Water mains and distribution pipes in soil – external corrosion and protection methods

G. Camitz
Swedish Corrosion Institute, Kräftriket 23 A, SE-104 05 Stockholm, Sweden

Abstract Extensive statistical investigations based on damage reports show that the corrosion damage frequency for buried water mains and distribution pipelines in Sweden increased during the 1970s and 1980s. For this reason, a number of statistical and technical investigations of the corrosion and counter-measures were carried out.

The paper reports on the corrosion damage statistics for water pipelines and the costs of the corrosion damage. Further, ways of actively working to reduce the corrosion damage frequency are described. These measures include the introduction of cast iron pipes with high quality coatings and the application of cathodic protection on different types of existing pipelines, and, further, the systematic replacement of pipeline sections, which show a high corrosion damage frequency.
Key words Corrosion; water main; pipelines, soil; damage statistics; protective coatings; cathodic protection

Introduction

During the 1950s, 1960s and 1970s, considerable extensions were made to the water main and distribution pipeline networks in Sweden. During the 1970s, an average of ca 1500 km water pipelines were laid per year at an annual cost of ca SEK 450 million.

Because an increase in the number of water leaks was observed during the 1970s, a number of statistical and technical investigations were carried out to determine the extent of the damage, the causes of the damage, and the damage costs. Investigations were also carried out to determine the reasons for premature corrosion damage on the pipelines. The effects of different countermeasures, such as the introduction of improved protective coatings on new water pipes and the application of cathodic protection on existing pipelines, were studied. This report presents the results from some of these investigations.

Document sources for the studies referred to in this report can be found in references 1–12 in the Swedish journal *Bygg & Teknik* (Stockholm) No 5, 1995 (Camitz, 1995).

Total length of pipelines and maintenance costs

The total length of underground water pipelines in Sweden is ca. 61000 km. Statistics are available for approximately half the pipeline network and this part consists of ca 57 % cast iron pipelines (grey iron and ductile-iron) and ca 7 % steel (including a small amount of hot-dip galvanised steel). Other pipe materials are PVC, PE and concrete. The figures relate to main and distribution pipelines. Buried service pipes to buildings are thus not included (see Table 1).

In the beginning of the 1980s, the operation and maintenance costs for the water pipeline networks in six densely populated municipal regions were between SEK 4 000 and 5 500 per km pipeline, which in today's (2000) value of money corresponds to ca SEK 10 000 – 14 000 per km pipeline. With regard to direct repair costs, an emergency action in the form of excavation and repair (e.g. because of pipe breaks, corrosion damage or joint leaks) cost on average SEK 25 000 in the middle of the 1980s, corresponding to ca SEK 40 000 in today's value of money. On average, ca 20 000 such cases occur per year on both the water

Water Science and Technology: Water Supply **Vol 1 No 3 pp 97–105** © IWA Publishing 2001

Table 1 Mains and distribution lines for water in Sweden – total length and pipe materials.

Pipe material	Total in Sweden	
	%	km
Cast iron (grey iron and ductile iron)	57	34 270
PVC	21	13 030
Carbon steel and hot-dip galvanised steel	7	4 433
Polyethylene	10	6 248
Others, e.g. concrete	5	3 156
Total	100	61 135

and sewage pipelines in Sweden, at a total annual cost of more than SEK 500 millions. The steel and cast iron pipelines in the Swedish water pipeline network have a replacement value, which is considerably higher than SEK 100 billion. Of the total amount of drinking water produced by Sweden's municipal water works, 22% is estimated to constitute losses, which depend on leaks and also on e.g. measurement errors in water meters.

Pipe materials and protective coatings

Cast iron pipes

Grey iron and ductile iron (the latter also called nodular-iron) are two different kinds of cast iron. They both have a high carbon content, 3.5–4 per cent by weight. In grey iron, the carbon is present as angular graphite flakes, whereas in the ductile iron, it is present as small graphite balls. This makes the ductile iron considerably stronger than grey iron, and ductile-iron pipes are therefore made with thinner walls than the older grey iron pipes. Pipes of grey cast iron were used in Sweden until the middle of the 1960s. The pipes were externally coated with a thin layer of asphalt or tar. The joints in these pipelines were sealed with lead and they therefore have a certain, but poor, electrical conductivity.

From the latter half of the 1960s and onwards, only cast iron pipes of ductile iron have been used. The joints in these pipelines are sealed with a rubber ring and they are therefore not electrically conducting, which is of great importance when cathodic protection is considered. The "first generation" of ductile-iron pipes, i.e. ductile-iron pipes that were laid during the period ca. 1965-1980, has an external protective coating consisting of a thin (50-100 μm) layer of bitumen. The bitumen layer could easily be mechanically damaged over large surfaces, where extensive pitting corrosion can take place.

The "second generation" of ductile-iron pipes, i.e. ductile-iron pipes laid after ca 1980 have a more efficient protective coating, either a hot-sprayed zinc layer (which in turn is coated with a bitumen sealer) or a thick layer of plastic applied directly on the iron surface. During the 1990s ductile-iron pipes were introduced in Sweden, which have a coating of even higher quality. It is a double layer coating, consisting of a hot-sprayed zinc layer, which in turn is coated with a rather thick polyurethane coating. All these reinforced coatings have a better resistance against mechanical damage than the older thin bitumen coating. It must be emphasised that the corrosion statistics referred to in this report only relate to the first generation of ductile-iron pipes. No external corrosion damage on the second generation of ductile-iron pipes (with zinc or plastic coating) has, as far as is known, been reported in Sweden.

Carbon steel pipes

Carbon steel pipes with medium or large diameter (DN >300) are used in Sweden principally in water pipelines taking raw water from a water catchment to a water treatment works, and in mains leaving the water works. Consequently these mains are long and they normally run outside built-up areas. The external protective coating on the older carbon steel pipes consists of a 3-5 mm thick bitumen layer, which is mechanically reinforced with a fabric. Until the 1960s, jute was used and thereafter a glass-fibre fabric. The bitumen coating is comparatively soft and it could easily have been damaged at certain spots, e.g. during the pipe laying. At these damaged spots pitting corrosion can take place. In these pipelines, different types of joints were used. Certain types of joints are electrically conducting and some are electrically insulating (sealed with a rubber ring).

Carbon steel pipes laid after ca 1980 have an external coating of polyethylene, which is much more resistant to mechanical damage than the bitumen coating. The joints in these pipelines are welded and thus electrically conducting. Many of these pipelines are therefore cathodically protected.

Stainless steel pipes

Since the 1980s some Swedish municipalities use stainless steel pipes, without any external coating, in their buried water pipelines. A particular example is the town of Karlskoga (35 000 inhabitants). In this town all water pipelines with a diameter of DN 100 – 150 laid since the mid 1980s consist of non-coated stainless steel pipes. The steel grade is AISI 316 (17Cr-12Ni-2.5Mo) and the pipes are surrounded by a backfill of sand where the pipeline goes through clay soils. The pipe joints consist of muff couplings with a tightening rubber ring, similar to those on cast iron pipes. The dominating types of soil in the Karlskoga region are sand, clay and till, all with no or very low chloride content. Today (year 2000), there are stainless steel water pipelines in the town of Karlskoga to a total length of 6 km. Karlskoga's waterworks confirms that, to date, no water leaks caused by corrosion have been observed. In the rest of Sweden, as far as is known to the author, only very few water leaks have occurred which were caused by external corrosion in buried water pipelines of stainless steel. Furthermore, investigations show that some of these leaks were not caused by the soil corrosivity, but by electric currents in the pipes, i.e. by stray current corrosion.

Hot-dip galvanised steel pipes

Hot-dip galvanised steel pipes are primarily used in buried service lines to buildings, but also, as already mentioned, to a small amount in distribution pipelines. In Sweden the problem with water leaks caused by external corrosion on this type of pipes was early observed. The zinc layer could have corroded away after a comparatively short period of service, especially in clay soils with no or only a low carbonate content. In such soils the corrosion rate can be quite high (Vinka and Camitz, 1996). On the whole, therefore, the laying of galvanised steel pipes in Sweden came to an end during the 1950s.

Copper pipes

Towards the end of the 1940s copper pipes with smaller diameters were introduced, primarily as a substitute for galvanised steel pipes in service lines. Usually the copper pipes were wrapped with a bandage impregnated with asphalt in order to shield off the copper surface, so that copper pipe connections to carbon steel and cast iron pipes should not cause any galvanic corrosion on these pipe materials. Copper has a very good corrosion resistance in all types of natural soil (Camitz and Vinka, 1992), and consequently no cases of damage caused by external corrosion have been reported for buried copper water pipes. On the whole, laying of copper pipes came to an end during the 1970s, when service lines of plastic were introduced.

Statistics over corrosion damage in Swedish municipal districts

The Swedish Water and Waste Water Works Association (VAV) has carried out four extensive investigations of breakdowns on water pipelines in a number of municipal districts across the whole of Sweden. The term breakdown here means damage which must be repaired. The investigations were carried out in four stages: 1974 -1975 (eight districts), 1975-1977 (12 districts), 1978 (20 districts) and 1986 (11 districts). The investigations show the total number of breakdowns during each period, and the breakdown frequency separately for each individual pipe material expressed as the number of breakdowns per 10 km pipeline per year.

In Table 2, the breakdowns and breakdown frequencies are compared for the same 11 municipal authorities during the two periods 1978 (stage 3) and 1986 (stage 4). During 1986, the number of breakdowns was 1.9 on grey iron pipes, 0.4 on ductile-iron pipes, 1.4 on hot-galvanised steel pipes and 3.3 on other steel pipes per 10 km pipeline per year. Between 1978 and 1986 the number of breakdowns had increased for these pipe materials.

The causes of the breakdowns during 1986 are shown in Table 3. On grey iron pipes, 16% of the breakdowns were caused by corrosion. Note that the causes are not given for 61% of the breakdowns; it can be assumed that a considerable proportion of these breakdowns with no reported cause were due to corrosion. The corresponding figure was 60% on ductile-iron pipes, 89% on hot-dip galvanised steel pipes and 94% on other (carbon) steel pipes. Corrosion was thus responsible for more than half of the breakdowns on ductile-iron pipes and nearly all breakdowns on hot-dip galvanised and carbon steel pipes. Note, however, that the total number of breakdowns on these three pipe materials was nevertheless fairly small in the studied municipalities.

Table 2 Operating disturbances on mains and distribution lines for water during 1978 and 1986 in the same 11 Swedish municipal districts.

Material		Stage IV (1986)			Stage V (1978)	
	Operating disturbances per 10 km per year	Number of disturbances	Pipe length (km)	Operating disturbances per 10 km per year	Number of disturbances	Pipe length (km)
PVC	1.0	58	606	1.8	76	431
PEL/PEH	0.3	14	445	0.4	17	404
Ductile iron	0.4	27	757	0.1	5	592
Grey iron	1.9	484	2 592	1.7	444	2 687
Hot-dip galvanised steel	1.4	42	293	0.7	23	334
Carbon steel	3.3	33	102	3.2	31	97
Others	0.5	18	391	0.1	3	291
Not reported	0.5	15	331	–	–	–
Total	1.3	691	5 517	1.2	612	5 196

Table 3 Causes of operating disturbances in 1986 in 11 Swedish municipal districts. (Distribution in percentages of pipe materials).

Distribution (%) / Cause of disturbance	PVC	Hot-dip galvanised steel	Carbon steel	Grey iron	Ductile iron	PE	Others
Uneven subsidence	11	2	3	20	18	7	10
Material fault	30	–	–	1	–	–	–
Corrosion	–	89	94	16	60	7	10
Deficiencies in laying	4	–	–	1	18	43	–
External influence	3	–	–	1	4	7	–
Others	1	–	–	–	–	7	–
Not reported	51	9	3	61	–	29	80
Total number of operating disturbances	73	47	33	538	27	14	10

Pitting corrosion rates on ductile-iron pipes

T-G. Vinka, at the Swedish Corrosion Institute, has statistically analysed the results from two extensive field studies, where 61 cases of external corrosion damage (penetrating corrosion) on ductile iron water pipes with only thin bitumen coating as surface protection (the first generation ductile-iron pipes) was investigated. The field studies were carried out in three Swedish cities by T. Reuterswärd- Wengström, Chalmers Institute of Technology and E. Levlin, Royal Institute of Technology, during a couple of years (Camitz, 1995). Practically all the individual occurrences of corrosion damage were caused by corrosive soil. The aim of the statistical analysis was to determine the average corrosion rate in corrosion pits, which leads to "premature" (unexpected) penetration corrosion and leaks on old ductile-iron pipes. The results are shown in Table 4.

Vinka indicates an average rate of pitting corrosion of 0.5–0.6 mm/year in those cases where pitting corrosion occurred which led to "premature" penetrating corrosion and water leakage in ductile-iron pipes (a couple of abnormally extreme values rejected). With a pitting corrosion rate of 0.5 mm/year, it takes about 13 years for penetration to occur on ductile-iron pipes with the dimension DN 200 mm, and about 16 years on pipes with the dimension DN 400 mm. Vinka emphasises that these figures apply only to those cases where unexpected penetration corrosion occurs on pipes exposed to strongly corrosive conditions. Other corrosion pits also occur, of course, with a considerably lower rate of corrosion, but these do not cause "premature" penetration corrosion.

The causes of the corrosion damage

External corrosion on water pipelines in Sweden is mainly due to the fact that the pipes are located in corrosive soils and that faults exist in the pipe coatings. These soils, mainly humid marine clays containing chlorides and humid organic clays containing sulphides and/or sulphates, can be found primarily in regions where the ground until very recently in a geological perspective (1000–6000 years ago) constituted the seabed. The soils were formed during and soon after the melting of the inland ice, which covered Scandinavia until as recently as 7000–12 000 years ago. Regions with these corrosive types of soil are primarily located along the coast and in a 100–200 km broad belt across the country from Stockholm to Gothenburg, and are thus associated with the most densely populated parts of the country.

A very small part of the corrosion damage is caused by stray DC current from DC traction systems, and by bimetal (galvanic) corrosion, e.g. because a service pipe of bare copper has been connected to a mains pipe of steel or cast iron.

Cathodic protection of existing water pipelines

The question of installing cathodic protection on an existing water pipeline is usually raised when repeated water leaks have occurred because of corrosion on a limited length of

Table 4 Rates of pitting corrosion through the pipe wall of ductile iron water pipes in three Swedish municipalities.

Statistical parameter	Field investigation No 1	Field investigation No 2
Number of cases	53	8
Lowest pitting rate	339 µm/year	320 µm/year
Lower quartile	457 µm/year	–
Medium value	357 µm/year	386 µm/year
Upper quartile	655 µm/year	–
Highest pitting rate	1 220 µm/year	1 133 µm/year
Mean value	577 µm/year	478 µm/year
Standard deviation	159 µm/year	268 µm/year

pipeline. In the application of cathodic protection on existing water pipelines, problems often arise which usually do not exist when the protection is designed and installed at the time when the pipes are laid. In many cases, this leads to greater costs for the design and installation. It is nevertheless well worth investigating the conditions for an installation, since this protective method makes it possible to prevent continued penetrating corrosion on the troubled length of pipeline. In the following, experiences are reported from the installation of cathodic protection on different types of existing water pipelines in Sweden.

The protective principle – complete and incomplete protection

Cathodic protection is achieved by feeding a small DC-current through the ground to the pipe, which results in the pipe-to-soil potential being shifted in the negative direction by a few tenths of a volt to a certain potential value. The potential of the pipe is measured against a reference electrode, normally a copper-copper sulphate electrode ($Cu/CuSO_4$), which has a fixed potential in relation to soil. In order to attain *complete* cathodic protection, i.e. complete elimination of corrosion, the potential of the pipe must be lowered to -0.85 V ($Cu/CuSO_4$) or more negative (in anaerobic soils containing sulphate reducing bacteria the limit potential value is – 0.95 V). If a certain potential decrease takes place, but not to -0.85 V, an *incomplete* cathodic protection is obtained. The corrosion is then not eliminated, but the rate of corrosion is reduced both generally and locally by a reduction of the potential differences between anodic areas (where local corrosion takes place) and cathodic areas (where oxygen consumption takes place).

The DC current, the protective current, is led out into the ground from buried metal anodes and is generated either galvanically by sacrificial anodes, i.e. galvanic cathodic protection, or electrolytically by an external DC source, i.e. cathodic protection with impressed current.

Harmful interference from cathodic protection

In the application of cathodic protection a harmful interference can in some cases arise and cause corrosion damage on other adjacent metal constructions in the ground, which limits the use of the protection or which results in extra work. The risk of interference exists within a limited region, which can be calculated or measured, around the anodes. The larger the output current and the higher the soil resistivity, the greater is the risk region around the anodes. If the protective current density is high on the pipes, there is also a certain risk area in the soil immediately adjacent to the protected pipeline. Further information about interference from cathodic protection and how interference can be avoided is available in the European Standard CENELEC prEN 50 162, “Protection against corrosion by stray current from direct current systems “ (in preparation).

Existing steel pipelines with electrically conductive pipe joints

As already mentioned, old steel pipelines normally have a thick and fibre-reinforced bitumen coating. On pipes having such a coating and buried in wet (poorly aerated) clay soil, the cathodic protective current requirement is low, usually 0. 1-1 mA/m^2 pipe surface. If the pipeline has electrically conductive pipe joints (e.g. flanged or welded joints), it is normally most suitable to apply cathodic protection with impressed current and remote anodes. Only a few operations need to be made on the pipeline. The pipeline needs to be exposed only where the connecting cable from the rectifier and the test wires for monitoring measurement of the protection potential are to be attached to the pipes. Further, the pipeline section to be protected should be electrically separated by the installation of an insulating pipe joint at each end.

Because of the low current requirement, complete cathodic protection can be attained on a long section of the pipeline with a moderately large current output from one single rectifier with an associated remote anode bed. With a small current output from the anode bed, the size of the region where there is a risk of harmful interference around the anodes will be small.

Existing steel pipelines with non-conductive pipe joints

For cathodic protection to function, each pipe joint must be electrically conductive on the pipe section to be protected, so that the return current can be led back to the rectifier or the sacrificial anode. If the pipe joints are sealed with a rubber ring, they are not electrically conductive. Although steel pipelines, for reasons which have been mentioned previously, are suitable for cathodic protection with an impressed current, such non-conductive pipe joints constitute an obstacle to the application of the protective method. In some cases, however, it can be motivated to dig out the pipe joints and bridge them with a cable so that they become conductive (see Figure 1). The operations become many and expensive, but the conditions for this operation should be investigated from case to case.

The damage development (penetrating corrosion through the pipe wall) on a water main of steel (DN 400) just north of Stockholm and the effects of the installation of cathodic protection has been followed up by the author. Repeated large water leaks caused by external corrosion occurred on a ca 1 km long section where the pipeline is laid in marine clay outside the densely populated area. The corrosive clay caused a high rate of pitting corrosion (probably by microbiological corrosion) at places where there was mechanical damage to the 4 mm thick bitumen coating. The damage development accelerated and after nine years, eight cases of penetrating corrosion had occurred on this short section of pipeline (see Figure 2).

The pipe joints were non-conductive because of rubber ring seals. It was decided to excavate the pipe joints and bridge them with a cable on a ca 700 m long section. Ca 80 joints were bridged in different stages during the summer period at an average rate of five joints per day. Cathodic protection with impressed current and one single remote anode bed was installed. Through this operation, the damage development was interrupted and no further water leaks occurred during the time period studied, which was more than 15 years (B. Gutfelt, Sollentuna Waterworks, personal communication, 1999).

Existing ductile-iron pipelines with non-conductive pipe joints

Existing ductile-iron pipelines can in certain cases also be protected with cathodic protection provided that rubber-sealed pipe joints are bridged over with a cable in the same way as on steel pipelines.

Because of the poor insulating ability of the thin bitumen coating on the first generation of ductile-iron pipes, the protective current requirement is from experience considerably higher on these pipes (ca 1-5 mA/m^2 in wet clay) than on steel pipes with a thick bitumen coating. If cathodic protection is applied with an impressed current, the current output from

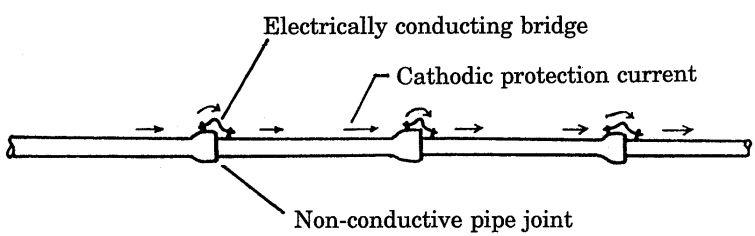

Figure 1 Electrically conductive bridging of non-conductive pipe joints (Camitz 1995)

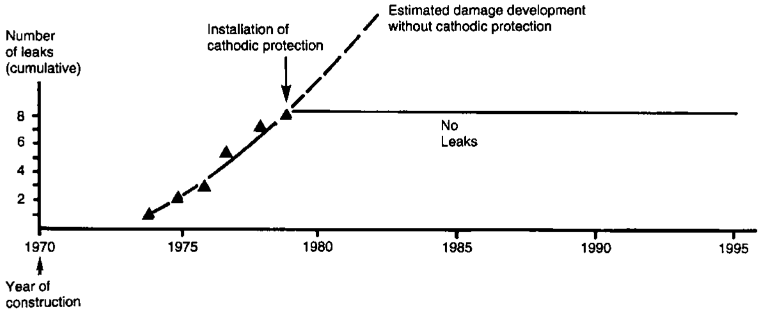

Figure 2 Corrosion damage development (water leaks) on a steel water main (DN 400) outside Stockholm, and the protective effect of a cathodic protection installation during 17 years (Camitz 1995)

a remote anode becomes large. The area around the anode with the attendant risk of harmful interference thereby becomes large, and it becomes difficult to find a suitable place for the anode bed without risk of damage to other pipelines, cables etc. For this reason, in some Swedish municipalities with corrosive soil conditions, a method is used which involves excavation and bridging of only every second pipe joint with a cable. A sacrificial anode of zinc or magnesium is placed in the excavated pit and is connected to the pipeline. Each anode thus provides protection to two pipe sections and one thus avoids excavating every other pipe joint (see Figure 3).

In soil with low resistivity, magnesium anodes give complete protection, but the disadvantage is that the lifespan of the anode becomes comparatively short (ca 10–15 years) because of the large self-corrosion. For some time zinc anodes which have a considerably longer lifespan have therefore been used. The weight and geometry of the zinc anode is optimised (12 kg, $20 \times 20 \times 2000$ mm) so that the lifespan becomes long (>30 years) and the grounding resistance low. The latter entails maximal current output from the anode. The aim of using zinc anodes is not to achieve complete cathodic protection in all possible conditions, but rather to reduce as far as possible high rates of pitting corrosion on the pipes (i.e. incomplete protection), and thereby to prolong the lifespan of the water main.

Between the towns of Nyköping and Oxelösund (ca 100 km south of Stockholm) runs a ca 10 km long main (DN 400) of ductile iron, which lies in corrosive marine clay over long distances. The pipeline was laid during the 1960s. In the 1980s, 3–4 water leaks occurred per year due to external corrosion. During the period 1991-1994, every second pipe joint (a total of ca 600 joints) was bridged over a 7.2 km long pipeline distance. A 12 kg zinc anode was placed at each excavated pipe joint. From 1995 until today (year 2000), no water leaks have occurred within the protected pipe section (as reported by Nyköping waterworks).

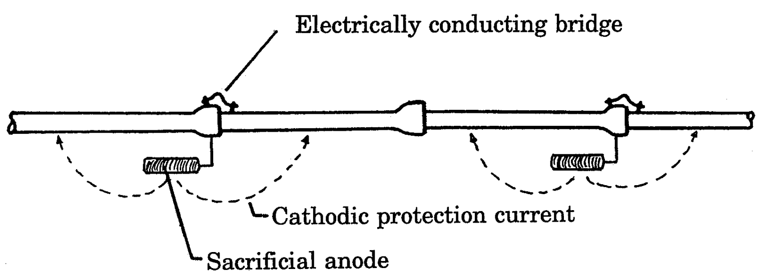

Figure 3 Cathodic protection with sacrificial anodes of ductile-iron water pipes with non-conductive pipe joints. Each anode protects two pipes, and consequently only every second pipe joint has to be bridged (Camitz 1995)

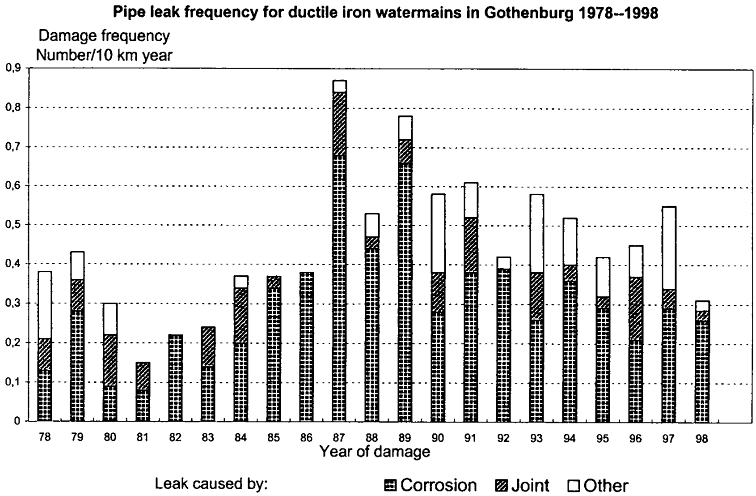

Figure 4 Damage frequency of ductile-iron water pipelines in Gothenburg during the period 1978 – 1998. First year of burial of ductile- iron pipes: 1969 (Data from O. Ljunggren, Gothenburg Waterworks, personal communication, 2000)

Fighting water pipe corrosion – the case of Gothenburg

The ground in the city of Gothenburg consists mostly of very corrosive, marine (chloride containing) clay soil, which can cause quite high pitting corrosion rates on steel or cast iron pipes. At Gothenburg's water works, Olle Ljunggren, together with Chalmers Institute of Technology, has analysed the damage statistics for the city's ductile-iron pipelines (total length 380 km in 1996) for the period 1978–1998 (Figure 4). The number of instances of corrosion damage per year increased until the end of the 1980s, but has thereafter decreased. The reason for the decrease in the corrosion damage frequency is a serious and systematic investment in counter-measures beginning in the middle of the 1980s. These measures include, in the first place, a transition to high quality plastic coating on new ductile-iron pipes and systematic replacement in stages of the most damaged pipeline sections. Cathodic protection was also installed on most existing large steel pipelines and on a few ductile-iron pipelines (O. Ljunggren, Gothenburg Waterworks, personal communication, 2000).

Conclusions

External corrosion on buried water pipelines of steel and cast iron can cause repeated, emergency water leaks, which are expensive to repair. Experience from Gothenburg's water-works shows that it is possible to reduce the corrosion damage frequency on both ductile-iron and steel pipelines through a systematic investment in different counter-measures. Properly designed, cathodic protection can be an efficient countermeasure on corroding, existing pipelines. Experience from the town of Karlskoga shows that non-coated stainless steel pipes of steel grade AISI 316 or equal have a good corrosion resistance in soils with no or low chloride content.

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