PUBLISHED PROJECT REPORT PPR630

Integrated monitoring system for drains and other tubular structures

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Prepared for: Transport Research Foundation
Project Ref: Drain Integrated Monitoring System (DRIMS)

Quality approved:

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Executive summary

The project investigated technologies suitable for continuous monitoring of non-pressurised tubular structures, with a particular focus on surface water highway drainage systems. Failures on the motorway and trunk road networks often resulting from heavy rainfall occur because drains are not able to cope with the large volume of water they suddenly have to evacuate. Currently the assessment of these drains is carried out every 10 years using visual (closed circuit television - CCTV) or manual (mandrel) techniques to identify structural failures, with additional reactive assessments undertaken if issues (blockages or build-up of debris) requiring immediate treatment arise. It is thought that the routine assessments aimed at identifying structural failures will always be necessary to some extent; however the reactive approach to dealing with emergencies is less than ideal. Hence, there is a potential need for continuous monitoring that would be able to provide real-time or near real-time information about the state of a drainage network.

Research was therefore carried out into a drain condition monitoring system which could be permanently installed and left in operation unattended. It was believed that such a tool would be ideally suited for the detection of problems requiring immediate treatment before the serviceability of the pipe reached an unacceptable level. Various technologies were considered for this work (namely water flow, radio wave attenuation, leaky coaxial cable, noise detection and acoustic pulse reflectometry based techniques) and two of these were selected for trialling:

i) A radio wave based approach that examined how the attenuation in signal strength between a transmitter and receiver, placed at either end of a pipe, changed due to the introduction of blockages into the pipe;

ii) An acoustic approach that examined the use of acoustic pulse reflectometry to measure the input impulse response of the pipe.

It was shown that the radio wave approach was very sensitive and useable for short pipes for which the condition (e.g. moisture) in the immediate vicinity of the drain was stable. A general decrease in the signal strength was observed as the size of the blockage was increased, with a five litre blockage causing an observable drop in the signal strength.

Acoustic pulse reflectometry was already known to work well on pipes much longer than was achieved using radio waves. This work investigated the introduction of a source tube to direct an excitation signal, produced away from the flow of water, into a pipe with minimal potential obstruction to the flow of water through the pipe. The short source tube introduced an echo into the measured signal that was undesirable and the removal of this echo using a longer source tube or preferably a mathematical procedure was discussed.

The work demonstrated that suitable technology is available for continuous monitoring of highway drainage, and more generally non-pressurised tubular structures. Assuming a suitable application and the support of interested industries was obtained, it is believed that the implementation of such systems would be highly valuable.
1 Introduction

Often, failures on the motorway and trunk road networks resulting from heavy rainfall occur because the drains are not able to cope with the large volume of water they have to evacuate. Currently the routine assessment of these drains is undertaken every 10 years using visual (closed circuit television - CCTV) or manual (mandrel) techniques to identify structural failures, with additional reactive assessments carried out as issues (such as blockages or build-up of debris) requiring immediate treatment arise. It is likely that routine assessments to identify structural failures will always be necessary to some degree, however the reactive approach to dealing with issues requiring immediate treatment is less than ideal. For this reason, there is a potential need for continuous monitoring systems that would be able to provide real-time or near real-time information about the state of a drainage network.

Research was therefore carried out into a drain condition monitoring system which could be permanently installed and left in operation unattended. This research formed part of a larger body of research undertaken by TRL to identify alternative tools to facilitate the inspection and maintenance of drainage systems. Previous work has led to the development of a novel acoustic drain inspection system [Harrington and Iaquinta, 2010] that could very quickly gain information about the condition of a drain (location of leaks and blockages). This system was based on the use of a technique called acoustic pulse reflectometry. The approach showed considerable promise, with the potential to greatly streamline the routine inspection (possibly in conjunction with CCTV) of drainage networks. However, the application of the technique to continuous monitoring was not considered straight forward, principally because of the way the equipment had to be installed (i.e., with inflatable seals that would completely block a pipe).

The present report examines the feasibility of developing a system for the continuous monitoring of the conditions within highway drains. It starts by describing the environment where such a system would be installed and highlights the main requirements of an integrated monitoring system. Possible inspection techniques are then discussed with focus placed on how well they meet these requirements as well as practical considerations. The most promising techniques are then presented in more detail along with the results of experiments carried out to assess their performance.
2 The Drainage Network

This research focused on the surface water drainage systems as found on UK highways, but more generally the research was looking at non-pressurised pipe systems. In general, the UK highways drainage network is designed such that surface water is directed into one or more plain pipes called “carrier drains” which usually have a circular cross-section (see Figure 1) and run parallel to the main carriageway. Access to these pipes is available through manholes, located at intervals of about 100 to 150m, that typically also incorporate a catch-pit which is a break in the pipe-run where debris can collect. The main drains also have branches of typically smaller diameter pipes which lead to gullies to collect the surface water. It is common to have several such gullies in each pipe-run between manholes.

There are alternative drainage pipes to the plain pipes and gullies described above. One of which is a “filter drain” made with perforated pipes, but these were out of the scope of the present work.

Figure 1: Example of plain plastic pipe used in this research.

The network consists of a large variety of pipes of different diameters (up to about 1m), materials (concrete, clay, plastic, bricks, etc.), ages and condition. This research focused on 300mm diameter plastic pipes which consultations with the industry and practitioners highlighted as their preference for current construction works.

The plastic pipes come in short units, generally a few metres in length, and are joined together to form the longer sections terminated by manholes. In most cases watertight joints are used.
3 Requirements

The typical layout of surface water drainage systems as found on most UK highways needed to be considered when evaluating the inspection/monitoring techniques. Specific points of interest about the layouts found were:

- Drainage systems are divided into sections by manholes spaced at about 100 to 150m, and these provide an obvious location for inspection/monitoring equipment;
- Branches to the surface, of typically smaller diameter pipe, sub-divide these sections;
- It is not always possible to see from one end of the sections to the other due to kinks at the joints or bends in individual units of pipe;
- The diameter of the main carrier pipes are in the range of 100 to 1000mm.

In addition to addressing the above, consideration of how the inspection system would integrate with the infrastructure had to be made. Key to this was that the system did not adversely affect the natural flow of water in the pipeline. The method of installation of the inspection/monitoring system also imposed some restrictions. An intricate installation process would increase initial costs and subsequent service costs. Complete integration in which a system would be built into the pipe walls, for instance, would require a complete replacement of the drain network. Since replacement of the existing infrastructure is generally done on an as needed basis, this would take a long time to completely cover the network.

A further consideration was the level of detail a continuous monitoring system would need to offer for it to be a useful tool. As a minimum, the system would need to provide information to alert the infrastructure owner that significant changes have occurred and that further inspections are necessary (using existing techniques such as CCTV). Since such further inspection work is costly the system would need to have a low false positive rate. The pipes are buried and current inspections are carried out between manholes. Therefore, it would be sufficient for the monitoring system to report on a section by section basis (i.e., between manholes).

With these requirement and considerations in mind the next stage was to evaluate the potential inspection techniques.
4 Inspection Techniques

4.1 Radio waves

Radio waves interact with materials they encounter along their path from a transmitter to a receiver, mainly through reflection, refraction, diffraction or absorption. By observing the signal at the receiver information can be gained about the path taken by the radio waves. This could be potentially exploited to provide a means of inspecting/monitoring drainage pipes.

The envisaged technique involved measuring the level of attenuation (mainly caused by absorption) of a signal emitted at one end of a length of pipe and received at the opposite end, see Figure 2. As the conditions of the pipe changed the level of attenuation would also change. If a relationship between the condition of the drain (such as the presence of blockages) could be linked to the level of attenuation, then measuring the level of attenuation could provide an early warning of the reduced serviceability of the drain.

However, there could be issues to using such an approach for inspecting drainage pipes:

- Firstly, if the pipe does not constrain the radio waves within its walls, then changes in the environment surrounding the pipe would affect the results of the inspection. If a pipe is able to confine radio waves then the only path available between a transmitter at one end of the pipe and a receiver at the other is through the pipe. If the pipe cannot confine the radio waves then it is possible for the radio waves to pass through the walls of the pipe and travel within the surrounding environment. If this were the case with drainage pipes, it might not be possible to use the received radio waves for determining the condition of the pipe.

- Secondly, if the level of absorption of the common materials that normally cause blockages in pipes are very different, and particularly if some materials cause very little attenuation, it might not be possible to confidently provide a measure for the condition of a pipe.

![Figure 2: Measuring the attenuation of radio waves transmitted at one end of a pipe and received at the other to determine the condition of the pipe.](image)

4.2 Leaky coaxial cable

Commercial systems are available that make use of (buried) leaky coaxial cables for perimeter detection around buildings. Typically, the systems use two leaky coaxial cables laid next to one another and separated by a small gap to form a continuous detection field, see Figure 3. The leaky coaxial cables have regularly spaced gaps in their shielding...
so that they produce a consistent electromagnetic field along their length. One of these cables is used to emit a field while the other is used to detect the field. As an object, typically a person, crosses between the cables this interacts with the field lines and it can be detected. In addition, using special techniques it is possible to determine where along the length of the cables the field had been disturbed. Typically, such systems are installed and calibrated by having a person walking across the cables to determine the magnitude of the response that can be expected. In doing this the systems can accurately alert when a person crosses the perimeter without alerting due to something like a small animal.

![Diagram of perimeter intruder detection using leaky coaxial cable systems.](image)

**Figure 3:** Perimeter intruder detection using leaky coaxial cable systems.

This technique has potential to be applied to the monitoring of drainage systems. Two leaky coaxial cables, laid either side of a pipe, internally or externally, could be used to detect changes in the pipe that cause a change in electromagnetic field between the cables. The major hurdle with this approach would be the cost of the cables and the cost of installing these cables. There are many possible ways in which the cables could be installed, they could be buried next to the pipes or built into the pipe walls during construction or they could be pinned to the inside of the pipes post construction. Since the drainage infrastructure is well established and pipe replacement tends to be as and when required, the option of pinning the cables to the pipe walls would be the most flexible approach. For industries such as telecoms, robots have been created to install cables in pipes removing the need to dig new trenches. It is possible that a robot of this kind could be used to install this type of monitoring system.

### 4.3 Flow measurements

When inspecting a pipeline for blockages it is in fact the ability of the pipe to pass water that is of greatest importance. A pipe with a blockage is less able to pass water and so is less likely to cope with the large volumes of water resulting from heavy rainfall.

Drainage pipelines are similar to rivers, in that they can be seen at as “open channels” with uniform flows because they are typically oversized for the amount of water they have to cope with, and so have the potential to be analysed using techniques taken from the hydrological field. The Manning formula [Manning, 1890] (Equation 1) is an empirical formula that relates the velocity of water to the slope and cross-section of the channel.

It is defined as:

\[ V = \frac{k}{n} R^{2/3} S^{1/2} \]

**Equation 1:** Manning formula.

where:
\( V \) is the cross-sectional average velocity;  
\( k \) is a conversion factor;  
\( n \) is the Gauckler–Manning coefficient, it is unitless;  
\( S \) is the slope of the water surface;  
\( R_h = \frac{A}{P} \) is the hydraulic radius;  
\( A \) is the cross-section area;  
\( P \) is the wetted perimeter.

The Manning formula is typically used to estimate the flow in a channel where it is not practical to measure it. To achieve this the slope, hydraulic radius and Gauckler–Manning coefficient must be estimated. The Gauckler–Manning coefficient is an empirically derived coefficient which is related to the resistance of the path to the flow of water, and is dependent on many factors including the surface roughness of the channel. Typically this coefficient is defined by examining the river using aerial photos and comparing it to rivers with known coefficients. The known coefficients are determined by measurement and using the rearranged version of the Manning formula.

It would be this approach, to measure the Gauckler–Manning coefficient, that could be used to quantify the resistance of the pipe to flow. As the pipe deteriorated (due to silting-up, tree roots, etc.) the value of the coefficient would increase. To make this measurement the depth, velocity and slope of the water in the pipe would need to be measured (see Figure 4).

![Figure 4](image)

**Figure 4:** A drainage pipe viewed as an open channel. Measurements of the flow could be used to determine the resistance of the pipe.

A possible complication might arise due to the inlets for surface water drainage. The Manning formula assumes that the water is flowing due to the action of gravity resulting from the slope of the water. At inlets the incoming water would have travelled a different path, possibly with a steeper gradient, which would affect the water flow in the main pipe. In addition, this technique would only be able to provide a measure of the Gauckler–Manning coefficient at each location of a flow sensor.

### 4.4 Noise Detection

As water flows in a channel it produces sounds at locations where the water is disturbed, due to for instance a blockage. For this reason, the sound produced by a channel will be characteristic of the flow of water through it.

This approach to inspecting a pipeline draws parallels with leak noise “correlators”, which are commonly used in pressurised systems. Such devices make use of acoustic signals created by leaks to pinpoint their locations. The acoustic signals are recorded using multiple microphones placed around a pipe network. With knowledge of the locations of
the microphones it is possible to use cross-correlation to locate the source of leak noises detected.

In a similar fashion, microphones placed within a drainage system (see Figure 5) could be tuned to detect characteristic signals associated with blockages, assuming such well defined signals exist, and pinpoint their location using time of flight calculations.

![Figure 5: Noise produced in the drain pipe could be detected at either end by microphones and used to pinpoint the location of the source.](image)

It was believed that the main problems with this approach would be that blockages might not produce signals that could be separated from the background noise, with the potential for the signals to take many forms depending on the amount of water flowing through the pipe. Also noises could originate from other sources (animals, surrounding traffic or other activities) which would disturb the detection.

### 4.5 Acoustic Pulse Reflectometry

Acoustic pulse reflectometry (APR) measures the input impulse response produced when an acoustic impulse, used to excite a system, is reflected at impedance changes. In the case of air filled ducts, impedance changes result from changes in the cross sectional area of the duct. The resulting input impulse response contains information about every cross sectional area change present in the duct, which can in some applications [like in Fredberg et al., 1980] be used to determine the bore along the length of the duct using bore reconstruction algorithms.

Earlier research carried out at TRL [Harrington and Iaquinta, 2010] showed APR to have considerable promise for drainage networks, with the potential to greatly streamline routine inspection. The research did not focus on bore reconstruction but explored the use of APR to very quickly identify sections in need of further investigation (for instance using CCTV). Although it was clear that the acoustic approach would be ideally suited for monitoring, the technique required the pipe to be completely blocked during an inspection (by the measuring equipment itself), making its application non-trivial. Overcoming this requirement was seen as the main hurdle to using this technique for permanent installation.

### 4.6 Summary

Different approaches were considered for use in a continuous monitoring system. One involved measuring the flow of water, two involved the detection of radio waves and two involved acoustics. Note that other techniques requiring a clear line-of-sight between the two ends of the pipe (use of lasers, cameras, etc.) were discarded at an earlier stage.
All the approaches were believed to have the potential to provide a sufficient level of detail on the position of faults. In addition, it was believed that all the techniques would be able to cope with the layout of the drainage infrastructure, such as the lengths of sections, the diameters of pipes and the lack of line of sight between manholes. For this reason, since all the methods showed enough potential to warrant further research it was necessary to consider each approach on its own merits and with consideration for what could be achieved within this project.

The noise detection based technique was eliminated because it was not within the scope of this research to be able to collect the potentially large amount of data from live drains that would have been necessary. Due to similar constraints, the flow based technique was ruled out as its development would require a working drainage system with flowing water. Finally, the leaky coaxial cable approach was rejected because compared to the remaining two techniques it was found that the current prices of leaky coaxial cable were prohibitive and incompatible with the application on a large network. The remaining two approaches were taken forward, and preliminary trials were carried out to assess their potential.
5 Radio wave technique

This approach investigated the use of radio wave transceivers to detect changes in the attenuation of a signal emitted at one end of a section of pipe and received at the other end. The assumption was that as blockages form in a pipe a reduction in the signal strength would be measurable.

In recent years, radio wave transceivers have become widespread, typically for use in wireless mesh sensory networks. One of the more established standards for such devices is Zigbee, which has been specifically designed with simple, cheap, low data rate, small and low powered sensors in mind. The devices typically operate at 868MHz, 915MHz and 2.4GHz, with the latter being an allowed frequency in most jurisdictions. These sensors appear to be perfectly suited to this application.

For the purposes of the trials, it was necessary for the devices to report a measure of signal strength. This is also a necessity of mesh networks, since in mesh networks signal strength and so the quality of the data link between nodes is used to determine the best path between nodes not directly within range of one another. The Zigbee protocol specifies that devices should provide a measure of the link quality between two devices, named the Link Quality Indicator (LQI). The LQI is reported by the devices as a number between 0 and 255 and is a unit-less quantity which is used as an estimate of the probability of successful transmission of the packets. The devices used for this research also reported the Received Signal Strength (RSS) indicator which has units of dBm. It was decided that the RSS data would be directly used and analysed for these trials.

Two sets of trials were conducted to examine the use of radio waves. To this end, a purpose built test rig was constructed in the laboratory. This experimental drain was created from 300mm diameter pipes identical to those found on the Highways Agency drainage network. The 300mm diameter pipeline was assembled from five 6m long sections, connected together by push-fit joints and ring seals with an inlet between the second and third sections. Figure 6 shows a diagram of the set-up. Since the pipeline was situated above ground, it was deemed necessary to increase the ability of the pipes to confine the radio waves, to better represent the shielding effect for buried pipes. For this reason, aluminium foil was used to surround the pipe walls, a metal plate was used to cover the opening at end a, whilst aluminium foil was used to cover the openings at the inlet and end b. Figure 7 is a photograph of the inlet and shows how it looked with the aluminium foil wrap, and the aluminium covering over the opening.

![Figure 6: A diagram of the set-up.](image-url)
The trials consisted of placing one device at either end of the stretch of pipeline and measuring the RSS whilst artificially degrading the serviceability of the pipeline, by the creation of a blockage with sand. Two trials were conducted, one looking at localised blockages and the other looking at non-localised blockages. In the first trial the sand was inserted into the pipeline through the inlet and allowed to create a mound. In the second trial, the sand was again added to the pipeline through the inlet but was spread out along the bottom of the pipe. The cross section of the blockage produced using this method can be seen in Figure 8.

Between the trials the pipe had to be dismantled to remove the sand introduced. During this process the aluminium wrapping was disturbed. Although measures were taken to
minimize damage, the shielding was not identical for the two trials. As a result, the
received signal strength at the start of the non-localised blockage trials differed from
that seen at the start of the localised blockage trials, even though both trials were set up
in the same way and had no sand in the pipe.

Figure 9 and Figure 10 present the results of the localised and non-localised blockages
respectively. Both trials exhibit an overall decrease in signal strength as the size of the
blockage was increased. However, both trials also saw a small increase in the signal
strength for the last few points (possibly resulting from limitations in the equipment used
to make the measurements). These preliminary trials confirmed that there was a
noticeable reduction in the strength of the signal received due to the presence of a
blockage. In both cases a measurable drop in signal strength was seen for a blockage
created with as little as 5 litres of sand.

![Figure 9: Results of the localised blockage trials.](image9)

![Figure 10: Results of the non-localised blockage trials.](image10)
6  Acoustic pulse reflectometry

Acoustic pulse reflectometry is the name given to a technique that involves measuring the reflections created by a system when an acoustic pulse is used to excite it [Sharp, 1997]. The reflections occur at impedance changes and in the case when the acoustic pulse is an impulse, the resulting reflections give the Input Impulse Response (IIR). A more detailed summary of the acoustic pulse reflectometry technique and its implementation during this research is provided in Appendix A.

The work described here did not aim to reproduce that already described in Harrington and Iaquinta (2010) but intended to evaluate the use of a similar approach in a way that was compatible with a permanent installation into a piped system. Indeed, it was highlighted during the initial stages of the research that the greatest hurdle to using acoustic pulse reflectometry for continuous monitoring was the difficulty of injecting an excitation signal into the pipe without obstructing the flow of water through the system.

One of the solutions considered was the use of small ultrasonic transducers arranged in the form of a parametric array [Pompei, 2002]; although promising this method was not pursued since initial experiments showed that the method worked (i.e., air nonlinearities effectively cause high frequency waves to interact, producing new frequencies that are a combination of the sums and the differences of their frequency components) but the level of sound produced by off-the-shelf transducers was extremely low.

The other solution examined here was the use of a tube to move the sound source away from the pipe opening.

![Figure 11: Depiction of how a source tube (flexible tubing) could be used to move the sound source away from the pipe opening.](image)

Source tube is the name given to a length of pipe commonly used in acoustic pulse reflectometry, and placed between the acoustic source and the object under inspection. The source tube plays two important roles in acoustic pulse reflectometry. The first is to allow for the isolated measurement of pulses created by the measurement apparatus and the second is to allow for reflections from an object under inspection to be measured before secondary reflections are introduced into the signal from waves reflecting off the acoustic source itself. For this purpose the minimum length of the source tube must be greater than the length of the object being tested. Since drainage pipes can be in the region of 150m in length this would have required the length \( l \) (see Figure 14 in the...
Appendix) to be in the region of 150m in total. This was considered impractical and therefore the use of a shorter source tube was investigated.

Typically, when source tubes are used in acoustic pulse reflectometry, tapered couplers are used to minimise reflections occurring at the joints in the apparatus, for instance those between the source tube and the object under inspection or between the source tube and the acoustic source. For this application, it would not be possible to use a coupler for the joint between the source tube and the object under inspection, since such a coupler would affect the flow of water. The effect of not using such a coupler was another focus of the trials conducted.

To assess the use of a source tube to direct the acoustic signal produced by a source located away from the entrance to the pipe, a 1m long section of semi-flexible pipe, which had an internal diameter of 100mm, was examined. To eliminate the need for coupling between the source tube and the sound source, a speaker with a cone diameter of 100mm was used. This removed the effect of the coupler from the results so that focus could be placed on the joint between the source tube and the pipe. A microphone was also coupled to the source tube, approximately 100mm away from the speaker. This set-up is shown in Figure 12.

![Image](image-url)

**Figure 12:** Set-up of the speaker, microphone and source tube.

The speaker was excited using an Exponential Swept Sine (ESS) signal with a pulse width much greater than the ~0.9m distance between the microphone and the start of the object. The ESS signal was produced between the frequencies of 0.01Hz and 1000Hz with a fade out at 55Hz. It was appreciated that this maximum frequency of 1000Hz was greater than the cut-off frequency (Equation 1 in the Appendix) of a 300mm diameter pipe (~665Hz), however due to the fade out at 55Hz and the limitations of the speaker, there was very little energy in the excitation signal above the cut-off frequency.

The same pipeline was used for these trials as was used during the experiments with the radio wave based technique. However, one change was made to the set-up; the inlet was removed and a blockage, made from dense foam, was placed into the pipeline. Figure 13 shows the results of an inspection carried out and the data shows three distinct events. The first event (numbered 1 in Figure 13) is the excitation signal passing the microphone and reflecting between the two ends of the source tube. The distance between the peaks and troughs are ~1m apart, which is the length of the source tube. The reflections within the source tube appear to have died away after ~10m. This is largely due to the losses experienced at the open end of the tube. Each time the acoustic
Wave is reflected at the open end part of the signal is transmitted into the pipe. This has the effect of stretching the excitation signal, making the effective excitation signal transmitted into the pipe longer. This can be seen in the next event in the data (numbered 2 in Figure 13). As the stretched excitation signal reaches the blockage in the pipe it is again partially reflected with the remaining signal transmitted. The reflected part returns up the pipe and at the boundary between the source tube and the pipe part of the signal continues to travel up the source tube to be recorded by the microphone. Since only part of the signal is transmitted into the source tube, with the remainder either reflected back into the pipe or transmitted out of the pipe, the returning signal has a lower amplitude than that of the initial excitation signal. This process happens again at the far end of the ~30m long pipe (numbered 3 in Figure 13), with a larger response seen due to there being a greater impedance change.

Figure 13: The data recorded by the microphone, in the source tube, with a short source tube placed in the entrance of the pipe under inspection, with three distinct parts to the signal 1, 2 and 3.

The preliminary trials demonstrated that a source tube with a sudden impedance change at the entrance to the pipe under inspection could be used to relocate the sound source away from the pipe entrance. They also established that the signal loss experienced due to the lack of coupling between the source tube and the pipe did not prohibit the reflection, which contained information about the cross sectional area changes within the pipe, from reaching a microphone within the source tube.

However, the source tube had the effect of stretching the effective excitation signal transmitted by the pipe under inspection. This stretching occurs whenever a short source tube, relative to the length of the object under test, is used, and research [Marshall, 1992] has shown that it is possible to account for it. The stretching is an echo caused by the reflections that form from sound waves passing the microphone and reflecting off of the speaker. These echoes are attenuated copies of the original signal with a delay due to the time to travel the distance between the microphone and the speaker. Marshall described a procedure for removing the echos from the signal. It involved making two calibration measurements. The first measuring the excitation signal in isolation and the second carrying out an inspection with a perfect blockage located immediately behind the microphone. These two calibration measurements could then be used to post process inspection data, such as that shown in Figure 13, to remove the effect of the short source tube.
7 Conclusion

Various techniques were considered to form the basis of a permanently installed drain condition monitoring system, with two shortlisted for the purpose of further trials. Those not selected were eliminated due to constraints imposed on the project (mainly time) and for practical reasons (cost, etc.). The two methods selected were a radio wave attenuation based approach and an acoustic approach.

The radio wave approach examined how the attenuation of the signal strength between a transmitter and receiver, at either end of a pipe, changed due to blockages in the pipe. Both localised and non-localised sand blockages were created. In both cases a decrease in signal strength was observed as the volume of the blockages was increased, with a 5 litre blockage causing a clear drop in the signal strength.

The radio wave approach which used relatively cheap and readily available equipment showed substantial potential. It was however noted that the experiments carried out for this work were sufficient only as a proof of concept and further trials would be necessary to confirm the findings in this report and develop the approach into a practical tool. Such further work would need to include:

- Trialling the approach in a real drainage system, particularly focusing on how well the electromagnetic waves are confined within the pipes, for example, looking at whether rain soaking into the surrounding earth affects the measured signal strength (although it is expected that waves having had a direct path through the pipe should always arrive at the receiver first);
- Determining the inspection range of the technology (the trials were conducted on a 30m pipeline however drainage pipelines up to 150m can be found);
- Examining how the location of blockages along the pipe affects signal attenuation;
- Determining how the composition of blockages affects signal attenuation;
- Consider the use of modelling to determine the relationship between the signal strength and the geometry and condition of the pipe.

The acoustic approach followed on from previous TRL work into the use of acoustic pulse reflectometry for the inspection of blockages in pipes. This work looked at how acoustic pulse reflectometry could be applied to continuous condition monitoring. The focus was placed on how the acoustic excitation signal could be injected in the pipe without causing an obstruction to the flow of water in the system. To this aim the use of a source tube (to allow for the electrical equipment including the sound source – and also the microphone digital signal processor, etc. – to be placed away from the water) were investigated. Trials demonstrated that a short source tube could be positioned in the entrance of a pipe, with minimum effect on the flow of water, and used to inject the excitation signal created away from the flow of water into the pipe. The use of the short source tube introduced an echo into the measured signal and the removal of this is the main aspect requiring further examination (note that for some applications the use of a much longer source tube could be a simple solution).

Implementation

This research was focused solely on techniques involved in the monitoring component of a continuous monitoring system. However it should be noted that further investigation
into a range of broader aspects of such a system would be needed prior to any potential implementation. In all of the designs considered, it was believed that it would be essential that the systems be able to provide condition data at a frequency appropriate for the maintenance regime of the drainage system, and that this would require wireless communication between the monitoring systems and a base station.

For this reason, how this communication could be achieved would need examining. Several issues surrounding this include: the difficulty of achieving communication wirelessly below ground, the expense of including such long range communication technology in every monitoring system and the increased energy consumption associated with this added electronics. The source of electrical power would be another aspect that would need to be considered. A wired power source would likely be unavailable in all locations that a monitoring system may be required and so battery power may be the only option. In this case power consumption would need to be a consideration for further design work.

It would be vital for the power consumption to be controlled so that the devices would last a sufficiently long time between servicing, otherwise the cost of servicing the monitoring units could make the technology prohibitively expensive.

**Beyond drains...**

To focus further work on the technology of continuous drainage monitoring systems, and more generally non-pressurised pipe based systems, it would be beneficial to better define the market for such technology. In terms of highway surface water drainage, consultation with the industry would highlight how this could be best deployed.

It may be that it would be considered an important tool for critical infrastructure but unnecessary for use in all situations. In terms of broader uses, an area that shows some signs of interest in this type of technology is in infrastructure security. This can be the drainage systems surrounding locations of national interest. Assuming a suitable application and the support of appropriate industries could be found, it is believed that further work could lead to the development of valuable tool.

Also a similar approach could be implemented for much larger tubular structures, in particular to detect changes from a reference state. This would typically be the case for instance in underground obstacle detection systems (e.g., Unattended Train Operation) for monitoring tunnels and detect people or objects on the tracks. One of the advantages of this approach compared to radar or video, is that there is no requirement for line of sight (i.e., it works the same if the tube is curved) with the ability to see beyond tunnel bends and corners.


Appendix A: Summary of acoustic pulse reflectometry technique

Acoustic pulse reflectometry is the name given to a technique that involves measuring the reflections created by a system when an acoustic pulse is used to excite it. The reflections occur at impedance changes and in the case when the acoustic pulse is an impulse, the resulting reflections give the Input Impulse Response (IIR). For all other excitation signals the resulting reflections are described by the convolution of the IIR with the excitation signal.

This technique has many applications, such as examining the layers in the Earth’s crust, which was one of the first applications [Ware and Aki, 1969], or characterising a room for which the acoustic properties need to be known. However, it is the use on air filled ducts that was the subject of this research. In the case of air filled ducts, impedance changes result from changes in the cross sectional area of the duct. The resulting input impulse response contains information about every cross sectional area change present in the duct, which can theoretically be used to determine the bore along the length of the duct.

For acoustic pulse reflectometry, theoretically, the signal used to excite the system under inspection should take the form of an impulse. However, due to the practical limitations of creating an impulse, and also a requirement for bore reconstruction that only plane acoustic waves are excited in the system (discussed further later), the use of an impulse is not possible. For this reason, an approximation of an impulse must be used, and such a signal can take many forms.

At its simplest a sudden sound, such as a starter’s pistol, can be used in an attempt to approximate an impulse. However, this approach has its limitations. Specifically, the sound wave produced has little energy and is similar in shape to background noise, both of which lead to a low signal to noise ratio. In addition, this method of creating the excitation signal provides little control over the spectral content of the signal, which can be of importance for the purposes of reconstructing the bore profile of the air filled duct.

Figure 14: Schematic diagram of a pulse reflectometer.
Alternative signals have been devised that involve longer more complex signals to be used to excite the system and post processing to extract the resulting input impulse response. This research made use of one of these alternative signals called an Exponentially Swept Sine (ESS) wave. This excitation signal can be produced using a loudspeaker and as such there is good control over the spectral content of the resulting pulse. The use of an ESS involves the creation of an excitation signal as well an inverse filter [Farina, 2000]. The excitation signal is used to excite the system and then during post processing the inverse filter is convolved with the recorded reflections. Figure 15 shows an example of an excitation signal, its inverse filter and the resulting pulse.

![Figure 15: Example pulse created using the ESS technique.](image)

As briefly mentioned in the preceding discussion on the form of the excitation signal, for accurate bore reconstruction to be possible, a constraint must be placed on the acoustic signal used to excite the system. The reconstruction algorithms assume that only plane waves are propagating in the pipe. For this condition to be true a cut-off frequency must be defined and the excitation signal must not contain frequencies above this. For an air filled tube the first non-planar mode is given by Equation 1 where \( \omega_c \) is the angular frequency [in Hz] of the first non-planar mode of an air filled tube, \( f \) is the frequency [in Hz], \( c \) the speed of sound [in m.s\(^{-1}\)] and \( r \) the radius of the pipe [in m]. Below this frequency only plane waves propagate. For a 300mm diameter pipe, this set a maximum frequency of \( f \approx 665 \text{Hz} \).

\[
\omega_c = 1.84c/r = 2nf
\]

**Equation 1:** Cut-off frequency for planes waves in a circular cross-section air filled tube.

Source tube is the name given to a length of pipe commonly used in acoustic pulse reflectometry, and placed between the acoustic source and the object under inspection. The source tube plays two important roles in acoustic pulse reflectometry. The first is to allow for the isolated measurement of the pulse created by the measurement apparatus and the second is to allow for the reflections from the object under inspection to be
measured before secondary reflections are introduced into the signal from waves reflecting off the acoustic source. This is achieved by separating the microphone and acoustic source by a section of source tube ($l_1$) and by separating the microphone and object by a section of source tube ($l_2$), see Figure 14. The separation between the microphone and the object is independent of the length of the object under inspection and instead decided by the width of the pulse used to excite the object. For example, a pulse with a width of 1ms, assuming a speed of sound of $340\text{ms}^{-1}$ would require $l_2 \approx 0.34\text{m}$. The separation between the acoustic source and the microphone is however dependent on the length of the object under inspection. As a minimum $l_1$ must be equal to the length of the object $l_3$. 