Rehabilitation of water networks : survey of research needs and on-going efforts
Rajani, B. B.

Publisher's version / Version de l'éditeur:
https://doi.org/10.1016/S1462-0758(99)00002-3
Urban Water, 1, 1, pp. 5-22, 1999-03-01

NRC·CNRC Institute for Research in Construction
CNRC·NRC Institut de recherche en construction
http://www.nrc-cnrc.gc.ca/irc

Rehabilitation of water networks: survey of research needs and on-going efforts

NRCC-43977

Rajani, B.B.

Date

A version of this document is published in / Une version de ce document se trouve dans:
Urban Water, 1, (1), pp. 5-22, March 01, 1999, DOI: 10.1016/S1462-0758(99)00002-3

ELSEVIER

Urban Water 1 (1999) 15–22

UrbanWater

www.elsevier.com/locate/urbwat

Rehabilitation of water networks ☆ Survey of research needs and on-going efforts

S. Sægrov [a,*], J.F. Melo Baptista [b], P. Conroy [c], R.K. Herz [d], P. LeGauffre [e], G. Moss [c], J.E. Oddevald [f], B. Rajani [g], M. Schiatti [h]

[a] *SINTEF Civil and Environmental Engineering, N-7465 Trondheim, Norway*
[b] *Laboratorio Nacional de Engenharia Civil, Portugal*
[c] *Water Research Centre, UK*
[d] *Technische Universität Dresden, Germany*
[e] *INSA Lyon, France*
[f] *Oslo municipality, Norway*
[g] *National Research Council, Canada*
[h] *Consorzio Agac, Reggio Emilia, Italy*

Received 23 December 1998; received in revised form 1 July 1999; accepted 20 July 1999

Abstract

Several water utilities experience and expect a great future challenge due to shortage of water, economical constraints and ageing water supply networks. The current and expected amount of pipe bursts and leaks are important indicators on network condition. Documentation of network properties, failures and water leaks, therefore, are of crucial importance for an efficient management. The paper refers different ways of handling this scope in European countries and in North America. The use of statistical methods for estimating existing and future rehabilitation needs and the use of software tools for prioritising actions are discussed. Current development on technologies for detecting leaks and for measuring pipe wall thinning is commented. It is argued that there is still a knowledge gap, and that joint international research could be a way to improve the knowledge, create new technologies and improve the water network management. A possible frame for an international programme has been presented.

Keywords: Best management approach; Karlsruhe procedure; Sewer inspection; Water network

1. Background and relevant work

1.1. General

The water networks serving the utilities in Western Europe and North America are up to 150 years old. The older part of the networks has been built under standards and construction practices, and with technologies that are no longer appropriate. Nevertheless, to replace this part of the networks is beyond the economic capabilities of the water utilities. It will, therefore, be necessary to handle older networks in other, more appropriate ways. To maintain or improve the performance of existing water networks, both old and modern, systems and technologies for inspection and control, operation and maintenance, and appropriate rehabilitation should be used. Additionally, basic knowledge of network deterioration factors and models for forecasting failures and rehabilitation needs should be available to support the network management strategies.

One common indicator of water distribution systems deterioration is the number of water main breaks. However, this indicator may in many cases be misleading because often a distinction does not exist between breakage attributed to actual deterioration versus breakage due to extraordinary operational or environmental stress, accidents, joint leaks, etc (Alegre, 1998;

☆ This document has been performed in a joint work under the COST C3 action "Diagnosis of Urban Infrastructure" in 1998. The working group has considered structural and functional deterioration of water pipes. The document represent the view of the group on the state of the art and current research needs in this field.

* Corresponding author. Tel.: +47-73-59-23-49; fax: +47-73-59-23-76.

E-mail address: sveinung.sagrov@civil.sintef.no (S. Sægrov)

1462-0758/99/$ - see front matter
PII: S 1 4 6 2 - 0 7 5 8 (9 9) 0 0 0 0 2 - 3

Alegre, Baptista & Faria, 1997; Coelho, 1997). Many case studies show that the general trend is towards an increase in the number of water main breaks, particularly in metallic water mains, while other studies show that the underlying trend due to deterioration has only a small increase. Most types of plastic pipe have not been in the ground long enough to show long-term performance trends, particularly when compared to more traditional materials.

An important question to pose is what is the expected water main breakage rate (generally expressed as breaks/km/year) in the future, and what is the appropriate strategy to rehabilitate (including renovate, reline or replace) water mains. Typically, water mains in fully developed networks are being rehabilitated at an annual rate of 0.5–1% of the existing length of the distribution system, which indicates that the average service life of these water mains is expected to lie in the range from 100 to 200 yr. Direct economic costs (e.g., rehabilitation investment, repair costs, water loss, etc.) as well as indirect costs (e.g., costs of water damage and service disruption as well as social costs of repair and replacement works in the streets, etc.) should be considered in a comprehensive economic analysis.

1.2. Inspection and control of water mains

The current state of the art depends on the type of material and diameter of the pipe that is to be inspected. There is also an important differentiation between a reactive and proactive approach. Reactive techniques will only detect problems once they have occurred, while proactive techniques are supposed to allow a water utility to detect developing problems before a pipe has failed. In general proactive techniques have greater "up-front" costs for the inspection, while reactive techniques imply greater "follow-up" costs for the repair of failures that have occurred. The technical and economical advantages of applying proactive techniques have so far not been verified in general. It needs comprehensive economic analysis for defining the extent to which it should be used. British experiences in the 1980s were that such techniques are not cost effective in smaller (distribution) pipes and are of limited use for predicting brittle failure.

The basic technique for inspecting all water mains is the water audit. Checking the flow into and out of a pipe or a water zone is the simplest way of detecting whether a leak exists. This technique is purely reactive and does not identify where exactly the leak is located, but it is the cheapest method for getting an overall assessment of the condition of a water network. Some water pipes, such as steel and ductile iron, leak before they fail. Others such as larger diameter pre-stressed concrete pipes break before they leak. This may also be the case for grey cast iron and traditional brittle materials. Some plastic pipe systems leak first and then fail, others fail before leaking. PVC pipes can do either, depending on the installation and operation conditions. In some circumstances, the nature of the failure can be predicted, even if the time and location cannot.

Leak detection is reactive in nature. The primary tool for locating leaks in operating pipes are currently acoustic leak detection systems. They rely on detecting leaks by the characteristic sounds they make as the water leaves the pipeline. The more sophisticated leak detection tools are locating the leak by automatically correlating the time of arrival of the sounds to two different locations on the pipe. This allows the utility operator to minimise excavation expenses. The technique is commonly used for small diameter metallic pipes. The Water Research Centre (WRC) in UK is in the process of developing and field testing a system that will operate inside all pipes down to 250 mm, while the National Research Council of Canada (NRC) is completing a project co-sponsored by the American Water Works Association Research Foundation (AWWARF) to develop techniques for leak detection in plastic pipes. While it is known that these systems have a high degree of success in finding leaks in pipes, no studies appear to have been done to indicate the number of false positives and false negatives created during a network wide campaign of leak detection.

Structural condition assessment of pipes provides a proactive approach, indicting the extent of corrosion even before it has progressed far enough to cause leakage. WRC has produced a Guidance Manual for the Structural Condition Assessment of Trunk Mains, which describes the strategic considerations and wide techniques available for determining present and projected structural condition.

Wall thinning and possibly cracking in metallic pipes can be detected by the remote field effect. This is a proactive, electromagnetic inspection technique that has been shown to be successful in indicating the depth of corrosion pitting in grey cast iron and ductile iron water mains. NRC is currently investigating the use of the technique to size corrosion pits and cracks in three dimensions, rather than simply depth. Remote field inspection requires access to the pipe interior. It is currently available for smaller diameter pipe sizes (up to 300 mm), with larger tools being built as required.

Sophisticated ultrasonic tools for determining pipe wall and lining thickness are also being developed. These proactive tools can produce results as accurate as the remote field effect in the laboratory but have not yet been field-tested. Ultrasonic tools can give information on the quality of any lining inside a pipe, which is not possible by using the remote field effect. However, the remote field effect is unaffected by the presence of tuberculation inside a pipe, while ultrasonic inspection is impossible where tuberculation is present. Recently developed acoustic techniques can also be used to monitor and inspect prestressed concrete pipes. Additionally, thermal imaging and detection systems developed for use on these barrier coatings may offer a potential for non-contact evaluation and of non-conductive pipelines.

There are a few possible approaches for detecting damage and deterioration in plastic pipelines. Those that exist are either inherently destructive or are impractical for use on a large scale. Non-destructive test systems that show some promise, such as ultrasonics, are usually effective only when combined with one ore more additional test approaches. A combination of larger scale monitoring, statistically based risk evaluation and highly selective targeted sampling offers a potential solution provided that the techniques can be integrated in a robust manner.

1.3. Structural deterioration of water pipes

Water main data, as well as historic data for water main bursts and leaks, are almost always collected by the individual utilities for internal use. Consolidated databases, either regional or national can be useful to identify broader trends in water main deterioration. Consolidated databases will necessitate standardised reporting of pipe damage events, which will result in higher quality data for future analyses. The privatisation of water utilities in UK has been a motive power in establishing documentation systems for water and sewer network condition. In Italy, the Parliament recently has approved a law to re-organise the water services. The law requires an improvement of efficiency and reliability of water distribution networks. A pilot project has been carried out for the water network of Reggio Emilia, where hydraulic and historic pipe break data has been analysed to make a diagnosis of the network. Monthly flow-rates by district and breaks in summer months illustrate a connection, which has been used in a rehabilitation planning strategy: lower flow gives higher pressure and thereby higher failure frequency. Pressure reduction in certain areas has been introduced, which has reduced the amount of failures. This project will now proceed (Di Federico, Mazzacane & Schiatti, 1998).

Seasonal trends in burst rate have also been found in one region of the UK. In this case both a winter and a summer peak were observed. The summer peak was attributed to drying and uneven shrinkage of clay soils, whilst the winter peak may have been due to frost loading or thermal contraction effects. In addition, the annual burst rate over a period of 10 years was found to be related to the mean annual daytime temperature and inversely related to the total annual rainfall (Conroy, 1996, Fig. 1). These findings are examples of necessary information to understand the trends, and thereby provide the correct use of trend analyses for rehabilitation planning.

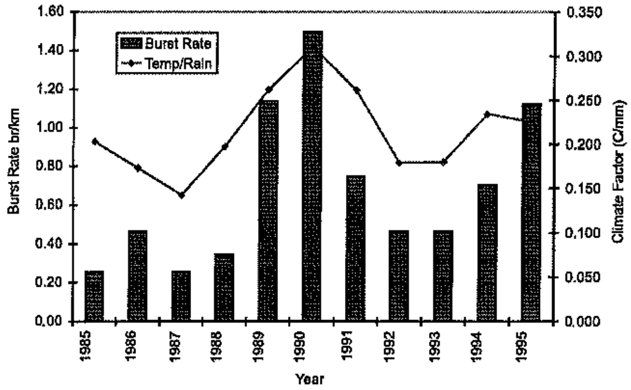

Fig. 1. Seasonal trends in burst rates. Example from British region (Conroy, 1996).

In Scandinavia, major cities have practicised computer assisted reporting on water main bursts and leaks for the last 10 years. The same holds for France, Germany and UK, where network information systems have been established, though not yet completed, by most water utilities including statistics on pipe failures and condition as well as rehabilitation work that has been done. Inspection of pipes and armatures is required at regular intervals according to technical standards and guidelines.

Over the years, several models have been developed to forecast water main breaks. Procedures based on water network records and commercial available statistical models have been applied in Italian and Norwegian cities, and research is carried out in France and the UK.

The example in Fig. 2 illustrates the connection between statistical modelling and spatial analysis of pipe breaks (Malandain, LeGauffre & Miramond, 1998). Map 1 shows areas in selected boroughs of the Lyon conurbation, where the observed breakage rate is significant higher than the rate predicted with a statistical model calibrated and validated on the overall water supply system. Map 2 is used to test the connection between these hot points and data showing probable external loading condition (ground movement: area with a high geotechnical risk). This kind of analysis is useful to determine new variables to be included in the database relative to pipes, and further to improve statistical breaks modelling.

Several major European cities have applied the German "Karlsruhe Procedure" for determining the length of water mains that will reach the end of their useful lifetimes in future years (Herz, 1996). The procedure has been cast into the user-friendly software KANEW in a research project sponsored by AWWARF (1998) Further extensions allow to analyse long range effects resulting from specific rehabilitation strategies (Herz, 1998). The framework for exploring rehabilitation needs and strategies is shown in Fig. 3.

Methods for statistical treatment of failure data, and distribution functions applied on existing failure data,

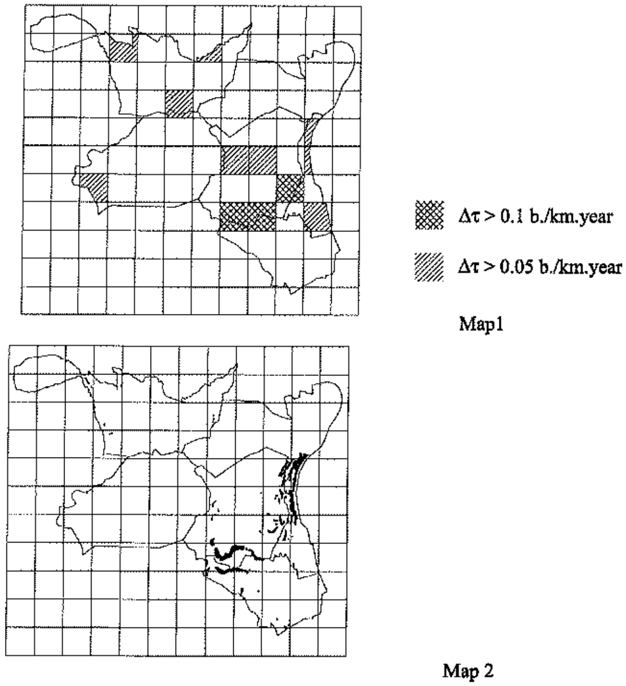

Fig. 2. Connection between statistical and spatial analysis of pipe breaks (Malandain, LeGauffre & Miramond, 1998).

have commonly been used for forecasting service life of constructions (Kim & Mays, 1994; Eisenbeis, 1997; Røstum, Dören & Schilling, 1997; Brèmond, 1998; LeGauffre, 1998; Lei & Sægrov, 1998). Fig. 4 illustrates the use of the Nelson Aalen plots and Cox Proportional Function for water network in Trondheim, Norway. Note that the term "survivor" in this context means the time the pipe survive without any failure.

Historic water main break data should be collected, analysed and ultimately combined with appropriate technologies for in situ pipe condition assessment, to yield water main deterioration rates. These deterioration rates should be evaluated against pipe environmental and operational stresses to yield information (possibly predictions) of breakage rates or frequencies. The deterioration rate of the hydraulic capacity of the water mains should be evaluated as well. A decision support system (DSS) should be applied, in which the rehabilitation alternative for every pipe in the network would be selected and scheduled, while achieving the following:

1. Minimise the total cost (investment including maintenance) of keeping the distribution network at defined levels of services for structural, hydraulic and quality aspects of performance.
2. Consider the deterioration in both the structural integrity and the hydraulic capacity of the network.
3. Consider the reliability of the network.
4. Consider water quality issues such as the increased risk of contaminant intrusion through deteriorated water mains.

Several DSS systems have recently been developed or are under development. WRC has made a software-based package, called Waterfowl, which provides a technical selection and whole life costing method for selecting the most appropriate rehabilitation option.

As a part of the EC INNOVATION research programme, several European research institutes are working out a computer assisted decision support system on water network renewal, called Util-Nets. This system includes, by a deterministic approach, detailed routines for the calculation of burst probability for cast iron pipes, and an advanced users interface (Eimermacher, 1998, Fig. 5).

The long-term performance of plastic pipes (PVC and PE) has been extensively researched in the UK on behalf of their water and gas utilities, albeit much of the related information has not been published. An example of the need for more UK information to be put into the public domain relates to the long-term influence of scouring or scratches on PVC and PE pressure pipes. More work has been done on PE pipes because of its extensive use in the water and gas distribution systems.

Corrosion rates of buried cast and ductile iron water mains have been extensively researched and are well understood. If not mitigated, it will eventually penetrate through the complete thickness of the metal pipe wall. Even though many studies have been conducted to assess the effects of corrosion on the longevity of water distribution systems, few methodologies have been developed that take into account its influence on structural resistance. Among a number of research institutions looking at this problem is NRC, SINTEF and WRC.

Cathode protection (CP) is used by many water utilities to diminish the external corrosion rate of metallic water mains. Most often the reduction in water main breaks is substantial and immediate but there is no clear understanding on the relation between an electrochemical process and structural strength of cast and ductile iron. Further studying of cathode protection is required, to quantify the added pipe longevity it provides and thus determine its cost effectiveness.

Materials used in the water distribution system have a definite impact on water quality. A number of ongoing projects are concerning this issue. AWWARF has one project underway on this and in Europe research has been carried out by among others KIWA (The Netherlands), SINTEF as well as Polytechnic (Italy). A new Italian research programme has been presented to address this important issue.

1.4. Maintenance measures in water distribution system

Any effective water mains network management strategy will look to maximise performance regarding level of service criteria, (e.g. flow, pressure, quality)

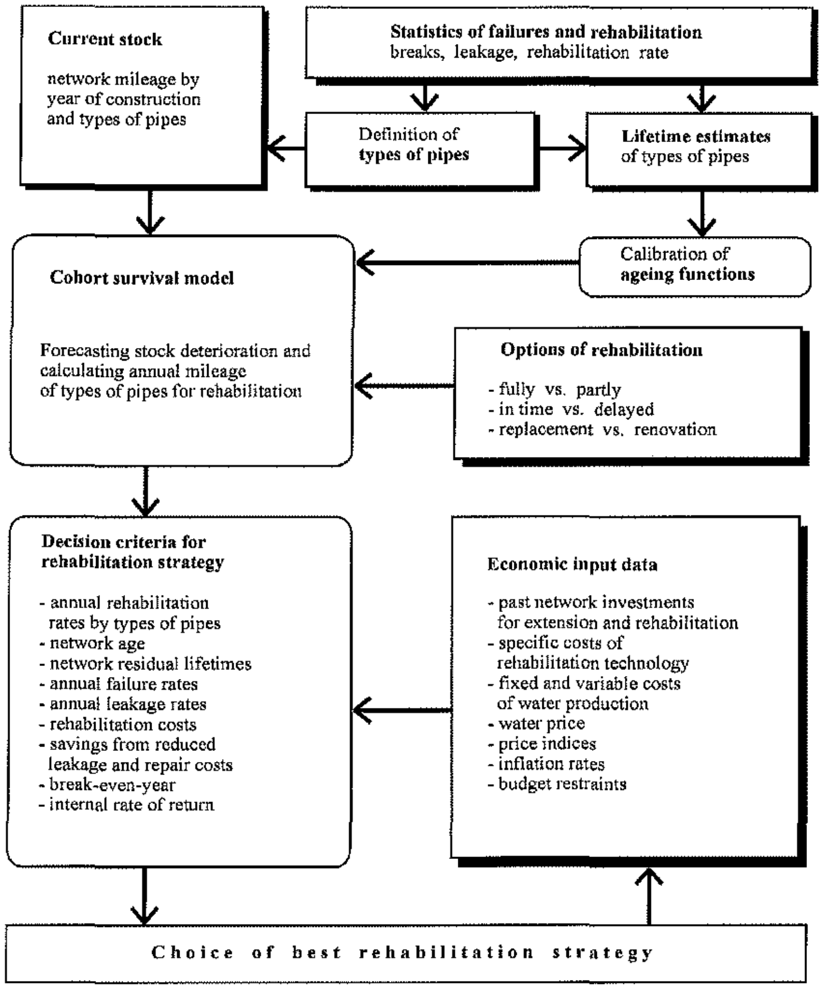

Fig. 3. Framework for exploring rehabilitation needs and strategies.

whilst minimising costs and interruptions to service. Analysis of water quality expenditure highlights that a significant proportion usually goes on what might be termed reactive maintenance, whereby maintenance is undertaken after a failure has occurred and damage has been done to the asset. It is further recognised that there is often significant potential to reduce costs if failure could be anticipated and the necessary maintenance was undertaken just before failure. If social costs, such as delayed journey times caused by a burst, are taken into account, the amount of proactive maintenance that can be justified will be correspondingly increased.

The outcome of any analysis to determine the most appropriate balance between proactive and reactive maintenance will be dependent on a number of critical factors. It is essential then to identify the critical factors, which indicate a trend towards "failure". This failure could be structural or related to the performance (or level of service) attained by the network. These critical factors may be static (e.g. ground condition, pipe material), or dynamic (e.g. pressure, water quality). *Research is required to ascertain what the critical factors are and their relationships with network failures.*

Advances in data management, sensor and inspection technology now enable many parameters of water network assets to be monitored. Having identified the critical parameters above, then these technologies may be applied to monitor the most appropriate network parameters, e.g. pressure, wall thickness. The most accurate and effective monitoring technologies need to be identified, along with best practice procedures for their use. Research in these areas will serve to assist in developing optimal network maintenance strategies.

1.5. No-dig techniques

No-dig techniques for water mains rehabilitation comprise a relatively new but rapidly evolving field. The importance of such techniques to an optimal network management strategy is recognised. However, many questions need answers to most of the techniques. The more established techniques include PE lining (slip lining, pipe eating and close fit), cured in place lining

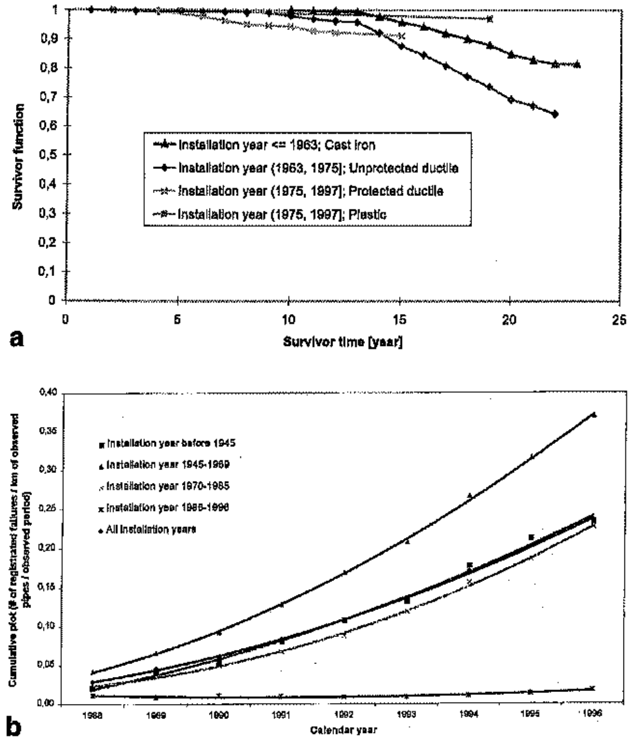

Fig. 4. The application of statistical functions (Nelson Aalen plots above and Cox Proportional Function below) for forecasting the survival of water networks (Lei & Sægrov, 1998, modified).

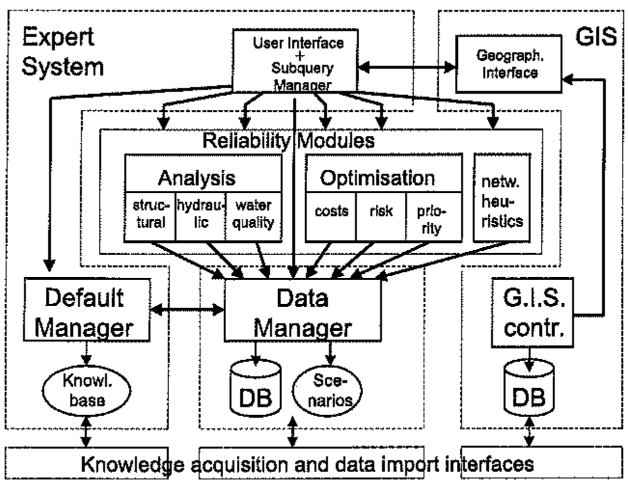

Fig. 5. Util-Nets system for network rehabilitation priority. System flow sheet (Eimermacher, 1998).

(e.g. the epoxy version of Insituform), and coating by epoxy resin lining and cement mortar lining. In Britain performance and installation issues have been studied for 20 years, and there are currently 30 techniques available. WRC has recently published a multi-media CD-ROM with the International Society for Trenchless Technology in order to disseminate related information. There is clearly a need for more awareness and access to available information about no-dig techniques.

AWWARF's research agenda for 1998, includes a project whose objective is to develop a decision tool to facilitate the selection of the most suitable pipe rehabilitation technique for a given set of conditions. This project will directly relate to WRC's Waterfowl software which is currently UK focused, and the global applicability of both approaches will be eagerly awaited.

As many of the no-dig techniques are new, little is known about their long-term performance. Installation practices, type of materials used, environmental conditions, site conditions and operational conditions are likely to affect the performance and longevity of all no-dig techniques. However, the quantification of these effects requires much more research for the newer techniques, and much more public domain sharing of related independently verified information for the more established techniques. An example of the need of sharing of information, or duplication of research, relates to rehabilitation with PE slip-lining, which can result in scouring or scratches, which combined with excessive pulling forces can lead to reduction in service life. In particular, no published research substantiates the claims of manufacturers and contractors about collateral damage to the PE pipe wall during slip-lining and how to design for an acceptable service life. It is known that related work has been undertaken in the UK and at the Centre for Advancement of Trenchless Technologies (CATT) in Waterloo, Canada.

Longevity and durability of the newer rehabilitation techniques remain important issues to be addressed. Instrumentation and long-term monitoring of specific field projects should be encouraged or undertaken to collect data so that a similar understanding is obtained on the performance of the newer rehabilitation techniques as for the established ones. Without objective and independent research, the pitfalls of many of the newer rehabilitation systems will only become evident after opportunities to collect related data have been missed.

2. Joint international research programme on water network management

2.1. Scope

There is a clear need for a greater international collaboration on water network management issues. This need for collaboration particularly exists within Europe, but also between European and North-American water authorities and research institutions. More specifically, the need relates to the exchange of current practices and insight into related static, dynamic and operating factors, which affect the cost-effective achievement of desired service levels. An example of the related static factors is iron pipe corrosion, while interference damage by another utility would be an example of a dynamic factor and valve turning (or lack of) would be an example of an operating factor. (The interaction of these factors is illustrated in the figure below.) By developing sufficient understanding of the related issues, it is possible to establish tools for optimising network management and as a sub-set of this, the criteria for justifying future rehabilitation needs.

The main objective should be to develop a "Best Management Practice" approach, based on better shared current knowledge and improved knowledge of water network performance, costs and risks. A dynamic network appraisal method should be established, referring to management of risk.

2.2. Knowledge gaps/research possibilities

Based on the former discussion, a number of topics should be included in any high level programme to address Europe's research needs.

2.2.1. Understand static and dynamic factors

The main questions will relate to data collection and the role for new technology (e.g. relating to network inspection and rehabilitation techniques). In particular, researchers should address how to best use existing data, which data is important for the development and calibration of predictive deterioration models, risk assessment methods etc. The research should include:

- Experiences on pipe damage (explanation by temperature, frost, corrosion, etc.).
- Statistical methods for analyses of pipe damages, and forecasting future rehabilitation needs.
- Investigation of the relationship between pipe condition, pipeline dynamics and pipeline performance.
- Advanced techniques of field inspection (leak detection and measurements of wall thickness and lining condition).
- Pipe sampling methods, statistical analysis, interpretation and generalisation.
- Mechanisms of pipe material deterioration, especially for plastic pipes.
- Material impact on water quality.

2.2.2. Understand operational factors

The key requirement is to better understand what operational activities can impact on the optimal balance between performance, cost and risk. The research will need to address issues such as:

- Data collection and management (e.g. regarding condition, costs and performance).
- Understanding the "operational" and seasonal variability in burst rates and separating them from the underlying trend of deterioration.
- Inducing transient pressures in water mains by valve turning operations.

2.2.3. Development of integrated network management strategy

The main objective of developing a generalised "Best Management Approach" will be justified using data from the preceding better understanding of static, dynamic and operational factors. Also identified in this stage should be the logic to justify future investment strategies, on a whole life-costing basis. Particular needs include:

- Standardised terminology and performance reporting.
- Trade-offs between performance, cost and risk.
- Unit-cost models for all aspects of water utility activities, including particularly capital works and related rehabilitation techniques. These will vary by country and possibly by region within larger countries.
- Social costs, whether to include and if so, how.
- Ongoing monitoring requirements (e.g. regarding reliability centred maintenance methods; long term durability).
- Demands on water network system to achieve optimal functionality (no degradation on water quality, no degradation of network materials).
- Material impact on water quality.
- Reliability of water supply.

2.2.4. Rehabilitation solutions

Traditional renewal methods will be too expensive and often inappropriate for many of the future upgrade requirements of water mains systems. In particular trenchless technologies will often be more cost effective. Current research needs include:

- Establish easily used methods to share previous objective and independently verified research and developments (e.g. via internet) relating to rehabilitation methods, selection, specifications, durability testing, prioritisation, etc.
- Establish framework and methods whereby newer rehabilitaton methods are encouraged but without compromising the need for objective and independent verification of key parameters, e.g. regarding durability and specification.
- Additional issues regarding decision support systems for establishing viable rehabilitation options (e.g. existing pipeline condition influence, structural contribution of existing pipeline).
- Technology Transfer projects to "pump prime" new markets for newer rehabilitation methods such that the expensive lessons learnt elsewhere are not relearnt. Many manufacturers and contractors are willing to subsidise such projects, and this route has been successfully used before. The team involved will need to organise suitable adaption of the technology, organising relevant approvals (e.g. regarding new materials in contact with potable water), etc.

2.3. Research benefit

The total value of water supply networks could be estimated to be £3 billion per million population. A significant part of this has been installed by codes of practices and technologies which are not appropriate by modern standards. Within a trend of increasing shortage of water in large regions, the challenge for network operators in securing water quantity and quality will be enormous. So very many aspects of common research needs are common to most developed countries, particularly those with the same or very similar legislative requirements. Hence there is significant potential for financial savings in meeting these research needs by co-operation, sharing and increasing the "leverage" of any related work done. Said more simply: We can all benefit by avoiding reinvention of essentially the same things in different countries and by greater collaboration and co-ordination.

Appendix A. Working group members

Mr. J.F. Melo Baptista, Laboratòrio Nacional de Engenharia Civil, Departemento de Hidràulica, Av.do Brasil, 101, P-1799 Lisboa codex, Portugal. Tel.: 351-1-847-3828; fax: 351-1-848-4897; e-mail: jmbaptista@lnec.pt

Prof. Raimund Herz, Technische Universität Dresden, Institut für Stadtbauwesen und Strassenbau, Mommsenstr. 13, D-01062 Dresden, Deutschland. Tel.: 49-351-4632383; fax: 49-351-4637730; e-mail: herz@rcs.urz.tu-dresden.de

Mr. Gerry Moss, WRC PLc, Frankland Road, Blagrove, Swindon, Wilts, UK-SN5 8YF Swindon, England. Tel.: 44 1793 511711; fax: 44-1793-511-712; e-mail: moss_g@wrcplc.co.uk.

Mr. Pascal LeGauffre, INSA Lyon, Laboratoire URGC – Hydrologie Urbaine, Avenue Albert Einstein 20 Bât.304, F69621 Villeurbanne Cedex, France. Tel.: 33-472-438209; fax: 33-472-438521; e-mail: le-gauffre@urgc.hu.insa-lyon.fr

Mr. Jan Erik Oddevald, Oslo Vann og Avløpsverk, Postboks 4704 Sofienberg, N 0506 Oslo, Norge. Tel.: 47-22-664040; fax: 47-22-664081.

Dr. Balvant Rajani, National Research Council Canada, Institute for Research in Construction, CA-K1A 0R6 Ottawa, Canada. Tel.: 1-613-9933810; fax: 1-613-9545984; e-mail: balvant.rajani@nrc.ca

Mr. Marcello Schiatti, AGAC – Corlsorzio Tra Comuni, Via Gastimelli 30, IT–Reggio Emilia, Italia. Tel.: 39-552-297439; fax: 39-552-297558; e-mail: agac@agac.re.it

Dr. Sveinung Sægrov, SINTEF Civil and Environmental Engineering, N-7034 Trondheim, Norge. Tel.: 47-73-592349; fax: 47-73-592376; e-mail: sveinung.sagrov@civil.sintef.no.

References

Alegre, H. (1998). Performance indicators for water utilities; The IWSA proposal. *International Conference on Master Plans for Water Utilities, IWSA.* Prague, Chech Republic.

Alegre, H., Baptista J., & Faria A. L. (1997). A general framework of performance indicators in the scope of water supply. *IWSA Workshop on Performance Indicators for Transmission and Distribution Systems.* Lisboa, Portugal.

AWWARF (1998). *Quantifying future rehabilitation and replacement needs of water mains.* Final report of research project 265, Denver, USA.

Brèmond, (1998). *Statistical modelling as help in network renewal decisions.* Cemagref, groupement de Bordeaux, Division Ouvrages et Rèseaux Hydrauliques.

Coelho, S. T. (1997). Water quality performance in distribution networks. *21st International Water Supply Congress and Exhibition,* IWSA, Madrid, Spain.

Conroy, P. (1996). Achieving a cost effective rehabilitation solution. *Chartered Institution of Water and Environmental Management training day seminar on the true cost of pipelines.* Swindon, UK.

Di Federico, V., Mazzacane, S., & Schiatti, M. (1998). Active control of water distribution systems: the Emilia Romagna experience. *5th Conference on Pipeline Construction,* October 1997. Hamburg.

Eimermacher, M. (1998). Personnal communication (e-mail: eim@ubis.de).

Eisenbeis, P. (1997). Estimating the ageing of a water mains network with the aid of a record of past failures. *Proceedings of the 10th European Junior Scientist Workshop.* Tautra, Norway.

Herz, R. (1996). Ageing processes and rehabilitation needs of drinking water distribution networks. *J. Water SRT-Aqua, 45,* 221–231.

Herz, R. (1998). Exploring rehabilitation needs and strategies for water distribution networks. *J. Water SRT-Aqua, 47,* 1–9.

Kim, H., & Mays, L. W. (1994). Optimal rehabilitation model for water-distribution systems. *Journal of Water Resources Planning and Management, 120* (5), 674–692.

LeGauffre, P. (1998). *Development and use of presumption models.* INSA de Lyon, Unitè de Recherche Gènie Civil/Hydrologie Urbaine.

Malandain, J., LeGauffre, P., & Miramond, M. (1998). Organising a decision support system for infrastructure maintenance: application to water supply systems. *First International Conference for Decision Making in Civil Engineering,* October 1998. Montreal, Canada.

Lei, J., & Sægrov, S. (1998). Statistical approach for describing lifetimes of water mains – case Trondheim municipality, Norway. *IAWQ 19th Biennal International Conference on Water Quality,* June 1998 (p. 21–26). Vancouver.

Røstum, J., Dören, L., & Schilling, W. (1997). Deterioration of the built Environment: Buildings, roads and water systems. *Proceedings of the 10th European Junior Scientist Workshop, Island of Tautra, Norway,* 24–28 May 1997. Norwegian University of Science and Technology, IVB-report B2-1997-2, ISBN 82-7598-040-2.