Rapid Detection of Sewer Defects and Blockages Using Acoustic Based Instrumentation

Détection rapide des défauts et colmatages de réseaux par l'utilisation de l'instrumentation acoustique

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RÉSUMÉ

En Grande-Bretagne, les inondations par débordement de réseaux sont de plus en plus fréquemment associées aux problèmes de colmatage. Il est difficile de traiter les colmatages car, bien qu'il y ait des endroits où ils sont plus susceptibles de se produire, ces incidents interviennent par intermittence. Pour assurer une gestion proactive des colmatages de réseaux, les responsables doivent pouvoir localiser rapidement les sites de colmatage. Les technologies traditionnelles d'inspection par caméras sont lentes et relativement onéreuses et donc inadaptées à l'inspection nécessairement rapide d'un réseau, pour la gestion proactive des colmatages. Ce document traite du développement d'une sonde acoustique. Ce dispositif a été testé en laboratoire sur une conduite en taille réelle, et a démontré qu'il était en mesure de faire la distinction entre des colmatages et des éléments structurels d'une conduite tels qu'un regard de visite ou un raccordement latéral. L'analyse du signal acoustique permet de localiser le colmatage et fournit des informations sur ses caractéristiques. La mesure est très rapide et objective et permet d'effectuer des inspections plus rapidement qu'au moyen des technologies existantes de systèmes caméra.

ABSTRACT

Sewer flooding incidents in the UK are being increasingly associated with the presence of blockages. Blockages are difficult to deal with as although there are locations where they are more likely to occur, they do occur intermittently. In order to manage sewer blockage pro-actively sewer manager need to be able to identify the location of blockages promptly. Traditional CCTV inspection technologies are slow and relatively expensive so are not well suited to the rapid inspection of a network. This is needed if managers are to be able to address sewer blockages pro-actively. This paper reports on the development of an acoustic based sensor. The sensor was tested in a full scale sewer pipe in the laboratory and it was shown that it is able to discriminate between blockages and structural aspects of a sewer pipe such as a manhole and lateral connection. Analysis of the received signal will locate a blockage and also provide information on its character. The measurement is very rapid and objective and so inspections can be carried out at much faster rates than using existing CCTV technologies.

KEYWORDS

Sewer blockage, inspection, acoustic intensity response

1 INTRODUCTION

1.1 Background

In the UK the underground sewer system totals some 300,000 km in length with an estimated replacement value of £104 billion. It is an ageing asset stock about which the owners have little information on its current condition and performance. In England and Wales, OFWAT imposes a statutory duty on the utility companies to maintain the condition and serviceability of this asset. Unfortunately, at present the available techniques with which they can assess the condition of sewers are slow, expensive and subjective, so it is difficult to demonstrate compliance with this duty.

Water companies also need enhanced information on sewers to manage efficiently both the day-to-day performance and the long-term condition of sewers, which is related to the current operational and structural conditions and rate of deterioration. The operational condition of sewer systems can changes over time due to blockages caused by sediment and fats, and due to structural changes associated with ageing and also outside interference. These factors generally have a harmful effect on the performance of the system and the incidence of blockages, and structural deterioration and collapses has been linked to flooding and other service failures. It is very difficult currently to gather sufficient information on the current condition of a sewer system to pro-actively prevent these failures.

As flooding caused by hydraulic overload has been progressively tackled through capital investment, 'flooding other causes' has become an increasingly significant service failure. Analysis by Arthur et al. (2008) of data produced by OFWAT in 2006 showed that, in England and Wales, that there were around 25,000 sewer blockages of which 13% resulted in internal property flooding. Water companies are therefore now looking for new ways of reducing these incidents through means such as modelling to identify hot-spots, CCTV inspection to locate developing problems, followed by pro-active sewer jetting.

In contrast to flooding due to hydraulic overload however, 'flooding other causes' problems commonly exist on small diameter local sewers, which make up by far the largest part of the sewer network. No longer therefore will it be sufficient to focus attention on the 20% or so of 'critical' sewers as has been the case in the past. Current technologies are limited by cost and time – new technology is needed that will work quickly and economically to permit an informed and financially justifiable ongoing program of pro-active maintenance to be carried out cost-effectively across the whole of the asset base.

Furthermore, the inspection and cleansing required is not a one-off activity. Having identified areas at risk it is important to regularly check for progressive operational deterioration and intervene again at the right time, before service deteriorates. Traditional CCTV techniques are not the ideal means of doing this, being relatively slow, expensive and subjective. As a result, a better alternative is required to provide objective measure of current operational condition of a sewer. By obtaining an objective measure of a sewer condition it will be possible to show, via repeated measurement and inspection to show that condition of a sewer is stable or not and whether a change in the on-going level of investment is needed to maintain levels of service.

1.2 Context of Work

In the UK in the past 20 years, the planning, maintenance and rehabilitation of sewers has been based around the Sewerage Rehabilitation Manual (WRc, 2001). This approach has focused on "critical sewers", which are those where it is expected that the consequences of failure would be sufficiently severe so that the consequences of failure would be sufficiently severe so that preventive inspection and action could be economically justified. The approach in other EU countries is different in that in many sewer operators are required to inspect all sewer assets at fixed time intervals.

In the UK, critical sewers make up around 20% of the total length of the sewer network. They are selected based on "knowledge" based rules related to consideration of factors such as pipe material, ground conditions and traffic loads. However, experience has shown that many of the critical sewers are in good structural condition and rarely suffer blockages. Blanksby et al. (2002) carried out an analysis of historical water company customer complaint and CCTV records to examine the causes of flooding incidents over a range of sewer sizes. Their study indicated that the majority of flooding incidents were in smaller sewers, and that the majority of these were caused by intermittent blockages rather than structural failures. The analysis also indicated that collapses were proportionately more prevalent in smaller sewers, but that the incidence of structural problems was low with around only 2% of the CCTV surveyed lengths showing signs of structural deterioration.

They concluded that it would be difficult to generate a pro-active cleaning routine based on prior predictions as the data indicated that the location of blockages generally could not be linked to a structural defect and so was thought to be linked with either the local hydraulic conditions, or local sources of slit and fat inputs. It appears that continual measurement or monitoring may provide an answer to manage sewer blockages rather than some predictive tool.

Several modelling approaches have been developed in order to predict the occurrence of sewer blockages and failure. Savic et al. (2006) used data-driven techniques to derive statistical relationships to predict the likelihood of sewer failure for different pipe classes. They used data from asset and customer complaint databases to develop and demonstrate these relationships. These techniques do not however identify individual locations within a catchment.

Arthur et al. (2008) examined the statistical significance between pipes with a high incidence of observed blockage and various factors. The study used data from a small catchment and considered each failure separately. The selected catchment had an existing sewer network model and hydraulic outputs from this model were combined with incidents in a customer complaints database. Analysis indicated that the risk of blockage was related to predicted locations of flooding and low velocities, it was also shown that there was a statistical link to smaller sewers.

In spite of these computational approaches, the need for direct inspection to identify sewer failures still exists. Traditional CCTV, and other optically based systems (SSET, 2001) used to identify failures are relatively slow and thus expensive and the analysis of the images subjective. Analysis of repeated CCTV surveys of the same sewer systems has shown that up to 20% of defects can “disappear” with time, even though there has been no intervening intervention between surveys (Korving and van Noortwijk, 2006). Better alternative techniques are required which are able to provide objective measure of current operational condition which will allow the operator to show that condition is stable and whether a change in the on-going level of asset condition is occurring. Image analysis systems for CCTV systems are now being developed to try aid operators by automatically identifying pipe joints and possible defects and so remove some of the objectivity in the analysis of the images, however these systems still require the CCTV camera to be inserted and then travel through each sewer pipe so are still slow and expensive to use (Fischer et al. 2006).

Work by Muller (2006) examined the effectiveness of different inspection strategies, and concluded that a selective inspection strategy was more effective than conventional fixed time interval inspections, but it relied on managers being able to carry out a rapid initial wide network inspection to identify key sewers for subsequent selective inspection. This is currently not technically possible at a reasonable cost.

This paper reports on a system that can measure the progress of the sewer along the condition curve. The system also has the potential to carry out network wide inspections at a rate and cost that selective inspection strategies are possible so that rehabilitation can be carried out in the right place at the right time and that the presence and location of intermittent sewer blockages could be identified.

2 METHODOLOGY

2.1 Sensor Concept and Design

The measurement technique is based on the analysis of reflected acoustic signals, as it was believed that these reflections carry sufficient information to identify pipe structural defects and blockages created by sediment and other materials such as rubble and fats. Sound propagation in a pipe is a relatively straightforward problem if the pipe diameter is much smaller than the acoustic wavelength and the acoustic impedance of the fluid is significantly less than the impedance of the pipe material. In air filled pipes, as found in combined sewers the impedance of air is several orders of magnitude less than that the acoustic impedance of any typical pipe wall materials (e.g. concrete). Unfortunately, the diameter of sewer pipes is often comparable to the wavelength of sound at audible frequencies, so in these pipes sound waves can travel in multiple directions and so analysis of the reflected signal is not so straightforward.

The constructed sensor consists of several in-line microphones and a speaker combined in a single unit. The sound source is a baffled 50mm speaker, aligned with a linear array of four microphones, placed at fixed intervals in front of the speaker. The intervals between the microphones are less than the acoustic wavelength for the sound frequencies used. Microphones measure acoustic pressure (a scalar) and by correlating their signals in the time domain, taking into account the microphone spacing it is possible to obtain acoustic intensity (a vector). Acoustic intensity is a vector defined by the product of the sound pressure at a point and the fluid particle velocity. The variation in acoustic intensity can then be analysed with time of receipt to identify blockages or other pipe defects. The sensor is used by being placed within a sewer pipe and then a long broadband signal is broadcast via the loudspeaker for 30 seconds. The measured temporal acoustic pressure signal is transformed using a Fourier series to obtain a frequency impulse response. This is done for the signals obtained from two microphones and the acoustic intensity. The acoustic intensity for the microphone pairs is filtered into narrow frequency ranges below the first cut-off frequency, which is given by eqn. 1 for a cylindrical pipe. The value of the reflected part of the acoustic intensity within these narrow frequency ranges is then used to identify defects or blockages with a pipe. For a duct with circular cross-section (i.e., cylindrical pipe) of radius *a*, the transverse, eigen-functions and values are

$$\Psi_{mn}^{\sigma} = (\cos or \sin)(m\theta) J_m \left(\frac{\pi q_{mn} r}{a} \right) \quad \text{and} \quad \chi_{mn} = \frac{\pi q_{mn}}{a}$$

where $\sigma = +1$ for cosine θ factor and -1 for the sine factor, and r and θ are polar coordinates about the central axis of the tube. The (*m,n*)-th wave has m plane nodal surfaces, extending radially out from the axis, and n cylindrical nodes concentric with the axis. The fundamental (0,0) mode for a rigid cylindrical pipe has a zero characteristic value and thus is a plane wave, propagating at the free-space velocity c. The cut-off frequency for the (m,n)th mode is $\frac{\alpha_{mn} c}{2a}$ where, α_{00}=0.0000, α_{01}=1.2197, α_{10}=0.5861 etc. Thus the first modes to become propagational are (1,0) and then (2,0). This limits the frequencies that can be used as a function of the pipe radius *a* and the speed of sound in air. An intensity value can be assigned a pipe location relative to the sensor location if the speed of acoustic wave propagation in air is known.

The system as currently constructed is able to measure pipe lengths of up to 100m. The sensor is controlled through an interface and connected to a PC which is used to control the loudspeaker and collect the data from the microphones. It emits short coded acoustic signals (e.g. Gaussian pulses, sinusoidal sweeps or other special waveforms) parts of the emitted signals are then reflected from any defects in the sewer wall, or obstructions in the pipe or from the downstream manhole and are then recorded via the microphones. These reflections are recorded via the four microphones in series for future processing. The processing algorithms are based on temporal windowing, combining two microphone signal and Fourier analysis so that the temporal and frequency response can be linked directly to the location, extent and geometry of sewer pipe deformation or blockage.

2.2 Experimental Testing

In order to test the capabilities and limitations of the system to measure blockages, tests were carried out in a full scale sewer pipe located in the Hydraulics Laboratory at the University of Bradford. The 150mm diameter clay pipe was located on a tilting rig, in which flow could be re-circulated (figure 2). The type of pipe was typical of small combined sewers found in the UK. The pipe was 14m long and was composed of pipe sections, each 600mm long. The five most downstream sections of pipe were attached to a jig and could be easily removed from the rig using an overhead crane. The allowed the sixth pipe section to be replaced with a pipe section in which a defect or a blockage had been located. A lateral connection could also be located in the pipe. In each test the sensor was placed by hand into the outlet of the pipe and a 30 second period of sound was generated to provide the incident noise. The reflected sound was then recorded via the microphones and saved for future analysis.

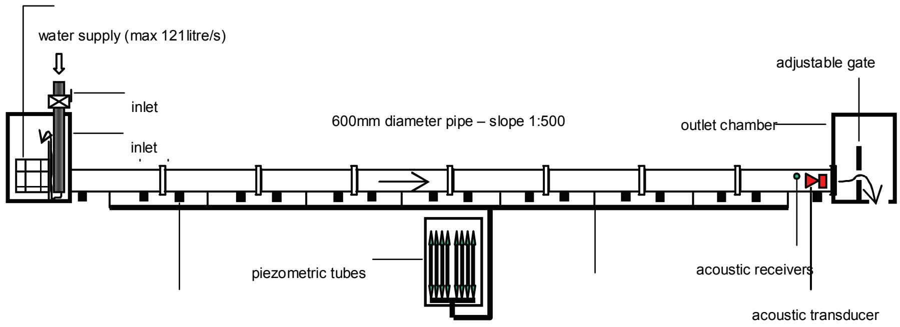
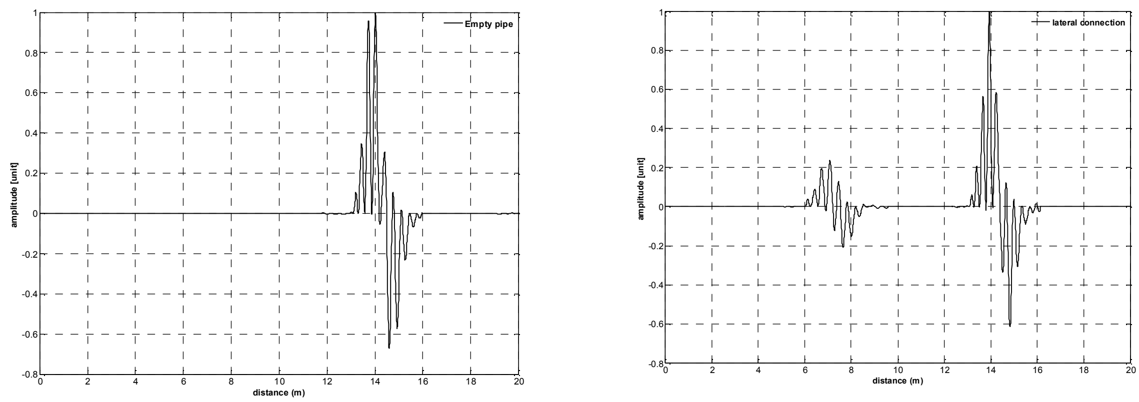


Figure 1. Sketch of laboratory pipe layout with sensor location indicated.

A typical intensity plot with distance for a clay pipe with no obstructions is shown in figure 2a. It shows clearly a significant reflected intensity caused by the downstream manhole at 14 m, with no significant reflections along the rest of the pipe. The second plot is of the same pipe but with a lateral connection now located at 7 m from the sensor (Figure 2b). It clearly shows that the lateral connection results in a significant reflected signal as well as the end manhole.



a) Reflection from pipe end of an empty pipe

b) Reflection from lateral connection and pipe end of an empty pipe.

Figure 2. Reflected acoustic intensity with distance.

3.2 Simulated blockages – size and location

Experiments were then carried out to examine the ability of the sensor to locate the position of a blockage and then estimate its size and character. In the first test series, blocks made of a clay brick material were used. Blocks of various heights (33 mm, 66 mm and 99 cm) but a constant width and depth of 100mm and 82mm were placed in the pipe at 7.5m from the pipe outlet. These rigid, non-porous blockages corresponded with a constriction in the pipe cross-sectional area of 19%, 37%, and 56%. Figure 3 shows the results of these tests. It clearly shows that if the blockage remains at a particular location that the maximum reflected intensity increases as the blockage increases with size.

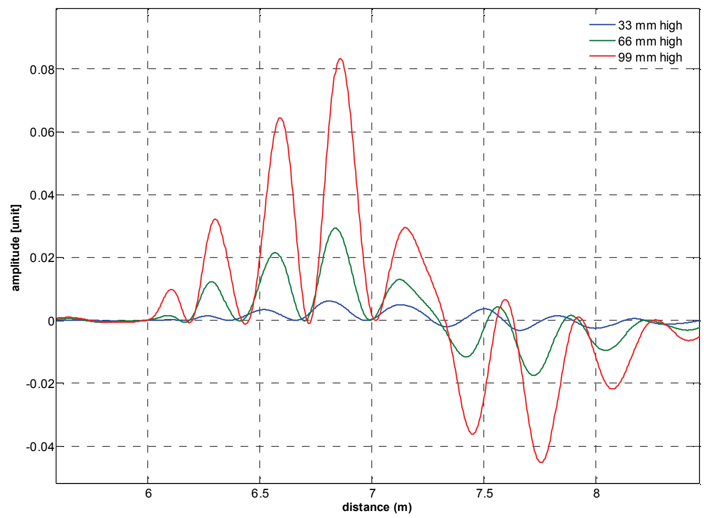


Figure 3. Reflected acoustic intensity from a rigid blockage with different sizes.

In the second test series, a porous sediment deposit was created by filling a long bag, made of acoustically transparent material, with sand with a d_{50} of 0.6mm. The deposit sediment resembled sediment found in certain combined and surface water sewers. The deposit was placed initially at 6.85 m from the pipe outlet and was then moved in steps and an acoustic reading taken each time the porous blockage was moved. The sediment simulated a deposit that corresponded to a 45% constriction of the pipe area. The location of the maximum reflected intensity is shown in figure 4. It clearly shows that the position of a porous blockage can be determined. The reduction in the peak value is a function of the distance that the reflected signal has to travel.

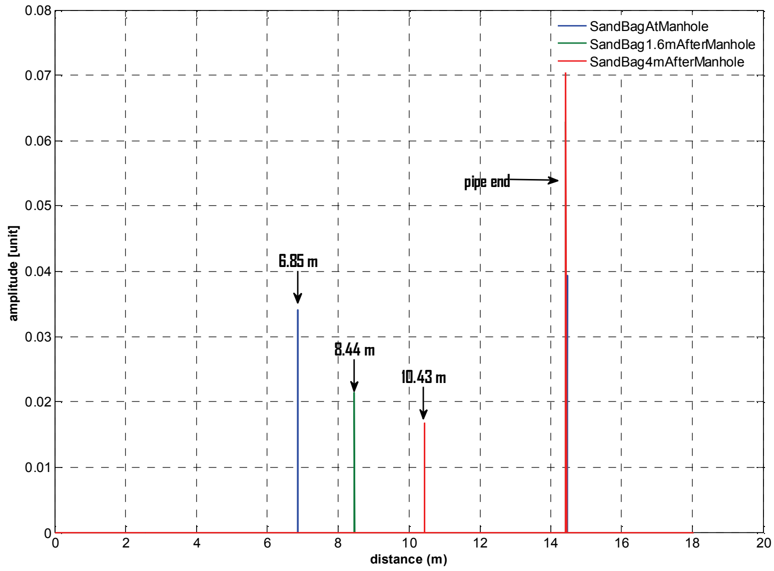


Figure 4. Reflected acoustic intensity of a sand deposit located at different positions in 150mm diameter clay pipe.

Figure 4 shows how the location of the peak of the envelope of the acoustic reflected signal corresponds with the location of the sand deposit. However it also indicates that the determination of the actual size of the deposit is not possible as the level of the maximum is also a function the distance the reflected signal has travelled.

2.3 Simulated blockages – character

More detailed analysis of the reflected intensity signal was carried out to ascertain whether the type of material that a blockage is composed of can be identified. This type of analysis depends on the phenomenon that the magnitude of the reflected intensity at different sound frequencies is a function of the characteristics of the deposit material. If the reflected intensity is plotted against frequency bands then a different pattern of intensity becomes apparent with different materials. This is caused by the way in which the sound energy at different frequencies is absorbed at different rates dependent mainly on the porosity of the reflecting surface. Fig 5a and 5b shows the pattern of frequency against intensity for signals measured for similarly sized sediment deposits and brick blockages. It clearly shows that the strength of the reflected acoustic signal is stronger at all frequencies for a non-porous blockage than for a porous blockage. Figure 5c indicates that this type of analysis can be used to distinguish between a blockage and a characteristic if the pipe such as a lateral connection. It shows that porous and non-porous deposits reflects reasonably equally across a range of frequencies and that a lateral connection reflects intensity in a non-homogeneous pattern.

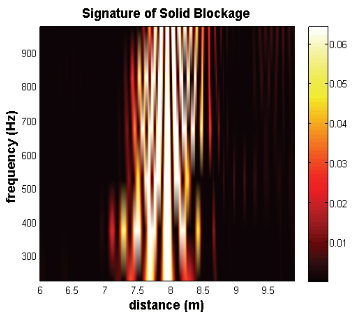


Fig 5a Reflected intensity signal against frequency for a non-porous blockage

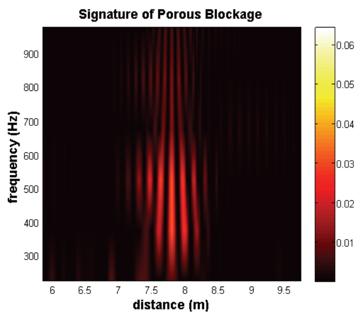


Fig 5b Reflected intensity signal against frequency for a porous blockage

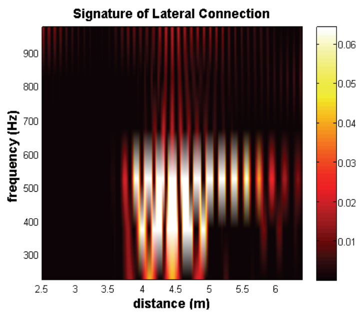


Fig 5c Reflected intensity signal against frequency for a lateral connection

3 CONCLUSIONS

In the UK sewer flow capacity issues caused by structural issues have been progressively dealt with via sewer replacement or rehabilitation so that sewer flooding incidents due to blockage have become increasingly common. Although some models have been developed to indicate pipes in a sewer network with a high likelihood of blockage sewer managers still need to inspect sewers on a regular basis in order to identify sewers that are becoming progressively blocked. Traditional inspection techniques are relatively slow and costly as so their use is limited. This work demonstrated that there are alternative means to detect pipe connections, manholes and blockages. A robust sensor has been built that is able to measure reflected acoustic intensity within drainage pipes. A series of experiments were carried out to ascertain whether the analysis of the reflected acoustic intensity could be used to identify the location of manholes and lateral connections and the location and character of blockages. The experimental results have shown that both manholes and lateral connections can be identified and their location from the sensor determined accurately. The only difference between the acoustic intensity response caused by the porous and non-porous blockages is in the frequency spectrogram. This indicated that by understanding the acoustic intensity pattern at different frequencies that it would be possible to identify whether a blockage was made of porous or non-porous material. It was also shown that rigid and porous blockages in a 150mm diameter clay pipe can be clearly identified and their location and character determined by the analysis of acoustic intensity over a defined frequency range. By carrying out measurements over time once the character and location of a deposit was known the magnitude of the reflected acoustic intensity relative could be used to estimate the cross-sectional area of the blockage relative to the pipe cross-sectional area. This method therefore provides a rapid and objective method for identifying the presence and character of blockages in sewer pipes. The laboratory data has clearly shown that analysis of the reflected acoustic intensity that the system can find manholes, lateral connections and blockages much more quickly that traditional CCTV based techniques and so offers the promise of a rapid inspection technique able to be widely used on sewer networks. This work indicates that acoustic based sensors could be used for the rapid inspection of a sewer network so as to indentify the location and character of blockages. Once sewer network managers have this information then they can pro-actively clean sewer pipes before blockages grow to an extent in which flooding becomes likely.

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