CHALMERS
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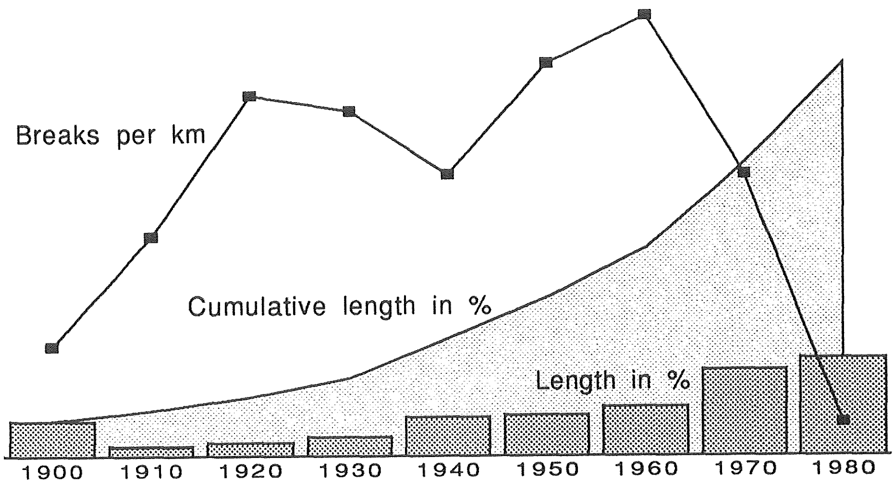
Institutionen för vattenförsörjnings- och avloppsteknik

Chalmers University of Technology
Department of Sanitary Engineering

Comparative Analysis of Pipe Break Rates
A Literature review



Teresia Rd. Wengström

Publication 2:93 **Literature review**

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ISSN 0280-4034

Keywords: water pipe system, breakage causes, comparative pipe failures, reliability analysis

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PREFACE

The literature study reported here is part of an ongoing research project at the Department of Sanitary Engineering, Chalmers University of Technology in Göteborg, Sweden. The project is being supported by the Swedish Council for Building Research (Project No. 900220-5) and is entitled "System Reliability in Water and Sewage Pipes". The objective of this literature study was to investigate factors and parameters which are essential for the analysis of water pipe systems. The project had an initial study based on ductile iron pipes previously reported in Swedish in the publication "Kartläggning av skador på segjärnsledningar i Göteborg 1977-1987" (A survey of ductile iron pipes in Göteborg 1977-1987). Dr. Gilbert Svensson, my supervisor, initiated the research project and has been a consistent source of support and guidance.

I would like to thank Dr. Torsten Hedberg, head of the department, and Dr. Greg Morrison for their inspiration and encouragement in the process of writing this literature review. I am very grateful to them, and to Linda Schenck for correcting the language. Special thanks go to Lisbeth Teiffel, for her assistance, excellent typing and table-making.

Göteborg in June 1993

Teresia Rd. Wengström

ABSTRACT

The principal base for water pipe analysis is historical pipe breakage records. With a literature review of pipe analyses and pipe models, from 1948 up to 1991, it is concluded that the traditionally based data used in water pipe breakage records might not be sufficient for future investigation of the break cause. Corrosion causes and impacts of the repair event are believed to be more important factors for future reliability pipe break analyses.

Other parameters of importance are concluded to be location or land development, failure types and inside water pressure variations. For these parameters it is essential that better methods for describing and comparing will be developed.

Soil type is often used and the parameter was found to be rather awkward for distinguish the tendency for corrosion. In addition most water pipes are laid in urban surroundings which have changed continually over the last 30 years and also the interaction between precipitation and soil water chemistry is poorly investigated but is pointed out as being an important field of research.

For pipe breakage analysis other components than pipe parts are also to be developed for better renewal strategies. The study outlines a method for trend evaluation of breaks based on pipe breakage records. The study stresses the importance of finding descriptive trends and the necessity of distinguishing between pipe condition based on pipe repairs and conditions based on the break rate for the whole pipe system. For the future it is desirable that pipe breakage records, pipe sampling and hydraulic models all be the basis for pipe reliability analysis.

CONTENTS

APPENDICES

GLOSSARY

break:	a recorded fault in pipe breakage records, which leads to maintenance action after a short time. Note that breaks are defined differently in literature, which explains why the term is used ambiguously in this study.
burst:	used as synonymous with break
break frequency:	used as synonymous with break rate
break intensity:	used as synonymous with break rate
break rate:	number of breaks per chosen pipe length*
cause:	the predominant reason for a break, burst or repair to occur
component:	any connecting item to the pipe
descriptive analysis:	analysis which organizes and summarizes the inventory, condition, break data and break patterns for pipes or systems
deteriorating system:	a pipe system where normal maintenance actions for breaks are regarded as too frequent or too short lived to make the system perform as its required functions
factor:	a cause used for evaluation of the behavior of breaks
length:	any chosen measurable length
mils:	length unit, multiply by 25.4/1000 to convert to SI (mm)
parameter:	a countable or physically measurable factor
pipe:	mains defined by any chosen length
physical analysis:	analysis which use physical methods such as laboratory and field tests to summarize condition, break performance and break causes for pipes or systems
pipe analysis:	investigation of the performance of pipes
pipe system:	a collection of pipes and their components which are to perform one or more functions for a specific consumer area
predictive analysis:	analysis using statistical methods to predict condition, occurrence of break and causal factors for pipes or systems
repair:	used as synonymous with break
repairable system:	a system which, after failure to perform at least one of its required functions, can be restored to perform all of its required functions, other than replacement of the entire system, Ascher and Feingold (1984)
segment:	used for computer storage of a length, essentially between pipe junctions, and would usually be the length isolated when repairing a break
susceptibility:	proportion of breaks in percent of total breaks per proportion of length in percent of total pipe system length

* Break rate is used instead of failure rate so as not to confuse it with statistical definitions.

INTRODUCTION

General

Many Swedish water municipalities today are in the process of introducing computerized surveying and digital maps for technical infrastructure. Information for maintenance decisions about the technical systems is also to be saved in computerized data bases. Repair events and pipe records are commonly used for maintenance decisions such as if and when old pipes should be replaced with new ones. As computerized data-analyses might be used in the future, the records have to be adapted as supervising tools. There are two interesting aspects for this type of pipe system. The first is the large number of construction items which, if computerized, would require time consuming data collection work. The second, is the long life span, these pipe records and pipe systems may be maintained and utilized for 200 years. This differentiates them from other reliability systems. For this type of system it is important to base predictions on reliable data. It is important today to reevaluate which data and parameters are to be used. We probably also have to set a limit on the number of parameters in order to achieve satisfactory reliability.

Evaluation of pipe condition

The knowledge for estimating the conditions of water pipes and sewerage pipes is focused in three different ways today:

- dug-up samples analyzed in the laboratory
- monitoring devices applied in and on pipes
- prediction with the help of historical pipe failure records

The sampling provides a good indication of the actual corrosion depths but is usually considered too costly to use on undamaged pipes. Usually the behavior of sound pipes is correlated to samples from long-term exposure tests in different soils. Alarm systems with monitoring devices hopefully give an indication of future breaks before they actually happen. One great problem is the enormous cost of applying these devices to the pipes which are buried under the streets. Usually only samples of pipes can be investigated and controlled in this way. Contrary to sample information are the pipe records which contain information from almost all damaged pipes for about the last 25 years. These pipe records might also give information of the laid pipe length and renewal actions from as early as the beginning of this century. The importance of pipe records cannot be neglected as it is the only information of the pipe systems we have and are still collecting continually over the years.

Objective of the study

This literature study will focus on the possibilities of judging pipe condition and behavior from pipe failure records. The literature studied is on comparative analysis of break rate and possibilities for finding safe and reliable parameters for judging the conditions of a community drinking water pipe system.

Pipe records and failure rates

Pipe records have essentially two types of failure data: break date and number of failures. The total length of the pipe system is usually also known, see Fig. 1. This figure tries to show the possible information from pipe breakage records in Göteborg during a study of seven years, Svensson (1990). For Göteborg was almost half of the system length laid after 1950. Break rates does, for the oldest installation group, tend to be very high, but also the youngest group after 1950 is normally expected to have a slightly increase in break rate, which is sometimes found to be alarming. Today, most failures are found in the group which have reached around 30 years of age, which gives concerns for the future as these pipe groups has an extensive pipe length if replacement have to be undertaken. Acceptable levels for pipe condition or pipe replacement are essential to evaluate, as well as finding good tools for such analyses.

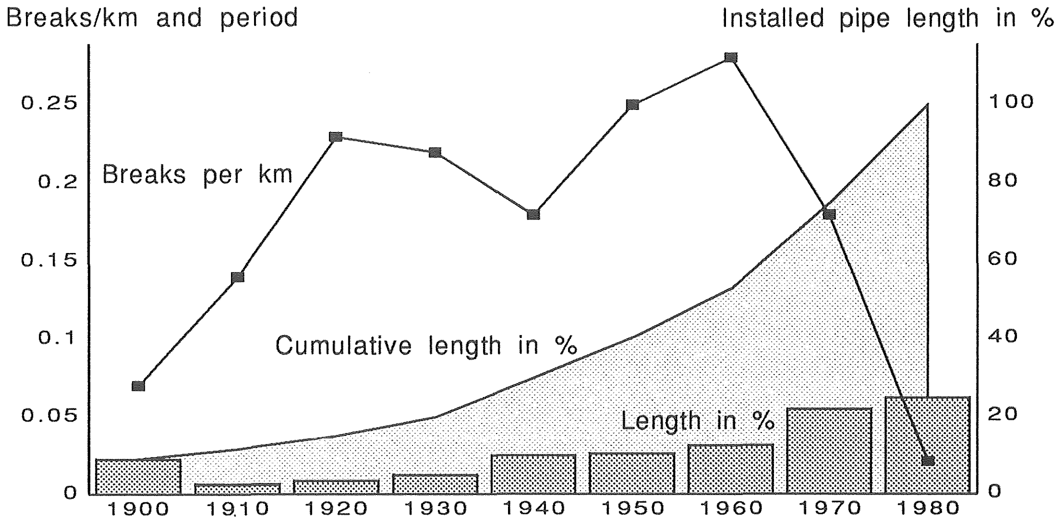

Fig. 1 Break information from pipe breakage records for a larger city, Göteborg, after Svensson (1990).

Often there is expressed a fear of that our water pipe systems slowly deteriorate. For deteriorating systems the corrosion rate is normally a parameter of interest. Unfortunately, the behavior of grey iron pipe, a brittle material, is often not registered in pipe records as a corrosion cause. The reasons for failure are not yet established, which gives rise to concern about the large amount of newly laid pipes. If analysis is to use historical pipe failure records parameters of importance have to provide if comparative analysis will be successful.

PREVIOUS RESEARCH ON COMPARATIVE ANALYSES

Definition of failure, breaks and leaks

In the literature, the definition of the parameter of failures, breaks and leaks may differ, and the different used definitions has here been accepted and used. O'Day (1982) and O'Day (1987) discuss leak and main break definitions as do Karaa and Marks (1990). All state breaks to be structural failures, such as cracks and holes (including corrosion holes) and call leaks to be at defective, leaky joints, valves or at the main barrel from corrosion. Clark, Cheryl, Stafford and Goodrich (1982) use maintenance event, which they define as any event when water is leaking and repair crews take remedial actions. This event does not include events on valves and clamps, only joints and mains failures.

Another definition is used in Goulter and Kazemi (1989), where leaks, failures and breaks are all grouped as failures requiring repair. This definition has the advantage that it could possibly be used on almost every historical pipe record. It would of course include all work on valves, fire hoses etc., which is normally not included in pipe records. This definition, although better, only suits a reliability analysis in which the repair event is the base. Other events such as cleaning and relining are normally not associated with unexpected shutdowns of pressure, which have to be under consideration if maintenance actions as well as repair actions should be investigated.

Not only failures are defined on different actions but are likely to be characterized different as in Goulter and Kazemi (1988) with definitions of leaks, releaks and repeated leaks, or as in Wengström (1989), with definitions of single repair, first repair, repeated repairs and last repair. This separation in time means that slightly more information is needed in pipe records but the definitions might suit reliability analysis better.

Factors affecting pipe failure rate

Age

The effect of age has already been discussed in several literature and comparative studies. In a literature study, Goulter and Kazemi (1988) state two different opinions which are prevalent for age. One opinion found age to be the major factor for break rate. The other one found other factors as well to be of importance. Here some other aspects such as the installation period and the differences in failure definitions for the effect on pipe age are discussed, as well as the factors commonly investigated.

In comparative studies it is common that all failures are included irrespective of whether they are a first failure or a subsequent failure. For individual pipes and in reliability analysis age is often used as a factor for the first known failure.

A comparative analysis was made by O'Day (1982) as an overview of four studies. Three of them concerned water main breaks in the city of Binghamton, N.Y., U.S.A., in the Severn-Trent Water Authority, England and in Manhattan, New York City, U.S.A. The fourth study concerned iron gas mains in Toronto, Canada. Breaks from pipe records were compared with break rates for the effects of pipe age, fault causes and geographic location. O'Day (1982) concludes that age is not a major determining factor for water mains, and points out that the geographic location is more important as it reflects the differences in the used pipe materials, manufacturers and soil conditions.

The regression analysis done by Goulter and Kettler (1985) on data from the city of Winnipeg found a correlation of increasing number of all failures with number of winter seasons after installation. The age span investigated was 16 to 23 years of age, i.e. winter seasons. Goulter and Kazemi (1988) find this ageing effect not to be a dominant factor, but rather suggests that other factors than age, such as diameter, pipe material, corrosiveness of soil, etc., are the underlying cause.

Most often the installation period is used in pipe record analyses, which is believed to reflect pipe materials and manufacturing defects. Compared with the above-mentioned impact of geographic location, the installation period is easier to find in records. The importance of age and installation period is investigated in Walski and Wade (1987) in a comparative study for two boroughs in New York City.

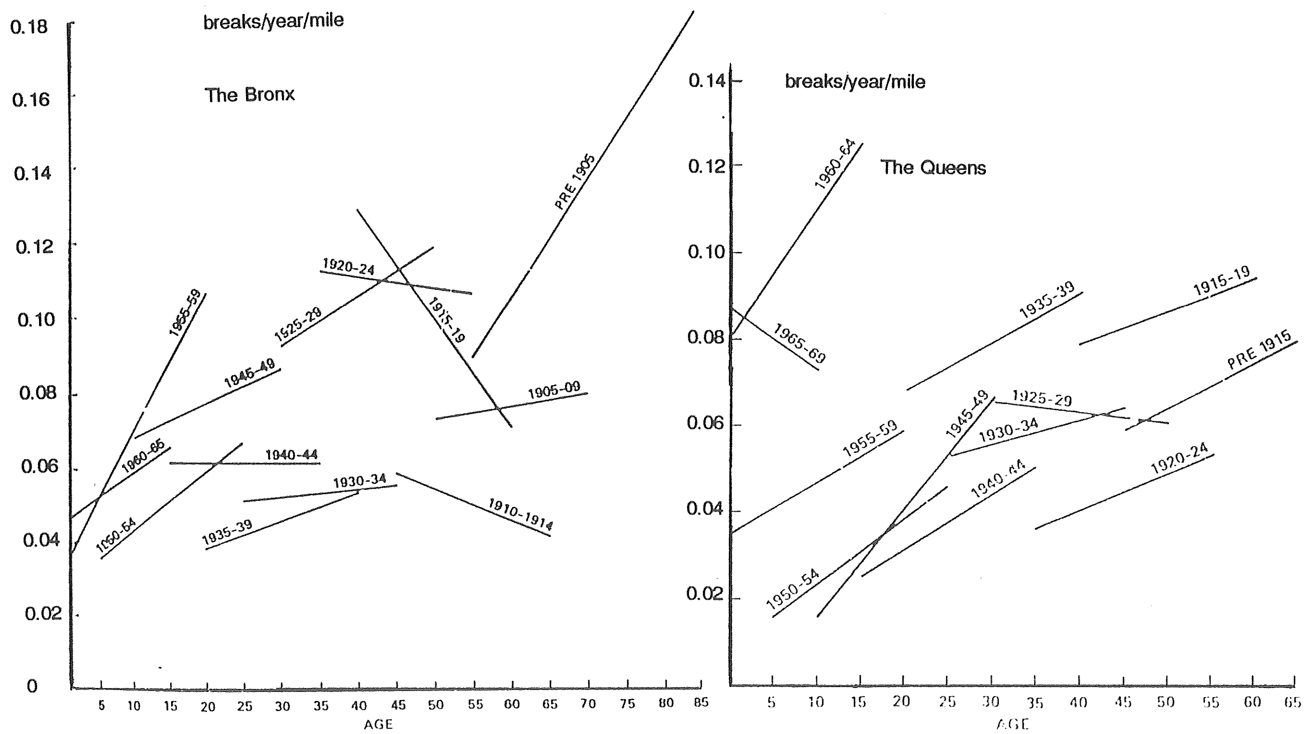

Fig. 2 Smooth break rate versus age for the Bronx and Queens, Walski, Wade, Sharp and Sjostrom (1987).

Walski and Wade (1987) found an increase of break rate with age for the Bronx but not for the Queens. They proposed the increase to be deterioration due to age, and found age to be a more significant factor than period laid (installation period). A five-year average of breakage rate was prepared from data for 1955 to 1979 (Queens) and 1954 to 1978 (Bronx) and is shown in Fig. 2. Most of the lines in Fig. 2 for the Bronx show break rates which have a sharp upward increase. For the Queens there was no or a slightly increase of the break rate. Walski and Wade conclude that the increase of break rates for the Bronx data can only be explained by age. The break rate for Queens is said to indicate more the influence of bad pipe materials in some installation periods and bad laying practices.

In a comparative study of New Haven and Cincinnati, Ohio, Andreou, Marks and Clark (1987) find for both cities that pipes installed in the 1940's, 1950's and later performed worse than the older pipes, installed in the 1930's and earlier. The explanation was that a larger amount of the younger pipes had subsequent failures.

O'Day (1982) finds break rates, for the Manhattan study when all failures were included, to be higher for the younger pipes than the older pipes. O'Day (1987) also finds for an older grey iron pipe system in Philadelphia, a distinct increase for the installation period of the 1940's and of the 1950's in comparison with earlier years. In O'Day (1987) failures were rather associated with mains laid in specific years.

Andreou, Marks and Clark (1987) suggest with regard to specific broken pipes, that the age at second failure is important. They found a tendency of pipes with failures at early ages to perform better than pipes which failed at later ages. The investigated material was mainly cast iron and steel pipes. They speculated on an unknown factor for this better performance of early failures. The failure types were not investigated. Their results seem to be in contradiction with what has been feared for ductile iron pipes suffering from corrosion. Premature failures have been recognized on ductile pipes and research was carried out for the ductile pipe material in Great Britain, de Rosa and Parkinson (1985) and for ductile pipes in the city of Göteborg, Sweden, Wengström (1989). Age as a cause of failure for ductile pipes was not found to be reflected in the pipe records. Rather the fault cause was stressed, Wengström (1989). The majority of ductile iron pipes were about 13 years of age and failures occurred as early as 3-7 years after installation. It is interesting to note Bubbis (1948), who complains about grey iron pipes which, after only 10 /or 12 years of service, are suffering badly from corrosion, in a system with an average age of 40 years.

To get a correct analysis of a pipe system, the early repair actions are important. The lack of information on early repairs before an investigation starts makes this difficult. Data is usually not available before 1955 as in Walski and Wade (1987). Slutsky (1988) descirbes a way to handle missing break rate data for the city of New York. In Fig. 3 the failure rate for the Philadelphia Water Department, O'Day et al (1987), is shown. This figure could be an example of the break rate patterns a pipe will pass during its life cycle.

The investigated time period was 1964-1980, about 25 years, and some of the investigated pipes seem to have reached over 100 years of age. The investigated time period is about one-fourth of the investigated maximum pipe age. Considering that almost half to 2/3 of a common system pipe length is laid after 1960, Svensson (1990), an investigated time period of 25 years could be satisfactory.

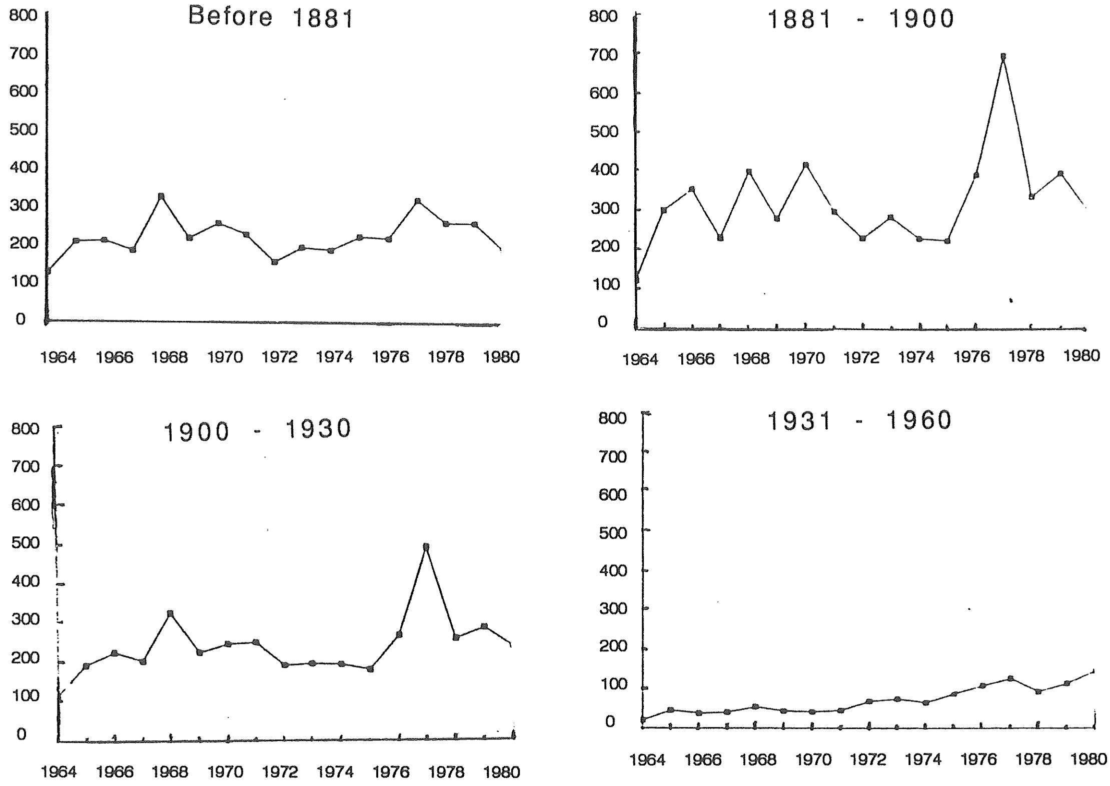

Fig. 3 Four periods of installed pipes and their variation of break rates during an investigated time period of 24 years for Philadelphia, O'Day et al (1987).

Corrosion

In general corrosion is not registered in pipe records. The usual failure types are the ones presented in Fig. 4. Few comparative analyses have therefore been made because of the often totally different ways of describing corrosion failure. Even if the cause of a failure was corrosion, the failure type may be registered as a break or a hole. Samples of water mains have, in several studies, been collected for measurements of external corrosion depth. These sampling techniques and their results are beyond of the scope of this literature survey. O'Day (1989) describes sampled (broken) mains having significant depth of corrosion, around 2.0-2.5 mm for both Boston and Philadelphia.

Lackington and Large (1980) investigated breaks for corrosion and find internal corrosion be more, about two-thirds as common than external. Russell, Habibian and Gahns (1988) find internal corrosion only be slightly more evident on pipe samples than external. As internal corrosion not commonly is recorded in pipe records, especially if the recorded break type is circumferential the major interest in pipe records is solemn for external corrosion.

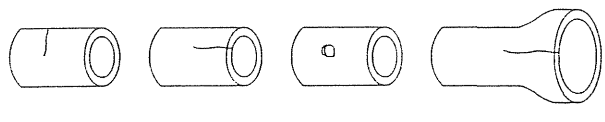

Fig. 4 Main break types: circumferential, longitudinal, hole and split bell, O'Day et al (1987).

O'Day (1982) compares corrosion-induced failures from three cities in the U.S.A. Corrosion was found to be responsible even in soils where non-corrosive environments were expected. These corrosion-induced breaks varied from around 30% up to 60% of total breaks for the cities, Forth Worth, Corpus Christi and Dallas, all cities with extensive clay soils. For the same cities Morris (1967) discusses soil movement, with swelling and shrinking soils, which cause the cast iron pipes, weakened due to corrosion by different soil types to break more easily.

Grey iron is a brittle material but has an appearance of being untouched by corrosion. This appearance is possible because the corrosion layer is of graphite. This makes it difficult to evaluate the effect of corrosion on pipe failure rate. The extent of deterioration (corrosion) is also difficult to evaluate on corroded test pipe samples, Newport (1981).

For evaluation, Fitzgerald (1968) uses a hypothesis that the rate of non-corrosive failures should remain constant as the corrosion failures would have a yearly exponential increase, Fig. 5, left diagram. He finds that the corrosion-related failures could be responsible for the yearly increase of leaks in the investigated cities of San Antonio, Indianapolis and Detroit. Sasse (1961) displays the increase for San Antonio as in the right diagram, Fig. 5. In Sasse (1961) it was found that most failures, more than 50 per cent, were in pipes with diameters of 6 inches (150 mm) and less. The smaller diameters had a significant increase of breaks during the investigated period while the larger diameters did not show any increase.

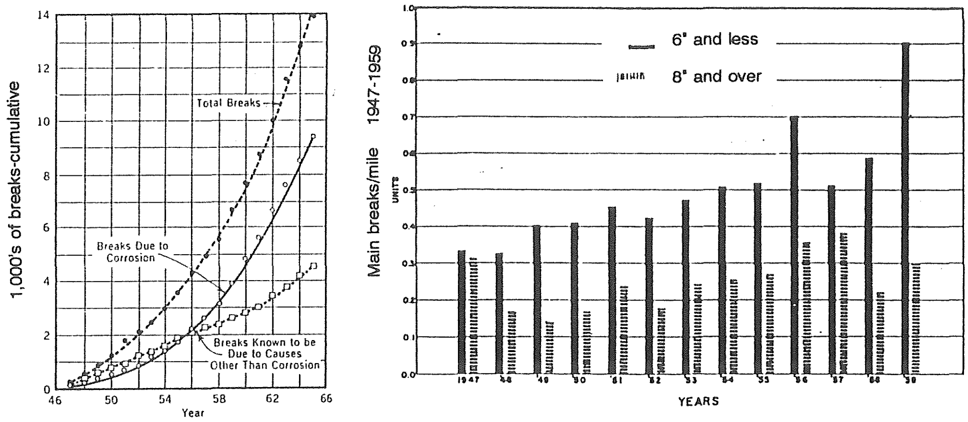

Fig. 5 Comparison of mains breaks due to corrosive and non-corrosive causes based on San Antonio distribution system which comprised about 95% of ferrous pipes, left diagram, Fitzgerald (1967). Right diagram, Sasse (1961), shows mains breaks in San Antonio for pipes at two different diameter groups.

The yearly rate of increase for corrosion failures on specific pipes has earlier been shown to halt when cathodic protection is applied, Wagner (1967) and Johnson (1953). Cathodic protection for all pipes in a city is not reasonable. Other ways of preventing corrosion have been tried, such as polyethylene sleeves and other corrosion protective surfaces on pipes. No comparative study in the field of material testing has here been investigated. Using pipe records for material testing of polyethylene sleeves, Jakobs (1987) found them unrealistic. The exact number of polyethylene sleeved pipes laid over the years was not known.

Newport (1981) also made use of the cumulative diagram for corrosion problems. Four areas in England are compared, namely Soar, Coventry, Rugby and a part of Nottingham, with cumulative failures during the winter period of 1977/1978. Newport (1981) suggests that the usual winter behavior, large numbers of failures in early winter, is characteristic for areas where non-corrosive breaks dominate. Rather than steep peaks in a curve, an even flat curve should identify areas with large corrosion problems.

In pipe system records, there are difficulties in distinguishing which failures are absolutely non-corrosion related from recorded the break type. In the future it might be important to distinguish between failures depending on internal corrosion and failures caused by external corrosion.

Wengström (1989) conducted a study with the purpose of investigating only corrosion failures of ductile pipes from pipe records, since the nature of ductile failures is restricted to external corrosion only. This was found to be impossible as "break" as a cause was prevalent. Corrosion was only noted in 40 per cent of the "breaks". Other results from the study indicated:

- * Almost all subsequent breaks were corrosion failures
- * Subsequent breaks accounted for almost 50 per cent of total breaks
- * 90 per cent of non-corrosion failures did not have a subsequent break during the analyzed period of 11 years
- * Corrosion failure was almost always marked as "hole"
- * There were few corrosion failures (subsequent breaks) in December and January
- * "Corrosion", "material or joint", "break", "accidental or badly laid" failures occurred in proportions of 30:30:30:10 (excluding subsequent breaks)

Diameter

A review of the literature, Goulter and Kazemi (1985), from 1960 until 1985 for four North American cities was made, where the rate of breakage was related to type and diameter of pipe. The break rate was found to increase with decreased pipe diameter in a strong relationship for pipes equal to or less than 300 mm. Fig. 6 shows the decreasing failure rate with increasing pipe diameter for Winnipeg data as compared with New York, St. Catherine and Philadelphia.

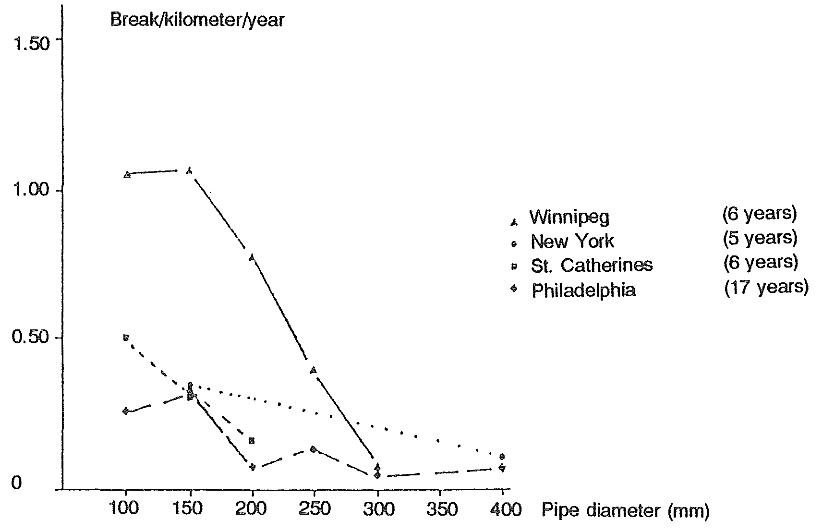

Fig. 6 Pipe sizes and breaks per kilometer per year in four cities, Goulter and Kazemi (1985).

Fig. 7 shows a regression analysis for the Winnipeg material when it is weighted with the annual variance of failures each year. The decrease of the break rate with increasing diameter has also been found for Berlin, diameters 80 mm up to 250 mm during 6 years, Kowalewski (1976). The break rate was similar for Severn-Trent for 75 mm pipes up to 300 mm, Newport (1981). It is also reported for the different pipe materials in a network registration study in the Netherlands, Fig. 8, van der Hoven (1988).

The reasons for the decreasing tendency of breakage with increasing pipe diameter were not fully understood, but Goulter and Kazemi (1985) suggest a number of factors such as pipe material, soil properties, depth of frost penetration, freeze-thaw characteristics, construction standards and as well as a reduced wall thickness for the smaller dimensions. The thinner wall of the 6 inch pipe would allow corrosion failures more easily and the pipes also have less reliable joints.

For pipes with larger diameters, from 6 to 48 inches, a comparative study for Bronx and Queens was made by Walski and Wade (1987). It was found that the smallest pipes, 6 inches, had a higher break rate than the other dimensions. For dimensions larger than 150 mm the break rate is lowest, Fig. 9. One

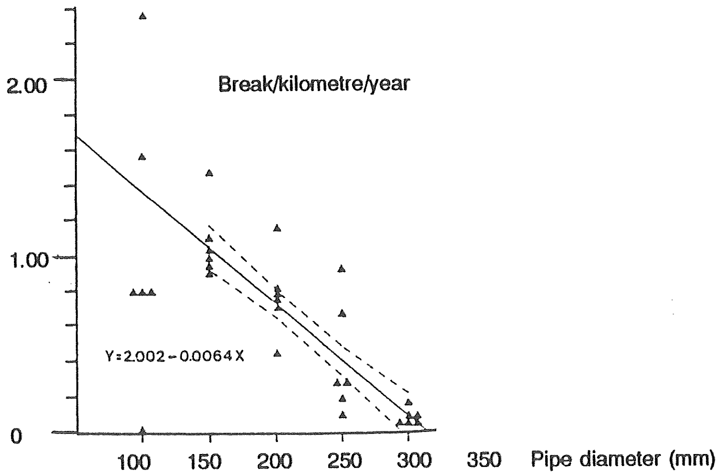

Fig. 7 Average annual breaks in Winnipeg per kilometer and year for different diameters for six years. Similar results were found if data were weighted with population or with annual variation of failures per year, Goulter and Kettler (1983).

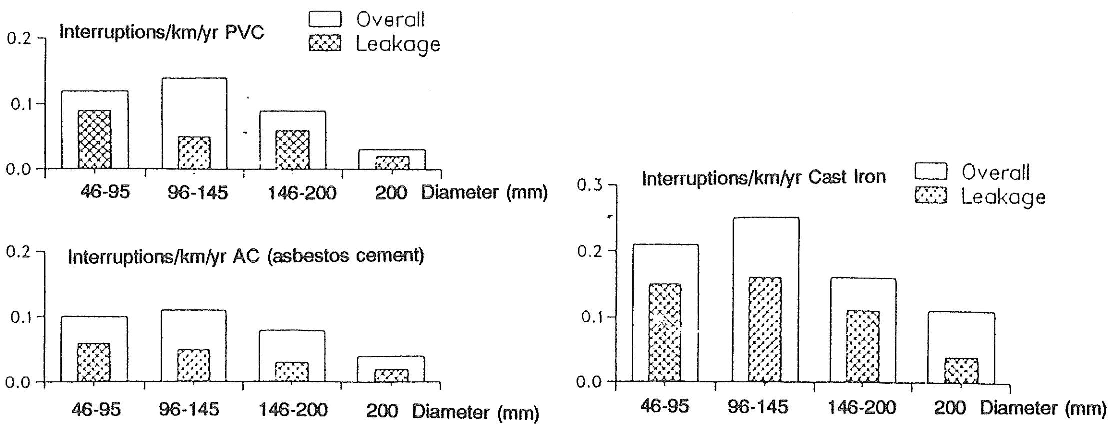

Fig. 8 Decreasing break rate was observed with increasing pipe diameters for cast iron, asbestos cement pipes and PVC pipes, van der Hoven (1988).

explanation is said to be the differences in break types. The longitudinal break and unknown cause are mainly registered for these larger dimensions as compared with the circumferential break for the smaller dimensions. Another difference for the two areas are the larger amounts of steel pipes used in Queens for the greater diameters. This may explain some of the differences.

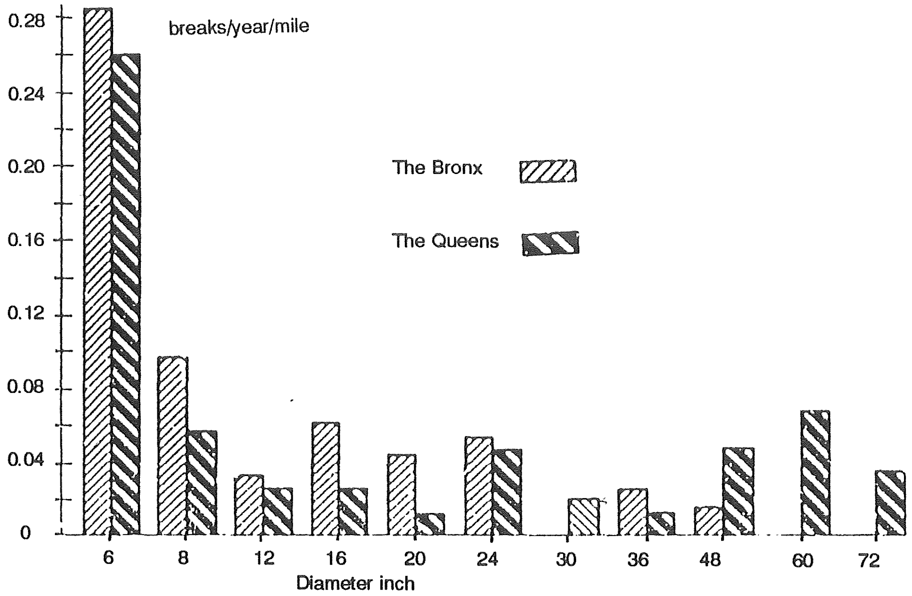

Fig. 9 Break rates as a function of diameter for Queens and the Bronx, Walski and Wade (1987).

In a comparative study, O'Day, Fox and Huguet (1980), the Bronx and Queen break rate are compared with Manhattan's. There was clearly higher break rate for Manhattan, especially for the 6 inches diameters. The break cause for the 6 inches pipes was primarily bedding problems (beam failure). The data for each diameter was not, in this 25 years period, considered to be age dependent, Fig. 10.

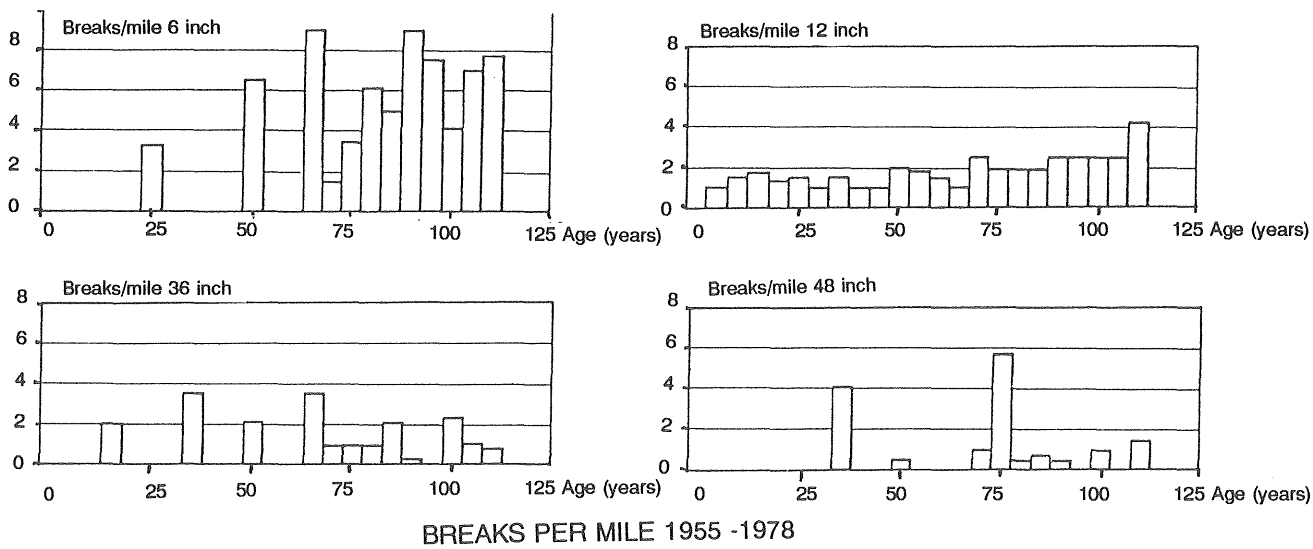

Fig. 10 Break rate in water mains in Manhattan for breaks at pipes 5-125 years of age and breaks per mile, versus pipe age and pipe dimension, O'Day, Fox and Huguet (1980).

Ciottoni (1983) gives a good illustration of total breaks and of the distribution of breaks according to diameter for 1964-1980 in Philadelphia (see Fig. 11). He concludes that a consistent feature for the smaller sized mains, 4, 6 and 8 inch diameters, is the high break rate. The number of total breaks is high for the 6 inches pipes as well. The number of failures in 4 inch pipes from Philadelphia seems to be low (see Fig. 11), compared with what Morris (1967) found for Dallas, where almost 49 per cent of failures occurred in pipes of 3 inches and less. When the diameter range 2-8 inches was used, 91 per cent of all failures occurred in these pipe sizes, which is similar to Fig. 11. For Binghamton, O'Day et al (1987), find only 65% of all failures to be in pipes of 8 inches and less.

In addition to the conclusions of Goulter and Kazemi (1985) the impact of the size of the city as well as the layout of the pipe system could possibly be important for the differences in breakage in relation to pipe diameters. For an example, a pipe as small as 6 inches in diameter might be considered large for a small city but small for a large city.

Pipe Diameter (inches)	Average Break Rate (breaks/year/100 miles of main)
4	41.2
6	51.5
8	10.9
10	21.7
12	8.0
16	10.9

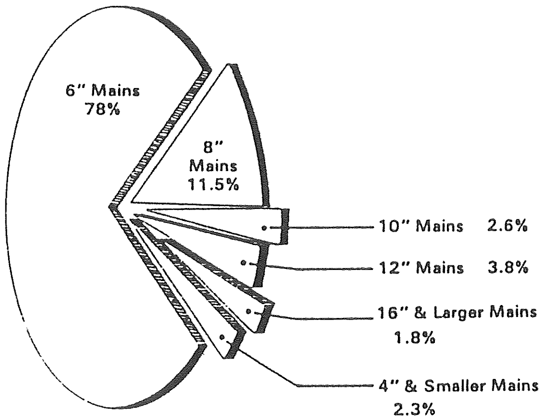

Fig. 11 Mains breaks according to pipe diameter in Philadelphia, Ciottoni (1983).

Break type

Break types and their break rates were investigated for Winnipeg data for time/age after installation by Goulter and Kettler (1985). Break rate for joint failure was found to increase with time after installation. However, the break type "circular crack" decreased and the "hole" failure type reminded constant with age.

Morris (1967) compares break types and their causes for Dallas, Forth Worth and Corpus Christie. The circumferential or transverse break varied from 30-70%, longitudinal 18-22% and blow outs 8-25%. The break causes for Houston, Forth Worth and Austin were reported to be: soil movement 22-70%, soil electrolysis 22-30%, temperature change and others causes 0-25%.

O'Day (1987) also compares break types in percent, for East Bay, Kenosha, Philadelphia and Manhattan and finds circumferential failures to be, around 60-

75%, and more common than longitudinal breaks and holes, for three of the four compared water utilities.

Clark and Goodrich (1989) presented frequency in per cent of break types for East Bay and Kenosha as well as Cincinnati (sample of the city). This comparison concludes that circumferential break was found to be common in smaller diameter pipes 150 mm and 200 mm (6 and 8 inches). For larger mains, 12 inch (300 mm), longitudinal break increases as well as holes. A few specific mains seemed to have numerous joint repairs and split bells. Also Newport (1981) finds the smaller diameter mains, less than 3 inches (80 mm) to have a likelihood for circumferential breaks and also a higher break rate than others.

The commonly used break types for cast iron are presented in Fig. 4. Unexpected mechanical fractures or the recorded type "break" are noted for ductile iron pipes in pipe records by Gilmour (1984), Jakobs and Hewes (1987), Björgum (1988) and Wengström (1989). Evidently "breaks" are to be expected in pipe records for ductile iron pipes, Fig. 12.

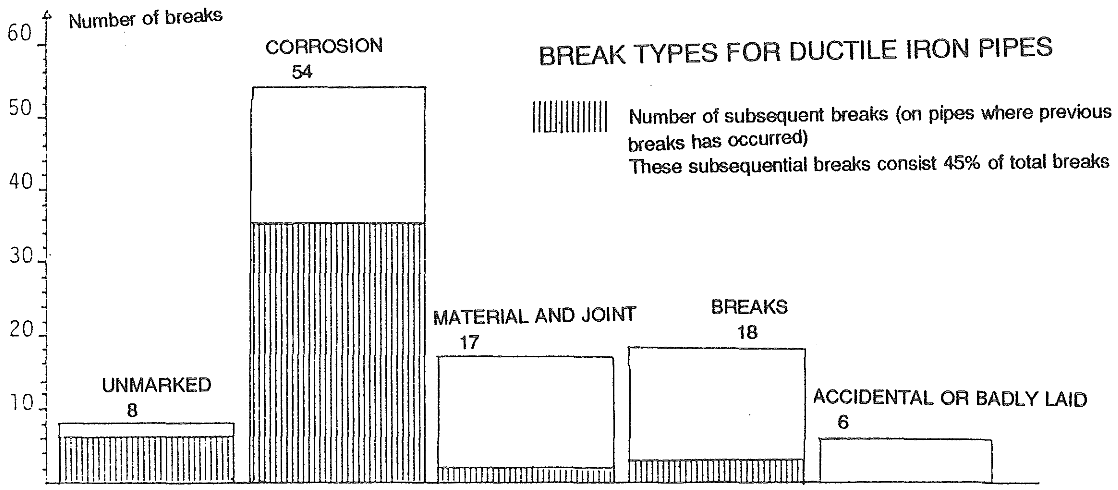

Fig. 12 Grouped break types for ductile iron pipe breaks in Göteborg 1977-1987, first event breaks and subsequent breaks (shadowed areas), Wengström (1989).

Pipe material

Pipe material seems to be paid little attention in comparative studies, maybe because most communities consist mainly of cast iron pipes, about 80-95% in Great Britain, in Canada, in the U.S.A. as well as in Scandinavia, when main breaks in big cities are discussed. For the different plastic materials used no comparative study of significance was found. Different joint materials are in this study not investigated. The history of construction practices and important events for pipes is described in Ciottoni (1983), who gives good information.

O'Day (1987) compares pipe materials for Denver and East Bay, Table 1. The highest break rate is found for cast iron (East Bay) and for galvanized iron (Denver). These materials were the oldest for each city. A similar, wide variation of break rates could be seen in Appendix I for some Swedish communities. The variation of break rate for pipe materials during the years was investigated by O'Day et al (1987). They found a decreasing break rate for cast iron, asbestos cement and steel during 13 years (1969-1982). Break rate for grey iron pipes decreased least, to approximately 30% of the break rate from 1969. For the six years of a survey in Swedish communities, Table 2, some materials had an increasing break rate, including ductile iron, a young material and galvanized iron an old material. Two materials PVC, a young material, and steel, a fairly old material, had decreasing break rates.

These differences in break rate mean that for comparable studies it is probably necessary to find another way of presenting the effect of pipe materials. One possible difference for the pipe materials used is maintenance policies, such as relining with cement and mortar. Relining is by Male, Walski and Slutsky (1990) found common for most of the cast iron pipes in New York. Linings for pipes were first used in Sweden in the 60's or 70's and is still used limited. The galvanized iron for service pipes seems to seldom have a cement lining.

Table 1 Pipe material comparison between Denver and East Bay from O'Day (1987).

	Number of breaks			
	Denver 1976-1983 3466 km		East Bay 1973-1982 5625 km	
	Per mile	*Per km*	*Per mile*	*Per km*
Asbestos cement	3.7	2.3	10.2	6.4
Cast iron	7.5	4.6	26.0	16.2
Concrete	0.9	0.5	-	-
Ductile	1.8	1.1	-	-
Galvanized iron	35.3	21.9	5.6	3.5
Steel	0.4	0.2	-	-

Kottmann and Hofmann (1990) used an assessment value called "susceptibility to damages" for investigated pipe materials, Fig. 13. For the city of Stuttgart they found steel to be the material with the highest susceptibility for all the four years investigated. This parameter was in Appendix 1 compared for some Danish and Swedish communities and is found here to show the variations about similar as the break rate.

The break rate for different pipe materials is concluded to be highly varied for different cities, possibly owing to the differences in system pipe length. These differences between cities might be a reason why comparative analyses for material behavior has been few.

Table 2 Summary of pipe material from 8 to 12 communities in Sweden. (1) from Pettersson (1978), (2) from Reinius (1981) and (3) from Larsson, Reinius and Svensson (1990).

	Median value, number of breaks		
	(1) *1975-1977*	(2) *1977-1978*	(3) *1981*
Asbestos cement	0.5	0	n
Cast (grey) iron	1.5	1.1	1.7
Concrete	0.25	0	n
Ductile iron	0.05	0.2	0.7
Galvanized iron	1.4	0.6	2.4
Steel	3.2	1.2	1.7
PVC	3.7	1.8	0.8
PEL/PEH	0	0.6	0.5
Others	0	0	0.3
Average number of observations:	138	56	85
Total length of pipe in survey, km:	526	540	658
Time of survey, months:	24	21	12

n = material not incorporated in survey

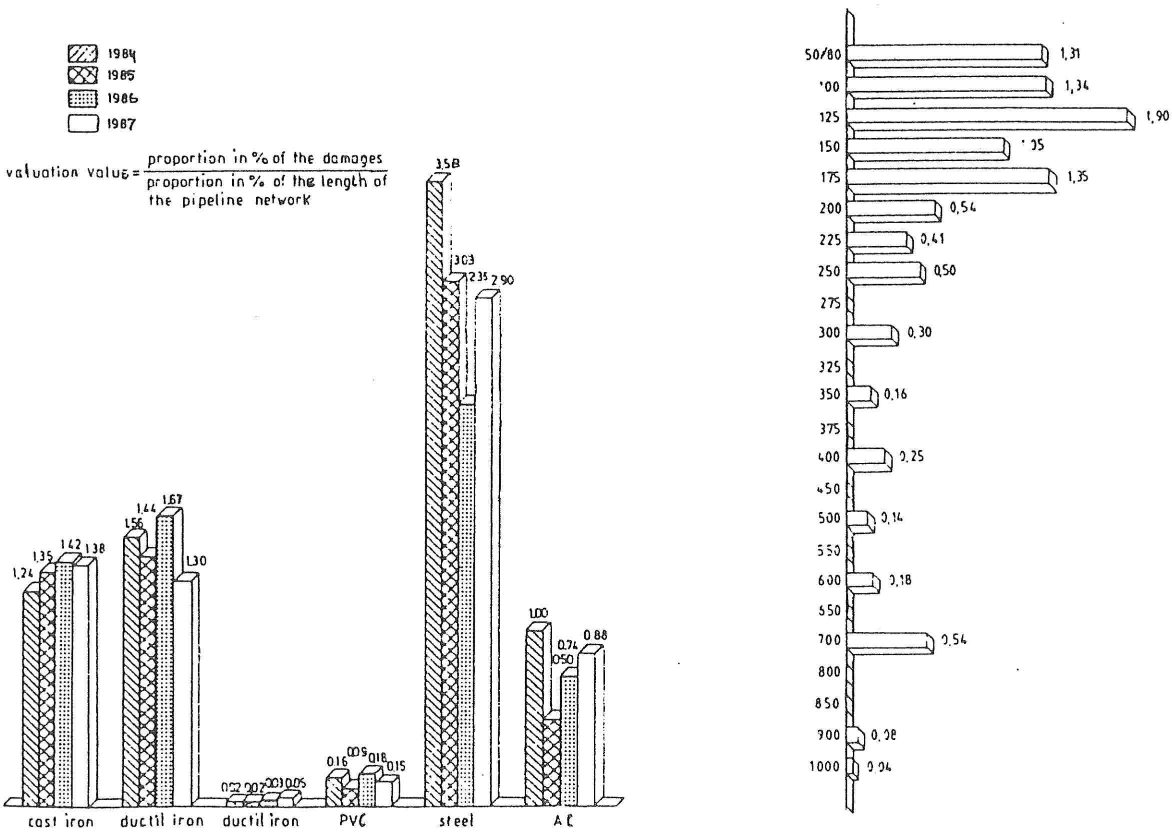

Fig. 13 Susceptibility to damage in Stuttgart of various pipe materials, left, and to various pipe diameters, right, Kottmann and Hofmann (1990).

Seasonal variation

The higher break rates during the winter seasons seem to be common to many pipe systems. The reasons for this higher break rate seems to be argued about, and various causes are discussed in the literature. Experimental tests in this field, for example Smith (1976), who measured frost loadings and frost depth in an out of service pipe, i.e. without inside pressure, found the causes such as frost loadings and frost depth to be a possible reason for a grey iron pipe to break. The moisture content in soil was found to fluctuate with recorded loads. Further discussion of experimental tests is not included in this literature study as its main objective is to describe break rate for whole pipe systems behavior.

Seasonal variation was investigated by Kottmann (1988), as circumferential breaks per month in the city of Stuttgart. The breaks were caused by uneven shrinking of the bedding material and were related to the conditions of soil temperature and air temperature. The seasonal pattern of failures is explained for dry summers which, if followed by a dry fall and a cold winter, increases failures. Few breaks can be seen after wet summers, mild winters and winters which come after a wet fall. The difference in seasonal pattern for two cold winters could thus be explained. For the break type "bursts", common in greater diameters and feeder pipe lines, there is no seasonality as the reasons for bursting are induced by air bubbles and air ventilation.

Niemeyer (1960) finds in the Indianapolis water pipe system indications of failure to water temperature, Fig. 14. He finds a seasonal pattern of both joint failures (sulphur compound joints only) and breaks of the circumferential type. It is interesting to note his proposal to prevent high frequency of breaks. On several occasions when the water temperature started to drop and the frequency of breaks increased, an addition of higher temperature well water was added to the supplied water, and the breaks seem to have halted completely. The temperature of supplied water, illustrated in Fig. 14, varied between 17 and 29 degrees Celsius.

Solid curve represent circumferential breaks

Dashed curve represent failures in sulphur compound joints

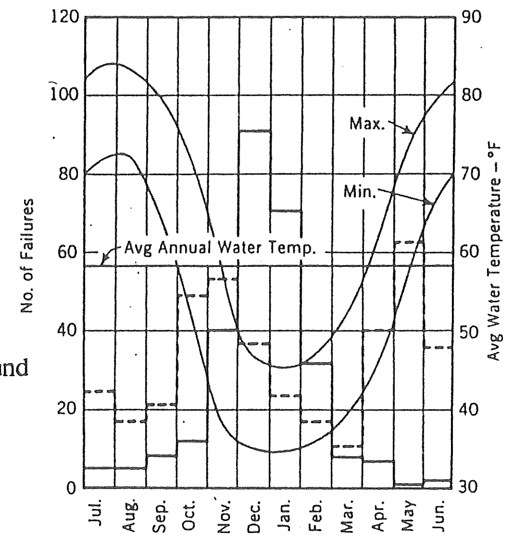

Fig. 14 Circumferential breaks and joint breaks during 1950-1959, related to a seasonal pattern caused by the change in temperature of the surface water supply, Niemeyer (1960).

A comparison of seasonal breaks for three water utilities, Denver, Philadelphia and New York, is expressed as per cent of repairs per month in O'Day (1987). The seasonal failure patterns showed moderate to substantial influence of increased breakage for breaks occurring in winter months. For Denver, Philadelphia and New York 33-50% of the total failures occurred in December, January and February.

Irle (1984) finds high break rates for other months when comparing two burroughs in the city of Duisburg. He relates monthly breaks to precipitation and ground water levels. Lower annual precipitation would be the main cause for less yearly failures. The differences in the burroughs' annual breaks are considered to be closely related to water losses.

Newport (1981) compares four divisions in Severn-Trent, England, and finds indications that exceptionally dry years can lead to an increased summer break rate. He concludes that it is caused by excessive soil cracking, which produces increased ground forces. He also finds a correlation between cumulative frost degrees per day and cumulative breaks per day for the winter period, September to March. He also concludes that an initial cold period produces proportionally more bursts than later cold periods.

Andreou (1986) carried out a literature review of seasonal patterns for break rate. He found it relevant that it is the smaller dimension, less than 8 inches, which have higher breakage in winter. He compared the cities of New Haven and Cincinnati and found a slightly higher breakage rate for the winter seasons only for New Haven. A high break rate was, instead, found for summer seasons in the Cincinnati system. He found Cincinnati winter behavior without the increase in failures during winter months to be due to the fact that the pipes were larger than 8 inches. He believed the high breakage for Cincinnati in summer be caused by the higher water demand during summer than winter.

Wengström (1989) and Trondheim (1988) show that ductile iron pipes have fewer breaks during winter months, while grey iron pipes show the normal rise in higher breaks during winter. This could give a change in the seasonal break rate caused by a change in pipe material as more ductile iron is used.

Soil environment

Collins and Padley (1983) review the various systems for characterizing the corrosivity of a soil. They conclude that the only parameter which has been demonstrated in the reviews to have a clear correlation with soil corrosivity is specific resistivity, although the measured correlation was low, about -0.5 for soils up to 1,000 ohm-cm. For soils above 5,000 ohm-cm no correlation was found, as such soils are virtually non-aggressive. Collins and Padley (1983) also suggest a differential concentration cell to have an impact on corrosion in sandy materials, which are normally considered the least corrosive soil type.

Levlin (1991) reports on water pipes damage occurring in mixtures of sand and clay, and assumes aeration cells to be important for corrosion. In an earlier study on soil samples from corrosion breaks from different parts of Sweden, Levlin (1988) found the resistivity low, below 1,000 ohm-cm, for only five (5) of 385 samples. Nearly 40% of all samples from the breaks in soils above 5,000 ohm-cm. All soil samples but three were clay or a combination of clay and sand. Corrosion behavior of the aeration cell and impact of acid rain are further investigated in his laboratory tests.

O'Day (1989) discusses Des Moines Water Works' program of relating soil samples from the site of broken mains to the scoring system for evaluating soil corrosion recommended by AWWA (American Waterworks Assoc.) Standard C105, the Ten Point Soil Test. He concludes there is little possibility to correlate break rate to a specific soil corrosiveness of soil environment. One explanation of this could be seen in the findings from Gerhold (1976), which indicate that the variability between different soil types is as significant as the difference within a soil for the corrosion rates, weight loss/year. Another explanation is the DC-current, which could have an impact on the measured soil resistivity, O'Day et al (1987).

Sasse (1961) investigated San Antonio's pipe breaks and soil resistivity, see Fig. 15. He concludes that most of the breaks appeared in soils with a resistivity in the range of 300 to 600 ohm-cm. He also points out that the soil moisture is about 20-25% at normal pipe depths, even during dry periods, and the soil resistivity is fairly constant at the encountered soil moisture.

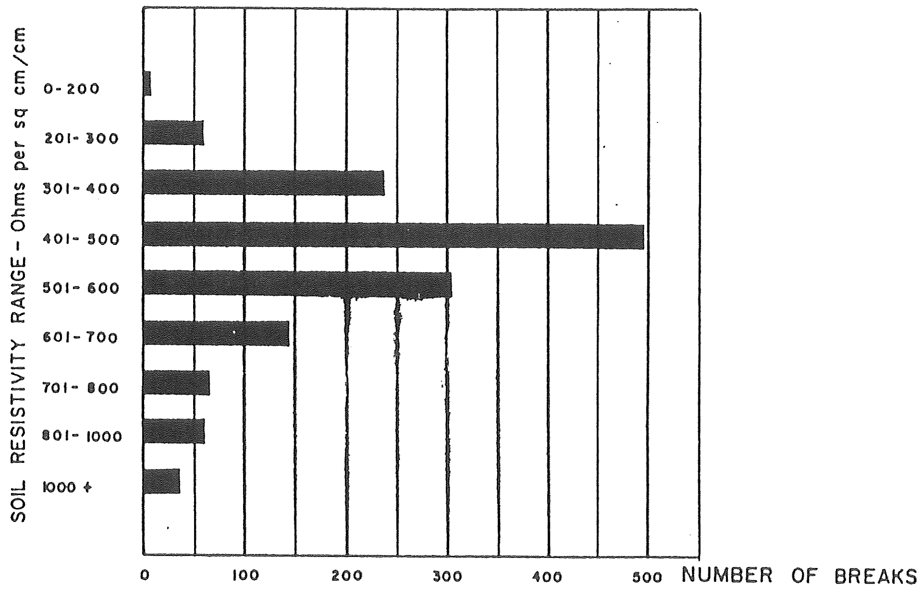

Fig. 15 All ferrous pipe breaks distributed in San Antonio by their approximate resistivity after soil resistivity mapping, Sasse (1961). Note non-saturated conditions.

For Des Moines, it was found by McMullen (1986) that both redox potential measurements and resistivity measurements with four pin resistivity were poor indicators of breaks. Where soil moisture was constant, saturated resistivity was used instead and found to be a better indication of corrosion breaks. 75%

of total breaks were considered to be caused by corrosion. 61% of these were found to have a resistivity less than 1500 ohm/cm, see Table 3.

Table 3 61% of the corrosion breaks were found in saturated soils with resistivities less than 1500 ohm/cm for main breaks in Des Moines, McMullen (1986).

Saturated resistivity ohm/cm	Percentage of total breaks
Greater than 2000	7
2000 to 1500	31
1500 to 1000	31
1000 to 500	27
Less than 500	3

Newport (1981) investigated breaks in rural areas and compared break rates with the major soil type for ten different soil types. He found higher break rates in clays than in sandy materials. The maximum break rate was 1.5 and the lowest 0.7 bursts/km. The influence of soil is debatable, as the nature of corroded gray cast iron makes the pipes able to withstand low or moderate pressure and still be in service, Romanoff (1964) and Kottmann (1988). It is not possible to judge the extent of soil corrosion from the appearance of a pipe at the repair site because grey iron pipe corrosion produces graphite which look the same as the uncorroded pipe.

It is not possible to see the impact of soil for the corrosion in buried pipes in pipe records. Further parameters which can categorize all effects of corrosion from soil environment would be necessary, but this seems inconvenient. These parameters might be bedding material, air content and water chemistry of surrounding soils, soil evaluation for soils glued to pipe surface, evaluation for possible sewage or other leakages, etc.

Previous breaks

Earlier comparative analyses of breakage records seem not to have distinguished between first failures and subsequent failures, but only compared total failures. In models, the distinction between first failures and subsequent failures is made, and the factor of previous break is often discussed.

The previous break or break history of a pipe is a significant factor for the future break rate, Walski and Pellica (1981). The break rate in Binghamton was investigated for two pipe materials. The break rate for cast iron was twice the rate of sand spun iron. When more than one break had occurred the rate was amplified ten times for both materials. The correction factor used for Binghamton in a predictive model was low where there were no previous breaks but high where there had been one or more previous breaks. Other factors used for correlation in the predictive model were pipe material and pipe diameter.

Andreou (1986) used Cox's regression and hazard model and applied it to pipe records from New Haven and Cincinnati. Fig 16 shows data from New Haven. Correlation of the number of breaks to the time at the first break was said not to have a high correlation coefficient. The investigated data were grouped into four installation periods. The probability of failure seemed to have a trend up to the third break, beyond the third break the break rate was found to be neither decreasing nor increasing, and pipes were assumed to be in a "fast breaking stage". The main differences between the two cities were the number of pipes entering the fast breaking stage. Several factors such as age, internal pressure, etc. were investigated. Break type, which is stressed as possibly important factor for understanding the failure pattern in future by Andreou and Marks (1987) was excluded in the study.

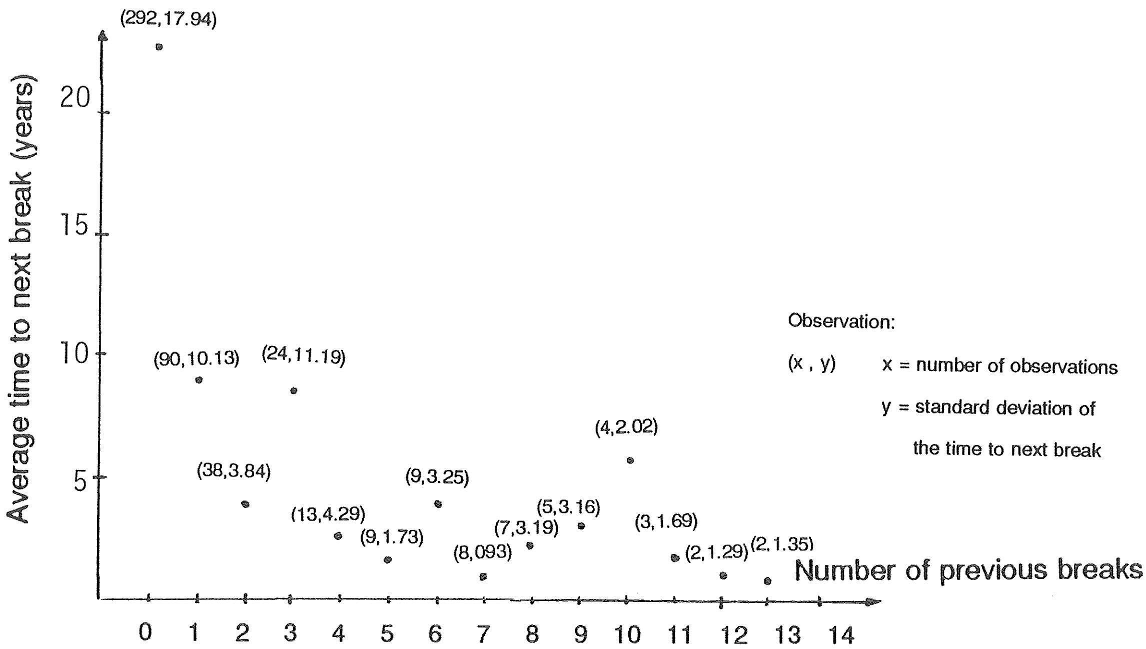

Fig. 16 Average time for following repairs for New Haven. Out of 1391 investigated breaks, 21% had one or more repairs, Andreou (1986).

Goulter and Kazemi (1988) and Goulter and Kazemi (1989) suggest that pipe breaks are caused by the repair process, using a cluster analysis for break type and time to next failure for Winnipeg pipe record. This would explain the strong clustering effects which were found for sequential repairs, Table 4. They found that from 22% to 46% of the breaks had a strong relation to previous breaks. Break types were investigated after the first break type to appear for location, age, time between failures and distance between failures. The longitudinal split and hole failures had a stronger clustering effect in distance than the circular crack type. They also found a strong clustering effect in time to failure for releaks. About 60% of all releaks occurred within three months of the previous break.

Table 4 Spatial and temporal grouping of breaks from the 20,213 pipe breaks in Winnipeg, Goulter and Kazemi (1988).

Maximum distance between breaks (meters)	Total number of breaks for: Maximum time between breaks (days)				
	1	2	7	30	90
0	1402	1464	1591	1732	1933
1	1860	1942	2102	2300	2541
2	2146	2238	2417	2646	2904
5	2594	2707	2938	3203	3503
10	2802	2924	3184	3503	3913
20	2979	3120	3418	3800	4315

The time between breaks, after the first break has occurred, for New Haven and Cincinnati were also presented by Clark and Goodrich (1989) and show similarity to the results of Andreou (1986) in Fig. 16. They investigated the previous break for several factors such as age, soil stability, operating pressure and date of installation. It was generally found that the first repair was important for the remaining life-behavior of a pipe, because the time to next repair becomes increasingly shorter. It was also found that the earlier the first event, the sooner the next break occurred, and thus a higher number of total breaks. The last statement is contrary to what was found in Andreou (1986) and Andreou, Marks and Clark (1987), where pipes with early failures seemed to have fewer breaks and behave better than pipes which fail at older ages.

Wengström (1989) noted that for ductile iron pipes 60% of subsequent breaks had corrosion as the first break. 60% of the total number of first breaks were registered as noncorrosive break type. Out of these noncorrosive breaks, less than 1% had a subsequent repair during the time period studied (11 years). This implies that sequential breaks were almost 100% corrosion breaks. The relationship between break type and following breaks for grey iron pipes might be interesting to investigate further.

Pressure

Internal pressure seems to be an unsuitable parameter for comparative analyses, as it is often not recorded in the pipe records. Internal pressure is, by Karaa and Marks (1990), interesting for break rate as internal pressure is a component for a complex break mechanism. The importance of the effects of internal pressure, such as air bubbles and air ventilation problems in relation to the break rate is found to be the main reason for breaks by Kottmann (1988) for pipes with greater diameters and feeder pipe lines, Fig. 17.

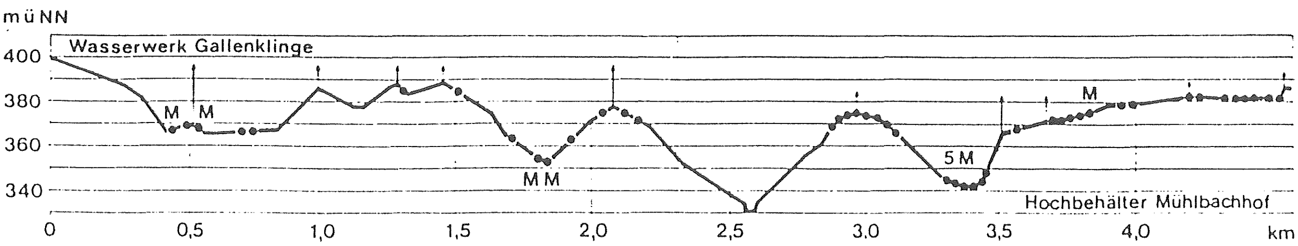

Fig. 17 Breaks in pipeline with small slope and air ventilation problems, Kottmann (1988).

Kowalewski (1976) made an investigation of the break variations in Berlin for the effects of water demand. He compared the hourly and weekly demand in winter and summer months. Fig. 18 shows that increased break rate during the morning is common on winter days but not on summer days. In Berlin, the water demand is higher for the summer period than the winter period. The explanation for the breaks in winter are frost and the frost loadings on pipes, especially when a rapid water demand change is made in the mornings. The

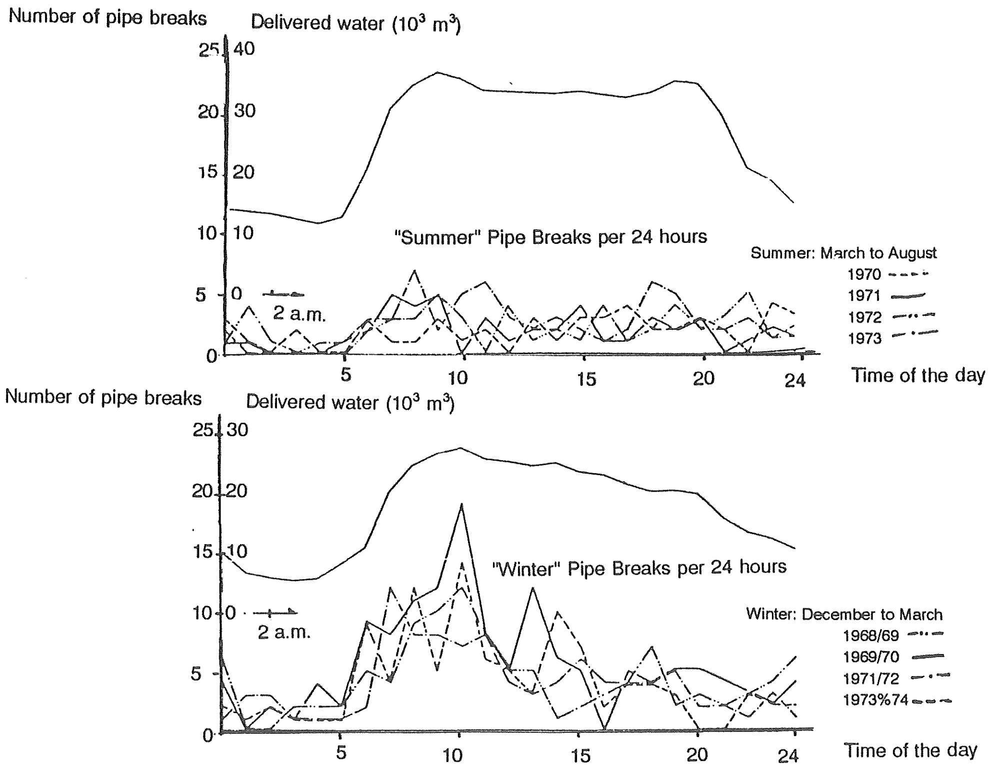

Fig. 18 Variation in hourly breakage in summer, top, and in winter, bottom, four year average for Berlin, Kowalewski (1976).

weekly break rate in winter weeks is both high and varied. Summer breakage varies more on Mondays than in the winter weeks, but there is a lower average summer break rate, see Fig. 19. The explanation of the difference is the same as for the hourly based break rate.

Lackington and Large (1980) investigated weekly break statistics to demand and pressure reductions, mainly for the years 1977 - 1978. They find the high break rates in winter periods and express the climate, i.e. winter periods, to be more important for high breaks than demand variations.

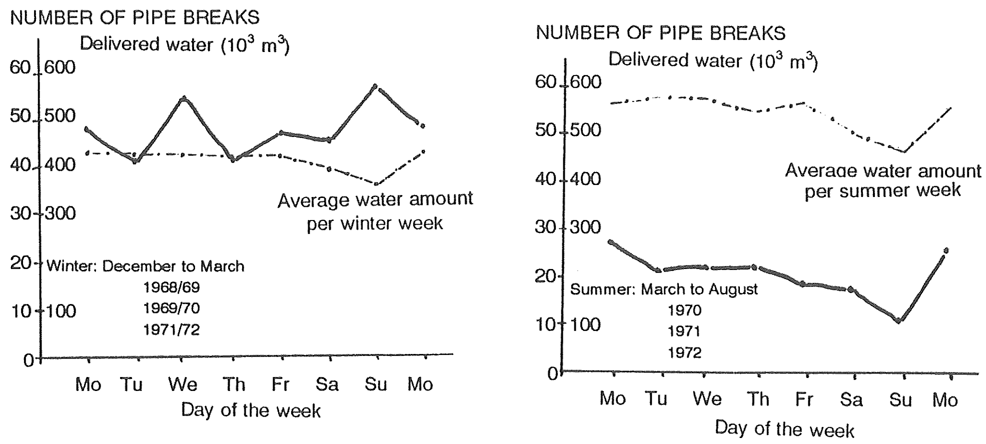

Fig. 19 Variation in weekly average breakage in a winter week, to the left, and in a summer week, to the right, for Berlin, three year average, Kowalewski (1976).

A comparative study including internal pressure was made by Andreou (1986). Pressure is used in his probability model, but the correlation was found to be low for pressure, as for most investigated factors. The higher breakage in larger diameter pipes (greater than 8 inches) was evaluated to be because of pressure changes for meeting higher demands. Higher breakage was found in winter months in New Haven, and in the summer months in Cincinnati. De Maré (1991) investigated subsequent breaks occurring the same day or the day after in the city of Malmö. Shutting and opening vents after a major break was believed to induce these subsequent breaks. Larger diameters than 12 inches (300 mm) had a high percent (79%) of subsequent breaks in relation to total failures for the diameter group, as compared with smaller diameter pipes of less than 10 inches (250 mm) which had only approximately 50% subsequent failures.

Land use

The environment of water pipes is believed to be related to infrastructure behavior which can often be described as land use, land development, etc. As every water utility seems to have its own unique way of describing these environmental factors, they are seldom used in comparative pipe record analyses. In O'Day et al (1987) several of these factors are listed and summarized, see Table 5. Factors excluded are those which have already been discussed such as soil, pressure changes etc. Few of the remaining listed factors have been used in comparative studies of breakage rates. Interesting factors for the break rate include abandoned service pipes, pavement parameters and DC-current.

Table 5 Some of the environmental factors and possible action on pipe behavior, after O'Day et al (1987).

Environmental factor	Forces and corrosion acting on water main during service	
	Forces	Corrosion
Abandoned Services Service which are abandoned but not disconnected at the tap may eventually leak, even if they are shut off at the curb stop. The degree of abandoned service leakage is a function of utility operation and practices (e.g. who is responsible for maintaining and disconnecting the service).	Abandoned service leakage may disrupt main bedding and increases potential for beam conditions. Increases potential for frost acting during the winter.	Leakage may increase soil moisture and reduce soil resistivities, thereby increasing external corrosion rates.
Construction Activities The equipment and activities involved in new construction or the maintenance of other agencies' facilities in the vicinity of the main.	These activities can result in excessive forces on nearby water mains.	
Groundwater Table Elevations Groundwater table elevations may be high enough to saturate the soil surrounding the main. This may be exacerbated by excessive water and sewer pipeline leakage.		Reduces soil resistivities by saturating the soil surrounding the main. High sulphate and chlorides levels may also reduce resistivities. Overall impact is an increase inn external corrosion rates.
Landsliding Mains constructed in steep slopes must be properly anchored and supported according to recognized design practices.	If not properly anchored these mains may shift as a result of soil saturation and undermining.	
Pavement Conditions Poorly maintained roads with numerous potholes or plumber's ditches can be a problem, especially on roads with frequent truck traffic.		The condition of the pavement and subbase is one factor to consider in estimating what portion of surface traffic loads are transferred to the pipeline.
Road Salting Snow melt runoff containing dissolved salts may increase the chlorides content in soils surrounding the main, especially in areas with excessive sewer main or lateral leakage.		Reduces soil resistivities, thereby increasing external corrosion rates.
Service Leakage The extent of service leakage is a function of service pipe deterioration and maintenance practices. Leakage control programs can help prevent future main breaks from occurring.	Service leakage may undermine the water main's bedding, establishing beam conditions. It may also contribute to excessive frost loads during the winter months.	Increases soil moisture levels and external galvanic corrosion rates. Galvanic corrosion may be particularly severe in the case where the water main and service are constructed with dissimilar materials and not protection exists against galvanic corrosion currents.
Stray Direct Currents Sources of stray current include surface rail lines, cathodic protection of other utilities, transit system substations, trailer parks, welding operations and DC powered cranes. In addition to galvanic and imposed current cathodic protection, other methods that have been utilized to minimize stray current impacts include electric screen installations, insulating pipe joints and various pipe conducting coatings.		Electrolytic corrosion can result from stray direct currents. The stray current travels through the soil seeking a path of least resistance. Underground metallic structures, such as cast iron water mains, serve as a pathway for the current. Severe external corrosion occurs at the point where the current discharges from the main.

Pipe length

Several comparative analyses, Andreou and Marks (1987), Sullivan (1982) and Walski and Wade (1987), conclude that pipe system length is not a sufficient factor for describing a system's breakage behavior. They refer to a report of a select committee on water main breaks in the city of New York, where breaks from 14 (to 16) cities in the U.S.A., see Table 6, were compared with system length and break rate. In Appendix III, Fig. III.7 and in Fig. 20 it can be seen that the larger system lengths for some cities do not have high break rates, but rather less than 0.1 breaks per km.

Table 6 System pipe length and breaks, Sullivan (1982).

Locations	Reporting period	Length of system km	miles	Number of breaks per year	Main breaks per km per year
Boston, Mass.	1969-1978	1,737	1080	39	0.022
Los Angeles, Calif.	1973-1974	10,941	6800	290	0.026
Chicago, Ill.	1973	6,674	4148	223	0.033
New York, N.Y.	1976	10,152	6310	476	0.047
St. Louis, Mo.	1973	2,209	1373	106	0.048
Indianapolis, Ind.	1969-1978	3,234	2010	167	0.052
San Francisco, Calif.	1973	1,892	1176	125	0.066
Washington, D.C.	1969-1978	2,262	1406	163	0.072
Louisville, Ky.	1964-1978	3,924	2439	300	0.076
Denver, Col.	1973	2,884	1793	280	0.097
Troy, N.Y.	1969-1978	241	150	25	0.104
Milwaukee, Wis.	1973	2,898	1800	421	0.145
New Orleans, La.	1969-1978	2,444	1519	1033	0.423
Houston, Texas	1973	6,432	3998	5144	0.800

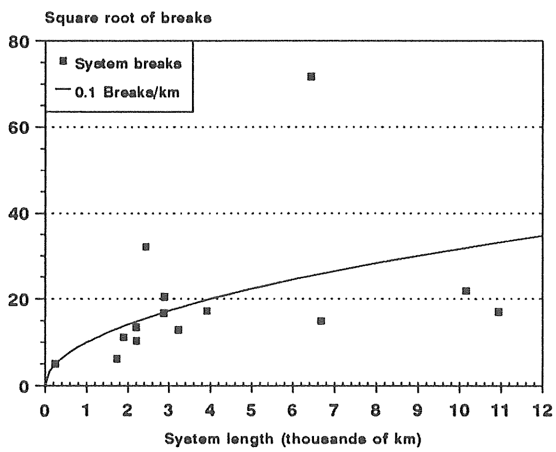

Fig. 20 System pipe length and breaks for some cities in the U.S.A. after Table 6.

Newport (1981) concludes that the overall system break rate depends on the lengths of each of the smaller diameters rather than on the total pipe length of the system, because of the remarkably high frequency of breaks for small mains, of less than 75 mm.

Clark and Goodrich (1989) express the increase of pipes laid in New Haven as a factor which adds to the increasing failures, see Fig. 21.

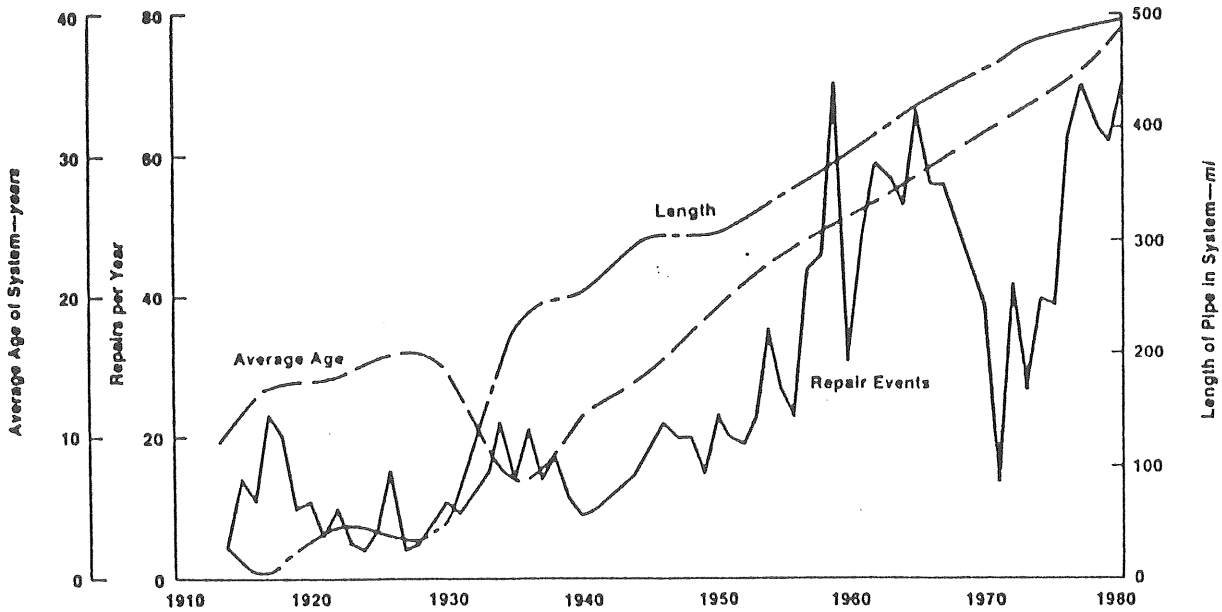

Fig. 21 System length, average system age and the numbers of breaks in New Haven, Clark and Goodrich (1989).

Irle (1984) reports on comparison of breakage for different utilities and finds the numbers of failures to be inversely proportional to length. Length was expressed as a parameter from several pipe factors.

In Andreou (1986) and in Mark and Andreou (1987) pipe length for individual pipes was used as a factor in a proportional model. The conclusion in both studies from a regression analysis was that the failures varied with the square root of pipe length.

Pipe length is commonly not used as a factor in pipe records. Even though is the relationship of length to failure important and might not be linear and might differ when analyses are made of systems, groups of pipes or of individual pipes. Commonly, pipe length is used to describe the total length laid in different installation periods. Sometimes pipe length is used when describing the actual length of laid segments. Pipe length can therefore be considered both a factor and a parameter. Pipe length as a parameter is further described in the Chapter "Parameters used in earlier research".

Combinations of factors

The difficulty of finding factors for judging pipe conditions on the bars of break rate from historical records is that there are believed to be many causes contributing to the variation in break rate, O'Day (1987). Karaa and Marks (1990) state that one way of describing the possible synergistic effects of factors is to define the various break types. They review factors which affect the break rate and give several explanations for each factor. Table in Appendix II summarizes the typical causes and factors used in pipe records.

One conclusion drawn in Goulter and Kazemi (1988) and Newport (1981) is that pipe age should not be the single factor used for judging pipe condition. Other factors such as diameter, pipe material, corrosiveness of soil, etc. should also be investigated. Appendix II lists the causes for breaks and failures on pipe systems found in the literature. Typical failure information data used in pipe records is included in the appendix, as well as a list of factors, some of which have been covered in this text. Examples of factors which are usually not included in pipe records are water demand, frost depth, precipitation and the length of pipes renewed.

Parameters used in previous research

System break rates

Break rate, defined as numbers of failures per system length, is a commonly used parameter in comparative studies of failures in pipe records. Break rate, defined as numbers of failures per grouped length, for example installation period or equal diameters, is discussed in the chapter on individual pipe break rates.

The investigated time periods for system break rates were from one year up to 25 years and often seem to be compared independent of time period. Table 6 exemplifies the variation in time periods used.

The variation in break rate is investigated for six water utilities: Denver, East Bay, Kenosha, Louisville, New York and Philadelphia, by O'Day (1987). He found break rates of roughly 0.05-0.22 breaks per system km for the water utilities. Goulter and Kettler (1985) compared the break rate for New York, Philadelphia, St Catherine and Winnipeg and found similar rates, from 0.05 to 1.1 failures per year per km. In Table 6 some other break rates in the U.S.A. are presented. Most were below 0.2 breaks/km with New Orleans and Houston as exceptions.

In addition, the break rate can vary in time. O'Day (1987) investigated an "annual growth rate". Annual growth rate was calculated on the basis of the change in three years' moving average break rate during the investigation period. Periods used were 8 to 49 years. He found that the annual growth rate was for one utility negative, -4%, which meant the break rate was decreased.

Another utility had constant rate and four utilities out of six, had positive rates, averaging 2.6%, which meant that they had increasing break rates.

Walski, Male and Slutsky (1990) made a similar comparison of "effective annual" increase for four different areas in New York during the years 1940 to 1979 and found that all areas had increases. The lowest increase was 0.6% and the highest was 2.9%. This was said to be typical of systems consisting of a large part of old grey iron mains.

O'Day (1987) found a higher break rate for the younger mains, but the length of young pipes as compared to the length of old pipes was also different between the water utilities. This age/length dependency for individual mains could be a reason for the differences in the overall break rates between the utilities.

O'Day (1982) found that the usefulness of comparing break rate is greatly reduced by the varying definitions of breaks used in pipe analyses.

The system length could be a factor for city behavior. However, this has not yet been established and it would be informative to understand its relationship to break rate. Andreou, Mark and Clark (1987) found an indication of breaks related to the square root of the individual pipe length. This relationship has not yet been investigated for total pipe system failures when comparing cities in pipe analyses. In Appendix III system length and system failures are compared both with the square root of system length and in other ways.

Similarly to Fig. 21, Fig. 22 displays break rate for some communities in Sweden on the basis of data from Pettersson (1978), Reinius (1981) and Larsson, Reinius and Svensson (1990). The average system length is much smaller for the Swedish cities. A comparison of the U.S. trends from Fig 21 gives a similar appearance, but quite different levels.

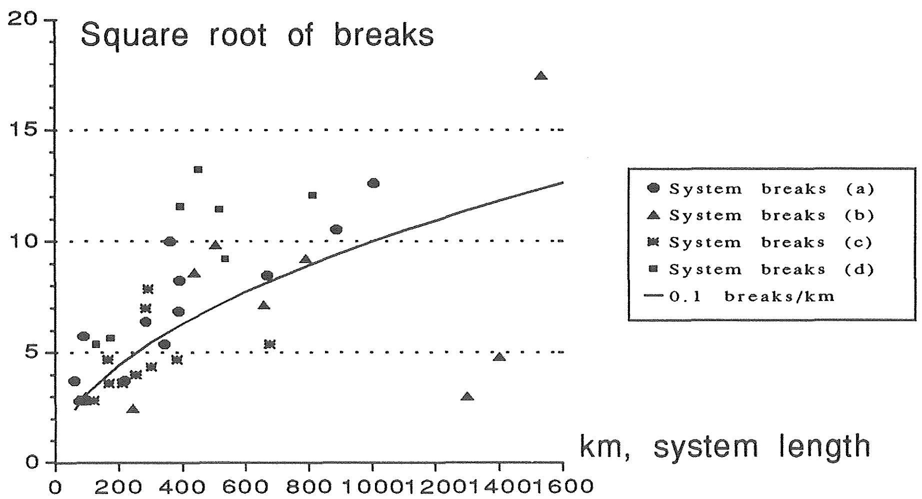

Fig. 22 Break rate presented as number of breaks per system length in km for investigated communities in Sweden, data from (a) Baekkegaard and Dyhm (1980), (b) Pettersson (1978), (c) Reinius (1981) and (d) Larsson, Reinius and Svensson (1990).

One way to analyze breaks per system length in comparative studies is using diagrams like the one presented in Fig. 23. Data from individual surveys are lumped together and grouped by pipe system length, with break rates from a comparative investigation of breaks in 31 towns in Denmark, Baekkegaard and Dyhm (1978). Break rate related to system length seems to have similarities with the U.S. cities (Fig. 21) and the Swedish municipalities (Fig. 22). The cities with long system lengths have similar number of breaks as the cities which have only half less of the pipe system length.

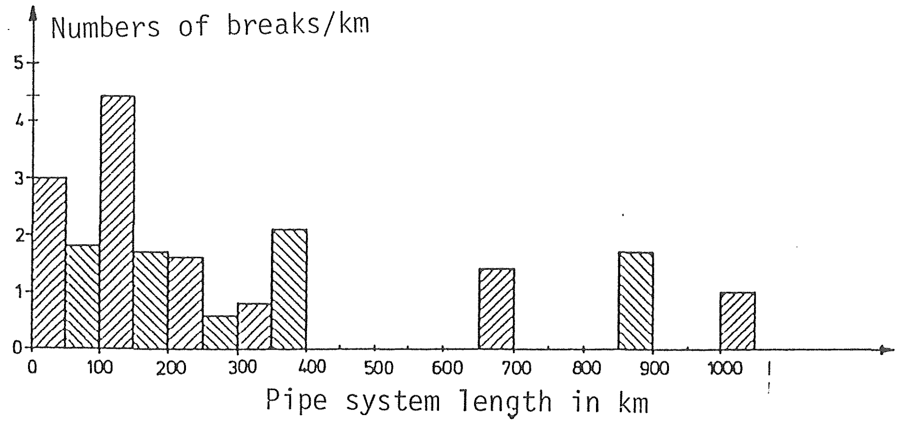

Fig. 23 Average break rate for townships with length intervals 0-50, >50-100, >100-150 km, etc., Baekkegaard and Dyhm (1978).

The break rate parameter can be a useful tool for judging pipe system condition. Break rate should gain from a stricter break definition, as well as from equal time length, perhaps five years, being used. The proposed bundling of pipes with similar characteristics, Walski, Male and Slutsky (1990), may also have to take pipe length into consideration. Fig III:7 in Appendix III also indicates a difference in break rate for small and larger cities.

Break rates for groups

Sometimes parts of a system's total length are used as a parameter in comparative studies. Such break rates are defined as the number of failures per length per year in the individual group. This is a commonly used way of presenting break rates in the literature, when comparing factors such as diameter, pipe material, break type, etc. The investigated time periods can be highly variable.

As the investigated breaks only represent part of a whole system's yearly breaks, Goulter and Kettler (1985) attempted to weight the individual break rate used with the fluctuating annual system failures, see Fig 7. This attempt is interesting, as it tries to grasp the dynamics of a system as well as the behavior of individual pipe groups.

Another interesting attempt to grasp the behavior of parts of the system were made by Goulter and Kazemi (1989), who compared different districts with the parameter of failures per area, Table 7. Perhaps the parameter of failures per unit area gives a good indication of a city behavior. Data from Table 7 are also presented in Fig. 24. District number 1 is described in Goulter and Kazemi (1989) as the most densely populated and oldest part of the city. The parameter is found to show this effectively, but gives only slight indications of differences for the other districts. In the figure, district number six is somewhat diverged from the other districts with a high number of failures, a large area and long pipe length. District number two might be of even poorer condition, as it has the second highest number of failures but the smallest pipe length of all districts.

Table 7 Failure information for districts of Winnipeg, Goulter and Kazemi (1989).

Water works engineering district	Area (km^2)	Length of distribution network (km)	Length of distribution network per unit area (km/km^2)	Total breaks	Breaks per unit area ($failures/km^2$)	Breaks per unit length of distribution network (failures/km)
1	28.0	351	12.5	3,029	108.2	8.6
2	110.1	275	2.5	3,759	34.1	13.7
3	63.5	378	6.0	2,502	39.4	6.6
4	61.9	392	6.3	2,265	36.6	5.8
5	108.8	362	3.3	3,420	31.4	9.5
6	197.1	474	2.4	5,219	26.5	11.0

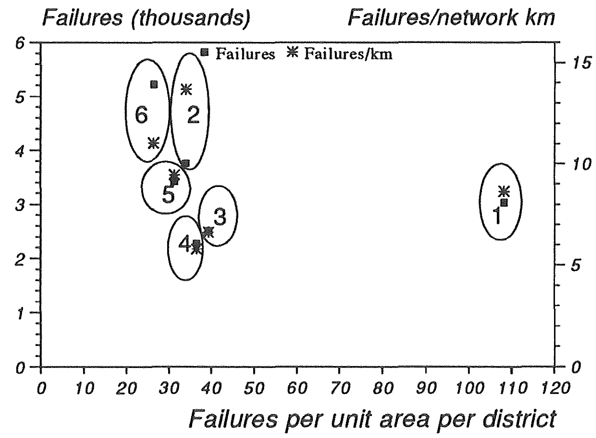

Fig. 24 Graphic display of data from Table 7.

Another way of using break rate on groups is to use the number of failures per pipe length at the same age, i.e. the system length is "weighted" by the total length of pipes which has reached that age. Here the term failure frequency is sometimes used in the literature, as in de Rosa and Parkinson (1985), who compared corrosion failures from Thames Water Sample Area with data from Calgary and general data from the U.K., Fig. 25. The U.K. material in Fig. 25 represents pipe failures from pipe types all over Great Britain, not only one pipe system.

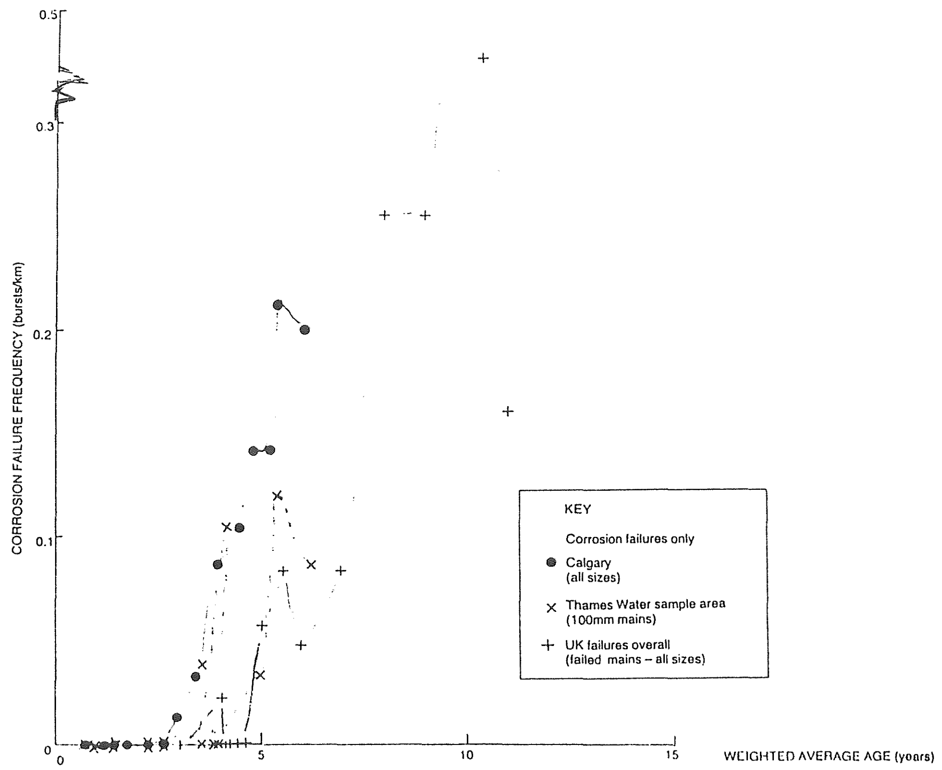

Fig. 25 Comparison of corrosion failure frequency in ductile iron mains in Calgary, Thames Water Sample Area and the U.K. generally, as a function of weighted average system age, de Rosa and Parkinson (1985).

Other attempts to compare data between cities have been made with the "cumulative frequency of the weighted length of age" for Calgary, Jakobs and Hewes (1987) and for Göteborg, Wengström (1989). To evaluate these cumulated frequency, the slopes of the curves and the breakpoint can be used. The ductile pipes in Calgary have a break point around four years of age, Fig. 26. One break point is around eight years of age for ductile pipes in Göteborg, Fig. 27.

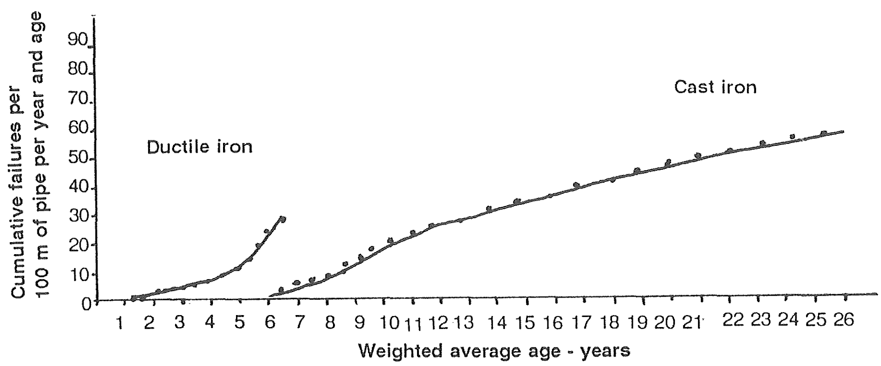

Fig. 26 Cumulative failures/100 km pipe and years of age vs weighted average of system, Jakobs and Hewes (1987).

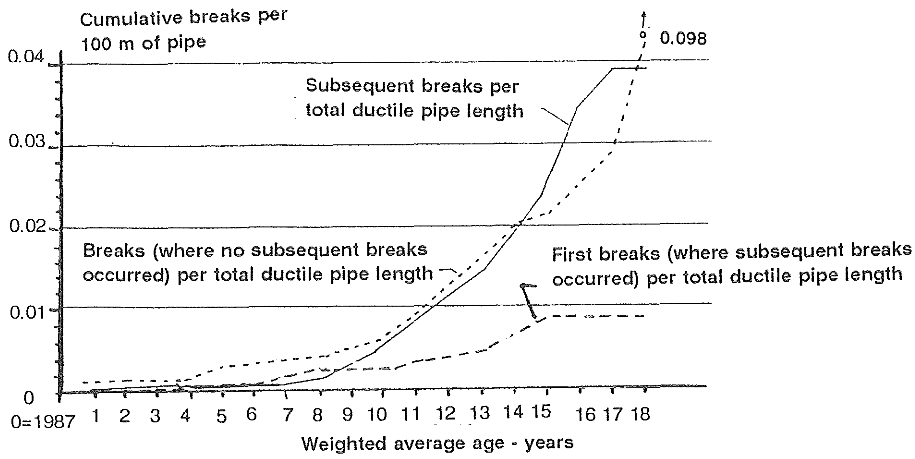

Fig. 27 Cumulative break frequency, ductile iron breaks per 100 m, as a function of weighted system age, Wengström (1989).

Individual pipe break rate

In comparative studies of break rate, the data is usually arranged on the basis of street address. The length of these segments is usually named pipes and they are of quite different lengths, from 30 meter up to 5 km, often depending on where it was suitable to change the data links.

O'Day (1987) compares New Haven's 1,391 main segments with Philadelphia's 1,061 main segments under 17 years of age. He finds that 21% of the New Haven pipes have been repaired and 19% of the Philadelphia pipes. O'Day (1989) finds that 3,592 links in New Haven were never broken. This gives about 12%, or 487 pipes which have needed repair. The parameter is interesting, as it has about the same value for all three. It is not noted however if there were always the same pipe links which failed during the investigated time period. By using only first breaks this would be solved. Marks, Clark and Andreou (1987) suggest to use the percent of first breaks for pipes with more than one failure to an indicator of system deterioration.

A break rate for individual pipes of 0.5 breaks per year and 1,500 ft equals 1.0 breaks per km, and is considered by Andreou (1986) as being at an indication that replacement would be appropriate in the future. The breaks investigated in New Haven and Cincinnati were found to be proportional to the square root of pipe length in regression analyses.

In de Rosa and Parkinson (1985), break rate for 43 pipes, both of ductile iron and spun grey iron, with known lengths for each laid year were investigated for corrosion behavior. The study was from a sample area in Thames Water, excluding mechanical fractures on grey iron and using only first breaks on 100 mm pipes. The study is interesting as it embraces the early break behavior at young ages of both grey iron and ductile pipes. In consideration of the fact that grey iron corrodes at the same rate as ductile iron, the corrosion rate for grey iron seems to have been underestimated when "mechanical fractures" are excluded, see Fig. 28. The Thames Water Sample Area was selected because it is an area with well known corrosion failures.

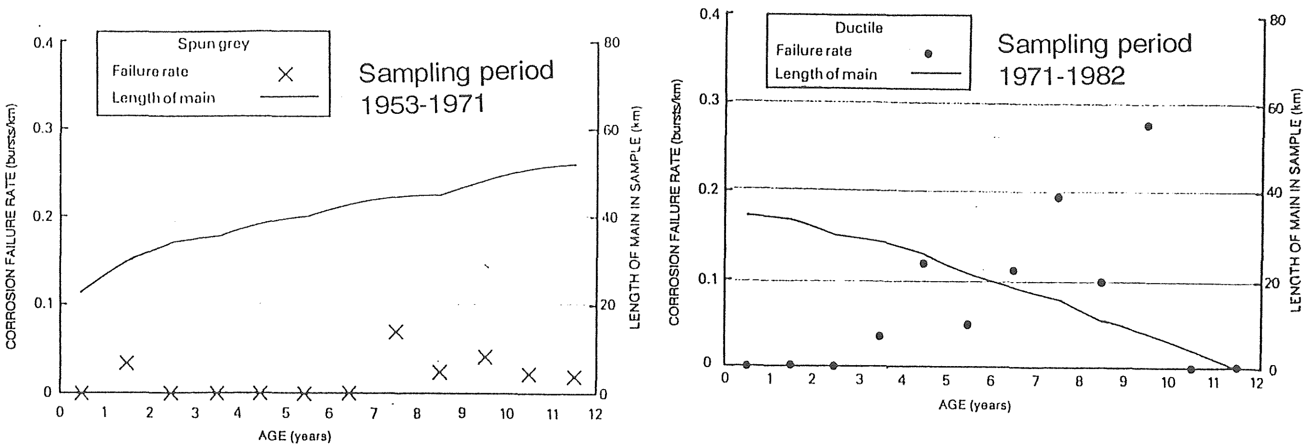

Fig. 28 Corrosion failure rate where mechanical breaks are excluded for spun grey iron mains, to the left, and for ductile iron mains, to the right, de Rosa and Parkinson (1985).

Computerized pipe data might use individual pipe link breaks, and the actual site of repair might also be localized within a meter. In the future the geographic location could then be coordinated and evaluated with the hydraulic network. Today, the differences in pipe length are dependent both on how the links were computerized as well as construction considerations. The use of breaks per block, Male, Slutsky and Walski (1990), may make the individual pipe length differences less dominant. The proposed relationship of Andreou, Marks and Clark (1987) gives indications that there may a dependency between breaks and pipe length, but this has been very little tested. The parameter "weighted length" seems promising and might be a good tool for future comparative pipe analyses.

RELIABILITY METHODS FOR PIPE SYSTEM EVALUATION

General

There are two main ways of evaluating pipe system reliability. A way is to rely on pipe records or leak detection surveys, combine repair strategies and/or optimize with economic costs. Another way is to rely on design supply networks, model the reliability and incorporate failure as a reliability factor. Some supply/distribution networks models are included, but the ones discussed here concentrate specifically on reliability of pipe components rather than on pumps and water supply.

Only methods based on pipe records are reviewed here. The different leak detection surveys are not included. The investigated models and methods found in the literature are described in these chapters. O'Day et al (1987) made a literature review of models and classified them into three classes, which are those used here and complemented with network analysis. Andreou (1986) and Karaa and Marks (1990) also made literature reviews of models, but they divided the predictive analysis into three separate types of models: aggregated models, regression models and probabilistic predictive models. This work uses these classes:

descriptive analysis
physical analysis
predictive analysis
network analysis

To evaluate a pipe system, methods for identification and a knowledge of the behavior of the pipe components are important. The identification phase should show where and how the failures or the problems in the system are distributed. The methods for this are called descriptive.

Rehabilitation of pipe systems is important, as planning and cost evaluations are needed. A common often discussed question is when replacement is necessary, instead of repair. Wear-out effects and unsuitable material or components are often discussed. Judgements for pipes are usually based on both economics and material testing. These methods of analyzing the conditions of water mains and components be called physical analysis. Economic methods are very much dependent on how the pipe systems are financed, and economic costs are not discussed here, although some of the models are included. The economic aspect should even so not be forgotten. Walski (1987) made a quantitative study of costs to develop replacement, recommended for further study by those interested in this area.

Maintenance has always been and remains necessary for pipe systems. It is essential to know how fast break will develop and how many breaks can be expected, and how relatively newly laid pipes and the older pipes will behave in future. Methods for this are called predictive.

Investigated models

Analytic approach for scheduling pipe replacement, from Shamir and Howard (1979)

Shamir and Howard present a predictive model for determining the optimum time for replacement of a pipe, with regard to the expected breaks in future. Their model is an exponential growth equation, Eq. (1) below, and developed a regression model for the number of breaks, which can be developed for a particular pipe as well as bundles of pipes or an entire pipe system. A linear equation, Eq. (2), was introduced as well, but the exponential one seemed to fit investigated data from Calgary better. The model showed an increase in pipe breaks with increasing age. The model was used for replacement costs, etc.

$$N(t) = N(t_0)e^{A(t-t_0)} \quad (1)$$

where

t =	time in years
t_0 =	base year for the analysis (the year the pipe was installed, or the first year for which data are available)
$N(t)$=	number of breaks per 1000-ft length of pipe in year t
A =	growth rate coefficient (dimension is 1/year)

$$N(t) = N(t_0)A(t-t_0) \quad (2)$$

According to Marks, Andreou, Clark (1987), the model constitutes the first known attempt to analyze break records statistically and to apply the results, for better maintenance decisions. The model does not refer to pipe characteristics but lumps all break factors together into one parameter. Walski and Pellica (1981) added correction coefficients for some pipe characteristics such as pipe diameter and number of previous breaks to this model.

Statistics of corrosion failure in pipes, from Davies (1979)

Davies has performed a theoretical analysis in the field of descriptive analysis for corrosion in pipes, describing the rate of occurrence of leaks (breaks) in a probability model, as well as with Bayesian estimation and the application of fuzzy set theory. Leakage (breakage) due to wall thinning because of corrosion for the first corrosion leak (break), in a new pipe, was found to be approximately exponential, Eq. (3). When a number of these leaks occur in the pipeline they are all Poisson distributed and the time intervals between successive leaks is exponential. Other corrosion processes such as stress cracking and fatigue could not be made amenable to this analysis. But these processes could themselves possibly be claimed to be independent Poisson processes, as the sum of the set of parallel running processes was believed to be Poisson.

$$F_T(t) = 1 - e^{-\theta L t} \qquad (t > 0) \qquad (3)$$

$F_T(t)$ = distribution of the time T to the occurrence of the first corrosion leak in a new pipe line of length L
θ = occurrence rate

Davies' conclusion was that the probability model was a good estimator of the occurrence of failure. It is reasonable to expect the Poisson model to be applicable to other failure modes than corrosion, such as mechanical failure, operational error, and natural hazards of third party activity.

Time-to-failure study to determine remaining service life of cast iron pipe, from Doleac, Lackey and Bratton (1980)

This is a physical model for predicting burst failures from external corrosion based on corrosion rates for pit cast iron pipes installed in about 1900 in Vancouver, Canada. This model is also described in O'Day et al (1987). The model makes it possible to plot pit depth and pipe wall reduction, against time at a proposed corrosion rate in soil that can be used to predict failure from internal pressure. Failures are defined here as "the reduction of pipe wall thickness to a point where pressure surge in the water line is equal to 50 percent of working pressure raised the internal pipe wall stress to its elastic limit". Barlow's formula for bursting stress is referred to for finding a minimum wall thickness. The equation used, Eq. (4), was derived from Rossum's theoretical equation for underground pit corrosion.

$$P = K_n K_a (10\text{-pH})^n \rho^{-n} t^n A^a \qquad (4)$$

A=area (sq ft)
K_a=relative pit depth constant
a=constant, depending on soil and metal
P=pit depth (miles) maximum
ρ=soil resistivity (ohm-centimeter)
K_n, n=aeration constants
t=time (years)
K_a, K_n, and a are constants derived empirically from the NBS tests.
pH=the negative log of hydrogen concentration in mol per litre

Calculated probability of maximum pit depth was correlated to 20 investigated pipe samples and about 200 soil samples from locations from the entire project area. Field tests for measuring pipe wall thickness and soil samples were taken for analysis. The internal corrosion was found to be minor, about 50 mils, in four investigated samples. The average external corrosion was measured as metal loss in five samples to 65 mils. The soil samples were analyzed for pH, resistivity, and soil aeration. The pH, and resistivity, of investigated soil samples varied from 4.6 to 9.4, for pH, and 3,400 - 900,000 ohm-centimeters, for resistivity. Soil aeration was related to redox-potential as shown in Table 8.

Table 8 Soil aeration classification, Doleac, Bratton and Lackey (1980).

Soil Aeration	Redox Potential (millivolts)
Good	> 250
Fair	150-250
Poor	50-150
Very poor	< 50

The model consists of a constructed curve, corrosion rate, for determining the wall thickness when corrosion occurs in a specific soil environment. Actual average pit depth was 9% lower than the calculated values. The work chart in Fig. 29 is for predicting the remaining time for a pipe before corrosion will reduce the wall thickness to the point of failure. With actual installation time, the modelled wall thickness is given in Fig. 30. Fig. 30 relate the minimum wall thickness for each pipe diameter to surge, or bursting pressure. With the minimum wall thickness it is then possible to determine the remaining time from Fig. 29.

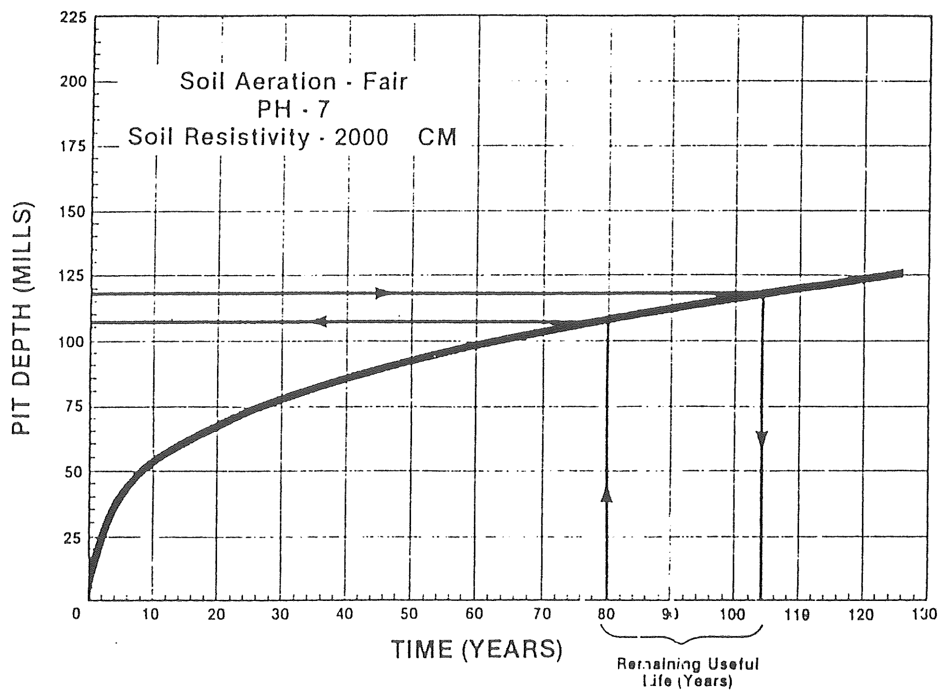

Fig. 29 Example of a model work sheet for theoretical pit depth vs time for old pit cast iron mains in Vancouver, Doleac, Lackey and Bratton (1980).

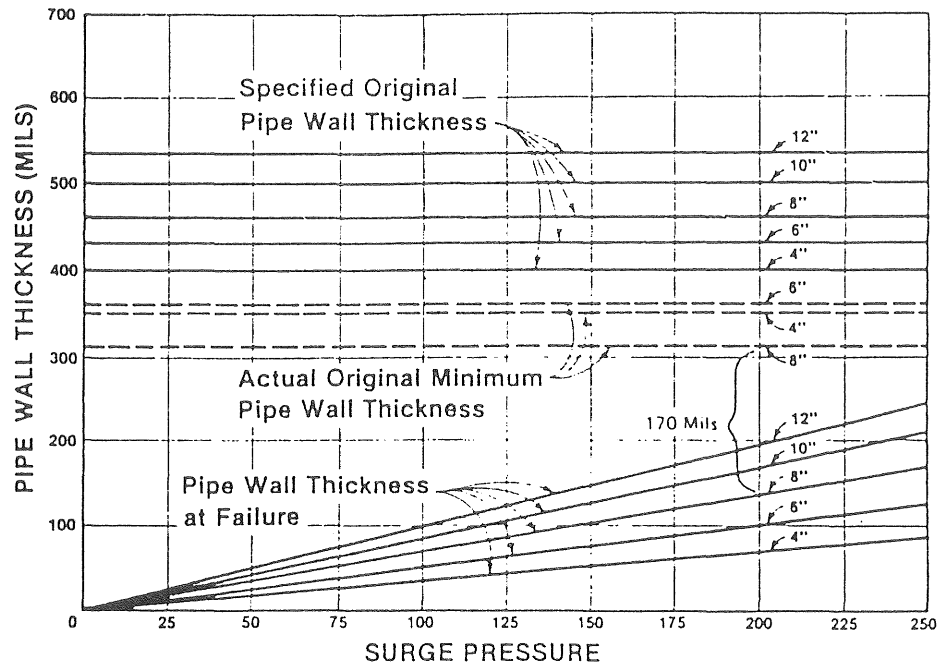

Fig. 30 Correlation of pipe wall thickness at failure and original pipe wall thickness to internal surge pressure, Doleac, Lackey and Bratton (1980).

Computerized case study of ageing urban water systems, Manhattan, from O'Day, Fox and Huguet (1980)

This study is based on 2,308 pipe repair reports during 25 years and computerized system maps from Manhattan, New York. The purpose was to find decision-making and planning tools for water mains breaks. The causes of breaks, trends in breaks, and recommendations for mains replacement were also investigated.

In the descriptive analysis, break rate was used as parameter for describing the system with the help of pipe records. Registered causes of breaks were tabulated with other factors, but few relationship were found for which the exact causes could be stated. Andreou (1986) summarizes their results of the descriptive analysis, in his literature review, to that high break areas were usually related to high levels of other activities as heavy traffic, major reconstruction, subways and underground utilities.

A predictive break model was developed using linear discriminant functional analysis. The model used break rate patterns by age, by location and by cause of breaks and predicted 70% of the actually occurring breaks correctly. Location was found to be the single most important factor for predicting breaks. Andreou (1986) finds the accuracy of the used linear discriminant function to depend upon the pipe diameter and suggests the accuracy to be low for the use as a predictive tool. An important conclusion, which was not possible to follow in the description of the model, was that the Manhattan system was not wearing out due to age.

Water main repair/replacement in Binghamton, from Walski and Pellica (1981)

Based on pipe records with only sand spun and pit cast iron for 6-12 inches in Binghamton. The ductile pipes were not included in the analysis. The objective was to predict whether a pipe should be replaced or repaired considering economic aspects. A break prediction model based on Shamir and Howard's model was constructed as shown in Eq. (5). Its purpose was to identify pipe costs for the next 20 years using break rate, with regression analysis for the coefficients for age, pipe type, diameter, temperature and occurrence of previous breaks. The model was not used for pipes ≥20 inches and excluded pipes with frequent breaks. Regression analysis for these pipe has shown significantly different break rate than for other pipes.

$$N(t) = c_1 \, c_2 \, a \, e^{b(t-k)} \qquad (5)$$

N(t)=break rate at age t, breaks/year/mile
c_1=correction factor for previous breaks
c_2=correction factor for size
a=regression coefficients, breaks/year/mile
0.02577, for pit cast iron
0.0627, for sand spun cast iron
b=regression coefficient
0.0207, for pit cast iron
0.0137, for sand spun cast iron
k=year installed

The maximum frost penetration was not available as a parameter, but temperature in the coldest month was. A multiple regression analysis was performed for break rate and temperature vs age. Fig. 31 shows the relationship. The best fit equations for break rate in the coldest months was presented as both exponential Eq. (6), and linear Eq. (7).

$$N(t,T) = 0.0707 \, e^{0.0118(t-k)} \, e^{-0.305T} \qquad (6)$$

$$N(t,T) = 0.0788 + 0.00086(t-k) - 0.0023T \qquad (7)$$

T=average temperature in coldest month, °F
k=year

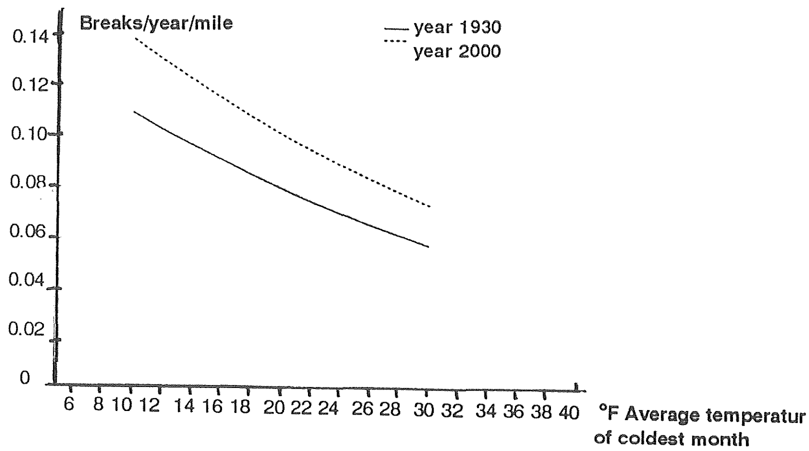

Fig. 31 Effect of temperature on break rate, Walski and Pellica (1981).

Statistical determinations for the condition of underground assets in Severn-Trent, from Newport (1981)

This study correlated cumulative burst per day and cumulative frost temperature per day for temperatures below 0°C based on pipe records mainly only circumferential breaks and daily temperature for up to seven years. A comparative analysis of four areas Soar, Coventry, Rugby and Nottingham was made.

Total breaks per year and total degrees of frost for a year had a high correlation, 0.90, and the relationship was given as Eq. (8) and is shown in Fig. 32.

$$\text{Total breaks/year} = 2.5 \times \text{Total degrees of frost} + 500 \qquad (8)$$

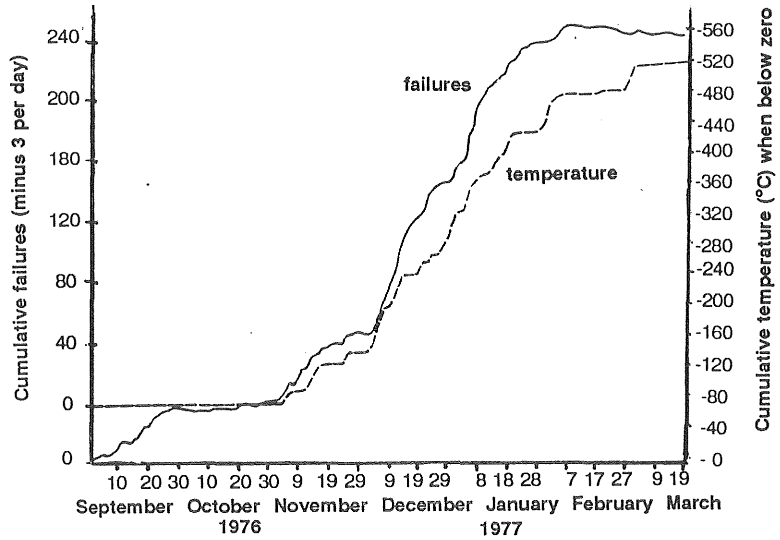

Fig. 32 Cumulative bursts and frosts 1976/77, Soar Division, Newport (1981).

Spatial evaluation of water distribution systems, from Environmental Protection Agency; Clark, Cheryl, Stafford and Goodrich (1982)

This study describes a regression type of predictive model for one small utility and one larger utility. Equations (9) and (10) show the combined data for both utilities. A total of 457 pipes were analyzed. For the individual equations, O'Day et al (1987) give further information. The equations are, in one sense, a possible scenario for optimum repair or replacement.

Several demographic variables such as industrial development and residential wdevelopment are used in the equations. Parameters used were natural features, length of pipe in corrosive soil, and pipe characteristics derived from records. After the first event, the number of breaks seemed to increase exponentially, are therefore two equations were developed, Eqs. (9) and (10). The first event equation was developed to predict the number of years from installation to first break. The next equation was to predict the number of expected breaks after the first break had developed. A main with maintenance events early in its life was believed to have a many more failure events than a comparable main with its maintenance events later, as can be seen in Fig. 33.

$$NY = 4.13 + 0.338D - 0.02P - 0.265I - 0.0983RES - 0.0003LH + 13.28T \quad (9)$$

(first event equation $R^2 = 0.23$)

$$REP = (0.1721)(e^{0.7197})^{T}(e^{0.0044})^{PRD}(e^{0.0865})^{A}(0.0121)^{DEV}(SL)^{0.014}(SH)^{0.069} \quad (8)$$

(accumulated event equation $R^2 = 0.47$)

NY=number of years from installation to first repair
D=diameter of pipe, in inches
P=absolute pressure within a pipe, in pounds per square inch
I=percent of pipe overlain by industrial development in a census tract
RES=percent of pipe overlain by residential development in a census tract
LH=length of pipe in highly corrosive soil
T=pipe type (1 = metallic, 0 = reinforced concrete)
REP=number of repairs
PRD=pressure differential, in pounds per square inch
A=age of pipe from first break
DEV=percent of land over pipe in low and moderately corrosive soil
SL=surface area of pipe in low corrosive soil
SH=surface area of pipe in highly corrosive soil

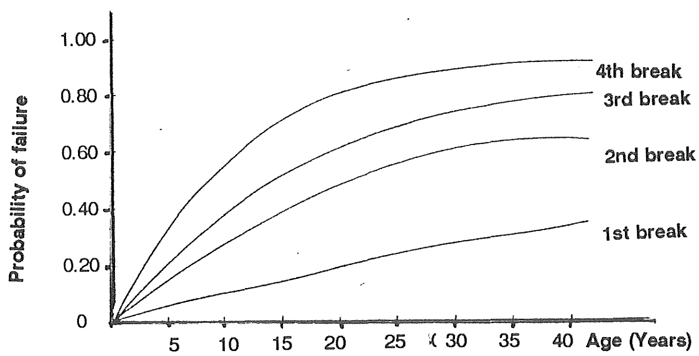

Fig. 33 Probability of pipe failure for first to fourth break, Clark, Stafford and Goodrich (1982).

The descriptive analysis of the 457 separate pipes and their repairs, from first to tenth repair, was also conducted on data from a period of 40 years, with mostly feeder and transmission mains with larger diameters. In Fig. 34 it can be seen that after 30 to 40 years 52.5% of investigated pipes had no maintenance events, 48% had one maintenance event, 30% had two maintenance events, etc. The first maintenance event did not usually occur until 15 years after the pipe has been laid. A minority of the pipes were responsible for a majority of the maintenance events.

Andreou, Marks and Clark (1987) point out that the model lacks pipe length as a covariate, and reflect that the same model structure was applied to pipes with few or many breaks. The model is a basis for further work by Andreou (1986) and Andreou, Marks and Clark (1987).

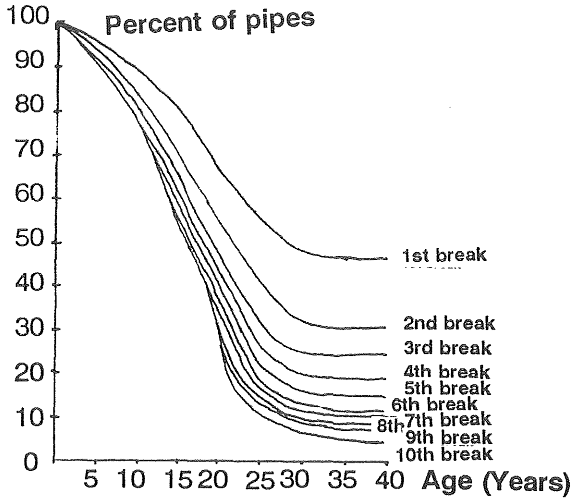

Fig. 34 Break repair (mortality) curves for pipes, percent of pipes having n repair events, Clark, Stafford and Goodrich (1982).

Condition assessment model of Philadelphia Water Department, from Andreou (1986) and O'Day et al (1987)

For the Philadelphia system, a physical model called CAM, condition assessment model, was developed based on pipe records, and water mains condition assessed from loads and remaining wall thickness. Andreou (1986) summarizes the model in his literature review and O'Day et al (1987). The model was for rigid grey cast iron pipes. Break rate was used as the parameter for defining the system.

The model adapts a safety factor to a pipe segment, derived and related to its geographical placement and parameters such as corrosion and loads. The assumed average rate of external corrosion is adjusted to areas with known leakage, proximity to existing rail lines with DC-current and cleaning and lining. The average external corrosion rate is derived from the samples tested using a physical testing program. The assumed loads are surge pressure, external loads and truck loads, based on the AWWA design standards. The assumed loads are also related to areas where there are abandoned service pipes. Leakage from service pipes is found to cause bad bedding conditions and insufficient support for the pipe, which is therefore at risk of breaking.

Prediction of corrosion status index of Corps of Engineers Construction Engineering Research Laboratory (CERL), from Kumar, Meronyk and Segan (1984)

This is a physical model using a quantitative corrosion condition status index for water pipelines. The model was originally made for gas pipes. The model was developed on the basis of data from the gas industry, petroleum industry and culvert studies. The model uses a corrosion status index, CSI, for characterizing pipe conditions in a specific soil, with prediction tables for future corrosion status. The model is based on the average pit depth and defines the corrosion index as in Eq. (11). P_{av}/P_{avmax}, the average pit depth/maximum pit depth, have been empirically observed to be 0.7. The first leak is said to occur when pit depth average is 0.7T or by definition when CSI is 30.

$$CSI = 100 - 100\ P_{av}/T \quad \textbf{(11)}$$

CSI=corrosion status index to characterize the condition of underground pipe
P_{av}=average pit depth of a 1-meter section of pipe
T=thickness of the pipe wall

Eq. (12), shows an example, how parameters used in the model, such as soil moisture, sulfides in soil, soil pH and the pipe coating material are used as multipliers in Eq. (10), for predicting the number of years until the first leak occurs.

$$(14\ \text{years}) \times (0.8) \times 0.66 \times 0.70 = 5.7\ \text{years to start for leaking} \quad \textbf{(12)}$$

where 14 years = first leak age
0.8=base pipe (no protection)
0.66=sulfides ppm in soil
0.70=pH in soil

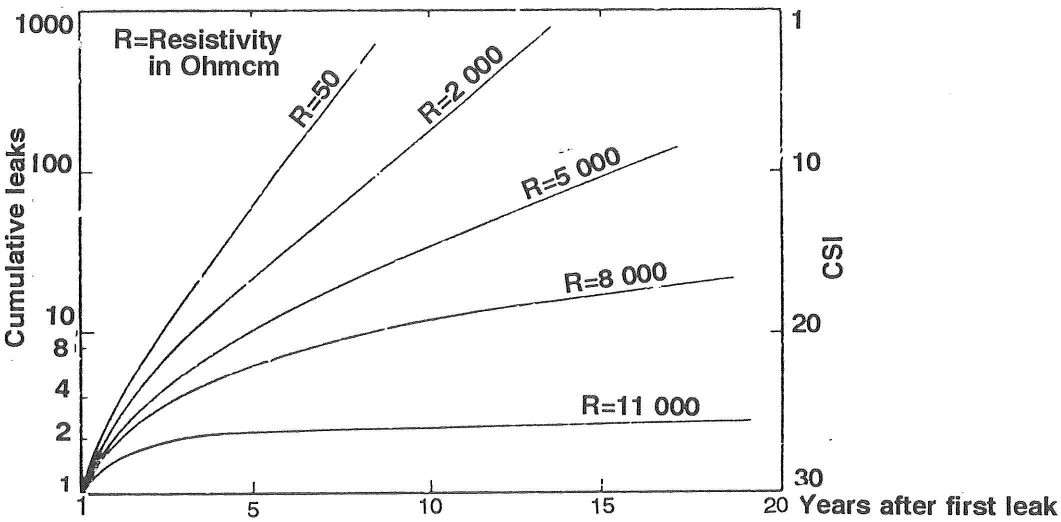

Fig. 35 Leaks in underground pipes, Kumar, Meronyk and Segan (1984).

For predicting the years to first leak, a design wall thickness, based on literature investigations for gas pipes and culverts, etc. are considered. The literature is from several places in the U.S.A., such as the state of New York, state of California and eastern Ohio. Of predicting the future numbers of breaks Fig. 35 gives the accumulated breaks. The model suggests a continuing program measuring maximum pit depth and using soil investigations to calibrate the model. According to the authors, in measurements for maximum pit depth on 1 foot pipe field samples could be regarded as equally valid as uncovered whole pipe lengths. The model is not specifically related to a water pipe material, but the common used grey cast iron is plausible.

Des Moines Waterworks study, from McMullen (1986)

This is a physical model based on the number of pipe breaks as correlated to different ways of measuring soil corrosion. Single parameter analyses were tried on measured four pin resistivity, saturated soil resistivity, and redox potential. The Ductile Iron Pipe Research Association Ten Point System was studied in a multiple way. The results from the redox study and Ten Point Test are shown in Table 9. Only the saturated resistivity was found to be a good indicator of breaks.

Table 9 Descriptive analyses of number of breaks in Des Moines correlated to Ductile Iron Pipe Research Association Ten Point System, left, and to redox investigations, right, McMullen (1986).

Points	Hole in pipe and split pipe	Crack around	Percentage of total failures
1	16	21	17
2	19	13	17
3	9	8	9
4	2	8	3
5	6	8	7
6	6	4	5
7	2	4	2
8	4	8	5
8	4	0	3
10	22	13	20
>10	10	13	12

Redox mV	Percentage of total failures
> +156	87
+156 - -44	10
-44 - -144	3
< -144	0

For predicting cast iron pipe life a multiple-variate parameter approach was used, based on both pipe characteristics (from break records) and soil characteristics. Various models were investigated, ranging from linear to logarithmic. The linear model was found to be the best, presented in Eq. (13), O'Day et al (1987). Even with additional parameters it was found to be no better than the saturated resistivity model. The correlation coefficients of pH, redox and pipe age was found to be negative. The influence of saturated resistivity indicated that an increase of 1000 ohm/cm would give rise to an expected life increase of 28 years.

$$Age=65.78+0.028*SR-6.338*pH-0.049*r \quad (13)$$

(coefficient of determination R^2=0.3747)

Age=age of pipe at first break, years
SR=saturated soil resistivity, Ohmcm
pH=soil pH
r=redox potential, mV

Predictive model for break failure in deteriorating water distribution systems,, from Andreou (1986), Andreou, Clark and Marks (1987), Andreou and Marks (1987), Karaa and Marks (1990)

This study presents 1986 as a failure hazard model giving the probability that a pipe will break based on several factors including age of pipe, number of previous breaks, and time since last break.

The investigation was based on pipe records for cast iron pipes in two cities, New Haven and Cincinnati. The results are believed not to be generalizable for other systems. 1,428 pipes in New Haven with diameters ranging from 8-48 inches were investigated. Most pipes had only one break, although some had three. The objective was to predict the probability of a break in the future for any pipe segment. The method was to relate clusters of installation periods to different factors such as length, corrosion, pressure, previous number of breaks, soil stability, and land development, using Cox's proportional hazard model.

The analysis concentrated primarily on predicting the failure probability after the first and second breaks, and the probability of entering the fast-breaking stage. The model showed a high variability of break rate among the individual pipes in the systems. For pipes with frequent breaks during short time periods, a Poisson type of model was proposed. For pipes in the slow-breaking stage the Cox proportional hazard model was used.

When using the Cox proportional hazard model, two assumptions are relevant. One assumption is the multiple effect which the break causing factors have on the break rate. The other is the log-linear relation between break rate and investigated break factors. Failures are assumed to occur independently in different pipes.

Probability of failure did not increase proportionally with pipe length, but rather with the square root of length. The hazard coefficients developed for length were about 0.5 for both systems. Some installation periods had a higher break rate than others. Usually the more recent periods, such as the 1940's and the 1950's, had high break rates. The break rate curve was found to have a bathtub shape for first and second breaks.

After two breaks, pipes seemed to enter a fast breaking period, estimated to be 0.5 breaks per year per 1,500 feet (457 m), which equals about 1.1 breaks per km per year. Data showed that a majority of these pipes had three or more breaks within a six-year period. When a pipe was in the fast-breaking stage, usually multiple breaks occurred within less than two years. Neither age nor previous breaks seemed to influence the break rate of the pipes with multiple breaks.

Break types were not included in the model. Maintenance, such as cleaning and lining, were investigated and it was noted that most pipes had been cleaned and lined before the first recorded break.

Multi-objective optimization and quantitative reliability assessment in pipe networks, from Goulter (1986), Goulter and Coals (1986)

Attempts were made to incorporate pipe component reliability in design supply networks. Two approaches for reliability in least-cost design of looped networks, and two approaches in multi-objective optimization, including costs, in networks were studied.

Briefly, it can be said that the approaches are valid for a constant break rate or break rates that increases with time. Table 10 shows the break rates used. The expected number of breaks in a link was Poisson probability distributed, Eq. (14).

$$\lambda=\sum_{n(j)}^{k=1} r_{jk}X_{jk}^{*} \qquad p_j=\sum_{x=1}^{\infty} e^{-\lambda}\frac{\lambda_j^x}{x!} \tag{14}$$

where λ_j=expected number of breaks per year for link j
r_j=parameter for the Poisson probability distribution
X_j^*=values of decision variables obtained from linear program solution
p_j=probability of one or more breaks in link j
x=number of breaks

Table 10 Network break rates, all pipe lengths 1000 m, from Goulter (1986).

Pipe size (mm)	Expected number of breaks/km/yr
700	0.023
600	0.0255
500	0.03
450	0.034
400	0.04
350	0.05
300	0.07
250	0.39
200	0.71
150	1.04
100	1.36

Compared with the work in Goulter and Coals (1986), Goulter (1986) found substantial differences in measuring reliability and in defining system reliability. In Goulter (1986) there is an important discussion on the different ways reliability can be measured.

The New York water supply infrastructure study, from Walski and Wade (1987) and Walski, Wade, Sharp and Sjostrom (1987)

Descriptive analysis for the boroughs The Bronx, Queens and Staten Island in New York City. Pipe records with about 5,000 breaks over a 25 year period (1954-1979) was used in a data base with information about census tracts, blocks and streets. The break rate per installation year was used as trend evaluation for ageing and for bad material, shown here in Fig. 2. An increase of break rate with time was noted and described as an exponential equation, Eq. (15).

$$J = a^{b'(t-1933)} \qquad (15)$$

J=break rate, in breaks per year per mile
a=regression coefficient, in breaks per year per mile estimated for the three boroughs to about 0.017-0.036
b'=regression rate constant, 1 per year, estimated to about 0.019-0.024
t=time, in year

Stress examination of the reasons for pipe damage, from Moruzzi (1987)

To describe how various pipe materials and various types of joints behave, a simple physical model was made to determine resistance status. The degree of resistance, mechanical and physical properties of a pipe, and joint constraints were evaluated for of all types of different stresses on a scale of 0 (minimum) to 10 (maximum), Fig. 36. The points for each stress were then added to different reasons for failure. The reasons for failure were described as a set of different stresses, and the resulting score is seen in Fig. 37. Steel pipes were the most durable. The model is dependent on how the primary degrees of resistance are estimated, as the resistance is evaluated descriptive.

TYPES OF STRESS	TYPES OF WATER PIPES AND JUNCTIONS											
	A / GS	A / GF	GG / GP	GG / GF	GS / GP	GS / GF	CA / GM	PA / GM	PA / GS	PVC / GP	PVC / GI	VTR / GI
Mf	10	9	5	6	6	8.5	4	7	10	6	5	8
Mt	10	9	6	5	6	9	6	6	6	5	5	6
T	10	10	5	5	9.5	9.5	4.5	1.5	1.5	1.5	1.5	2.5
A	10	9	0	6	0	9	0	0	1.5	0	1.5	2.5
C	9	9	7	10	7	9	4.5	1	1	1	1.5	1.5
Pt	10	10	7.5	8	9	10	8	7.5	8	7.5	8	8.5
Pc	3	3	7.5	10	5.5	5.5	9	4.5	4.5	4	4	5

0 = minimum: no resistance and/or maximum liability
10 = maximum: maximum resistance and/or maximum hyperstatics

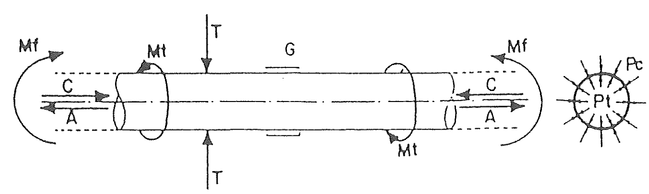

Fig. 36 Degree of resistance of water pipes (various pipe types and junctions) with respect to various types of stress, Moruzzi (1987).

1) violent movement of the soil:
earthquake, landslip, building collapse, remarkable facts of war, etc
(M_F, M_t, T, A, C, P_E);

2) slow movement of the soil:
subsidence, road settlings and settling of the water pipe section on work (M_F, T, A);

3) excessive direct transmission of surface accidental loads:
poor thickness of layer (M_F, T, P_C);

4) low temperatures:
only under certain conditions when pipe is not protected (P_T, A);

5) water hammer:
an overpressure or depression from different sources (P_C-P_T-A);

6) road works:
over and under the soil (M_F-M_T-T-A-P_C)

REASONS FOR FAILURE	TYPES OF WATER PIPES AND JUNCTIONS											
	A/GS	A/GF	GG/GP	GG/GF	GS/GP	GS/GF	CA/GM	PA/GM	PA/GS	PVC/GP	PVC/GI	VTR/GI
1	52	49	29.5	42	34	45	26	20	24.5	17.5	18.5	25.5
2	30	28	10	17	15.5	27	8.5	8.5	13	7.5	8	13
3	23	22	17.5	21	21	23.5	17.5	13	16	11.5	10.5	15.5
4	20	19	7.5	14	9	19	8	7.5	8.5	[illegible]	8.5	11
5	23	22	15	24	14.5	24.5	17	12	14	11.5	13.5	16
6	43	40	22.5	32	27	36	23.5	19	23.5	16.5	17	24

Fig. 37 The sum of degrees of resistance of water pipes with respect to various failure reasons, Moruzzi (1987).

Systems evaluation of break reliability and degradation rates for asbestos cement pipes, from Aaby (1988)

This is a physical model for the evaluation of system reliability for a specific pipe material. The model is based on field samples of selected asbestos cement pipe segments, collected and laboratory tested for strength, durability and pressure.

Comparison of new pipes to field samples of old asbestos cement pipes gave an average strength reduction of 20%. The deterioration speed for asbestos cement pipes is assumed to be constant. The system reliability will depend on loads and the pipes' durability/resistance for loads over time. Eq. (16) defines a pipe's breaking resistance under load in service. Fig. 38 shows the decreasing load durability over time.

$$F = W_s/W_b \qquad \textbf{(16)}$$

F=durability for breaks for a pipe
W_s=break load when testing
W_b=load on pipe when in pipe trench

$$R=100/F \qquad \textbf{(17)}$$

$$V=\Delta R/\Delta A*100 \qquad \textbf{(18)}$$

R=relative risk for breaking
V=deterioration rate
ΔR=differences in R for selected time period
ΔA=selected time period

The time interval for pipe evaluation should be a minimum period of five years. The resulting system reliability and system deterioration rate are shown in Table 11. The system deterioration is defined in Eqs. (17) and (18).

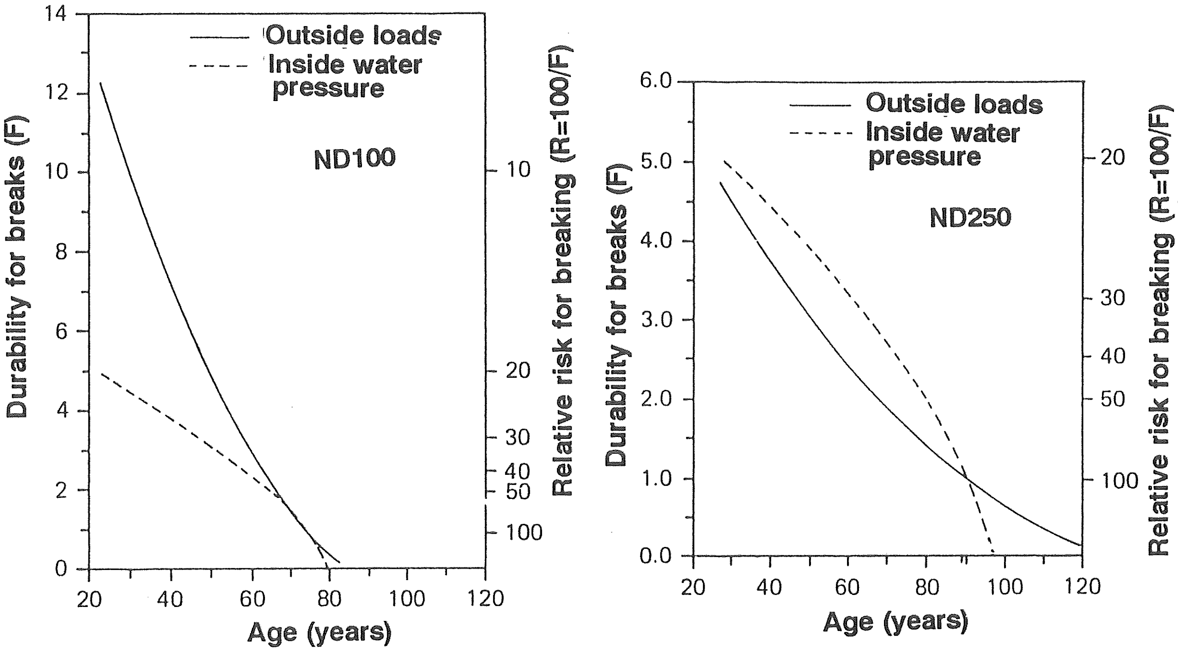

Fig. 38 Durability, as resistance to break loads and increasing age, for a 250 mm pipe, right, and a 100 mm pipe, left, Aaby (1988).

Table 11 Pipe system reliability for breaks and deterioration rate, Aaby (1988).

Priority group	Relative risk (R)	Name of pipe section	Break type evaluation for R	Deterioration rate (V)	Break rate (breaks/km and year)	Dominate cause of break load
1	1.0 - 10	A B C	K S S	30 24 20	2.0 1.0 1.0	fill compaction water hammer water hammer
2	11 - 20	.				
.	.					

K=broken
S=burst

Reliability analysis of water distribution networks, from Shamsi and Quimpo (1988)

This is a network analysis with a simulation of preventive maintenance strategies using reliability analysis. The investigated water distribution network had ten nodes, and its hydraulic properties, such as flows, discharge, demand and hydraulic head were determined using hydraulic analysis. The assumed break rate for specific diameters was developed from historical pipe records, Table 12. Component reliability, or reliability for blocks of components, in series, is computed here. The developed network was a stochastic network, and the reliability over a given time period was then computed by either minimal cutsets or minimal pathsets.

Table 12 Assumed reliability and break rates for network components after 5 years, Shamsi and Quimpo (1988).

Components	Break rate (λ), breaks/year	$R(5)=e^{-5\lambda}$
Tank	0.01	0.95
Pump	0.03	0.86
Valve	0.05	0.78
Pipes:		
16 inches	0.02	0.90
14 inches	0.05	0.78
12 inches	0.10	0.61
6 inches	0.18	0.41

Analytical and simulation methods of water distribution network reliability, from Wagner et al (1988a) and Wagner et al (1988b)

This study proposed a simulation model of system reliability in supply networks, mainly pipe and pump failures, including repair events. The simulation was tried for a smaller network and for a larger network for 200 years and 140 years, respectively. Some of the conclusions were that the probability parameters were conspicuously high, that all node failures occurred close to pumps and conditions for failure occurred relatively frequently. The important determinant of reliability of the system was found to be the pumps.

The simulation used generated failures and repair events according to specific probability distributions for the break rate, repair times, and parameters, shown in Fig. 39. The break rate was assumed to be one failure per mile per year.

The second part is the hydraulic network section, which gives the flows and the heads at nodes for specified demands. The reliability of the system was defined in three modes. The system was made to function for the normal mode where all nodes was receiving normal supply, or reduced mode if a node was receiving a reduced supply, or failure mode if any node was completely shut off.

In the analysis the pipes were all to fail independently. Assumptions of dependency of several pipes failing at the same time might be possible for future work.

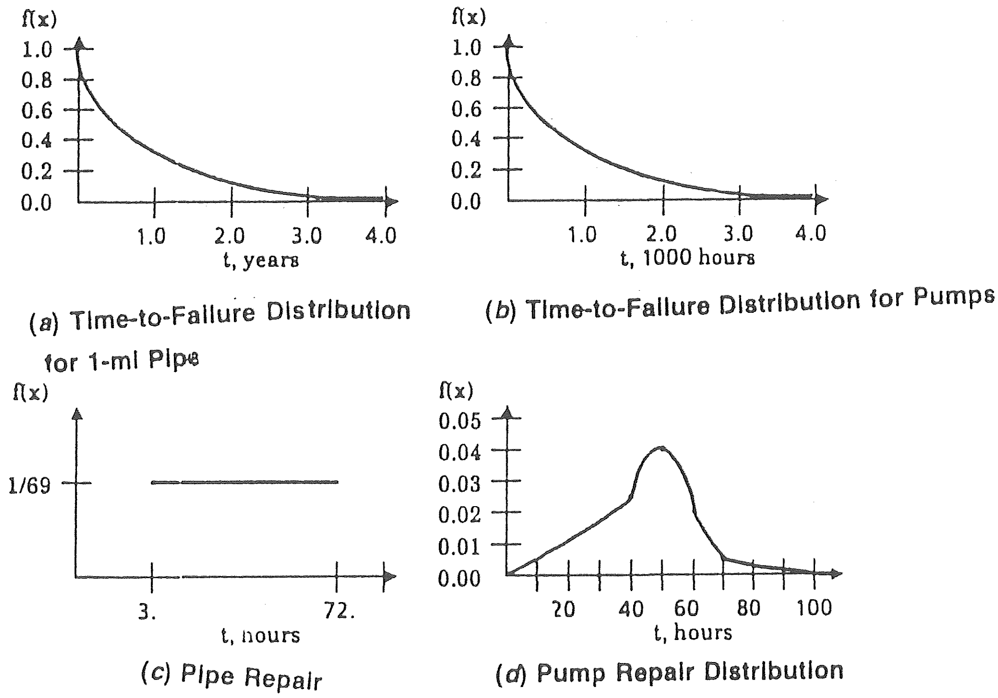

Fig. 39 Network break and repair time probability distributions for 1 mile of pipe, Wagner et al (1988b).

Quantitative reliability of water distribution systems, from van der Hoven (1988)

This is a model for design and operation of distribution networks in the Netherlands, on the basis of calculating network reliability. The model considers water demand of consumers as well as incorporating failure interruptions, irrespective of failure cause. Interruption rate are based both on failures and leakage, from a one year registration program, covering a network with the length of 20,000 km of different pipe materials.

Model for simulation of network deterioration and renewal, from Hertz and Hochstrate (1988), Hochstrate, Malm and Hogland (1989)

This is a predictive model for empirical forecasting of system costs considering age and different replacement strategies. The model is based on two different ways of describing the system. One is descriptive, and uses age of pipe, installation period and sample inspection for pipe maintenance needs. The other is based on pipe condition, evaluated as repair costs for breaks occurring.

Three simulation strategies are used, one is replacement of pipe, the second strategy uses different renewal events and the third adds new pipe length to create better safety and cover expansion needs. The ageing of pipes is estimated from experience. The modelled system tries to describe the lowest age the different system's parts or groups can achieve with a survival function, Fig. 40, and the modelled cost conditions, shown in Fig. 41. The model had been tried in Stuttgart and Malmö on sewerage systems.

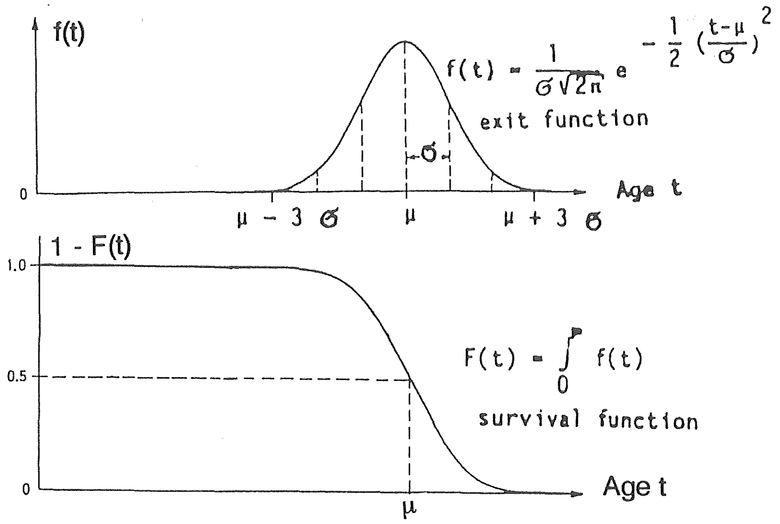

Fig. 40 Pipes grouped by age, pipe type and deterioration cause are believed to be normally distributed, with an standard deviation of 1/8 of their estimated, mean life-span, Hertz and Hochstrate (1988).

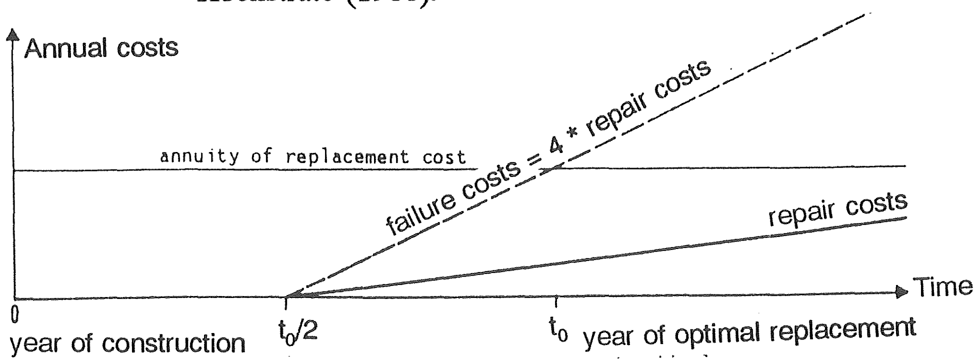

Fig. 41 Assuming that failures occur in the middle of the life of a pipe, Hertz and Hochstrate (1988).

Analysis of water main replacement policy, New York, from Male, Walski and Slutsky (1990) and Male and Slutsky (1990)

This is a simulation model for replacement and repair cost strategies based on pipe records and replacement length for five burroughs in the city of New York. The simulation model was used for bundles of pipes with equal characteristics with regard to diameter, installation year, and break rate. Five different replacement strategies were tested, from only repairing to replacing pipes after one, two, three or four breaks. The simulation model did not consider replacement made for poor carrying capacity or water leakage. The model did not consider the yearly extension in newly laid pipes, but used a constant system length.

The simulation model applied a Poisson distribution to groups of mains pipes according to expected breaks. The validity of the Poisson distribution was not proved by statistical tests. A comparison with actual data and data predicted by

Poisson distribution was made. The predicted break rate was multiplied by the total length of pipes in each group, see Table 13.

The least costly strategy was found to be "replace after first break" and was found to be the most aggressive one for smaller dimension of mains, e.g. only 6 inches. For larger mains, e.g. 8, 12 or 16-24 inches pipes, the least costly strategy was "do nothing", a passive strategy. The explanation for this are firstly, that a higher break rate was found for the 6 inches pipes and secondly, large costs are involved when larger mains are replaced.

The result of the simulation was that after a 50-year period of simulation, the differences in costs did not vary much between the least cost replacement strategy and the high cost strategy. Another result found was that the conditions of a system are a result of the strategy applied. This would indicate a higher break rate in systems using less aggressive strategies, Fig. 42. The first fluctuation in Fig. 42 is the result of today's replacement rule of changing all 6 inch pipes to 8 inch pipes because they are believed to have much better performance. This would indicate that the most aggressive strategy gives the lowest break rate but at some point the cost of replacing pipes in a practically sound pipe system would become excessive.

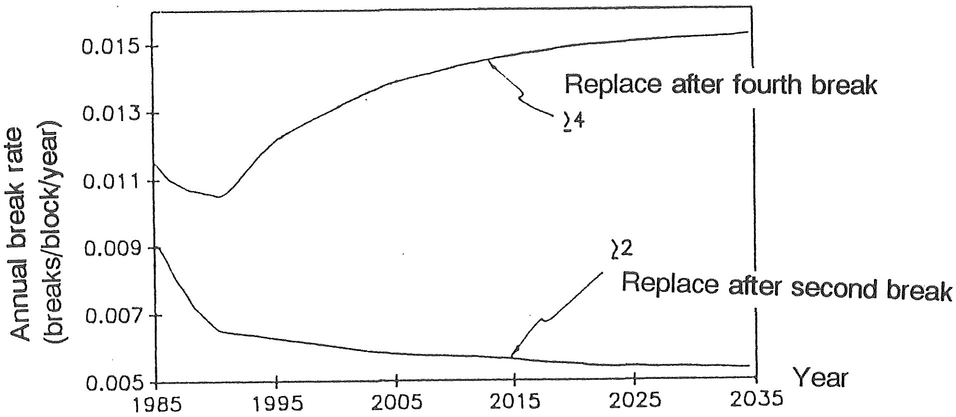

Fig. 42 Number of breaks per block and year in Brooklyn when simulation model for two different replacement strategies is applied, Male and Slutsky (1990).

Table 13 Actual and predicted failures per block of pipes having 0, 1, 2, 3 and 4 or more breaks in Staten Island, N.Y., U.S.A., Walski, Male and Slutsky (1990).

Number of breaks	8 inches		12 inches		16 - 24 inches	
	Actual	Simulated	Actual	Simulated	Actual	Simulated
0	5,611	5,534	2,054	2,050	826	816
1	213	337.7	83	90.9	17	32.7
2	39	10.3	6	2.0	2	0.7
3	8	0.2	0	0.03	3	0.009
>4	11	0.003	0	0.0003	1	0.0001

DISCUSSION OF INVESTIGATED METHODS

General

Municipal pipe breakage records are most common studied in pipe analysis. The pipe analyses studied appear to have a dual purpose, described by Andreou (1986) as:

a) development of better understanding of break causing mechanisms and key factors contributing to pipe failure

b) derivation of quantitative tools that will help us to make correct repair, replacement and rehabilitation decisions for deteriorating water mains.

The literature survey focused on how the various factors are used in pipe breakage records, how they are evaluated as causes of breaks and how their contributions to system performance are recorded. The study also aimed at determining which factors are simple to define, which are easily accessible and which are available for comparative systems pipe analyses.

The literature survey presented a large number of factors, described in the previous chapters. In Appendix II, Table II:c, the common views on break cause are summarized for eight of the most important factors. This chapter discusses and evaluates the same factors and gives recommendations for comparative analyses.

Factors and parameters investigated

Age and installation period

The survey concludes that it is not possible, today, to evaluate age dependency from pipe breakage records. A age dependency is commonly not found for pipe systems if the analyses are based on pipe breakage records. Pipe materials, laying practices and geographic location are more important to the occurrence of breaks than age, O'Day (1987). In many pipe systems, the pipes are eventually exchanged for other reasons than complete deterioration, or the investigated periods may be too short to enable description of the lifetime behavior of a pipe. Repair strategies might also mask all age dependency, i.e. few pipes are allowed to stay in the ground after more than, let us say, five repairs.

It is possible to derive a linear correlation for individual broken pipes of age and increase of breaks from pipe breakage records as shown by Goulter and Kettler (1985). However, this might be a result of a clustering effect of repair dependency, as suggested in Goulter and Kazemi (1988). They show that the repair events of pipes could have an impact on future breaks.

An increase in numbers of breaks for relatively new pipes, around 12 years of age, has been noted for grey iron pipes by Bubbis (1948), which might be similar to the early breaks found today for ductile iron pipes. This increase is reminiscent of the "bathtub" break function applied by Andreou, Marks and Clark (1987). They found that pipes which break at early ages are to perform better than pipes which breaks late in life.

The exact renewed length per year at specific locations, historical breaks, and time periods between breaks for individual pipes or group of pipes is essential information for age evaluation and should be included in pipe breakage records immediately. In the future, age dependence might be better evaluated than in the pipe breakage records of today.

Location and land use

This factor is presented inconsistently for all investigated breakage records. Geographic location is often mentioned, sometimes as land use, and is measured as, for example, age percent of industrial or residential area. This has diminished the possibility of analyzing contributions from this factor, but it is still an important factor, as it is used in models such as the Computerized Case Study of Ageing Urban Water Systems (O'Day, Fox and Huguet, 1980), the Spatial Evaluation of Water Distribution Systems (Clark, Stafford and Goodrich,1982) and the Predictive Model of Break Failure in Deteriorating Water Distribution Systems (Andreou, Marks and Clark,1987). These models seem to give good results in predicting of breaks and years to first repair. In the modelled municipalities, a small proportion of the pipes were responsible for a majority of the recorded breaks.

In analyzing the contribution of location, it is important to differentiate between one pipe with several subsequent repairs and several pipes in the same area with one repair. First break, good break type definitions and careful definitions of parameters of actual break site would make it easier to perform better analysis of the impact of location. Graphic mapping on computer screens would be a helpful device.

Pressure

Many pipe breakage records do not register internal pressure. Others use pressure zones but the exact pressure in the pipe when break develops is too difficult for many utilities to record. Pressure seems to be the most common factor in models, but it is not normally used in historical pipe records. Some models use the corrosion depth to estimate bursting pressure or internal pressure, other use working pressure. The external pressure loads on pipes is used only in some models.

Bursting pressure is theoretically correlated to corrosion depth, but in reality corrosion might not be the sole cause of pressure breaks in pipe systems. Water demand variations also give differences in breaks, Kowalewski (1976).

Others have noted design problems with air vents, where some pipes are liable to break more, Kottmann (1988). If the variations in internal pressure could be better determined to a specific main or mains, this might also indicate location as an important parameter.

Diameter

There seems to be total agreement in the literature that the highest number of breaks is found in pipes with small diameters. The largest number of breaks in large cities are found to be in pipes with diameters equal to or less than 8 inches (200 mm). It should be noted that these diameters are used principally in many populated areas.

Pipe diameter is commonly used in many models, and often found in pipe breakage records. The high frequency of breaks for the 6 inch (150 mm) pipes, believed by many to be attributable to less pipe strength, could have other explanations. The pipes are situated in city areas where there is continuous activity. The dynamic behavior of a city includes expansion of the infrastructure such as streets, subways, electricity systems, energy transmissions systems, etc. A city's behavior might have an influence on water pipe damage and performance of systems.

One conclusion of the survey is that the main cause of breakage of pipes with small diameters, instead of being their poorer strength, might be other events such as building activities and maintenance actions for repairing pipes.

Previous breaks

The factor previous breaks can only be derived manually from most pipe breakage records. This factor is described in models as subsequent breaks. In Andreou (1986), subsequent breaks are modelled by break rate, but found to have low regression values for many factors. Walski and Pellica (1981) find an important difference in the break rate depending on whether or not previous breaks have occurred. They used an exponential model based on the model of Shamir and Howard (1979). Another model, that of Clark, Goodrich and Stafford (1982), estimates the probability of a subsequent pipe break, given one break, and finds a high probability of subsequent breaks in a short time, less than five years. The model finds that the number of breaks increased exponentially after the first break.

Davies (1979) stated the time intervals between corrosion breaks to be exponentially distributed. He stated that the time to first break, if pipe is corroded because of wall thinning, is exponential. He found Poisson distribution useful for estimation of number of leaks. Goulter and Coals (1986) use the Poisson distribution in a model, as do Male and Slutsky (1990) in a simulation model.

The findings of Clark, Cheryl and Goodrich (1989) show the time intervals for subsequent breaks to be increasingly short. The reasons for this might not be age, as Goulter and Kazemi (1988) conclude that repeated breaks depend more on other factors than age. Sequential repeated breaks and the relationship of the factor of location was discussed by Goulter and Kazemi (1988) for repairing activity, by Wengström (1989) for corrosion, and by de Maré (1990) for pressure variations.

It will be important to investigate and characterize the distribution and break type of first break and time to second breaks.

Break types

Many pipe analyses show that the circumferential break is the most common type, Newport (1981), Clark, Cheryl and Goodrich (1989), O'Day (1987), Morris (1967). The circumferential break is prevalent in pipes with smaller diameters, less than or equal to 8 inches (200 mm), Clark, Cheryl and Goodrich (1989). The relationship between time and break type has also been investigated by Goulter and Kettler (1985). They show that the frequency of circular cracks (circumferential break) decreased with age. The study of Goulter and Kazemi (1988) investigated break types, but not from a corrosion point of view. Important tasks for future analysis are to investigate different break types and their dependence on corrosion, and to investigate the repair event impact of corrosion.

Main break types are commonly used in pipe records. It is not possible to carry out comparative analyses of other variables than the main break types, i.e. circumferential, longitudinal, hole and split bell until break cause and break type are strictly defined and interrelated. It is essential that the definition of break type includes corrosion, which could, in fact, be one of the main causes of all break types.

Soil

Soil parameters are common in models. Doleac, Bratton and Lackey (1980) model corrosion rates using soil resistivity, soil aeration/redox potential and pH. Kumar, Meronyk and Segan (1984) model corrosion rate using saturated soil resistivity, pH and sulfides. McMullen (1986) correlates actual break numbers to pH, redox potential and saturated resistivity. Clark, Stafford and Goodrich (1982), use pipe length in highly corrosive soil and percentage of land in low or moderately corrosive soil. O'Day et al (1987), adjusts the exterior corrosion to areas with know leakage, DC-current and a physical testing program.

One proposed conclusion is that the soil aggressivity encountered shows the normal environment and conditions for pipes and not the necessarily an extraordinarily corrosive environment. The environment could be called urbanized. Many pipes laid after 1960 are in places with substantial amounts of "filler material", such as old building materials and city dumps. It seems difficult to use the modelled corrosion rate from rural soil parameters to predict reliable break propagation.

An essential problem, if pipe breakage records are to be used for analysis, is that corrosion is not commonly recorded as a break type. The commonly recorded soil parameters for broken pipes are therefore found to be limited in use, as correlated to an eventual increase of breaks.

One practical aspect relating to the definition of break type is that it is impossible to judge the extent of corrosion on grey iron pipes ocularly at the repair site. The corrosion behavior of a grey iron pipe is that it develops almost invisible graphite layers, which make the pipes functional even when they are fairly corroded, Romanoff (1964) and Kottmann (1988).

The interaction of filler materials and the polluted rainwater from cities could possibly be corrosive, to a much higher extent than was previously thought, Lekander (1991). One way of better understanding corrosion on pipes might be to make corrosion studies which include precipitation, water transport around pipes, and the possibly rapid changes in water chemistry occurring in the ground water around underground structures.

Pipe materials

Traditionally, pipe breakage records consider the pipe material to be cast iron, and they only consider breaks on mains. Occasionally asbestos cement, concrete, steel, galvanized iron and ductile iron are also incorporated, often lumped together with the commonly used pipe material, grey iron. Break rates and pipe materials for different municipalities are compared in O'Day (1987), Pettersson (1978), Reinius (1981, Larsson, Reinius and Svensson (1990), Baekkegaard and Dyhm (1980). The latter review finds that the break rate is not a good variable for comparing different pipe materials. Another factor used is susceptibility, introduced by Kottmann and Hofmann (1990). This factor consists of weighted breaks in proportion of all breaks and pipe lengths. Susceptibility is compared with break rate vs system pipe length in Appendix I. It is concluded that neither break rate nor susceptibility is a good enough parameter for full evaluation of pipe materials.

Grey iron pipes are often used as a basis for the models, with the exception of the model of Clark, Stafford and Goodrich (1982) which also includes reinforced concrete. Only Walski and Pellica (1981) use a model where cast iron is differentiated, into cast iron and sand spun iron.

One of the most interesting problems for the future is to find good and secure pipes, and it is most important to include pipe components as well as pipe material in pipe analysis. Today, there is little possibility of judging and evaluating good pipe conditions from the breaks collected from pipe records.

Seasonality

A seasonal pattern with large numbers of breaks during the winter is common for many pipe systems. In a comparative analysis, O'Day (1987) found that approximately 40% of all breaks occur in three winter months. The parameter used to investigate seasonal patterns is most commonly calculation of breaks per month. Other parameters, such as cumulative frost degrees, Newport (1981), and average temperature are also used but mainly after the high break pattern during winter has been established.

An increase in breaks during summer months is also noted for certain municipalities by Newport (1981) and Andreou (1986). The reason for the higher number of breaks in any given period is not agreed upon. Andreou (1986) suggests the influence of high water demand, and the fact that the pipe system he studied consisted largely of large diameter pipes. Wengström (1989) and Trondheim (1988) find that the seasonal pattern for the ductile iron pipes might be different from the common grey iron pipes.

Seasonality are applied in descriptive methods to breaks per month, or per winter, respective summer, seasons. The factor is not found in any model. The analysis of seasonal breaks seems important for understanding the breakage in pipe systems. Internal pressure patterns for the municipalities might be very important, too. The parameter of breaks per months might therefore have to be defined differently to be really useful.

Descriptive methods

The review investigated six descriptive models. None of them was able to spot key factors for pipe breaks. The descriptive methods investigated did not differentiate between "first break" and subsequent breaks. Few of the descriptive models could analyze system performance, except for Newport's (1981) finding of seasonal breakage in winter time, and the occurrence of subsequent breaks (the combined effect of two pipe systems) found by Clark, Stafford and Goodrich (1982).

If descriptive methods were able to use "first break", have similar definitions for pipe length and stricter definitions of the break type the possibility of comparing the systems would be greater and the factors which contribute to pipe break would be possible to establish. One of the most important things to include in descriptive analyses is the history of renewed pipes.

Physical methods

Six physical models were investigated. Sampling and testing for corrosion are the basis of four of the models. Two of the models evaluate external loads and stresses.

Physical methods which correlate soil type or measured loads to the potential for breaking are commonly based on theoretical estimations, in order to relate corrosion or bursting to pipe breaks. In practice, the relation to recorded breaks is not verified. Physical methods have usually concentrated on broken mains or on places where soil corrosion was well known. This implies sampling programs where only small parts of the system are investigated. I believe it is not fruitful to evaluate the performance of a system on the basis of physical methods based only on these broken pipes until larger sections of pipes, broken and unbroken, have been sampled and tested. But, as long as soil corrosion is not fully investigated in urban areas and sampling on undisturbed pipes is too costly, the use of physical testing and sampling have to be continued.

Predictive methods

All the predictive models use the parameter of break rate, but they use it different. For example, break rate is used by Andreou (1986) with a hazard function, by O'Day, Fox and Huguet (1980) with a linear equation, and by Walski and Pellica (1981) with an exponential equation. Another predictive models used years to first break, Clark, Stafford and Goodrich (1982) with a linear equation, and numbers of breaks with an exponential equation. Another parameter, age, was predicted using a linear equation, by McMullen (1986), and with survival function, by Hertz and Hochstrate (1988). Pipe components and break types are not used in predictive models.

The purpose of predictive models was to help future maintenance decisions by finding causes of breakage and trends. However, it has been found that causes cannot be pointed out from predictive models. Andreou (1986) states that for variables such as age, installation period, soil corrosion, etc. no good relationships were found. One conclusion is that for all predictive models the use of many variables could mask any possible relationship. Andreou (1986) did find a relationship for the pipe length. He found that the break rate, called hazard rate, was approximately proportional to the square root of pipe length.

The predictive models have presented some trends for individual pipe behavior. One finding, by Andreou (1986), is that pipes seem to enter a fast-breaking stage after first break. The fast-breaking stage consists of many subsequent breaks as well as decreasing time between successive breaks. Another trend is noted in Clark, Stafford and Goodrich (1982) who propose a dependence such that pipes which fail early in life would developed fewer breaks when ageing.

They found that large percentages of industrial development gave a decrease in the time until first repair. For pipe systems behavior the predictive models have not presented any comparative trends. A proposed dependence of increasing breaks and location of industrial development is believed to be strong in a descriptive analysis by Wengström (1989). In the predictive model of O'Day, Fox and Huguet (1980) location was found to be the single, most important factor for predicting breaks. For comparative analyses it is difficult to find a parameter for location suitable for predictive models. The underlying causes of breaks are not known, and the factors analyzed could probably not be used for renewal actions for the future.

Simulation in networks

Two models for simulation in networks with reliability analysis were presented, Shamsi and Quimpo (1988) and Wagner et al (1988b). A theoretical presentation of reliability for networks, Goulter (1986) and Goulter and Coals (1986) was included as well. Two methods based on pipe breakage records for simulation of repair strategies were included, one by Hertz and Hochstrate (1988) and one by Male, Walski and Slutsky (1990). This latter model is most interesting as it presents a predicted system behavior for the next 30 years with respect to different repair strategies. It uses bundles of pipes, where breaks are Poisson distributed for estimation of break rate. The system length was set as a constant in the simulation, and renewed length was not considered to be renewed again during the simulation time of 30 years. This could of course have an impact on the evaluation of the simulated repair strategies.

The network design models include repair times for pipes and pipe components. These data are not found in pipe breakage records today. At present, network analyses which use historical breaks are few, and they are not yet adapted to larger municipal distribution systems. For hydraulic models of networks the small diameter pipes are not included. For the future, it will be most interesting to develop hydraulic network models further, and combine them with the breakage of pipes and components. A pipe system for a municipality consists of a large percentage of pipes with small diameters, and it is important to include them in the analysis. Using the smaller diameter pipes could give clearer indications of how the water demand is related to pressure variations. It would also be interesting if seasonal break behavior could be simulated with demand variations and internal pressure variations.

The work with simulation methods in network design will hopefully lead to effective definitions of reliability for pipe systems.

Recommendations

To find parameters suitable for comparative pipe analyses based on pipe breakage records, the following aspects have to be covered;

1. The factors should be measurable for all types of systems.
2. The factors should have a strong correlation to the recorded breaks.
3. The factors should be included in pipe breakage records.

Factors of interest for comparative pipe analyses are location, pressure, break type, number of first breaks and time to second break or breaks, see Table 14.

Some of these factors are available today in pipe breakage records, but need to be better defined and improved for comparative analysis. First break and time to second break are available but need better definition. Location has to be better characterized and defined, possibly to the exact break site. It does not seem possible to include pressure as a factor in pipe breakage records, but with the analysis of network system design, the interpretation of pressure variations might be understood.

Table 14. Evaluated factors of most importance for pipe behavior.

Factor	Remarks	Used in: pipe records	pipe models
Location	Important, but lacks a coherent definition. Commonly used as an estimation for several factors	No	Yes
Break type	Some studies indicate a possible dependency	Yes	No
Internal pressure	Theoretical bursting pressure used in models. Internal pressure as pressure zones is important	No	Yes
Previous breaks	Interesting results show dependency. Stated as important.	No	Yes

The use of break rates with variables such as diameter, age, etc. is limited, as the often assumed linearity of breaks and pipe length has not been sufficiently investigated. The dependence, investigated by Andreou (1986), with break rate as proportional to the root of pipe length, seems not to be valid for whole pipe systems, see Fig. 42. Possibly pipe systems could be presented as in Fig. 43, with the square root of system breaks.

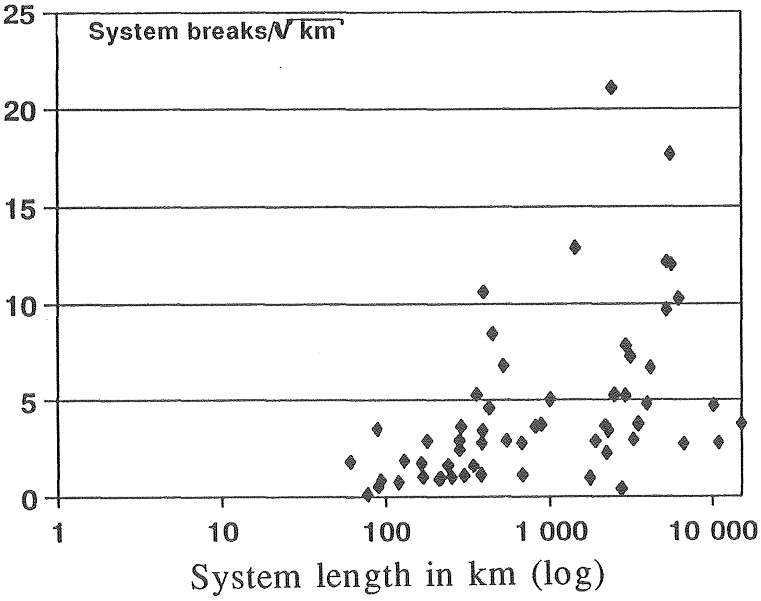

Fig. 42. System breaks per square root of system length, for about 60 cities and municipalities. Data from Appendix III.

The appearance of Fig. 43 and Fig III.4 (Appendix III) made it interesting to investigate whether data in some Swedish municipal pipe breakage records could be used to confirm Andreou's hypothesis, Wengström (1992). The finding was that break rate could be proportional to the square root of pipe length, but other proportional dependencies were likely as well. One reason for this could be that for individual pipe analyses the pipe breakage records in Swedish municipalities normally have too short pipe lengths to be suitable for analysis. Pipe length data for the investigated municipality were not segmented to block lengths, street lengths, etc. but to short segments of approximately 5 - 150 meters.

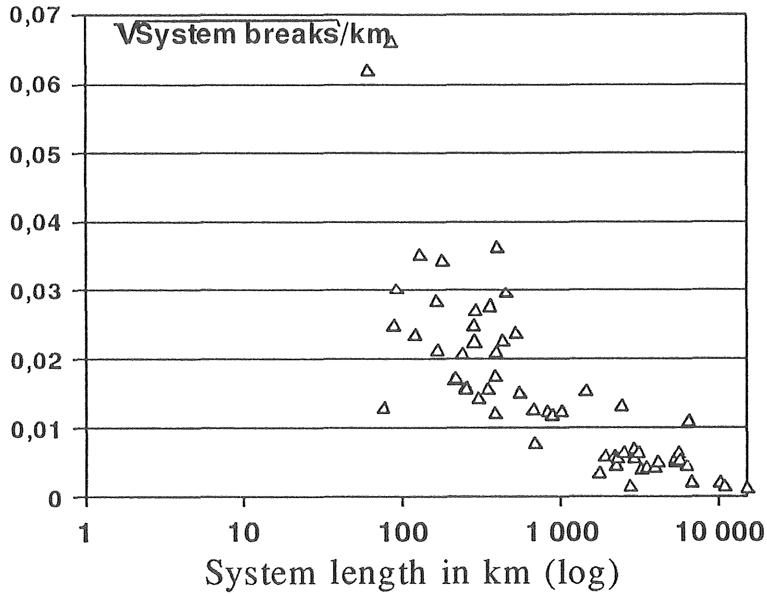

Fig. 43. Square root of system breaks per system length, for about 60 cities and municipalities. Data from Appendix III.

System trends can be presented cumulatively as in Fitzgerald (1968), de Rosa and Parkinson (1985), Jakobs and Hewes (1987) and Wengström (1989). The corrosion behavior of pipe systems was believed by Fitzgerald (1968) to be possible to analyze using the trend of cumulative breaks. The conclusion from this review is that, for grey iron pipes, the break cause, corrosion or non-corrosion, is not well enough recorded in any pipe breakage records. For separating and detecting the impact of corrosion, the use of cumulative trends is promising and important to develop for the trend evaluations of pipe systems. Comparative methods for pipe system evaluation could, essentially, be said to be lacking. Comparative analyses between municipalities might possibly use only the first breaks in the weighted length graphs. To use these graphs, each pipe length has to be known, as well as the age. The repair events and maintenance policies might possibly give renewal lengths too dominant an influence on these graphs.

Trend analyses with accumulated breaks for whole city systems, exemplified in Fig 44, seem useful, especially with respect to fiscal years. Trends have to be presented, differentiating between first and subsequent breaks, repair and renewal policies do not influence the presented trends of first breaks.

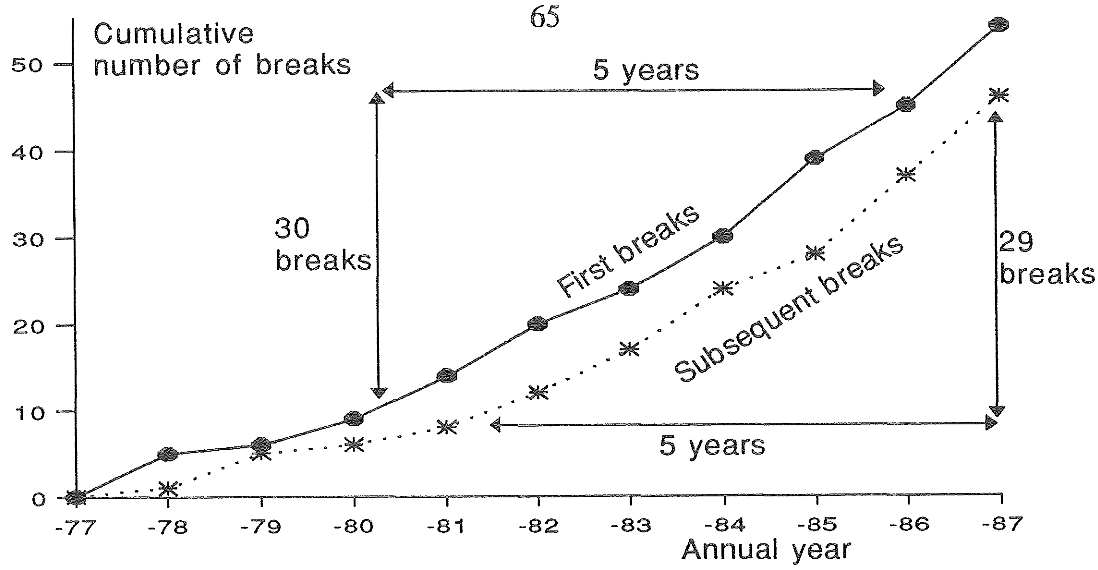

Fig. 44 Trend comparison of repairs with first breaks and repairs with subsequent breaks, ductile iron pipes in Göteborg, after Wengström (1989).

Fig. 45 shows the first breaks for a system and the data split into two curves, where the importance of the "bad" pipes with more or less expected breaks can be seen, as well as the individual, unexpected breaks. Acceptable levels should be developed for each pipe material with known laid length and replacement strategy. By differentiating between pipes with single breaks and pipes with subsequent breaks, these curves could give some maintenance information for the system. In the diagram, the fiscal year is considered but not the age of pipes. The age dependence of water pipe systems might be negligible because of renewal practices, i.e. renewal policies certainly have, an impact on the occurrence of breaks after a couple of repeated breaks. Especially in these municipal pipe systems where a minority of the pipes have the majority of the breaks. A break rate defined by only the first break could be a useful tool for comparative analyses.

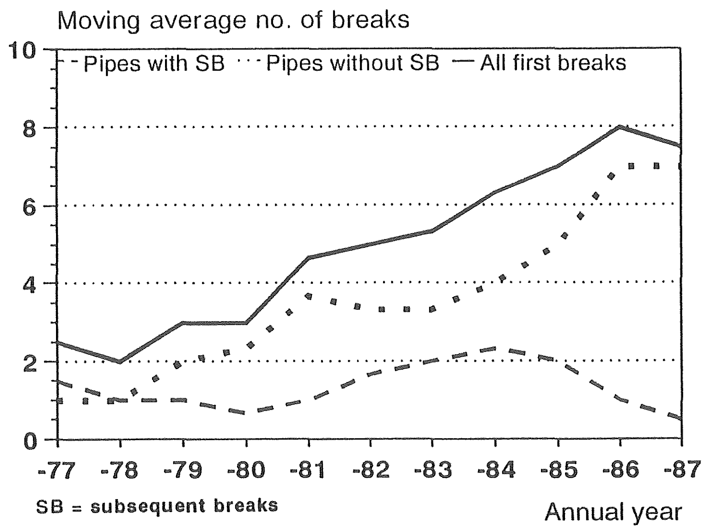

Fig. 45 Analysis of ductile iron pipes, showing a constant occurrence of pipes which had subsequent breaks, lowest line, and an increasing occurrence of pipes which had only one, single break, middle line, after Wengström (1989).

To achieve an understanding of the causes of breaks for the factors of location and internal pressure, it is suggested that representative parts of the pipe system be analyzed. Table 15 show that there are individual pipes which mainly have breaks. For these individual pipe analyses, the first break over fiscal years could be useful, as illustrated in Fig. 44 for ductile iron pipes. The pipe analyses should include individual pipes, pipe components of different types and investigations for description of break patterns. The time to subsequent, second, break is found to be important as a variable. It is also important to investigate the role of filler material and the chemistry of percolated precipitation in evaluating the possibility of corrosion. Pipe breakage records have to be improved to make good reliability studies. One common parameter for failure descriptions in reliability analyses is time to failure, or time between failures. It is therefore recommended as important to include the pipe history and the renewed pipe lengths in pipe analyses. Better definitions of break type with regard to corrosion, first break and subsequent breaks should also be identified and included in pipe breakage records. Pipe breakage records are great information bases with regard to break appearance, as well as time to subsequent breaks, and if we are ever to understand the behavior of a pipe, the actual fault information for single pipes will have to be evaluated.

Table 15 Data from a 16-year break record in a distribution system of 1061 km, after Evins and Dolphin (1990).

Break rate	Number of links*	Proportion of links	Proportion by length	Proportion of breaks
Free from breaks for 16 years	5701	90%	77%	0%
1 break in 16 years (=0.06 breaks/year)	445	7%	12%	40%
2-3 breaks in 16 years (=0.12-0.19 breaks/year)	164	3%	7%	34%
4-7 breaks in 16 years (=0.25-0.44 breaks/year)	44	1%	3%	19%
8 or more breaks in 16 years (>_0.5 breaks/year)	7	0%	1%	7%

* A link was essentially a length between pipe junctions and would usually be the length isolated when repairing a break.

For further comparative studies it is important to define break rate for municipal pipe systems similarly, and in terms of deterioration aspects. To define deterioration in pipe systems, a suitable parameter has to consider both renewal actions and the specific break patterns for the systems. Table 15 illustrates a break pattern for a pipe system. To serve as a basis, a parameter useful for comparative pipe analyses, acceptable levels for deterioration have to consider the proportions of length and/or the proportion of breaks in pipe system.

SUMMARY AND CONCLUSIONS

General

Decisions about the maintenance and replacement of large municipal pipe systems are traditionally based on pipe breakage records. With the help of modern computer systems, extensive data bases are being created which include repair events and specific pipe data to assist in decision-making about renewal and repair strategies. These records also contain parameters which are supposed to be combinations of the actual causes of breakage.

There are also reliability assessment models for evaluating the possibility of upcoming pipe breakage, and the costs involved in repairing pipes. But the causes of pipe failures are only vaguely known. Today it is unclear what information is essential to collect for understanding pipe breakage and system behavior. A literature search was therefore carried out to review how pipe breakage records have been used to identify parameters of interest with regard to pipe breakage.

Objectives of the study

The purpose of this study was to investigate the use of pipe breakage records as tools for analysis of pipe breakage and reliability of pipe systems. One aim of the study was to evaluate the methods used to find suitable parameters for comparative pipe analyses and for assessment of water system conditions.

The study was carried out as a literature review focused on common pipe break-causing factors. The objective was to describe and discuss:

- factors normally used for the registration of pipe breaks and how these are related to the cause of the pipe breaks,

- factors which have a strong correlation with the cause of pipe breaks,

- factors which are simple to define and easily accessible at the failure site, and their availability for comparative pipe analysis.

Only breaks in mains were considered. Breaks are commonly defined as failure events which demand repair activities and occur at pipe mains. Other breakages of components such as pumps, hydrants, service lines, etc., and leak detection surveys have not been investigated here.

Review of investigated methods

There are two basic purposes of pipe analysis, Andreou (1986):

a) understanding the break causing mechanism and investigating the key factors contributing to pipe failure

b) derivation of quantitative tools which will help to make correct repair, replacement and rehabilitation decisions about deteriorating water mains.

Pipe analysis has traditionally been based on pipe breakage records, and inspections of broken mains. There are other methods, complimentary to the commonly based analyses of pipe breakage records. Two useful ones are sampling analysis with pipe wall samples and monitoring analysis with the help of devices attached to the pipe surface. The pipe wall sampling provides a good indication of the actual corrosion depths, but is usually considered too costly to use on undamaged pipes. The long-term behavior of corrosion is therefore correlated to iron test samples from long-term exposure in different soils. Monitoring analysis with devices attached to the pipes which are buried under the streets is very costly. Usually, only samples of pipes can be investigated in this way.

The pipe breakage records which cover information from almost all broken pipes for approximately 25 years are supplementary to these methods. Occasionally, pipe breakage records also have information on renewal actions, from about the beginning of this century.

Literature surveys have previously been made, for example by Andreou (1986), O'Day et al (1987) and Karaa and Marks (1990). The reviewed methods for pipe analysis were commonly divided into categories such as descriptive analysis, physical analysis and predictive analysis. In this study 20 methods are summarized, including a few simulation models for network analysis.

Survey of used pipe breakage records

The aim of the literature study was to describe factors and parameters used in pipe breakage records and discuss whether they could be used for judging pipe condition. Investigated factors were age, corrosion, diameter, break type (circumferential, split bell, hole and longitudinal), pipe material, seasonal variation, soil environment, previous break, pressure, land use and pipe length. Several other factors are used in pipe breakage records but they are recognized as being impossible to use in comparative pipe analysis, partly because typical data bases do not include them. Factors which not are considered are, for example, abandoned pipe service lines, construction activities, ground water table elevation, landsliding, soil movement, pavement conditions, road salting, service pipe leakage, stray direct currents and traffic. Combinations of investigated factors are discussed briefly, as there often are several reasons for a particular burst, Newport (1981) and Karaa and Marks (1990).

The most frequently used parameter in the pipe analyses is found to be break rate. Break rate is expressed as number of breaks per system length, per length of bundles and per length of each main. Other ways of expressing break rate are breaks per length in age period (weighted length), per block or per district area. Another parameter for investigating pipe breakage records was time, commonly used but differently defined in the models. Annual growth rate was also used as a parameter in pipe analyses, O'Day (1987). Another parameter is the effective annual increase, which is a moving average of a calculated break rate for systems, expressed as percent of a break rate at a certain start event, Walski, Male and Slutsky (1990).

The importance of break - causing factors for the pipe breakage has been evaluated in pipe analyses, using these different parameters. The next seven sections summarize, for each factor, the findings of several pipe analyses.

Age

A common opinion is that age is not a dominant factor for pipe breakage, O'Day (1982), Goulter and Kazemi (1988). Installation period and age are compared by Walski and Wade (1987). They conclude that age is a more significant factor than installation period for system deterioration. This is in contradiction to O'Day (1987) Andreou, Marks and Clark (1987) and Newport (1981), who find that certain installation periods behaved worse than previous periods. Goulter and Kettler (1985) investigated number of pipe breaks per winter seasons after installation from the 16th to the 23rd winter season. They found a linear correlation between age for broken pipes and increasing breaks over the observed time of seven years. Andreou, Marks and Clark (1987) suggest that age at the second break is important, as pipes with breaks at early ages perform better than pipes which break later in life.

Pipe material, laying practices and geographic location are thought to be more important to the occurrence of breaks than age. These factors are not consistently registered in pipe breakage records, and seldom used in models. For long observation periods it is likely that break information in pipe breakage records is removed when new pipes replace old ones.

Corrosion

Corrosion is not separated as a specific break type in pipe breakage records. External corrosion assessments are usually judged from physical sampling evaluation of pit depth and approximations of soil aggressivity. It seems to be difficult to judge the extent of internal corrosion and external corrosion on grey iron pipes at the repair site. The combination of both internal and external corrosion, which gives a thinner pipe wall, might come to be registered as any of the main break types, as pipe breakage records do not include corrosion as a break type. The parameters for investigating a corrosion break from grey iron pipe breakage records are, therefore, not sufficient for pipe analyses. The methods for distinguishing a corrosion break from a non-corrosion break need to be improved.

Diameter

Diameter seems the easiest factor to analyze in the pipe breakage records. Goulter and Kazemi (1985), Kowalewski (1976), van der Hoven (1988), Walski and Wade (1987), O'Day, Fox and Huguet (1980) and Ciottoni (1983) all use break rate expressed as breaks per length per diameter. Their results show decreasing break rates with increasing pipe diameters for pipes with diameters of 6, 8, 10, 12 and 16 inches (100, 150, 200, 250 and 300 mm). One prevalent point of view is that 6 inch pipes are less strong than other diameters. Another reason for many pipe breaks for the smaller diameters might be the influence of long pipe lengths. In Ciottoni (1983) it can be seen that the total pipe length in these groups increase with decreasing diameters. Morris (1967) mentions that for pipes of less than 6 inches, breaks are common. Analyses should consider that pipe systems often have many links of pipes with smaller diameters.

Break type

The most common break type for the grey iron pipe systems is circumferential breaks (approximately 70%), Morris (1967), O'Day (1987), Clark and Goodrich (1989). For larger diameters, equal to 12 inches (300 mm), Clark and Goodrich (1989) find longitudinal breaks and holes to be more common. Time dependence was investigated by Goulter and Kettler (1985) for different break types, with break rate as the parameter. The break rate for joint failures was found to increase with time after installation, while break rate for circular cracks decreased. The break rate for hole breaks remained constant. Wengström (1989) discusses subsequent breaks for ductile iron pipes and finds a higher percentage of corrosion breaks among subsequent breaks than among first breaks.

Pipe materials

Little attention is paid to pipe materials in pipe analyses and models. Two of the models differentiate between pipe materials. Walski and Pellica (1981) use spun cast iron and pit cast iron. Clark, Goodrich and Stafford (1982) categorize pipes as metallic and reinforced concrete.

Comparative pipe analyses using break rate were carried out for several other pipe materials, O'Day (1987), Baekkegaard and Dyhm (1980), Pettersson (1978), Reinius (1981) and Larsson, Reinius and Svensson (1990). A decreasing break rate over 13 years was found for cast iron, asbestos-cement and steel, O'Day et al (1987). In Pettersson (1978), Reinius (1981) and Larsson, Reinius and Svensson (1990) only PVC showed a consistent decrease. Ductile iron showed an increase in breaks. A parameter called susceptibility was used in Kottmann and Hofmann (1990) to analyze pipe material. Steel was found to have a high susceptibility to breakage, which is similar to the findings from an evaluation made on data from Baekkegaard and Dyhm (1980), Pettersson (1978), Reinius (1981) and Larsson, Reinius and Svensson (1990). Susceptibility does not differ much from the commonly used break rate. It is essential to evaluate the material behavior as long as material quality of pipes and components is being debated for improvements to prolong the life of the pipes.

Seasonality

A seasonal pattern with high numbers of breaks during the winter is common for many pipe systems. Approximately 40% of all breaks occur in three winter months, O'Day (1987). An increase in breaks during summer months is also noted for certain cities, Newport (1981) and Andreou (1986). One of Andreou's conclusions (1986) is that pipe systems with larger diameter pipes develop a seasonal pattern with many breaks, caused by the higher water demand during the summer. Newport (1981) finds dry years and soil cracking to be the cause of increased summer break rates. There seem to be several reasons for the high break rates in winter. Newport (1981) correlates cumulative frost degrees with cumulative breaks per winter season. Irle (1984) relates high monthly breaks to precipitation and ground water levels. Kottmann (1988) relates winter breaks patterns with dry summers, dry falls and a cold winter. The investigations for seasonal patterns show that not only break rate given as breaks per months but other parameters can be used as well. The break behaviors noted by Kottmann (1988) and Andreou (1986) would be of interest to investigate further in other pipe systems. In the future, ductile iron will be more common. The seasonal break pattern for ductile pipes seems to be the opposite of the pattern common for grey iron pipe systems, Wengström (1989) and Trondheim (1988). Similar patterns might also be seen for the corrosion breaks in ductile pipes presented by Gilmour (1984). To understand seasonal break patterns, more information is needed than usually is registered in pipe breakage records.

Soil environment

The soil environment of pipes is commonly evaluated only for corrosion aggressivity at broken pipes. Our knowledge of the environment for all pipes in a system is therefore restricted to deductions based on a few soil samples. Number of breaks in a pipe system related to the actual soil resistivity is shown by Sasse (1986), and for saturated resistivity by McMullen (1986). Break rate distribution in different, rural soil types is investigated by Newport (1981). Many pipe models use several soil aggressivity parameters, but the correlation with the modelled parameter is often poor, Doleac, Bratton and Segan (1980), McMullen (1986), Clark, Goodrich and Stafford (1982)and Goodrich, Adams and Clark (1985). One conclusion from this literature survey is that the soil environment encountered shows normal conditions for pipes, and not necessarily an extraordinarily corrosive environment. To understand the environmental impact on the occurrence of breaks more corrosion investigations of the break types are needed. Interactions of fill material, common in urban areas, and polluted rain water are found to have a larger impact on the corrosion than has previously been thought by Lekander (1991).

Previous breaks

Previous breaks seem to be one of the most interesting and significant factors. Walski and Pellica (1981) were probably among the first to use previous breaks in their model. In the model of Clark, Stafford and Goodrich (1982) subsequent maintenance events are studied, and it is shown that small proportion of the pipes are responsible for a large proportion of the breaks. Andreou (1986) also investigated the probabilities of subsequent breaks. The break rate was found to be constant after the third subsequent break. The time from installation to the first break had a low correlation factor with the break rate. Andreou, Marks and Clark (1987) propose a dependence, such that pipes which are broken early in life have fewer subsequent breaks, while a theory to the contrary is presented by Clark, Cheryl and Goodrich (1989), where the time to each subsequent break becomes increasingly short, and thus the sooner a break occurs the higher the number of total estimated breaks. Goulter and Kazemi (1988) investigated both the time and the distance between breaks. They found that about 60% of all subsequent breaks occurred within three months of the previous break. De Maré (1990) reports from investigations in Malmö that many subsequent breaks occurred the same day or the day after a leak. Subsequent breaks were believed to be induced by pressure variation in the shutting vents. Goulter and Kazemi (1988) point out the possibility that the repair methods might create a corrosive environment for the pipes, where pipes would break more easily. They also investigated break types and found that longitudinal splits and hole failures had a more clustering effect in location than the circular crack break type. Wengström (1989) investigated ductile pipes only, and found especially the corrosion breaks to be concentrated to and repeated in certain locations.

Recommendations for pipe analyses

Individual pipe breaks in a water distribution system might be a sign of a city's behavior, where renewal and building of underground structures such as electrical cables, telephone lines and sewage pipes, etc. are continually ongoing. This normal but complex environment for pipes is difficult to cover in pipe breakage records. Investigations show that only a small proportion of the pipes develop the large proportion of the breaks, Clark, Stafford and Goodrich (1982), Goulter and Kazemi (1988), Wengström (1989). Pipe analyses should concentrate on these bad pipes, because there is a constant need for better pipe materials, components which require less maintenance, improvements in pipe laying practices, etc. The pipe analyses should therefore include all components and not only the pipes. The pipe breakage records, which usually contain only the main leaks, are not sufficient; all components have to be incorporated. The proposed influx of repeated breaks after repair activity, indicated by Goulter and Kazemi (1988), might hold true for components as well as pipes. Each pipe material should be evaluated on its own, with components and joints included. Important fields for future study include:

- description of possible life patterns of broken pipes;
- investigations of pipe components and their life patterns and the impact on the behavior of the pipes;
- evaluation of the corrosion behavior related to fill materials and soil water chemistry;
- further research on the importance of internal pressure and water demand variations preceding pipe breakages.

For pipe analyses, models such as Davies (1979), Clark, Goodrich and Stafford (1982) and Andreou (1986) could be interesting. For the last two, the number of parameters might be restricted. Both these models show individual pipe behavior, and to illustrate it graphically. In the model of Davies (1979), different break distributions for corrosion are proposed. He took time to first corrosion leak to be exponentially distributed. For other break modes than corrosion of wall thinning, such as stress corrosion and corrosion fatigue, he found a Poisson distribution to be possible. A definition of a pipe has to be made, either generalized to the short pipe segments or else by defining the individual pipes for certain lengths and pipe material characteristics. Break rate as a parameter has to be more strictly defined to be appropriate for use in comparative analyses of individual pipes.

When studying individual pipes, the cause of break is important. Conclusions from the literature review are that the factors of importance are location/land use, internal pressure, previous breaks and corrosion/break type. There are various difficulties in finding the break cause from pipe breakage records, owing to:

- corrosion not being registered as a break type;
- breaks correlated to soil aggressivity are difficult to evaluate for grey iron pipes in service;
- the influence of fillings and backfillings, at the repair site, to the corrosion degradation is difficult to evaluate;
- pipes might, after some breaks, be relined with a PE-pipe or a cement lining, but remain recorded as the original pipe in the records;
- the repair of grey iron pipes with new segments of a different material, commonly ductile iron, is commonly recorded similarly to those pipes repaired with a repair-bandage;
- sometimes information of earlier breaks is removed from the records as the older main is renewed with a new pipe.

To overcome these repair changes in pipe characteristics and soil environment, the pipe analyses should differentiate breaks in previous and repeated breaks. Pipe breakage records do not distinguish between data such as first breaks and subsequent breaks. It is essential that future pipe breakage records include this information.

Recommendations for system analysis

The purpose of many methods was to identify trends and to describe a specific pipe system and its behavior for future maintenance with the help of pipe data. The methods investigated showed few possibilities to generalize about trends and differences in pipe systems. The literature survey notes that the majority of the breaks occur in pipes with smaller diameters, and that pipe systems normally consist mainly of these small diameter pipes.

The effects of the many breaks during winter seasons on system behavior have been modeled by many researchers, such as Walski and Pellica, (1981), Newport (1981), Walski and Wade (1987) and de Maré (1990) but the parameters used vary greatly. A trend graph for example, is presented in Newport (1981) with cumulative breaks per frost day. A summer trend was noted by Andreou (1986), with high numbers of breaks in large pipes and at times of high water demand. For some pipe systems this might be important to consider. Water demand and internal pressure variations might have to be further investigated.

The investigations of Wengström (1989) and Trondheim (1988) showed a decrease of breaks during winter periods in ductile iron pipe systems. This might indicate that corrosion breaks are likely to occur before or after the winter period. This may imply that it is the excessive loads during the winter which break the grey iron pipes, as they have less durability for loads when weakened by corrosion. Another finding is that the continuous replacement of grey iron pipes by ductile iron pipe material may lead to an important change in future system behavior.

Models were commonly unable to show any trends in system behavior, except for Andreou, Marks and Clark (1987), who define a fast-breaking stage, repeated subsequent failures, for the pipe system of New Haven. This fast-breaking stage was considered a sign of system deterioration. No other definitions of pipe system deterioration or reliability are found. Reliability definitions of pipe systems are considered to be lacking by Goulter (1986). It might also be important to evaluate water pipe systems as repairable systems. Ascher and Feingold (1984) point out that repairs in repairable systems are often treated very unrealistically in probability modeling. Deterioration of repairable components might not always lead to the conclusion that the whole system is deteriorating, as it consists of exchangeable parts. Effort have to be made to decide whether the maintenance actions undertaken when repairing pipes can be considered as renewal of the pipe system, or whether the maintenance events cause the system to deteriorate even faster.

The review concludes that break rate is the most often-used parameter, but might not be a good comparative parameter for different factors. Break rate seems especially insufficient for pipe material and soil aggressivity.

For comparative analysis of system behavior, the break rate expressed as weighted length was found to give interesting graphs. Further information on evaluation of these graphs is essential as they seem useful for comparative analyses. Break rate has been used in several age investigations, and is found not to be a sufficient parameter if the system analyses do not include renewal lengths throughout the pipe lifetime.

Showing pipe breakage trends in systems by using the number of breaks per fiscal year is a reliable simple method. The actual number of breaks ought to further relate to some sort of acceptance level of maintenance actions for making comparative analyses possible. The cumulative number of breaks per fiscal year is suggested for a basic trend evaluation and for comparison of pipe systems. The simulation analysis of Male and Slutsky (1990), with different repair strategies, is interesting and might be useful in comparing different behaviors of pipe systems.

If break rate is to be used comparatively, the dependence between breaks and pipe system length has to be evaluated. Andreou (1986) suggests that pipe breaks are proportional to the square root of the individual pipe length. Note that the literature survey finds this not to be the case for system pipe lengths, and that other relationships appear possible as well. Smaller systems with shorter installed pipe length are indicated as having wider and higher variations in number of breaks per length than larger systems.

Conclusions

To find parameters suitable for comparative pipe analyses based on pipe breakage records, the following aspects have to be included:

1. the factors should be measurable for all types of systems;
2. the factors should have a strong correlation to the recorded break;
3. the factors should be included in pipe breakage records.

The literature survey investigates several existing methods and models based on pipe breakage records. The three above-mentioned aspects were found not to be included in any of investigated models. Break patterns with the break rate were found to be difficult to generalize from, as many methods and parameters were found to be specific to a certain city pipe system.

Goulter and Kazemi (1987) have used pipe breakage records, and found important clustering relationships of location and time for pipe breaking. Several authors have emphasized the importance of location for determining break cause. Location may also include factors such as installation period, pressure, environment and land use, and is not defined identically by all authors. A suitable definition for location would have to take the corrosion aspects of increasing occurrence of subsequent breaks into account, as is proposed by Goulter and Kazemi (1987).

The common factor in pipe breakage records is break type, but it needs to be redefined, as the understanding of pipe performance in corrosion behavior is essential. It is important for break type that the descriptions of the repair event, excavation activities, unsuitable material combinations, corrosion, etc. be well-defined, and introduced in evaluations of pipe performance. As Lekander (1991) finds unexpectedly aggressive ground water in urban environments, corrosion studies have to be further extended to include urban soil types, and to investigate the ground water chemistry in urban areas.

For the factor previous breaks, it is essential to include the differentiation of first breaks and subsequent breaks in pipe breakage records. The models of Andreou (1986), Goulter and Kazemi (1988), Clark, Goodrich and Stafford (1982) gave interesting results by differentiate into first and subsequent breaks. Good models for comparative analyses with break rate were not found. Parameters other than break rate were also used in the models, and time especially is important to include in comparative analyses.

In reliability studies, time to first break and time between breaks are important parameters. Many pipe models investigated have included these parameters, often with several factors for investigation of break cause. The models have not evaluated the repair event, i.e. considered that the exchanged or repaired part might other be a copy as good as the original part or be better than the original part. The modelled correlations have usually been low, and the investigations showed pipe life behavior rather than finding the cause of breaks or factors important to breakage.

A first break approach to pipe breakage records might give the commonly used parameter, break rate, a strict definition and make it possible to use break rate as a comparative tool in pipe system analyses. Conclusions with regard to further investigations for finding suitable tools for comparative analyses are:

* the first break needs to be described with regard to corrosion;
* time to the second break can be found in pipe breakage records and be valuable for analyses;
* all breaks have to be defined to a specific pipe segment;
* pipe segments which have been repaired or exchanged with new parts should be evaluated;
* the individual pipe breaks should be thoroughly analyzed including all components;
* municipal pipe systems have to be described with respect to deterioration criteria

Municipal pipe breakage records are invaluable for the analysis of pipe system deterioration and of single pipe breaks. The pipe breakage records of today do not fulfill these needs. They cannot, however, be neglected as they are the only source of information we have. Pipe breakage records have been in use for several years in most municipalities and we are collecting and saving information for the future.

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APPENDIX I

Susceptibility and break rate

Investigation for comparing the use of susceptibility and break rate for different pipe materials of failure data after Bækkegaard and Dyhm (1980), presented in four tables for each pipe material and in six figures:

Fig. I.1	The break rate and susceptibility of steel versus system length in km
Fig. I.2	The break rate and susceptibility of asbestos cement versus system length in km
Fig. I.3	The break rate and susceptibility of PVC versus system length in km
Fig. I.4	The break rate and susceptibility of PEL and PEH versus system length in km
Fig. I.5	The break rate and susceptibility of galvanized iron versus system length in km
Fig. I.6	The break rate and susceptibility of grey iron versus system length in km
Table I.1	Data statistics of susceptibility for the pipe materials steel, asbestos cement and PVC
Table I.2	Data statistics of break rate for the pipe materials steel, asbestos cement and PVC
Table I.3	Data statistics of susceptibility for the pipe materials PEL and PEH, galvanic iron and grey iron
Table I.4	Data statistics of break rate for the pipe materials PEL and PEH, galvanized iron and grey iron

Excluded: susceptibility (1.44, 18.94) and susceptibility (7.13, 8.89)

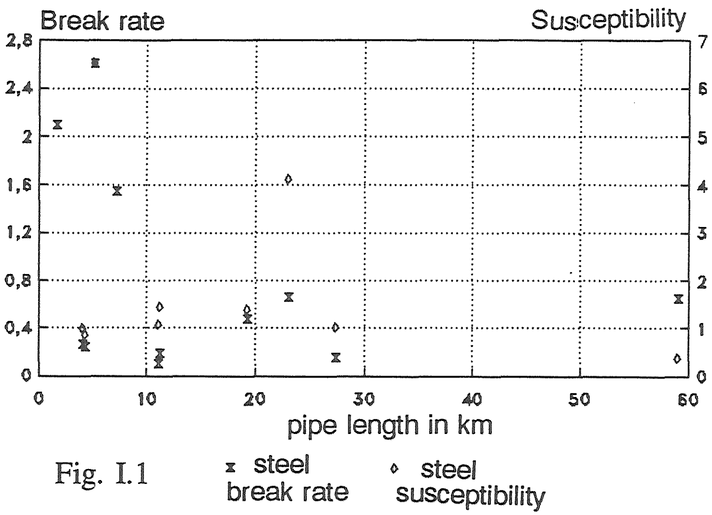


Fig. I.1

Table I.1

Susceptibility (%breaks/%km pipe length)

	Steel	Asbestos	PVC
maximal value	18.94	90.50	6.23
minimal value	0.36	0.23	0.27
median	1.43	0.95	0.90
average	4.14	10.36	1.34
st. deviation	5.62	28.20	1.44
no. obs.	11	10	17

Table I.2

Break rate (breaks/km pipe length)

	Steel	Asbestos	PVC
maximal value	2.60	1.29	1.58
minimal value	0.09	0.02	0.03
median	0.25	0.11	0.17
average	0.81	0.37	0.33
st. deviation	0.87	0.47	0.40
no. obs.	11	10	17

Excluded: susceptibility (53.1, 90.5)

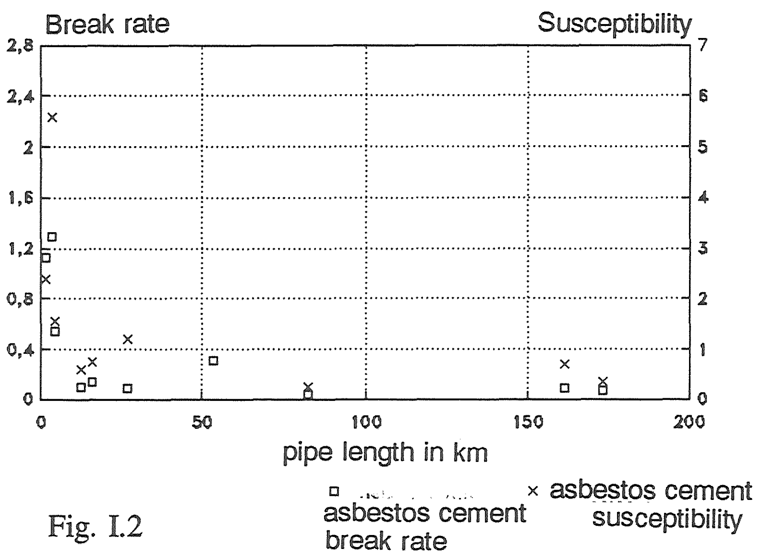


Fig. I.2

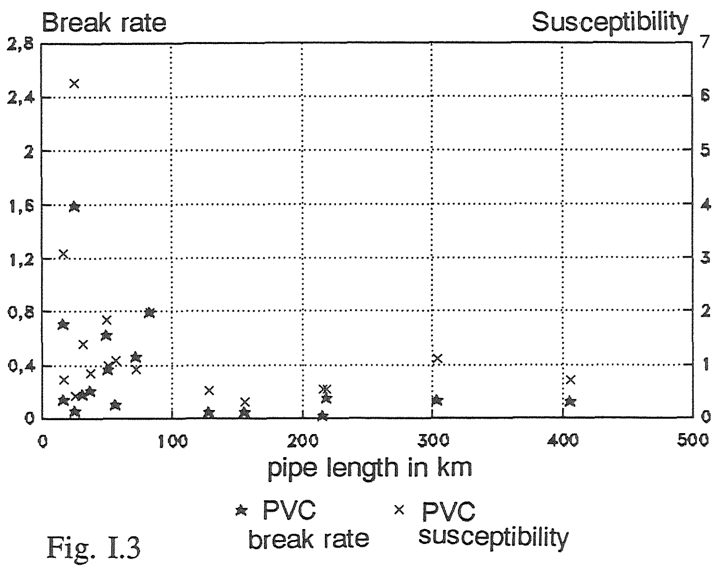


Fig. I.3

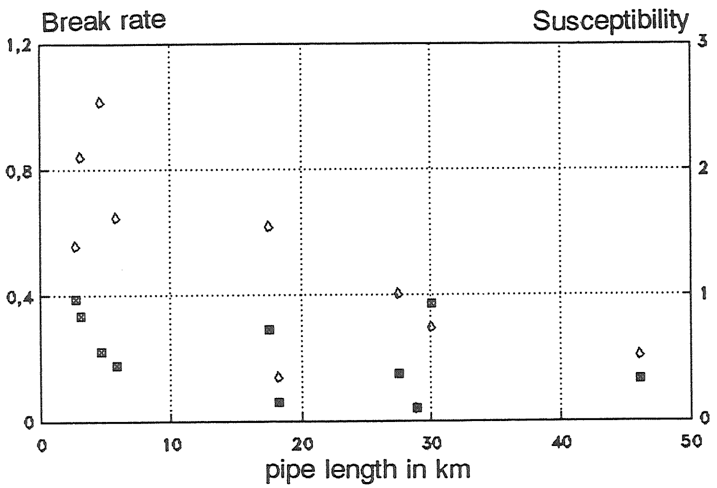


Fig. I.4

Table I.3

Susceptibility (%breaks/%km pipe length)

	PEL/PEH	Galv. iron	Grey iron
maximal value	2.53	2.80	1.60
minimal value	0.09	0.15	0.26
median	1.20	0.70	0.80
average	1.19	0.92	0.77
st. deviation	0.79	0.82	0.29
number	10	8	21

Table I.4

Break rate (breaks/km pipe length)

	PEL/PEH	Galv. iron	Grey iron
maximal value	0.38	0.50	0.62
minimal value	0.04	0.05	0.08
median	0.19	0.14	0.23
average	0.21	0.24	0.28
st. deviation	0.13	0.19	0.16
number	10	8	21

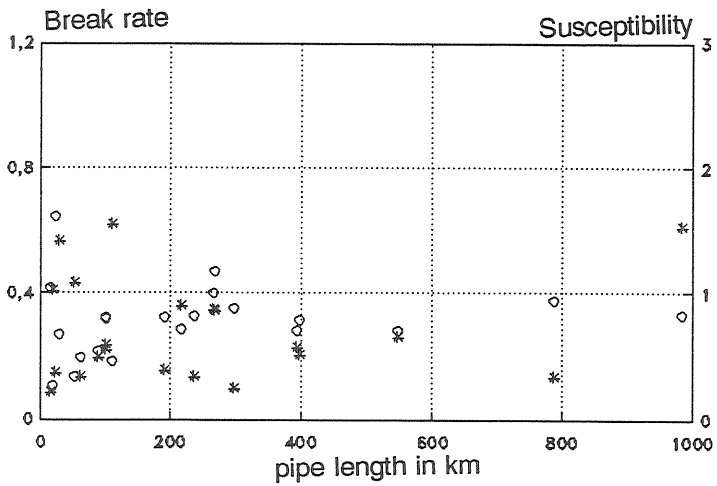


Fig. I.5

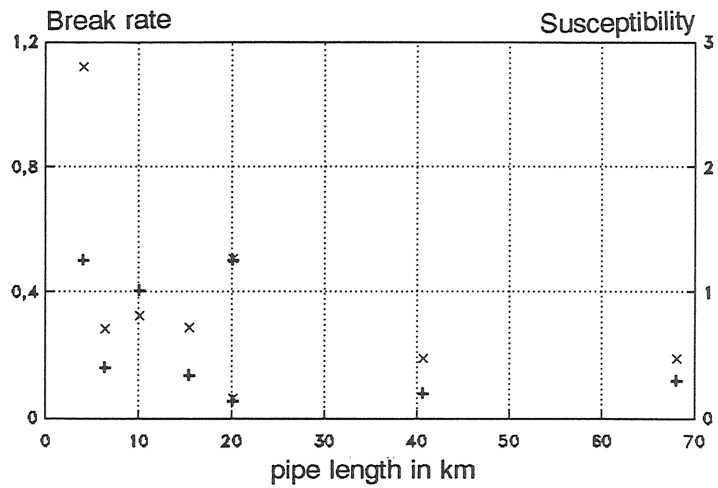


Fig. I.6

APPENDIX II

Common pipe information in breakage records

Causes, factors, parameters and data base commonly used in pipe breakage records, after Morris (1976), Walski and Pellica (1981), O'Day (1982), Goulter and Kettler (1985), O'Day (1987), Goulter and Kazemi (1989) and Karaa and Marks (1990).

Table II:a Some different causes of pipe failure.

Morris (1976)	**Walski and Pellica (1981)**	**O'Day (1982)**
Soil movement Corrosion Temperature differential Improper installation impact or combination	Geographic location Prior leakage	Excessive loads Temperature Corrosion or combination

Goulter and Kettler (1985)	**Karaa and Marks (1990)**
Depth of frost Soil properties Freeze-thaw characteristics Construction standard	*Corrosion:* Surrounding soil, stray currents, internal corrosion process *Physical forces:* Thermal contraction, internal pressure, external loads, beam loading

Fig II:b Typical data base for pipe breakage records

O'Day (1987)	**Goulter and Kazemi (1989)**
Report date Pipe characteristics Environmental data Leak/break damage data Leak/break repair data Excavation and paving data Other	Location of failure Date of failure Soil type during repair Material and diameter of the pipe Type of failure/type of joint repair

Table II:c Factors for pipe breaks and views of possible break causes.

Factor	Explanation
Break/ failure type	Excessive longitudinal stresses caused by thermal contraction, beam contraction and or longitudinal pressure effects or transverse stress, including hoop stresses from internal pressure and ring stresses from external loads, Karaa and Marks (1990)
Land use	Land development surrogate for external loadings due to traffic, structures, utility which creates structural stress at pipe involving: type of soil covering, bedding material, method of support conduit, width and depth of trench, backfilling method, rigidity of conduit, unevenness of street, Karaa and Marks (1990)
Pipe age/installation time period	Casting and design and construction practices and materials, Karaa and Marks (1990)
Pipe material/ diameter	Design and construction practices, Karaa and Marks (1990)
Pressure	Internal pressure such as water hammer, unbalanced dynamic pressure, or local pressure on corroded areas, Karaa and Marks (1990)
Previous break	Repair impact, Goulter and Kazemi (1988) Pipe material behavior, Walski and Pellica (1981) Time dependency, Clark, Cheryl and Goodrich (1989)
Soil type	Corrosion owing to the soil moisture, pH and chlorides and sulfides, Karaa and Marks (1990), and oxidation reduction potential, sulfides, resistivity and in special cases loads from expansive soils, Morris (1976)
Weather/temperature/ frost/seasonal variations	Environmental conditions such as construction activities, expansive soil, frost penetration, ground movement, traffic, Karaa and Marks (1990)

Table II:d Common factors in pipe breakage records used in comparative literature

Factor	Measured as
Age	Numbers of failures per km (mile) per year
Break types	Per cent of breaks
Diameter	Number of breaks per km (mile) per year or per cent of total failures
Installation period	Number of failures per period per km (mile)
Pipe material	Numbers of breaks per km (mile) per year
Seasonal variation	Per cent of total breaks in three winter months
Soil environment	Number of breaks or per cent of total breaks

Table II:e Factors not direct found in pipe records but used by models*

Factor	Measured as
Corrosion/non corrosion Corrosion related break types	Number of breaks cumulative per km (mile) per year or cumulated number of breaks in per cent of total breaks
Location or land use	Per cent residential or industrial area covering the pipe
Pressure	Pressure zones or evaluated from corrosion depth as bursting pressure
Previous break history	Time interval in years between number of sequentially failures, time in years or seasons to first failure
Soil corrosion	Resistivity or aeration/redox potential or as soil aggressivity by points estimated from several parameters as pH, soil type, etc.
Temperature	Frost degrees per day

* Factors used by network design analysis models are not included.

APPENDIX III

System breaks and system lengths

Failure data of pipe systems compared to the system pipe length. Presented in seven figures as:

Fig. III.1 Breaks versus system lengths for cities in the U.S.A, Denmark and Sweden. Data after O'Day (1982), O'Day (1987), Andreou (1986), Walski and Wade (1987), Bækkegaard and Dyhm (1980), Reinius (1981), Pettersson (1978), Larsson, Reinius and Svensson (1990)

Fig. III.2 Breaks versus system lengths for Danish municipalities, after Bækkegaard and Dyhm (1980)

Fig. III.3 Square root of breaks versus system lengths for cities in the U.S.A, Denmark and Sweden. Data after O'Day (1982), O'Day (1987), Andreou (1986), Walski and Wade (1987), Bækkegaard and Dyhm (1980), Reinius (1981), Pettersson (1978), Larsson, Reinius and Svensson (1990)

Fig. III.4 Square root of breaks versus system lengths for Danish and Swedish municipalities. Data after Bækkegaard and Dyhm (1980), Reinius (1981), Pettersson (1978), Larsson, Reinius and Svensson (1990)

Fig. III.5 Break rate presented as breaks per square root of system pipe lengths versus system lengths for cities in the U.S.A, Denmark and Sweden. Data after O'Day (1982), O'Day (1987), Andreou (1986), Walski and Wade (1987), Bækkegaard and Dyhm (1980), Reinius (1981), Pettersson (1978), Larsson, Reinius and Svensson (1990)

Fig. III.6 Break rate presented as square root of breaks per system lengths versus system lengths for cities in the U.S.A, Denmark and Sweden. Data after O'Day (1982), O'Day (1987), Andreou (1986), Walski and Wade (1987), Bækkegaard and Dyhm (1980), Reinius (1981), Pettersson (1978), Larsson, Reinius and Svensson (1990)

Fig. III.7 Break rate, breaks per km, versus system lengths. Data after O'Day (1982), O'Day (1987), Andreou (1986), Walski and Wade (1987), Bækkegaard and Dyhm (1980), Reinius (1981), Pettersson (1978), Larsson, Reinius and Svensson (1990)

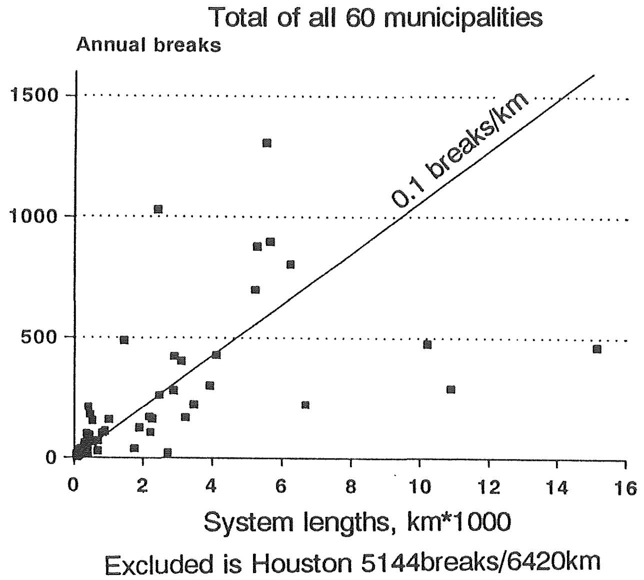


Fig. III.1

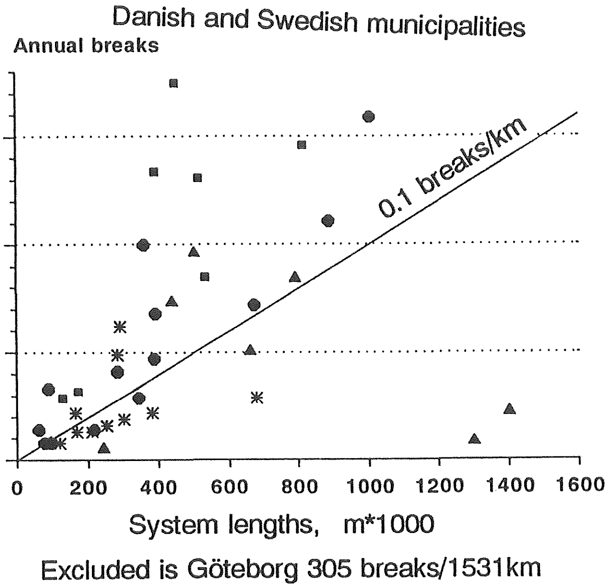


Fig. III.2

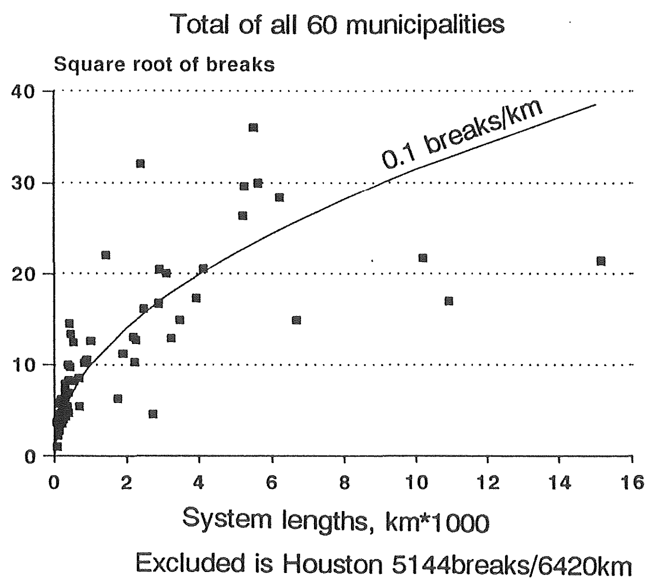


Fig. III.3

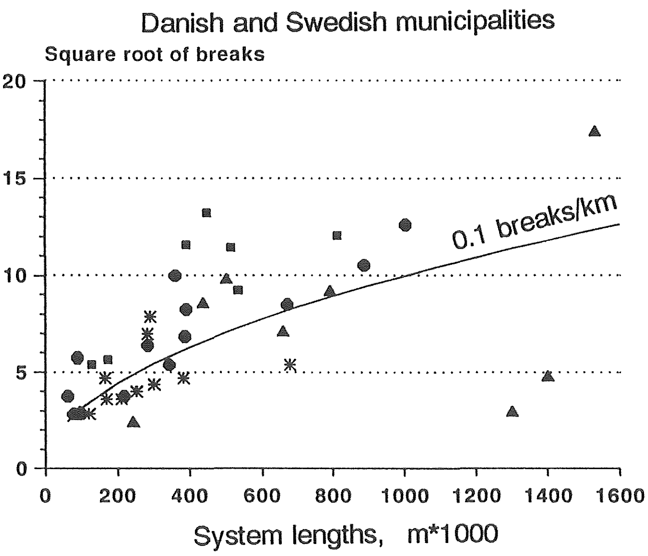
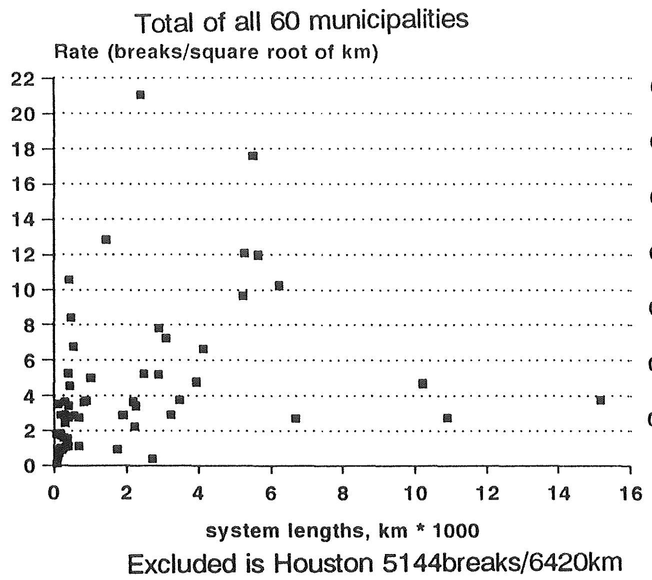


Fig. III.4



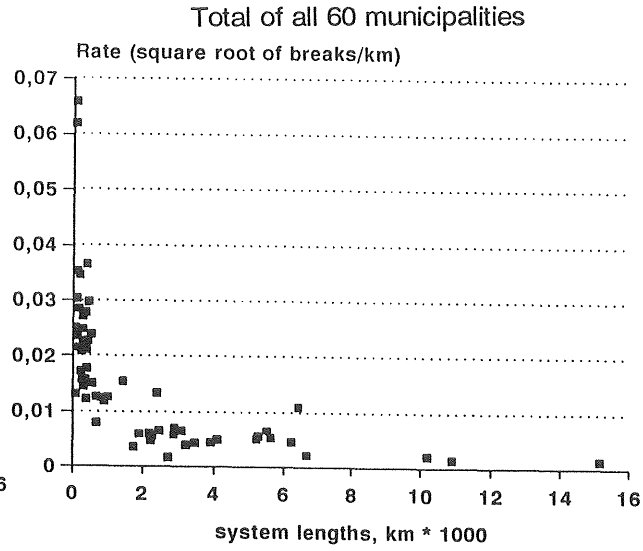


Fig. III.5

Fig. III.6

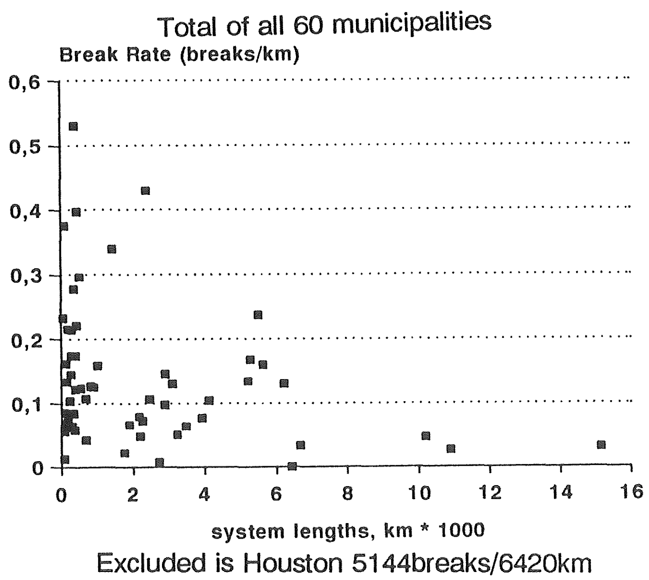


Fig. III.7

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Göteborg 1993