ENVIRONMENTAL ENGINEERING

May 22-23, 2008
The 7th International Conference
Faculty of Environmental Engineering
Vilnius Gediminas Technical University
Saulėtekio ave 11, LT-10223 Vilnius, Lithuania
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FAILURE MONITORING AND ASSET CONDITION ASSSESSMENT IN WATER SUPPLY SYSTEMS

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Abstract. The main focus of this paper is the failure management and pipe condition assessment in water supply systems. The failure development mechanism, management cycle and associated costs are discussed and a brief review of existing methods and research results is made. The central focus of the paper is to present the main results of the PhD project carried out by the author. The aim of the work was to explore the feasibility of using the available low cost measurements and information to improve the operation, reliability, safety and availability of the urban water supply system. Continuous pressure monitoring was selected as a source of information. Algorithms for failure detection and location in both single pipelines and pipe networks were developed and tested in the field, using real water supply systems. Good results were obtained showing the potential of the proposed methods. A pressure transient based method for a low-cost non-intrusive pipeline condition assessment was developed and tested with positive results. Finally, a pressure transient based inline valve testing methodology was introduced allowing for a quick testing of valve seal quality. All presented methods can serve as tools to increase the reliability, availability, safety and efficiency of urban water supply systems.

Keywords: failure, monitoring, detection, location, asset condition

1. Introduction

Urban water supply system has been built and developed for more than a hundred years now. Ageing of the infrastructure imposes a new challenge on water utilities – to maintain and rehabilitate the system in a most efficient way. Rapid development in other parts of urban infrastructure (telecom, transport, etc.) puts a pressure on water industry for an improvement of the operation in water supply systems by increasing the reliability, availability, safety and efficiency. A continuous improvement of the operational practise is necessary. As a result, water industry is forced to search for new advanced methods for failure and asset management.

The water supply system can be divided into two major parts – transmission and distribution systems. A transmission system consists of components that are designed to convey large amounts of water over great distances, typically between major facilities within the system. The water transported in transmission pipelines to the residential areas is distributed through the water distribution systems. Transmission and distribution systems have different topology, pipe sizes and materials, hydraulic profiles.

To be able to evaluate and discuss different pipe failure management and condition assessment approaches, a good understanding of the failure mechanism, management cycle and associated costs has to be established.

2. Pipe failure management

Pipe failure is the part of the infrastructure deterioration process. Pipe failure is a multi-step process as shown in Fig. 1. The lengths of time intervals and the mechanism of the failure are case dependent and extremely difficult to predict. Two main events in the failure process are: (i) partial failure – when the leak or a burst is developed, but the pipe remains in service; and (ii) complete pipe failure – when the hydraulic balance of the system is influenced to an extent when a repair or replacement is necessary.

The area of failure and asset management in water supply systems has been in the focus of both researchers and practitioners in water industry for the last few

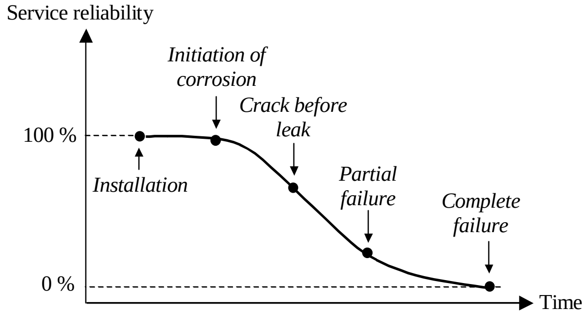

Fig. 1. Pipe failure development

decades. Since pipe failure has become a frequent event in the urban water supply systems, failure management is a part of the everyday operation of pipelines and pipe networks. A range of methodologies has been described in the literature; however, the number of failure management techniques currently practised by the water industry is not large.

Depending on the timing of the failure management activities with respect to the failure itself, two types of pipe failure management strategies can be defined:

- **proactive** failure management, when the pipe repair/replacement decisions are made prior to the failure event to prevent the failure;
- **reactive** failure management, when the repair/replacement is performed only after the failure has occurred.

The failure management cycle is shown in Fig. 2. The cost of pipe failure management is highly dependent on the type of techniques and practises that are used. The choice of the pipe failure management technique depends on which stage of the pipe deterioration process it is applied. Generally, the earlier stage of the pipe deterioration is considered, the more complex and expensive inspection technique has to be applied.

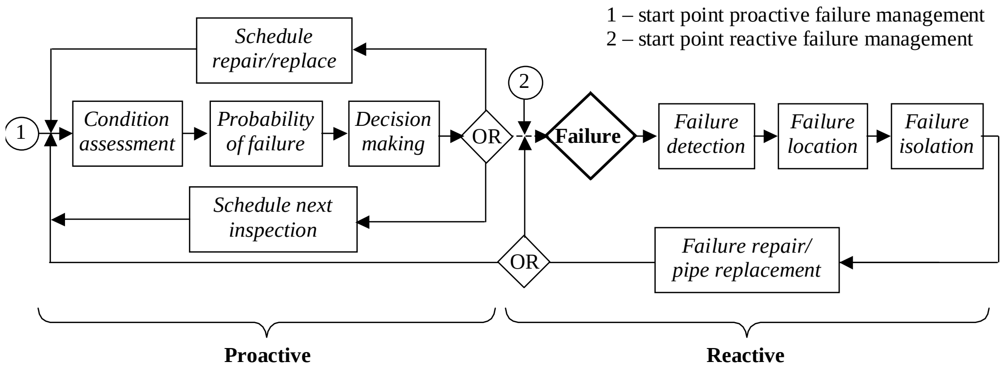

Fig. 2. The pipe failure management cycle

Fig. 3 shows the inspection cost as a function of the application time. The actual shape of curves in Fig. 3 and, consequentially, the minimal pipe failure management cost depends on the particular situation. In general, Fig. 3a can be applied for distribution networks and Fig. 3b can be used for transmission pipelines. The consequences of a failure (both partial and complete) in the large transmission mains can be quite expensive and therefore the cost of failure increases faster than in the case of the distribution network. Still, due to the relatively low cost of water and fairly high cost of currently available proactive failure management techniques along with restrictions on the budget of water utilities, only reactive failure management can be justified in water supply systems.

3. Current practise and available research

The review of existing approaches and research results found in the literature is divided into two parts: (1) failure monitoring, detection and location methods and (2) asset condition assessment techniques.

3.1. Failure monitoring, detection and location

A number of techniques and methods were developed and presented for the detection and location of failure in water systems. Pipe failure has different types depending on the size and the character. Due to the fact that for most of the techniques that are described in the literature the type of failure is not specified, a leak will be used as a general term here. Depending on the application, leak detection can be associated with two different operations. In larger transmission pipelines, where larger failures are common, leak detection is usually associated with identifying discrete pipe failure events. Subsequent leak location involves the identification of the actual position of the leak. In distribution networks, leakage detection is often integrated with leakage assessment, where the amount of water that is lost due to leaks present in the system is estimated. Leakage is detected collectively and the identification of a particular leak is part of the location process. Generally, two leakage detection and location (sometimes also referred to as leakage control) strategies can be used for both pipelines and pipe networks.

Passive or manual. The reaction to a leak incident is based on visual observations. For example, the appearance of water on the ground surface following pipe failure is visually detected by the staff or reported by customers. Manual location techniques are then used to identify the actual location of the failure.

Active or automatic. Active leakage control includes management policies and processes that are used to locate and repair unreported leaks from the water supply system [1]. Active leakage control can involve systematic manual leak inspections or continuous monitoring for automatic detection of leaks.

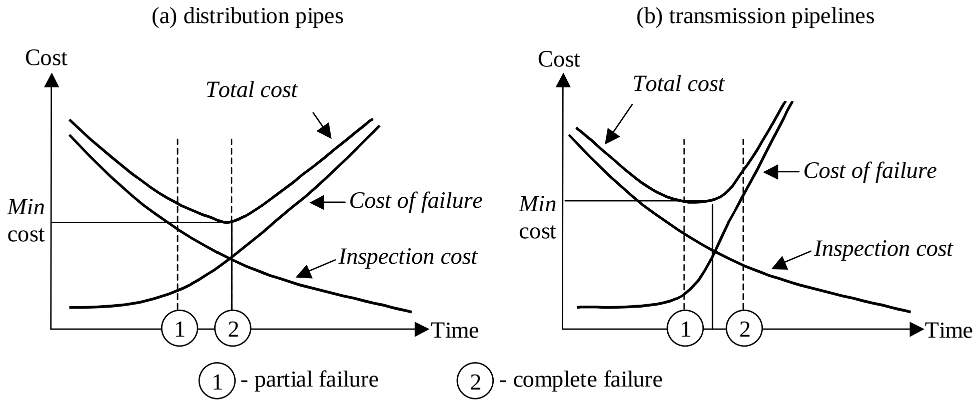

Fig. 3. Variation of inspection and failure costs during the deterioration process

Manual leak location techniques are normally used, although some leak monitoring systems provide automatic location.

Passive leakage detection is straightforward, simple and does not involve any systematic action. Thus, it will not be discussed here. The main focus of the work presented here is on active leakage detection and location strategies. Active leakage control techniques can further be divided into two groups:

Inspection (survey). Inspection or survey leak detection is a planned action that is performed at discrete time instances. The inspection involves checking the whole or a part of the system to assess the level of leakage and find leaks that are already present.

Monitoring. Continuous failure monitoring is used for detection of leak events in real-time. A monitoring system is installed on a pipeline or in the network permanently and is continuously checking for new leaks. Some monitoring systems can perform

A large number of leak detection and location techniques have been applied in real systems or have been described in the literature. Some of the existing techniques are designed for detecting leaks only and are not capable of locating them. Other methods are developed specifically to locate leaks. Finally, there are methods that allow for both detection and location.

Commercially available leakage inspection methods can generally be divided into two large groups - acoustic inspection techniques and non-acoustic inspection techniques. In addition to these two groups, transient-based leak inspection methods can also be identified. The most developed acoustic inspection techniques are listening [2], acoustic monitoring [3] and cross-correlation [4]. Examples of non-acoustic inspection methods are tracer gas technique [5], thermography [6], ground penetrating radar [7] and pig-based methods [8]. Although not yet available commercially, transient-based approaches have been given a lot of attention from the research community. The most developed methods are: leak reflection methods [9], inverse transient methods [10], impulse response analysis [11], transient damping method [12] and frequency domain response analysis [13].

Leak monitoring approaches can be divided into measurement-based and model-based techniques. Measurement-based methods are using the analysis of measured parameters to detect leaks. Most common techniques are: acoustic monitoring [14], volume balance [15], pressure-point analysis [16], negative pressure wave [17], statistical pipeline leak detection [18], and district meter areas [19]. Model-based leak monitoring techniques combine the modelling of the system with the measurement analysis. Techniques, presented in literature, are: real time transient model [20], inverse analysis [10, 21] and state estimation [22].

Some general observations can be made before the application of the reviewed techniques can be discussed.

Leak inspection techniques. Validation results for nine different techniques are analysed, twelve test cases were considered. 44% of the techniques (4 out of 9) are commercially available, while the rest are still under development. All approaches can be applied on single pipelines. However, only 3 out of the 9 techniques are suitable for application in networks. It has to be noted that the method was not considered to be applicable in the network in case when it can only be applied on a single branch of the network. Only 2 out of 5 methods that are under development were tested in the field and leaks that were detected using those methods were at least 2 − 3 times larger (Dl/D) than the leaks that can be detected using available techniques. All available techniques, except pigging (the only intrusive method), have quite a short range, i.e. are labour-intensive. Available inspection techniques have mainly been applied in water pipelines and networks.

Leak monitoring techniques. Total of sixteen presented monitoring methods are equally divided between pipeline and network applications. However, only 1 out of 8 network approaches is commercially available, whereas 63% of pipeline leak monitoring techniques are applied in the field. This situation can be explained by the fact that most of the existing leak monitoring applications are implemented in oil or gas transmission pipelines. The instrumentation level of oil and gas pipelines is fairly high and the monitoring techniques used in these pipelines require more measurements. Due to the high risk associated with failure of oil or gas pipelines, monitoring approaches are chosen. Acoustic monitoring is the only available approach for the network case. It requires a large number of sensors and therefore is labor intensive.

Application in water supply systems. It is extremely difficult to find one leak detection and location technique that would have the best performance in all cases. There is a number of aspects that have to be considered before making conclusions regarding the performance of a particular method. It is clear that the main parameter that is used as a performance indicator is the cost-benefit ratio. However, evaluation of the cost and the benefit is not that straightforward. First of all, limitations may apply to the maximum allowable cost in the water industry. On the contrary to the oil and gas industries, large investments cannot be made by water utilities. At the same time, evaluation of the benefit of using one or another leak detection technique is not a simple process. Very limited practical experiences of using different techniques can be found. Some general conclusions can be made from the review of available techniques:

1. Since leak inspection techniques are labour intensive, leak inspections are not frequently performed. This results in long leak detection and location times.

2. To achieve a quick response to a leak, continuous monitoring is necessary.

3. Most of available monitoring techniques can only be applied on single pipelines and, in some cases, single branches of the network.

4. Monitoring of every single branch in a network is financially infeasible.

5. Available pipeline monitoring approaches require the pipeline to be well instrumented.

6. Failure location capabilities have to be improved in both pipelines and networks.

Considerable differences exist between water transmission pipelines and distribution networks in terms of the topology and hydraulics, the regime of operation as well as types and consequences of failure. The differences are also reflected in the choice of failure detection and location techniques. The overall conclusion is that failure monitoring techniques have to be developed separately for pipeline and network applications. The cost-benefit ratio of failure detection depends on the cost of failure. Medium and large pipe breaks (bursts) present the highest risk and have the most expensive consequences out of all types of pipe failures observed in the water supply systems. With system getting older, the frequency of these failures is increasing. The techniques that are currently used in the water industry are not suitable for quick reaction to pipe bursts. Thus, the following directions have been formulated for the work on failure detection and location in pipelines and pipe networks:

- medium and large bursts are the primary target;
- continuous monitoring or periodical diagnosis;
- low installation and maintenance costs;
- automatic analysis.

Automatic techniques that have been developed for the pipeline failure monitoring, detection and location and the network failure monitoring, detection and location are presented in the next section.

3.2. Asset condition assessment

There are two main approaches for assessing the condition of a pipe. The first approach is direct inspection and monitoring, also called non-destructive testing (NDT). The second condition assessment approach is based on using indirect indicators, such as soil properties and historical pipe breakage rates.

Nondestructive testing is the type of testing that allows detecting and evaluating of defects in materials without disturbing the specimen’s structural or surface integrity. The history of NDT started with studies of ultrasonic waves and their application for detecting flaws in metal objects [31]. In the 1950s, ultrasonics was applied for manufacturing flaw testing in pipes. Later on, the benefits of using nondestructive testing to assess the deterioration of metal structures were identified [32]. Currently, nondestructive testing is used for in-service inspection, condition monitoring and measurement of components and their physical properties. NDT techniques are sometimes called nondestructive evaluation (NDE) or nondestructive inspection (NDI) techniques. The term nondestructive evaluation will be used here. The main benefit of NDE is that the testing has no negative effects on the condition of the materials or structures that are tested. A wide range of NDE techniques are available today with different degrees of complexity and operational costs, as well as specific application areas and limitations. The techniques can vary from simple visual examination of a surface to more complex radiographic, ultrasonic or magnetic methods and finally to new advanced and highly specialised approaches. To select the optimal NDT method for a particular application, a comprehensive knowledge of both the method and the tested object is necessary.

A large number of contributions to the development and application of NDT techniques can be found in the literature. Reviews of different NDE techniques are presented in literature [33-35]. In general, all NDE techniques can be divided into two main categories: (1) visual NDE methods and (2) non-visual NDE methods. Most popular visual techniques are: closed-circuit television inspection, pipe scanner technology and laser-based scanning. Examples of non-visual methods are:

ultrasonic testing, guided waves, magnetic flux leakage, remote field eddy current, georadar, ground penetrating radar, linear polarization technique, field signature method, acoustic emission monitoring, impact echo, mechanical and free vibration methods.

Historically, NDE methods have been developed for large oil or gas pipelines, where inspection budget and failure risk are considerably larger than in water supply systems. As already noted earlier in Chapter 2, the main requirements for condition assessment techniques from the perspective of the water industry would be low cost and a fast inspection, whereas high precision of the inspection is less crucial. None of the existing NDE techniques can satisfy those objectives. Furthermore, the range and the speed of inspection are very small. A number of techniques require the inner surface of the pipe wall to be clean. Water pipelines often have an accumulation of tuberculation on the inside wall and therefore cleaning would be necessary before inspection. The cleaning would further increase the cost of inspection and, in many cases, water utilities are reluctant towards any disturbances due to health and safety concerns, i.e. intrusion of contaminants due to pressure drop or disinfection of the pipeline after inspection. Currently CCTV inspection is the main tool for condition assessment of water pipes. Recent developments of the technology allow for good quality of the captured image, but a number of drawbacks still remain. The analysis of the data from CCTV inspection is usually done manually, which is extremely time and labour intensive. To be able to insert the camera and the transporter into the pipe, cutting the wall is often required. Since the range of CCTV inspection is only around 300 m on each side of the access point, a large number of access points will be necessary in a long pipeline. Finally, de-watering is usually required. The combination of all these factors and related health and safety issues prevent large-scale applications of CCTV inspection in water transmission pipelines. Other available NDE techniques reviewed earlier in this chapter, have similar drawbacks to those of CCTV inspection. Thus, further development of NDE methods is required to make their use in water supply systems more frequent and systematic. New techniques, offering low cost and time-effective inspection, represent another alternative.

4. Developed methods

The work presented in this paper is a summary of the doctoral thesis written by the author [23] and was focused on the development of systematic approaches for effective failure management in urban water supply systems. Both proactive and reactive failure management techniques have been developed. The results can be divided into two parts: (1) failure monitoring, detection and location methods and (2) asset condition assessment techniques.

4.1. Failure monitoring, detection and location

Reactive failure management techniques that were developed are summarised in Fig. 4. Due to different topological and hydraulic characteristics, separate failure monitoring approaches were developed for single pipeline and pipe network applications. As knowledge about the burst development (burst opening) process is limited, two burst opening scenarios were considered. The first scenario assumes a sudden rupture of the pipe wall and the second scenario considers a burst, which develops over a longer period of time. Each scenario was applied to a pipe case and a network case and, as a result, a total of four approaches for failure monitoring, detection and location were developed. The first two techniques are applicable for automatic failure monitoring in pipelines and the other two methods were derived for automatic failure management in pipe networks.

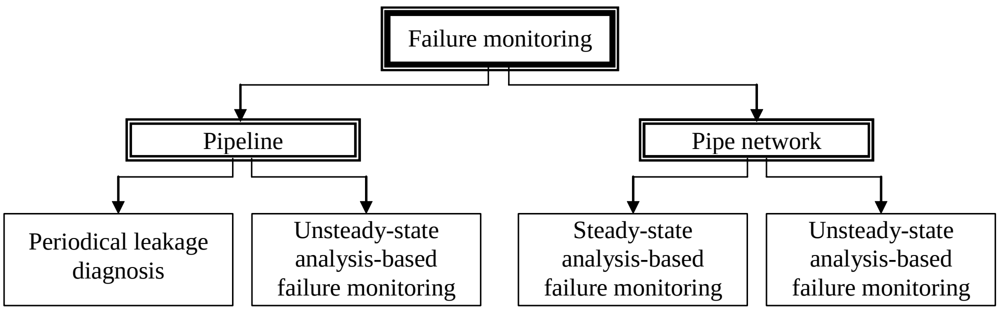

Fig. 4. Techniques for failure monitoring

Pipelines. For the pipeline case, two approaches were developed and tested. The first approach involves periodical diagnosis of leaks based on transient response difference monitoring [24]. Only one pressure monitoring station is necessary for the whole length of the pipeline, making the implementation and maintenance costs reasonably low. The proposed system has been successfully validated both in laboratory and field conditions. The results indicate that such a system can be applied in water transmission pipelines or in single branches of a distribution network, where immediate reactions to failures are critical.

An artificial hydraulic transient is periodically generated and the measured response trace is compared to the reference transient response that corresponds to a leak-free situation. It is sufficient to have a single pressure measurement point and a single transient generation point along the pipeline in order to detect and locate a leak. When the approach was validated on a full scale transmission pipeline, a relatively small leak was detected and located with a precision of 0.3% of the total length of the pipeline. In addition, the technique was shown to be capable of detecting an air pocket and a partial blockage in the pipeline.

The second technique is a burst monitoring, detection and location system designed for a quick reaction to sudden pipeline ruptures [25-27]. A transient-analysis based approach is capable of issuing an alarm of a burst event and deriving the burst location automatically after the failure has occurred.

The two pipeline failure monitoring approaches can be integrated into a multi-type failure monitoring, detection and location system. The integrated system would enhance the reliability and precision of failure detection and location.

Pipe networks. Two failure detection and location techniques were developed for application in water distribution networks. The first approach is based on steady-state analysis and can be applied on the level of a district metering area (DMA) [28]. The inflow rate is continuously monitored and the burst-induced change of flow rate is automatically detected. The location of the burst is derived using the distribution of the pressure, which is measured at a number of monitoring stations within the network. The method was successfully validated using simulated data. The optimal measurement point placement, uncertainty of the results, performance limits and implementation aspects of the technique were investigated. It was shown that a small DMA (300 properties) can be successfully monitored using one flow rate and between 2 and 4 pressure measurement points. The derived failure locations had an error of less than 30 m.

The second approach for failure detection and location in a network is based on an unsteady-state analysis [29, 30]. Continuous monitoring of the pressure is performed at a number of locations within the network. In case of a sudden pipe failure, the burst-induced pressure wave is automatically detected at two or more monitoring stations. Arrival times and magnitudes of the transient wave measured at different monitoring stations are used to derive the location of the failure. The method enables quick and precise location of the failure regardless if it occurs at nodal or non-nodal (along pipes) locations. The technique has been successfully tested on a real water distribution network. Different aspects, such as the optimal placement of pressure monitoring stations, limits of burst sizes that can be detected, uncertainty of results and implementation aspects of the system, were investigated. Test results demonstrated that three pressure measurement stations were sufficient to monitor a network supplying around 250 households and bursts were located with a precision of 9 m without pre-calibration of the network model.

Combining the two systems into one would allow for a wider range of detectable failures as well as higher reliability of the failure detection and location.

4.2. Asset condition assessment

The asset-condition assessment-related techniques that were developed are summarised in Fig. 2. Two different assets of the water supply system were considered -- pipes and valves. Pipe condition assessment is part of the proactive failure management strategy, whereas valve condition testing is essential for isolation of the failure, i.e. is part of the reactive failure management exercise. A nondestructive pipe evaluation (NDE) technique designed for condition assessment of transmission pipelines was presented [31, 32]. This technique can be used for two purposes: (1) as a proactive failure management tool and (2) for rehabilitation planning. The proposed inspection technique has a longer range and higher inspection speed than currently available NDE methods. A hydraulic transient wave is generated artificially and the measured response is analysed for pipe condition assessment.

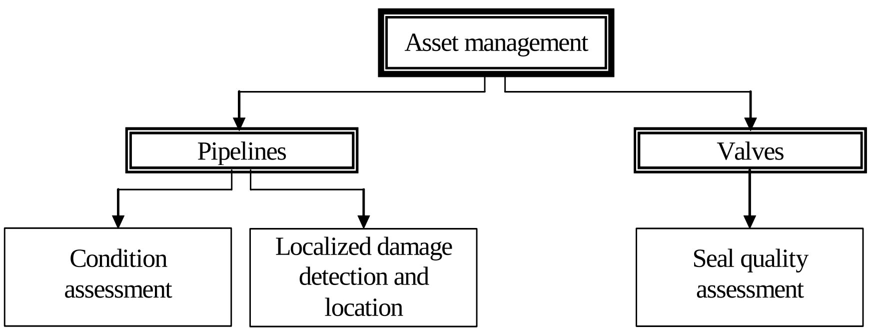

Fig. 5. Techniques for asset management

A comparative evaluation can be made where different sections of a pipeline are ranked depending on their condition. The proposed technique can also be used to identify sections of a pipeline where further inspection using more precise NDE techniques is necessary. The approach has been tested on a real transmission pipeline.

The last technique that was developed was a transient-based inline valve seal testing methodology [33]. For effective isolation of a failure, it is necessary that inline valves seal properly. Currently, there is no established methodology for testing the seal quality of valves. The developed approach is based on analysis of the transient wave reflection from a closed valve. The size of the valve opening is estimated and the corresponding leak flow rate through the valve is derived. The approach has been tested on inline valves in transmission pipelines.

5. Significance of results

The new techniques presented in this paper contribute to different points in the pipe asset management cycle and can improve *reliability, availability, safety* and *efficiency* of the urban water supply.

The developed transient-analysis-based non-destructive evaluation technique enables systematic condition assessment, which is faster and cheaper than currently practiced pipe inspection methods. A larger-scale condition assessment can make the proactive failure management more effective and increase the *reliability* of the water supply system. More *efficient* planning of the rehabilitation process can be achieved by having more information about the current state of the assets. Proactive failure management prevents the failure itself, increasing the *availability* and *safety* of the water supply system.

Considering the average age and condition of pipe assets, it is reasonable to assume that, even if the proactive failure management practices are improved, the rate of pipe failures will increase in the future. Therefore, the reactive failure management practices have to be improved to reduce costs associated with failures. The developed techniques for leak and burst monitoring in pipelines and networks can be used to reduce failure detection and location times. The presented valve testing methodology is designed to evaluate the quality of a valve's seal, which is essential to guarantee successful isolation of pipe failures. Quick and effective isolation of failures minimise associated losses, thus, increasing the *efficiency* of the supply system. At the same time, rapid and effective isolation reduces the probability that a failure will have consequences, which could be hazardous to society. The continuous failure monitoring system combined with the valve testing enhances the *safety* of the supply. By reduction of the reaction time to failure, the *availability* of the supply system is increased, since service interruption times are reduced.

Acknowledgements

The PhD project carried out by the author was funded by the Department of Industrial Electrical Engineering and Automation, Lund University, Sweden. Part of the research work presented in this paper was conducted in cooperation with the School of Civil and Environmental Engineering, University of Adelaide, Australia. Author wants to thank United Water International and South Australian Water Corporation, Adelaide, Australia for the access to their systems during field testing.

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