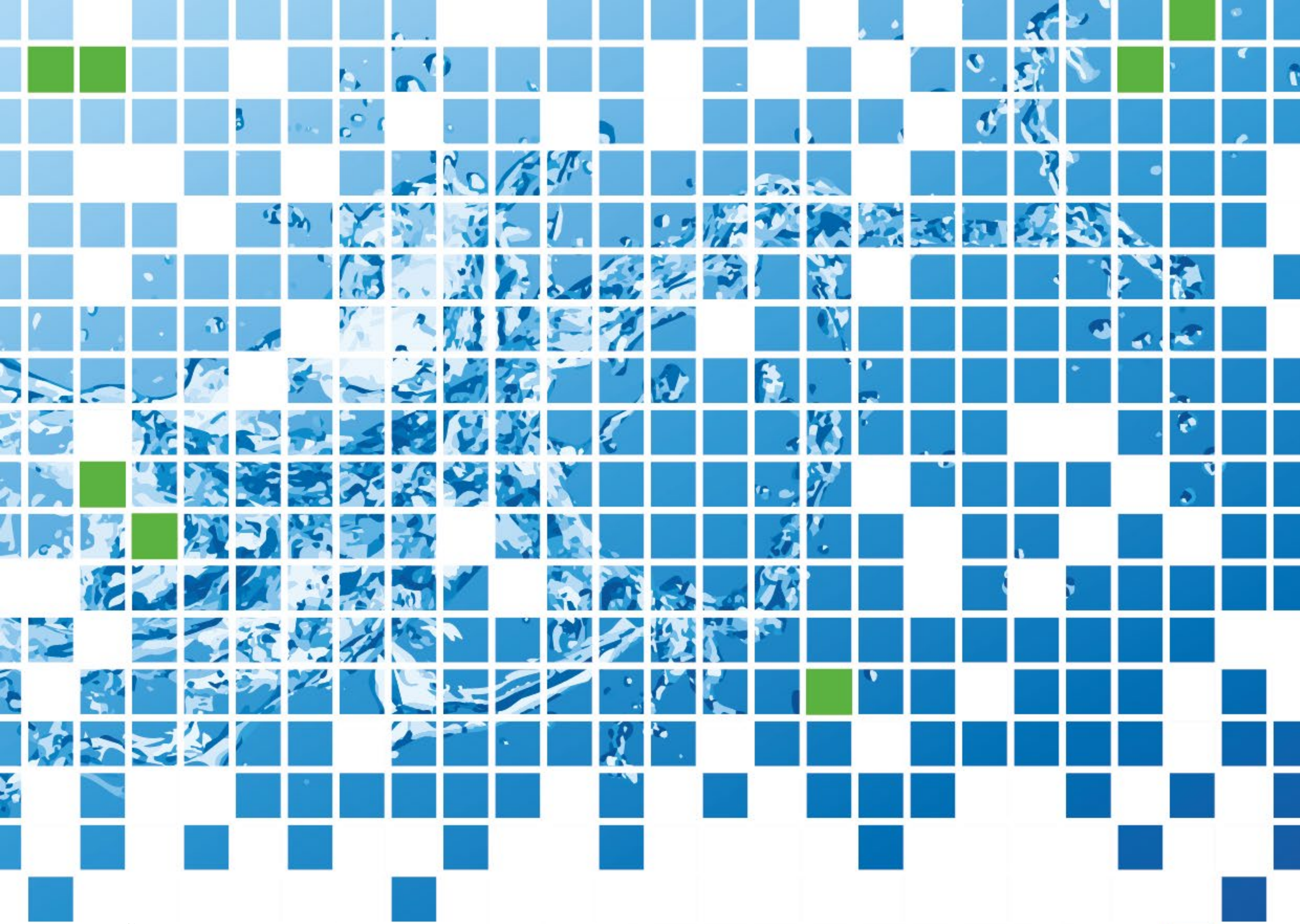

Co-UDlabs

Building Collaborative Urban Drainage research Labs communities

D7.4 Report on the development of mechanistic models to simulate deterioration of drainage assets

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Background: about the Co-UDlabs Project

Co-UDlabs is an EU-funded project aiming to integrate research and innovation activities in the field of Urban Drainage Systems (UDS) to address pressing public health, flood risks and environmental challenges.

Bringing together 17 unique research facilities, Co-UDlabs offers training and free access to a wide range of high-level scientific instruments, smart monitoring technologies and digital water analysis tools for advancing knowledge and innovation in UDS.

Co-UDlabs aims to create an urban drainage large-scale facilities network to provide opportunities for monitoring water quality, UDS performance and smart and open data approaches.

The main objective of the project is to provide a transnational multidisciplinary collaborative research infrastructure that will allow stakeholders, academic researchers, and innovators in the urban drainage water sector to come together, share ideas, co-produce project concepts and then benefit from access to top-class research infrastructures to develop, improve and demonstrate those concepts, thereby building a collaborative European Urban Drainage research and innovation community.

The initiative will facilitate the uptake of innovation in traditional buried pipe systems and newer green-blue infrastructure, with a focus on increasing the understanding of asset deterioration and improving system resilience.

List of acronyms

Acronym / Abbreviation	Meaning / Full text
DIC	Digital Image Correlation
ICAIR	Large test facility used in CoUDLabs - 45m x 6m x 5m test cell for testing buried pipes/assets.
IKT	IKT – Institut für Unterirdische Infrastruktur (Institute for Underground Infrastructure)
TA	Transnational Access
UDS	Urban Drainage Systems
USFD	University of Sheffield
WWTW	Wastewater treatment works

Executive Summary

This report is aimed at academic researchers, water utility engineers and R&D engineers involved in the design, construction and maintenance of wastewater sewer and stormwater drainage pipes who need to (i) understand the impact of joint defects on pipe performance, and (ii) to provide evidence on the key parameters regarding displaced pipe joints that impact on the amount of exfiltration/infiltration experienced.

In-pipe joint defects are one of the most common defects found in sewer and stormwater drainage systems. They are known to cause both infiltration and exfiltration; both of these processes can have a significant impact on the performance of such systems. There is strong evidence that exfiltration of wastewater can contaminate local groundwater. This has an environmental impact but can have public health implications if water supply pipes located close to the failing sewer are also leaking. If the water supply pipes are managed inappropriately in terms of their pressure management so that transients (with +/- ve pressures) are allowed to be created, then there is a significant risk that pathogens within the wastewater could enter the public water supply. Infiltration also causes significant issues in that in areas with groundwater higher or similar levels to the wastewater collection sewer or stormwater sewer levels then a significant proportion of the flows carried by these sewers is simply infiltrated groundwater. This results in excess flows to the end of system wastewater treatment plants, resulting in poor quality treatment and high energy use, or more frequent spills from combined sewer and storm sewer overflows due to the hydraulic overloading caused by the infiltration of groundwater. Both issues cause significant environmental harm, either through the more frequent spills, or the enhanced energy use (and carbon emissions) from the large volumes treated at end of system wastewater treatment plants.

Given the significant impacts caused by displaced joints and the widespread prevalence of displaced joints it was decided to focus on the underlying mechanisms associated with joint displacement and infiltration and exfiltration. Two complementary series of experiments were carried out at IKT, in Germany and the University of Sheffield in the UK. These experiments required the joint development of new measurement techniques, visits and the sharing of data. The results of these experiments provided the data to start to identify and quantify the potential joint mechanisms that control exfiltration from jointed pipes in soil

The results indicated that the pipe material (and relative stiffness) of the joints and pipes were important. In stiff pipe materials such as concrete and vitrified clay the exfiltration rates increased as the angle of relative pipe articulation increased. In PVC pipes after a small angular articulation the exfiltration rate did not rise. Detailed in-pipe measurements using a Digital Image Correlation system indicated that the pipe walls had deformed, and this is an explanation as to why the rise in exfiltration rate essentially stopped even though the pipes were articulated to a larger angle.

Exfiltration was only observed when the joint seals were damaged. In the initial tests in which undamaged joint seals were used, negligible amounts of exfiltration were observed.

In tests with a concrete pipe buried in soil exfiltration rates were larger in size than the exfiltration rates observed in the tests at IKT, in which the pipes that were not buried. This shows that the presence of the pipe bedding material does not appear to impact on the exfiltration rate and that the exfiltration rate is controlled by the condition of the joint and not the surrounding material.

Further tests were carried out in which the buried pipe was loaded with a cyclic load that mimicked a heavy goods vehicle. Even with cycles that represented over 238,000 cycles no appreciable increase in exfiltration rate was observed.

In summary, pipe material is significant, it is important to measure the internal displacement within the pipe as the external angular displacements do not correlate well with the joint displacement especially if the pipe material has a relatively low stiffness. (e.g. PVC). In pipes with stiff pipe wall material such as vitrified clay and concrete exfiltration rates rose with the size of the relative angular articulation between the pipes. Exfiltration rates were also related to the size of joint seal damage. Exfiltration rates were related to the level of water in the IKT pipe and the USFD upstream manhole. More analysis is needed to assess the reason for the differences. Comparing pipes in the air and those buried in high porosity bedding material, the rate of observed exfiltration does not appear to be restricted by the bedding material.

1 Introduction

Sewer and stormwater drainage networks consist of mainly buried jointed pipes. These networks are large and complex and contain a range of underground assets. These assets are expected to operate for many decades and are subjected to a range of forces, which are influenced firstly by internal factors such as water flows and pressures, and secondly by external factors such as local soil and traffic loading conditions.

There have been a small number of academic studies that have aimed to investigate how in-pipe defects develop but these have often been hindered by scale or instrumentation issues. Some lack complexity and scale, and simulate the pipe defect in a simplistic manner, e.g. the small-scale experiments of Guo et al., (2013), and Tang et al. (2022) studied the impact of pipe exfiltration on the erosion of surrounding soil, and others have used small scale pipes with poorly described defects for example Khan and Patil (2018) in their testing on measuring in-pipe cracks. Typically, academic studies use small scale surrogates that lack the complexity of the full-scale system. It was an objective of this work that full-scale surrogates would be used to better understand the mechanisms behind deterioration. In trying to achieve this objective we appreciated not only the difficulty in measuring defect development but also the wide range of possible defects that could be studied. The team examined the data on defect type likelihood in order to select a relevant defect in terms of likelihood. Berger et al., (2020) indicated that the third most common defect in sewer and drainage systems was defective pipe connections and joints.

Studies in the UK have estimated that 40-50% of the flow entering wastewater treatment works (WWTW) in at least 25% of the sewer catchments in the UK is from unintended infiltration via leaky joints (UKWIR, 2012). Indirect evidence of large-scale infiltration is strong with many WWTPs treating unexpectedly larger daily flow volumes with the subsequent higher energy use and carbon emissions. This “extra” flow results both in unnecessary wastewater treatment and in the worst-case scenario localised flooding and extra overflow spills due to system capacity exceedance during extreme weather events. This indicated that defective pipe joints/connections can have a significant impact on the performance of many sewer and drainage systems.

The physical resilience of shallow, buried pipe systems is ultimately governed by the geotechnical properties of the fill surrounding the pipes. Sewer and drainage pipes are susceptible to joint articulation and deformations because they are generally only partially full and thus buoyant relative to surrounding water-filled backfill. Such pipes are mostly buried in the vicinity of the ground water table, the surrounding soil is partially saturated. Often these pipes are buried close to the ground surface so suffer from surface loading such as from traffic. Elshesheny et al., (2019) observed that pipes buried deeper experienced lower stresses and less deformation than pipes installed closer to the ground surface. Wu et al., (2020) indicated that pipes buried at a depth of less than 5 pipe diameters are particularly susceptible to dynamic loading. This is the range of depths that many sewer and drainage pipes are buried. Small scale testing by Ratkitin and Xu, (2015) indicated that applied traffic loads to concrete pipes could have an impact on vertical displacement and rotation. So, although the geotechnical community has investigated the potential for joint displacement and movement, these studies have never examined the potential infiltration/exfiltration from a displaced joint.

Therefore, researchers at USFD and IKT decided to investigate the levels of infiltration/exfiltration possible from displaced joints (measured at full-scale) and if the level of joint displacement would be replicated in a buried pipe under realistic loading. As the investigation progressed, an instrumentation need was identified, that is the need to be able to measure the actual internal displacement and rotation within a joint that had been loaded so that the tests at both IKT and USFD could be compared. A second requirement was added to the investigation and that was to develop a measurement method to measure the movement of internal pipe joints so that we could investigate what type and level joint movement could be linked to infiltration/exfiltration rates.

By gaining such information for typical sewer pipes, it was intended to elucidate the mechanisms that may be the cause of joint displacement and subsequent exfiltration/infiltration in shallowly buried sewer and drainage pipes.

2 Development of In-pipe joint displacement measurement

During the planning phase of the work, it was recognised that there was a need to measure the internal displacement inside the pipe. It was decided to examine the potential for developing a low-cost, robust image-based system that could be deployed in full-scale pipes in the laboratory. Digital Image Correlation (DIC) was selected as the technique to use. As the name suggests DIC is an optical technique enabling accurate non-contact deformation, displacement, and strain measurement in structures. DIC is based on the analysis of changes between images taken before and after deformation of a target surface from cameras of known spatial and optical characteristics. Depending on the task multiple cameras are used. There is no evidence in the literature that DIC had been used before to measure the inside characteristics of the curved surface of the inside of a pipe. The advantages of using DIC is that it is a non-contact technique that can be used at a variety of distances from the target surface. DIC provides a Full-Field Measurement unlike point-based techniques such as strain gauges and therefore provides a more comprehensive view of deformation and strain over the entire visible surface of the specimen. DIC is material agnostic and can be performed on any material or system capable of carrying the required speckle overlay.

The measurement requirement was to develop a system that could operate inside a jointed 300 mm internal diameter pipe with the aim of measuring the articulation between two pipe sections and surface deformations at the joint. In the design phase there was a focus on image capture and camera geometry calibration. The system had to be low-cost, and capable of sharing with other CoUDLabs partners such as IKT. Appropriate lighting is essential to avoid inconsistencies, shadows and reflections that result in poor image quality. The in-pipe device was required to generate a repeatable and reliable light illumination as cameras once calibrated may not be altered either in physical orientation or optical adjustment (Focus or Aperture) without the need to fully recalibrate the device. The processing of high-resolution images can be computationally intensive. For this reason, it has been decided that the analysis be undertaken on a computer that was optimised for the commercial DIC software offered by Dantec Dynamics.

In the absence of real-time quality feedback from the on-board acquisition software there is a need to generate significantly more frames than would be expected from a commercial system. It is expected that many images will be discarded by the image processing software in order to achieve optimal calibration and measurements. It will not be possible to return the device to the test pipe and retake images, so sufficient on-board memory to recover several 10’s of images.

The solution to this requirement was four low-cost cameras, placed on a frame which aligned the four cameras in a geometry that provided overlapping images of the far pipe wall in a 300 mm diameter pipe. The camera frame was placed on a wheeled trolley that could be dragged into a pipe. The frame also contained a Raspberry Pi 4B with 8GB Ram, 4 x 1 Mp Monochrome cameras obtained from an Arducam 1MP*4 Quadrascopic Monochrome Camera Kit - B0267, a synchronised global shutter, ancillary power for electronics and the illumination source. Remote access via wireless connection was provided and custom Python scripts for calibration and measurement image acquisition and for preprocessing images in preparation for final analysis using the Dantec Dynamics software. Dantec Dynamics offered technical support as they are interested in seeing if their current software product can be enhanced for the internal measurement of pipes. It is the intention to continue working with the technical specialist from Dantec Dynamics to publish an open access publication on the development of this system and its use in this Joint Research Activity. Dantec Dynamics are also examining the technical feasibility of enhancing their software by including a definable cylindrical co-ordinates Frame of Reference option in their software, rather than just 3D orthogonal co-ordinates to make their software more user friendly for end users wishing to use their DIC system within pipes.

The 4-camera system used at IKT is shown in Figure 1.

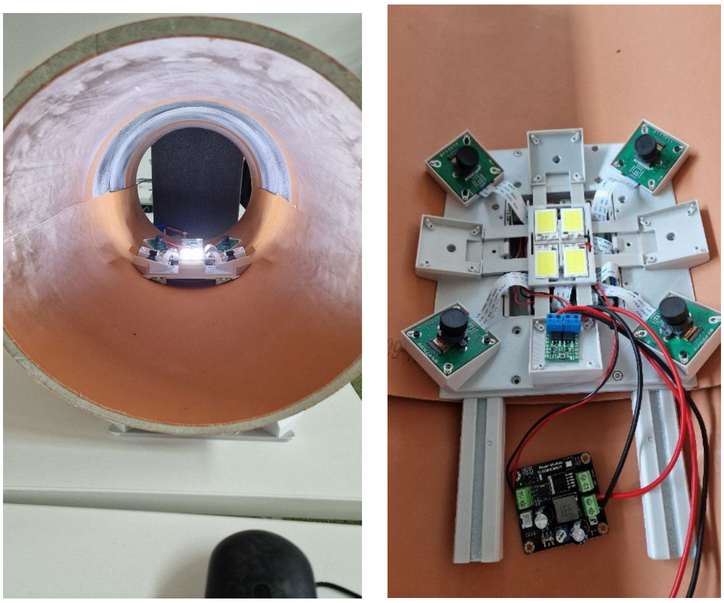

Figure 1. Four camera low cost DIC system, with central illumination system, placed in pipe with illumination in use for image capture

The camera array geometry is calibrated before any in-pipe measurement can be taken. This is achieved by taking multiple synchronised images of a calibration target of known dimensions. By moving the target around the field of view and varying the spatial attitude, each camera's view can be cross referenced and an accurate geometry for the camera array is established. This can be done before or after installation into the pipe, access space permitting. Figure 2 shows calibration target images being accepted for calibration by the DIC software. Green circles highlight points of geometric confidence. In an offline system multiple images need to be taken, and sub-standard images discarded manually to ensure accurate calibration.

Figure 2. Calibration images for the DIC system, taken inside of a 300mm dia concrete pipe with bespoke calibration target

To present accurate image data to the correlation algorithm care should be taken to maintain the original pixel data as captured from the image sensor without alteration. This means common image compression formats such as jpeg must be avoided due to the irreversible changes inherent in the compression process. RAW, DNG and Bitmap images offer the highest fidelity and flexibility. There is several post processing actions required to prepare the ARDUcam images for DIC analysis. This is done using the Python image capture and processing software that was written for this application. Figure 3 shows the single output image from the four cameras. This image was split into its constituent 1280 x 800-pixel images with a simple cropping function. The individual images were then changed from native 10 bit to 8 bit monochrome and labelled for each camera. This image data was now ready to be processed by Dantec Dynamics DIC Istra4d software.

Figure 3. Camera cropping - The original image is output as a composite of all four cameras in the array at a size of 5120 x 800 pixels

Images taken from within the IKT pipes were processed with their calibration files to resolve pipe geometry and surface profiles in Dantec Dynamics Istra4d software. From these evaluations various line and point gauges can be applied to extract information as required. To assess the articulation across a pipe joint a gauge line is placed along the pipe axis across the joint to create the baseline x-axis with the z-axis being normal to the pipe surface. This line will contain spatial data for pipe walls at either end and typically an area of noise or blank data corresponding to the occlusion / discontinuity at the joint. Using one pipe as a baseline the angle between the two pipe walls can be calculated. With the current optical array up to a 15cm gauge line is typically available for analysis considering the field of view of the cameras and variable quality of images, giving a ~70mm gauge line for evaluation of each pipe wall. Results show this scale to be adequate for rigid materials such as Concrete and Clay, but gross angular displacement in Plastic pipes are underestimated near joints where load stresses contribute to local material deformation (Figure 4a and 4b). DIC successfully captures the deformation as it presents at these scales at a high accuracy.

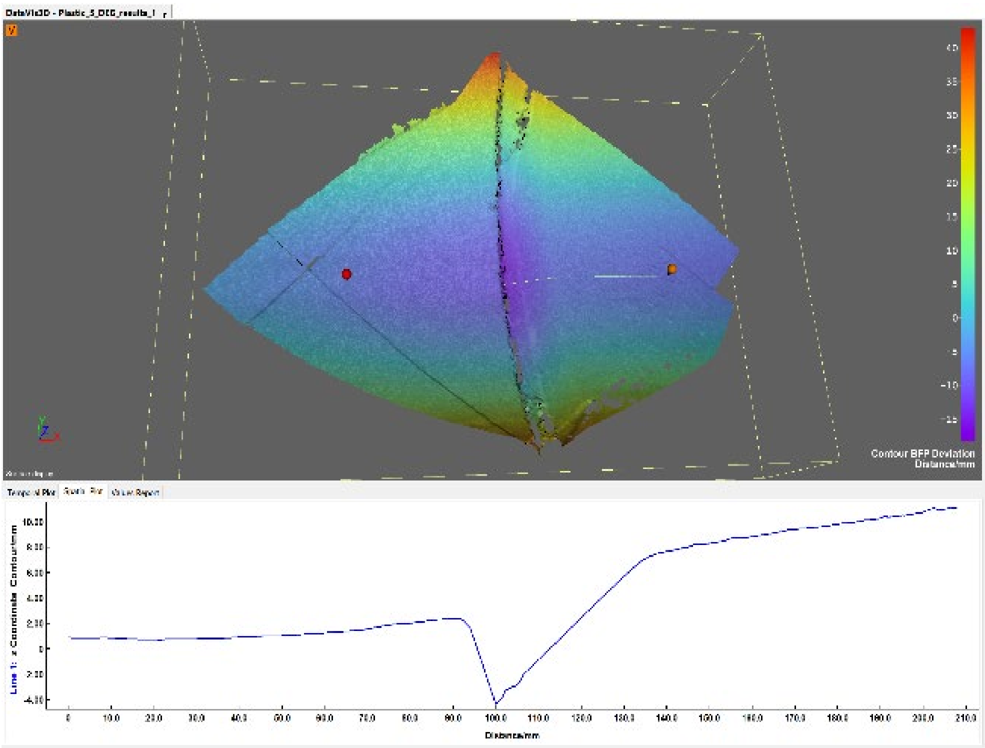

Figure 4a. Typical output of line gauge assessment – Clay 2°. Screen shot from Dantec Dynamics Istra4D software. Colour indicates level in the z axis, if x axis is taken as the axial direction

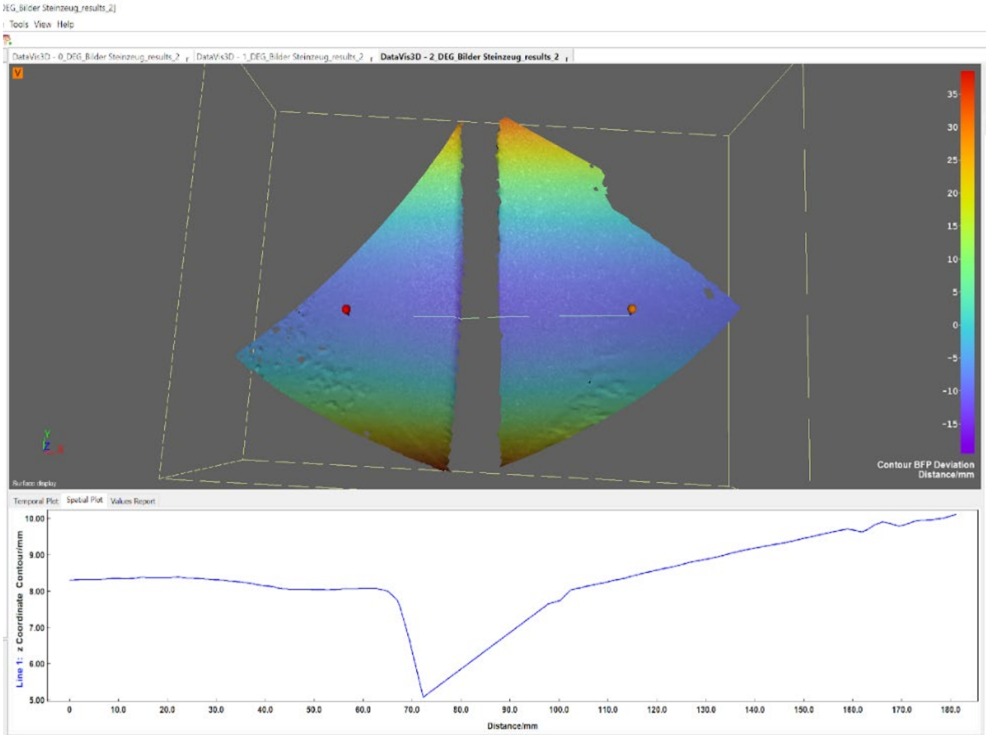

Figure 4b. Typical output of line gauge assessment – Plastic 5°. Screen shot from Dantec Dynamics Istra4D software. Colour indicates level in the z axis, if x axis is taken as the axial direction

3 Complimentary Laboratory Testing at IKT and the University of Sheffield

3.1 Introduction to test program and facilities

The program of tests was designed so that staff at USFD carried out experiments to investigate the impact of pipe movement and potential exfiltration or infiltration through pipe joints that are buried in an approved pipe bedding material. Given the size of this test only one pipe type could be examined. These were complemented by many tests at IKT, in which several full-scale pipe configurations were examined. These pipes were not buried but could be articulated and the joint seal systematically damaged to investigate further factors that may impact on the level of exfiltration that may result from a displaced or damaged joint.

The large-scale test setup at USFD was slightly modified from a Co-UDLabs Transnational Access (TA) project set-up. This was used to ensure a good use of resources. The test setup consists of connected, jointed concrete pipes (300 mm in diameter) and manholes, placed in conventional, compacted bedding material at USFD's ICAIR facility see Figure 5a and 5b. The surface loading was dynamic and designed to simulate periods of heavy traffic loading.

For the experiments at USFD, it is of interest to know at what level of damage in the pipe joint and at what level of angulation of the connected pipes a corresponding measurable loss of water (exfiltration) is to be expected. This makes it easier to estimate the loads that need to be applied at USFD to create corresponding damage patterns in the joints with leaks.

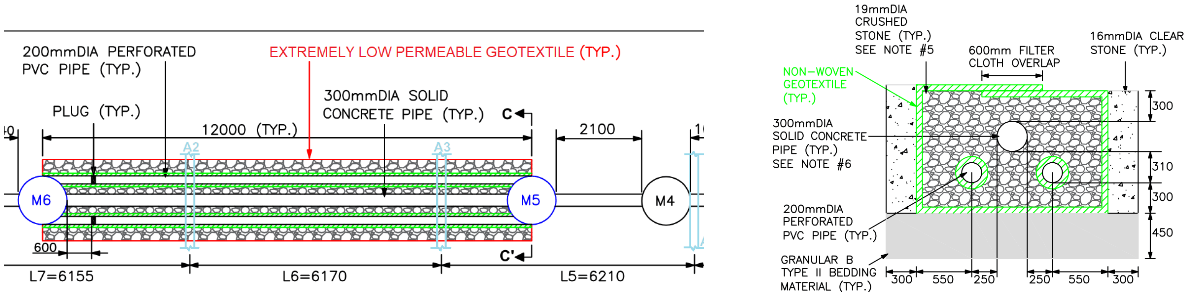

Figure 5a. (left) Long section ICAIR test setup
Figure 5b. (right) Cross-section

In addition to the information on the level of joint displacement there is also the fundamental question of the extent to which specific damage to the pipe joint seals leads to measurable water losses (exfiltration) that exceed the permissible water addition value in the leak test (see current standard BS EN 1610:2015-12). Defects to the joint of pipes (displaced, sealing, settlement protruding) is the third most common type of defects (see results of Berger et al. 2020). Exfiltration of wastewater into soil and groundwater through leaking pipe joints is usually not detectable. In addition, infiltrating groundwater is not always visible, as this can depend on seasonal fluctuations in the groundwater level. In view of an efficient maintenance strategy, knowledge about leakage mechanisms depending on the damage in the area of a pipe joint is essential. Therefore, preliminary tests were implemented at IKT to understand the scale of exfiltration that could result from displaced pipe joints that had been articulated in a controlled manner.

The main objective of the IKT tests was to determine the leaks in damaged pipe connections considering the size of the damage, pipe angulation and water level. To this end, systematic investigations were carried out on three different pipe materials – PVC, concrete and clay – including their associated sealing systems, in order to analyse the exfiltration behaviour and gain insights relevant to practice. In addition to the exfiltration tests, a DIC system, developed at USFD was placed in the angled pipes that uses 4 cameras to record and “measure” the movement of the inner pipe walls to measure the actual deformation experienced by the pipe joint. The IKT tests were able to assess the risk of exfiltration based on physically measured changes in the external positions of the pipes and optically detectable changes in position of the pipe walls over a wide range of angular articulations for the three different types of pipe materials.

The IKT test setup consisted of two pipes, one inside the other (Figure 6). One pipe is placed on a frame and secured horizontally with two tension belts. The other pipe lies on a movable frame that can be tilted downwards to create the desired angle. The frame is attached to a 5.5 cm thick metal plate and provided with iron rings for stabilisation. A tension belt pulls the pipe downwards and also secures it in position. The test setup is suitable for PVC and clay pipes. Since the concrete pipes have a so-called foot, the frame or supports are adapted accordingly.

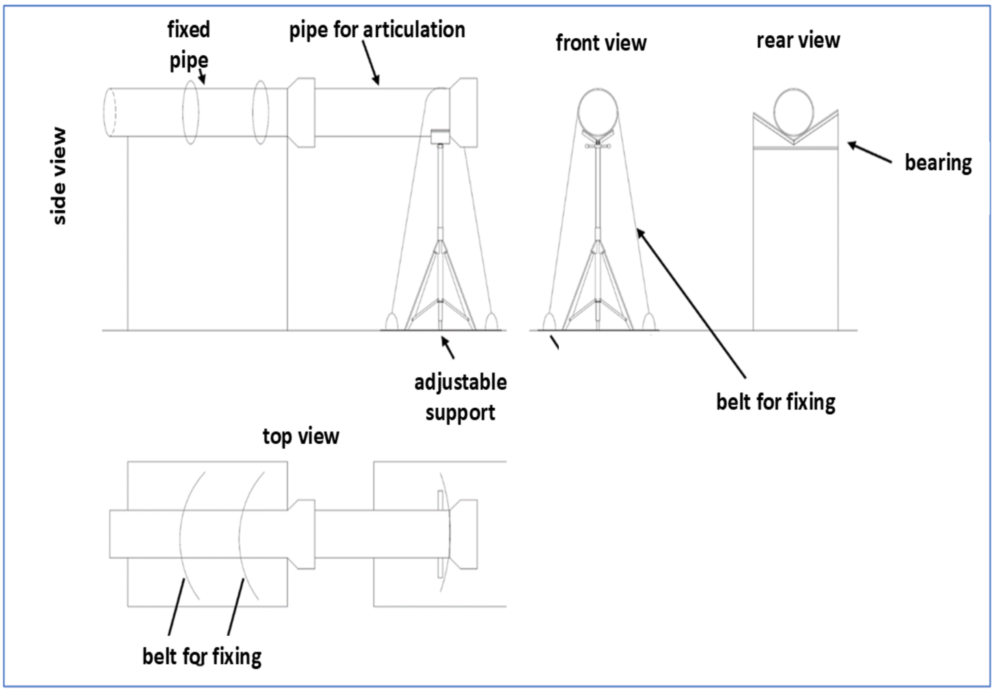

Figure 6. Sketch of the IKT experimental set up

3.2 Measurement Equipment and Program - IKT tests

The following experimental methods were used for articulating the pipes and measuring the resulting exfiltration rates.

3.2.1 Measuring water tightness and exfiltration rate

According to DIN EN 476, the test pressure for internal water pressure in wastewater pipes outside of buildings is 0 bar, increasing to 0.5 bar. The leakage measurements were carried out with a water pressure of 0.5 bar. To achieve this pressure, a water column was used with a height of 6 m minus the height at which the pipes are located, 1 m which results in a net height of 5 m. Sealing bladders at the end of the pipes were used to create a test space in the pipes (see Figure 7).

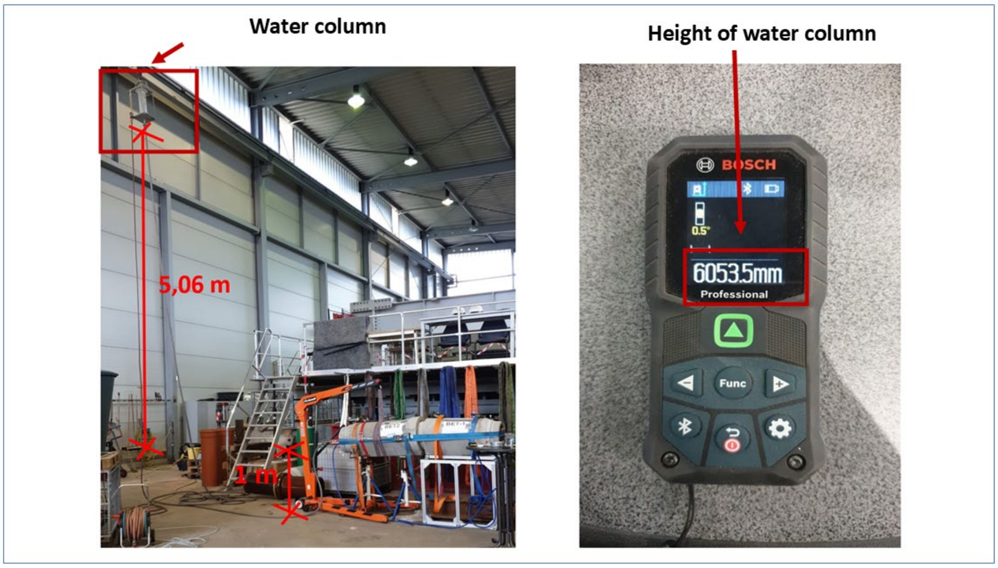

Figure 7. Water pressure set up for water tightness test

The exfiltrated water was collected in a measuring beaker. During the experiments, the measuring beaker was held under the pipe connection for 60 seconds to collect any leaking water. The mass of the filled beaker was then determined. The exfiltrated amount of water was calculated by subtracting the empty weight from the total weight of the filled beaker; this value was converted to volume and so the exfiltration rate was determined taking into account the duration of the measurement.

3.2.2 Setting and measuring the angle of inclination

The angulation of the pipes was controlled using the support frame support shown in Figure 6. To measure the angulation, an inclinometer was placed on the angled pipe and it displayed the angle. In addition, the angles were checked by using measuring rule spirit level and trigonometric functions. Furthermore, black marks were applied to the pipe connections to show that the pipe was really being angled and these marks were checked for consistency. This provided the external angle between the pipe sections.

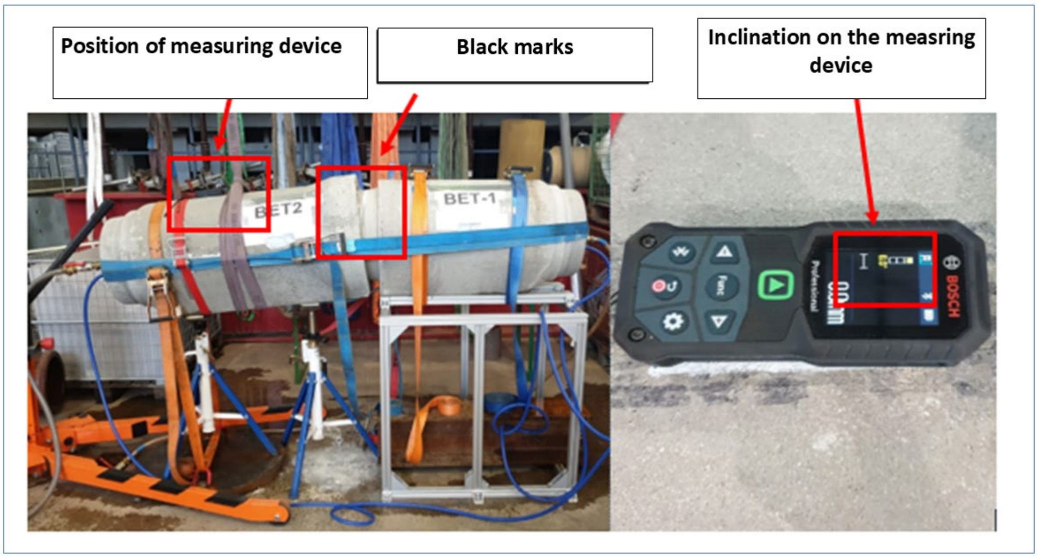

Figure 8. Test setup and equipment used to measure the external angle of articulation

The four camera in-pipe DIC system was used to measure the internal deflections within the pipe joint as one of the pipes was articulated to the desired angle (Figure 9). This measurement was made before the internal bladders were installed to create a watertight rig. See Section 3 to describe the capabilities of the DIC system.

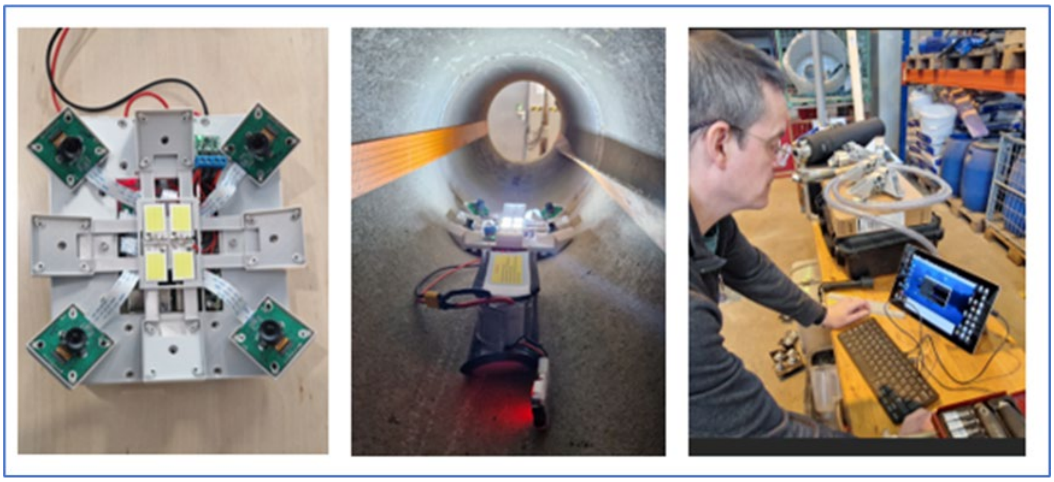

Figure 9. Four camera In-pipe DIC system used to measure the internal pipe wall articulation

3.3 Experimental Results

Two test series were conducted, in the first test series, using scenario 1, see Table 1 tightness tests of undamaged pipe seals and connections were carried out under an internal pressure of 0.5 bar. First, the pipes were assembled and then each open pipe end was sealed with a watertight bladder to ensure that no water escapes during the test. The pipes were then completely filled with water. The pipes were then articulated starting at horizontal then each angle (1° step size) was tested for tightness for 15 minutes, with any escaping water from the joint (exfiltration) being collected and its quantity weighted so that an exfiltration rate could be determined.

Test scenario 1 gave similar exfiltration rate results for all pipe types. All undamaged PVC pipe connections were watertight at angles of 0° to 7°. The concrete and clay pipe joints were found to be watertight between 0° and 5°; at a further increase in the angle, the pipes began to slip out of the connection (seal), so that it could not be determined beyond doubt whether the water was leaking through the damaged seal or due to the pipes “slipping apart”. In the second series of tests, in which a single defect was installed in the joint seals the following pattern of behaviour was observed.

Test scenario	Test procedure	Angle of inclination	Position of the defect	Filling level / water level
1. Undamaged pipe connections	Testing the tightness of the pipe connections at different angles of inclination	PVC: 0°-7° Concrete: 0°-6° Clay: 0°-6°°	-	Fully filled and 0.5 bar overpressure
2. Pipe connections with a single crack, initially small and then enlarged, in the seal at one point in each case	Conducting the tests at different angles and filling heights, as well as different positions of the damage in the seal of the joint	PVC: 0°-7° Concrete: 0°-6° Clay: 0°-6°	6 o’clock or 3 o’clock	6 cm 18 cm 24 cm

Table 1. Experimental test series for IKT tests

3.3.1 PVC Pipes

A “small” linear defect was created in the seal at the joint of the PVC pipe. The size of the defect corresponds to the width of the blade of the knife used to create the defect. The defect was approximately. 0.4 mm in width see Figure 10, left. The damaged seal is located in the pipe floor (6 o'clock), water levels of 6 and 18 cm were set. Exfiltration was observed at angles between 0° to 2°, with the amount ranging from a negligible rate at 0° angle to 0.004–0.029 l/min as the pipe was articulated up to a 2° angle. At higher angles of 3° to 6°, there was no observed exfiltration. In tests with the damaged seal in the pipe's transom area (3 o'clock), no exfiltration was detected either at these higher angles - see Appendix A1.

In the test series with the damaged seal at 6 o'clock (pipe base) and a filling level of 6 cm, exfiltration of 0.004 l/min and 0.029 l/min could only be measured at an angle of 0° and 1° with a crack width of now observed to be 2 mm in width. There was no water leakage at larger angles. At a filling level of 18 cm, exfiltration in the range of 0.102 l/min to 0.501 l/min were again measurable at low angles between 0° and 2°; in the articulation range of 3° to 7° the exfiltration rates were at a maximum of 0.004 l/min, but mostly negligible exfiltration rates were visible.

When the crack (2 mm) was located in the area of the top of the pipe at the 3 o'clock position, a drop formation was only detected at a filling level of 18 cm when the angle was between 0° and 3°, and a maximum water loss value of 0.051 l/min was measured. In contrast, no water leakage was detected at larger angles in the range of 4° to 7°.

Overall, the PVC pipes examined here tend to show greater exfiltration at low angles than at higher angles (above 3°). This was a common observation for all water levels and defect sizes and positions.

Figure 10. Left: crack measured with an electronic caliper.
Right: location of damaged seal in PVC pipe at 6 o'clock

3.3.2 Concrete Pipes

A "small" linear defect was created in the seal at the joint of the concrete pipe, the size of the defect was approximately 0.4 mm in width, however cutting through the elastic seal resulted in a wider defect, approximately 2.7mm in width - see Figure 11. Initially, tests were carried out on seals with a defect located in the pipe floor at 6 o'clock. In the 6 cm water level tests, there was almost no exfiltration at angles of 0° to 2°. At angles between 3° and 5°, exfiltration rates of 0.006 l/min to 0.175 l/min were measured. At a water level of 18 cm in the pipe, the exfiltration rates were between 0 and 0.328 l/min at angles of between 1° and 5°. The pipe connection was watertight when the pipes were not angled (0°). Compared to the PVC pipes, the angle already ends at 5°, as the pipes slid apart at higher values and thus no further investigations would have been possible. If the small crack is located in the area of the pipe abutment (3 o'clock), a comparable exfiltration behaviour to the previously described tests can be seen at a water level of 18 cm (corresponds to 3 cm coverage). No water escaped at angles between 0° and 3°, and at 4° and 5° the exfiltration rate was between 0 and 0.2 l/min. At a water level of 24 cm, water leakage of 0.47 l/min was measured only at an angle of 5°. See Appendix A2.

A defect in the seal of 6mm in width was then created for further tests. The damaged seal is located in the pipe floor (6 o'clock), water levels of 6 and 18 cm were studied. Exfiltration was observed at all angles between 0° to 6°, with the amount ranging from 0.307→1.884 l/min. At higher angles, exfiltration was observed to increase significantly as the articulation angle increased. In tests with damaged seals at different radial locations, the same pattern was seen, increased exfiltration with higher degrees of articulation, and higher values of exfiltration with the larger seal defect.

Figure 11. Left: defect in seal at 6 o'clock. Centre: measurement of the width of the crack (2.7 mm). Right: length of the defect in the seal 59mm

3.3.3 Clay Pipes

Finally, a defect was created in the joint seal for the clay pipes, as is shown in Figure 12. Here, too, the same knife blade (width of crack = 0.37 mm) was used to damage the seal as previously for the PVC and concrete pipes. First, the exfiltration behaviour is examined with the crack in the pipe floor (6 o'clock) at different water levels, as before. For a water level of 6 cm, the pipe connection remains tight between 0° and 5° angling. At an angling of 6°, however, slight water leakage can be observed (range: a few drops to 0.044 l/min). In the test series with filling levels of 18 cm, the pipe connection remained tight over the entire angle of 0° to 6°. This result was also observed at water filling levels of 18 and 24 cm and with the location of the damage in the area of the pipe's transom at 3 o'clock. In a further series of tests, a larger crack was created in the seal with a width of 2.5 mm and the location of the damaged area in the invert area at 6 o'clock was installed. The exfiltration quantities were initially measured at a water level of 6 cm in the pipe. If the pipe remains without bending (0°), the exfiltration volume is between 0 and 0.002 l/min. At angles between 1° and 4°, the pipe connections were always tight. If angles of 5° are set, exfiltration can be expected to start again (range between 0 and 0.009 l/min), the exfiltration rate is slightly higher at an angle of 6° (0.014 to 0.054 l/min). At a water level height of 18 cm in the pipe, the same behaviour is observed, but with different exfiltration rates (0°: 0 to 0.006 l/min; 5°: 0 to 0.009 l/min; 6°: 0.042 to 0.075 l/min). If the damaged seal in the pipe transom area was at 3 o'clock and the other boundary conditions were maintained (crack width of 2.5 mm and filling level height of 18 cm), only slight exfiltration occurred, in about half of the measurements it was negligible, the measurements of the second half were only slightly higher between 0.001 and 0.002 l/min (distributed over the different degrees of bending). So infiltration rates did increase with the level of articulation in a non-linear fashion but the size of the rates were smaller than those observed in the concrete pipes. See Appendix A3.

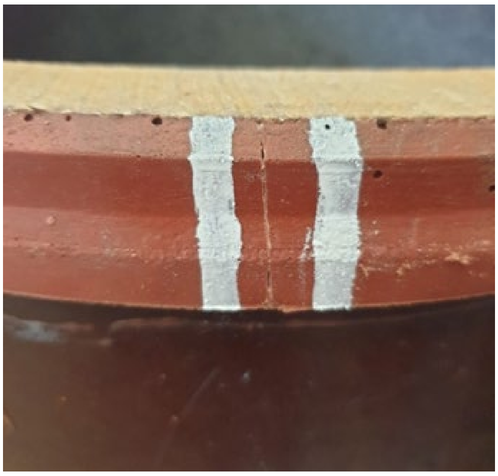

Figure 12. Defect created in clay pipe seal 0.37mm in width

3.3.4 Comparison in behaviour between PVC, Concrete and Clay pipes

In order to be able to examine the exfiltration behaviour of leaking pipe connections (with damaged seals) under different angles, leak tests were carried out on undamaged seals in advance in accordance with DIN 1986-30. At the same time, it was checked whether the minimum requirements according to DIN EN 476 with regard to their tightness under bending had been met. The results showed that all the pipe joints examined (concrete, PVC, clay) met these requirements and even exceeded them (see max. angles of 6° or 7°). However, only a maximum angle of 6° could be set for the concrete and clay pipes, since the pipes threatened to slip apart when this (maximum) angle was reached.

When the angulation tests were carried out on PVC pipes, a different picture emerged in the case of individual cracks: with horizontal connections and small angulations of 1° and max. 2°, small measurable exfiltration rates were observed. With larger angles of angulation, the pipe connections were (largely) tight again at different filling levels. In contrast to the PVC pipes, which have seals to be fitted for installation on site, concrete and vitrified clay pipes are manufactured with integrated seals. These are therefore already firmly connected to the actual pipe when delivered and can no longer be removed. The exfiltration behaviour of the other two pipe materials (with their associated sealing systems) is essentially comparable. A remarkable observation was made when sealing the concrete pipes: When the crack was made, the material proved to be very elastic and “lost” its tension, so that the crack opening ended up being larger than initially planned. The tests were nevertheless carried out with this parameter or crack width. The sealing of the vitrified clay pipes was different in this respect and the cracks could be produced as planned.

With regard to the exfiltration behaviour of the concrete pipe joints, it can be summarised that these become much larger with increasing articulation angle and defect width, albeit with a range of individual values in the measurement series.

The vitrified clay pipes, on the other hand, are tight over a wider range of pipe articulations (predominantly between 1° and 4°) and even at larger bends of 5° and 6° the exfiltrating water quantities are comparatively low compared with the concrete pipes. However, even with a horizontal position (0°), low exfiltration rates were observed in most cases.

3.3.5 DIC experimental results between Clay and PVC

The DIC displacement results of the surface across the joints were used to estimate angular displacement on a transect that was perpendicular to the radial position of the joint - see Section 3, Figures 4a and 4b. This estimated internal angular displacement was compared with the external angular displacement. Table 2 shows the results for the measured external and internal angular measurements for the vitrified clay and PVC pipe results. This table clearly shows that the vitrified clay external and internal angular displacements are practically the same and the results for the PVC pipe show that once the external angle is 2° or greater the value of the internal articulation becomes more stable.

Table 2. Internal and external articulation angles vitrified clay and plastic pipes in the IKT tests

Vitrified Clay		**Plastic**	
IKT Measured Angle	DIC Measured Angle	IKT Measured Angle	DIC Measured Angle
0°	0.44°	0°	0.3°
1°	0.67°	1°	0.2°
2°	1.93°°	2°	1.7°
3°	2.8	3°	1.2°
4°	3.71°	4°	1.6°
5°	4.90°	5°	1.9°
6°	6.0°	6°	3.6°
7°	6.90°	7°	2.5°

3.4 Measurement Equipment and Testing at USFD

A small number of experiments were carried out at USFD. These tests were undertaken using a 300mm diameter concrete pipe and were done to examine the influence of the surrounding material on observed exfiltration rates. The buried configuration is shown in Figure 4a and 4b. The bedding material was 19mm clean crushed stone which is a common pipe bedding material in the UK. During the experiment, a dynamic actuator was used to load the soil above a joint of the concrete pipe. The loading actuator was mounted on a fixed frame and the actuator applied a predetermined load to a stiff steel plate (0.9m x 1.0m) placed on the soil surface. The loading frame ensures that the actuator is fixed in place during loading. The load is controlled by computer software that allows different load profiles to be applied. In these tests a sinusoidal load profile with an amplitude of 110kN and a frequency of 4 Hz was applied to simulate the effect of a heavy goods vehicle travelling at 80 km/hr. The loading system is shown in Figure 13.

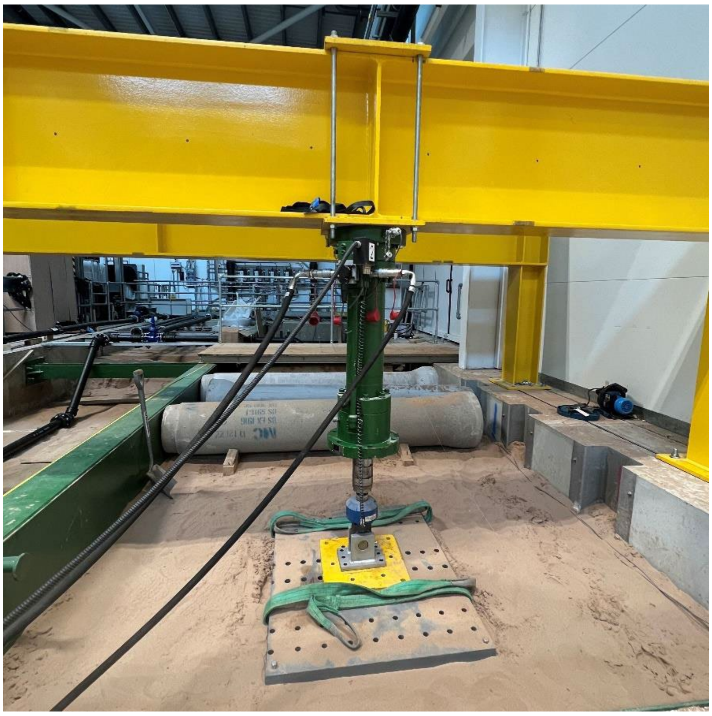

Figure 13. Automated loading system applying 110 kN cyclic load above a buried pipe joint

Before applying the loading and after around 60000 cycles (around 500 heavy vehicles/day) had been applied the internal pipe joint configuration was measured using the four-camera system. The load cycles were applied 4 times and then the pipe exfiltration rate was measured.

To measure the exfiltration rate from the buried 300 mm diameter concrete pipe the ends of the pipe in manhole 4 (upstream) and manhole 6 (downstream) – see Figure 5a were sealed using rigid watertight pipe stops and Manhole 4 was filled with water (Figure 14) so that the initial water level was 420mm above the pipe soffit. This water level then fell due to exfiltration from the pipe section with the loaded joint. By timing of the change in water level with time using images captured by a video camera meant that it was possible to estimate exfiltration rates as the water level dropped. The exfiltration rate values in this report correspond with water levels at the pipe soffit.

Figure 14. Manhole 4 (upstream) sealed; water level high at start of exfiltration test

The exfiltration rates estimated ranged from 7.1 l/min to 5.9 l/min. This suggests that the exfiltration rates observed at IKT were smaller in magnitude than those seen in buried pipes at USFD. This suggested that the soil did not impede the exfiltration. The larger values could suggest that there was less engineering control when installing pipes under buried conditions than in the overground conditions in IKT. The water levels were also higher in the USFD test rig, so a slightly higher exfiltration rate is to be expected. DIC measurements were taken after every 4 hours of dynamic loading and indicated that the level of articulation that could be achieved around the joint was small and not able to influence the exfiltration rate observed.

4 Discussion and Conclusions

At IKT the exfiltration behaviour of three different pairs of pipes, made from PVC, concrete and vitrified clay, including their associated sealing systems were tested. Initially the seals were undamaged and a high level of water tightness was observed for a wide range of pipe articulations for all pipe types. However once the seals were damaged different types of exfiltration behaviour were observed. The exfiltration behaviour was related to the pipe wall material and the seal type. Other influencing factors such as the location of the damaged area and the water level in the pipe were also studied. In summary, a wide range of exfiltration rates were observed from effectively 0 l/min to > 1.9 l/min. There were clear visible differences with regard to the joint sealing systems integrated in the pipe (concrete, vitrified) and those that had to be installed on the construction site (PVC). Concrete and vitrified clay show comparable exfiltration behaviour, in contrast to the PVC pipes. Exfiltration behaviour was only observed once the joint seal had been damaged to some extent. The level of exfiltration was related to the size of the seal damage.

It must be noted at this point that the damage to the sealing elastomers used here was “artificially” created and in all likelihood only corresponds to real damage to seals to a limited extent. The main thing here is that these areas cannot be seen and in the event of removal from the sewer trench, the individual pipes with their seals would suffer further damage and thus no longer reflect the damage (leakage) in the installed state. To what extent this problem can be clarified is and remains unclear.

The difference in behaviour can be explained by the data collected during the DIC measurements carried out. These clearly show a different mechanical behaviour. In the concrete and clay pipes, the articulation angle measured externally is close to the articulation angle measured internally. This shows that the stiff pipe sections continue to deform the joint seals as they are articulated to higher angles. This corresponds with higher exfiltration rates. The size of the rates are different for the concrete and clay pipes but the trend and the mechanism are similar. It is clear from the PVC pipe DIC measurements that as the external articulation angle exceeded 2°, that the internal DIC measurements indicated that the pipe itself started to deform and the joint geometry remained similar. As the pipe deformed the exfiltration rate reduced to negligible values.

The new low-cost DIC measurement system, developed in Co-UDLabs, has been able to measure joint and local pipe deformation, this explained the different pattern of observation in the stiff clay/clay pipes compared to the more flexible PVC pipes. This pattern of behaviour indicated that the relative stiffness of the pipe and joint is important in being able to limit exfiltration from sewer and drainage pipes.

Furthermore, it should be noted that in the IKT tests exfiltration quantities in the experiments were always measured without the surrounding soil, so a “free” outflow” condition into the atmosphere was created. In Sheffield tests, exfiltration occurred with an additional influencing factor of the “bedding” material surrounding the with its potential sealing effect. The results indicated that the bedding material did not significantly impact the exfiltration from pipe joints. Demonstrating that in-air exfiltration tests could be used to estimate exfiltration rates from articulated pipes, and also joints with damaged seals.

These experimental observations provide information on the joint exfiltration in common pipe materials. It is clear that with stiffer material pipes (e.g. concrete and clay) the angle of articulation is important, and that the exfiltration rate rises non-linearly. For flexible pipes exfiltration is limited after an articulation angle of around 2 by the deformation of the pipe. This suggests that different models need to be considered dependent on pipe material. The relative head difference between the internal water level and the external conditions appears to have a much more minor influence on the exfiltration rate. This suggests that the size and character of the defect in the joint seal controls the exfiltration rate.

The large-scale test with buried pipes indicated similar but larger exfiltration rates, this reflected that it was more difficult to construct the layout, and it was conducted by a working contractor rather than specialist technicians, so the exfiltration rates measured may be more reflective of actual conditions found on construction sites. This increase should be considered when considering exfiltration data obtained under laboratory conditions.

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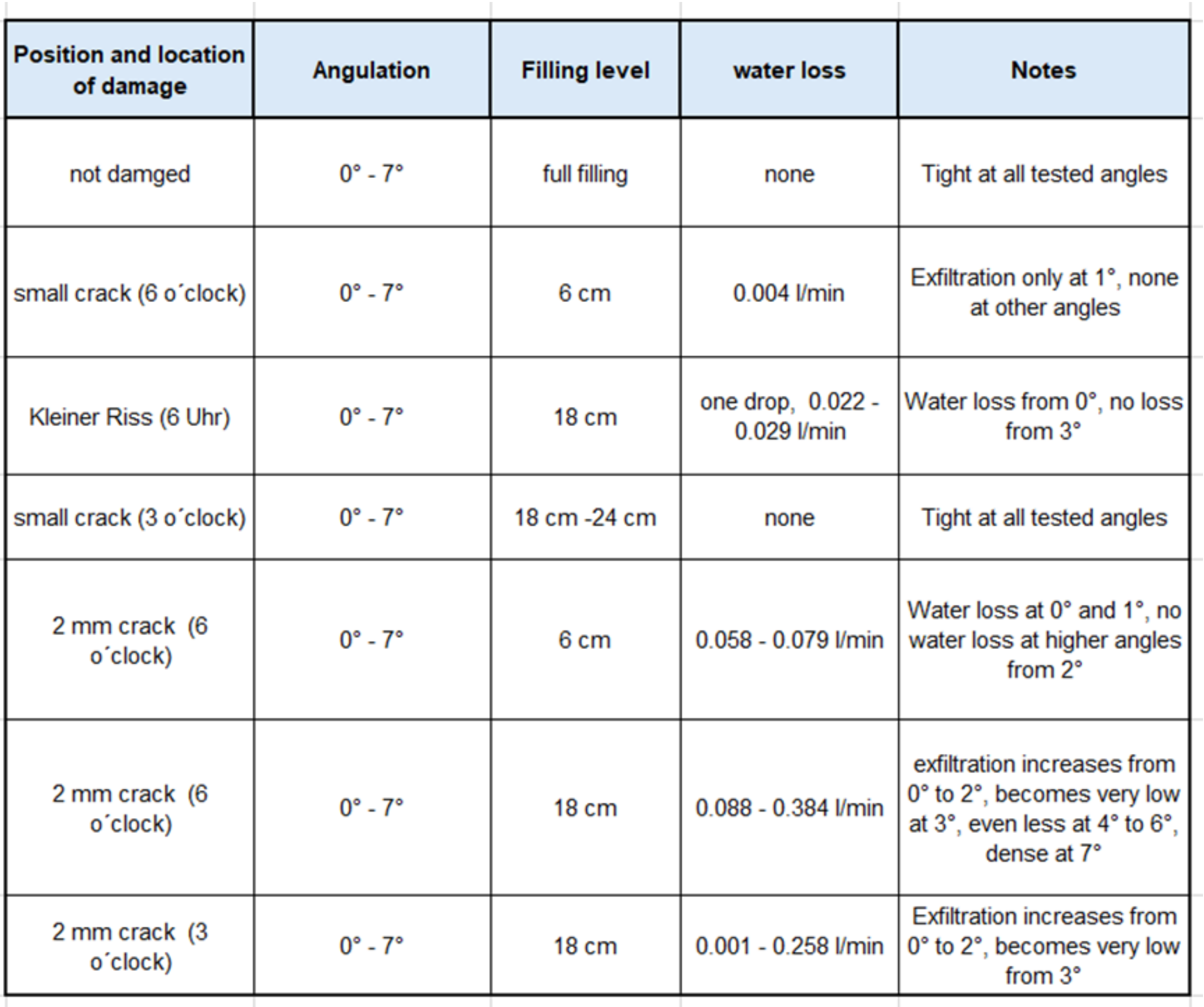
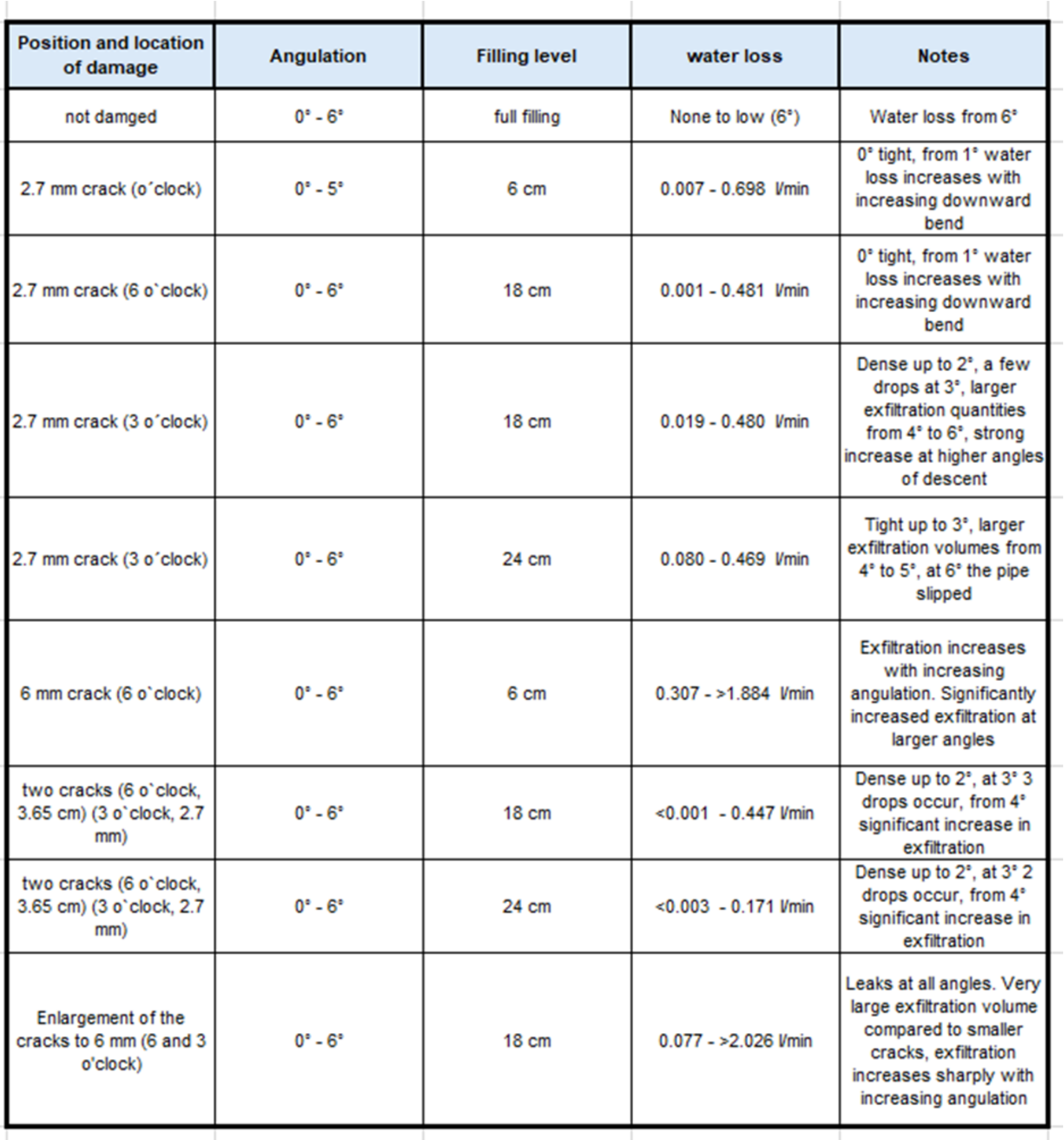
Appendixes - Experimental Results

Appendix A1 - PVC pipe



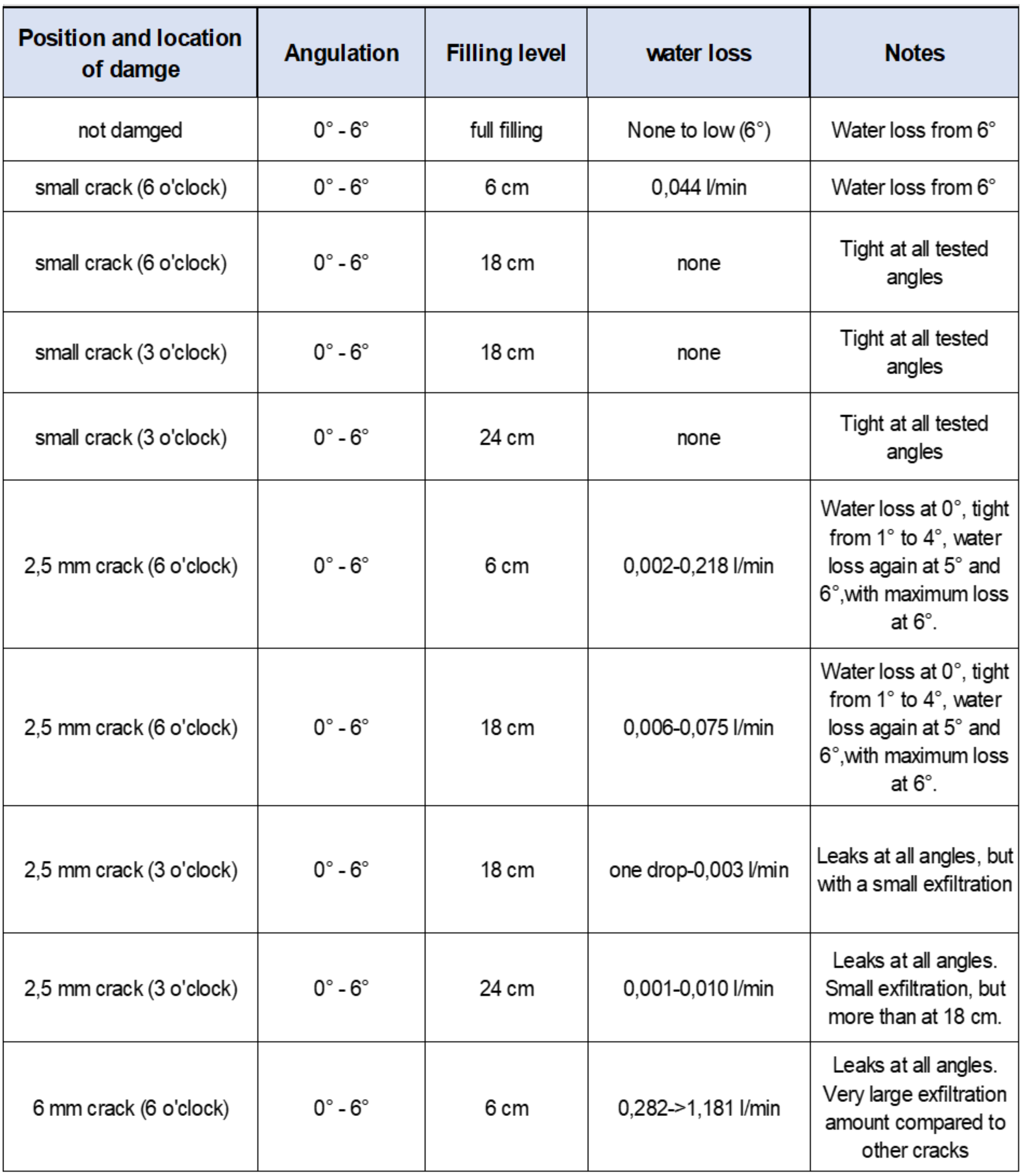
Position and location of damage	Angulation	Filling level	water loss	Notes
not damged	0° - 7°	full filling	none	Tight at all tested angles
small crack (6 o´clock)	0° - 7°	6 cm	0.004 l/min	Exfiltration only at 1°, none at other angles
Kleiner Riss (6 Uhr)	0° - 7°	18 cm	one drop, 0.022 - 0.029 l/min	Water loss from 0°, no loss from 3°
small crack (3 o´clock)	0° - 7°	18 cm -24 cm	none	Tight at all tested angles
2 mm crack (6 o´clock)	0° - 7°	6 cm	0.058 - 0.079 l/min	Water loss at 0° and 1°, no water loss at higher angles from 2°
2 mm crack (6 o´clock)	0° - 7°	18 cm	0.088 - 0.384 l/min	exfiltration increases from 0° to 2°, becomes very low at 3°, even less at 4° to 6°, dense at 7°
2 mm crack (3 o´clock)	0° - 7°	18 cm	0.001 - 0.258 l/min	Exfiltration increases from 0° to 2°, becomes very low from 3°

Appendix A2 Concrete Pipe



Position and location of damage	Angulation	Filling level	water loss	Notes
not damged	0° - 6°	full filling	None to low (6°)	Water loss from 6°
2.7 mm crack (o´clock)	0° - 5°	6 cm	0.007 - 0.698 l/min	0° tight, from 1° water loss increases with increasing downward bend
2.7 mm crack (6 o`clock)	0° - 6°	18 cm	0.001 - 0.481 l/min	0° tight, from 1° water loss increases with increasing downward bend
2.7 mm crack (3 o´clock)	0° - 6°	18 cm	0.019 - 0.480 l/min	Dense up to 2°, a few drops at 3°, larger exfiltration quantities from 4° to 6°, strong increase at higher angles of descent
2.7 mm crack (3 o´clock)	0° - 6°	24 cm	0.080 - 0.469 l/min	Tight up to 3°, larger exfiltration volumes from 4° to 5°, at 6° the pipe slipped
6 mm crack (6 o`clock)	0° - 6°	6 cm	0.307 - >1.884 l/min	Exfiltration increases with increasing angulation. Significantly increased exfiltration at larger angles
two cracks (6 o`clock, 3.65 cm) (3 o`clock, 2.7 mm)	0° - 6°	18 cm	<0.001 - 0.447 l/min	Dense up to 2°, at 3° 3 drops occur, from 4° significant increase in exfiltration
two cracks (6 o`clock, 3.65 cm) (3 o`clock, 2.7 mm)	0° - 6°	24 cm	<0.003 - 0.171 l/min	Dense up to 2°, at 3° 2 drops occur, from 4° significant increase in exfiltration
Enlargement of the cracks to 6 mm (6 and 3 o'clock)	0° - 6°	18 cm	0.077 - >2.026 l/min	Leaks at all angles. Very large exfiltration volume compared to smaller cracks, exfiltration increases sharply with increasing angulation

Appendix A3 Clay pipe



Position and location of damge	Angulation	Filling level	water loss	Notes
not damged	0° - 6°	full filling	None to low (6°)	Water loss from 6°
small crack (6 o'clock)	0° - 6°	6 cm	0,044 l/min	Water loss from 6°
small crack (6 o'clock)	0° - 6°	18 cm	none	Tight at all tested angles
small crack (3 o'clock)	0° - 6°	18 cm	none	Tight at all tested angles
small crack (3 o'clock)	0° - 6°	24 cm	none	Tight at all tested angles
2,5 mm crack (6 o'clock)	0° - 6°	6 cm	0,002-0,218 l/min	Water loss at 0°, tight from 1° to 4°, water loss again at 5° and 6°,with maximum loss at 6°.
2,5 mm crack (6 o'clock)	0° - 6°	18 cm	0,006-0,075 l/min	Water loss at 0°, tight from 1° to 4°, water loss again at 5° and 6°,with maximum loss at 6°.
2,5 mm crack (3 o'clock)	0° - 6°	18 cm	one drop-0,003 l/min	Leaks at all angles, but with a small exfiltration
2,5 mm crack (3 o'clock)	0° - 6°	24 cm	0,001-0,010 l/min	Leaks at all angles. Small exfiltration, but more than at 18 cm.
6 mm crack (6 o'clock)	0° - 6°	6 cm	0,282->1,181 l/min	Leaks at all angles. Very large exfiltration amount compared to other cracks