GAS PIPELINE INCIDENTS

12th Report of the *__E__*uropean *__G__*as Pipeline *__I__*ncident Data *__G__*roup (period 1970 – 2022)

Comprising:

DESFA (Greece)
ENAGAS, S.A. (Spain)
Energinet (Denmark)
EUSTREAM (Slovak Republic)
FGSZ (Hungary)
Fluxys (Belgium)
Gasconnect (Austria)
Gasgrid Finland (Finland)
Gas Networks Ireland (Ireland)
Gasunie (Netherlands / Germany)
GRTgaz (France)
National Gas (UK)
NET4GAS (Czech Republic)
Open Grid Europe (Germany)
REN (Portugal)
Snam (Italy)
Swedegas A.B. (Sweden)
SWISSGAS (Switzerland)
Teréga (France)

Doc. number VA 23.0304
08th of September 2023

DESFA (Greece)
ENAGAS, S.A. (Spain)
Energinet (Denmark)
EUSTREAM (Slovak Republic)
FGSZ (Hungary)
Fluxys (Belgium)
Gasconnect (Austria)
Gasgrid Finland (Finland)
Gas Networks Ireland (Ireland)
Gasunie (Netherlands / Germany)
GRTgaz (France)
National Gas (UK)
NET4GAS (Czech Republic)
Open Grid Europe (Germany)
REN (Portugal)
Snam (Italy)
Swedegas A.B. (Sweden)
SWISSGAS (Switzerland)
Teréga (France)

Comments or questions to this publication can be directed to the EGIG secretariat:

N.V. Nederlandse Gasunie	***N.V. Nederlandse Gasunie***
dr. ir. M.T. Dröge	***mr. S. Koops***
Project Manager EGIG	***Secretariat EGIG***
P.O. Box 19	***P.O. Box 19***
NL - 9700 MA GRONINGEN	***NL - 9700 MA GRONINGEN***

E-mail: **S.Koops@gasunie.nl**

Website: **https://www.EGIG.eu**

EGIG encourages the reader, who would like specific information not available in the report, to make direct contact with the companies involved. Company addresses are available on the EGIG website.

CONTENT

CONTENT **3**

List of appendices **4**

List of tables **4**

List of figures **4**

Summary **6**

Conclusions **6**

1 Introduction **7**

2 EGIG database **8**

2.1 Objective **8**

2.2 Criteria **8**

2.3 Contents **8**

2.4 Definitions **10**

2.5 The use of EGIG data **10**

3 Analyses and results **12**

3.1 Trends gas transmission system **12**

3.1.1 Total length 12

3.1.2 Exposure 16

3.2 Trends of the number of incidents **17**

3.3 Failure frequencies analyses **18**

3.3.1 Primary failure frequencies 18

3.3.2 Primary failure frequencies per leak size 22

3.3.3 Secondary failure frequencies 27

3.3.3.1 Relationship between diameter class and size of leak (all failure causes) 27

3.3.3.2 Relationship between external interference, size of leak and design parameter 29

3.3.3.3 Relationship between corrosion, leak size and design parameter 33

3.3.3.4 Relationship between construction defect/material failures, leak size and design parameter. 38

3.3.3.5 Relationship between hot tap made by error, size of leak and design parameter 40

3.3.3.6 Ground movement 42

3.3.3.7 Other and unknown 45

3.4 Other analyses **46**

3.4.1 Relationship between corrosion and age 46

3.4.2 Ignition of releases 48

3.4.3 Injuries and fatalities 49

3.4.4 Detection of incidents 51

4 Conclusions **53**

5 Bibliography **54**

LIST OF APPENDICES

APPENDIX 1: Statistics....................55
APPENDIX 2: Poisson law....................57

LIST OF TABLES

Table 1: Primary failure frequencies....................19
Table 2: Primary failure frequencies per cause....................22
Table 3: Primary failure frequency (five year moving average) per leak size over the period 2018-2022....................23
Table 4: Primary failure frequency, cause and size of leak (2013-2022)....................26
Table 5: Secondary failure frequency pipeline diameter and size of leak (2003-2022)....................28
Table 6: Secondary failure frequency, pipeline diameter and size of leak (2013-2022)....................29
Table 7: Ignition of releases per leak size....................49
Table 8: Detection of incidents....................51
Table 9: Primary failure frequencies and confidence intervals over different time intervals....................55
Table 10: Primary failure frequencies and confidence intervals per leak size (period 2015–2022)....................55
Table 11: Primary failure frequencies and confidence intervals per cause (1970-2022)....................55
Table 12: Primary failure frequencies and confidence intervals per cause (2000-2019)....................56
Table 13: Primary failure frequencies and confidence intervals per cause (2010-2019)....................56
Table 14: Primary failure frequencies and confidence intervals per cause (2015-2019)....................56

LIST OF FIGURES

Figure 1: Total length of the European gas transmission system in EGIG....................12
Figure 2: Total length per diameter....................13
Figure 3: Total length per year of construction....................13
Figure 4: Total length per type of coating....................14
Figure 5: Total length per cover depth (cd)....................14
Figure 6: Total length per wall thickness (wt)....................15
Figure 7: Total length per grade of material....................15
Figure 8: Total length per maximum operating pressure (p)....................16
Figure 9: Evolution of the exposure....................17
Figure 11: Number of incidents per year....................17
Figure 12: Cumulative number of incidents....................18
Figure 13: Primary failure frequencies....................19
Figure 14: Distribution of incidents (2013–2022)....................20
Figure 14: Primary failure frequencies per cause (five year moving average)....................21
Figure 15: Primary failure frequencies per cause (five year moving average) 2003 - 2022....................21
Figure 16: Primary failure frequency (five year moving average) per leak size....................22
Figure 17: Distribution for incidents with leak size: pinhole/crack (2013-2022)....................23
Figure 18: Distribution for incidents with leak size: hole (2013-2022)....................24
Figure 19: Distribution for incidents with leak size: rupture (2013-2022)....................24
Figure 20: Relationship primary failure frequency, cause and size of leak (1970-2022)....................25
Figure 21: Relationship primary failure frequency, cause and size of leak (2013-2022)....................26

Figure 22: Number of incidents per cause in the period of 2013 to 2022 27
Figure 23: Secondary failure frequency, pipeline diameter and size of leak (2003-2022) 28
Figure 24: Relationship external interference, leak size and diameter (d) (1970-2022) 29
Figure 25: Relationship external interference, leak size and diameter (d) (2013-2022) 30
Figure 26: Relationship external interference, leak size and cover depth (cd) (1970-2022)..........30
Figure 27: Relationship external interference, leak size and cover depth (cd) (2013-2022)..........31
Figure 28: Failure frequency of external interference (five year moving average) and cover depth (cd) (1970-2022) 31
Figure 29: Failure frequency of external interference (five year moving average) and cover depth (cd) (2013-2022) 32
Figure 30: Relationship external interference, leak size and wall thickness (wt) (1970-2022).......32
Figure 31 : Relationship external interference, size of leak and wall thickness (wt) (2013-2022) ..33
Figure 31: Relationship corrosion, leak size and construction year (1970-2022) 34
Figure 32: Relationship corrosion, leak size and construction year (2013-2022) 34
Figure 33: Relationship corrosion, leak size and coating type (1970-2022) 35
Figure 34: Relationship corrosion, leak size and coating type (2013-2022) 35
Figure 35: Relationship corrosion, size of leak and wall thickness (wt) (1970-2022) 36
Figure 36: Relationship corrosion, size of leak and wall thickness (wt) (2013-2022) 36
Figure 37: Breakdown of corrosion incidents on basis of location and appearance (1970-2022)....37
Figure 38: Breakdown of corrosion incidents on basis of location and appearance (2013-2022)....38
Figure 39: Relationship construction defect, leak size and construction year (1970-2022) 39
Figure 40: Relationship construction defect, leak size and construction year (2013-2022) 39
Figure 41: Relationship material failure, leak size and construction year (1970-2022).................40
Figure 42: Relationship material failure, leak size and construction year (2013-2022).................40
Figure 43: Relationship hot tap made by error, leak size and diameter (1970-2022)...................41
Figure 44: Relationship hot tap made by error, leak size and diameter (2013-2022)...................41
Figure 45: Relationship ground movement, size of leak and diameter (1970-2022) 42
Figure 46: Relationship ground movement, size of leak and diameter (2013-2022) 43
Figure 47: Distribution of the sub-causes of ground movement (1970-2022) 44
Figure 48: Distribution of the sub-causes of ground movement (2013-2022) 45
Figure 49: Relation wall thickness and failure frequency of incidents caused by lightning............46
Figure 50: Failure frequency (five year moving average) of corrosion incidents and year of construction 46
Figure 51: Relationship failure frequency of corrosion incidents and the age at the time of failure 47
Figure 52: 3D plot of failure frequency of corrosion incidents and the age at the time of failure....48
Figure 53: Percentages ruptures that ignited subdivided in diameter and pressure (1970-2022) ..49
Figure 54: Percentage of accidents of groups involved in pipeline incidents (1970-2022)............50
Figure 55: Percentage fatalities of accidents of groups as a function of leak size (1970-2022)......50
Figure 56: Detection of incidents per leak size (2013-2022) 51

SUMMARY

In 1982 six European gas transmission system operators took the initiative to gather data on the unintentional releases of gas in their transmission pipeline systems. This cooperation was formalised by the setting up of EGIG (**E**uropean **G**as pipeline **I**ncident data **G**roup). Presently, EGIG is a cooperation of nineteen gas transmission system operators in Europe and it is the owner of an extensive database of pipeline incident data collected since 1970.

The EGIG database is a valuable and reliable source of information that is used to establish pipeline failure frequencies and analyse causes of failures in the gas transmission pipeline systems.

CONCLUSIONS

- The EGIG database is a valuable source of information on European gas pipelines and pipeline incidents.

- EGIG has maintained and expanded the European Gas pipeline incident database. Nineteen gas transmission system operators in Europe now collect incident data on 150 thousand km of pipelines every year. The total exposure, which expresses the length of a pipeline and its period of operation, is 5.29 million km·yr.

- In the EGIG database 1,463 pipeline incidents are recorded in the period from 1970-2022.

- The history of incidents collected in the database gives reliable failure frequencies. The overall failure frequency over the period 1970-2022 is 0.277 incidents per year per 1,000 km.

- The five year moving average failure frequency in 2022, which represents the average failure frequency over the past 5 years is 0.101 per year per 1,000 km.

- The five year moving average and overall failure frequency show a general downward trend with fluctuations over the years.

- Incidents caused by external interference and ground movement are characterised by potentially severe consequences. This emphasises the importance of measures taken by pipeline operators and authorities to prevent these incidents.

- Over the last 5 years, corrosion as a primary cause has the highest failure frequency followed by external interference that used to have the highest failure frequency up to and including the 11th EGIG report. The consequences of corrosion failure are typically pinholes, whereas consequences of external interference can be much more severe.

- Over the last ten years, corrosion, external interference, ground movement and construction defects, represent 25.7%, 22.8%, 19.3% and 17.5% respectively of the pipeline incidents reported.

1 INTRODUCTION

The use of pipelines for the transport of large quantities of natural gas to industry and to commercial and domestic consumers represents a reliable mode of transport of energy.

In 1982, six European gas transmission system operators took the initiative to gather data on the unintentional releases of gas in their transmission pipeline systems. This cooperation was formalised by the setting up of EGIG (European Gas pipeline Incident data Group). The objective of this initiative was to provide a broad basis for the calculation of safety performance of pipeline systems in Europe, thus providing a reliable picture of the numbers and frequencies of incidents. Nowadays, EGIG is a cooperation of nineteen gas transmission system operators in Europe and it is the owner of an extensive database of pipeline incident data collected since 1970. The participating companies are now:

DESFA (Greece)
ENAGAS, S.A. (Spain)
Energinet (Denmark)
EUSTREAM (Slovak Republic)
FGSZ (Hungary)
Fluxys (Belgium)
Gasconnect (Austria)
Gasgrid Finland (Finland)
Gas Networks Ireland (Ireland)
Gasunie (Netherlands / Germany)
GRTgaz (France)
National Gas (UK)
NET4GAS (Czech Republic)
Open Grid Europe (Germany)
REN (Portugal)
Snam (Italy)
Swedegas A.B. (Sweden)
SWISSGAS (Switzerland)
Teréga (France)

Considering the number of participants, the extent of the pipeline systems and the exposure period involved, the EGIG database is a valuable source of information on European gas pipelines and pipeline incidents. The results of the database present an average of all participating companies and do not highlight geographical differences.

Definitions have been used consistently over the entire period. Consequently, provided that the data is correctly used and interpreted, the EGIG database gives useful information about trends which have developed over the years. Nevertheless, particular care must be given to the use and interpretation of the statistical data. The EGIG report gives the failure frequency per design parameter (diameter, pressure, wall thickness) and conclusions about combination of design parameters cannot be drawn.

This report describes the structure of the EGIG database and presents different analyses and their results. The results of the analyses are commented on and give the most interesting information that can be extracted from the database. Linking of results of different analyses is provided where possible. Anyone who would like to combine different results should be very careful before drawing conclusions.

2 EGIG DATABASE

The EGIG database is a database for pipeline data and pipeline incident data. Pipeline data and incident data of natural gas transmission pipelines are in the database from 1970 onwards.

2.1 Objective

The objective of EGIG is to collect and present data on loss of gas incidents in order to present the safety performance of the European gas transmission network to the general public and authorities.

2.2 Criteria

The required criteria for an incident to be recorded in the EGIG database are the following:

i. The incident must lead to an unintentional gas release.
ii. The pipeline must fulfil the following conditions:
    - To be made of steel.
    - To be onshore.
    - To have a maximum operating pressure higher than 15 bar(g).
    - To be located outside the fence of a gas installation.

Incidents on production lines or involving equipment or components (e.g. valve, compressor) are not recorded in the EGIG database.

2.3 Contents

The EGIG database contains general information about the European gas transmission pipelines system as well as specific information about the incidents.

Every year the length of the pipeline system is collected for the following parameters:

i. Diameter
ii. Pressure
iii. Construction year
iv. Coating type
v. Cover depth
vi. Material grade
vii. Wall thickness.

Specific information about incidents comprises:

i. The characteristics of the pipeline on which the incident happened, namely the general information listed above.
ii. The leak size:
    - Pinhole/crack: the effective diameter of the hole is smaller than or equal to 2 cm
    - Hole: the effective diameter of the hole is larger than 2 cm and smaller than or equal to the diameter of the pipe
    - Rupture: the effective diameter of the hole is larger than the pipeline diameter.

iii. The initial cause of the incident
    - External interference
    - Corrosion
    - Construction defect/material failure
    - Hot tap made by error
    - Ground movement
    - Other and unknown.

iv. The occurrence (or non-occurrence) of ignition.
v. The consequences.
vi. Information on the way the incident has been detected (e.g. contractor, landowner, patrol).
vii. A free text for extra information.

Additional information is also given for every cause:

i. External interference:
    - The activity having caused the incident (e.g. digging, piling, ground works)
    - The equipment involved in the incident (e.g. anchor, bulldozer, excavator, plough)
    - The installed protective measures (e.g. casing, sleeves).
ii. Corrosion:
    - The location (internal, external, unknown)
    - The appearance (general, pitting, cracking)
    - In line inspected (yes, no, unknown).
iii. Construction defect/material failure:
    - The type of defect (construction or material)
    - The defect details (hard spot, lamination, material, field weld or unknown)
    - The pipeline component type (straight, field bend, factory bend).
iv. Ground movement:
    - The type of ground movement (dike break, erosion, flood, landslide, mining, erosion of riverbed, erosion of the riverbank or unknown).
v. Other and unknown:
    - The sub-causes such as design error, lightning, maintenance error.

This information has been used for the analyses given in this report. EGIG is always considering whether changes in the information would be useful to enhance these analyses.

2.4 Definitions

Failure frequency*:* The failure frequency is calculated by dividing the number of incidents by the exposure. The EGIG report presents two kinds of failure frequencies, the **primary** and the **secondary**. They refer to the notions of total and partial exposure respectively. These notions are defined below.

- Exposure is the length of a pipeline multiplied by its exposed duration and is expressed in kilometres-years [km·yr]. Example: a company has a constant length of transmission pipelines over 5 years of 1,000 km. Its exposure is then 5 times 1,000 km, so 5,000 km·yr.
- The total system exposure is the exposure as defined above, calculated for the complete system.
- The partial system exposures are the exposures calculated per class of a certain design parameter, e.g. per diameter class or per cover depth class.

Five year moving average: In order to illustrate trends, a five year moving average has been introduced. The five year moving average for the year in question means that the frequency is calculated by dividing the number of incidents in the five year period by the exposure of that period.

Confidence interval: A confidence interval gives an estimated range of values which is likely to include an unknown population parameter, the estimated range being calculated from a given set of sample data. In this report, a confidence interval of 95% is calculated for the failure frequencies.

2.5 The use of EGIG data

The objective of the EGIG group is to show the incident data of gas transmission pipelines, registered by a European group of operators which in general follow similar design, construction, inspection and maintenance practices.

Within EGIG, all data collected, reported and analysed is data of the group as a whole and no distinction can and will be made per operator.

EGIG publishes statistics over different time intervals. In this report, the statistics of the whole database (covering the period 1970-2022), but also the most important statistics over the last 40, 30, 20, 10 and 5 years are reported. It must be noted that given the theory of statistics, the confidence interval of the mean values of the failure frequencies over five years is larger than for a longer period (for instance 20 years). The user of EGIG data must consider the statistical reliability of the data when deciding how it is to be used (see also APPENDIX 2).

Graphs

Some of the graphs presented in this report will cover the whole period of the EGIG database (1970-2022). To demonstrate developments and trends over more recent periods, the EGIG report also shows graphs that cover the last ten years (2013-2022) or represent the five year moving average.

The report aims to interpret the information contained in the data in order to draw conclusions from the sample or the population from which the sample is taken. The statistical analyses are based on the calculation of indicators such as failure frequency and the percentage of the releases that ignited.

The EGIG database offers an overview of the failure frequencies of the European gas transmission pipelines system. It gives information on the failure frequencies in relation to one pipeline parameter (e.g. diameter, pressure, wall thickness), but does in general not offer the possibility of making correlation analyses. For example, with the EGIG database it is possible to establish the failure frequency of ≥42-inch pipelines or to establish the failure frequency of pipelines with a wall thickness of >15 mm, but it is not possible to calculate the failure frequency of ≥42-inch pipelines with a wall thickness of >15 mm.

3 ANALYSES AND RESULTS

3.1 Trends gas transmission system

This paragraph gives information on the trends in the European gas transmission system. It not only shows the evolution of the exposure, but also which design characteristics tend to be more or less used in today's construction. This paragraph gives a picture of the European gas transmission system from 1970 up to and including 2022.

3.1.1 Total length

The evolution of the total length of the system is shown in Figure 1 and is also given per class in Figure 2 to Figure 8 for several pipeline parameters (diameter, pressure, etc.).

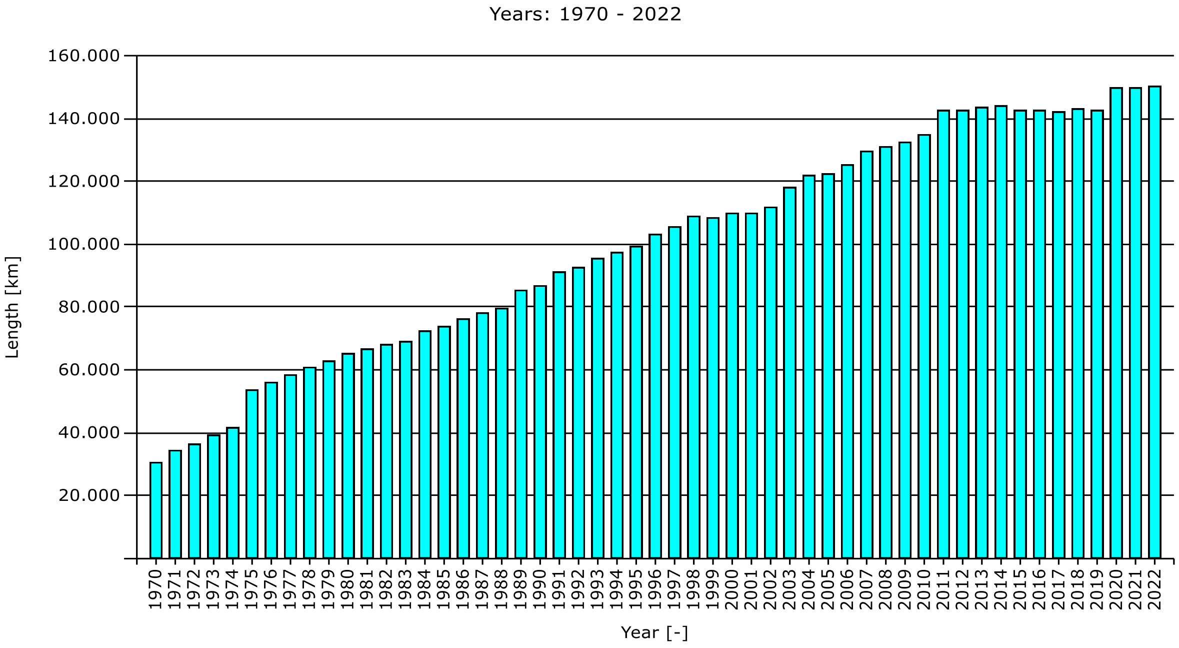

Figure 1: Total length of the European gas transmission system in EGIG

Figure 1 shows the increase in the length of the European gas transmission system in EGIG. The step changes correspond with constructing new pipelines or new members joining EGIG.

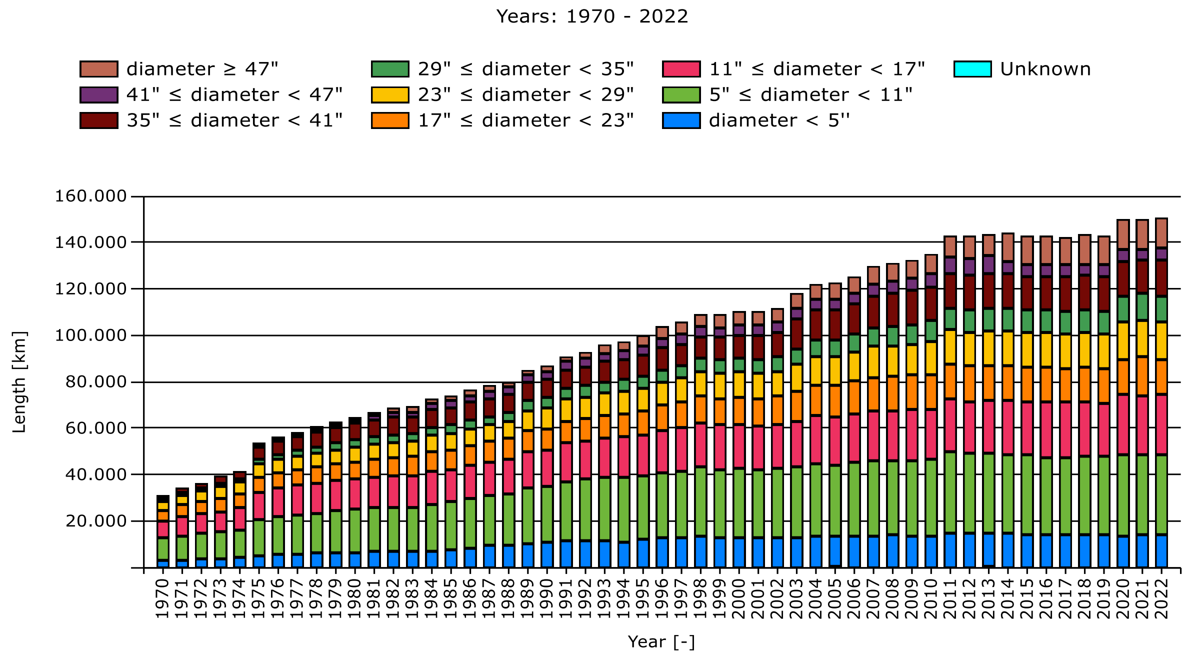

Figure 2: Total length per diameter

Figure 2 demonstrates that the 5″≤diameter<11″ and the 11″≤diameter<17″ classes are still the most commonly used classes.

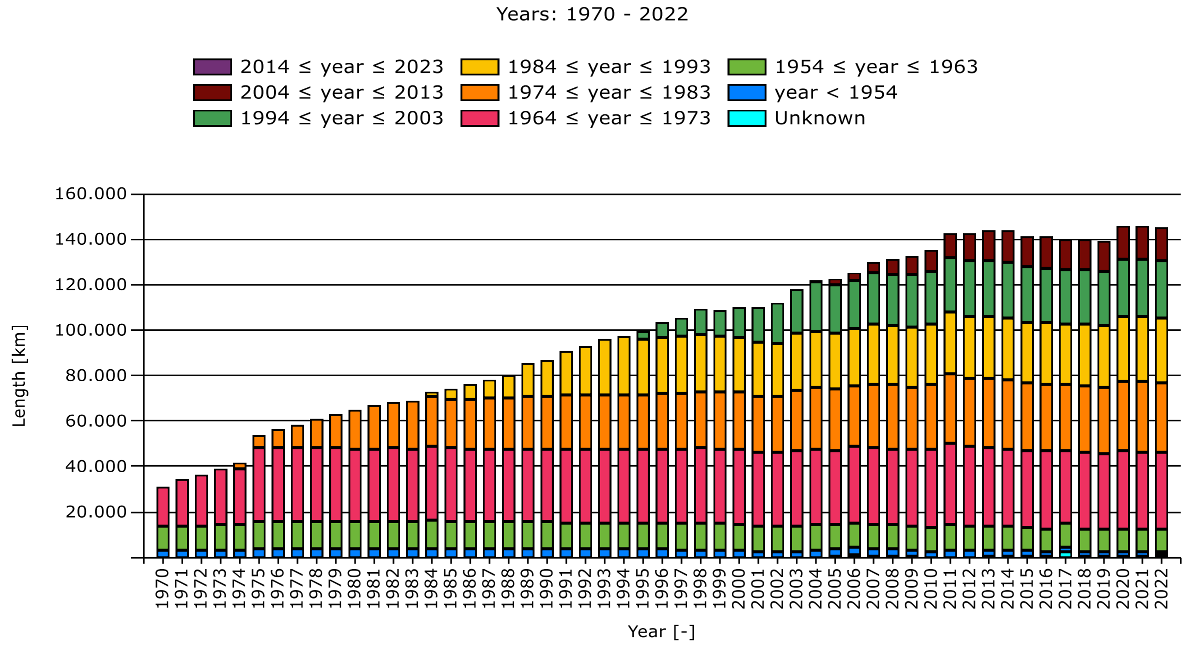

Figure 3: Total length per year of construction

Figure 3 shows that most of the pipelines that are currently in service were built in the period 1964 till 1973. No significant drop can be observed in any time frame, which means that most of these pipelines are still in operation. Also new pipelines continue to be constructed.

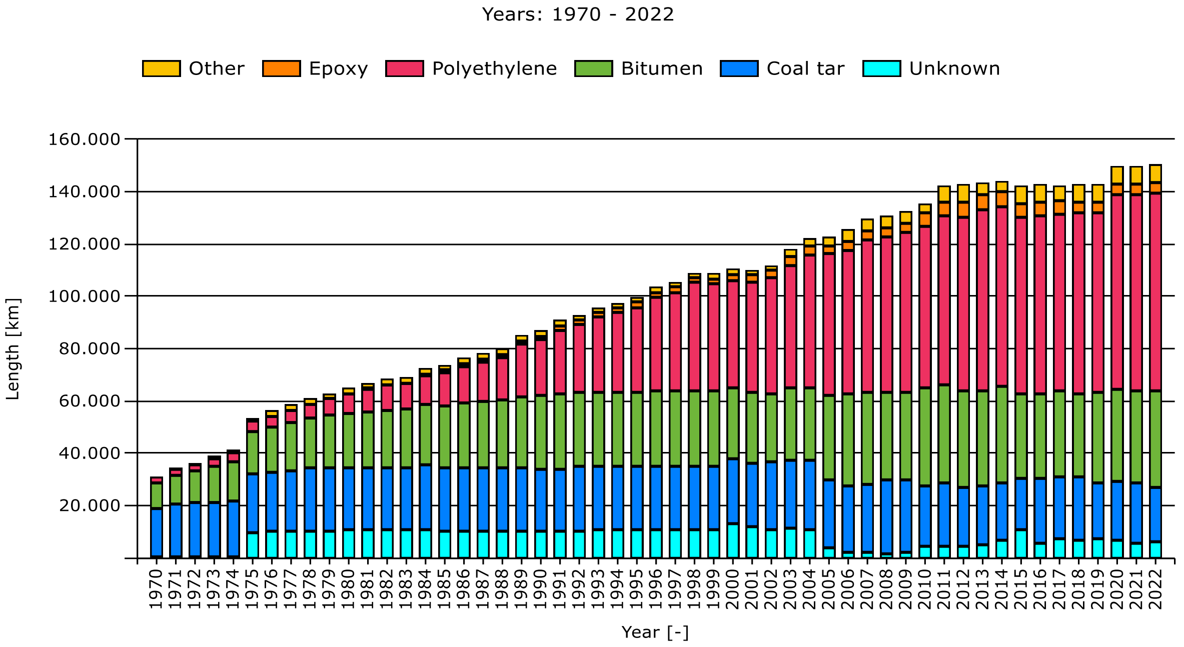

Figure 4: Total length per type of coating

Figure 4 shows that coal tar, bitumen and polyethylene are the most common coating types in the database, with a clear predominance of the last one. In the most recent decades the vast majority of new pipelines have been coated with polyethylene.

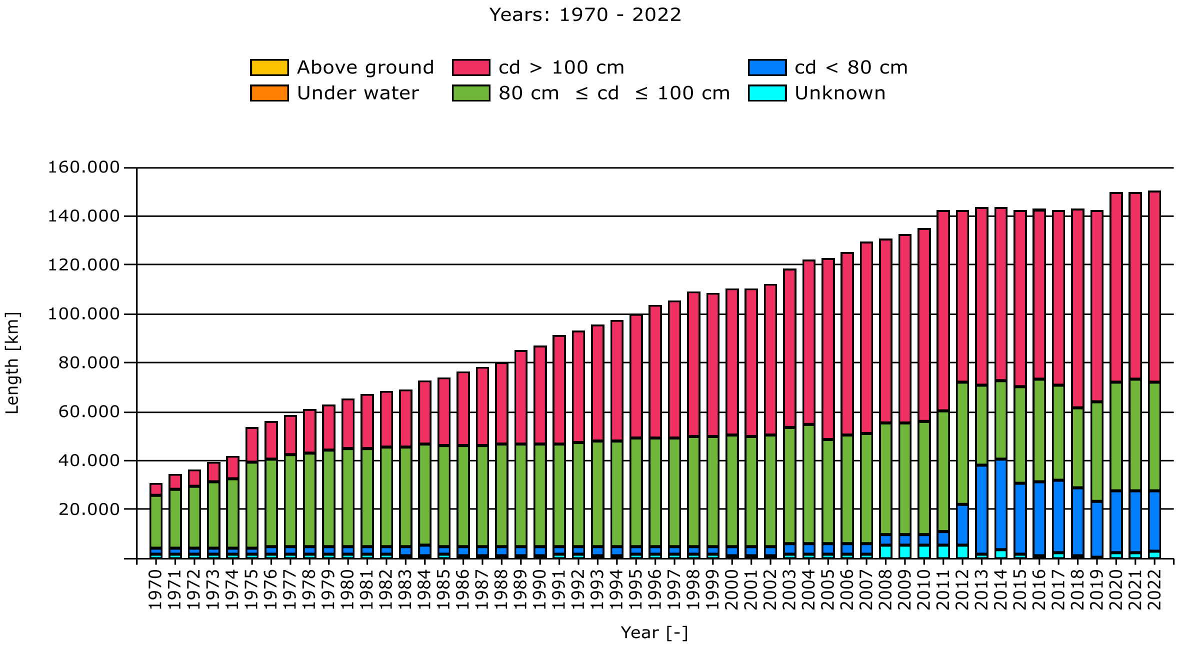

Figure 5: Total length per cover depth (cd)

Figure 5 shows that the vast majority of the pipelines have a cover depth greater than 80 cm.

Most companies and design codes recognise cover depth as an important factor in reducing exposure to external interference.

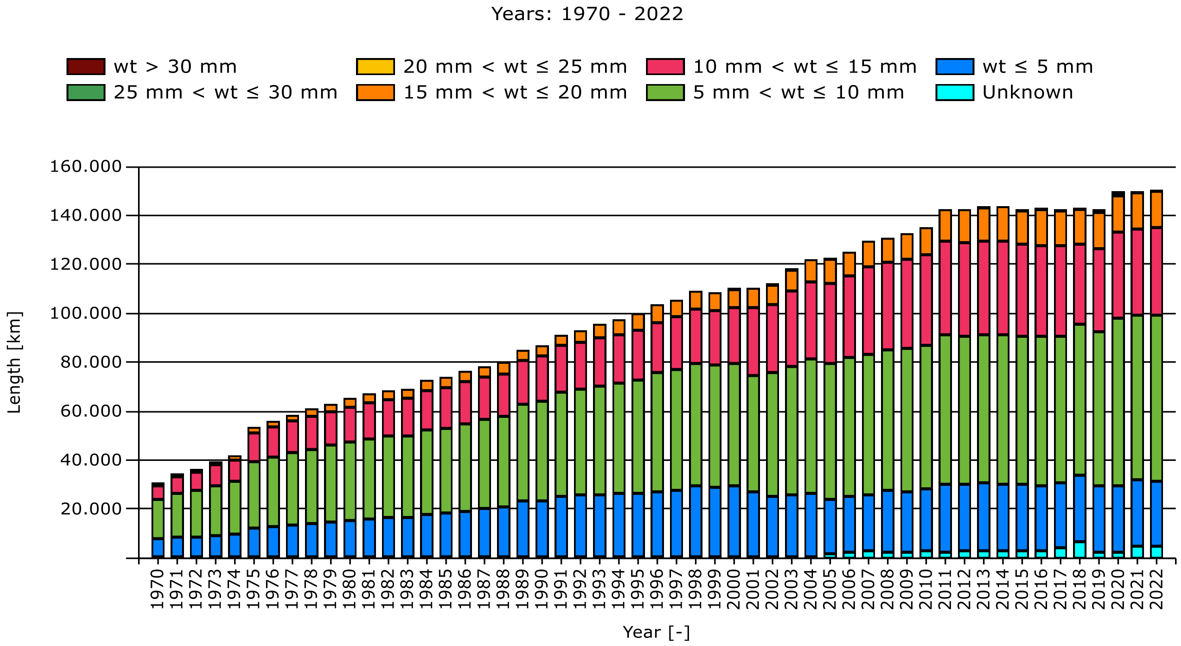

Figure 6: Total length per wall thickness (wt)

Figure 6 shows that the most commonly used pipeline wall thicknesses are 5 to 10 mm. The figure also shows that the pipeline length for every wall thickness class increases constantly over time except for the ≤ 5 mm class, which has remained more or less constant in length since 2001.

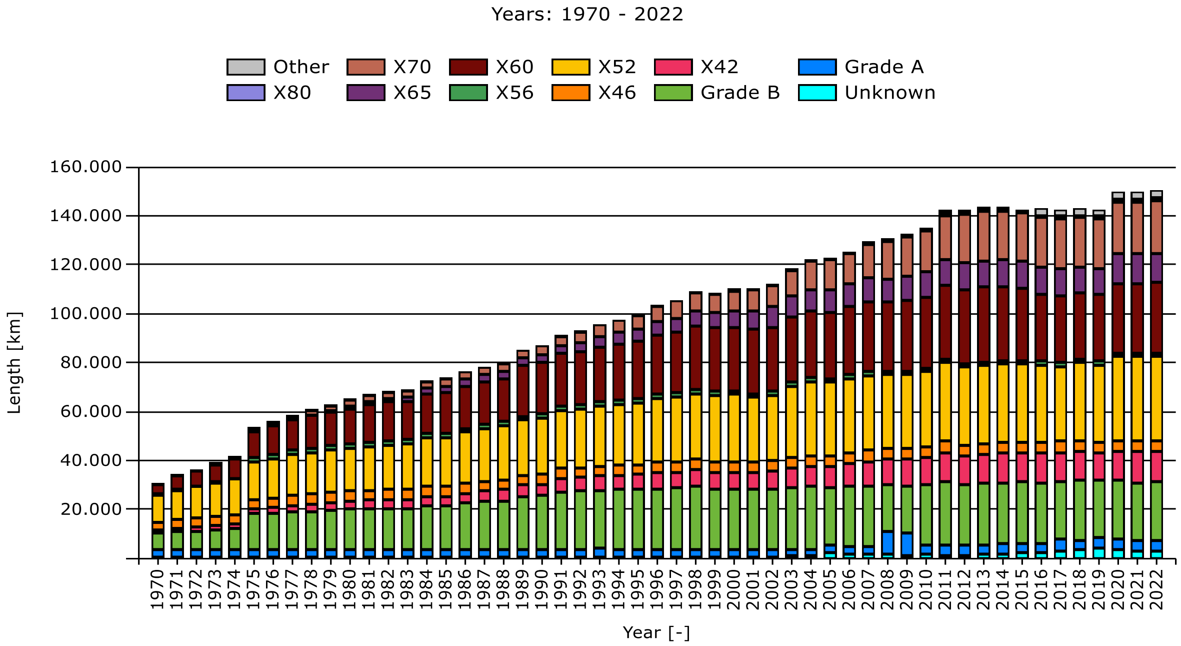

Figure 7: Total length per grade of material

Line pipe grade designations come from different specifications. The EGIG database is arranged according to equivalent API 5L grades, i.e. line pipe can have grade A, B or a higher grade with designation X followed by a number specifying the minimum yield strength (in kilo pounds per square inch) of the pipe steel. Grade A has been used in older pipelines. Grade B is still used in new pipelines, especially for pipelines with relative small diameters.

Figure 7 demonstrates that four grades of material are predominant, namely: Grade B, X52, X60 and X70.

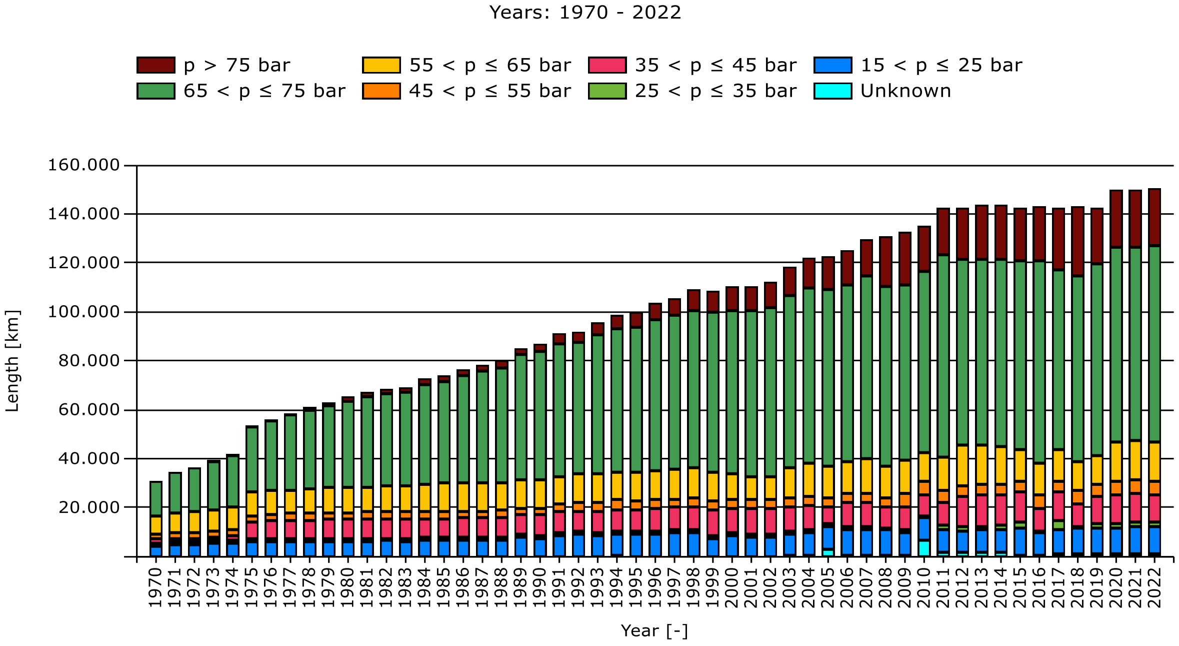

Figure 8: Total length per maximum operating pressure (p)

Figure 8 shows a predominance of maximum operating pressure between 65 and 75 bar.

3.1.2 Exposure

Figure 9 shows the increase of exposure over the years. As explained in paragraph 2.4, exposure is the length of a pipeline multiplied by its exposed duration and is expressed in kilometres-years [km·yr]. In 2022, the total system exposure was equal to 5.29 million km·yr.

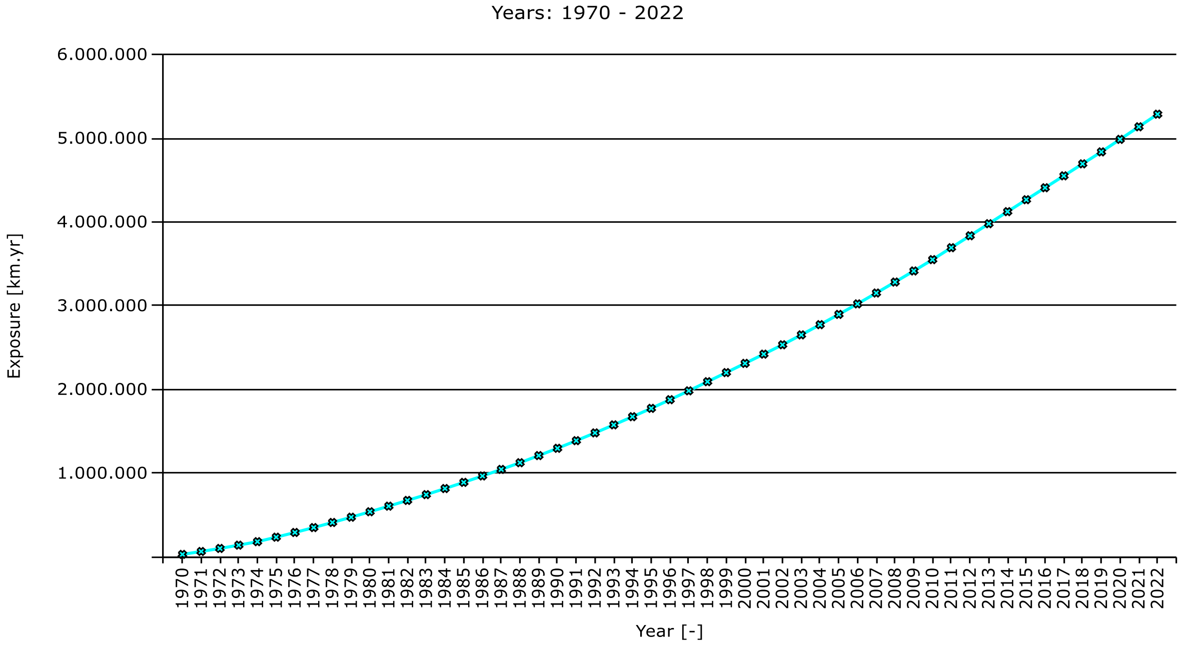

Figure 9: Evolution of the exposure

3.2 Trends of the number of incidents

In the eleventh EGIG report, which covers period 1970-2019, a total of 1,411 incidents were recorded. In the last three years, 52 incidents were reported by the EGIG members, which brings the total number of incidents to 1,463 for the period 1970-2022. Figure 10 shows the number of incidents per year. Figure 11 shows the cumulative number of incidents.

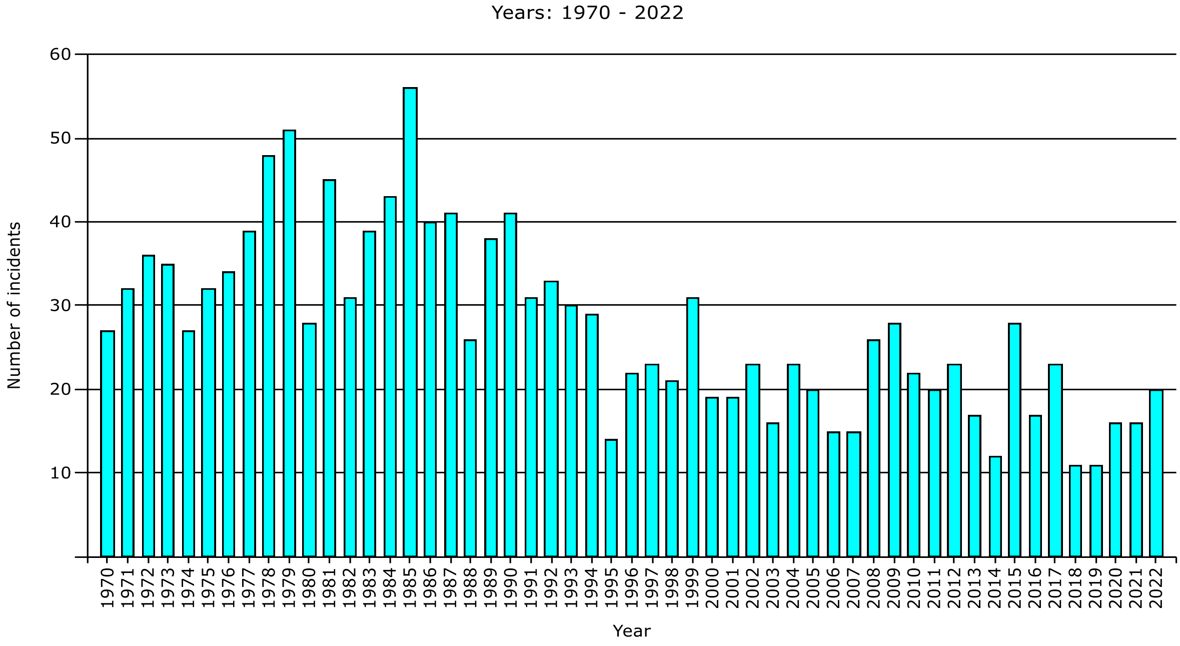

Figure 10: Number of incidents per year

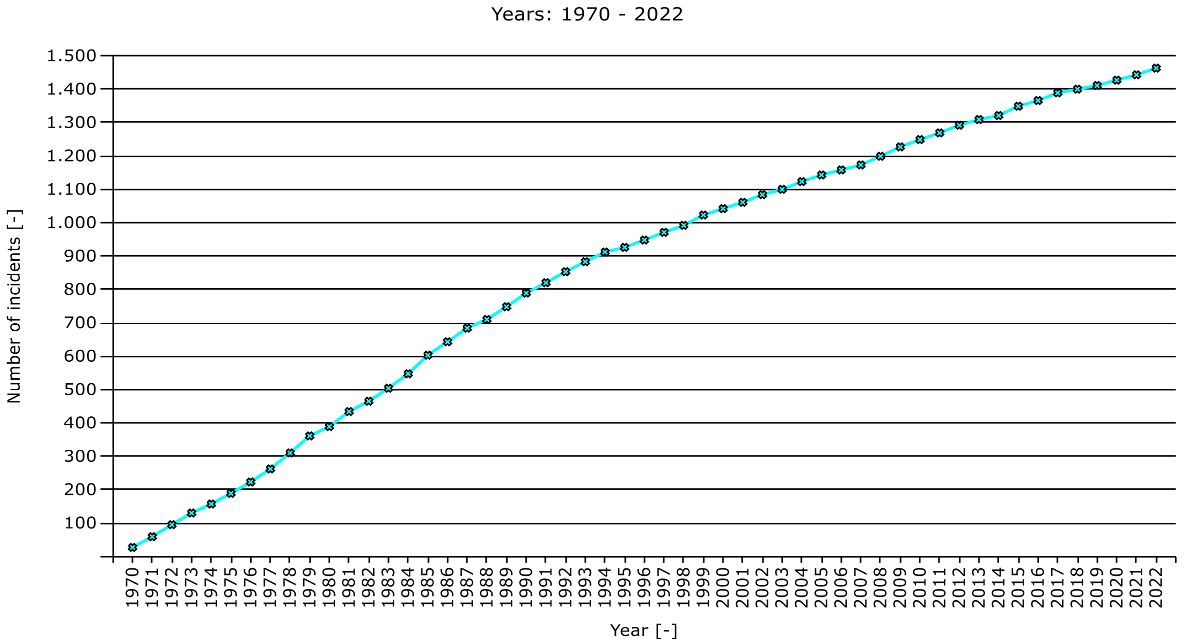

Figure 11: Cumulative number of incidents

3.3 Failure frequencies analyses

This paragraph deals with the calculation of safety indicators, namely the primary and secondary failure frequencies.

3.3.1 Primary failure frequencies

As explained in paragraph 2.4, the primary failure frequency is the result of the number of incidents (Figure 11) within a period divided by the corresponding total system exposure (Figure 9). Depending on the period considered, the number of incidents varies and so does the total system exposure.

EGIG has compared the primary failure frequencies of different periods, namely the total period (1970-2022), periods corresponding to the previous EGIG reports and of periods of the last 40, 30, 20, 10 and 5 years.

The primary failure frequencies of these periods are given in Table 1. The 95% confidence limits of the failure frequencies of these periods are given in APPENDIX 1. For the statistical analysis the assumption is made that the number of incidents follows Poisson's law (see APPENDIX 2).

Period	Interval	Number of incidents	Total system exposure ·1,000 km·yr	Primary failure frequency per 1,000 km·yr
1970 – 2007	7th report, 38 years	1,173	3,152	0.372
1970 – 2010	8th report, 41 years	1,249	3,551	0.352
1970 – 2013	9th report, 44 years	1,309	3,980	0.329
1970 – 2016	10th report, 47 years	1,366	4,409	0.310
1970 – 2019	11th report, 50 years	1,411	4,837	0.292
1970 – 2022	12th report, 53 years	1,463	5,288	0.277
1983 – 2022	40 years	998	4,613	0.216
1993 – 2022	30 years	610	3,806	0.160
2003 – 2022	20 years	379	2,754	0.138
2013 – 2022	10 years	171	1452	0.118
2018 – 2022	5 years	74	736	0.101

Table 1: Primary failure frequencies

In 2022, the primary failure frequency over the entire period (1970-2022) was 0.277 per 1,000 km·yr. This is slightly lower than the failure frequency of 0.292 per 1,000 km·yr reported in the 11th EGIG report (1970-2019).

The primary failure frequency over the last five years was equal to 0.101 per 1,000 km·yr, showing an improved performance over recent years.

Figure 12 illustrates the decrease of the primary failure frequencies. The primary failure frequency over the entire period decreased from 0.875 per 1,000 km·yr in 1970 to 0.277 per 1,000 km·yr in 2022. The five year moving average primary failure frequency decreased by more than a factor 8, from 0.860 to 0.101 per 1,000 km·yr in respectively the time frames 1970-1974 and 2018-2022.

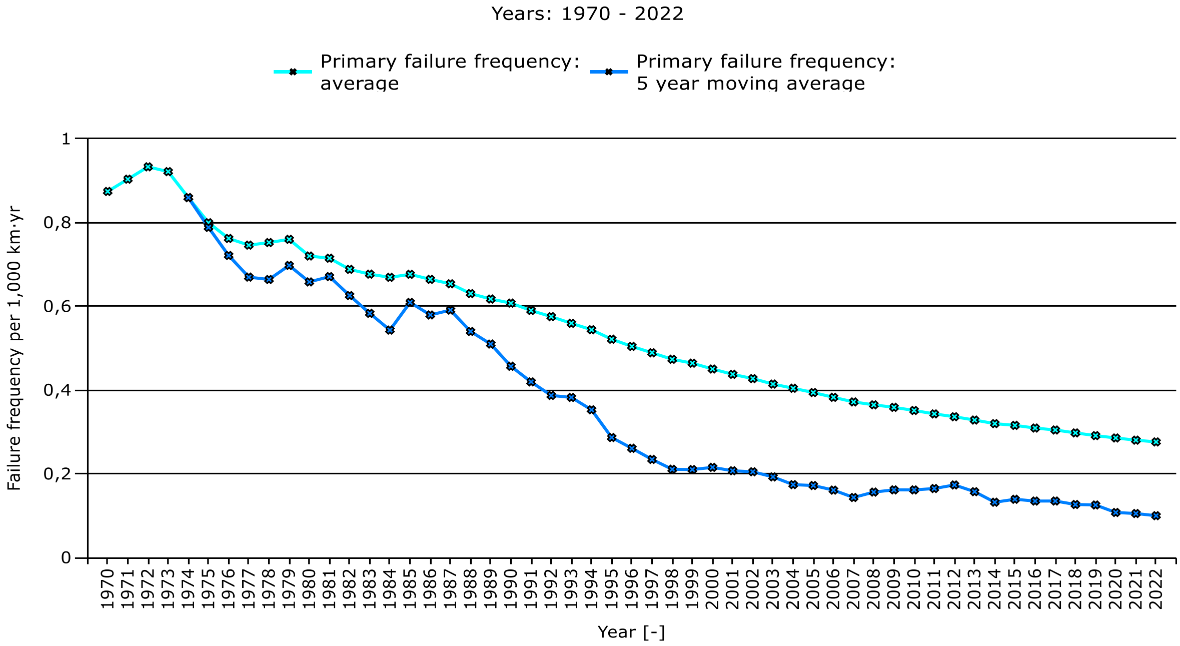

Figure 12: Primary failure frequencies

In Figure 13, the incident distribution per cause over the last 10 years is given. Corrosion and external interference incidents occurred in about the same rate. However, corrosion incidents tend to have smaller leak sizes (see Figure 20 and Figure 21).

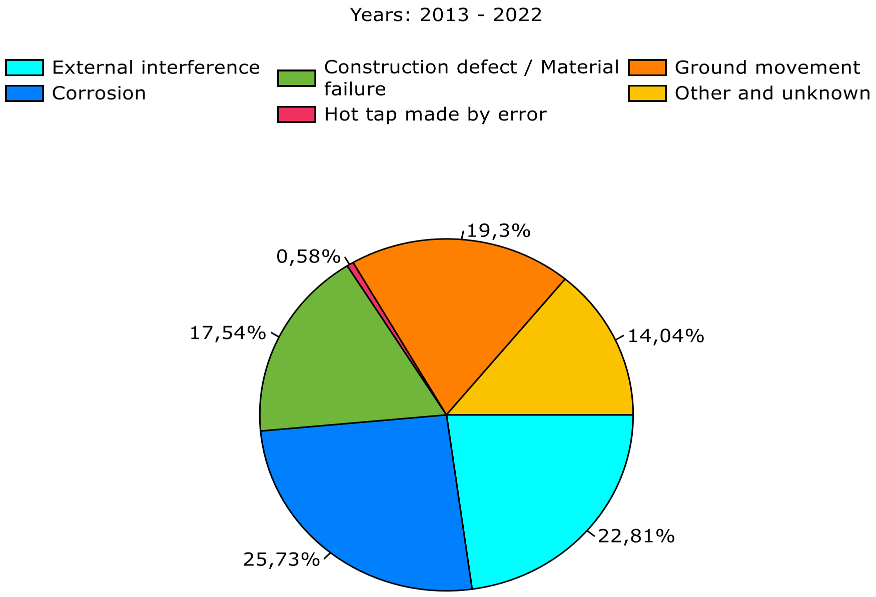

Figure 13: Distribution of incidents (2013–2022)

Figure 14 illustrates the decreasing five year moving average failure frequencies per cause over the years. Figure 15 illustrates the decreasing five year moving average failure frequencies per cause in the years 2003 till 2022. The decrease may be explained by technological developments, such as: welding, inspection, condition monitoring using in-line inspection and improved procedures for damage prevention and detection. Improvements in the prevention of external interference incidents may be explained by a more stringent enforcement of land use planning and the application of one-call systems for the digging activities of external parties. In several countries, there is now a legal requirement to report digging activities. Companies have adopted appropriate actions, like supervision or marking of the pipeline in the direct neighbourhood of the digging activities.

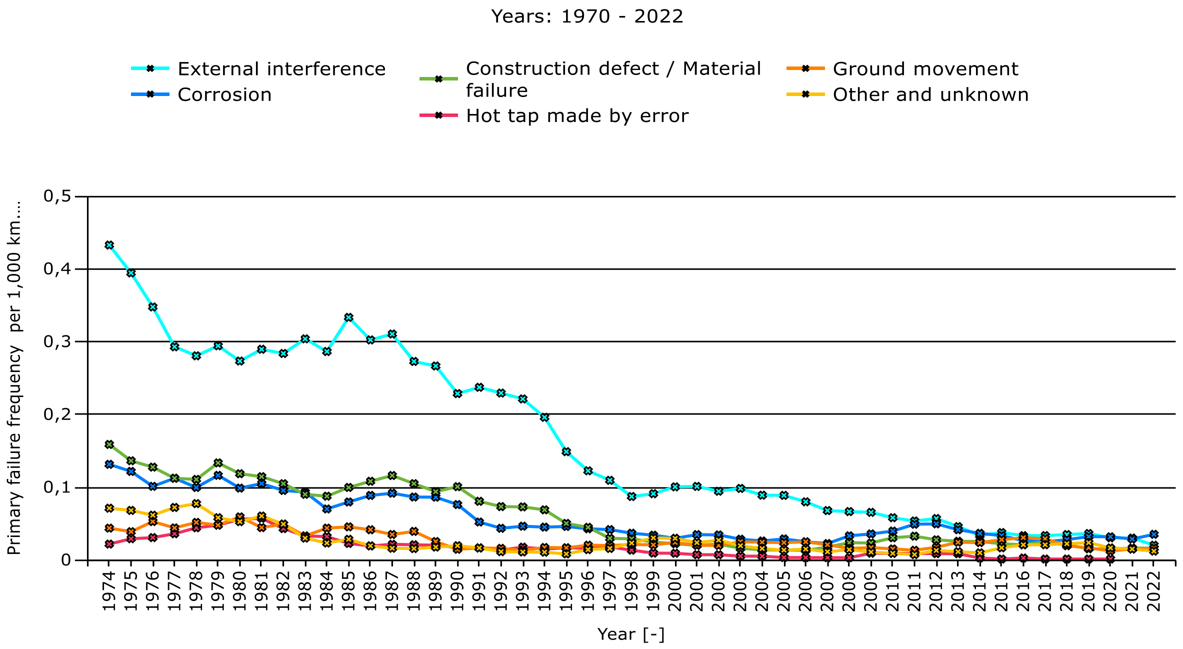

Figure 14: Primary failure frequencies per cause (five year moving average)

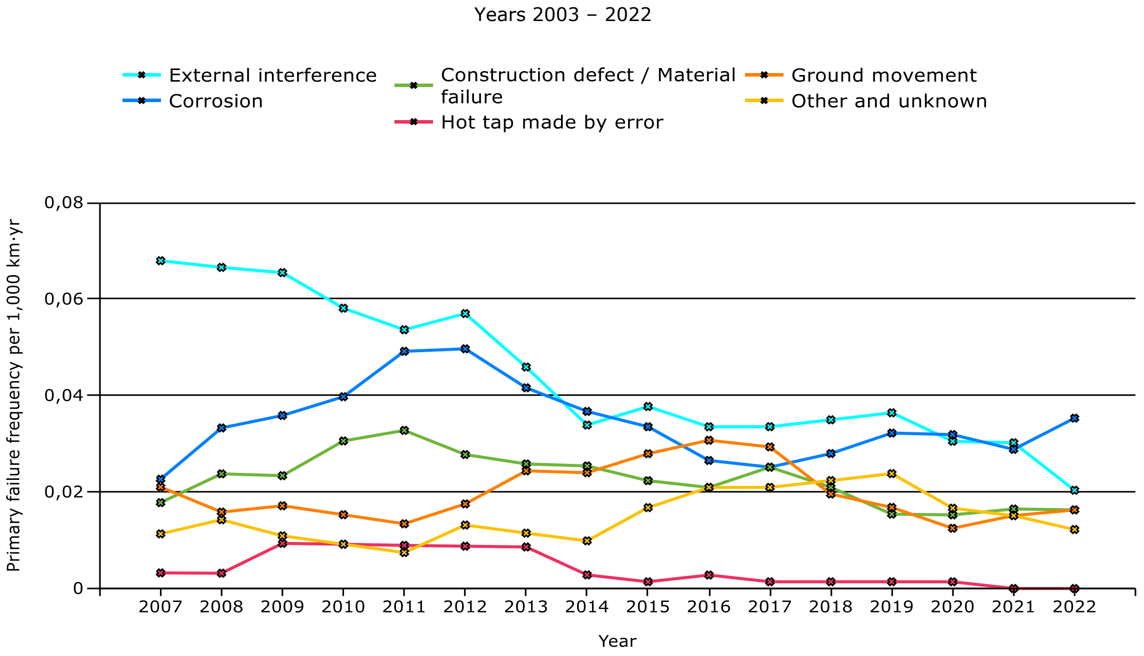

Figure 15: Primary failure frequencies per cause (five year moving average) 2003 – 2022

Cause	Primary failure frequency per cause			
	1970-2022 per 1,000 km·yr	2003-2022 per 1,000 km·yr	2013-2022 per 1,000 km·yr	2018-2022 per 1,000 km·yr
External interference	0.125	0.044	0.027	0.020
Corrosion	0.049	0.033	0.030	0.035
Construction defect / Material failure	0.046	0.022	0.021	0.016
Hot tap made by error	0.012	0.003	0.001	0.000
Ground movement	0.025	0.021	0.023	0.016
Other and unknown	0.021	0.015	0.017	0.012

Table 2: Primary failure frequencies per cause

To demonstrate failure frequencies over a more recent period, Table 2 also presents, in addition to the frequencies for the whole period, frequencies over a time span of the last 20, 10 and 5 years. As far as the causes external interference and corrosion are concerned;

- The primary failure frequencies over a five year time span of external interference has further decreased to 0.020 per 1,000 km·yr to a level similar to construction defect / material failure, ground movement, and other and unknown,
- the primary failure frequencies over the five year moving average of corrosion has levelled off between 0.030 and 0.040 per 1,000 km·yr.

3.3.2 Primary failure frequencies per leak size

Not all leaks result in severe consequences. The EGIG database distinguishes between incidents with different leak size (ruptures, holes and pinholes/cracks). Figure 16 demonstrates the five year moving average failure frequency per leak size.

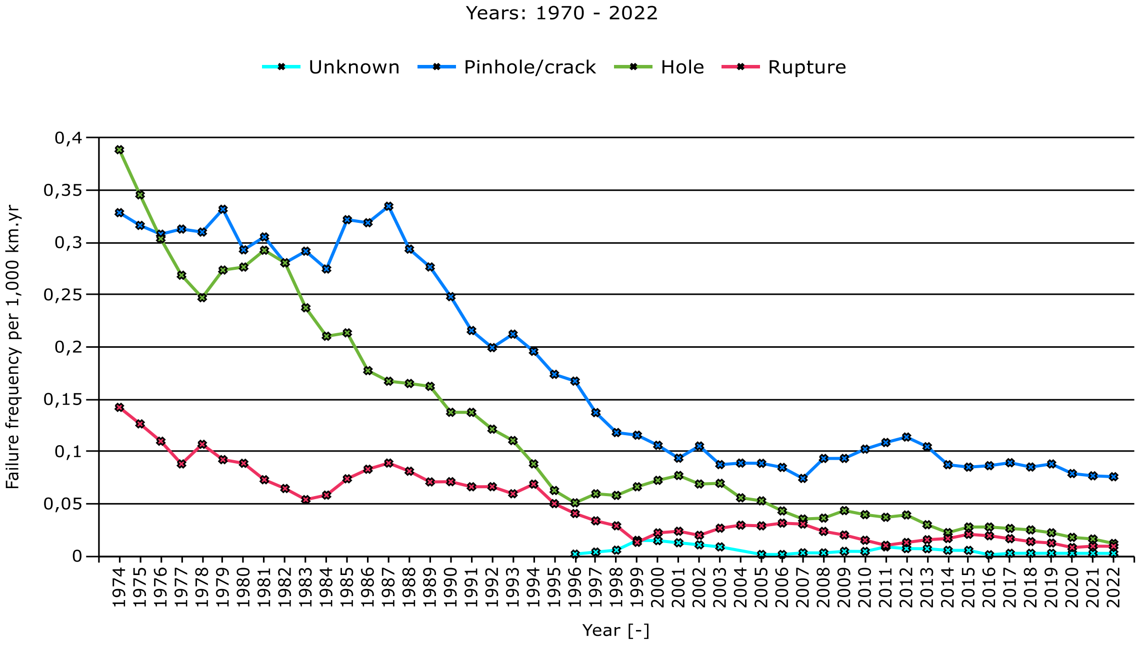

Figure 16: Primary failure frequency (five year moving average) per leak size

Figure 16 shows that the failure frequencies for holes and ruptures are smaller than the failure frequencies for pinhole/cracks. Also a decrease over the years of the five year moving average can be seen for all leak sizes. From the year 2000 this trend stabilises. For the year 2022 these values are given in Table 3.

Leak size	Primary failure frequency per 1,000 km·yr (five year moving average)
Unknown	0.0027
Pinhole/crack	0.0761
Hole	0.0122
Rupture	0.0095

Table 3: Primary failure frequency (five year moving average) per leak size over the period 2018-2022

Figure 17, Figure 18 and Figure 19 show the distribution of the incidents per leak size over the period 2018 till 2022. From these figures it can be seen that pinholes are mainly caused by corrosion, holes are mainly caused by external interference followed by ground movement and the main causes of ruptures are ground movement followed by external interference.

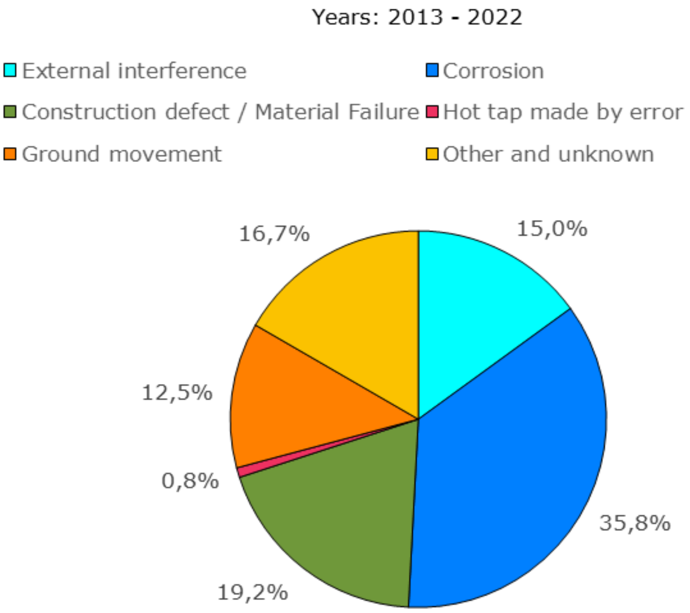

Figure 17: Distribution for incidents with leak size: pinhole/crack (2013-2022)

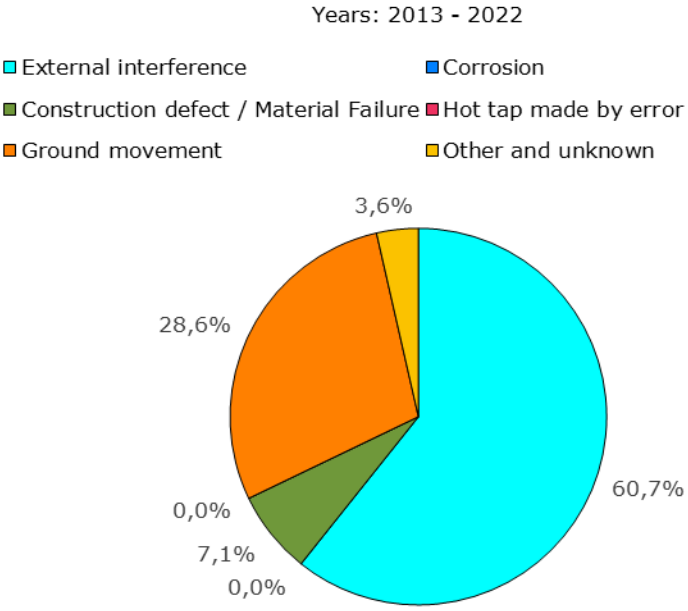

Figure 18: Distribution for incidents with leak size: hole (2013-2022)

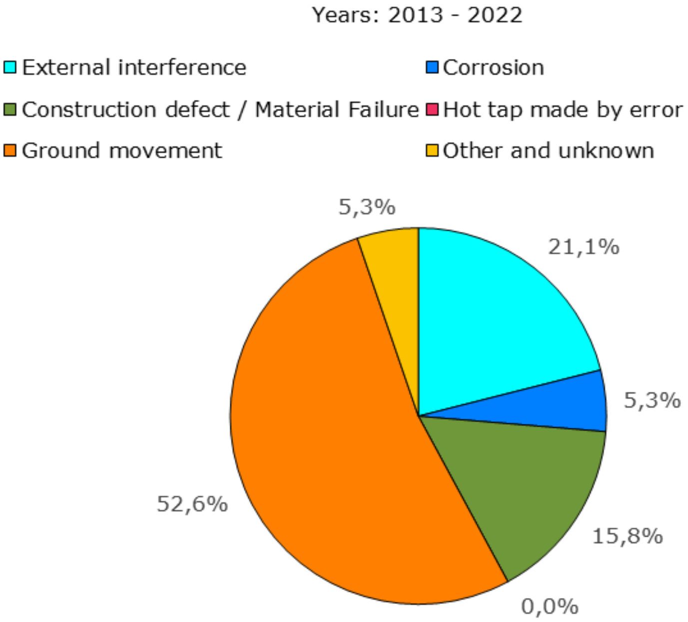

Figure 19: Distribution for incidents with leak size: rupture (2013-2022)

Figure 20 (period 1970-2022), Figure 21 (period 2013-2022) and Table 4 show the failure frequency per leak size and per incident cause. The failure frequency decreased over the years (2013-2022 vs. 1970-2022). The general distribution of the leak sizes remain the same: Corrosion remains the main cause for pinhole/crack leak sizes. Holes were mainly caused by external interference. For ruptures however, ground movement is the prime failure cause in the more recent period over external interference in the entire period.

Figure 20 and Figure 21 show that corrosion in the vast majority of incidents led to pinhole/crack type of leak.

Given the cause corrosion; Seven holes were observed in the period 1970 till 2022 and two ruptures occurred in this period.

One of these ruptures was caused by internal corrosion of a pipeline originally used for the transportation of coke oven gas. This 16” pipeline was constructed before 1954.

The second corrosion incident that led to a rupture was a stress corrosion cracking incident that occurred on a 4” pipeline. Stress corrosion cracking is a special mechanism of corrosion, that can only happen under special circumstances.

Both corrosion incidents are exceptional and not representative for normal corrosion incidents.

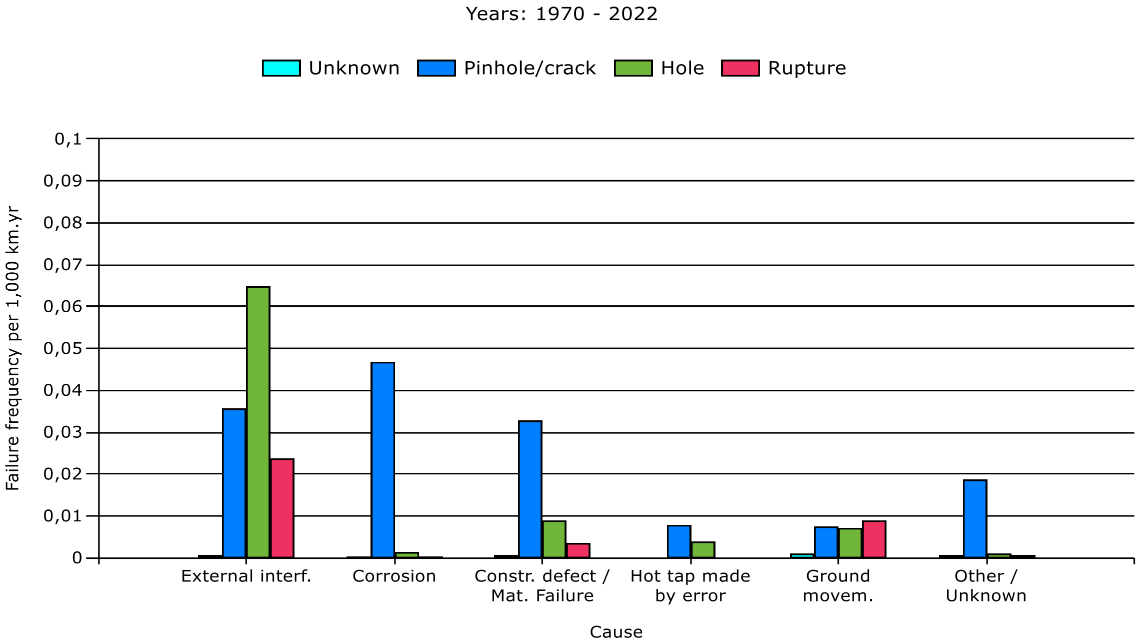

Figure 20: Relationship primary failure frequency, cause and size of leak (1970-2022)

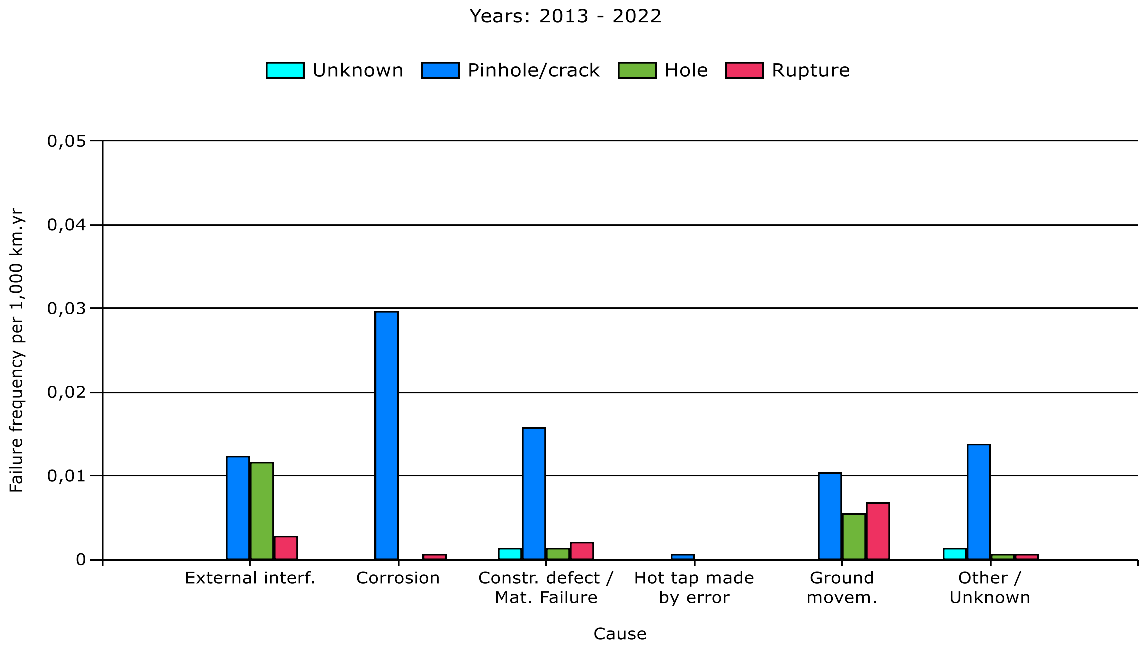

Figure 21: Relationship primary failure frequency, cause and size of leak (2013-2022)

Leak size	Failure frequency per 1,000 km·year					
	External interference	Corrosion	Construction defect / Mat. Failure	Hot tap made by error	Ground movement	Other and unknown
Unknown	0.0000	0.0000	0.0014	0.0000	0.0000	0.0014
Pinhole/crack	0.0124	0.0296	0.0158	0.0007	0.0103	0.0138
Hole	0.0117	0.0000	0.0014	0.0000	0.0055	0.0007
Rupture	0.0028	0.0007	0.0021	0.0000	0.0069	0.0007

Table 4: Primary failure frequency, cause and size of leak (2013-2022)

Figure 22 shows the number of incidents per cause that occurred in the last 10 years. What can be seen is that corrosion incidents together with external interference incidents and ground movement incidents are the largest cause of the incidents in the past decade.

However, external corrosion incidents rarely lead to ruptures of pipelines. Ground movement incidents can lead to ruptures because of the large forces released onto the pipelines in this type of incidents.

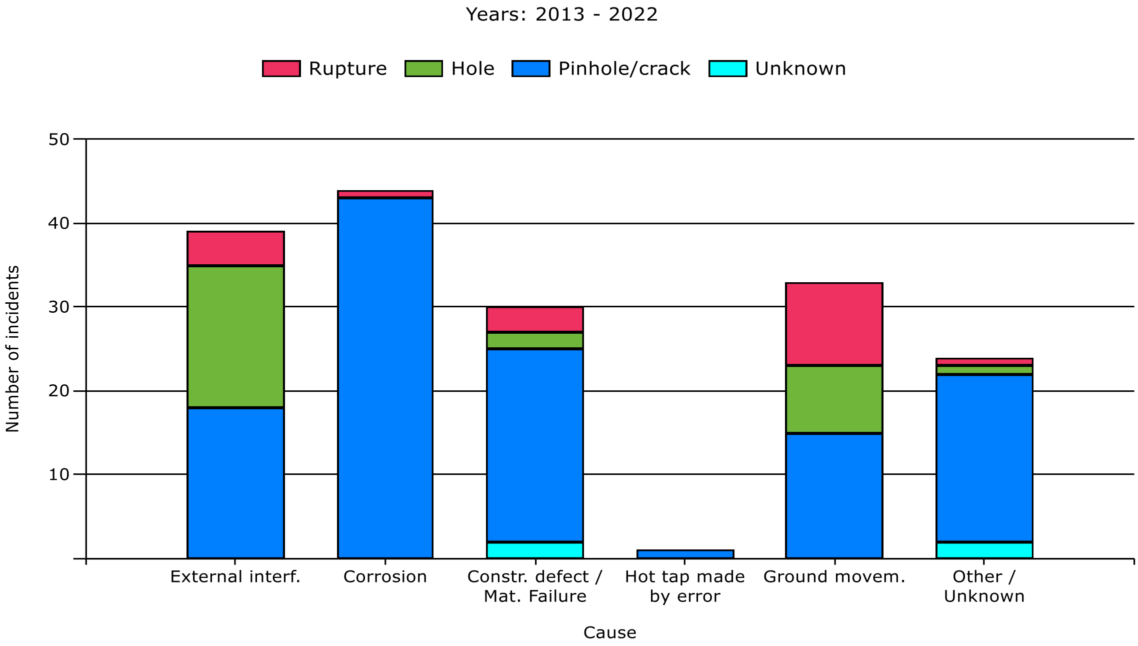

Figure 22: Number of incidents per cause in the period of 2013 to 2022

3.3.3 Secondary failure frequencies

The secondary failure frequencies are calculated by dividing the number of incidents by a partial system exposure. Partial system exposure means, for example, the exposure related to one diameter class or one year of construction class.

The calculation of secondary failure frequencies is done to consider the influence of design parameters (pressure, diameter, cover depth, etc.) on the failure frequencies per incident cause and per type of leak size. The calculations are performed for the whole database and for a more recent time period of the last 10 years (2013-2022).

For six incident causes, the secondary failure frequencies have been calculated according to the following design parameters:

- External interference: the diameter of the pipeline, the cover depth and the wall thickness.
- Corrosion: the year of construction, the type of coating and the wall thickness.
- Construction defect/material failure: the year of construction.
- Hot tap made by error: the diameter of the pipeline.
- Ground movement: the diameter of the pipeline.
- Other and unknown: main causes.

For "Ground movement" and "other and unknown" causes other more relevant considerations are reported.

3.3.3.1 Relationship between diameter class and size of leak (all failure causes)

Figure 23 demonstrates the relationship between the secondary failure frequency, the leak size and diameter of the pipeline. The secondary frequencies are given for a time period of 20 years as this is considered more representative for the current operating practises than taking the whole period.

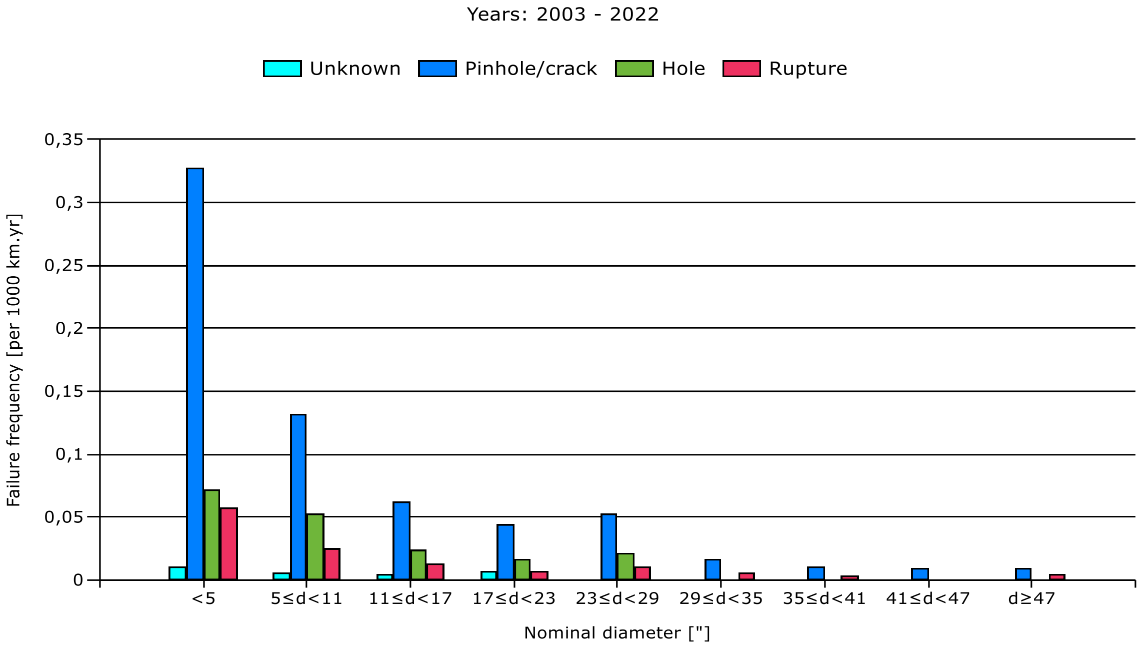

Figure 23: Secondary failure frequency, pipeline diameter and size of leak (2003-2022)

Nominal diameter	System exposure $\cdot 10^3$ km·yr	Secondary failure frequency per 1,000 km·yr			
		Unknown	Pinhole/crack	Hole	Rupture
diameter < 5′′	277.2	0.0108	0.3283	0.0722	0.0577
5″ ≤ diameter < 11″	667.0	0.0060	0.1319	0.0525	0.0255
11″ ≤ diameter < 17″	452.3	0.0044	0.0619	0.0243	0.0133
17″ ≤ diameter < 23″	294.8	0.0068	0.0441	0.0170	0.0068
23″ ≤ diameter < 29″	285.3	0.0000	0.0526	0.0210	0.0105
29″ ≤ diameter < 35″	181.1	0.0000	0.0166	0.0000	0.0055
35″ ≤ diameter < 41″	287.8	0.0000	0.0104	0.0000	0.0035
41″ ≤ diameter < 47″	107.5	0.0000	0.0093	0.0000	0.0000
diameter ≥ 47″	199.5	0.0000	0.0100	0.0000	0.0050

Table 5: Secondary failure frequency pipeline diameter and size of leak (2003-2022)

Nominal diameter	System exposure $\cdot 10^3$ km·yr	Secondary failure frequency per 1,000 km·yr			
		Unknown	Pinhole/crack	Hole	Rupture
diameter < 5′′	140.9	0.0142	0.3266	0.0426	0.0426
5″ ≤ diameter < 11″	343.1	0.0029	0.1253	0.0466	0.0175
11″ ≤ diameter < 17″	238.4	0.0000	0.0755	0.0168	0.0168
17″ ≤ diameter < 23″	151.4	0.0066	0.0330	0.0000	0.0066
23″ ≤ diameter < 29″	152.8	0.0000	0.0196	0.0131	0.0131
29″ ≤ diameter < 35″	100.5	0.0000	0.0100	0.0000	0.0000
35″ ≤ diameter < 41″	149.8	0.0000	0.0134	0.0000	0.0000
41″ ≤ diameter < 47″	53.3	0.0000	0.0000	0.0000	0.0000
diameter ≥ 47″	120.9	0.0000	0.0165	0.0000	0.0000

Table 6: Secondary failure frequency, pipeline diameter and size of leak (2013-2022)

Figure 23, Table 5 and Table 6 illustrate that ruptures mainly occurred at pipelines with smaller diameters and that failure frequencies decrease with increasing diameter.

3.3.3.2 Relationship between external interference, size of leak and design parameter

Figure 24 to Figure 31 show the failure frequencies for the incident cause "external interference" for different pipeline design parameter classes and leak sizes. The design parameters considered are: pipeline diameter, cover depth and wall thickness. For the design parameters diameter and wall thickness the graphs are presented for both the whole period 1970-2022 and the last ten years (2013-2022). For cover depth a graph is presented for the period 1970-2022 and a graph is presented with the development of the five year moving average failure frequency per cover depth. Although the graphs are presented separately, it must be noticed that the design parameters are correlated. No quantitative correlations between parameters have been studied.

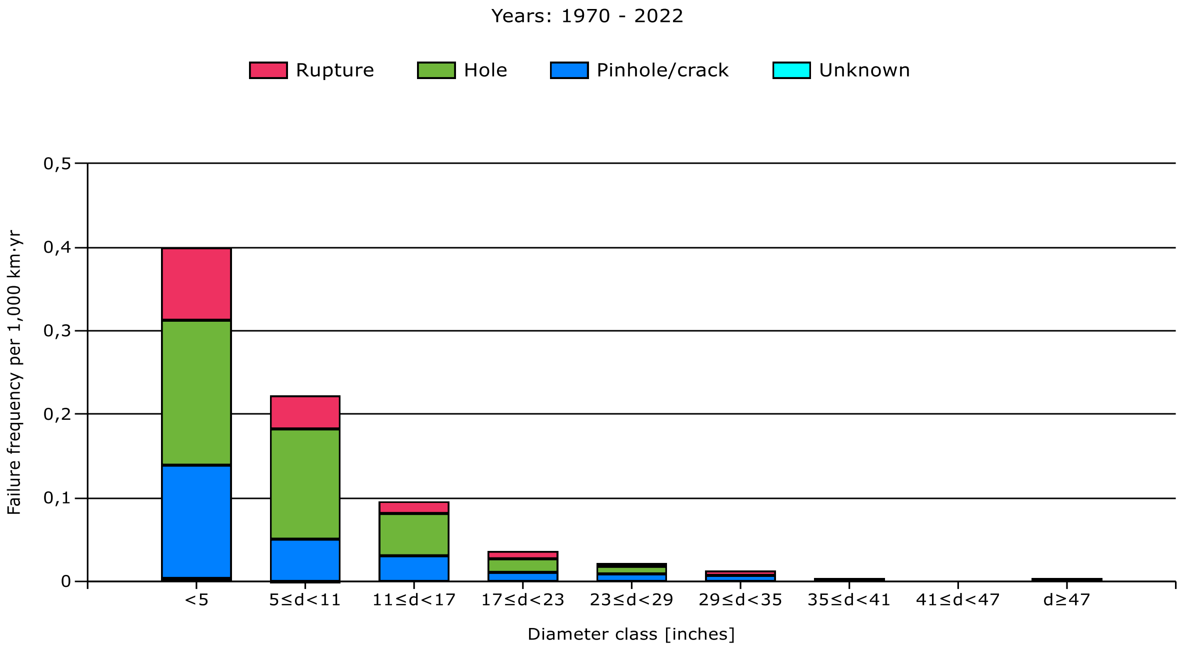

Figure 24: Relationship external interference, leak size and diameter (d) (1970-2022)

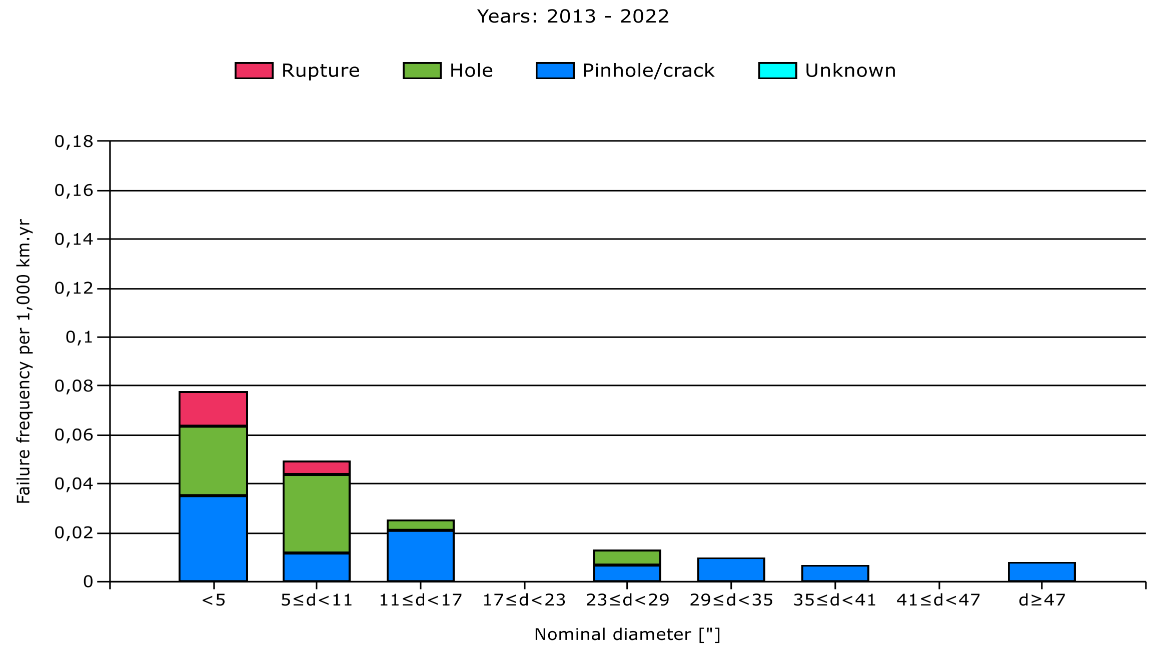

Figure 25: Relationship external interference, leak size and diameter (d) (2013-2022)

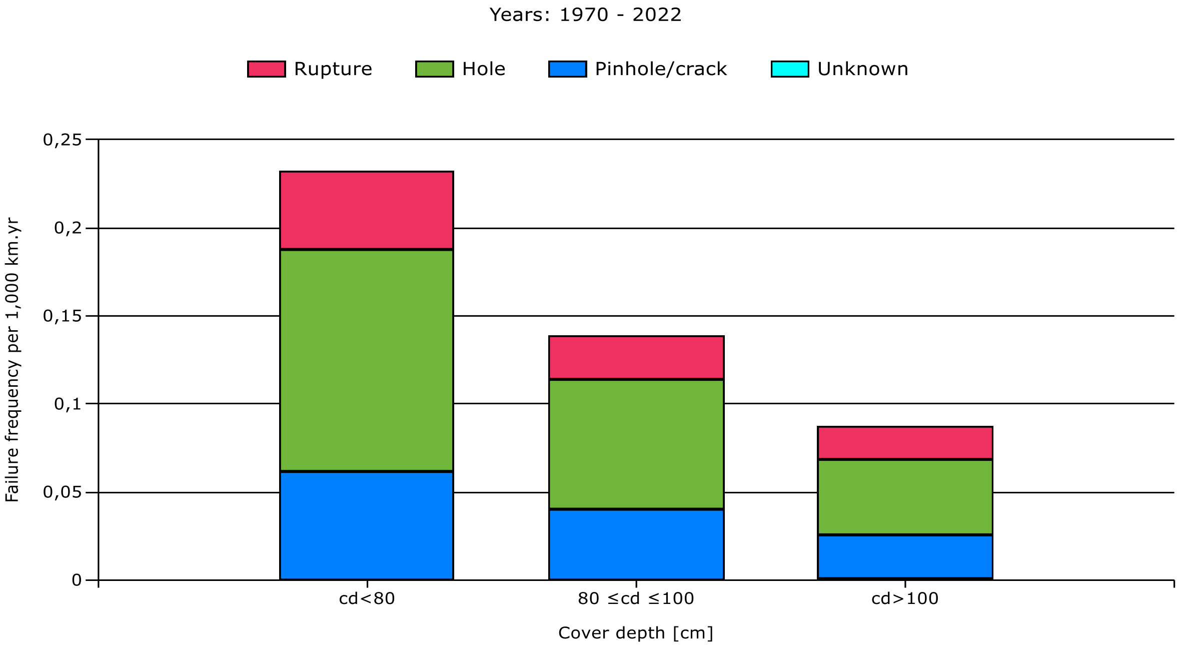

Figure 26: Relationship external interference, leak size and cover depth (cd) (1970-2022)

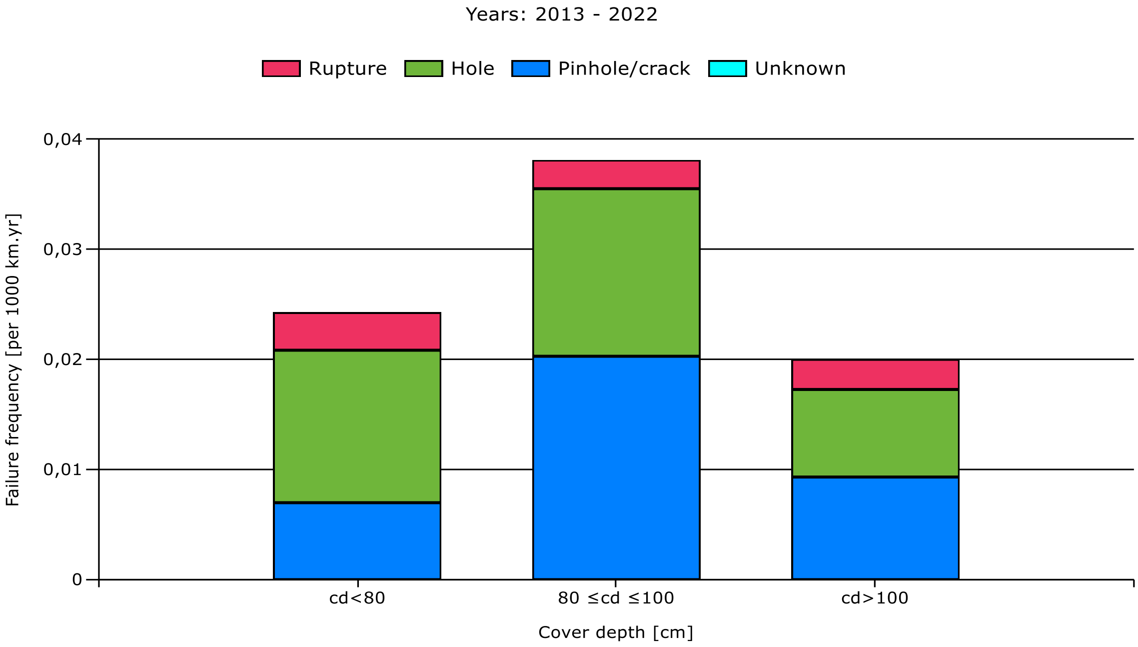

Figure 27: Relationship external interference, leak size and cover depth (cd) (2013-2022)

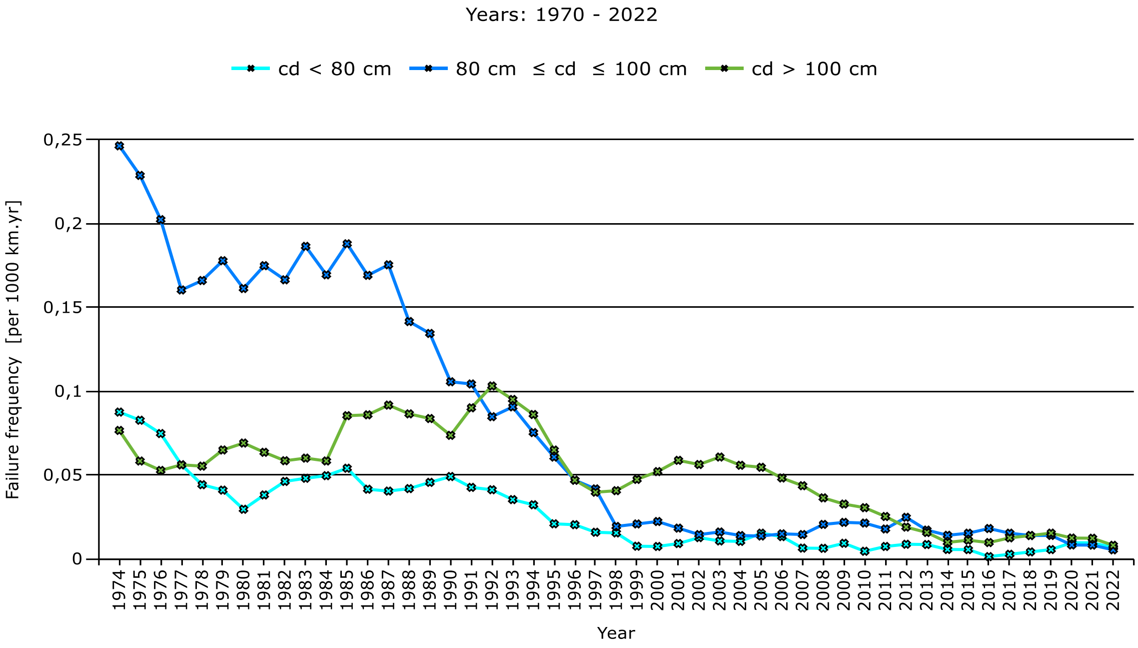

Figure 28: Failure frequency of external interference (five year moving average) and cover depth (cd) (1970-2022)

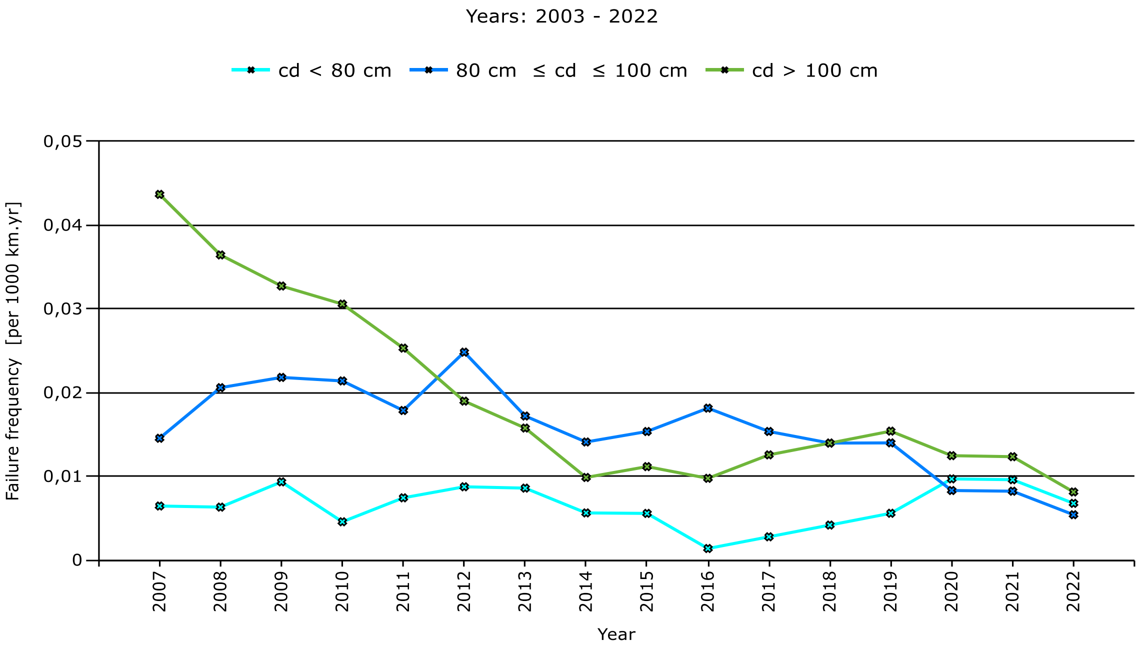

Figure 29: Failure frequency of external interference (five year moving average) and cover depth (cd) (2003-2022)

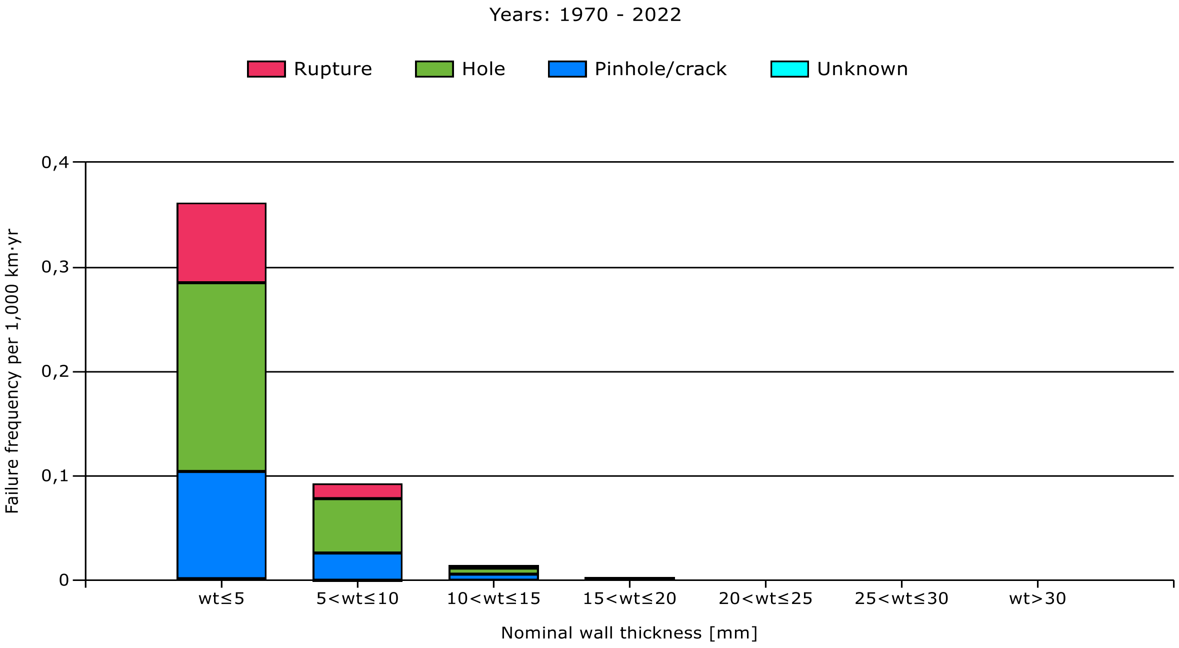

Figure 30: Relationship external interference, leak size and wall thickness (wt) (1970-2022)

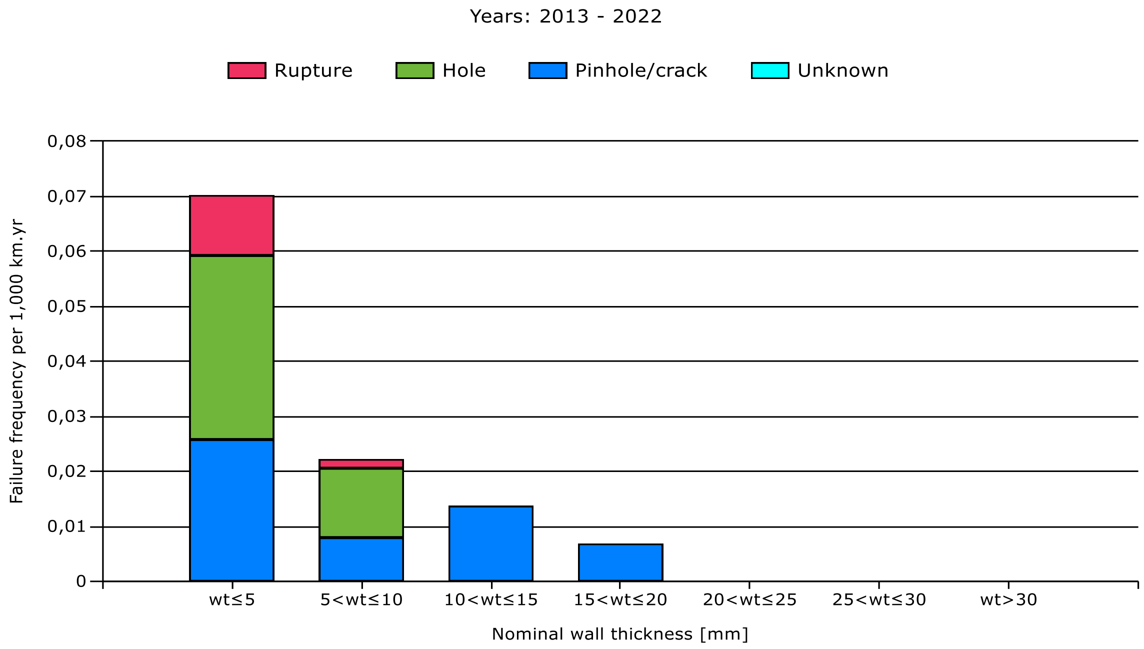

Figure 31 : Relationship external interference, size of leak and wall thickness (wt) (2013-2022)

From these figures, some general conclusions can be drawn:

- Large diameter pipelines are less vulnerable to external interferences than smaller diameter pipelines (Figure 24 and Figure 25). There might be several explanations for this: small diameter pipelines can be more easily hooked up during ground works than bigger pipelines, their resistance is often lower due to smaller wall thickness and they might be found more frequently in urban areas where third party activity is generally higher.
- The cover depth has been a leading indicator for the failure frequencies. Failure frequencies of all cover depth classes have decreased over the years. (Figure 28) However, in the last 10 years, the failure frequencies are at the same order of magnitude (Figure 29).
- Pipelines with a larger wall thickness have a lower failure frequency for external interference (Figure 30 and Figure 31).
- No external interference incidents occurred with wall thicknesses above 20 mm.

3.3.3.3 Relationship between corrosion, leak size and design parameter

Figure 32 to Figure 37 show the failure frequencies for the incident cause "corrosion" for different pipeline parameter classes and leak sizes. The parameters considered are year of construction, coating type and wall thickness. For each design parameter two graphs are constructed: one for the period 1970-2022 and one for the period 2013-2022.

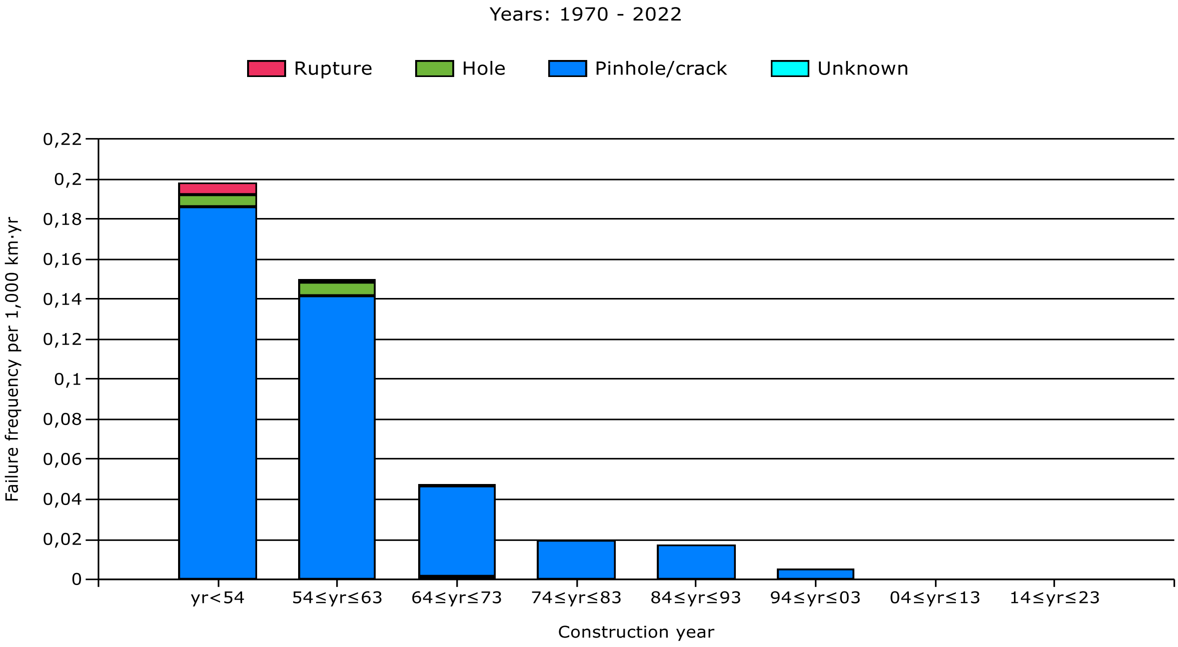

Figure 32: Relationship corrosion, leak size and construction year (1970-2022)

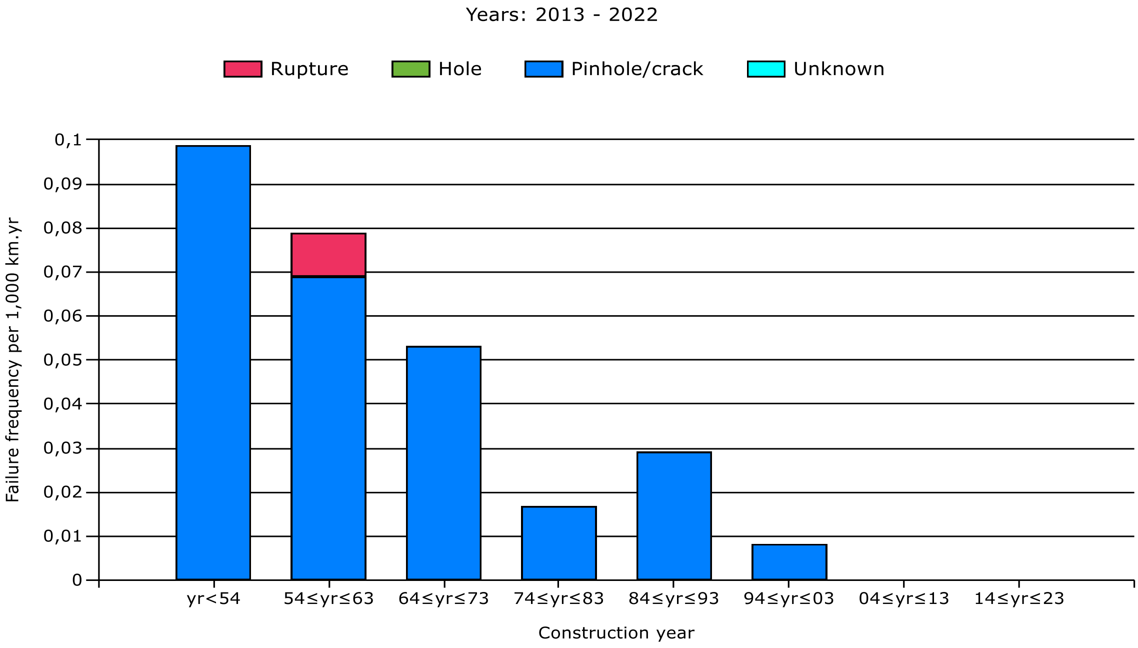

Figure 33: Relationship corrosion, leak size and construction year (2013-2022)

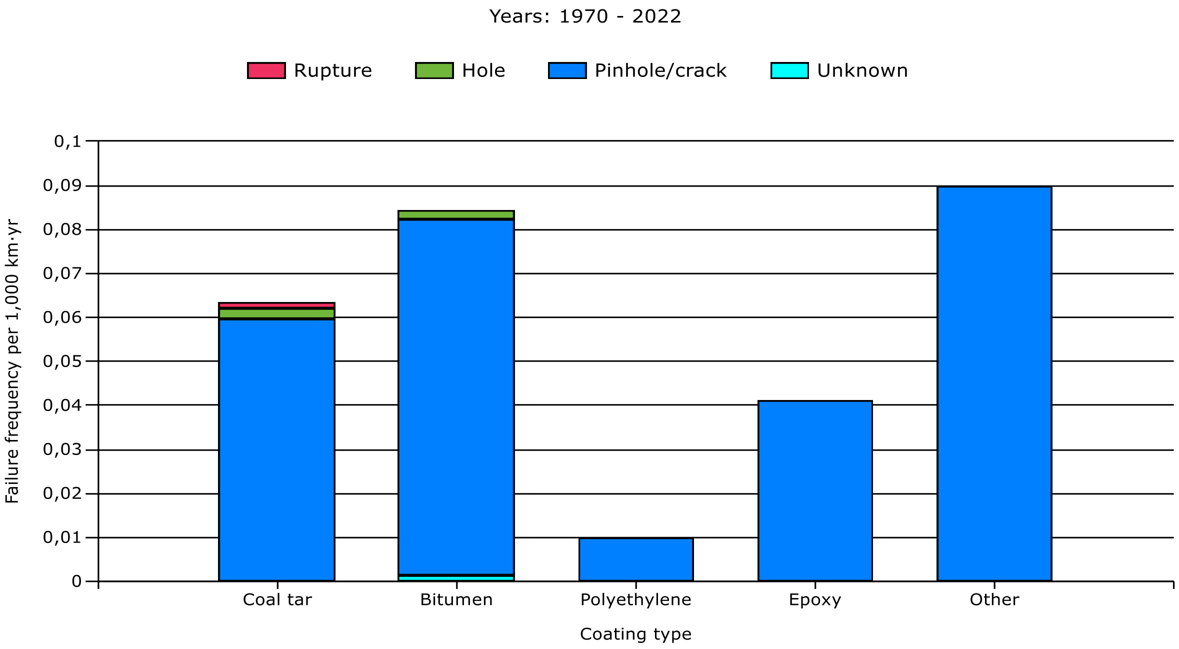

Figure 34: Relationship corrosion, leak size and coating type (1970-2022)

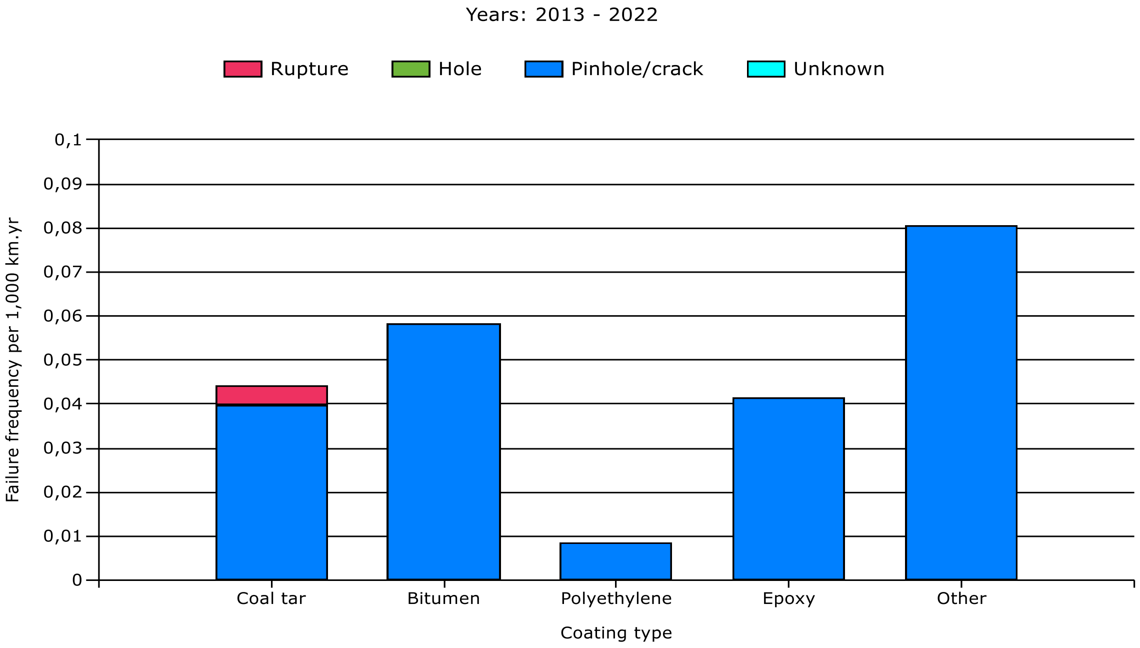

Figure 35: Relationship corrosion, leak size and coating type (2013-2022)

From these figures, it appears that older pipelines, with predominantly tar coatings, have higher failure frequencies. Nowadays, most transmission operators use coatings like polyethylene, which appears to have a low failure frequency for corrosion.

Different protective measures are undertaken by pipeline owners to prevent leakage due to corrosion. These measures are for example cathodic protection and pipeline coating. In-line inspections and pipeline surveys also allow corrosion to be detected at an earlier stage.

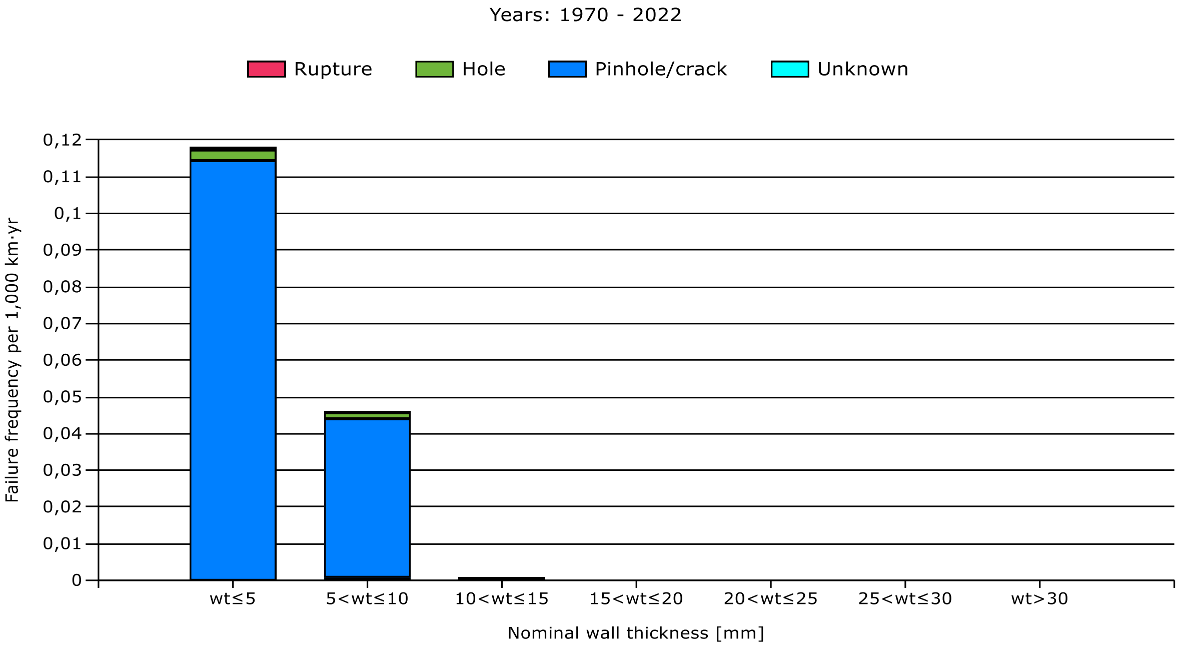

Figure 36: Relationship corrosion, size of leak and wall thickness (wt) (1970-2022)

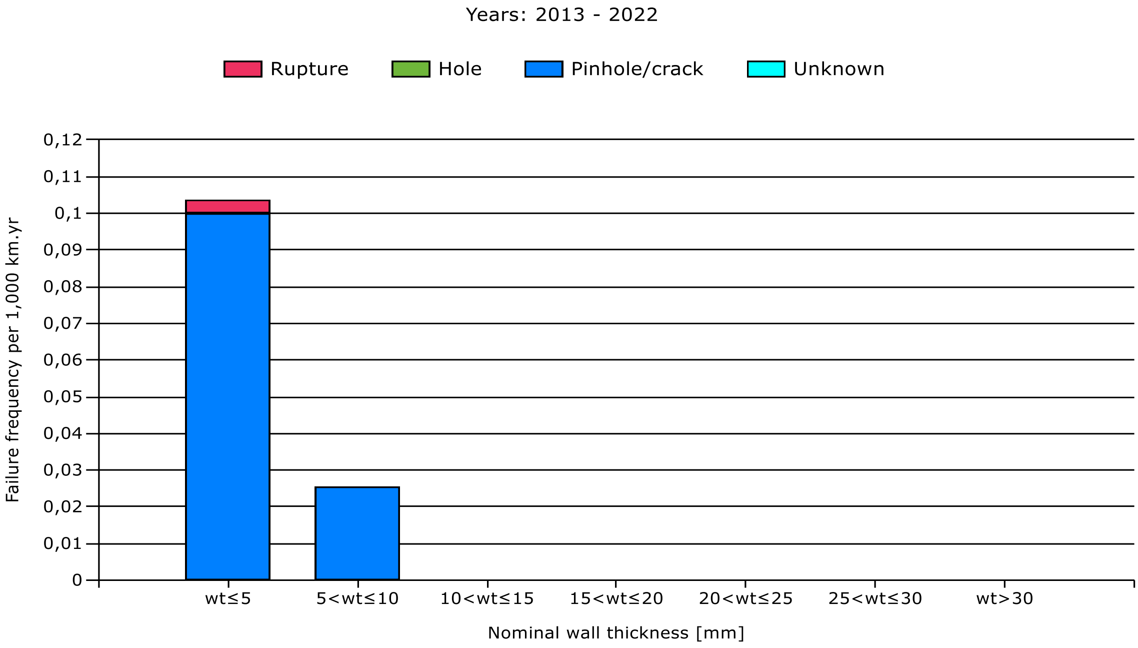

Figure 37: Relationship corrosion, size of leak and wall thickness (wt) (2013-2022)

From these figures some general conclusions can be drawn:

- The failure frequency decreases with increasing construction year.
- The failure frequency decreases with increasing wall thickness. Corrosion is a time dependent phenomenon of deterioration of the pipelines. Corrosion takes place independently of the wall thickness, but the thinner the corroded pipeline wall, the sooner the pipeline fails. Corrosion on thicker pipelines takes longer before causing an incident and therefore has more chance to be detected by inspection programs.
- Pipelines coated with a polyethylene coating have a far lower failure frequency than pipelines with other types of coating.
- No corrosion incidents occurred with wall thicknesses > 15 mm.

For the corrosion incidents, two other types of data are registered:

- the location of corrosion (internal, external, unknown),
- the appearance of corrosion (general, pitting, cracking, unknown).

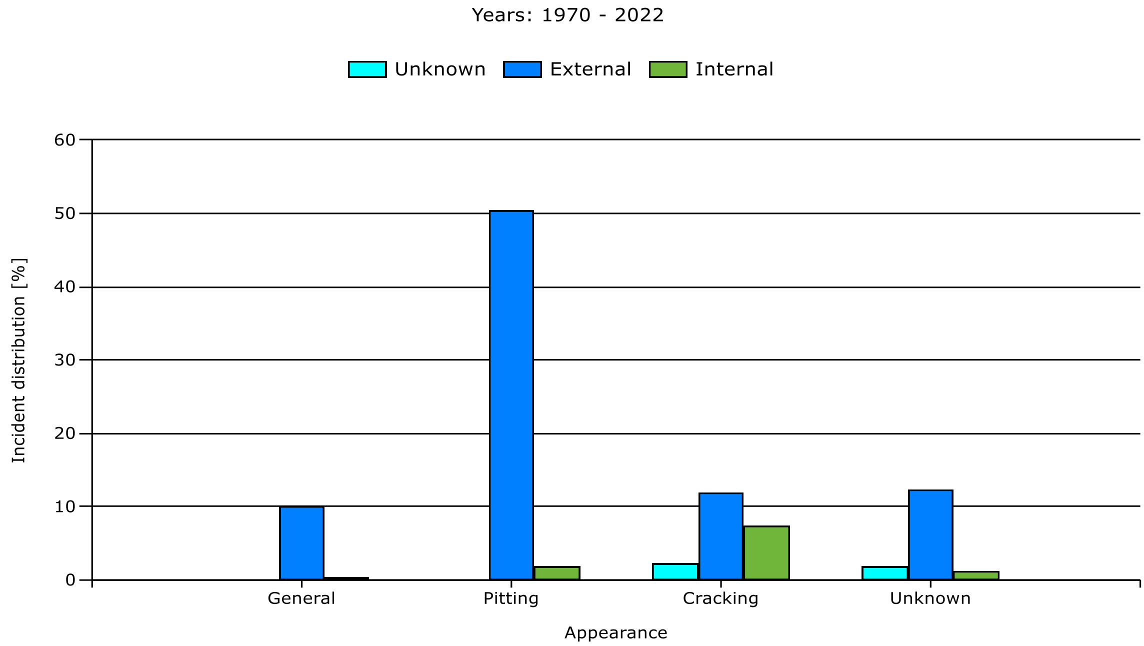

Figure 38: Breakdown of corrosion incidents on basis of location and appearance (1970-2022)

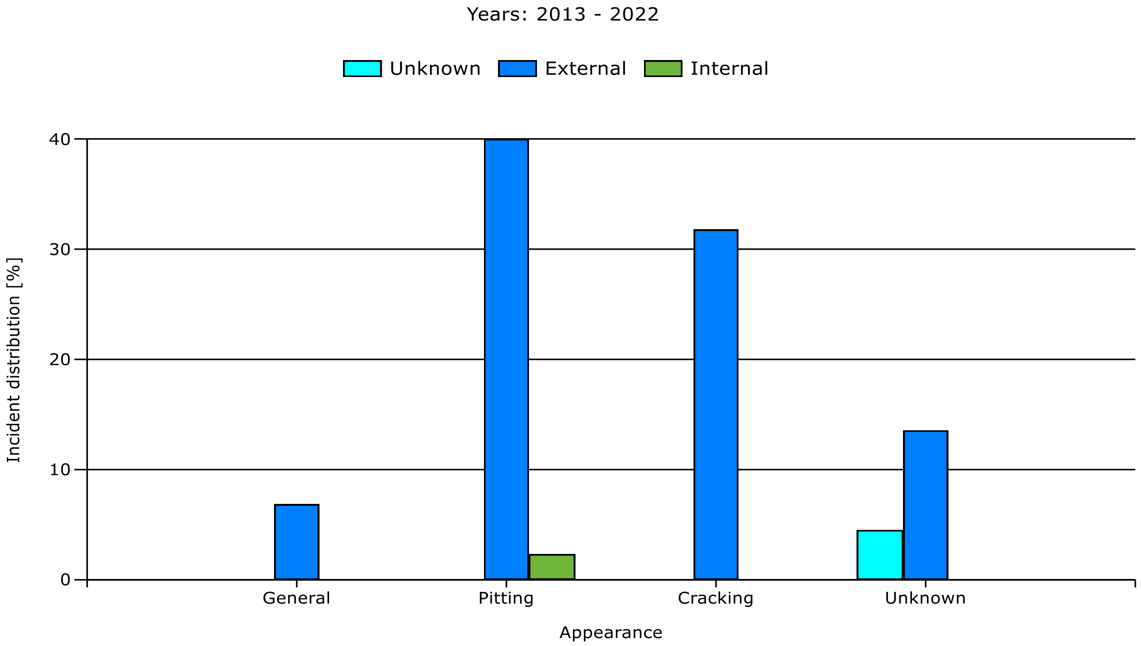

Figure 39: Breakdown of corrosion incidents on basis of location and appearance (2013-2022)

Figure 38 to Figure 39 demonstrate that pitting is the most common form of corrosion. Almost all corrosion incidents with pitting occur on the external surface of the pipelines.

Corrosion appearing as cracks is the second most common form of corrosion. These cracks are found on both the inner and the external surface of the pipelines. For the more recent period of 2013-2022 all cracks were found on the external surface.

3.3.3.4 Relationship between construction defect/material failures, leak size and design parameter

EGIG recognizes construction defects / material failures as one of the causes of pipeline incidents. During the last ten years, they represented 17,5% of the pipeline incidents and are ranked on a fourth position in the causes of incidents after corrosion, external interference and ground movement (Figure 13).

The EGIG database makes it possible to distinguish between construction defect and material failures.

Figure 40 to Figure 43 show the failure frequencies for the incident cause 'construction defect' and 'material failure' in relation to construction year and leak size for the periods 1970-2022 and 2013-2022.

From these figures, some general conclusions can be drawn: failure frequencies for 'construction defects' and 'material failure' generally decrease with increasing year of construction. New pipelines are less vulnerable to construction defects due to technical improvements.

The failure frequency of construction defects with leak size 'pinholes/cracks' for pipelines constructed in the decade 2014-2023 is based on one recorded incident. This is equal to pipelines constructed in the decade 2004-2013 (also one incident). The exposure of pipelines built between 2004 and 2023 is low compared to the other construction year classes.

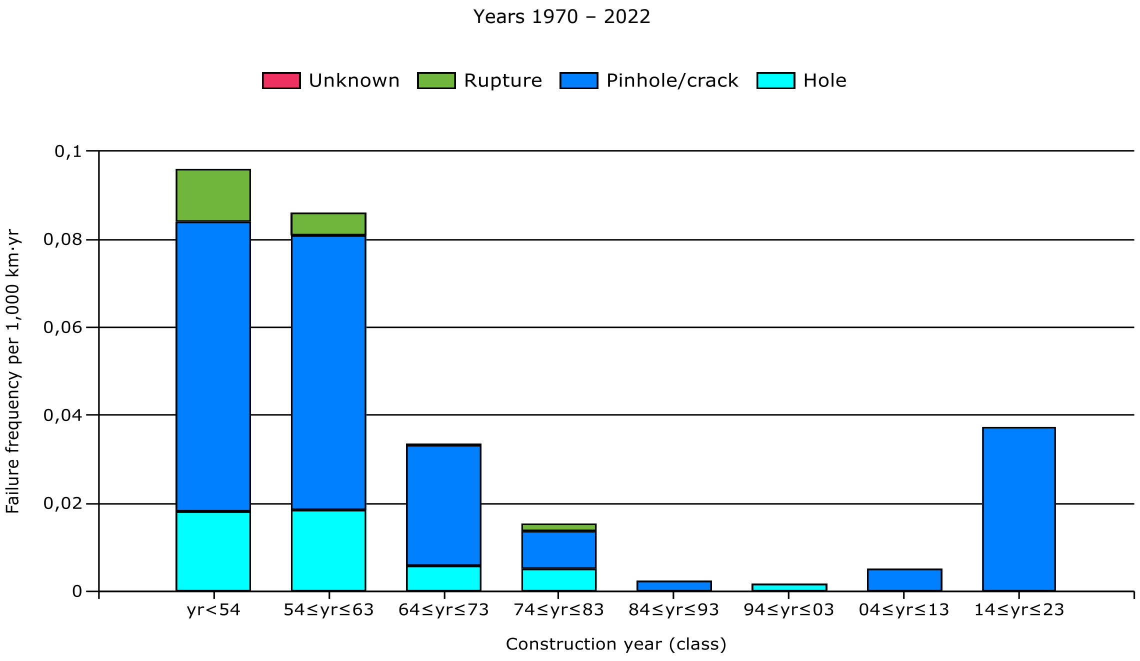

Figure 40: Relationship construction defect, leak size and construction year (1970-2022)

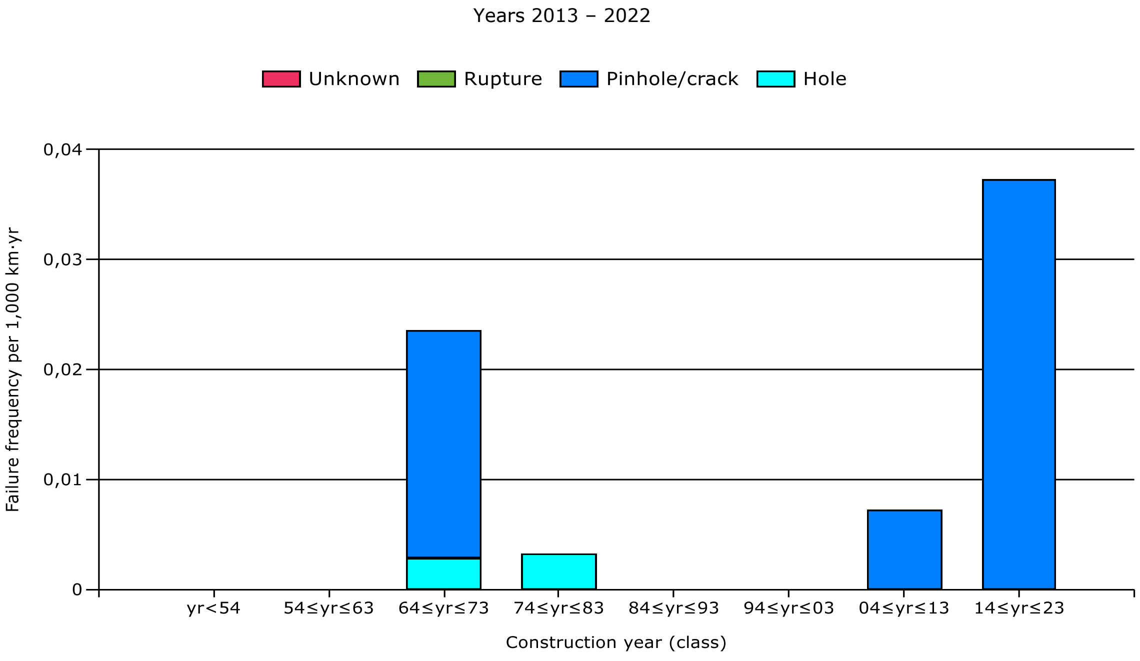

Figure 41: Relationship construction defect, leak size and construction year (2013-2022)

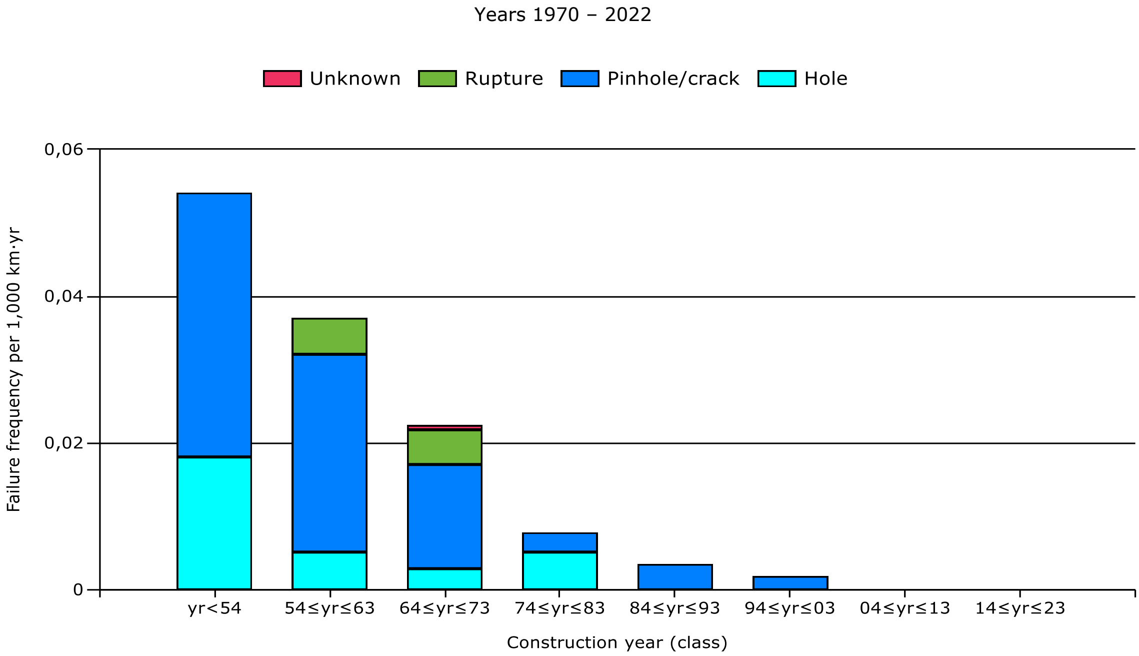

Figure 42: Relationship material failure, leak size and construction year (1970-2022)

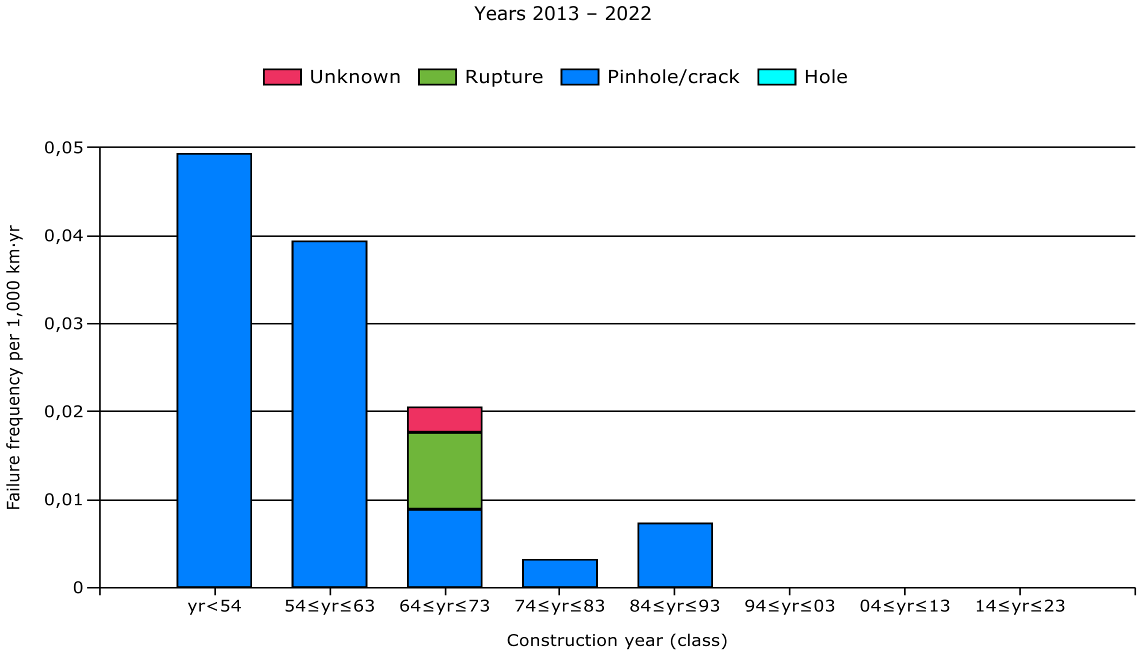

Figure 43: Relationship material failure, leak size and construction year (2013-2022)

3.3.3.5 Relationship between hot tap made by error, size of leak and design parameter

The term "hot tap made by error" means that a connection has been made by error to the gas transmission pipeline, assuming it was another pipeline.

Figure 44 and Figure 45 show the failure frequencies for the incident cause 'hot tap made by error' for different pipeline diameter classes and leak sizes. The first graph presents the failure frequency for the period 1970-2022 and the second graph for the period 2013-2022.

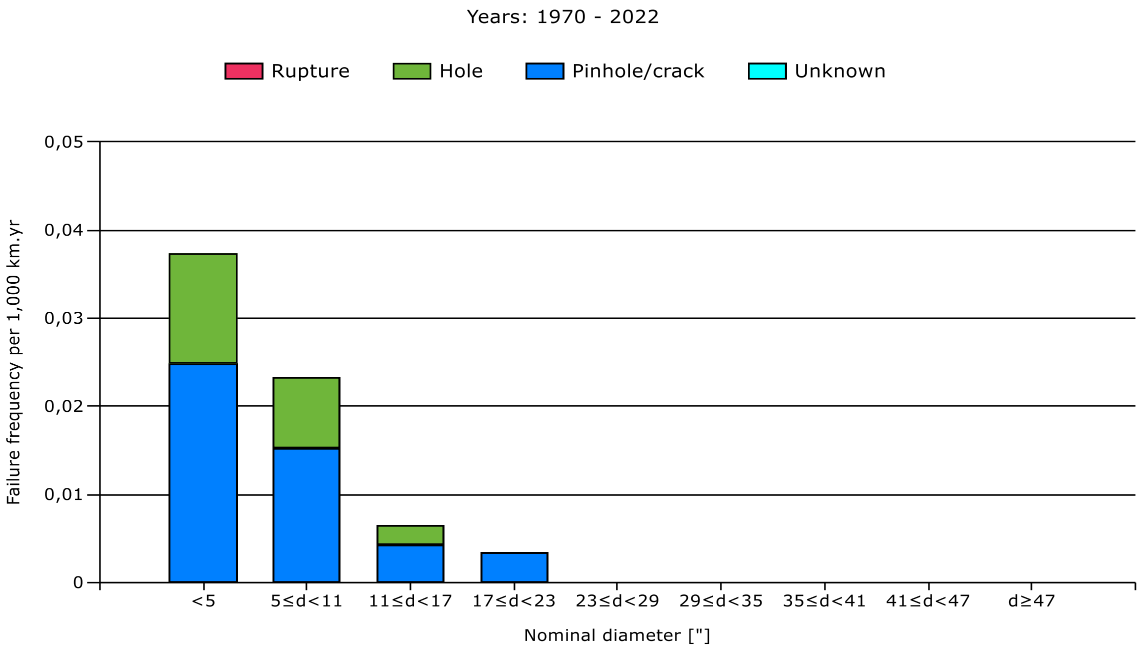

Figure 44: Relationship hot tap made by error, leak size and diameter (1970-2022)

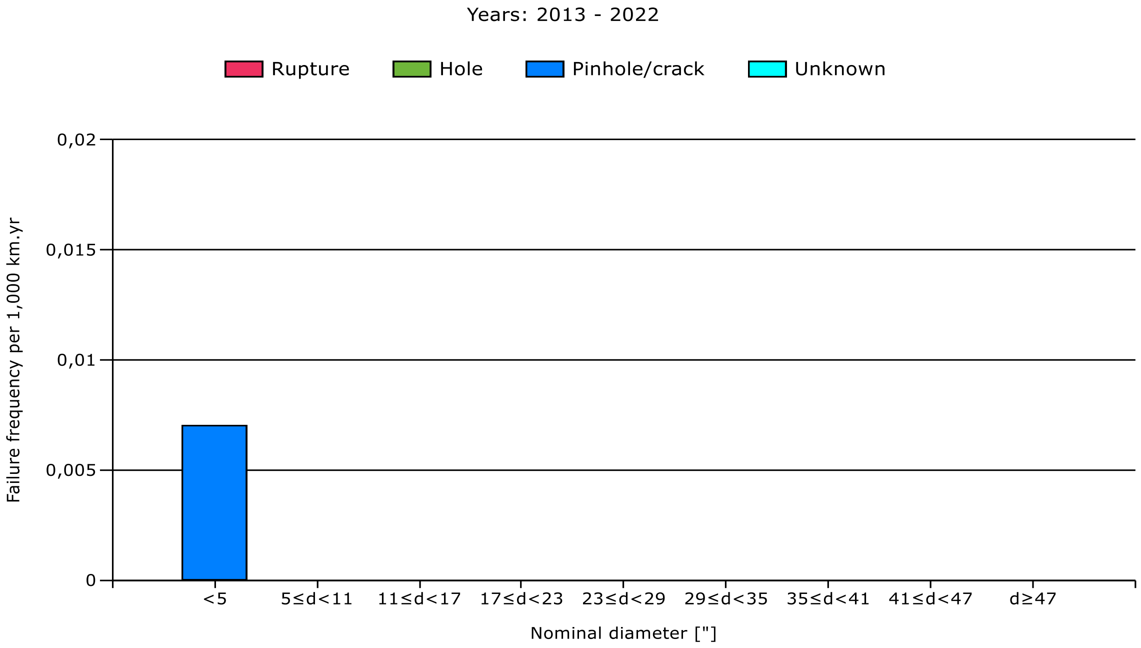

Figure 45: Relationship hot tap made by error, leak size and diameter (2013-2022)

From these figures, some general conclusions can be drawn: the failure frequency for 'hot tap made by error' decreases with increasing pipeline diameter. The same trend is true for every leak size. The failure frequency of 'hot tap made by error' has decreased over the years (Figure 14).

3.3.3.6 Ground movement

Ground movement is responsible for approximately 19% of the incidents over the last ten years (see Figure 13). Figure 46 and Figure 47 show the failure frequencies for the incident cause 'ground movement' for different pipeline diameter classes and leak sizes.

Both graphs present the failure frequency per pipeline diameter class, one for the period 1970-2022, the second for the period 2013-2022.

From these figures some conclusions can be drawn:

For the period 1970-2022 failure frequencies for 'ground movement' generally decrease with increasing pipeline diameter. The failure frequency for the diameter ≥ 47'' is caused by one ground movement incident.

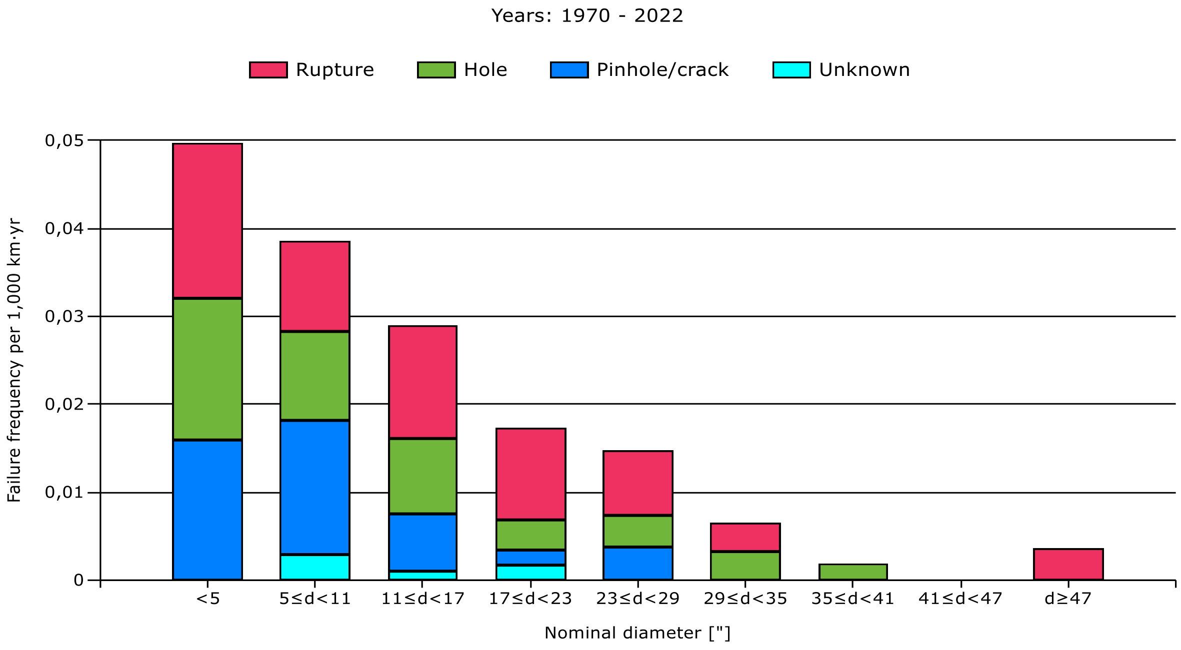

Figure 46: Relationship ground movement, size of leak and diameter (1970-2022)

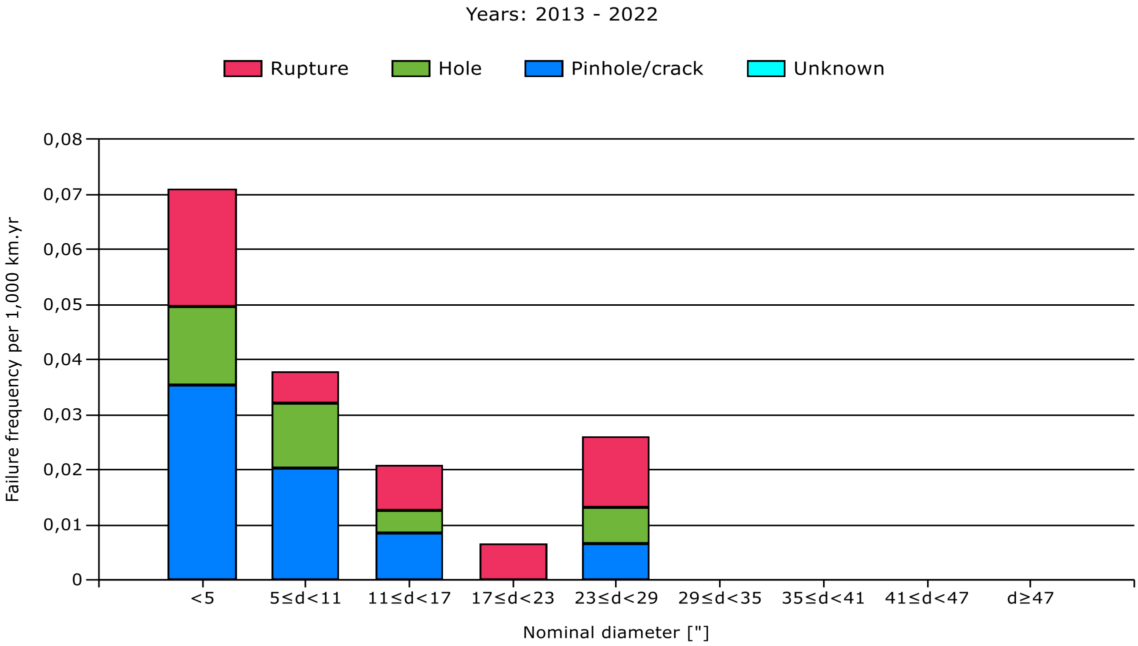

Figure 47: Relationship ground movement, size of leak and diameter (2013-2022)

There are many types of 'ground movement' incidents. Figure 50 and Figure 51 give more details on the different types of ground movements that caused a pipeline incident. Landslides is by far the most common sub-cause of a ground movement incident. Failing of pipelines by flooding is the second largest sub-cause of pipeline incidents within this group.

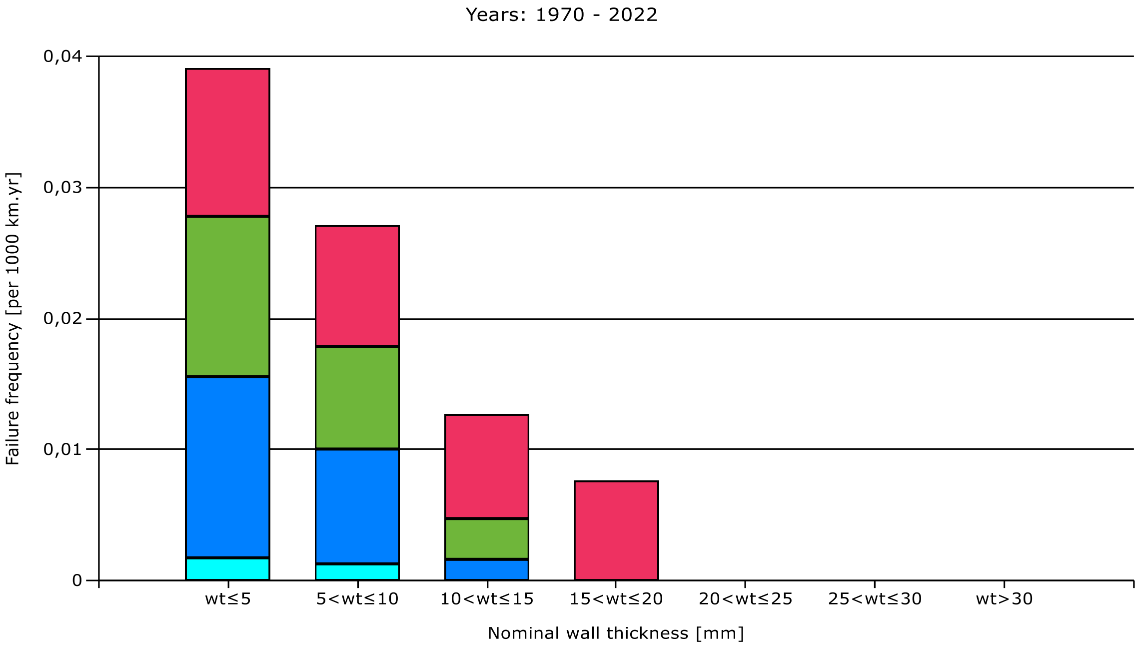

Figure 48: Relationship ground movement, leak size and wall thickness (wt) (1970-2022)

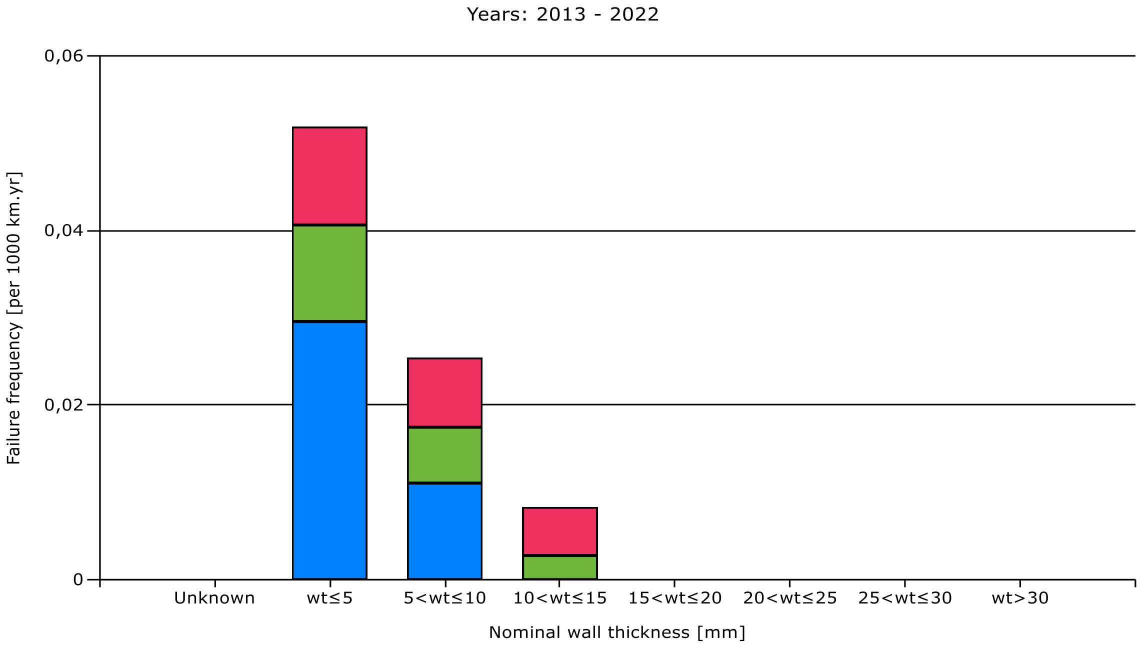

Figure 49: Relationship ground movement, leak size and wall thickness (wt) (2013-2022)

No incidents were recorded that were caused by earthquakes.

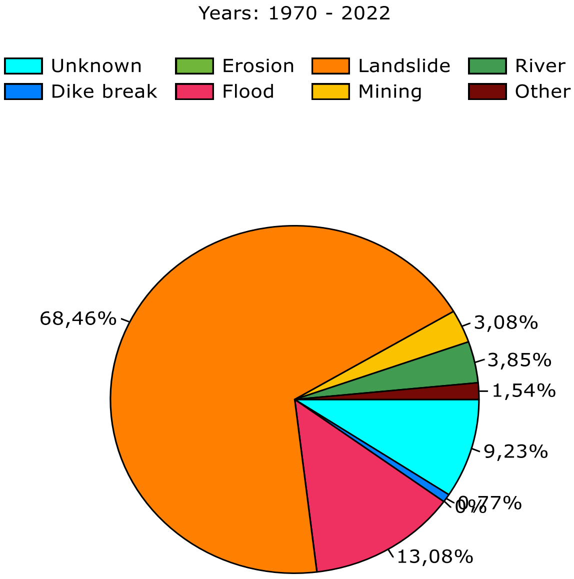

Figure 50: Distribution of the sub-causes of ground movement (1970-2022)

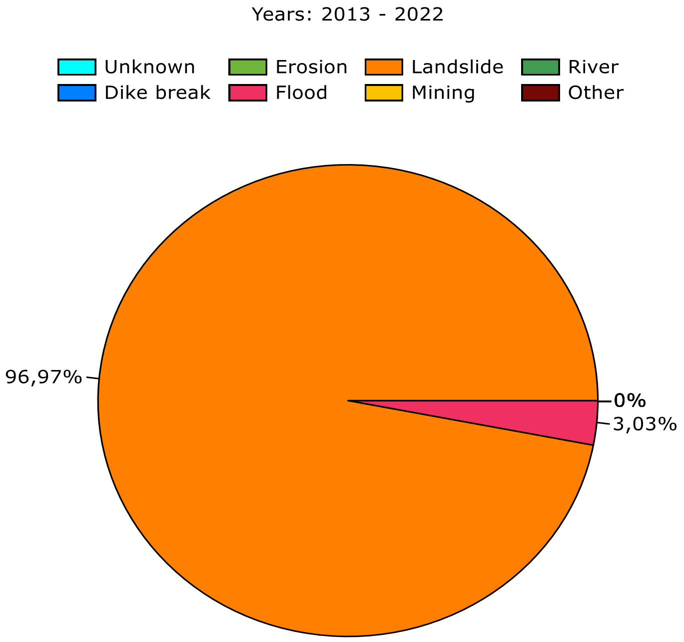

Figure 51: Distribution of the sub-causes of ground movement (2013-2022)

3.3.3.7 Other and unknown

36 out of 112 (32.1%) of the incidents in the category ’other and unknown’ are caused by lightning. Within the period 1970-2022, 36 incidents caused by lightning have been recorded in the EGIG database, which represents a failure frequency equal to 0.0068 per 1,000 km·yr. EGIG examined the distribution of the consequences of lightning in terms of leak sizes. Out of 36 incidents, 34 were pinholes/cracks and 2 resulted in a hole.

Figure 52 shows the failure frequency for the incidents caused by lightning in relation to the wall thickness. Here it can be seen that the failure frequencies for the incidents caused by lightning decreases with increasing wall thickness. This might be explained by the higher energy density of a lightning for a lower wall thickness.

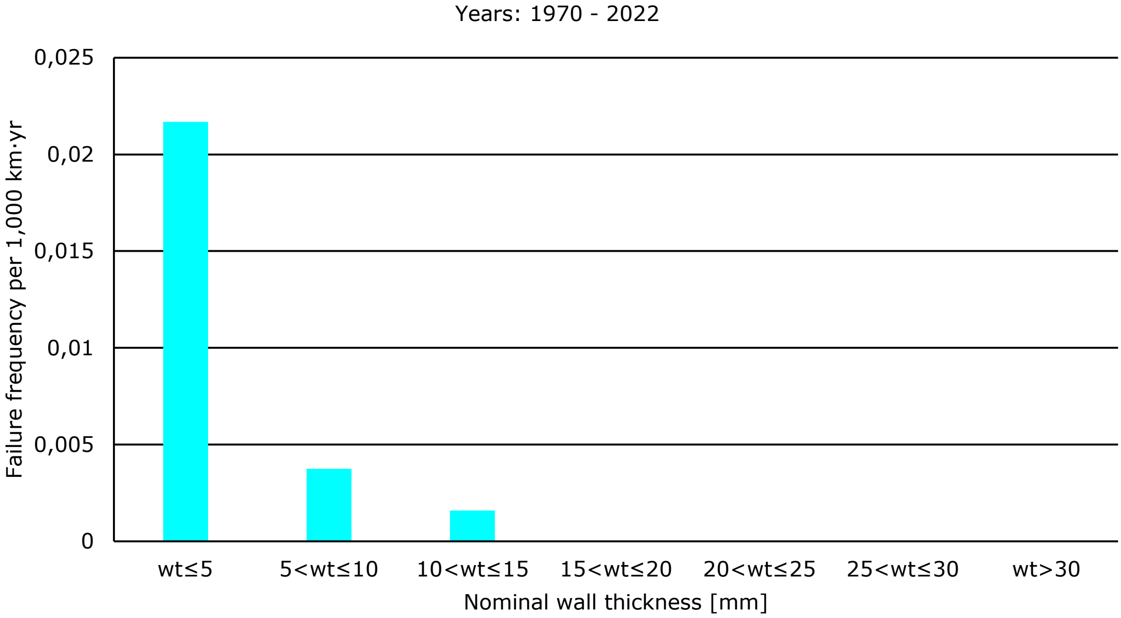

Figure 52: Relation wall thickness and failure frequency of incidents caused by lightning

3.4 Other analyses

3.4.1 Relationship between corrosion and age

In this analysis, the failure frequency of corrosion incidents has been studied as a function of construction year and the age of the pipeline at the moment of the incident.

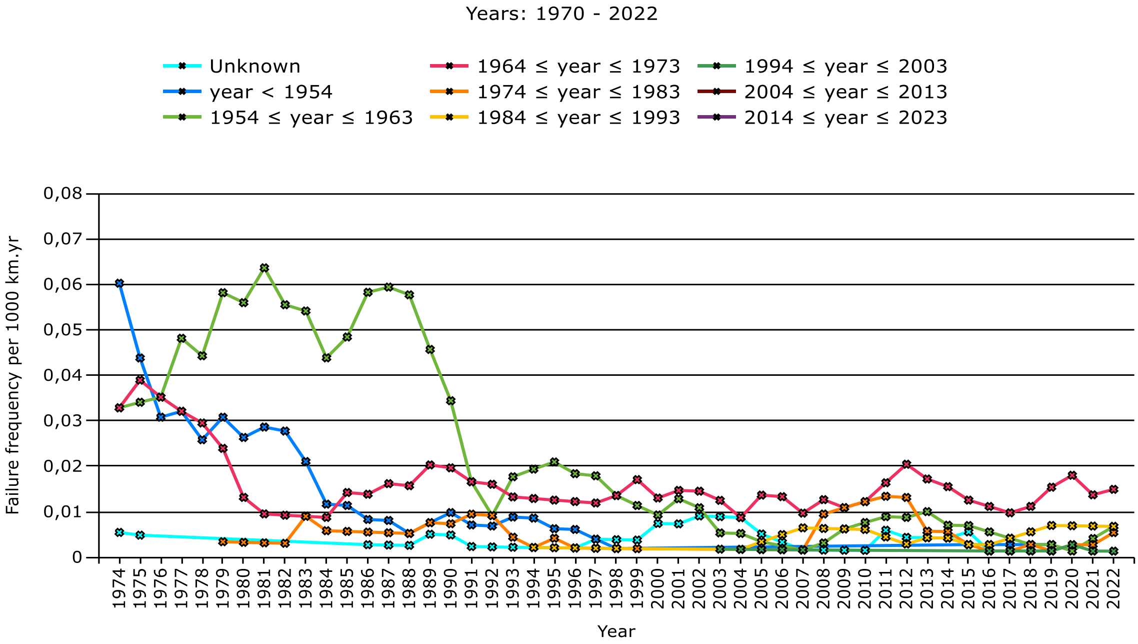

Figure 53: Failure frequency (five year moving average) of corrosion incidents and year of construction

The increase of the failure frequency of pipelines with an age older than 60 years constructed before 1954 was caused by two incidents in 2015 and a decreasing population in the years after 2015.

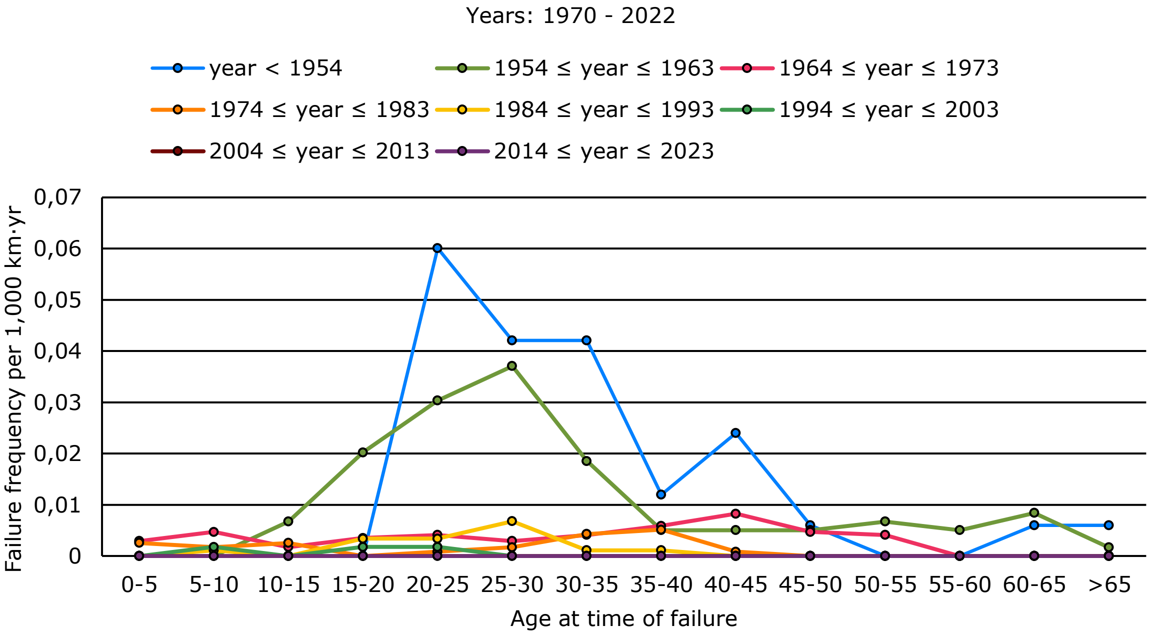

Figure 54: Relationship failure frequency of corrosion incidents and the age at the time of failure

Explanation Figure 54:
in Figure 54 for instance a pipeline constructed before 1954: the failure frequency 20 to 25 years after construction is 0.0601 per 1,000 km·yr, whereas it is 0.0120 per 1,000 km·yr after 35-40 years. EGIG started data collection from 1970 on, therefore no data is available for failure frequencies at the early life stage of pipelines constructed before 1954 or pipelines constructed between 1954 and 1964.

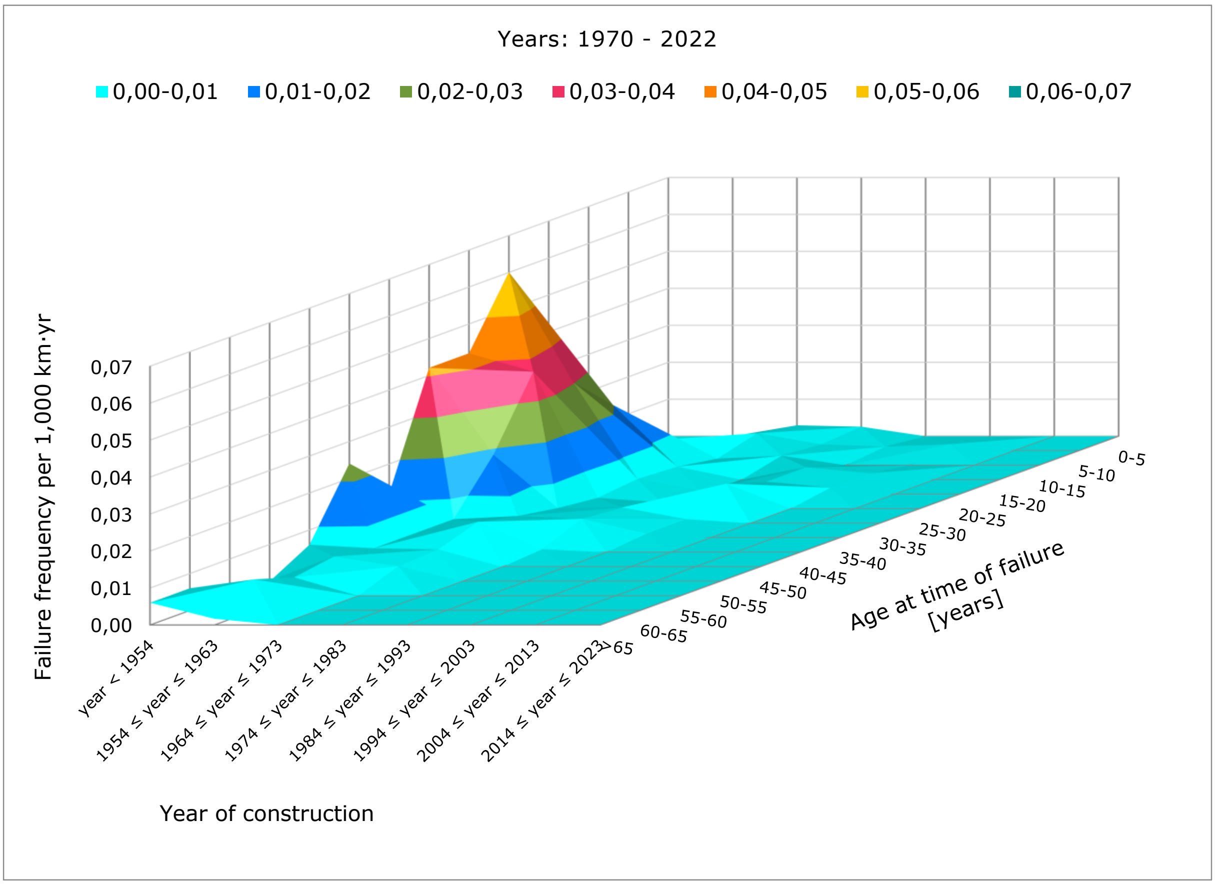

Figure 55: 3D plot of failure frequency of corrosion incidents and the age at the time of failure

Figure 55 shows the dependency of failure frequency with the age of the pipelines and the year of construction.

The first conclusion of Figure 54 and Figure 55 is that early constructed pipelines (before 1964) had higher failure frequencies than recently constructed pipelines at the same age. Pipelines constructed in the last 50 years do not show a dependency between the failure frequency of corrosion and their age or construction year class.

3.4.2 Ignition of releases

Fortunately, not every gas release ignites, which limits the consequences of the incidents. In the period 1970-2022, only 5.2% of the gas releases recorded in the EGIG database ignited. Pipeline ruptures with ignition can cause severe societal consequences. This is especially the case for pipelines with larger diameters. Figure 56 shows that gas releases from large diameter pipeline ruptures at high pressure have ignited with a higher ratio than smaller diameter pipeline ruptures at lower pressure. This data is based on only a few ruptures. Care should be taken when using it as an ignition probability, as the uncertainty is high. In the paper (Michael R. Acton, 2008) ”Ignition Probability for High Pressure Gas update to 2019” an analysis is made of ignition probabilities. This paper shows that even ruptures of large diameter pipelines and high pressure not always ignite.

Information on ignited releases is presented in Table 7 as a function of size of leak and pipeline diameter.

Size of leak	% of releases with ignition
Pinhole-crack	4.8%
Hole	2.2%
Rupture [all diameters]	14.3%
Rupture [d < 17] (inch)	10.1%
Rupture [d ≥ 17] (inch)	39.3%

Table 7: Ignition of releases per leak size

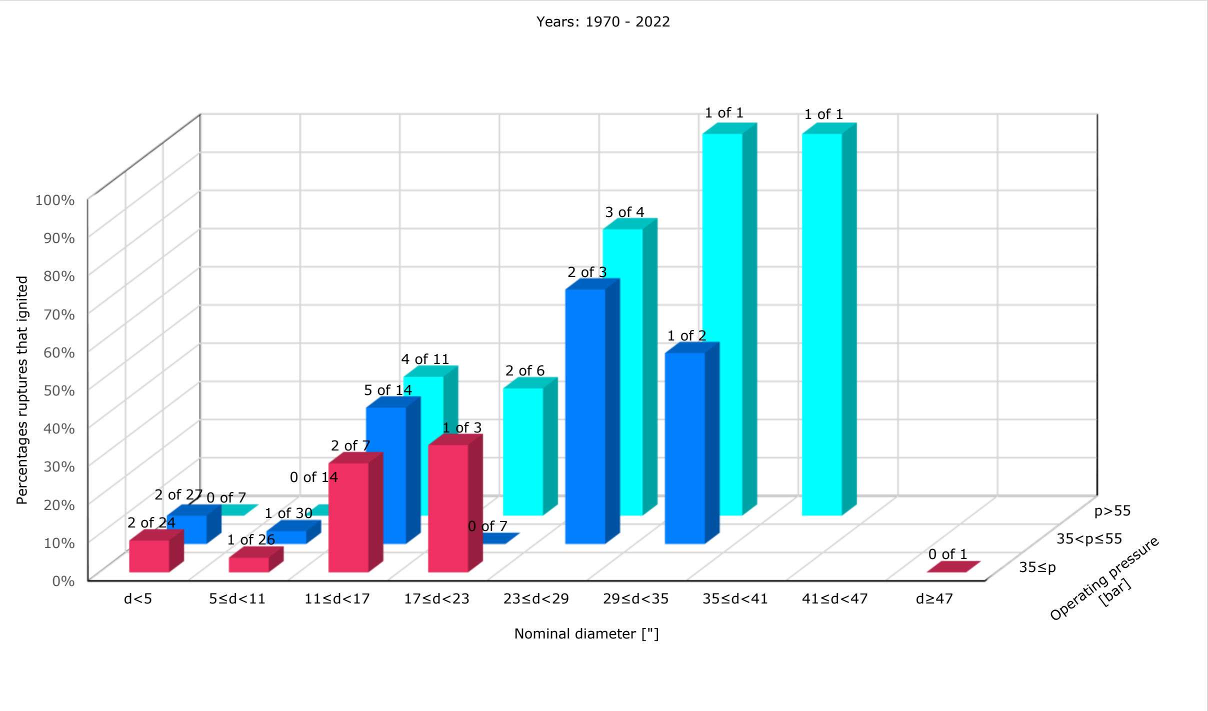

Figure 56: Percentages ruptures that ignited subdivided in diameter and pressure (1970-2022)

3.4.3 Injuries and fatalities

EGIG database also registers qualitative information about the consequences of incidents, amongst other injuries and fatalities that, unfortunately, occurred in some of them.

EGIG studied the injuries and fatalities among different groups involved in pipeline incidents. These groups are:

- employees or contractors of the gas company;
- third party directly involved in causing the incidents (for example digger drivers in the case of external interference incidents);
- emergency services (firefighters, medical assistance);
- the general public.

The EGIG database contains a total of 1,463 incidents, but as is shown in Figure 57 only a small percentage leads to injuries and fatalities. The highest fatality and injury rate can be found among the people who are directly involved in causing the incident. In 6 cases (0.41%) these incidents caused fatalities among the people causing the incident. Two incidents (0.14%) involved fatalities among the public. In Figure 58 it can be seen that the fatalities mainly occurred when the incident was a pipeline rupture.

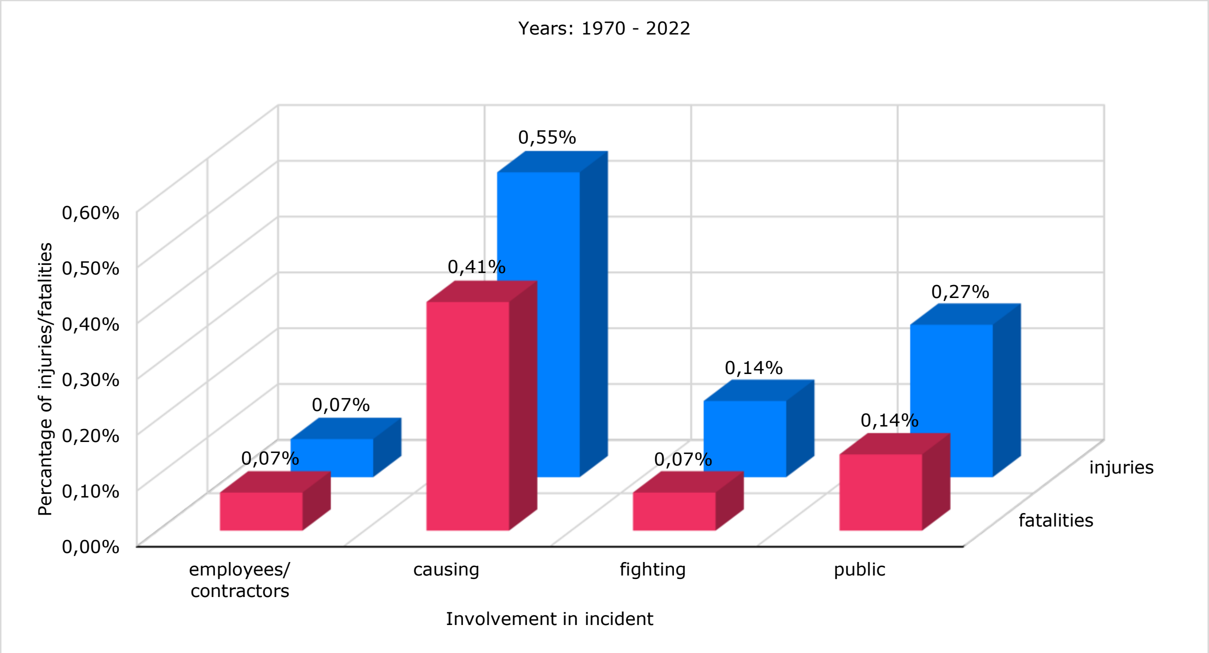

Figure 57: Percentage of accidents of groups involved in pipeline incidents (1970-2022)

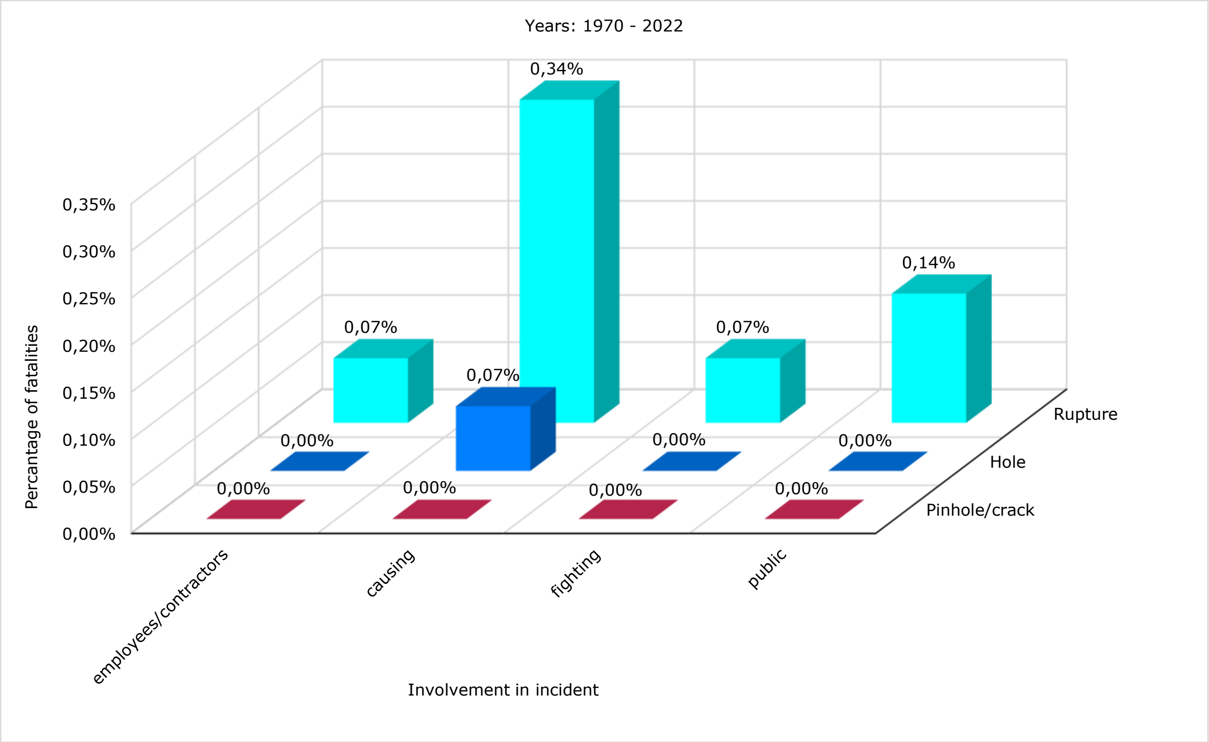

Figure 58: Percentage fatalities of accidents of groups as a function of leak size (1970-2022)

Although the occurrence of injuries and fatalities is low, safety remains the highest priority for the gas transmission companies.

3.4.4 Detection of incidents

Incidents are detected in different ways. Table 8 shows the distribution per detection type. People directly involved with the transmission networks (gas company), like patrol, contractors and staff, are the most common detector (approximately 42% of the incidents).

In the period 1970-2022, 14.6% of the incidents were detected by the patrols, 14.5% by contractors and 13.4% by staff (including in-line inspection). Public also detect a significant part of the incidents. In the period between 1970-2022 public detected 34.1% of the incidents.

In the last 10 years (2013-2022) the number of public detected incidents decreased to 18.1%. The percentage of incidents detected by landowners and others has increased in the last ten years.

Detection	Incident distribution 1970 – 2022 [%]	Incident distribution 2013–2022 [%]
Public	34.1%	18.1%
Gas company	42.4%	50.3%
Unknown	6.5%	0.0%
Landowner	5.7%	12.3%
Distribution company	4.9%	5.3%
Other	6.4%	14.0%

Table 8: Detection of incidents

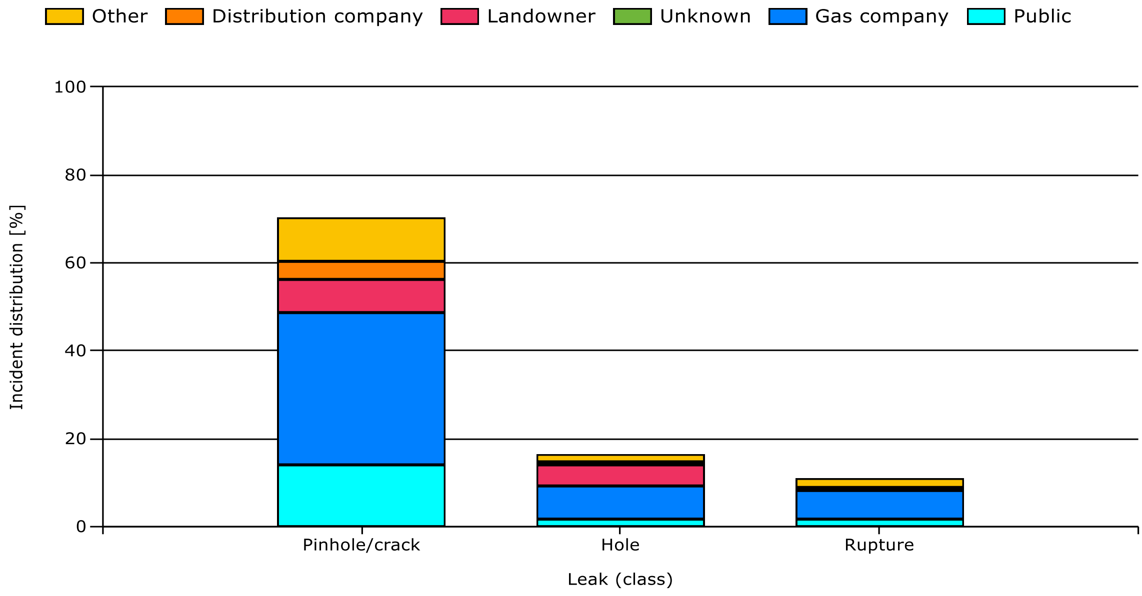

Figure 59: Detection of incidents per leak size (2013-2022)

Figure 59 shows that most pinhole/cracks are detected by the gas company and public. Holes are mainly detected by the gas company and landowners. Ruptures are mainly detected by the gas company.

4 CONCLUSIONS

- The EGIG database is a valuable source of information on European gas pipelines and pipeline incidents.

- EGIG has maintained and expanded the European Gas pipeline incident database. Nineteen gas transmission system operators in Europe now collect incident data on 150 thousand km of pipelines every year. The total exposure, which expresses the length of a pipeline and its period of operation, is 5.29 million km·yr.

- In the EGIG database 1,463 pipeline incidents are recorded in the period from 1970-2022.

- The history of incidents collected in the database gives reliable failure frequencies. The overall failure frequency over the period 1970-2022 is 0.277 incidents per year per 1,000 km.

- The five year moving average failure frequency in 2022, which represents the average failure frequency over the past 5 years is 0.101 per year per 1,000 km.

- The five year moving average and overall failure frequency show a general downward trend with fluctuations over the years.

- Incidents caused by external interference and ground movement are characterised by potentially severe consequences. This emphasises the importance of measures taken by pipeline operators and authorities to prevent these incidents.

- Over the last 5 years, corrosion as a primary cause has the highest failure frequency followed by external interference that used to have the highest failure frequency up to and including the 11th EGIG report. The consequences of corrosion failure are typically pinholes, whereas consequences of external interference can be much more severe.

- Over the last ten years, corrosion, external interference, ground movement and construction defects, represent 25.7%, 22.8%, 19.3% and 17.5% respectively of the pipeline incidents reported.

5 BIBLIOGRAPHY

API. (2012, December). 5L Specification for Line Pipe 45th edition.

EGIG. (2008). *7th Report of the European Gas Pipeline Incident Data Group, 1970-2007.* https://www.egig.eu/.

EGIG. (2011). *8th Report of the European Gas Pipeline Incident Data Group, 1970-2010.* https://www.egig.eu/.

EGIG. (2015). *9th Report of the European Gas Pipeline Incident Data Group, 1970-2013.* https://www.egig.eu/.

EGIG. (2018). *10th Report of the European Gas Pipeline Incident Data Group, 1970-2016.* https://www.egig.eu/.

Michael R. Acton, P. J. (2008). 7th International Pipeline Conference. *Ignition Probability for High Pressure Gas Transmission Pipelines.* Calgary, Alberta, Canada, September 29–October 3, 2008: ASME.

APPENDIX 1: STATISTICS

Primary failure frequencies over different time intervals

Period	Interval [years]	Number of incidents	Total system exposure ·10^6 km·yr	Primary failure frequency per 1,000 km·yr	95% LL Primary failure frequency per 1,000 km·yr	95% UL Primary failure frequency per 1,000 km·yr
1970 – 2007	7th report, 38 years	1,173	3,152	0.372	0.351	0.394
1970 – 2010	8th report, 41 years	1,249	3,551	0.352	0.333	0.372
1970 – 2013	9th report, 44 years	1,309	3,980	0.329	0.311	0.347
1970 – 2016	10th report, 47 years	1,366	4,409	0.310	0.294	0.327
1970 – 2019	11th report, 50 years	1,411	4,837	0.292	0.277	0.307
1970 – 2022	12th report, 53 years	1,463	5,288	0.277	0.263	0.291
1983 – 2022	40 years	998	4,613	0.216	0.203	0.230
1993 – 2022	30 years	610	3,806	0.160	0.148	0.174
2003 – 2022	20 years	379	2,754	0.138	0.124	0.152
2013 – 2022	10 years	171	1452	0.118	0.101	0.137
2018 – 2022	5 years	74	736	0.101	0.351	0.394

Table 9: Primary failure frequencies and confidence intervals over different time intervals

Leak size	Primary failure frequency per 1,000 km·yr	95% LL Primary failure frequency per 1,000 km·yr	95% UL Primary failure frequency per 1,000 km·yr
Unknown	0.0027	0.0003	0.0098
Pinhole/crack	0.0761	0.0575	0.0988
Hole	0.0122	0.0056	0.0232
Rupture	0.0095	0.0038	0.0196

Table 10: Primary failure frequencies and confidence intervals per leak size (period 2018–2022)

Cause	Primary failure frequency per 1,000 km·yr	95% LL Primary failure frequency per 1,000 km·yr	95% UL Primary failure frequency per 1,000 km·yr
External interference	0.125	0.115	0.135
Corrosion	0.049	0.043	0.055
Construction defect / Material failure	0.046	0.040	0.052
Hot tap made by error	0.012	0.009	0.015
Ground movement	0.025	0.021	0.029

Table 11: Primary failure frequencies and confidence intervals per cause (1970-2022)

Cause	Primary failure frequency per 1,000 km·yr	95% LL Primary failure frequency per 1,000 km·yr	95% UL Primary failure frequency per 1,000 km·yr
External interference	0.044	0.036	0.052
Corrosion	0.033	0.027	0.041
Construction defect / Material failure	0.022	0.017	0.028
Hot tap made by error	0.003	0.001	0.006
Ground movement	0.021	0.016	0.027

Table 12: Primary failure frequencies and confidence intervals per cause (2003-2022)

Cause	Primary failure frequency per 1,000 km·yr	95% LL Primary failure frequency per 1,000 km·yr	95% UL Primary failure frequency per 1,000 km·yr
External interference	0.027	0.019	0.037
Corrosion	0.030	0.022	0.041
Construction defect / Material failure	0.021	0.014	0.030
Hot tap made by error	0.001	0.000	0.004
Ground movement	0.023	0.016	0.032

Table 13: Primary failure frequencies and confidence intervals per cause (2013-2022)

Cause	Primary failure frequency per 1,000 km·yr	95% LL Primary failure frequency per 1,000 km·yr	95% UL Primary failure frequency per 1,000 km·yr
External interference	0.020	0.011	0.034
Corrosion	0.035	0.023	0.052
Construction defect / Material failure	0.016	0.008	0.028
Hot tap made by error	0.000	0.000	0.005
Ground movement	0.016	0.008	0.028

Table 14: Primary failure frequencies and confidence intervals per cause (2018-2022)

APPENDIX 2: POISSON LAW

A confidence interval is made to take uncertainty into account. To calculate a confidence interval the population is assumed to have a known distribution. The assumption is made that the number of incidents follows Poisson's law, also called law of rare events.

Exact Poisson confidence limits for the estimated rate are found as the Poisson means, for distributions with the observed number of events and probabilities relevant to the chosen confidence level, divided by time at risk. The relationship between the Poisson and chi-square distributions is employed here

$$Y_i = \frac{\left(\chi^2_{2Y,\frac{\alpha}{2}}\right)}{2}$$

$$Y_u = \frac{\left(\chi^2_{2(Y+1),1-\frac{\alpha}{2}}\right)}{2}$$

where Y is the observed number of events, Y_l and Y_u are lower and upper confidence limits for Y respectively, $\chi^2_{v,\alpha}$ is the chi-square quantile for upper tail probability on v degrees of freedom.

REFERENCE

Ulm K. A simple method to calculate the confidence interval of a standardized mortality ratio. American Journal of Epidemiology 1990;131(2):373-375.