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Drinking Water Pipe Breakage Records

A Tool for Evaluating Pipe and System Reliability

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PREFACE

The licentiate thesis presented here is the result of a research project carried out at the Department of Sanitary Engineering, Chalmers University of Technology in Göteborg, Sweden. The project has been financed by the Swedish Council for Building Research (Project No. 900220-5) and is entitled "System Reliability in Water and Sewage Pipes". In the licentiate work the main focus has been on municipal drinking water pipes. The initial phase of the project focused 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). Further work concentrated on a study "Modelling Water Pipe Break Rates in Six Swedish Municipalites" and a literature survey "Comparative Analysis of Pipe Break Rates - a literature review". Dr. Gilbert Svensson, my supervisor, initiated the research project and has been a constant source of support and guidance.

I would like to thank Prof. Torsten Hedberg, head of the department, and Dr. Greg Morrison for their inspiration and encouragement in the process of writing. I am very grateful to them, and to Inger Hessel for her help with typing and lay-out. Special thanks go to Bo Segerberg, Department of Sanitary Engineering and Olle Häggström, Department of Mathematics, for their assistance and help in statistical discussions.

Göteborg in September 1993

Teresia Reuterswärd Wengström

ABSTRACT

The objective of this licentiate thesis is to describe and analyze the water pipe system in terms of reliability. The purpose is to establish methods and tools suitable for reliability analysis of a repairable system based on available and common pipe data.

A literature study reveals that few of the common parameters used are suitable for analysis. It is also likely that pipe analysis has to be rather complex to be useful for reliable pipe analysis.

To assess pipe performance and maintenance control it is suggested that the time between breaks, the break type and location are necessary parameters. Evaluation of water pipe systems for preventative maintenance are found to be manageable when considering individual pipes. It is necessary to aggregate breaks for evaluating individual pipe performance. For predicting future breaks a regression analysis as a proportional hazard model was found to be best.

The water pipe system is a continuously repairable system. Evaluation of system performance is illustrated through a quality variable in an additive hazard model. The main feature of the model is that it captures the influence of the continuous pipe repairs and the time between repairs for pipes with subsequent breaks.

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GLOSSARY

AHM:	Additive Hazard Model is a regression model where, compared to the PHM, the covariates act in an additive way on the hazard function
block:	segments of mains, defined in Slutsky (1988) as a length of 440 ft. To convert to SI (m) multiply by 0.3048
break:	a recorded fault in pipe breakage records, which leads to maintenance action after a short time. Note that breaks are defined differently in the literature, which explains why the term is used ambiguously in this study.
burst:	used as a name for breaks which have similar appearance.
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 or repair to occur.
component:	any connecting equipment or 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 .
mils:	corrosion length unit, multiply by 25.4/1000 to convert to SI (mm).
parameter:	a countable or physically measurable variable used for evaluation of the break performance of pipes.
PHM:	Cox's Proportional Hazard Model, a regression model where the explanatory variables or covariates are assumed to act in a multiplicative way on a baseline hazard function so that for different values of the covariates the hazard functions are proportional to each other over time.

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

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:	pipe mains defined by any chosen length or pipe defined by one segment with break, and the adjacent segments if breaks have occurred.
pipe analysis:	investigation of the performance of pipes.
pipe diameters	pipe diameters for drinking water pipes are usually of following size:

Pipe diameters in mm	Pipe diameters in inches
1200	48
1050	42
1000	40
900	36
750	30
600	24
500	20
400	16
300	12
250	10
200	8
150	6
100	4
80	3
50	2

pipe records:	the collective information from pipe breakage, repair and replacement actions. Contains data such as break date, pipe material etc.
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.
S_U:	upper acceptance level in an $\bar{x}$-chart, see Appendix B.
$\bar{x}$-chart:	diagram with sample means, see Appendix B.

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1. INTRODUCTION

Drinking water distribution systems in Sweden were usually constructed parallel to the growth of modern urban cities some 100-150 years ago. The public demand for supplied water is today served from about 300 utilities and includes a total pipe length of 60,000 km with a value of more than 100 billion SEK (Svenska vatten- och avloppsverks-föreningen, 1992).

In their current condition pipes have a low frequency of failure, typically 0.1 failure per km of pipe length. The level of service is such that the few disruptions creating a disproprtional level of inconvenience to the users. Reliability criteria for allowable recurrence intervals between interruptions of delivery for consumers have recently been discussed as beeing an average of one failure event per 10 years. Most municipalities maintain a high service level through immediate repair actions after a failure event. This calls for planned maintenance and renewal work, however the basis for preventative maintenance actions relies only upon information on the distribution pipe system collected in pipe records. Common practice is to collect information of repairs and to show distribution pipe repair history through descriptive statistics. The main drawback is that the possibilities of planning maintenance and renewal actions are small. A more dynamic way of describing the distribution pipe performance has to be developed.

At present, 250 million SEK is spent on repairs of the distribution system, which in 1991 reached 40% of the total cost for maintenance and operation, estimated at 673 million SEK (Svenska vatten- och avloppsverksföreningen, 1992). Common renewal practice is adequate but preventative maintenance tools to evaluate and analyze pipe breakage are not sufficient, for above all economic reasons.

Pipe analysis of pipe systems is traditionally based on pipe breakage and repair events. Repair events and specific pipe characteristics are commonly recorded in pipe breakage records. These records also contain a large number of parameters thought to be combinations of the actual causes of breakage. Karaa and Marks (1990) and O'Day et al (1987) have specified various parameters which affect the breakage, such as differences in pipe material used, geological and soil conditions, severity of winters and site-specific causes. Commonly, these parameters are not uniformly included in pipe records.

For comparable analysis, information used in pipe records has to be reevaluated and redefined to determine which information is of a high enough quality and of sufficient interest for storage in computer bases.

2. OBJECTIVES OF THE STUDY

This thesis aims to describe which parameters are of importance for breakage and which parameters have to be used to allow comparative pipe analyses. The aim is to find tools which adequately describe individual pipe break frequency and evaluate pipe system breakage behavior in a continuously repairable system.

The objective was to perform a literature study in order to evaluate factors and develop methods for evaluating factors in data bases and indicating suitable parameters for data management and for comparable pipe analysis.

3. METHODS OF PIPE ANALYSIS

The basis for the investigations was the literature concerning main breaks in water pipes. Breaks are defined differently in the literature. Here, the term breaks is used for all recorded actions on mains, commonly known as failures, repairs, breaks, maintenance events and leaks. The breaks in water mains do not include repair actions or recorded failures of other components in the pipe system, such as hydrants, valves, service lines and pumps. Literature concerning other components, leakage and economic aspects of pipe breakage have not been used.

3.1 Pipe records

Pipe condition in practice is usually assessed through a combination of leak detection programs, complaints about water quality and pipe breakage reports. Pipe breakages are commonly collected, stored and retrieved in pipe records which contain information from almost all broken pipes for approximately 25 years. Verification of a correlation between pipe break performance due to physical and environmental actions into parameters used in records is an ongoing process and may involve large numbers of factors collected through special investigations. Some of the input parameters used in pipe records are shown in Table 3.1. Other environmental breakage parameters than those presented in Table 3.1 are in use and it is debateable which factors contribute most to break causes. Certain environmental factors have been assessed as critical forces for pipe breakage, such as construction activities, expansive soils, frost penetration, ground movement, traffic and land sliding (O'Day et al, 1987). Over and above these parameters are aggravating and synergistic physical and chemical effects, such as corrosion (Karaa and Marks, 1990).

Table 3.1 Some of the input parameters used in pipe records.

Environmental characteristics	**Pipe characteristics**	**Failure characteristics**	**Repair and replacement actions**
Location	Diameter	Reported failure date	Repair date
Soil corrosivity	Pipe material	Failure type	Repair routine
Demographic development	Installation date	Joint type	Part damaged
	Pressure	Main depth	Part repaired
Pressure zone	Original wall thickness	Soil type at failure site	Repair type
Priority zone		Soil data if sampled	Relining, year and part
	Joint type	Local flooding	Leak detection program
		Pit depth	
		Internal corrosion	
		External corrosion	
		Apparent cause of failure	

It is important to reevaluate the breakage parameters as the recorded data is to be used in comparative analysis. Records are usually manually recorded by each water utility and the recorded parameters may differ through:

the purpose which they were collected for
the labeling of names, based on how they were measured
the efficiency of recording

It is now recognized that the parameters should be both computer compatible as well as being of use for maintenance reliability analysis.

3.2 Analysis

Examples of pipe analysis, based on factors found in pipe records, have been described in Andreou (1986), O'Day et al (1987), Goodrich et al (1989) and Karaa and Marks (1990). Typical factors used in pipe analysis include age/installation period, diameter, break type (circumferential, split bell, hole and longitudinal), pipe material, previous break, seasonal variation and location/soil environment (Wengström, 1993). Other factors used in pipe analysis are difficult to compare between studies because either pipe data normally do not include them or a combination of factors are responsible for a particular break (Karaa and Marks, 1990). It is essential in pipe analysis to describe the actual pipe break performance, even if a direct cause of failure cannot be identified.

Individual pipe breakage has been analyzed in two pipe models (Clark et al, 1982, and by Andreou, 1986) and both models also illustrate pipe breakage performance graphically.

The model used by Clark et al (1982) provided an insight into the difficulties of describing factors suitable for pipe analysis as well as important results of pipe performance. The model involved not only common pipe characteristics from pipe records, but also demographic parameters such as land development, residential development and industry, and parameters such as length of laid pipe in corrosive environments, see the explanations in eqs 3.1 and 3.2 (page 8).

The basis for the study was 457 mains from two water utilities in the USA. A survival analysis of pipes with none, two or up to ten breaks, over a period of 40 years, is presented in Fig 3.1. Approximately 53% of the pipes survived, i.e. did not have any breaks. The performance of pipes with breaks was analyzed and a lag period occurred between the time the pipe was laid until the first break. The number of subsequent breaks occurred exponentially. The difference in lag period and performance is illustrated in Fig 3.2.

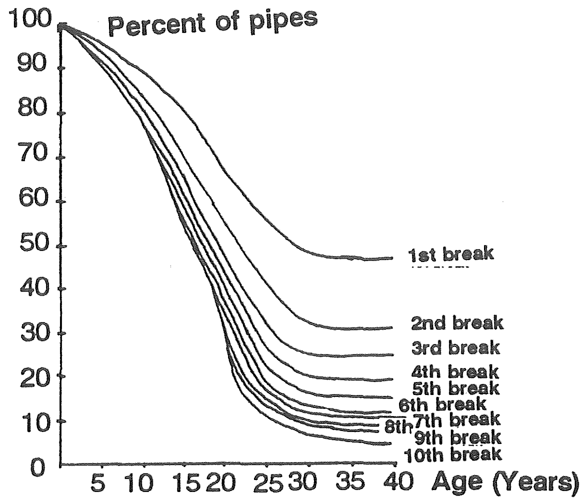


Fig 3.1 Break repair (mortality) curves for pipes, percent pipes having n repairs, (Clark et al, 1982).

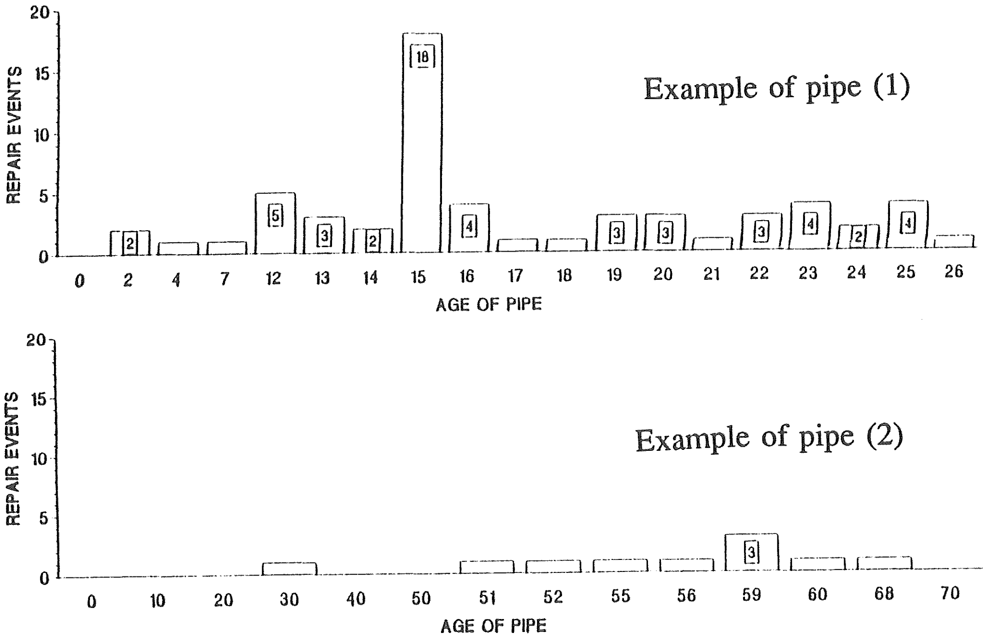


Fig 3.2 Individual pipe breaks per year versus year after installation for two utilities in Cincinnati (1) and New Haven (2) (Goodrich et al, 1989).

Two break event equations were constructed and evaluated by linear regression in a prediction model. The two event equations, eqs 3.1 and 3.2, separated number of years to first repair and the expected number of repairs in the future. These equations were based on pipes surveyed in both cities. The exponential failure behavior, after a break, was further investigated in a new model by Andreou (1986).

The first event equation gave a rather low R^2-value of 0.23.

$$NY = 4.13 + 0.338D - 0.02P - 0.265I - 0.0983RES - 0.0003LH + 13.28T \qquad (3.1)$$

The accumulated event equation gave an R^2-value of 0.47.

$$REP = (0.1721)(e^{0.7197})^{T}(e^{0.0044})^{PRD}(e^{0.0865})^{A}(^{0.0121})^{DEV}(SL)^{0.014}(SH)^{0.069} \qquad (3.2)$$

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

The model given in Andreou (1986) and Andreou et al (1987) uses Cox's proportional hazard model, PHM, where parameters are added exponentially, eq 3.3, and evaluated by regression analysis. For one of the two studied pipe systems the following parameters were used: length (logarithmic), pressure, lowland development, a dummy variable for period of installation, break rate at second break and a dummy variable for previous breaks. Table 3.2 shows results from the analysis for a model for predicting the next break.

$$h(t;z) = h_0(t)e^{zb} \qquad (3.3)$$

h	rate of failure (breaks/year)
h_0	unspecified baseline hazard function where $h(t)=a_1 - a_2t + a_3t^2$ and $a>0$
t	time of survival
b	vector of coefficients estimated from regression
z	vector of covariates (see Table 3.2)

A model for the probability of entering into a fast-breaking stage was made with the same parameters but the approximation of breaks was made through a Poisson distribution. The definition of the fast-breaking stage was based on the fact that most pipes had a break rate of 0.5 breaks per year, i.e. pipes with subsequent breaks had three or more breaks within a six-year period. A fair correlation, see Table 3.2, was only found between pipe length and number of breaks, while correlation was low for other factors. The break rate was assumed to be approximately proportional to the square root of the pipe length, and therefore not linear.

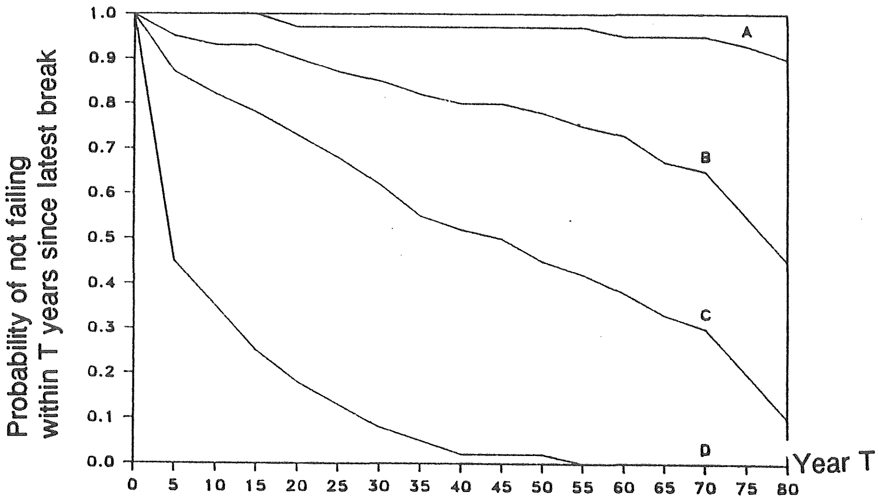
Table 3.2 Proportional hazard model for entering into fast-breaking stage, conditional on having one break (Andreou et al, 1987b).

	Variable z_1	Coefficient b_1	Standard error
Logarithm of pipe length (feet)	LNLENGHT	0.5299	0.0666
Internal pipe pressure (psi), if pipe has no breaks, 0 otherwise.	PRESBRK	0.9310	0.2760
Fraction of pipe covered by low land development (measured from 0 to 1).	LOW	-0.5404	0.1222
= 1 if pipe installed in the period 1930-1950, 0 otherwise.	C35	-0.6459	0.1258
= 1 if pipe installed after 1950, 0 otherwise	C50	0.2631	0.1365
= 2 (pipe age at second break), if pipe has two breaks, 0 otherwise	AGEBRK	1.7839	0.5831
= 1 if pipe has one or two breaks, 0 otherwise	P12	1.5726	0.2626

Pipe systems were studied in New Haven and Cincinnati. The model was applied to the systems because of the noted difference in the number of pipes which had subsequent repairs, i.e. the number of pipes which entered a fast-breaking stage, for the cities.

Fig 3.3 presents the calculated probability of no failure fail for 4 pipes with different histories. The "D"-pipe might be considered to enter a fast-breaking stage, as the second break occurred as early as four years after installation. The investigations only included pipes which were equal to or greater than 200 mm in diameter. The studied pipe systems were found to differ in seasonal breakage patterns.

The conclusion was that the model could provide a generalized method for predicting breaks, but it could not be used for evaluating the contribution of a certain factor. Evaluation of variables for maintenance requires the use of a relative risk concept for comparing the risk of a given pipe breaking to a representative pipe breaking. A practical finding of importance was that the age at the time of the second (next) break is a very important predictor of further breaks. The pipes with an early second break seemed to have a higher hazard rate than pipes with the second break at a later stage.



Curve A 30.5 m of pipe installed from 1930-1935, totally covered with minimum land development which had already experienced 2 breaks, with the last break occurring after 77 years of installation.

Curve B 30.5 m of pipe, with no previous breaks, installed after 1950, covered with maximum land development, and subject to very high internal pressure of 173 psi.

Curve C 30.5 m of pipe with two previous breaks, installed after 1950, covered with maximum land development and which experienced the second break after 4 years.

Curve D 4,267.2 m of pipe with two previous breaks, totally covered with maximum development and which experienced the second break only 4 years after installation.

Fig 3.3 Four individual pipe breakage patterns and their survival function as the probability of not failing within T years since latest break, O'Day et al (1987).

Many previous studies have investigated pipe system performance through descriptive analysis. In these studies the break rate was used as the major parameter (Wengström 1993). For the assessment of system break performance the definitions of number of failures per length and per time period vary and result in difficulties in evaluating a comparable increase or decrease in break rates. A similar situation exists with the use of other parameters such as the annual growth rate (O'Day, 1987) and the effective annual increase (O'Day, 1982 and Male et al, 1990). The latter is a moving average calculated as a linear regression and expressed as a percent increase of break rate at a certain starting event.

Other ways of expressing break rate include failures per length where the pipes group according to age i.e. weighted length (Jacobs, 1987 and Wengstöm, 1993) and, failures per block or per district area (Goulter and Kazemi, 1989). Fig 3.4 shows cumulative breaks in Calgary, Alberta, per weighted length. These curves show a pipe performance for two groups of pipes, ductile and iron pipes. To obtain the weighted length, the specific pipe length for each pipe age group is required, however the parameter seems to be comparable and effective in showing differences of pipe performance in a maintained municipal pipe system.

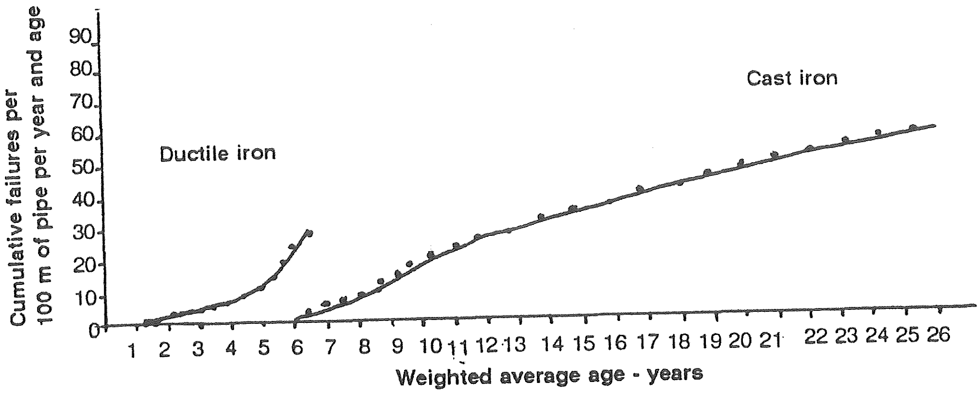


Fig 3.4 Cumulative failures per length of pipe and weighted average age for pipe system length, Jacobs (1987).

Replacement and repair strategies may more reflect system performance (deterioration) than a pipe analysis where only the break rate is considered. There has been some concern that the replacement actions undertaken are too few, which may prove to lead to an unreliable and expensive water net in the future. In order to evaluate the replacement strategy used in New York, Slutsky (1988) and Male et al (1990) modelled the efficiency of different replacement strategies as cost evaluation in relation to the replacement of bundles of pipes. The model is interesting as it is fully based on pipe records. Data on pipe length of segments with zero, one, two breaks etc were not possible to obtain from records but on the other hand the number of blocks having one, two, three or more breaks, were (Table 3.3). For these data, an average break rate per diameter group was calculated and used in estimating the probability of having breaks (Poisson distributed, eq 3.4).

$$P(x) = J^x * e^{-J}/x! \qquad (3.4)$$

P(x) probability of having x breaks
J weighted average break rate for a pipe diameter, breaks per block
x number of breaks (0....4)

These probabilities were then multiplied to achieve a simulated total length of pipes with one, two, three and four or more breaks. Table 3.4 compares the simulated values with the actual, recorded breaks. A Poisson distribution was found to adequately predict break occurrence. The simulation showed that the costs of an aggressive policy, replacement after first break, meant only a small difference in costs as compared with policies where replacements were made after several breaks. However, the modelled results are specific for the chosen water utility. They suggest that trying the same model on other water pipe systems might give other results.

Table 3.3 Number of blocks in Staten Island having 1, 2, 3, or 4 and more breaks (Slutsky, 1988).

Diameter (inches)	Number of blocks having n number of breaks				
	0*	1	2	3	≥4
8	5611	213	39	8	11
12	2054	83	6	0	0
16	308	6	0	1	0
20	343	8	2	1	1
24	175	3	0	1	0
Total	**8491**	**313**	**47**	**11**	**12**

*) 0 breaks were calculated by subtracting the length/blocks which had breaks from the total length/blocks.

Table 3.4 Actual and predicted number of blocks/lengths of water mains having 0, 1, 2, 3 and 4 or more breaks in Staten Island during a 30-year period (Slutsky, 1988).

Number of breaks	Number of pipe blocks					
	Pipe diameter					
	8 inch		12 inch		16-24 inch	
	actual	simulated	actual	simulated	actual	simulated
0	5611	5533.7	2054	2050.1	826	815.7
1	213	337.7	83	90.0	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	0.003	1	0.0009

Another possibility for estimating the number of breaks by a known total pipe length in diameter groups is by using unit pipe segment length for each diameter group (Wengström, 1992). Estimated failures were calculated through eq. 3.5. The unit pipe lengths per diameter group, were estimated as the sample mean of actual data. The unit lengths showed a rather small variation of length (82, 104, 121 and 166 m) between the diameter groups. The model was applied in six municipalities in Sweden.

$$f_{\text{diameter no i}} = C'^{*}L_i/l_i^{1/2} \qquad (3.5)$$

$f_{\text{diameter no i}}$ total breaks in diameter group i
C' constant, specific for each municipality, but similar for all diameter groups
L_i total pipe length in diameter group i, meter
l_i unit pipe length, meter

Predictions of system performance for future breakage have usually been made in connection with cost evaluations (Shamir and Howard, 1979 and Walski and Pellica, 1981). Shamir and Howard (1979) presented an equation, eq. 3.6, to estimate the number of breaks per unit pipe length, in any given year, as an exponential increase of the break rate. Davies (1979) clarifies the difference of distributions for time and number of breaks. The distribution of time to the occurrence of the first corrosion leak is suggested to be exponential, while the number of such leaks follows a Poisson distribution.

$$NB(t) = NB(t_0)\, e^{a(t-t_0)} \tag{3.6}$$

$NB(t)$	number of breaks per unit length of pipe at time t
$NB(t_0)$	number of breaks at the beginning of the period, t_0
a	coefficient relating the rate of increase in breaks with time

Average time between breaks was found, for a given pipe, to decrease after each subsequent break (Shamir and Howard, 1979, Clark et al, 1982, Andreou, 1986). Goulter and Kazemi (1988) compared time between failures, as well as distance between failures, to number of occurred failures for data from Winnipeg. A result was that an occurrence of a break appears to initiate other breaks, both in time and in the vicinity of the break. The time investigated was between 0 and 90 days after a break. The distance investigated was 0 to 20 m. The investigation period as based on recorded breaks was from 1975-1985.

Some reliability studies have estimated parameters such as reliability of pipe breakage and repair times in network design models, while investigating the hydraulic and geometric properties of the layout of water nets. The actual use of such reliability models is rare as computation time is long and therefore they have mainly been applied in theory (Goulter 1992). The reliability concepts used do not seem to be attractive in practice.

It is clear from the literature that the use of simple models using pipe breakage data is limited in its potential for predicting and estimating both time and place of future breakage. There is a need to be able to understand how maintenance actions are preventive at the pipe and at the whole system level. Although previous work seems to provide promising results, it is important to provide tools for a more detailed and structured statistical analysis of available pipe breakage data.

4 PARAMETERS AVAILABLE FOR ANALYSIS

Parameters suitable for maintenance reliability analysis should be measurable for all types of systems, have a strong correlation to the recorded fault, and in the near future, be possible to include in pipe records (Wengström, 1993). The parameters should be measurable, easily accessible at failure site and comparable. Some parameters which are available today are found in pipe records and have been widely studied. Some factors used in models have been collected through special investigations and are not available in pipe records. This investigation considers important parameters, not selected because they are the causes for breakage but because they have partly been found important in earlier reviews and models. Many factors are used in pipe records but few of them have been successfully used in models.

4.1 Age and installation period

Different installation periods show different break patterns and the cause is more dependent on the quality of workmanship rather than on time of installation. Age has not been found to be a dominant factor for pipe breakage (O'Day, 1982, Goulter and Kazemi, 1988). Some installation periods behave worse than other periods (O'Day, 1987, Andreou et al, 1987, and Newport, 1981). It can be concluded that pipe records today are unable to show age dependency (Wengström, 1993). It is possible that the repair strategies mask age dependency, i.e. few pipes are allowed to stay in the ground after more than approximately four repairs. Andreou et al (1987) suggests that age at the second failure is important, as pipes with failures at early ages perform better than pipes which fail late in life.

4.2 Diameter

Diameter seems the easiest parameter to retreive from the pipe records. A number of studies used break rate expressed as failure per length in groups of diameter. (Goulter and Kazemi, 1985, Kowalewski, 1976, van der Hoven, 1988, Walski and Wade, 1987, O'Day, 1982, Fox and Huguet, 1980 and Ciottoni, 1983). Results show decreasing break rates with increasing pipe diameters for pipes with diameters of 6, 8, 10, 12 and 16 inches (100, 150, 200, 250 300 and 400 mm). One prevalent point of view is that a 6 inch pipe is liable to excessive breakage (Male et al, 1990). A reason for many failures of 6 inch pipes might possibly be the influence of densely populated areas with large numbers of pipes. Newport (1981) remarks that the commonly measured break rate more reflects the breakage pattern of pipes at smaller rather than larger diameters.

4.3 Break type

It is usual to identify four main break types on water mains in pipe records: circumferential, longitudinal, hole and split bell. Comparative analysis of break type is possible for these. A stricter definition of break type, both to general appearance and break cause, is necessary to develop. A study by Goulter and Kazemi (1988) investigated failure types and suggested a time dependency for joint failures (increasing break rate with time) and circumferential cracks (decreasing rate with time). Hole failures had a constant rate. Wengström (1989) found that breaks related to corrosion are more common in subsequent failures in ductile iron pipes.

4.4 Pipe materials

Pipe materials receive little attention in pipe analyses. Grey iron pipes are the general basis for all pipe records. Walski and Pellica (1981) differentiated between spun cast iron and pit cast iron, while Clark et al (1982) categorized pipes into metallic and reinforced concrete. Pipe materials have commonly only been compared with break rate or with susceptibility (Kottmann, 1988). Evaluation of pipe material behavior is important, especially if pipe parts such as joints, tees, etc. are to be evaluated. Breaks in water mains will not be sufficient as the only basis for the reliable investigation of pipe materials.

4.5 Seasonal patterns

A seasonal pattern with high numbers of failures during the winter is common for many pipe systems. An increase in breaks during summer months is also probable as noted by Newport (1981), Andreou (1986) and Walski and Wade (1987). Andreou (1986) concludes that pipe systems with larger diameter pipes develop seasonal patterns with many failures, caused by the higher water demand during the summer. Walski and Wade (1987) postulated for Staten Island, US has more breaks in the summer months due to pressure surges.

In the future, ductile iron will be more common. The seasonal failure pattern for ductile iron pipes seems to be not similar to the pattern common for grey iron pipe systems. The ductile pipe systems might have low numbers of breaks during winter and somewhat higher in summer (Wengström, 1989, Björgum, 1988). Differences in breakage pattern of ductile and grey iron pipes in Calgary could also possibly be noted in Gilmour (1984).

4.6 Soil environment

The soil environment surrounding pipes is generally only evaluated for corrosion aggressivity. Many pipe models use different soil aggressivity parameters, but the correlation with the modelled parameter is often low (Doleac et al 1980, McMullen, 1986, and Clark et al, 1982). To understand the impact of the environment on failures, more investigations of external corrosion of pipes are needed. Interactions of construction waste such as the concrete commonly used in urban areas as fill material, and acid rain were found by Lekander (1991) to generate more severe attacks on pipes than had previously been thought.

4.7 Previous breaks

The number of previous breaks are reported in some of the reviewed literature as a parameter of interest for pipe breakage analysis. The differentiation into first failures and subsequent failures gave and showed interesting results (Andreou et al, 1987, Goulter and Kazemi, 1988, and Clark et al, 1982). The previous breaks enable three important variables to be analysed in reliability studies; time to first failure and time between failures as well as the number of first breaks. Many pipe models investigated have included these parameters. The modelled correlation between predicted and measured data has usually been low. It seems that it is not in models considered whether the repaired part might be as good as or better than the original part. To investigate this, it is of great importance that first failures and subsequent failures are used, and adequately recorded in pipe records.

4.8 Location

Clustering effects of both location and time have been found through the use of pipe records (Goulter and Kazemi, 1988). The proposed corrosion dependence of the repairs could probably not be evaluated from pipe records alone. Investigations have to use first failure, time between failures, and repair or exchange of parts. It is important for further studies that the descriptions of the repair event and of failure types such as third party activity, unsuitable material combinations and corrosion be well defined and introduced in evaluations of pipe failures.

The importance of location and population development have been stated by several authors (O'Day 1982 and Clark et al 1982). As a factor, location has no accepted definition but can be combined with several factors such as installation period, pressure, environment and land use. It is essential to provide a better definition of location or alternatively parameterize two previously mentioned factors, repair dependence and failure type.

4.9 Evaluation of parameters for pipe behavior

Many parameters affect the pipe breakage. There are many different opinions separated by several investigations. In the following tables, Tables 4.1, 4.2 and 4.3, the parameters are grouped according to an evaluation by Wengström (1993). The literature review (Wengström, 1993) mainly concentrated on cast iron pipes.

Table 4.1 presents the four factors selected as being of most interest with regards to the occurrence of breaks. These are location, break type, internal pressure and previous breaks. Only one of these, break type, is commonly used in pipe records today. Unfortunately, there are several different ways of describing the type of break and these have therefore to be considered.

Table 4.2 presents five of the parameters which are widely used and found to be of some interest for break cause. Four of these parameters are of a descriptive nature and are found in pipe records. However, uniform definitions of the factors do not exist and are almost too difficult to agree upon.

This demonstrates that the most important parameters to evaluate in pipe analysis is previous breaks and, from a corrosion point of view, break type. Both can be included in pipe records. Previous breaks have the advantage of including a time parameter, a repair and a maintenance parameter. This results in that few of the available parameters, in pipe records, are satisfactory for comparative pipe analysis.

Table 4.3 presents two evaluated parameters, found to be of less importance in comparative studies of municipal water pipe breakage.

Table 4.1 Parameters of most importance for analysis of pipe breakage behavior (based on Wengström 1993).

Parameters	Found in: pipe records	Found in: pipe models	Remarks
Break type	Yes	No, only as corrosion/non-corrosion	Some studies indicate a possible dependency.
Internal pressure	No	Yes	Theoretical bursting pressure commonly used in models. Internal pressure as zones, found important.
Location	No	Yes	Important, but lacks a uniform definition. Commonly estimated as a parameter for several factors.
Previous breaks	No	Yes	Interesting results shows dependency. Found important.

Table 4.2 Parameters found to be of some importance for analysis of pipe breakage behavior (based on Wengström 1993).

Parameters	Found in: pipe records	pipe models	Remarks
Age	Yes	Yes	Different opinions on the importance of age are found in the literature. The repair strategies are probably too dominant. Premature breaks, i.e. breaks at an early age seem to be common.
Installation period	Yes	Yes	Certain bad periods are distinguished but are specific to each pipe system.
Pipe diameter	Yes	Not common	100 mm pipes are found to be less strong. For some pipe diameters decreased breakage with an increasing pipe diameter is found.
Seasonal variation	Yes	Not common	Good dependency is found for certain years. Increasing numbers of failures in the summer seasons are not widely investigated. High winter failure patterns are suggested to be caused by several factors, such as precipitation, internal pressure and frost loading.
Soil corrosivity/ Environment	Not common	Yes	Studies show poor correlation of measured parameters and actual number of breaks.

Table 4.3. Parameters of less importance for analysis of pipe breakage behavior (based on Wengström 1993).

Parameter	Found in: pipe records	pipe models	Remarks
External load	No	Not common	Cannot be evaluated for pipes in service. Sometimes traffic intensity is used.
Pipe material	Yes	No	Most studies are based on cast iron, mainly grey iron pipes. Ductile pipes are found to show different break behavior than grey iron pipes.

5. ASSESSMENT OF MODELS FOR ANALYSIS

Pipe breakage records are commonly the basis on which many municipalities assess replacement needs. To guarantee that break records will be a safe tool for establishing pipe reliability criteria and system improvements, the records have to be adapted to meet the requirements of modern pipe analysis. In the previous chapter it was shown that as many as three out of four of the important parameters for pipe analysis cannot be found in common pipe records. By assessing the right parameters in pipe breakage records, reliability would be analyzed more easily.

Three reliability aspects of the municipal water pipe system are important in pipe analysis:

* water delivery performance
* maintenance requirements
* design improvements

To ensure water delivery in water pipe systems with daily pipe breakages, water utilities make delivery safety plans. These plans consist not only of the hydraulic conditions of the water distribution network but also of a plan for determining the need for, and the priority, of water pipe improvements and pipe replacements. The priority either ranks or groups all the pipes in the water distribution network. An example is presented here in Fig 5.1. Firstly, a group with pipes where the system runs the risk of low capacity of supplied water. Secondly, a group with pipes where too frequent service disruptions due to breaks are likely to give severe delivery stops. Finally, a third group consisting of the rest of the pipes. For the third group of pipes the risk of breakage is difficult for water utility managers to estimate. The aim of this individual pipe analysis would be to identify uniform breakage patterns for these pipes as early as possible to prevent an increasing occurrence of breaks, and to implement design improvements.

5.1 Evaluation of pipe performance based on pipe data

The water utilities have had few opportunities to describe pipe performance and make pipe analyses as the pipes of interest have low break frequencies and as the investigations of pipe records are commonly limited to a short time period, around 10 years, The first individual pipe analyses were shown in the models of Clark et al (1982) and Andreou (1986). A difference of break performance for two pipes was identified as time to first break, see Fig 3.1, where the break performance is exemplified through a comparison of one year contra 15 years. Representative, individual break patterns for four pipes were based on an analysis of the city of New Haven and are presented in Fig 3.3. Andreou (1986) and Andreou et al (1987) suggested that time to break was important, and in particular time to the second break. The pipes presented in Fig 3.3 show a variation of time to second break, from four years up to 77 years. Andreou (1986) also introduced a "fast-breaking stage" as performance criteria for some pipes. An individual pipe analysis should therefore describe the differences in individual pipes

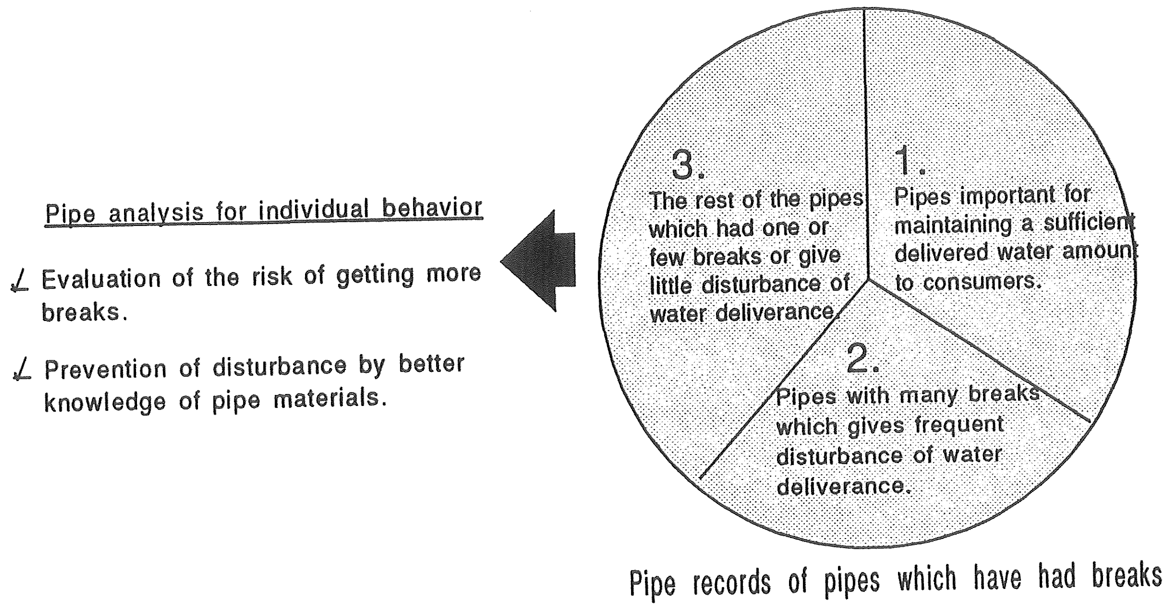


Fig 5.1 Range of the individual pipe analysis, based on pipe records.

performance by investigating time to first failure and time between failures, and should include a time variable to evaluate individual pipe breakage performances.

Break causes have been of great interest in the definition of pipe performance, but the causes are seldom found in pipe records. The common way of dealing with the problems of uncertain break cause has been to describe and record several of the existing pipe parameters in pipe records, see Fig 5.2. Fig 5.2 also shows, in the center, three main break factors which might be useful for the determination of system reliability:

Operational stress:	service disruptions caused by temperature variations, water surges, pressure of earth loads and environmental stress during pipe operation.
Wear and tear:	individual pipe wear during operation, caused by several parameters as operational stress, for example external and internal corrosion.
Quality of construction and maintenance:	individual variations such as installation practices, pipe manufacturing, trench construction methods e.t.c.

In the determination of system reliability the three factors in Fig 5.2 are of interest. Table 4.1 shows that the most interesting parameters to investigate in pipe analysis, for cast iron, are internal pressure, break type, previous breaks and location. To date only two of the four in Table 4.1, break type and previous break, can be obtained from pipe records. Evaluation of pipe performance should be characterized through the three reliability parameters. It is suggested that operational stress should use a minimum of parameters, thus internal pressure and location could be used to describe operational stress. It is suggested that break type should be more carefully investigated for use in quality of construction and maintenance. Previous breaks, i.e. time to next break, could be used for the characterization of the effects of wear and tear.

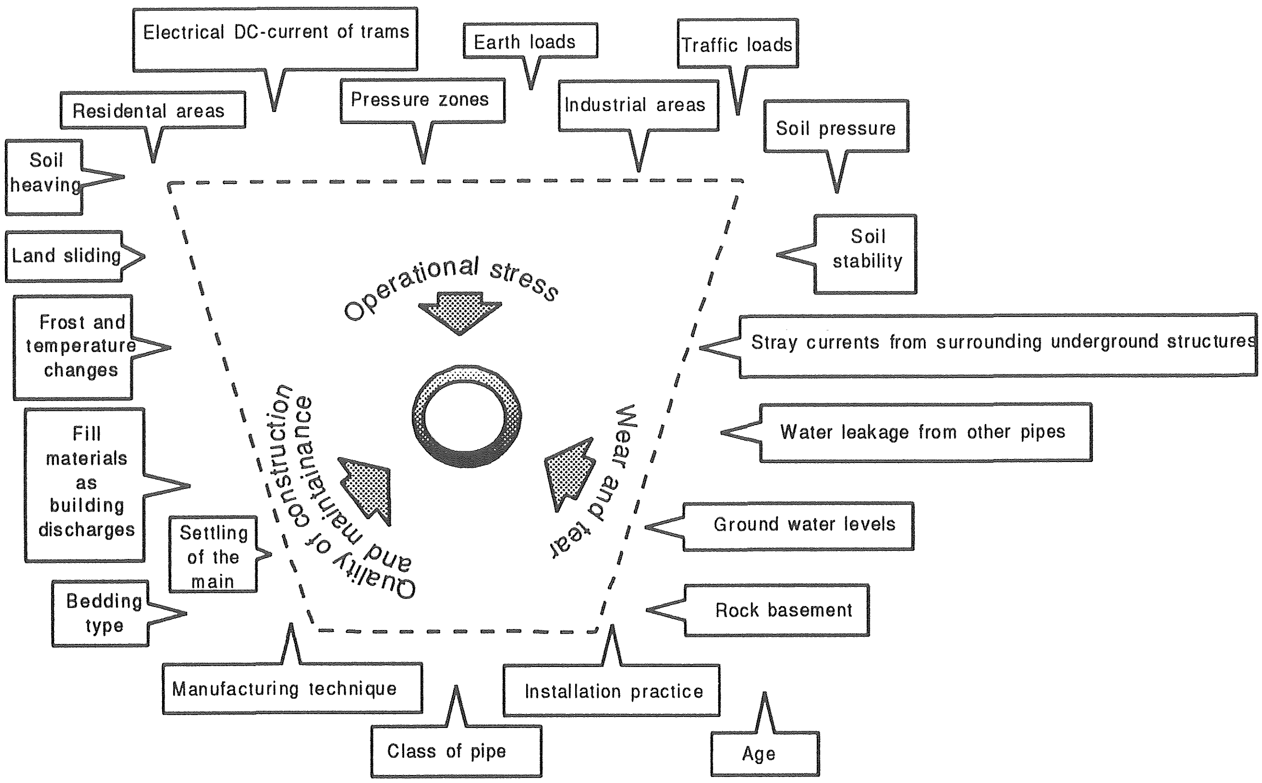


Fig 5.2 Pipe characterization parameters and three main reliability factors.

It follows that individual pipe analysis should focus on individual pipes with descriptive analysis, followed by a predictive analysis to improve the reliability of pipes and components. The main work of pipe analysis would be to define the individual pipes through location-variables and describe pipe breakage patterns, firstly in a descriptive manner through previous failure and secondly predictively through break type analysis. It is suggested that a few well-defined parameters should be used; well-defined meaning the following:

* easily accessible at break site or from operational records or charts.
* measurable for many individuals.
* available for comparative analyses.

5.2 Evaluation of system reliability based on repair data

Although it has been shown above that individual pipe analysis concerns the description and prediction of break causes from records of maintenance improvements of specific components, on the contrary, system analysis should be used to control and evaluate the influence of repairs in order to improve system reliability. This means that the water pipe system might have to be considered as a repairable system. In the literature, (Ascher and Feingold 1984) remarks that for a repairable system there are few ways of investigating whether the repairs improve system reliability or whether the system deteriorates. In order to evaluate water pipe systems as repairable systems, some points of importance which are typical of water pipe systems require definition:

* A repair is defined both as mending a section or exchanging a section.

* Break rate is commonly quantified as breaks per total system length and not as number of individual repairs.

* Breaks are sometimes likely to occur dependent of each other, i.e. when a break has occurred pressure variations might contribute to the occurrence of more breaks.

* Break rate might not relate to actual efforts for rehabilitating pipes and maintenance actions as environmental stresses, for example, whether temperature fluctuates greatly.

Fig 5.3 illustrates two water systems, with two extreme breakage patterns. The left-hand one illustrates a system with several breaks clustered in a few places. The right-hand system illustrates a system with unexpected breaks at several places over the whole city. Several questions arise: Which system is deteriorating? Which system utility has to put more effort into repair and replacement? Do the repairs give a better system or a worse one over a longer time period?

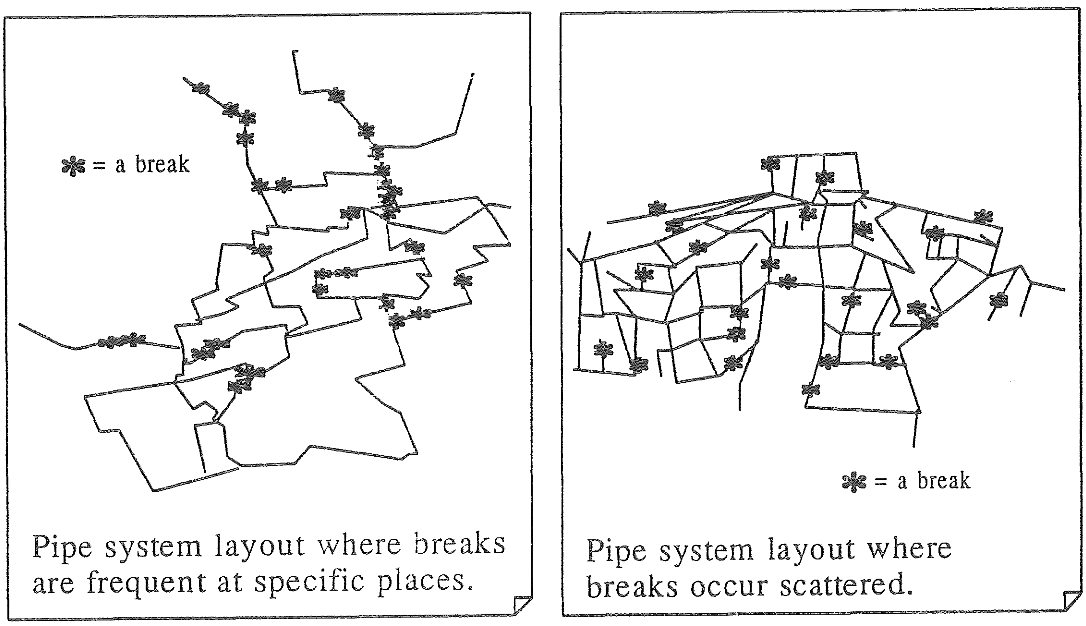


Fig 5.3 Two water distribution networks, illustrating a deteriorating system, to the right, and a repairable system to the left.

It might be suggested that the maintenance efforts to keep the right-hand system performing and functioning are harder than for the left-hand system. The left-hand system could be characterized through repairs of a few deteriorated pipes and not of the system itself. It is essential to find suitable parameters in order to evaluate the deterioration or improvement of water pipe systems. In practice, this knowledge concerning reliability is based on daily maintenance work and on pipe records. Commonly, break rate, i.e. breaks per system length, is used. Fig 5.4 presents a collection of different break rates for several municipalities, based on data from the USA, Denmark and Sweden, (Appendix A). Approximately 60% of the cities with long pipe system length (>2,000 km) have break rates lower than median, while for the cities with system length less than 2,000 km, approximately 40% have break rates below median value, Table A.3, Appendix A. For the smaller systems, less than 2,000 km pipe length, the break rate seems to be a poor parameter to compare reliability. Using only the break rate would lead to a false estimation for the comparison of costs for water utilities of repair and of replacement. The influence of the repair and replacement of actual pipe lengths leads to that comparable break rates have to be assessed. If the assessment of water system reliability is to be based on pipe records then a limited number of parameters are available. Table 5.1 describes some possible parameters and their disadvantages.

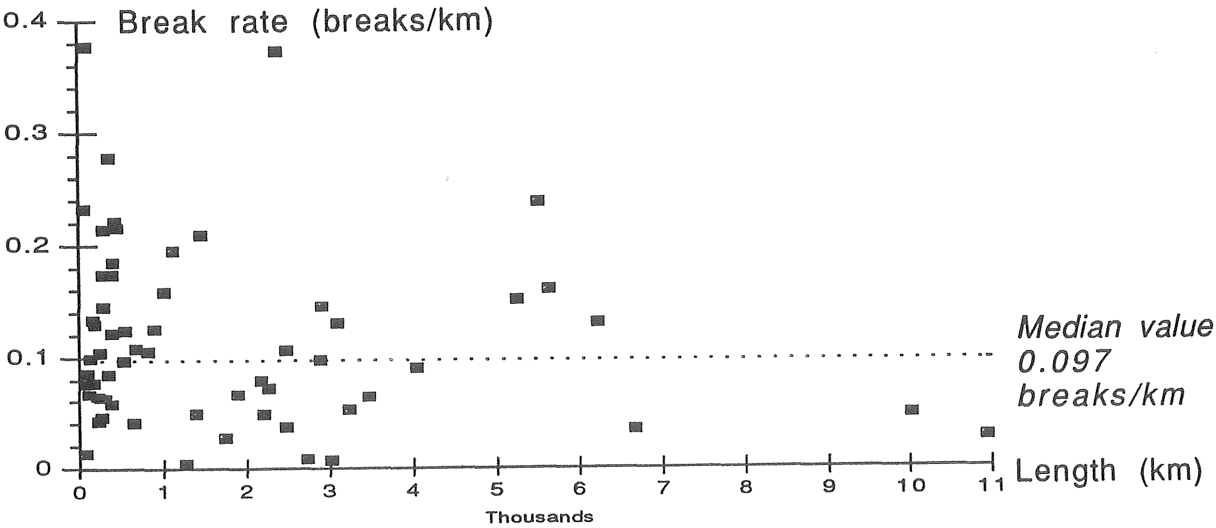


Fig 5.4 Break rates for approximately 60 municipalities, from the USA (Andreou, 1986, Male et al, 1990b, O'Day, 1982 and O'Day, 1987), Denmark (Baekkegaard and Dyhm, 1980) and Sweden (Larsson et al 1990, Reinius, 1981, and Pettersson, 1978) (Appendix A).

The parameters for system analysis have to be easily recognizable and have to include replacement actions as well as repair events. System analysis should include quality measurements to promote improvements and to encourage future actions. An attractive idea is to use diameter as well as pipe lengths per diameter as these seem to be reliable data in pipe records. Breaks per diameter group were investigated for six municipalities, by Wengström (1992) in order to investigate the correlation of number of breaks to pipe length, see eq 3.5. There were, however, difficulties in making uniform diameter groups suitable for statistical analysis. If the length of pipe segments and the actual number of pipe segments are available in each diameter, further studies might lead to descriptions of system performance, but evaluations of system reliability will not be gained. Reliability studies should aim to show deterioration, or improvement, of whole pipe systems. It is suggested that reliability could be evaluated as changes in a chosen quality parameter of repairs, based on time between breaks. This approach is somewhat unsatisfactory as the definition of a pipe is still neither exact nor statistically uniform.

Table 5.1 Examples of measurable parameters in a water system and their disadvantages in terms of reliability.

Measurable parameter	Comments
Replaced meters of pipe	Replacements are sometimes not based on reliability needs. Replacements are sometimes long-term actions undertaken more than five years after the problems have been established.
Number of breaks	Maintenance actions, i.e. number of breaks permitted on a pipe before replacement is undertaken, are different for each utility.
Time between breaks	The system is repaired. The pipe length is defined differently.
Pipe diameter	No obvious disadvantages
Pipe length or pipe segments	Not uniform in length.

6. ASSESSMENT OF A METHOD FOR INDIVIDUAL PIPE ANALYSIS

Using individual pipe model analysis and descriptions of pipe performance it is important to add goals for preventative maintenance of pipes to secure reliability of replaced pipe parts. The following questions are of interest:

> Will a certain break type/repair accelerate the number of subsequent breaks?
> How long a period without breaks might be expected after a repair?
> Is there a difference in break types in first failures as compared with subsequent failures?
> How should a pipe segment be defined?
> Will the evaluation of pipe breakage patterns be dependent on the chosen pipe length?

To accomplish preventative maintenance for distribution piping it is necessary to establish practical tools suitable for surveying and controlling faults. Earlier discussions have stated two variables, previous break and break type, as suitable for describing pipe performance and for pipe analysis. The basis for individual pipe reliability requirements is through pipes which have one or more breaks. These pipe segments are recorded in pipe records, by break date and break site. The main parameter of interest for maintenance is the break type, which could be found in pipe records. Generally, information on previous breaks are not found in pipe records. The breaks are simply recorded as breaks without any information of which break was the first, i.e. the previous break. The importance of including previous breaks is dual. By including the previous breaks a time variable, time between breaks, is estimated in the analysis, as well as the frequency of breaks at specific pipe segments. The assessment of the individual pipe model analysis for preventative maintenance tools is discussed and related to a previous study made in Göteborg on ductile iron pipes (Wengström, 1989).

6.1 Occurrence of previous breaks and subsequent breaks

During a study of ductile iron pipes, (Wengström 1989), an investigation of previous breaks was carried out by defining first breaks and subsequent breaks, see Appendix D, Figures D.1 - D.5. The study was based on manually kept pipe records for a time period of eleven years. The record guaranteed a possibility of evaluating previous breaks. The evaluation is presented as a chart, shown in Fig 6.1, with a sample mean of number of breaks of moving two years. The upper acceptance level is 7.3 breaks. (Calculations are shown in Appendix B). Fig 6.1 shows that subsequent failures are almost equal to the numbers of the single/first breaks. This indicates that almost 50% of the breaks occurred at places where repairs had been made earlier. The increase in number of breaks at the same places could not be explained in terms of age dependence. A dependence between breaks was, however, more plausible. Fig 6.1 shows the performance of only ductile iron pipes in Göteborg, but similar performance might be possible for grey iron pipes. Goodrich et al (1984), and Goulter and Kazemi (1989) also state that a majority of breaks are found for a minority of the break locations, referring to pipe systems mainly consisting of grey iron pipes. These locations, where many breaks occur, could be important in early identification with a characterization of pipe breakage patterns. Especially important is to gain knowledge about repair actions, if the repair actually contributes to the occurrence of more breaks.

For preventative maintenance, an evaluation of system performance could be developed, as in Fig 6.1. Comparative analysis of breakage patterns could be made for different pipe materials or for specific break types. Fig 6.1 is simple but enables assessments of different repair strategies for a few or for a large number of pipe segments in a system, regardless of the age of the pipe segments. The investigation period can be as short as about 10 years. The evaluation could be made with a $\bar{x}$-chart, as in Fig 6.1, with first breaks and, if chosen, subsequent breaks. When total pipe length (laid and replaced length) is recorded the acceptable number of breaks is traditionally related to increasing pipe length. For the ductile pipes the installed pipe length would, with a break rate of 0.1 give a total number of breaks of 15-22. Similar, a break rate of 0.05 would give a total number of breks of 8-11. The actions for replacement of some ductle pipes started already in 1986.

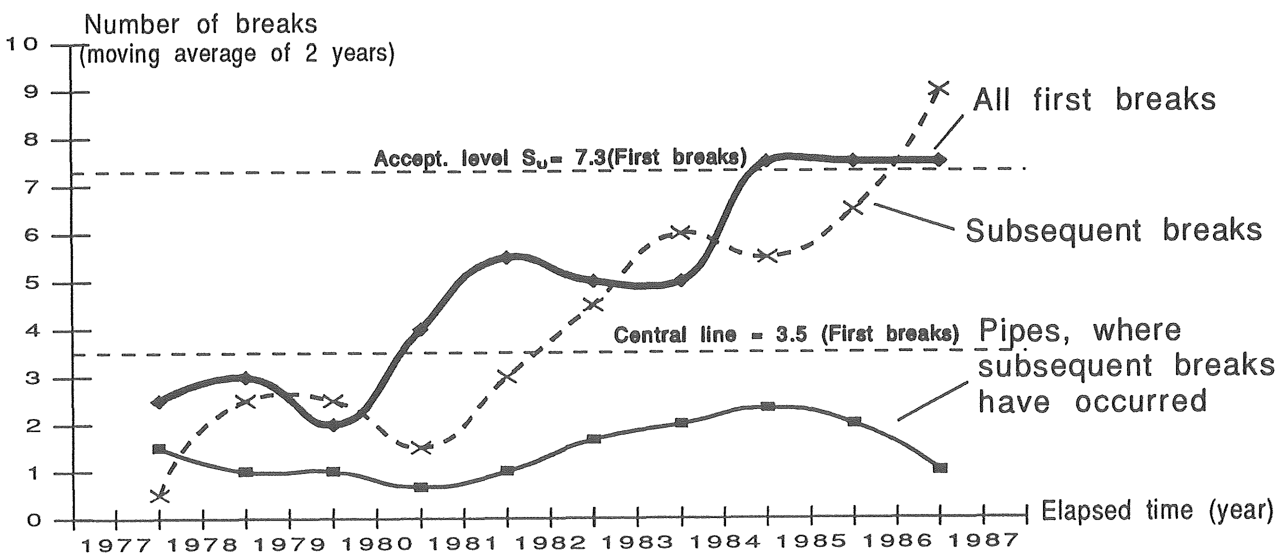


Fig 6.1 Breakage performance in ductile iron pipes in Göteborg 1977-87, presented as $\bar{x}$-chart, Appendix B.

The suggestion here is to state an acceptance level by a $\bar{x}$-chart similar to what is practice in quality of control. The acceptance level, S_u, may be compared to the break rate. There are difficulties in estimating the control indicator from real breakages if the pipe length is unknown. Statistically, it would be better to use the length of the broken pipe segments, but these data are usually not specified.

For long investigation periods it must be preferable to develop sample mean of five years. Acceptance levels for breaks can be presented in various Shewhart diagrams. Bergman and Klefsjö (1991) presents some use of Shewhart diagrams and a "R-method".

In Appendix B an estimation of level of acceptance is developed with moving two year averages, for ductile iron performance. The average sample mean was estimated to 3.5 breaks with an upper level of acceptance of 7.3 breaks.

It is often essential to control the number of the subsequent breaks, in terms of both delivery and economy. Total breaks could consist of up to 50% of subsequent breaks, see Fig 6.1. For different replacement policies, a control level for total breaks is unmanageable if a prediction of the probable increase of subsequent breaks is not made. The number of subsequent breaks which is due to specific pipes, or pipe segments liable to high breakage and acceptance levels, is difficult to set to these specific pipes (shown as the lowest line in Fig 6.1). For the ductile iron pipes the increase of subsequent breaks was approximated as similar to eq. 6.1, see Appendix D.

The subsequent breaks in the ductile iron study occurred surprisingly soon after the first break, from 1 month to 44 months. The average increase of places with subsequent breaks was a little higher than 1 per year.

$$R_t = t(D_r - 1)^{1/2} \qquad (6.1)$$

R_t total, cumulated number of subsequent breaks at time t

t time in years

D_r total, cumulated numbers of places/pipe segments where repeated breaks occur divided by t or the average increase per year of places where repeated breaks occur.

For water utilities which have areas dominated by repeated breaks, there may be a choice of economic art or a choice for fulfillment of service how to develop acceptable control levels. The control criteria for costs of replacement and repair are usually based on optimal time for replacement and an exponential function for the increase of the break rate (Shamir and Howard 1979 and Walski and Pellica 1981). The cost evaluation, presented here (Appendix C) is based on eq. 6.1 and an estimation of present values for two different repair strategies, replacment of pipes in short intervals of five years or replacment of pipes after 10, 15 or 20 years. The cost evaluation is based on repair cost and replacement cost in present values. The evaluation use a fictive yearly increase of places with repeated breaks and a fictive increase of repeated, subsequent breaks at these places, based on eq 6.1 and actual data from ductile iron pipes, Appendix D, Table D.1. The variables used are number of pipe segments aimed for replacement, the replaced length of pipe segment and number of repairs per segment. The indirect costs for water service and disruptions in water deliverance and traffic are not included. The prediction of future breaks by eq. 6.1 gave an approximate increase of places with subsequent breaks of 33-50%, and the increase of breaks per segment as approximately 33-73%, see Fig. C.1 and C.2 in Appendix C.

The result of the cost evaluation, for the two strategies, demonstrates that a continued repair of pipe segments in areas with high breakage is somewhat more costly. A better strategy in these areas is to replace pipes at short intervals. It is of importance to mark that the actual replacement length does not increase substantially even with an increase of two breaks up to seven breaks (Table C.5 in Appendix C). Table C.5 is based on actual replacement investigations made for pipe segments over a five year period in

Göteborg (Göteborgs vatten-och avloppsverk 1989) and implies that there is about the same, short replacement lengths of about 100-300 m regardless of the number of breaks.

6.2 Problems in connection with the assessment of variables

To make it possible to use a preventative maintenance evaluation the breaks should be ordered into a list of first and subsequent breaks in the analysis. This means that the location or break site will have to be defined and be available in pipe records. The identification of a pipe segment/break location, as well as the identification of a break type, always has to be made. One way of identifying breaks could be to use all maintenance events where direct actions were taken to make the pipe function. The break date is commonly defined as the day the break was observed which is not always, the same as the repair date.

In manually kept records the street address is commonly used for identification of the break site. This often leads to the pipe being defined by the street length. It is recommended that the street name is used as a label but that the break site specific to the pipe segments is used in computerized pipe records. Rather short pipe segments were commonly found in Swedish data bases (Wengström, 1992) which gives the impression that the utility has many pipe segments with single breaks, or only a few pipe segments with many subsequent breaks.

The bundling of several breaks/pipes into blocks (Slutsky, 1988 and Male et al, 1990) does not seem relevant to the Swedish municipality structure. It is recommended that two, or more, adjacent pipe segments are used to define one pipe, when two, or more of these pipe segments have breaks. This may not be strictly statistically correct, but it has the advantage that the aggregation of breaks can be done reapetedly and consistenly. Further more, aggregation can be done on a computer, which numbers and links segments together. The manual work with defining breaks based on geographical areas is impractical.

The individual pipe model aims to evaluate environmental characteristics (Table 3.1) and their influence on break performance. Environmental factors have to be characterized as covariates and the studies of Andreou et al (1987) may give some helpful indications of the importance. Fill areas and bad building ground, as well as the influence of heavy traffic should be included. The pressure covariates used in Andreou (1986) is not recommended until hydraulic models can give indications of pressure variation. Clark et al (1982) points out possible higher break rates in areas with few pressure zones. Kottmann (1988) relates pipe breakage to pressure and water demand variations, as does Lackington and Large (1980), but the correlation seems good only for winter periods. Neither daily, weekly or monthly pressure or demand variations are available in pipe records. Knowledge about these variations in distribution piping are difficult to assess. The information about pressure zones is more likely to be presented and is recommended for inclusion as a variable.

Clark et al (1982), O'Day et al (1987) and Wengström (1989) propose location as an important factor for individual pipe analysis as investigations show that up to 40% of the pipe segments develop the majority of the breaks. The demographic parameters used in Clark et al (1982), such as industrial areas or residential areas to characterize land use and location were useful and the analysis showed an increase of breaks in industrial areas.

By including the different kind of repairs distribution components better reliability for the individual pipe segment could be gained. Up to now, these component repairs are normally not included in pipe records.

The repair information about earlier failures in pipe records is often removed when the water main is replaced for maintenance reasons. This historic repair information is valuable for guidance and to increase the knowledge and background of the pipe system for new staff. In Sweden, the retrieval of previous breaks from pipe records is still a manual project as long as the exact break site cannot be established and shown on a computer screen graphically. Old pipe records could be used for finding the break time as time between breaks, if some amount of manual work for the localization of breaks to specific sites is made, even if the first break is not investigated. These failure patterns of old pipes could be compared with patterns of the newer pipe materials.

6.3 Adding break type to the model

A model cannot be applied to common pipe records until the break type is better characterized. The typical behavior of grey iron pipes is, for example, difficult to describe at the field site from both corrosion aspects and pressure fatigue. A first step would be to define simple, well defined break types, as suggested here, based on maintenance actions taken, parts repaired and the appearance of breaks.

The break pattern of ductile iron pipes in the city of Göteborg was investigated (Wengström, 1989) and break types were characterized in terms of repair actions, parts repaired and appearance of breaks. About 100 ductile pipe segments with breaks were grouped according to appearance of the first break into four break type categories; accidental failures, joint- and material failures, bursts and corrosion failures. For two of the breaks nothing significant was recorded and they were named unmarked failures. Appendix D, Figures D.1 - D.5 shows the break categories and time to first break for each individual pipe segment. Fig 6.2 presents the median value of time to first break for each break category, the value for 25% of the pipe segments, the value for 75%, the lowest value, the highest value. Fig 6.2 is based on Table D.2, Appendix D, and the table show as well the value of the residual time for the same pipe segments.

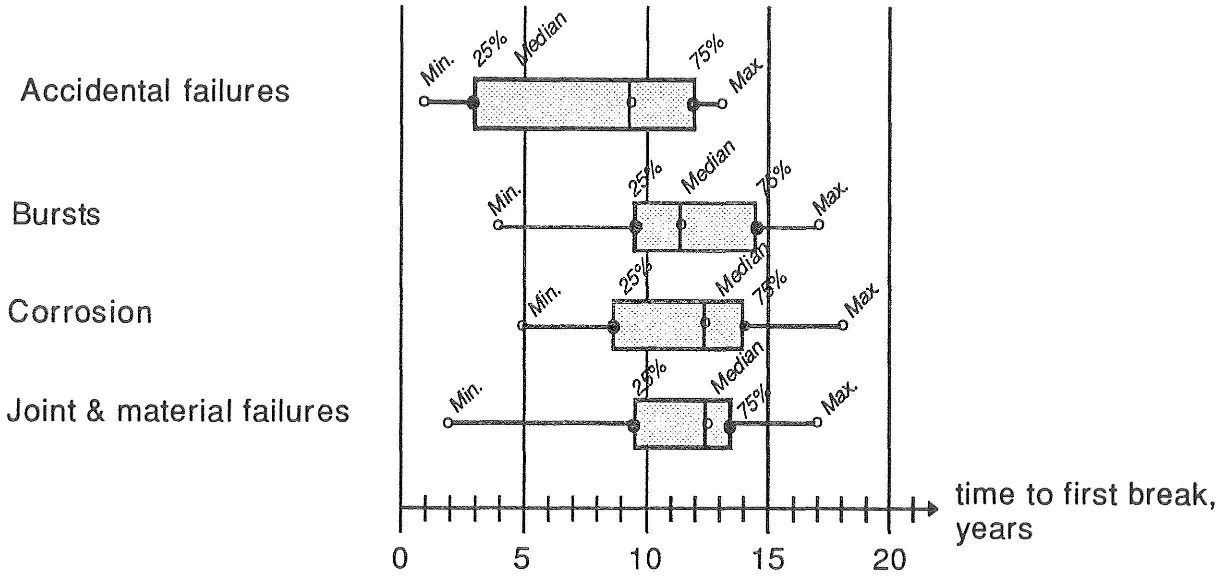


Fig 6.2 Differences in time to first break (similar to age at first failure) for break categories based on the appearance of first failure, Table D.2, Appendix D.

From Fig 6.2 and Appendix D it can be concluded that the break categories have differences in breakage performance. Primarily, the differences seem to fall into three types:

getting subsequent breaks
time to first break
residual time

Breaks categorized as corrosion failures had, in 10 out of 18 pipes, subsequent breaks and a remarkably short residual time (approximately less than 2 years). This differed from the other three break categories where there was only a total of three of the pipe segments with subsequent breaks. For the accidental breaks the first break had a tendency to appear after 9 years, where the first break or the other break categories appeared approximately after 12 years.

For the category joint- and material failures the first breaks seemed to appear at the end of the investigation period. This means that there is some uncertainity if the residual time could be assumed to be longer than 2.5 years or not. A similar situation is found for the residual time, the trouble free time until the next break, when estimated for eight of the pipe segments which had been labeled as corrosion, a short residual time was found because the breaks appeared during the last, or next to last year of the investigation period. The other 10 pipe segments might for the corrosion break category be the basis for a hypothesis that the eight pipes have a high probability of subsequent breakage soon after the investigation ended. This has not been investigated nor verified.

The water mains break types used today in pipe records for grey iron pipes are: hole, split, circumferential or longitudinal breaks. These are believed to be too generalized to be of use for maintenance evaluations. Using better descriptions of the break type, based on actual maintenance actions, might lead to the conclusion that the influence of operational stress, wear and tear, quality of construction and maintenance could be analyzed in the model. The breaks are complex and may be caused by a number of factors (Karaa and Marks, 1990, and O'Day et al, 1987) as well as by the repair actions undertaken. Operating water pressure might be a dominant factor for brittle and corroded pipes of grey iron. Both break cause and water pressure are essentially site specific, which means that the location is of great interest.

After the third break it might not be of any interest to evaluate a pattern based only on the first break type, as repair policies have a strong impact on the subsequent breaks. Probably, after a couple of repairs, the repair methods change, for example, shorter parts of the pipe segments are replaced and often with different pipe material. The focus of reliability should be on the maintenance actions undertaken. My suggestion is that the dominant variable to use should be the time between breaks. This means that the analysis could start anytime, regardless of the pipe age when the investigation begins. The time between breaks could with some effort be made available in pipe records today.

6.4 Model structure for individual pipe analysis

A model is suggested for individual pipe segments with one, or more, breaks. The essential question in modelling pipe reliability is the performance of the pipes so that preventive maintenance actions can be evaluated. The expectation of breaks after a repair is of more interest than when a pipe will break.

Break type as a variable has not previously been tried in pipe models, although it is commonly used in pipe records. Other factors such as location/land use, internal pressure, seasonal variation and previous breaks have been used in some pipe models but these are only partly available from pipe records. Analyzing pipe records with a proposed model with time between previous breaks and the break type as variables would give reasonably good predictions of pipe segment reliability. With better definitions of repair actions and location, information concerning different pipe performance could be gained and the basis for pipe breakage causes could be evaluated.

The model for pipe analysis suggested here is a multiple regression model, similar to the applied proportional hazard model used for individual pipes in Andreou (1986) and Andreou et al (1987 and 1987b), and shown in eq. 3.3. The model given here (eq. 6.2) uses time to subsequent break, favoring time from first break to second break, instead of using system age.

By introducing new descriptions of break types, as discussed earlier, i.e. include maintenance actions, repaired parts and appearance of break, data can be aggregated and different baseline functions chosen. It might be reasonable to omit the system age as a variable because different baseline functions, h_0 could include system ageing in terms of the different break types chosen. One suggestion is only to use variables for characterization of pressure and break site/location. These variables are like stress factors and should be synchronised for all data. Only the baseline function would be varied.

$$\mathbf{h_j(t;z) = h_{oj}(t)e^{zb}} \qquad t \geq 0 \qquad (6.2)$$

h_j rate of failure (breaks/month)
h_{oj} unspecified baseline hazard function of Weibull type $h(t)={}^b/_a * t^{(b-1)}$
t time
t_o time at first break
t_n time to subsequent break interval $0=<t<t_n$
j the j number of stratum baseline functions. In Fig 6.3; "bursts" and "corrosion" are exemplified.
b vector of coefficients estimated from regression
z vector of covariates

In the model used in Andreou (1986) the baseline function was believed to express an ageing process as "t", time, was set to the lifetime of a pipe. The baseline function chosen in Andreou (1986) and Andreou et al (1987) was a "bathtub" function. Here the baseline functions more describe break behavior for each subset. The different baseline functions have to be estimated. A proposal in Andreou et al (1987) is to use Kaplan-Meier methods for the estimation of baseline functions. In Andreou et al (1987) a two degree polynomial equation was proposed as the baseline. A Weibull-type function, shown in Fig 6.3, is proposed here. Fig 6.3 shows some examples of general baseline functions of the Weibull type and two modelled baseline functions. The modelled baselines are estimated to illustrate two possible examples of baselines for pipe performance. These show two break types, corrosion and bursts, based on some points from ductile pipe data (see Appendix E).

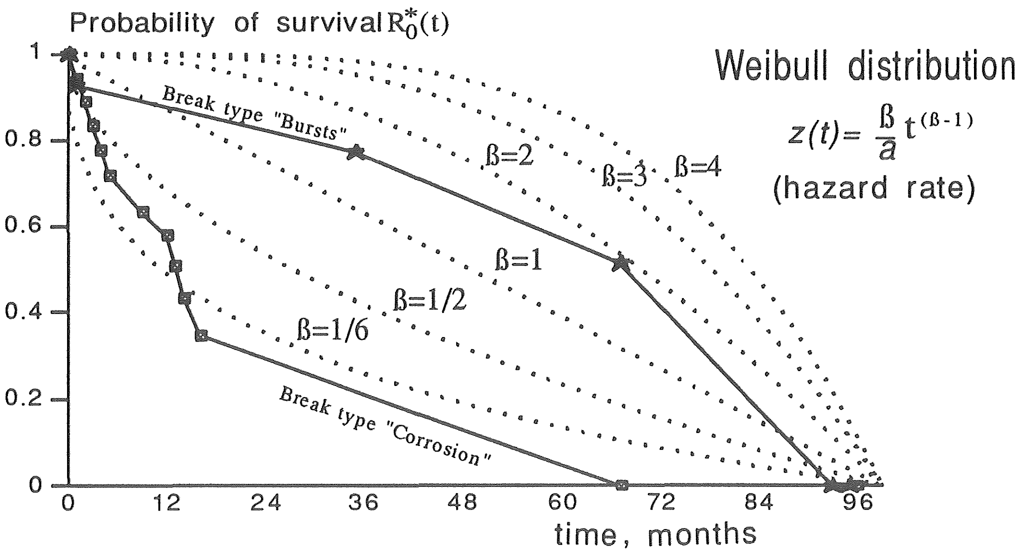


Fig 6.3 Proposed general baseline functions of Weibull type if time between first break and second break is used for different break types, including two subsets as baselines estimated ho* from the data presented in Wengström (1989).

7. Discussion of Assessment of a Model for System Analysis

7.1 Structure of the model

The challenge of this work has been to find tools for describing system behavior from break records and to evaluate the influence of repairs on system improvement. It is suggested here that such an evaluation should be based on a regression analysis, commonly known as an additive hazard model (AHM), and presented in Pijnenburg (1991). The base data for the evaluation of water system performance is time between repairs, and therefore it is necessary to define breaks as first and subsequent repairs in order to show system improvement or deterioration. The model suggested, eq 7.1, is an additive hazard model, which differs from Andreou (1986), where a proportional multiplicative hazard model was used. The model has some practical aspects suitable for water pipe breaks. Equation 7.1 does not consider the ageing of the pipes, but evaluates the time between breaks/repairs. It handles the breaks in terms of running time/investigation period. The evaluation of deterioration/improvement is based on a function greater or smaller than zero, thus making it comparable between utilities and allows an evaluation of the influence of the used repair strategies. These are favorable in maintenance aspects.

Pijnenburg (1991) describes the AHM by using components in a series system and $\alpha(z_i)$ as a quality variable to show the effects of repair if the system improves, ($\alpha(z_i)<0$), or deteriorates, ($\alpha(z_i)>0$), related to the time elapsed from the beginning of the study until the break or breaks occur. The AHM has the hazard rate added to a baseline function. In eq 7.1 equal baseline hazards for subsequent breaks are assumed, i.e. for each stratum all hazard rates were assumed to be equal. By plotting the log of negative hazard rate against the time elapsed, the distance of each successive rate between failures to the rate of failures in chronological order (stratum i=1), is $\alpha(z_i)$.

$$\mathbf{h(t;n(t),z_{n(t)}) = h_1(t-t_{n(t)})+\alpha(z_{n(t)})} \qquad (7.1)$$

h	hazard rate, rate of repairs
t	time elapsed from beginning of study to repairs
n(t)	number of repairs up to time t
$\alpha(z_{n(t)})$	hazard rate of the covariate component, assumed to be constant in $[T_i, T_{i+1}]$
$z_{n(t)}$	can be stratified as z_i where
i	is the i number of the stratum baseline hazard function
z	vector of covariates

7.2 Assessment of pipe system behavior

To gain knowledge of how the model would work for water pipe systems, actual pipe breakages from a Swedish municipality, Örebro, were used. This isolated attempt used aggregated data and may not be used to draw conclusions about the behavior and appearance of pipe systems in general. The Örebro data are presented with the actual investigation period, 4 years, and are further used to simulate a 12-year investigation period.

The breakage data from Örebro were stratified into first breaks, subsequent breaks and such breaks which did not have a second break within the investigation period. Appendix F show the resulting data, 181 breaks, where 55 had subsequent breaks with up to four subsequent repairs. A few pipes had more than five subsequent repairs, sometimes up to eight subsequent breaks but these are not analyzed. To aggregate breaks to specific repairs at the same pipe, the segments used in the computer were considered as definitions of a pipe, or in cases when the nearby segment had breaks, the pipe was defined including that segment. The formulated definition of a pipe may be controversial statistically but the pipe segments are defined at random. There is therefore no strong evidence against a nearby segment being part of the same individual pipe.

The hazard rate for each repair stratum was calculated, through eq. 7.2, as the probability of survival, where the number of unbroken pipes during time t, is compared with the total number of unbroken pipes at the beginning of the study.

$$R_i=n_i(t)/n_i(t=0) \qquad (7.2)$$

R= probability of survival
$n_i(t)$= number of pipes which are not broken up to the time t

In order to model water pipe systems performance the repairs may have different break patterns, the Örebro data was manipulated for simulation. It was of interest to evaluate whether, by simulated break patterns, the model gives negative α, or if α equals zero, i.e. if a system, with repairs occurring a longer time after the first break, has an appearance of "better than old" (improved system), or at least a system which does not show signs of being "worse than old" (deterioration). Fig 7.1 shows the type of break pattern used in the simulation. The first figure shows the break pattern of the original Örebro data over a four-year period, the next the break patterns used in the three simulation runs. In 7.1b) the repairs are set as mostly occurring shortly after the first break, similar to Örebro, 7.1c) which shows the breaks occurring evenly over time, and 7.1d) most of the breaks occurring a long time after first breaks. Simulation data is presented in Appendix G, as well as the original repair data from Örebro.

The simulations were made by repeating the original repairs of the first stratum so the investigation period was for 12 years (3x4 years). The different break patterns, shown in Fig 7.1, as b), c) and d) were used and the suggested model, eq 7.1, was applied. The computer handling of the model equations is shown in Appendix G. The simulations of the three break patterns are presented in Fig 7.2, 7.3 and 7.4. Figure 7.2, seems to definitely show a deteriorating system, both in second and third repairs. The curves in

Fig 7.3 show a system where the repairs do not improve or negatively affect system reliability. The curves in Fig 7.4 show a definitely improved system. The break patterns used in Fig 7.4, is d) in Fig 7.1. It is not known whether such a breakage pattern occurs in real life, however, the pattern shown in Fig. 7.1 (d) does not seem unreasonable for a water distribution system. The results of the simulation are that the model seems to have a good ability to show differences in break patterns, and there is good manageability for comparison of system behavior. The model should be applied to break data from other municipalities.

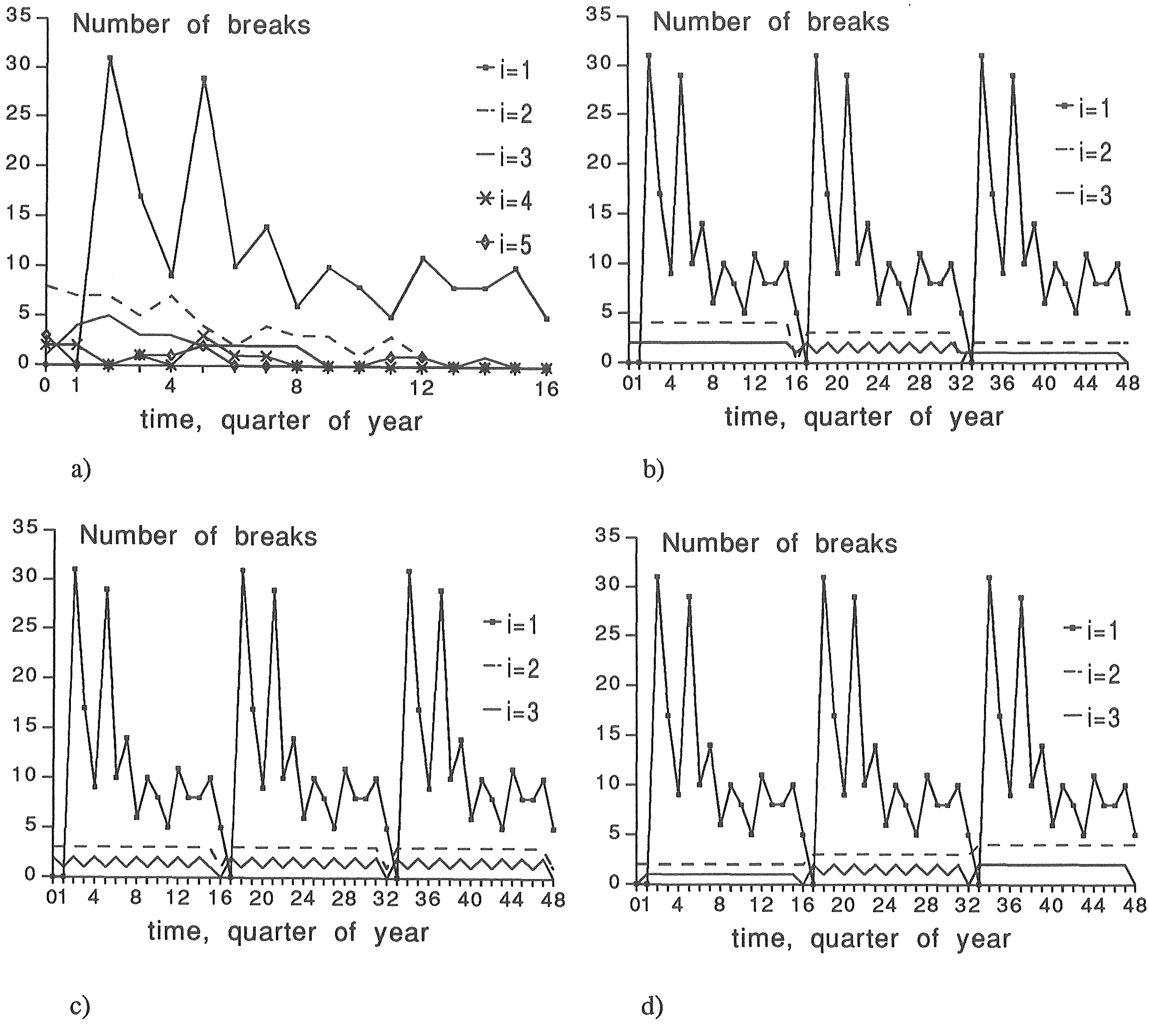


Fig 7.1 Break patterns, a) original during a four years investigation in Örebro, b) simulation of the Örebro data to gain a 12-year period of investigation c) simulated breaks which occurring evenly over the 12-year period, and d) simulated break pattern where the most breakage occurs after a long time after first breaks in a simulation of 12-year investigation period (i=1 is breaks in chronological order, i=2 and up is successive repairs, 2nd, 3rd etc.).

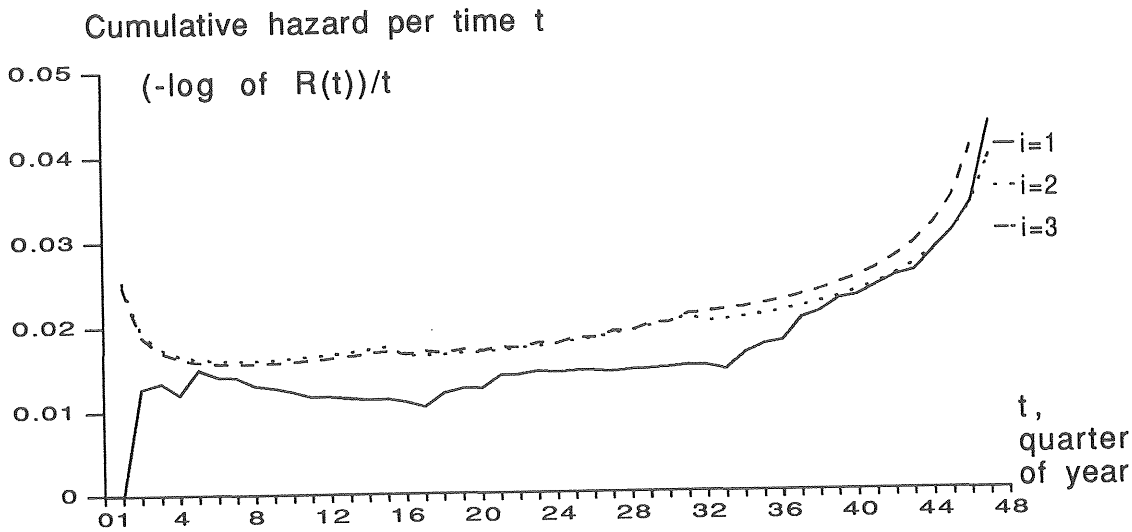


Fig 7.2 Simulation of break data to show $\alpha(z_i)>0$, for a water system. The system can be considered "worse than old", or may be interpreted as an deterioration (i=1 is breaks in chronological order, i=2 and i=3 is successive repairs, 2nd and 3rd).

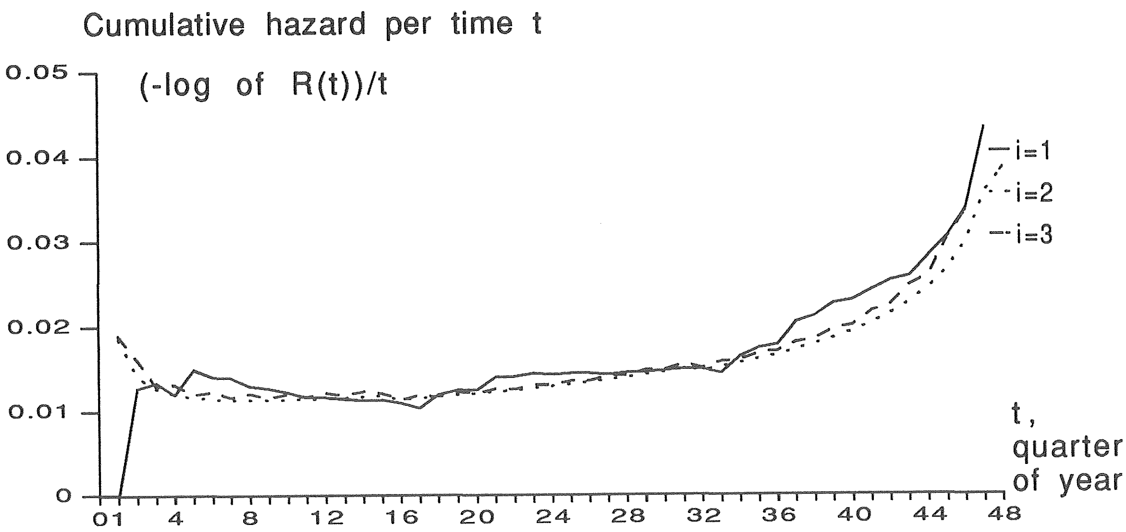


Fig 7.3 Simulation of break data to show $\alpha(z_i)=0$ for a water system. The system can be considered as "bad as old", or may be interpreted as the repairs neither improve, nor make the system worse (i=1 is breaks in chronological order, i=2 and i=3 is successive repairs, 2nd and 3rd).

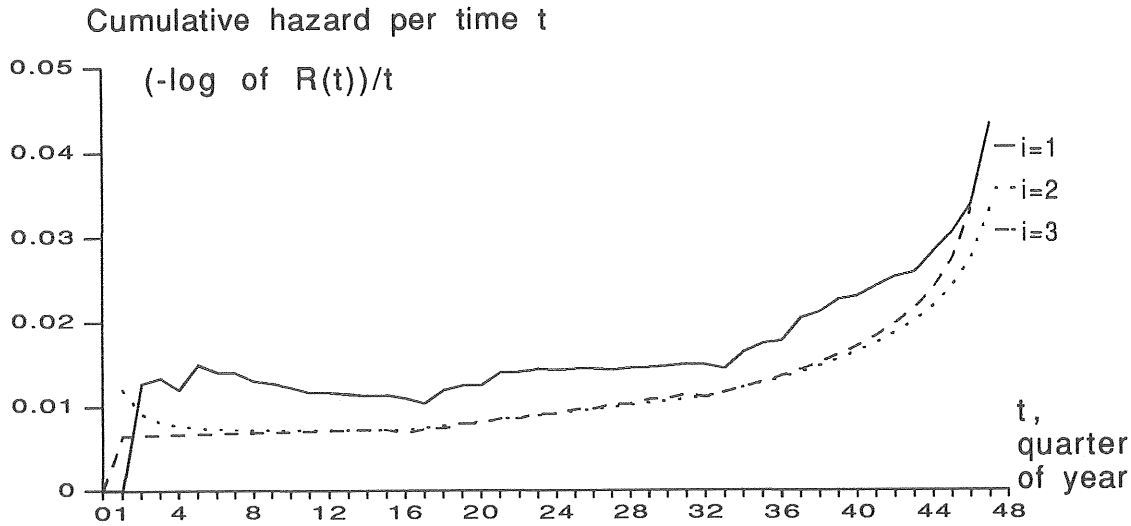


Fig 7.4 Simulation of break data to show α<0, for a water pipe system. The system can be considered "better than old", or may be interpreted as an improvement (i=1 is breaks in chronological order, i=2 and i=3 is successive repairs, 2nd and 3rd).

The results, of the simulation, Fig 7.2, 7.3 and 7.4 indicate that there is a possibility to evaluate pipe system behavior with an AHM. It is clear in the figures, except for Fig 7.4 that the second stratum is parallel and differs from the first. The third stratum seems to be at a similar distance. The curves are presented with the repair values quarterly (per three months), which gave smoother curves, although the base data could be displayed in monthly values.

In accordance with Pijnenburg (1991), and if further analysis of some explanatory variables is attempted, it is essential to control if the data actually suits the AHM, or if a proportional model (PHM) is favorable. To test the proportionality respective to additivity the base data from Örebro, 4-years of repair data, was plotted for this test as cumulative hazard, see Fig 7.5, and compared to the general appearance of a typical AHM, Fig 7.7 and PHM, Fig 7.8. As shown in Fig 7.5, the 4-year investigation period of the Örebro data shows neither a strong evidence to be AHM, nor to be PHM.

Pijnenburg (1991) suggests also a second test, a test for proportionality through a plot of log of (log minus R(t)), where parallel curves provide evidence for proportionality. Fig 7.6 shows only stratum 1 and 3 to be parallel. A conclusion is that the used data consist, especially of the strata >1, of few observations, and some outliers, which make testing for proportionality or additivity unsatisfactory.

Hence, by assuming AHM an estimation of α can be made in Fig 7.5. The strata of second, third, fourth and fifth are from inspection of Fig 7.5, approximately of similar, positive distance, from the first stratum. Table 7.1 gives the average α as a sample mean of six, similar times at each curve. If AHM is accepted then the repairs in stratum 2 do not improve the hazard rate. As the second, third, fourth and fifth strata are of similar

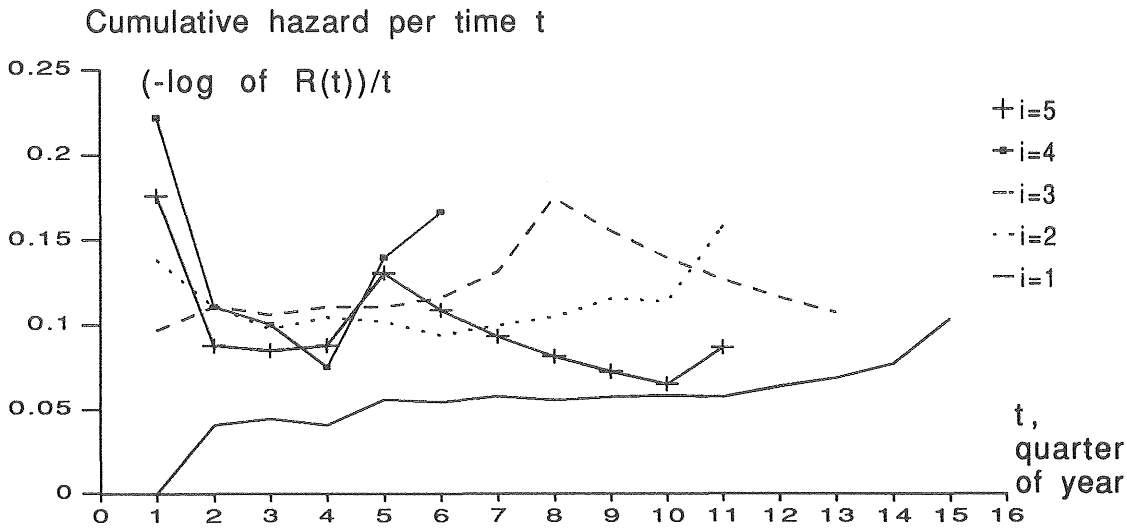


Fig 7.5 A total of 280 breaks from break records from a municipality over a four-year period are plotted as (-logR(t))/t. Breaks and repairs were recorded by date but are aggregated here by quarter or per three month period (i=1 is breaks in chronological order, i=2 and up is successive repairs, 2nd, 3rd etc).

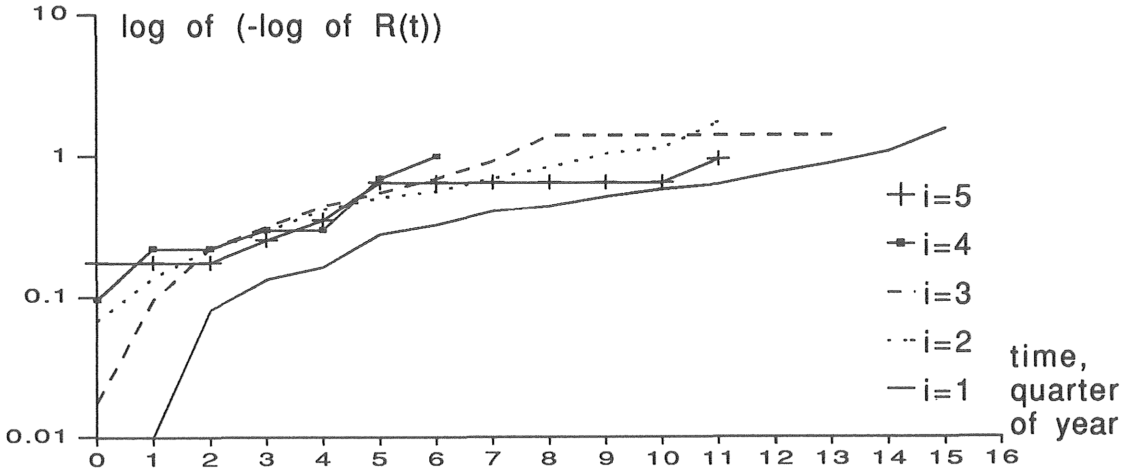


Fig 7.6 A test for proportionality. A total of 280 breaks from break records from a municipality over a four-year period are plotted as log(-logR(t)). Breaks and repairs were recorded by date but are aggregated here by quarter or per three month period (i=1 is breaks in chronological order, i=2 and up is successive repairs, 2nd, 3rd etc).

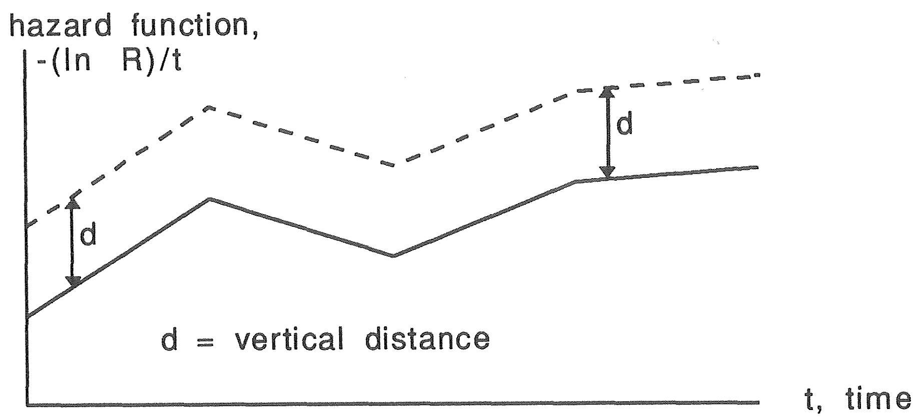


Fig 7.7 General appearance of an additive hazard function (AHM) plotted against the gap time t. To consider additivity the curves should be parallel, having the same vertical distance.

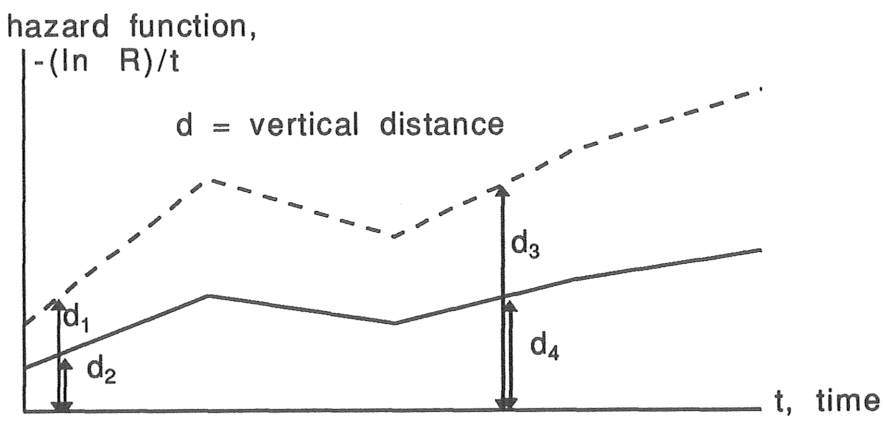


Fig 7.8 General appearance of a proportional hazard function (PHM) plotted against the gap time t. To consider probability the value of the vertical distance of d_1/d_2 should be the same as the value of the vertical distance of d_3/d_4.

distance, the system reliability is not improved by the repairs. The sample means of time before repair, Table 7.2, indicate that the repair times are short and decreasing. However, as neither the distribution of repair times was known, nor their standard deviation, a signifance test was carried out, Appendix H, in order to make the assumption that the curves really differs.

Table 7.1 Estimation of α, a quality variable, for Örebro from Fig 7.5. A positive α value, if the data fits the AHM, shows a system which deteriorates, or actually the repairs do not show a reliable system for an investigation period of four years.

	α between S_1-S_2	α between S_1-S_3	α between S_1-S_4	α between S_1-S_5
mean α values	0.06	0.09	0.07	0.04

Table 7.2 Estimation of sample means of time to repair.

Sample means of time to repair	For first repair, S_1	For second repair, S_2	For third repair, S_3	For fourth repair, S_4	For fifth repair, S_5
months	19.4	12.6	12.2	10.0	13.7

The significance, i.e. that the strata really do differ from one another, is made by comparing the differences of expectation value of each strata, given that an exponential distribution of mean life is assumed, Appendix H. The significance test shows that for small differences in expectation value it is necessary to model large numbers of breaks. For pipe data it can be assumed that stratum=1 and stratum=2 are of quite different distributions and the expected lives of unbroken pipes is long and therefore likely to have a considerable difference in mean life between repairs of stratum i=1 and strata 2, 3, 4 and 5. This gives, if an exponential distribution is assumed, referring to Appendix H, good significance with the used number of breaks.

The evaluation of the data from Örebro indicated that the influence of early breaks, within a couple of months from first break, can be revealed through this model. The results from an estimation of α, the quality variable for Örebro, gave positive α which may represent a system which is deteriorating. In other words, during the investigation period of four years, the repairs may not contribute to improve the hazard rate for the system.

Used as shown here the suggested model is reliable in showing system performance with time to repairs related to the running, elapsed time. One problem with this model is that parameters of baseline hazard function and quality variable cannot be identified separately and this leads to mathematical difficulties in estimation.

8. CONCLUSIONS

Today, the possibility for investigating deterioration of pipe systems is limited to visual sample inspections. Information about maintenance actions and repair events and their contribution to deterioration is commonly not in use but is recorded in break records. The break records contain the essential factors, age (time), diameter and previous breaks. Other factors are of a more descriptive nature.

The literature includes some models for break analysis. These models are partly based on pipe records although the recorded factors are often found to be insufficient for analysis. There are three main factors which are important in break analysis, location, previous breaks and operating pressure. To fit pipe records to reliability aspects, some conclusions are set:

a) It is essential that pipe records include previous failures. This implies that the break location site has to be specified so that subsequent failures can actually be numbered. The location needs to be more strictly characterized and defined. Break rate based on first failures can be more easily adapted for use in comparative analysis if due regard is paid to these stricter definitions.

b) The dependence of corrosion/location/repairs has to be analyzed. The break types used in pipe records today cannot be used in analysis to define corrosion. The break types should essentially be defined from the actual maintenance actions undertaken and specified in terms of reliability aspects such as operational stress wear and tear, quality of construction and maintenance. The pipe records where only main breaks are recorded will therefore be insufficient as long as the repair actions and repairs of components are not incorporated.

c) The history of replaced pipes should not be discarded when the pipes are replaced. It is important to save this information for further analysis.

I suggest basing a preventative reliability analysis on pipe records, but it is necessary to develop two separate models, one for individual pipes and component performance, the other for describing and evaluating system performance.

The model for individual analysis should be based on broken pipes, where the knowledge of break patterns is good. The individual analysis should evaluate the different pipe materials, evaluate pipe components used in relation to maintenance events and improve the understanding of corrosion by evaluating break patterns. The model should be a proportional hazard type of model, similar to that of Andreou (1986). The break patterns could be evaluated by defining the type of the first break and the use of modelled, different baselines for break rates. The time used in the model is the time between breaks, which gives an opportunity to evaluate pipes regardless of their age and to use short investigation periods of 10 years.

The system model should describe system behavior in terms of the variations of breaks and the influence of repair and replacements. The model is based on the work of Pijnenburg, (1991) which defines a quality variable, an explanatory covariate to the elapsed time between breaks and next repair. A reliability parameter for water pipe system improvement or deterioration is developed in this model which is based on the water pipe system as a repairable system with repairable parts. The aim of the model is to investigate whether pipe repairs renew the system or not. Further comparative studies, with the model, of more systems is necessary if the model is to be accepted as a good tool for the evaluation of the influence of repairs on reliability. The critical point of application of the model is the delay in making the simple effort of defining first failures and repairs. Pipe records based on first break and subsequent breaks will greatly improve the possibilities of evaluating and modelling system reliability.

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APPENDIX A COMPARISON OF MUNICIPALITY SYSTEM BREAKS

Table A.1 Municipality system breaks part I, references are 0) Andreou (1986), 1) Larsson et al (1990), 3) Male et al (1990b), 4) O'Day (1982), 5) O'Day (1987), 6) Pettersson (1978) and Reinius (1981).

System length (km)	Number of breaks/1yr	Break rate (breaks/km)		ref no
60.17	14	0.233	Ringköping	1
76.341	1	0.013	Dragör	1
87.643	33	0.377	Korsör	1
91.7	7	0.076	Tibro	2 and 7
93.218	8	0.086	Skandeborg	1
120.1	8	0.067	Surahammar	7
131.2	13	0.099	Oskarshamn	2 6 and 7
165	22	0.133	Gagnef	7
168	13	0.077	Tierp	7
185.1	24	0.130	Avesta	2 6 and 7
217.385	14	0.064	Lindesberg	2 and 7
226	9.5	0.042	Hjörring	1
240	25	0.104	Troy	5
253	16	0.063	Timrå	7
264.7	12	0.045	Bollnäs	2 and 7
282	49	0.174	Höganäs	7
283.016	41	0.145	Fredrikshavn	1
290	62	0.214	Kungsbacka	7
301	19	0.063	Varberg	7
342.73	29	0.085	Gentofte	1
360.07	100	0.278	Fredericia	1
381.9	22	0.058	Växjö	7
386.684	47	0.122	Ålborg	1
391.09	68	0.174	Esbjerg	1
400.7	74	0.185	Eskilstuna	2 6 and 7
429.696	95	0.221	Kenosha Ky.	5
450.1	97	0.216	Västerås	2 6 and 7
527	51	0.097	Linköping	2 6 and 7
544.5	67.5	0.124	Helsingborg	6 and 7
640	26	0.041	Piteå	2 and 7
670.075	72	0.107	Odense	1
813.2	85	0.105	Malmö	2 6 and 7
886.463	111	0.125	Köpenhamn	1
1004	159	0.158	Århus	1
1117.852	23	0.195	Manhattan	3
1266.556	4.6	0.004	Staten Island	3
1394	67.3	0.048	Bronx	3
1461	305	0.209	Göteborg	2 6 and 7
1735	46.5	0.027	Boston Mass.	0 and 4
1892	125	0.066	San Fransisco, Calif.	4
2172.618	171	0.079	District of Columbia	0
2209	106	0.048	St. Louis, Mo.	4
2262	163	0.072	Washington D.C.	4
2369.5	881.5	0.372	New Orleans, La.	0 and 4
2465.841	89.1	0.036	Queens	3
2467.129	261	0.106	Baltimore	0

Table A.2 Municipality system breaks part II, references are 0) Andreou (1986), 1) Larsson et al (1990), 3) Male et al (1990b), 4) O'Day (1982), 5) O'Day (1987), 6) Pettersson (1978) and Reinius (1981).

System length (km)	Number of breaks/1yr	Break rate (breaks/km)		ref no
2724.624	21	0.008	Seattle	0
2884	280	0.097	Denver, Col.	4
2898	421	0.145	Milwaukee, Wis.	4
3016.882	19.9	0.007	Brooklyn	3
3096.384	403	0.130	Kansas City	0
3234	167	0.052	Indianapolis, Ind.	4
3472.971	222	0.064	Denver (DWD)	5
4037.5	363.5	0.090	Louiseville, Ky.	4 an 5
5241.6	789.5	0.151	Philadelphia	0 and 5
5507.185	1309	0.238	Detroit	0
5626.277	901	0.160	East Bay (EBMD)	5
6220	808	0.130	Cincinnatti	4
6420	5144	*	Houston, Tex.	4
6670	223	0.033	Chicago, Ill.	4
10020.7	476	0.048	New York, N.Y.	0 4 and 5
10941	290	0.027	Los Angeles, Calif.	4

*) Houston excluded in Fig 5.4 (5144 breaks/6420 km)

Table A.3 Evaluation of Table A.1 and A.2 with median value of 0.097 breaks/km.

Number of municipalities		Number (percent) of municipalities below median value	Number (percent) of municipalities above median value	Number (percent) equal to median value
less than 2000 km	40	17 (43%)	22 (55%)	1 (2%)
larger or equal to 2000 km	22	13 (59%)	8 (36%)	1 (5%)

APPENDIX B EVALUATION OF PIPE DATA BY $\overline{\text{X}}$-CHART

Processing total number of pipe breaks per year after an 11 year period for a $\overline{x}$-chart, based on break data from Wengström (1989). The upper acceptance level, S_u, is estimated by, for this data applied, "R-method", derived after Bergman and Klefsjö (1991).

the upper acceptance level: $S_u = \overline{\overline{x}} + A_2 * \overline{R}$

$\overline{\overline{x}} =$ $(\overline{x}_1+\overline{x}_2+\overline{x}_3+\overline{x}_4+\overline{x}_5+\overline{x}_6+\overline{x}_7+\overline{x}_8+\overline{x}_9+\overline{x}_{10}) / k$

$\overline{R} =$ $(R_1+R_2+R_3+R_4+R_5+R_6+R_7+R_8+R_9+R_{10}) / k$

$A_2 =$ constant from Table B.1, based on number of individual segments in the k groups.

Table B.1 The A_2 constant, from Bergman and Klefsjö (1991).

Number of individuals in each k group	2	3	4	5
The A_2 constant	1.880	1.023	0.729	0.577

Table B.2 Estimation of upper acceptance level with data from Wengström (1989).

k groups	Year	Occurrence of breaks (single, first breaks only)	Moving, sample mean in k groups of broken pipe segments, $\overline{x}$	R_k, variance in each k group: max. value - min. value
	1977	0		
1			(0+2)*1/2=1	2-1=1
	1978	2		
2			(2+1)*1/2=1.5	2-1=1
	1979	1		
3			(1+3)*1/2=2	3-1=2
	1980	3		
4			(3+3)*1/2=3	3-3=0
	1981	3		
5			(3+5)*1/2=4	5-3=2
	1982	5		
6			(5+2)*1/2=3	5-2=3
	1983	2		
7			(2+3)*1/2=2.5	3-2=1
	1984	3		
8			(3+7)*1/2=5	7-3=4
	1985	7		
9			(7+5)*1/2=6	7-5=2
	1986	5		
10			(5+9)*1/2=7	9-5=4
	1987	9		

Calculations: $k=10$

$A_2=1.880$

$\bar{\bar{x}}=35/10=3.5$

$\bar{R}=21/10=2.0$

$S_u=3.5+1.880 * 2.0=7.26=7.3$

Appendix C Evaluation of Costs for an Increase of Subsequent Breaks

An evaluation of present values of repair and replacement costs for two replacement strategies after 10, 15 and 20 years when the fictive increase of places with subsequent breaks is 1, 2 or 3 places per year.

Table C.1 Present values at a discount rate of 4%, used in estimation of total costs for 10 years, Table C.2, for 15 years, Table C.3 and for 20 years, Table C.4, after Gustafsson and Svensson (1992).

For year i	Discount factor (DF)**	Sum of discount factors over year i (SDF)*
i=5	0.8219	not used
i=10	0.6756	8.1109
i=15	0.5553	11.1184
i=20	0.4564	13.5903

*) equals present value of 1 SEK per year for each i year
**) equals present value of 1 SEK to be recieved after i years

Calculations of cost of repairs are made in Table C.2, C.3 and C.4, such as following equation (eq C.1):

Present value
for cost of repairs = total breaks over period, year 0 to i * cost of repair for each break * PS_i/i

(the cost of repair for each break was estimated to be 35 000 SEK)

Calculations of cost of replacement are made in Table C.2, C.3 and C.4, such as following equation (eq. C.2):

Present value
for cost of replacement = total replaced pipe length in periods, year 0 to replacement year, up to year i*cost of replacement for each meter pipe * $DF_{(\text{at each replacement year})}$

(the cost of a replacement per m pipe were estimated to be 2 000 SEK)

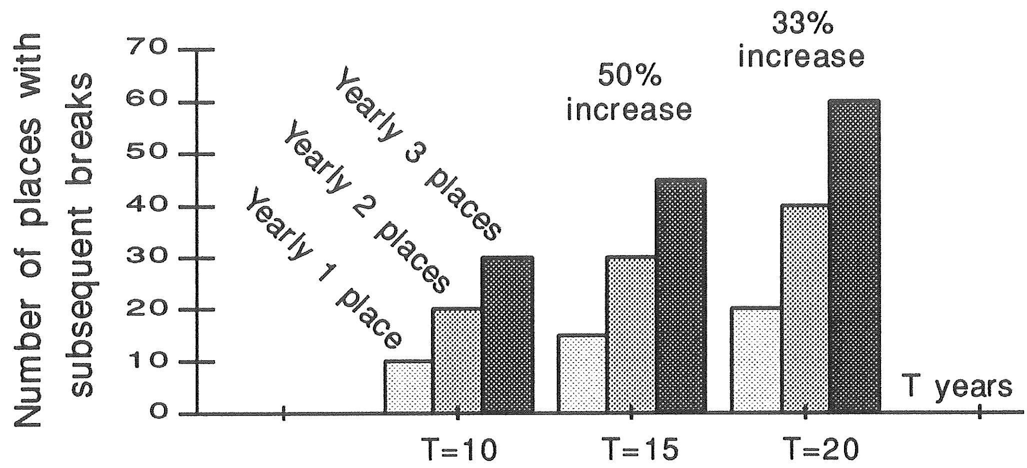


Fig C.1 A fictive increase in number of places with subsequent breaks if the assumed increase is 1 place per year, 2 places per year or 3 places per year.

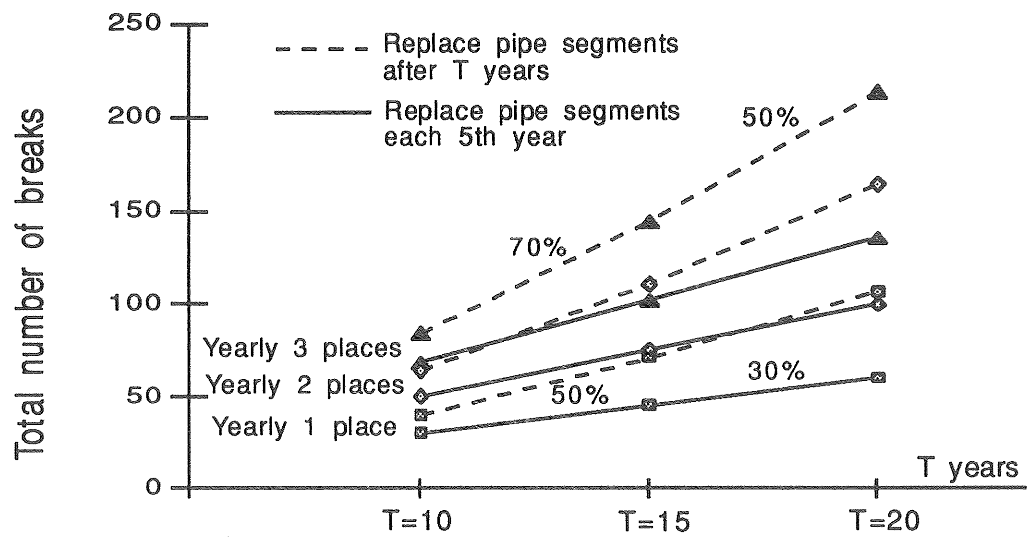


Fig C.2 The fictive number of total breaks, estimated by eq. 6.1, when the increase of places with subsequent breaks is 1 per year, 2 per year or 3 per year.

Table C.2 Total costs for replacement and repairs, in present values of Swedish crowns (SEK), when the yearly increase in numbers of pipes where subsequent breaks occurs is varied between 1, 2 or 3 pipes per year. The subsequent breaks are estimated with eq. 6.1. The costs are estimated with a discount rate of 4% and present values from Table C.1.

D-rate	Total breaks	Replaced pipes	Breaks per pipe	Approx. pipe length* (m)	Cost of repairs (SEK)	Cost of replacement (SEK)	Total cost (SEK)
Replace each 5th year, in 10 year							
1	30	10	3	200	852 000	2 995 000	3 847 000
2	50	20	2.5	200	1 419 000	5 990 000	7 409 000
3	68	30	2.2	200	1 930 000	8 985 000	10 915 000
Replace after 10 years							
D-rate	Total breaks	Replaced pipes	Breaks per pipe	Approx. pipe length* (m)	Cost of repairs (SEK)	Cost of replacement (SEK)	Total cost (SEK)
1	40	10	4	300	1 135 000	4 054 000	5 189 000
2	64	20	3.2	200	1 817 000	5 405 000	7 222 000
3	84	30	2.8	200	3 385 000	8 107 000	11 492 000

* approximation is based on breaks per pipe to be equivilent to number of breaks in Table C.5
D-rate = the yearly increase in numbers of those pipes which gets subsequent breaks

Table C.3 Total costs for replacement and repairs, in present values of Swedish crowns (SEK), when the yearly increase in numbers of pipes where subsequent breaks occurs is varied between 1, 2 or 3 pipes per year. The subsequent breaks are estimated with eq. 6.1. The costs are estimated with the a discount rate of 4% and present values from Table C.3.

Replace each 5th year, in 15 year							
D-rate	Total breaks	Replaced pipes	Breaks per pipe	Approx. pipe length* (m)	Cost of repairs (SEK)	Cost of replacement (SEK)	Total cost (SEK)
1	45	15	3	200	1 167 000	4 106 000	5 273 000
2	75	30	2.5	200	1 946 000	8 211 000	10 157 000
3	102	45	2.3	200	2 646 000	12 317 000	14 963 000
Replace after 15 years							
D-rate	Total breaks	Replaced pipes	Breaks per pipe	Approx. pipe length* (m)	Cost of repairs (SEK)	Cost of replacement (SEK)	Total cost (SEK)
1	71	15	4.7	300	1 842 000	4 998 000	6 840 000
2	111	30	3.7	300	2 880 000	9 995 000	12 875 000
3	145	45	3.2	200	3 763 000	9 995 000	13 757 000

* approximation is based on breaks per pipe to be equivilent to number of breaks in Table C.5
D-rate = the yearly increase in numbers of those pipes which gets subsequent breaks.

Table C.4 Total costs for replacement and repairs, in present values of Swedish crowns (SEK), when the yearly increase in numbers of pipes where subsequent breaks occurs is varied between 1, 2 or 3 pipes per year. The subsequent breaks are estimated with eq. 6.1. The costs are estimated with a discount rate of 4% and present values from Table C.1.

Replace each 5th year, in 20 years							
D-rate	Total breaks	Replaced pipes	Breaks per pipe	Approx. pipe length* (m)	Cost of repairs (SEK)	Cost of replacement (SEK)	Total cost (SEK)
1	60	20	3	200	1 427 000	5 019 000	6 446 000
2	100	40	2.5	200	2 378 000	10 037 000	14 793 000
3	136	60	2.3	200	3 235 000	15 055 000	18 291 000
Replace after 20 years							
D-rate	Total breaks	Replaced pipes	Breaks per pipe	Approx. pipe lenght* (m)	Cost of repairs (SEK)	Cost of replacement (SEK)	Total cost (SEK)
1	107	20	5.4	300	2 545 000	5 477 000	8 022 000
2	165	40	4.1	300	3 924 000	10 954 000	14 878 000
3	214	60	3.6	300	5 090 000	16 430 000	21 520 000

* approximation is based on breaks per pipe to be equivilent to number of breaks in Table C.5
D-rate = the yearly increase in numbers of those pipes which gets subsequent breaks.

Table C.5 A study of actual individual break places, their pipe lengths and the number of breaks over a five year period, (1980-85), from Göteborgs vatten- och avloppsverk (1989).

Number of breaks over investigation period	Pipe length, (km)	Median pipe length (km)
1		not investigated
2	0.2	0.2
3	0.2 0.15	0.2
4	0.3 0.15 0.15 0.2 0.4 0.2 0.2 0.9 0.5 0.4 0.3	0.3
5	0.35 0.25 0.25 0.25 0.1 0.5 0.25 0.3 0.5 0.7	0.3
6	0.35 0.2 0.4 0.25 0.25 0.2 0.45 0.3 0.4	0.3
7	0.3 0.5 0.4	0.4
8		-
9	0.7	0.7
10	1.0 0.9 0.7	0.9
11	0.9 1.4 1.0 1.2 1.0	1.0
12	2.0 1.8	1.9
13		-
14	2.0 1.2 2.5 1.1	1.6
15		-
16		"
17	1.3	"
18	1.7 1.0	"
19		"
20	2.2	"
21		"
22	2.5	"
23	3.0	" = 2.5
24		"
25	7.5	"
26	3.0	"
27	3.0	"
28		"
29		"
30		"
31		-
32		"
33	6.5 2.0	"
34		"
35	3.0	"
36		"
37		"
38	6.0	"
39		"
40		" = 5.5
41		"
42		"
43		"
44		"
45		"
46		"
47		"
48	5.5	-

APPENDIX D EVALUATED PIPE RECORD DATA FROM GÖTEBORG

Table D.1 Comparison of actual ductile break data and an approximation of the yearly increase of subsequent breaks processed with eq. 6.1.

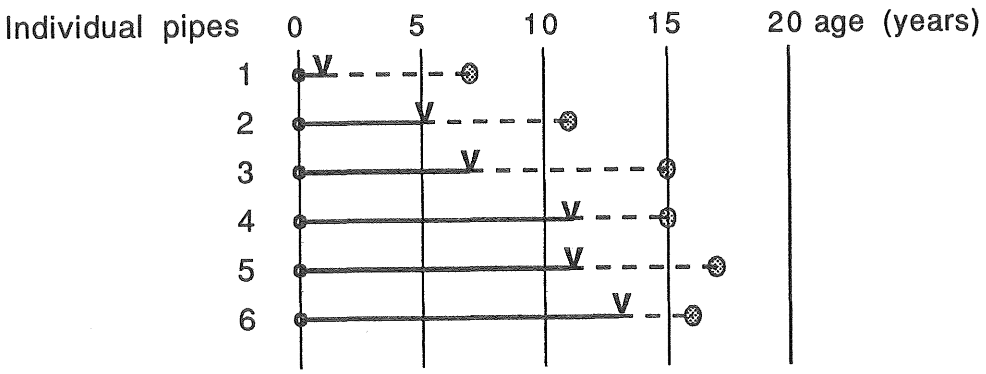
Year	Number of breaks where no subsequent breaks occurred	Number of first break where later subsequent breaks occurred	Number of subsequent breaks	Actual cumulative numbers of subsequent breaks	Subsequent breaks, (cumulative) with eq 6.1 when the increase of places with subsequent breaks are 1/year
1 (1977)	0	0	0	0	0
2 (1978)	2	3	1	1	2.8
3 (1979)	1	0	4	5	4.2
4 (1980)	3	0	1	6	6.9
5 (1981)	3	2	2	8	10
6 (1982)	5	1	4	12	13.4
7 (1983)	2	2	5	17	17.1
8 (1984)	3	3	7	24	21.2
9 (1985)	7	2	4	28	25.5
10 (1986)	5	1	9	37	30
11 (1987)	9	not evaluated	≤9	37-42	34.8

Table D.2 Break type categories, time to first break and residual time, time without breaks after one break occurred.

Break type defined on the basis of first break	Variable	value for 25% of pipe segments (years)	median value (years)	value for 75% of pipe segments (years)	Number of pipes	Average value (years)
Accidental failures	time to first failure	3	9	12	6	8
	residual time	3.5	6	6	6	5.5
Bursts	time to first failure	9.5	11.5	14.5	17	11.7
	residual time	0	1	2.5	17	2.6
Corrosion	time to first failure	8.5	12.5	14	18	11.8
	residual time	0	1	1.5	18	1.4
Joint- and material failures	time to first failure	9.5	12.5	13.5	14	11.1
	residual time	1	2	4	14	2.6
Unmarked*	Time to first failure		11.5		2	11.5

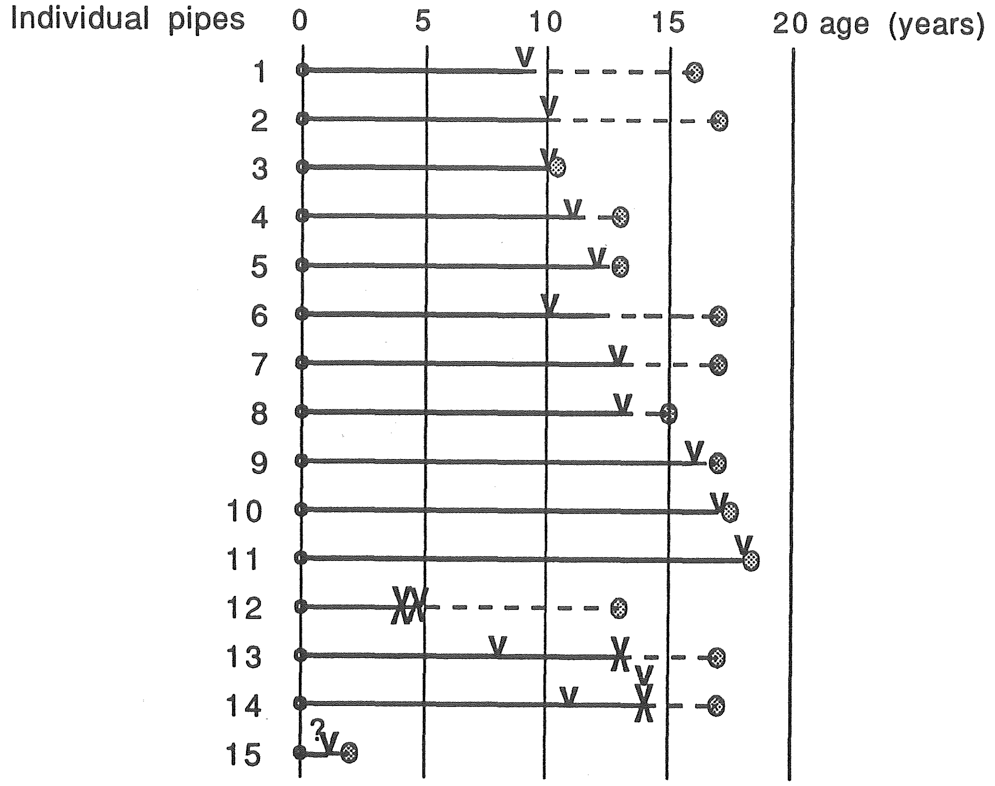
* some broken pipe segments had nothing of significant recorded for base a break type.

The following figures, D.1 - D.5, are based on ductile iron pipe breaks, retrieved from pipe records 1977-1981, from Wengström (1989). The break categories are based on the recorded appearance of first breaks. A "V" marks the breaks for the pipe segments with more than one repair. The dotted line show the residual, trouble-free time without breaks, until the investigation period ends. Pipes, marked with * are repaired once, or more times during the investigation period. The residual time, i.e. time to second break, includes break times for pipes having a second break as well as the censored break time for pipes having no breaks, indexed with c, during the investigation period. Table D.2 shows the summarized results for four of the break type categories.



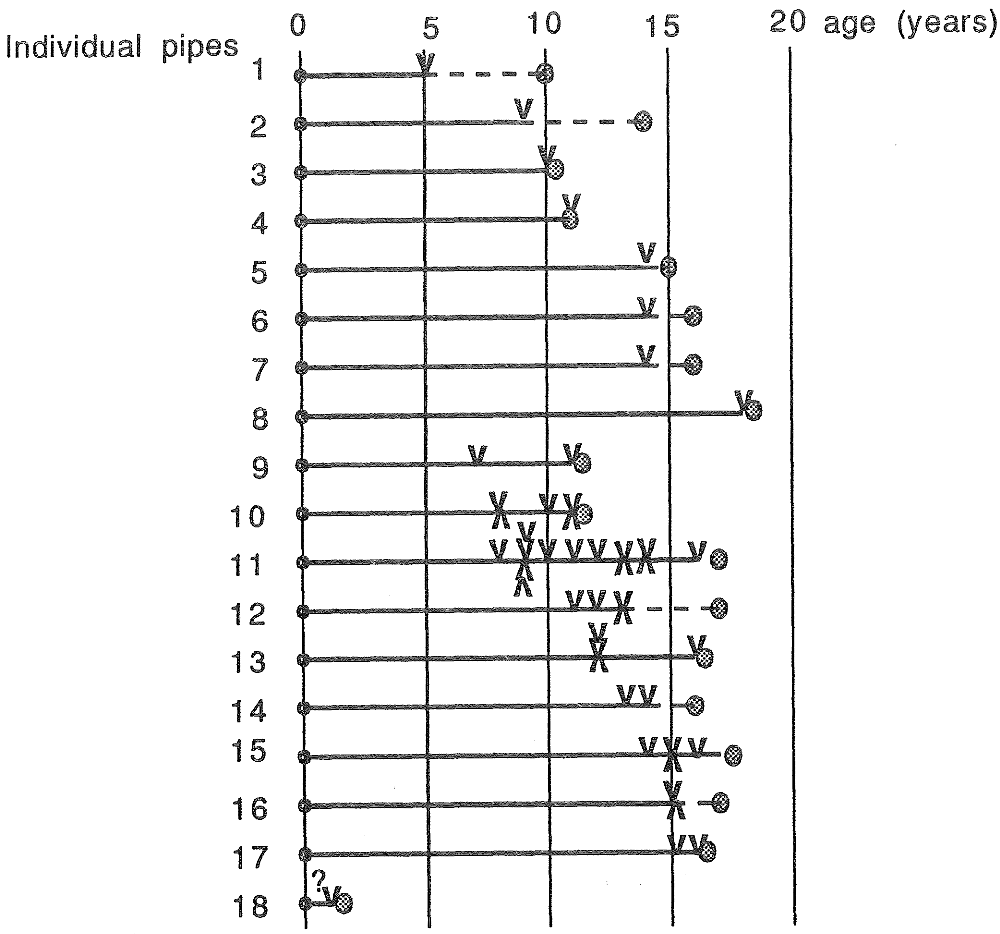
Pipe segment number, j	1	2	3	4	5	6
Age at first break, years	1	5	7	11	11	13
Age at end of period, years	7	11	15	15	17	16
Time to second break/-residual time, years	6_c	6_c	8_c	4_c	6_c	3_c

Fig. D.1 Processed pipe record data for pipe segments "Accidental failures".



Pipe segment number, j	12	13	1	2	3	4	14	5	6	7	8	9	10	1
Age at first break, years	4	8	9	10	10	11	11	12	12	13	13	16	17	18
Age at end of period, years	13*	17*	16	10	17	13	17*	13	17	15	17	17	17	18
Time to second break/residual time, years	0	5	7_c	7_c	0_c	2_c	3	1_c	5_c	4_c	2_c	1_c	0_c	0_c

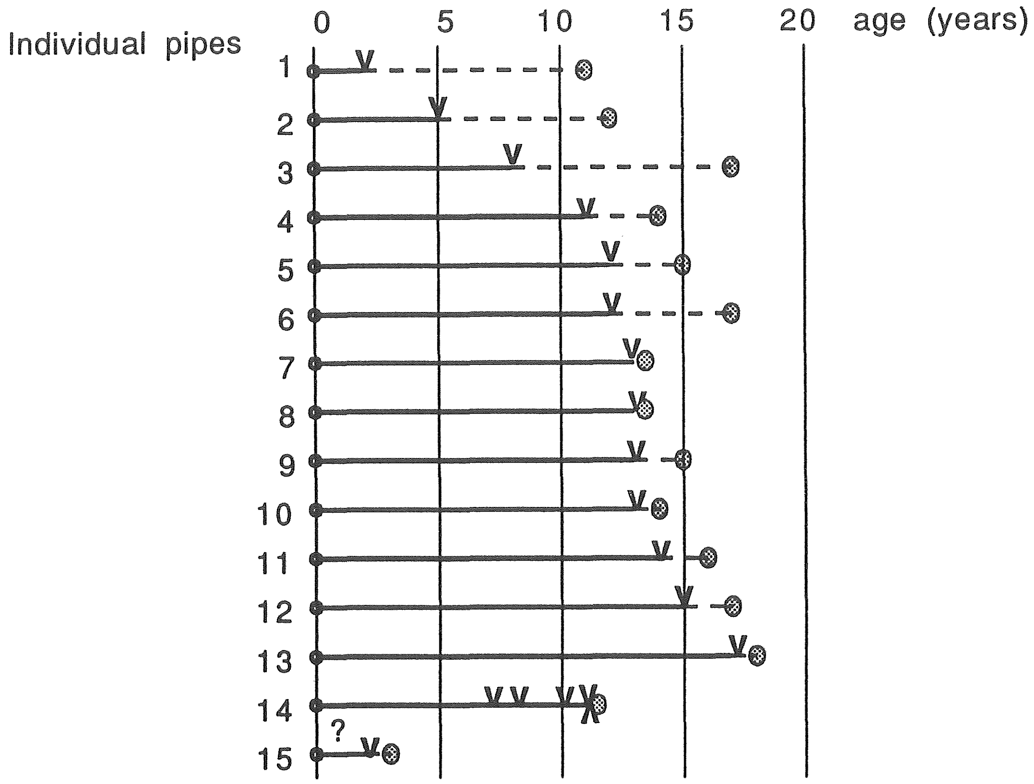
Fig. D.2 Processed pipe record data for pipe segments "Bursts".



Pipe segment number, j	1	9	10	11	2	3	4	12	13
Age at first break, years	5	7	8	8	9	10	11	11	12
Age at end of period, years	10	11*	11*	17*	14	10	11	17*	17*
Time to second break/residual time, years	5_c	4	0	1	5_c	0_c	0_c	1	0

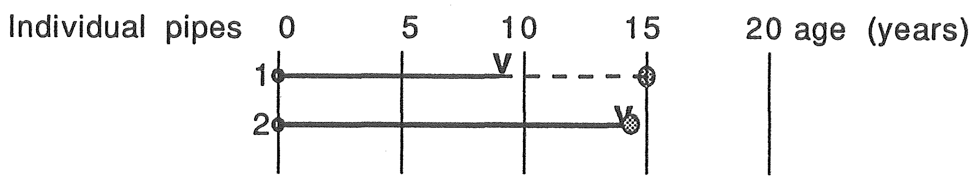
Pipe segment number, j	14	5	15	16	6	7	17	18	8
Age at first break, years	13	14	14	14	14	14	15	15	18
Age at end of period, years	16*	15	16*	17*	16	16	17*	16*	18
Time to second break/residual time, years	1	1c	2	2	1c	1_c	0	1	0_c

Fig. D.3 Processed pipe record data for pipe segments "Corrosion".



Pipe segment number, j	1	2	14	3	4	5	6	7	8	9	10	11	12	13
Age at first break, years	2	5	7	8	11	12	12	13	13	13	13	14	15	17
Age at end of period, years	11*	12*	11*	17	14	15	17*	13	13	14	15	16	17	18
Time to second break/residual time, years	1_c	9_c	7	1_c	3_c	3_c	5_c	0_c	0_c	2_c	1_c	2_c	2_c	1_c

Fig. D.4 Processed pipe record data for pipe segments "Joint- and material failure".



Pipe segment number, j	1	2
Age at first break, years	9	14
Age at end of period, years	15	14
Time to second break/-residual time, years	6_c	0_c

Fig. D.5 Processed pipe record data for pipe segments "Unmarked".

APPENDIX E BREAK TYPE PERFORMANCE AND ESTIMATION OF BASELINE FUNCTION

Estimation of baseline, h_0^*, time between first and second break (TTF) or time between first break and censored residual life (RT). Based on pipe breakage of ductile iron pipes, from Wengström (1989). The investigation period was from 1977 to 1987 and in the cases where pipe segments had only one break recorded during these 11 years, the time to next break was censored with the year the investigation ended. The data is not continuous, but monthly values.

Table E.1 Estimation of time between break by break dates, (year-month) and censored with the investigation end (1987-12) for data grouped as bursts.

Type of data, C=censored F=not censored	Installation year	First break date/second or to 1987-12	Estimation of time to break as TTF or RT	Time between break in months
C	1971	1980-03/1987-12	9months+7years*12months/year 3 +7*12	93
C	1970	1980-09/1987-12	10 +0	87
C	1977	1987-02/1987-12	8 +2*12	10
C	1974	1985-04/1987-12	10 +12*1	32
C	1974	1986-02/1987-12	0 +5*12	22
C	1970	1982-12/1987-12	3 +4*12	60
C	1970	1983-01/1987-12	8 +2*12	51
C	1972	1985-04/1987-12	11 +1*12	32
C	1970	1986-01/1987-12	10	23
C	1970	1987-02/1987-12	8	10
C	1969	1987-04/1987-12	2	8
F	1974	1978-03/1978-05	5 +5*12 + 2	2
F	1970	1978-07/1983-02	8 +2*12 + 3	67
F	1970	1981-04/1984-03		35

Table E.2 Burst data ordered and calculation of sample mean range as n-v/(n-v+1) with n=14.

Ordered data	Time between breaks (months)	v	Sample mean range	$\hat{R}$, probability of not failure
		0		1
F	2	1	13/14	0.929
C	8	2	.	
C	10	3	.	
C	10	4	.	
C	22	5	.	
C	23	6	.	
C	32	7	.	
C	32	8	.	
F	35	9	13/14*5/6	0.774
C	51	10	.	
C	60	11	.	
F	67	12	13/14*5/6*2/3	0.516
C	87	13	.	
C	93	14	.	

Result: Assuming h_0^* for burst to be equal to $\hat{R}$. $\hat{R}$ is estimated:

t>2	$\hat{R}$=1
2<=t<35	$\hat{R}$=0.93
35<=t<67	$\hat{R}$=0.77
67<=t<93	$\hat{R}$=0.52
t>=93	$\hat{R}$=0

Table E.3 Estimation of time between break by break dates, (year-month) and censored with the investigation end (1987-12) for data grouped as corrosion.

Type of data, C=censored F=not censored	Installation year	First break date/second or to 1987-12	Estimation of time to break as TTF or RT	Time between break in months
C	1977	1982-06/1987-12	6 months+5years*12months/year	66
C	1973	1982-08/1987-12	4 +5*12	64
C	1977	1987-01/1987-12	11	11
C	1976	1987-07/1987-12	5	5
C	1972	1986-10/1987-12	2 +1*12	14
C	1971	1985-08/1987-12	4 +2*12	28
C	1971	1985-07/1987-12	5 +2*12	29
C	1969	1987-07/1987-12	5	5
F	1976	1983-05/1986-09	7 +9	16
F	1976	1984-06/1984-08	2	2
F	1970	1978-07/1979-04	5 +4	9
F	1970	1981-07/1982-08	5 +8	13
F	1970	1982-01/1982-06	5	5
F	1971	1984-12/1983-03	3	3
F	1970	1984-06/1985-07	6 +7	13
F	1971	1985-10/1986-02	2 +2	4
F	1970	1985-06/1985-07	1	1
F	1971	1986-09/1987-09	3 +9	2

Table E.4 Corrosion data ordered and calculation of sample mean range as n-v/(n-v+1) with n=14.

Ordered data	Time between breaks (months)	v	Sample mean range	$\hat{R}$, probability of not failure
		0		1
F	1	1	17/18	0.944
F	2	2	17/18*16/17	0.889
F	3	3	17/18*16/17*15/16	0.833
F	4	4	17/18*16/17*15/16*14/15	0.778
C	5	5	. 17/18*16/17*15/16*14/15*12/13	
F	5	6	.	0.718
C	5	7	17/18*16/17*15/16*14/15*12/13*10/11	
F	9	8	. 17/18*16/17*15/16*14/15*12/13*10/11*8/9	0.633
C	11	9	17/18*16/17*15/16*14/15*12/13*10/11*8/9*7/8	
F	12	10	17/18*16/17*15/16*14/15*12/13*10/11*8/9*7/8*6/7	0.580
F	13	11	.	0.508
F	13	12	17/18*16/17*15/16*14/15*12/13*10/11*8/9*7/8*6/7*4/5	0.435
C	14	13	.	
F	16	14	.	0.348
C	28	15	.	
C	29	16		
C	64	17		
C	66	18		
		>18		0

Results: Assuming h_0^* for corrosion to be equal to $\hat{R}$. $\hat{R}$ is estimated:

t=0	$\hat{R}$=1
t=1	$\hat{R}$=0.944
t=2	$\hat{R}$=0.889
t=3	$\hat{R}$=0.833
4<=t<6	$\hat{R}$=0.778
6<=t<8	$\hat{R}$=0.718
8<=t<10	$\hat{R}$=0.653
t=10	$\hat{R}$=0.580
t=11	$\hat{R}$=0.508
11<=t>14	$\hat{R}$=0.435
14<=t>18	$\hat{R}$=0.348
>18	$\hat{R}$=0

Appendix F Time Ordered Repair Data for the Additive Hazard Model

Table F.1 The time ordered data are repairs of mains from the water utility of Örebro, collected and aggregated from pipe records from 1986-1989.

Running time/ start of period (year/month)	X_1	Time to next break (months)	X_2	X_3	X_4	X_5
		0	8	1	2	3
1986-1		1	3	1	1	
2		2	1	2		
3		3	3	1	1	
4	13	4	4	2		
5	8	5	3	1		
6	10	6		2		
7	3	7		2	1	
8	6	8	3			
9	3	9	2	1		1
10	1	10		1		
12	5	11	5	1		
1987-1	12	12	2	1		1
2	6	13	2			1
3	11	14	2		2	1
4	6	15		2	1	
5	2	16	1		1	
6	2	17	1	1		
7	3	18		1		
8		19		1		
9	11	20	2		1	
10	3	21	2	1		
11	3	22	1	2		
12		23	1			
1988-1	3	24	1			
2	4	25	1			
3	3	26	1			
4	2	27	1			
5	2	28				
6	4	29	1			
7	1	30				
8	1	31	2			1
9	3	32	1			
10	2	33				
11	4	34				
12	5	35				1
1989-1	7	36	1			
2		37				
3	1	38				
4	2	39				
5	2	40				
6	4	41				
7	2	42		1		
8	3					
9	5					
10	3					
11	1					
12	1					
Total	**181**		**55**	**25**	**10**	**9**

APPENDIX G DATA FILE USED FOR MODELLING SYSTEM PERFORMANCE

This is an example of the edit-file used for model system performance with an additive hazard model using the program MathLab. The data-files were transformed to and used with HarwardGraphics to produce figures.

'Repair data from Örebro, time t from beginning of the study 1986 up to each repair on N pipe segment: X1= first repair (months), X2=second repair (months), X3=third repair (months), X4=fourth repair (months) and X5=fith repair (months) '

```
t=[0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29
30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48];

X1=[0 0 0 0 13 8 10 8 3 6 3 1 5 12 6 11 6 2 2 3 0 11 3 3 0 3 4 3 2 2 4 1 1 3 2 4 5
7 0 1 2 2 4 2 3 5 3 1 1];
N1=191

X2=[8 3 1 3 4 3 0 0 3 2 0 5 2 2 2 0 1 1 0 0 2 2 1 1 1 1 1 1 0 1 0 2 1 0 0 0 1 0 0 0
0 0 0 0 0 0 0 0 0];
N2=55

X3=[1 1 2 1 2 1 2 2 0 1 1 1 1 0 0 2 0 1 1 1 0 1 2 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 1 0 0 0 0 0 0];
N3=25

X4=[2 1 0 1 0 0 0 1 0 0 0 0 0 0 2 1 1 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0];
N4=10

X5=[3 0 0 0 0 0 0 0 0 1 0 0 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 1 0 0 0 0
0 0 0 0 0 0 0 0 0];
N5=9
```

'Model calculation of R, probability of survival for each strata,1,2,3,4 and F equals failure time'

```
        F1=cumsum(X1);
        R1 = 1-F1/N1;

        F2=cumsum(X2);
        R2 = 1-F2/N2;

        F3=cumsum(X3);
        R3 = 1-F3/N3;

        F4 =cumsum(X4);
        R4 = 1-F4/N4;

        F5 = cumsum(X5);
        R5 = 1-F5/N5;
```

```
'to test for additivity (H) for each strata against gap time t (i), (U=H/i)'
            H1 = -log10(R1);
            H2 = -log10(R2);
            H3 = -log10(R3);
            H4  = -log10(R4);
            H5 = -log10(R5);
                for i=1:49
                U1(i)=H1(i)/t(i);   U2(i)=H2(i)/t(i);   U3(i)=H3(i)/t(i);   U4(i)=H4(i)/t(i);
                U5(i)=H5(i)/t(i);
                end
plot(t, U1,t, U2,t,U3,t,U4,t,U5)

'to test for proportionality (P) for each strata'
         P1 = log10(H1);
         P2 = log10(H2);
         P3 = log10(H3);
         P4 = log10(H4);
         P5 = log10(H5);

'to save data H in other programs, such as Harvard Graphics'
         sim=[t;H1;H2;H3;H4;H5];
         simt=sim'
         save fsim.HNN  simt /ascii

'to plot proportionality test in MathLab'
plot(t,H1,t,H2,t,H3,t,H4,t,H5)
semilogy(t,H2)

'Quarterly values, (the sum of three months) indata are: StratumX1=Q1, StratumX2=Q2,
StratumX3=Q3, StratumX4=Q4 and StratumX5=Q5, and i=17'
T=[0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16];
Q1=[0 0 31 17 9 29 10 14 6 10 8 5 11 8 8 10 4];
Q2=[8 7 7 5 7 4 2 4 3 3 1 3 1 0 0 0 0];
Q3=[1 4 5 3 3 2 2 2 2 0 0 0 0 0 1 0 0];
Q4=[2 2 0 1 0 3 1 1 0 0 0 0 0 0 0 0 0];
Q5=[3 0 0 1 1 2 0 0 0 0 0 1 1 0 0 0 0];
'for i=1:17 ...... end'
```

Break patterns were simulated for approximately time of 12 years and data used for simulation was quarterly values:

in b) in Fig 7.1, for stratum 1: N=543
0 0 31 17 9 29 10 14 6 10 8 5 11 8 8 10 5 0 31 17 9 29 10 14 6 10 8 5 11 8
8 10 5 0 31 17 9 29 10 14 6 10 8 5 11 8 8 10 5

for stratum 2: N=141
4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 0 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 0 2 2 2 2 2
2 2 2 2 2 2 2 2 2 2

for stratum 3: N=72
2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 1 2 1 2 1 2 1 2 1 2 1 2 1 2 2 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 0

in c) in Fig 7.1, for stratum 1: N=543
0 0 31 17 9 29 10 14 6 10 8 5 11 8 8 10 5 0 31 17 9 29 10 14 6 10 8 5 11 8
8 10 5 0 31 17 9 29 10 14 6 10 8 5 11 8 8 10 5

for stratum 2: N=143
3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 1 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 1 3 3 3 3 3 3
3 3 3 3 3 3 3 3 3 1

for stratum 3: N=70
2 1 2 1 2 1 2 1 2 1 2 1 2 1 2 1 0 2 1 2 1 2 1 2 1 2 1 2 1 2 1 2 0 2 1 2 1 2 1
2 1 2 1 2 1 2 1 2 0

in d) in Fig 7.1, for stratum 1: N=543
0 0 31 17 9 29 10 14 6 10 8 5 11 8 8 10 5 0 31 17 9 29 10 14 6 10 8 5 11 8
8 10 5 0 31 17 9 29 10 14 6 10 8 5 11 8 8 10 5

for stratum 2: N=146
2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 4 4 4 4 4 4
4 4 4 4 4 4 4 4 4 4

for stratum 3: N=68
0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 2 1 2 1 2 1 2 1 2 1 2 1 2 1 2 0 2 2 2 2 2 2
2 2 2 2 2 2 2 2 2 0

Time, quarterly, is from 0 up to 49.

APPENDIX H TEST OF SIGNIFICANCE

To test that the noted difference in the different strata, i=1, i=2 and i=3 is significant the following test was made.

Basic definitions

Let $\xi_1, \ldots, \xi_n$ be samples from an exponential distribution of expectation μ_1, and let $\eta_1, \ldots \eta_n$ be samples from an exponential distribution of expectation μ_2.

To state that the values μ_1 and μ_2 are different, we test the null hypothesis H_0: $\mu_1 = \mu_2$. The test statistic T is used

$$T = \frac{1}{n}\sum_{i=1}^{n}\xi_i - \frac{1}{n}\sum_{i=1}^{n}\eta_i \quad \text{(the difference of observed means)}$$

T is approximately from a normal distribution with expectation $\mu_1 - \mu_2$ and standard deviation = $\sqrt{\frac{\mu_1^2+\mu_2^2}{n}}$

For a reasonable large number of n we may use the observed standard deviation as if it were the actual standard deviation. A 95% confidence interval for $\mu_1-\mu_2$ is then given by

$$\mu_1-\mu_2 = T \pm 1.96 * \sqrt{\frac{\mu_1^2+\mu_2^2}{n}}$$

Suppose $\mu_1>\mu_2$. Let $\rho = \mu_1/\mu_2 < 1$. Reject H_0 if $T > 1.96 * \sqrt{\frac{\mu_1^2+\mu_2^2}{n}}$, that is if

$$T > 1.96 * \sqrt{\frac{1+\rho^2}{n}}$$

The power of the test is the probability of rejecting H_0 and is given by

$$P(\text{reject } H_0) = P(T > 1.96\, \mu_1 * \sqrt{\frac{1-\rho^2}{n}}) = 1 - \phi(1.96 - \frac{\sqrt{n}(1-\rho)}{\sqrt{1-\rho^2}})$$

(Underlined is obtained from a table of normal distribution)

For some values of n and ρ the power of the test will be as shown in Table 1.

Table H.1 Level of significance for the test of the hypothesis.

n \ ρ	0.9	0.8	0.5
20	0.05	0.10	0.52
50	0.08	0.19	0.89
100	0.11	0.34	0.99
200	0.18	0.60	1.00
500	0.38	0.94	1.00
1000	0.65	1.00	1.00

It can be seen that the essential number of observations to show difference between strata is dependent on ρ. For ρ=0.9, which corresponds to a difference in observations means of 10%, a number of for example, below 1000 observations, gives a low power of the test, while for ρ=0.5 a sample of 50 to 100 observations are enough for give a good test.

However, the assumption that lifetimes follow an exponential distribution is a rough estimation, compared with lifetimes of the additive hazard model, but gives an indication of the necessary sample size.

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1993