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An Improved Basis for Estimating Riser Leak and Damage Frequencies

By

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Master’s Thesis

Faculty supervisor: Professor Terje Aven
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Dedication

Dedicated to my family and my son Daniel

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To the memory of my beloved father`s soul, for his support and being there for me, always.

Emera Mostafa

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Abstract

In the petroleum industry, risers are widely used to transport fluids and gases. Risers are intended to be critical integral components as they are subjected to numerous failure factors, where in case of a leak, a highly combustible material may be released. Failure frequency is generally estimated based on historical data, to be used later in the Quantitative Risk Assessment (**QRA**) in order to reduce the risk associated with leakages. Several works were done previously to estimate the riser failure frequency based on the historical data from the Norwegian Continental Shelf (**NCS**) combined with other global data sources. The result of previous work relies mainly on assumptions and simplifications where the uncertainties are high, well as poor descriptions and low availability of data and incidents. The main goals of the present thesis are to estimate non-biased leak and damage frequencies for risers and to compare the result with previous studies. Also, in this study, the aim is to define the impact of the result in terms of risks and uncertainty by uncertainty analysis, knowledge characterisation and determining how to use the available relevant information to describe the risk. In addition, the intention is to identify challenges related to data and to provide possible solutions. This study was carried out by studying, systemising, and combining incidents reported to Corrosion and Damage database (**CODAM**) from Petroleum's Safety Authority (**PSA**) and the internal database at Equinor (**Synergi**). None of the studied databases had a full overview of registered incidents; therefore, different frequencies were estimated from different databases used to highlight the quality of these databases. The quality of the databases used in this study has been enhanced, e.g. multi reported incidents were removed from CODAM with major severity. A combination of the internal registered incidents at Equinor and registered incidents in CODAM was carried out to have a sufficiently large data set. The estimated frequencies for flexible risers from the combined databases are considered to be more robust and less sensitive compared to the estimated frequencies for the static risers. The assumptions which were taken under historical data analysis were highlighted and discussed, and uncertainty analysis of assumptions was done. Besides this, robustness and sensitivity analysis were carried out together with quality classification of the data in order to provide a base for discussion of the results in terms of risk and uncertainty and how to use the historical data to describe the risk.

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Abbreviation

A: An event
A': A specific event
B: Barrier failure
C: Consequences of event **A**
C': Consequences of a specific event A'
CI: Confidence interval
CODAM: Corrosion and Damage, PSA's database on damage related to pipelines and risers.
CP: Cathodic Protection
DFUs: Definerte fare og ulykkessituasjoner (in Norwegian), in English **DSHA:** Defined situations of Hazard and accident

DIKW: Data Information Knowledge and Wisdom
DIV: Drilling Induced Vibration
FPSO: Floating Production Storage and Offloading
FPU: Floating Production Unit
FSU: Floating Storage Unit
HSE: Health, Safety, and Environment

I: Initiating event
JIP: Joint Industry Project
Km/s: Kilometer per second
MODUs: Mobile Offshore Drilling Units

NCS: The Norwegian Continental Shelf
NPD: Norwegian Petroleum Directorate
PARLOC: Pipeline and Riser Loss of Containment.
P_f^*: Estimated frequentist probability
P_f: Frequentist probability
PSA: The Petroleum Safety Authority Norway
PTIL: PetroleumsTilsynet
QHSE: Quality, Health, Safety, and Environment

QRA: Quantitative Risk Assessment
RNNP: Risk Level in Norwegian Petroleum Project
SCR: Steel Catenary Riser
TDP: Touch Down Point
TTRs: Top Tensioned Risers
TUF: Transportation and Utilisation Facilities
U: Uncertainty
UKCS: The United Kingdom Continental Shelf

Definitions

Aleatory (stochastic) uncertainty: *variation of quantities in a population* [1].

Damage: "*An issue/anomaly which degrades the riser construction/performance over time. Damage tends to be a Failure Initiator, which if left undetected could progress through a Failure Mechanism, leading to an ultimate Failure condition in short to medium term. There are cases where a damaged riser may remain in operation following the identification of damage if the risk can be defined and managed /mitigated, but it is possible that the original design service life capability may be impacted. Cases, where a riser is unable to perform the intended design function are normally included as damage cases, e.g. reduced capacity or blockage*." [2]. Only events where riser was under operation were considered in this study.

Failure cause: is defined by (ISO 14224:2016)[3] as a set of circumstances that leads to failure.

Failure Mechanism: "*The stages of progress from damage/failure initiator through to ultimate failure. Depending on the specific situation the timeframe for initial damage to reach ultimate failure can vary between instantaneous (e.g. impact damage) up to many years (e.g. relatively low corrosion rates leading to gradual degradation over time).*" [2]

Failure Mechanism: A chemical, physical or operational mechanism leading to failure [4].

Failure mode: is defined by (ISO 14224:2016)[3] as the manner in which failure occurs.

Flexible Riser: Is flexible conduct that can withstand both vertical and horizontal movement mostly used in the floating facilities [5].

Flowline: *Pipe transporting fluid over large distances, that is primarily subject to static loads*[6].

Riser year: Operational experience year.

Riser: Is a conduit used for the safe transportation of fluids and gases between the seafloor and the host platform in both direction, that is primarily subject to dynamic loads [5, 6].

Risk Assessment: *Overall process of risk analysis and risk evaluation* [7].

Risk: **"***In relation to an activity, risk is defined as the two-dimensional combination of consequences (C) of the activity with associated uncertainties (U) about the consequences***"**[8]. According to the Petroleum Safety Authority (PSA), risk is defined as the consequences of the activities with associated uncertainty [9].

Static Riser: Is a fixed conduit that is usually deployed from fixed platforms and jack-up the drillings rig [5].

Uncertainty description: *A measure of uncertainty and associated background knowledge* [7].

Uncertainty: *Not knowing something, where "something" refers to the true value of a quantity or the true future consequences of an activity* [7].

Chapter 1 Introduction

1.1 Background

Risers are critical integral components in the petroleum industry as they are subjected to several failure factors. Failure mechanisms include mechanical defects, corrosion, external impacts, natural hazards, design and construction failures, material, weld and manufacturing failures, operation and maintenance, and monitoring and inspection [4, 10]. The consequences might be severe, such as leaks or blow out, which may result in environmental disasters and fatalities.

Thus, there is a need for mitigation of the risk associated with riser events, especially in the offshore industry, as it has a unique set of environmental circumstances. One of the risk level prediction methods used in the oil and gas industry is the Quantitative Risk Assessment (**QRA**), where the generic failure frequency is an essential input for the method [10].

DNV GL [3], has prepared an updated report to estimate the failure rate within the Norwegian Continental Shelf (**NCS**) on behalf of Equinor ASA. The results of the report have been disputed as events from the last years is not prominent. Moreover, there is low availability and poor description of data and events. Due to lacking information, this work relies in part on assumptions and simplifications where the uncertainties are high, and background knowledge is weak.

Additionally, the Pipeline and Riser Loss of Containment (**PARLOC**) database from the United Kingdom Continental Shelf **(UKC**S) was used as primary input and combined with a database from NCS to produce the new failure frequency estimates [2]. The NCS and UKCS have different environmental circumstances, e.g. water depth and temperature, regulations, production, activities, and conditions. Such a combination might result in uncertainties in the estimated failure frequency. In order to mitigate the associated risk with riser events, the uncertainties in the estimated failure rates need to be reduced. Hence, the database that will be used in this study is limited to the historical data in the NCS.

1.2 Objectives

The overall aim of this thesis is to establish a risk foundation for data analysis related to riser damage and leaks, including statistical treatment of data and reducing the uncertainties.

The specific goals are as follow:

1. To suggest non-biased leak and damage frequencies for risers.
2. To compare the result with other sources and explain the differences and similarities.

3. To provide an improved basis for estimating the damage and leak frequencies of various hole sizes.
4. To define the impact of the result in terms of risk and uncertainty
    a. Uncertainty analysis
    b. Knowledge characterisation
    c. Fundamental principles for how to use the available relevant information to describe the risk.
5. To identify challenges related to the data and to provide possible solutions.

This study will be carried out by extracting and combining more information from sources owned by the Norwegian Petroleum Safety Authority (**PSA**), Norwegian Petroleum Directorate (**NPD**) and Equinor ASA. The database used is limited to risers in offshore operations at the **NCS** from all operators.

1.3 Content

This thesis is divided into six chapters. The *first chapter* gives an introduction to the thesis, including the background and aims of the thesis. The *second chapter* outlines the theoretical background, definitions, explanation of key concepts and earlier work needed to understand the aim of the study.

In the *third chapter*, data used in the thesis will be presented and described, including a description of assumptions made during the data analysis. In the *fourth chapter*, the achievements and results of data analysis will be presented. This will then be discussed in *chapter 5, together with* assumptions made during data analysis. Conclusion and recommendation for further work will be given in *chapter 6.*

Chapter 2 Theoretical Background and preliminary work

In this chapter, context to the problem will be provided, including an introduction to risers, failure factors and mechanisms, and uncertainty related to historical data analysis and how it could affect the risk picture and preliminary work.

2.1 Flexible pipelines and risers

In general, a flexible pipe comprises different flexible layers that act together as one unit for the containment of produced oil, gas, or injection of water and gas [6, 11]. The section of a flexible pipe system that links the production unit to the first subsea construction is called the riser section [6]. There are various types of riser systems, which are used in different industries and locations (**Figure 1**). The riser is defined as a conduit used for the safe transportation of fluids and gases between the seabed and the host platform in both directions, that is primarily subjected to dynamic loads [5, 6].

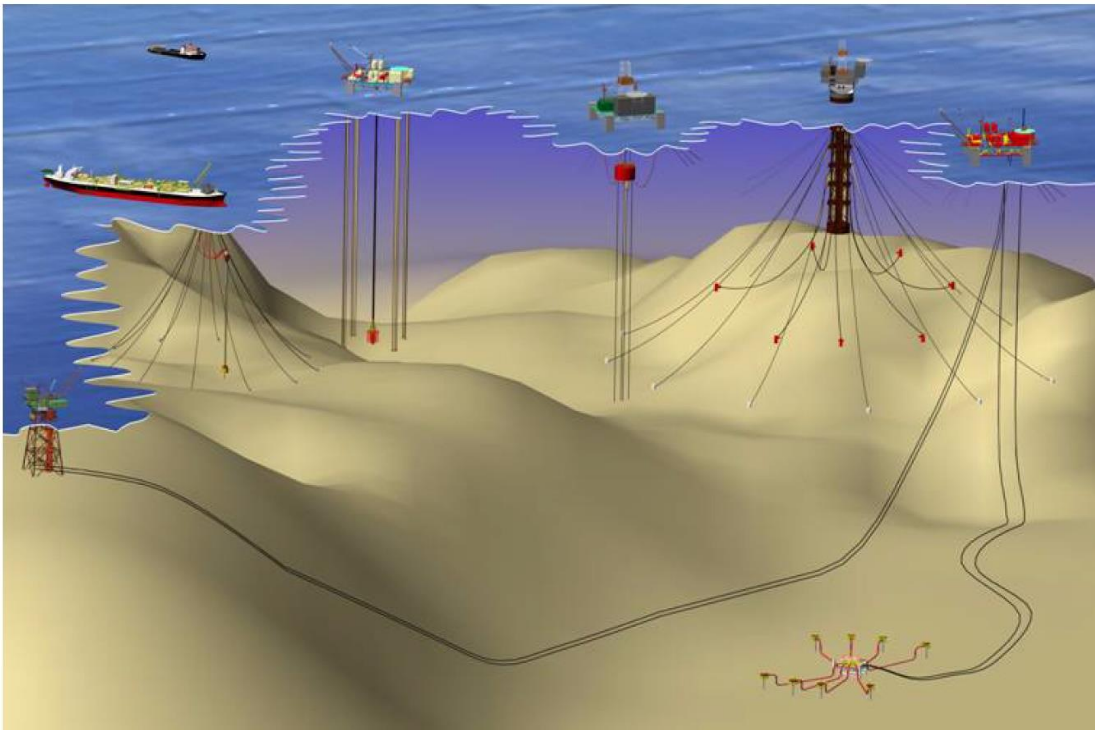


Figure 1 Different type of risers used in offshore industry (Courtesy Subsea7)

Additionally, the riser systems are used to facilitate different offshore operations, e.g. drilling operations, well completion and intervention, and injection of water or gas into the reservoir to enhance recovery [5].

In the early stage of the offshore industry, riser systems were used from fixed platforms and mobile offshore drilling units (**MODUs**). The riser systems for floating platforms were only developed when the offshore industry moved into deeper water (>3 kilometres) and can be used at water depths of 3 kilometres [5].

There are two classifications of risers based on criteria. For riser classification based on material type, there are two categories; static and flexible risers. On the other hand, based on the configuration, risers can be divided into catenary, free-standing, hybrid, and top tensioned risers (**Figure 2**) (**Appendix A**) [12]. A typical riser system is mainly composed of the conduit, interface with floater and wellhead, components and auxiliary. The components of the riser must be strong enough to withstand bending and high tension and have enough flexibility to resist fatigue [12].

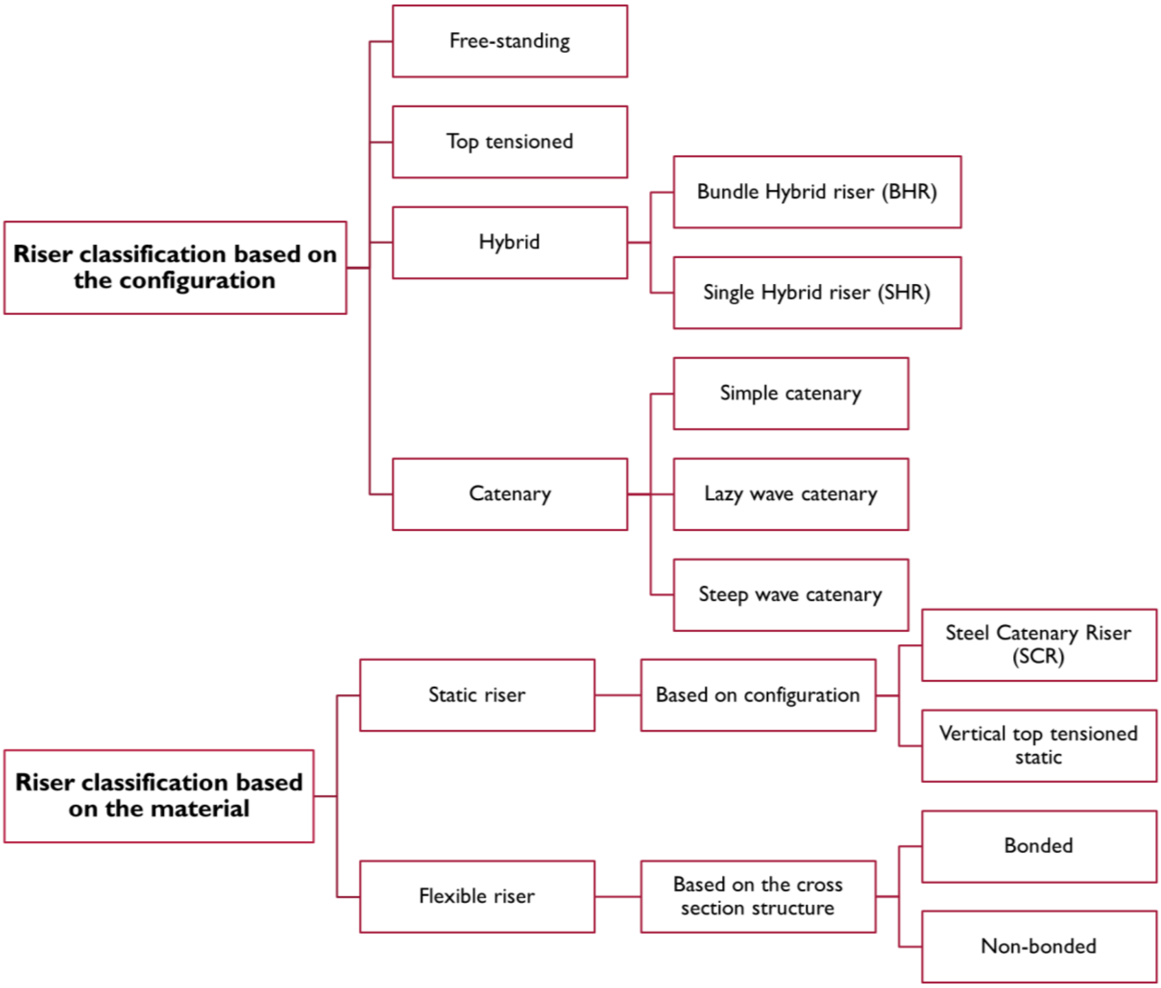


Figure 2 Classification of risers based on configuration and material used, input from [12].

2.1.1 Flexible Riser

Generally called a catenary riser or flexible riser, this is a riser with flexible conduct that can withstand both vertical and horizontal movement and is mostly used in floating facilities [5]. Approximately 85% of risers designed for floating facilities are flexible risers [13]. The flexible riser must be designed to withstand the environmental loads and dynamic loads from the vessel motions [6]. There are various marine riser configurations, such as free hanging catenary, lazy S, steep S, lazy wave, steep wave, and top tensioned production riser (**Appendix A**) [12]. When the riser system is configured, the external loading should be kept within acceptable limits, for tension, bending, torsion, compression and interference [12]. Conditions in deep-water environments are harsh, and in order to preserve the configuration, optimisation theory can be applied to obtain an optimised riser configuration. The optimisation might result in a difference in the wall thickness along the entire riser length [12].

2.1.1.1 Flexible riser components

Based on the cross-section structure of flexible risers, there are two generic types: a bonded and a non-bonded flexible riser. The non-bonded type is mainly used in the oil and gas industry. The structural layers in non-bonded flexible riser can slide relative to neighbouring layers. **Figure 3** shows a cross-section of a non-bonded flexible riser where different kinds of materials are used, such as steel, polymer, foam and synthetic fibres [14, 15]. Detailed descriptions of layers and their functionality are presented in **Table 1**.

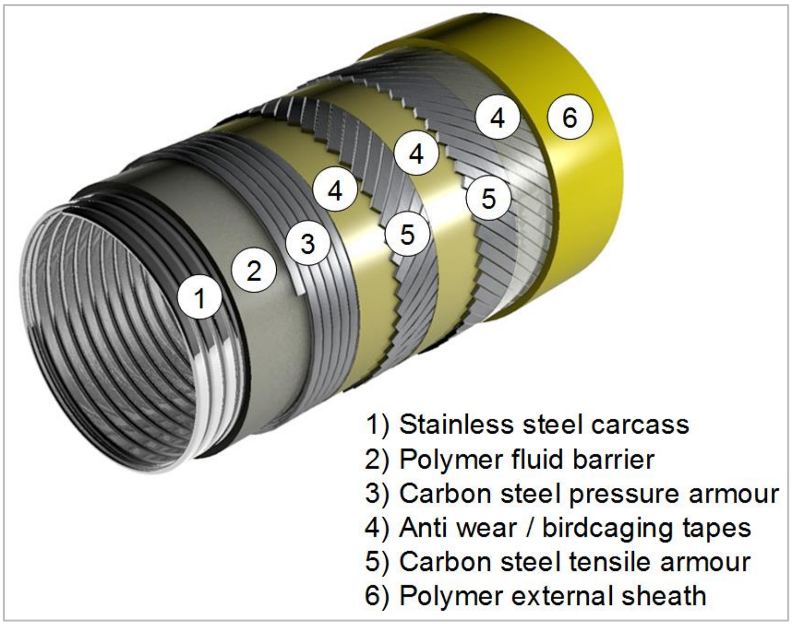
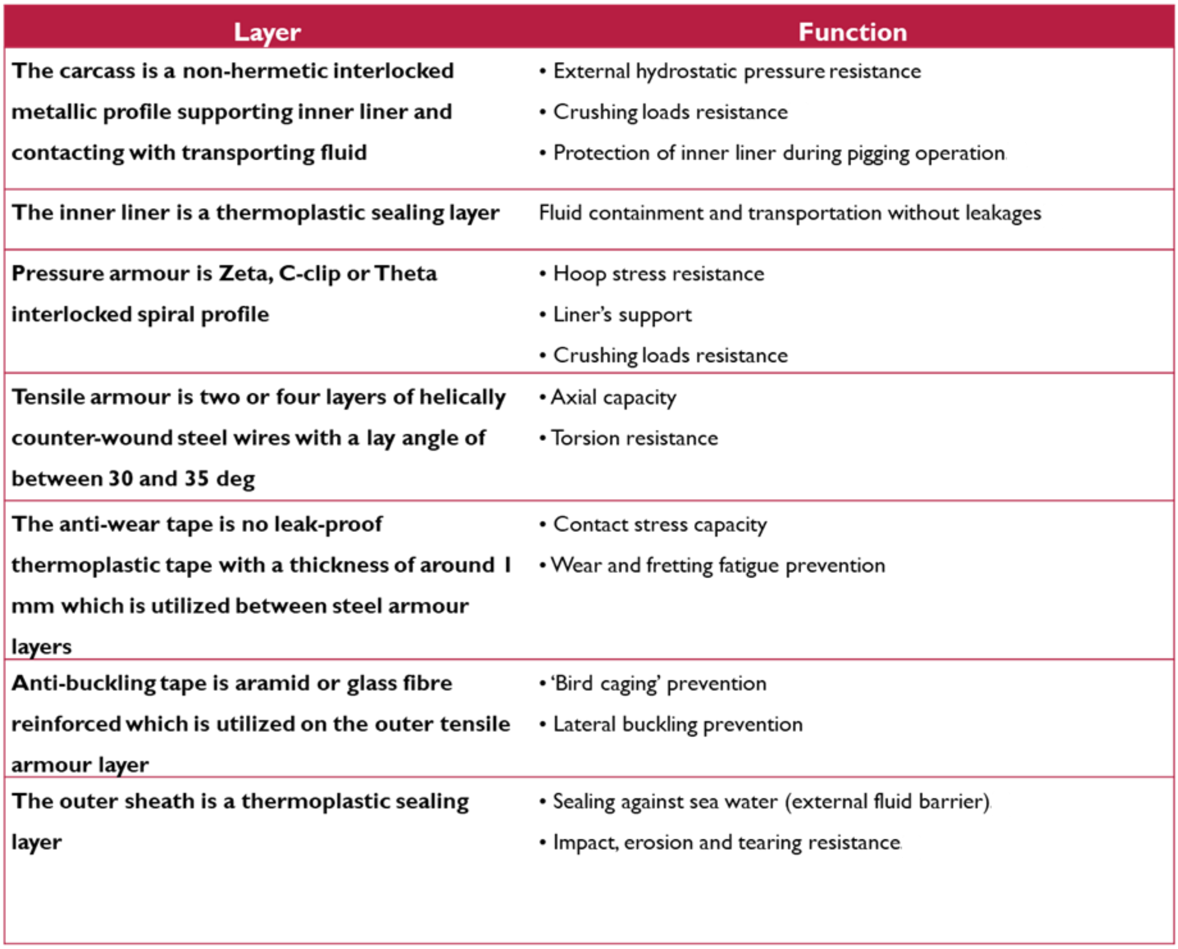


Figure 3 Non-bonded flexible riser internal components (Courtesy GE Oil and Gas).

Table 1 Flexible riser layers and their functions[14, 15]



Layer	Function
The carcass is a non-hermetic interlocked metallic profile supporting inner liner and contacting with transporting fluid	• External hydrostatic pressure resistance • Crushing loads resistance • Protection of inner liner during pigging operation
The inner liner is a thermoplastic sealing layer	Fluid containment and transportation without leakages
Pressure armour is Zeta, C-clip or Theta interlocked spiral profile	• Hoop stress resistance • Liner's support • Crushing loads resistance
Tensile armour is two or four layers of helically counter-wound steel wires with a lay angle of between 30 and 35 deg	• Axial capacity • Torsion resistance
The anti-wear tape is no leak-proof thermoplastic tape with a thickness of around l mm which is utilized between steel armour layers	• Contact stress capacity • Wear and fretting fatigue prevention
Anti-buckling tape is aramid or glass fibre reinforced which is utilized on the outer tensile armour layer	• 'Bird caging' prevention • Lateral buckling prevention
The outer sheath is a thermoplastic sealing layer	• Sealing against sea water (external fluid barrier) • Impact, erosion and tearing resistance

2.1.2 Static riser

There are different names for the static risers, e.g. rigid and steel. Low carbon steel has been the principal material for most static risers; material characterisation is defined by X60, X65 or X70, where the number stands for the percentage of carbon steel used. However, deep-water applications require different material and aluminium and titanium alloys are used instead [16]. Titanium in particular has been considered for harsh conditions like ultra-deep-water (>15 kilometres), high-pressure application, and high-temperature settings.

Titanium is more suitable for harsh environments due to its higher flexibility, because of its low modulus of elasticity that is almost half of steel. Titanium also has higher yield stress and is lighter in weight than steel [16]. Also, titanium is more expensive than steel. However, Steel catenary risers (**SCR**) and vertical top tensioned risers (**TTRs**) are common types of static risers used in the oil and gas industry. In general, 15% of risers for floating facilities worldwide are static risers, and 75% of these are top tensioned risers (**TTRs**) mainly used for production applications [13].

2.1.2.1 Top Tensioned Riser (TTRs)

The top tensioned riser is a vertical riser that requires the application of external tension near the top section to obtain its structural ability, such as buoyancy models, tensioner system, or a combination of both [2]. Top tension riser is often used in fixed platforms or jack-ups and may look like free-standing risers where there is no subsea wellhead used (**Figure 4a**).To obtain the stability of the riser system, hydraulic and/or no motion-compensating mechanical tensioners is applied [5]. A top tensioned riser could be used for production, drilling, injection and as an export riser. However, the requirements for a top tensioned riser for the deep-water application becomes significantly more difficult to achieve in order to prevent bottom compression and to support riser weight [16].

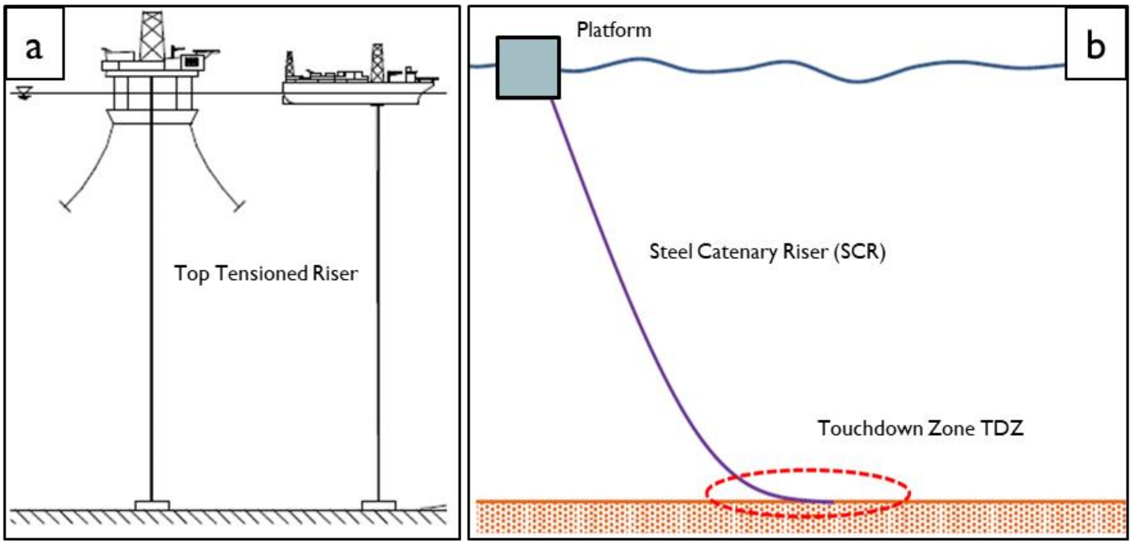


Figure 4 a) Top Tensioned Riser configuration modified after [16], b) Simple catenary riser configuration modified after[5].

2.1.2.2 Steel Catenary Riser (SCR)

Steel catenary risers are made from the rigid steel pipe [5] and are often used in ultra, and deep waters field developments exposed to harsh environments and large floating production units motions [17]. Moreover, it requires more complex design and installation than required for flexible risers due to the harsh environmental conditions and high sensitivity to dynamics and fatigue [18]. **Figure 4b** shows a simple catenary riser configuration that comprises one catenary shape [5].

2.2 Failure factors and mechanisms of risers

According to *4Subsea report* [10], the robustness of flexible risers is a concern, and there is a substantial reliability challenge facing the oil and gas industry. This concern is based on the indication of a high failure rate internationally, and an updated Norwegian statistic for 2010-2013 shows that the probability of failure per riser per year is 1,5% (**Figure 5**).

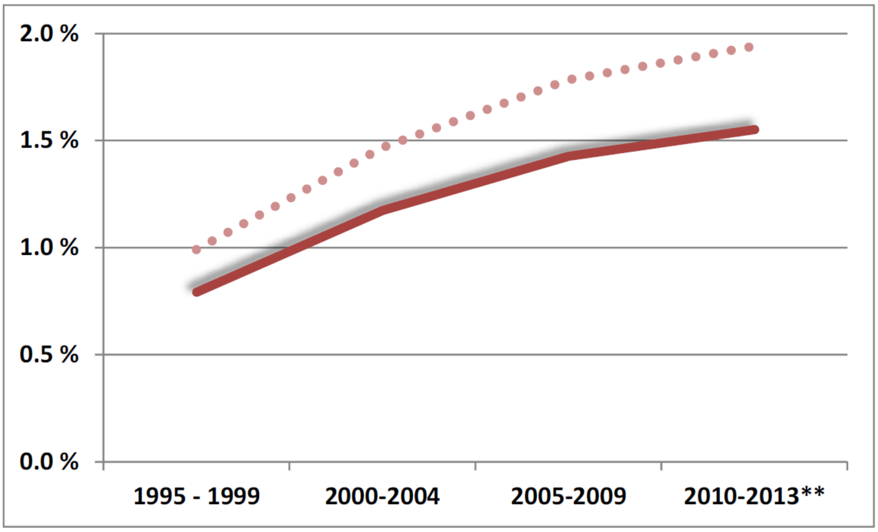


Figure 5 Flexible riser incident rate per riser operational year, based on major incidents as reported in CODAM, (2010-2013 scaled to five years). Dotted curve represents all data, including estimated data for the major unreported incidents[19].*

The consequences associated with leaks from risers and pipelines may be severe. Therefore, several concerns were highlighted by PSA [20]:

- Risers and pipelines contain a large amount of hydrocarbon, which can be a great feeding source in case of a leak.
- A significant dimension of pipelines and risers used combined with high pressures operational conditions in NCS.
- Development of a connection between the risers and floating production facilities.
- There is a substantial risk of ignition if the leak occurs beneath the facility.

From 2000 to 2017, several incidents with severe damages to risers and pipelines occurred (**Figure 6**), the majority of which corresponds to complex and floating production units [21]. Also, notable **Figure 7** shows a variation in failure mode and mechanism and the dimension of the flexible riser incidents from 1995 to 2012. The predominant failure for reported incidents from flexible risers is failure modes related to the carcass, e.g. fatigue, hydrates, pull out and sand erosion. For this dataset, the definition of major and minor incidents is mainly based on the operator's judgement [19].

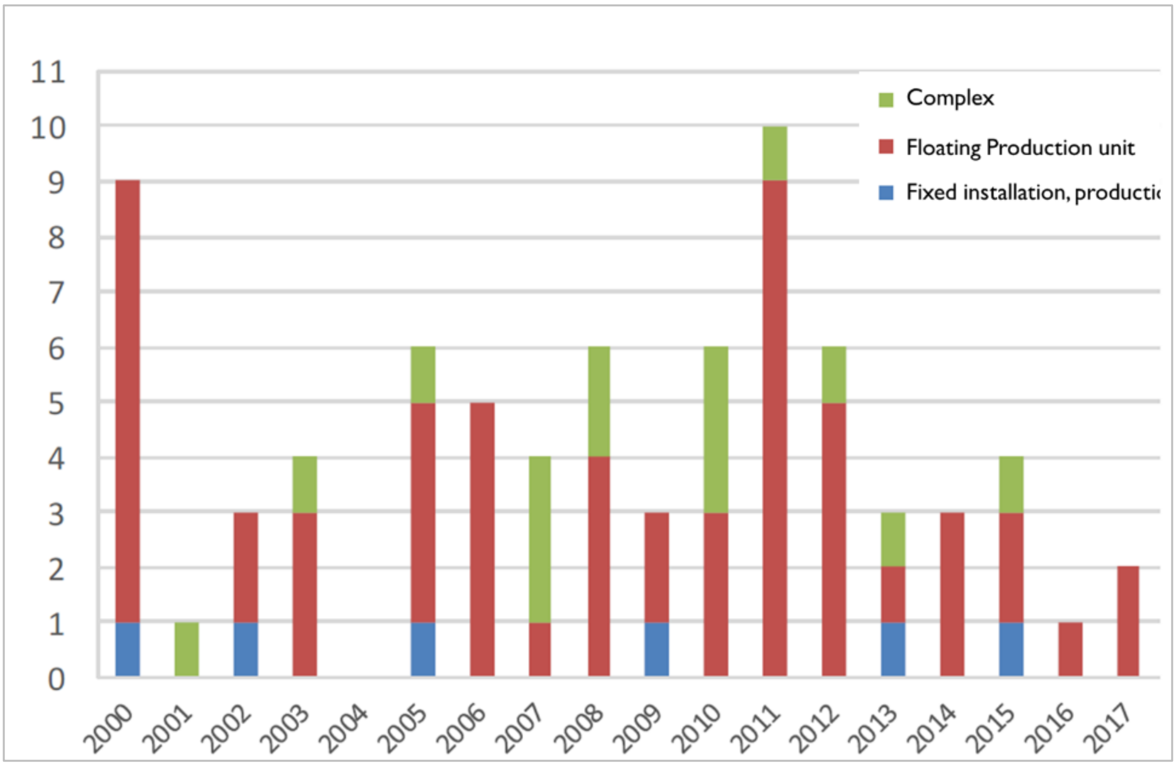


Figure 6 Showing the number of major damage for risers, pipelines, and production facilities from 2000 to 2017 [21].

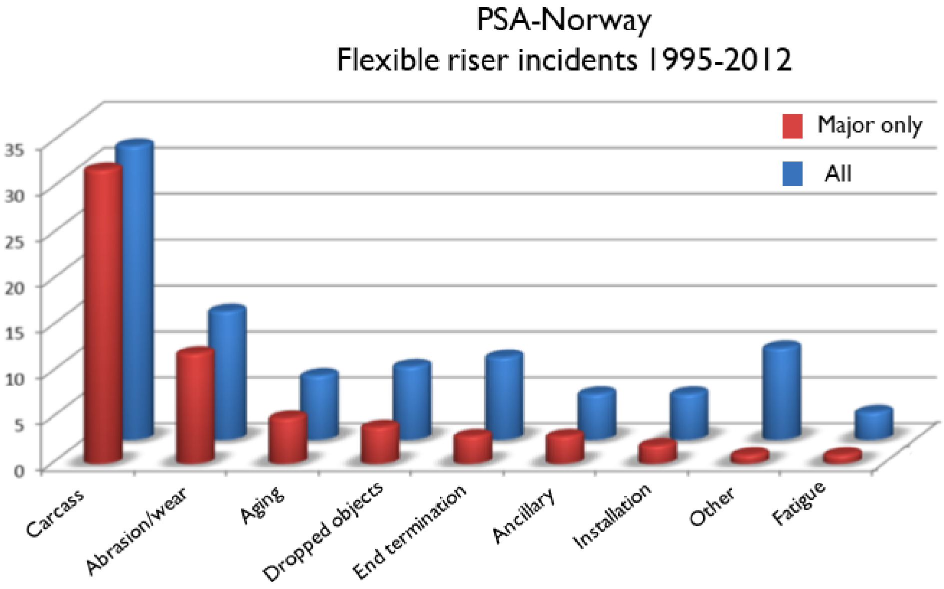


Figure 7 Flexible riser incidents from CODAM database [19].

In the next section, an overview of typical failure modes and mechanisms based on the type of riser will be presented.

2.2.1 Static riser failure

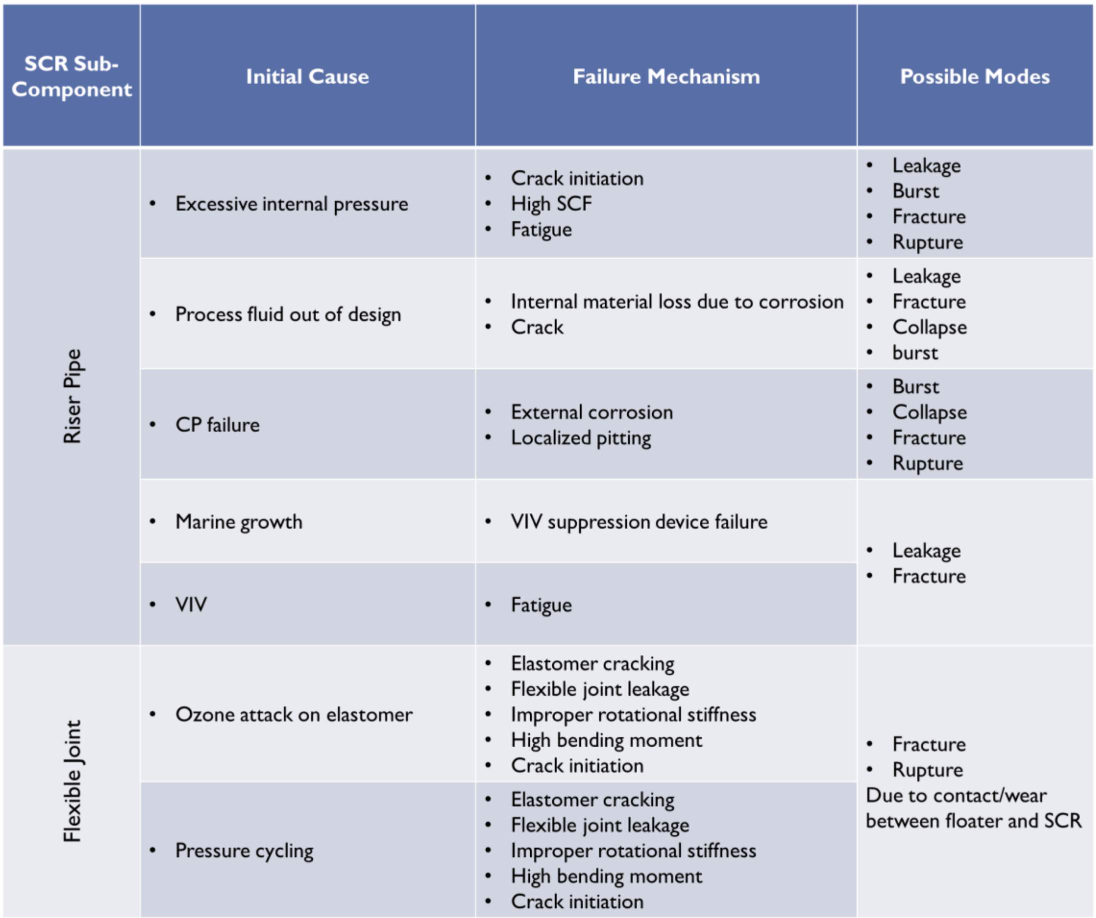
The most common threats for static risers are internal and external corrosion, overstress, fatigue, structural wear and instability, material degradation, dropped objects, third party interference and fire or explosion in surface segments [22]. Additionally, for re-drilling and side-track operations, two most common failure modes are identifiable: Drilling Induced Vibration (**DIV**) fatigue and riser wear from direct contact with the drill string. These failure modes might result in thickness reduction, and DIV can greatly reduce riser life or lead to total failure of the riser [22, 23]. Typical failure mechanisms for static risers with their causes and possible system failure modes are illustrated in **Table 2**.

The main fatigue contributors for steel catenary risers are: first order vessel motion, slow drift, vortex induced vibration and fatigue during transportation [24]. For the different sub-components of the SCR, an illustration of a typical failure mechanism with associated cause and failure modes is presented in **Table 3**.

Table 2 Example of static riser failures where initial causes and possible system failure modes are included. Modified after [22, 23]

Failure Mechanism For static risers		Initial Cause	Possible System Failure Modes
Corrosion	**External**	• Cathodic Protection failure	• Burst • Collapse • Buckling with external/internal pressure • Fracture • Rapture
	Internal	• Production tubing leak	
Internal cracking		• Sour fluid	• Fracture
Pipe deformation		• Accidental impact • Excessive external pressure • Bending moment	• Collapse or buckling
Fatigue		• Accidental impact • Production tubing leak	• Fracture
Overload		• Tensioner failure	• Rupture or buckling
		• Excessive internal pressure	• Burst
Wear		• Workover or drilling	• Burst • Collapse • Buckling with internal/external pressure • Fracture • Rupture

Table 3 Initial cause, failure mechanism, and failure modes for SCR, modified after [22, 23].



SCR Sub-Component	Initial Cause	Failure Mechanism	Possible Modes
Riser Pipe	• Excessive internal pressure	• Crack initiation • High SCF • Fatigue	• Leakage • Burst • Fracture • Rupture
	• Process fluid out of design	• Internal material loss due to corrosion • Crack	• Leakage • Fracture • Collapse • burst
	• CP failure	• External corrosion • Localized pitting	• Burst • Collapse • Fracture • Rupture
	• Marine growth	• VIV suppression device failure	• Leakage • Fracture
	• VIV	• Fatigue	
Flexible Joint	• Ozone attack on elastomer	• Elastomer cracking • Flexible joint leakage • Improper rotational stiffness • High bending moment • Crack initiation	• Fracture • Rupture Due to contact/wear between floater and SCR
	• Pressure cycling	• Elastomer cracking • Flexible joint leakage • Improper rotational stiffness • High bending moment • Crack initiation	

2.2.2 Flexible riser failure

Flexible risers are more vulnerable to damage and present a high number of failure modes due to their complex, layered configuration [22]. Around 25 % of flexible risers in Norway were replaced without meeting their design service life, and several failed before reaching their intended lifetime[19]. The most common failure modes for flexible risers are fatigue, corrosion, erosion torsion, burst, collapse, and overbending [11](**Figure 8**). A summary of the most common failure modes and associated failure mechanisms for flexible risers is presented in **Table 4**.

Simonsen 2014[11], has stated that collapse is the most common incident for double annulus risers in the NCS based on data from CODAM. This corresponds to Equinor's reports of several incidents due to carcass collapse observed at Njord A, Visund and Snorre B fields [11].

An investigation by Equinor was carried out in 2013 to identify the cause of increased carcass failure[25]. The focus was multilayer PVDF risers, as most of the failures observed in multilayer PVDF risers were initiated by damages to the inner carcass.

From 1998-2001 several carcass collapse incidents were observed, especially in multipurpose risers operating as gas injectors with pressure around 400 bars. It was assumed that this could be explained by the gas release theory, which is based on pressure build up in the gap between the second and third barrier layer resulting from dissolved gases in the polymer [25]. Consequently, all multilayer PVDF risers operating as gas injectors were replaced in order to mitigate the operational risk. However, carcass collapse incidents were again observed from 2005 and onward, this time in production risers operating at a moderate pressure of 80-90 bars. Thus, the gas release theory was irrelevant here as the operational pressure was relatively low. In addition, several incidents with hydrate plugs were observed in multilayer risers as they are more vulnerable to pressure drop.

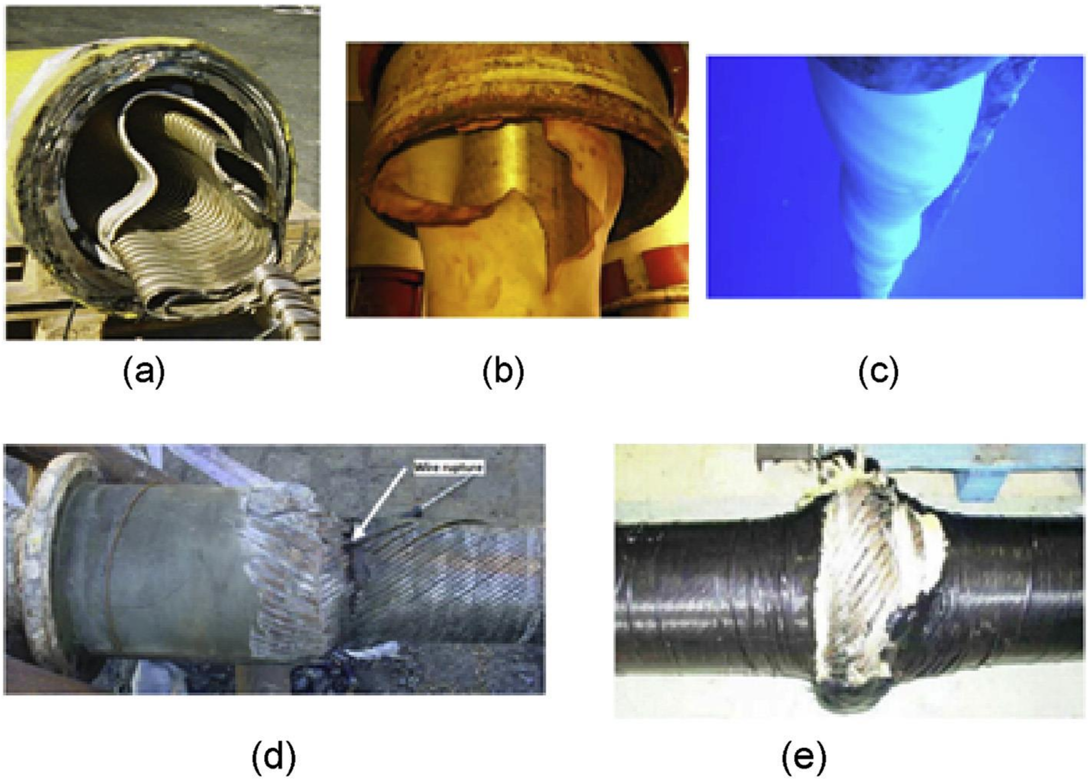


Figure 8 Common failure modes for flexible risers: (a) carcass collapse; (b) rupture of external sheath due to blocked vent tubes; (c) torsion at riser top due to ruptured armour wires; (d) tensile armour wire rupture due to fatigue; (e) bird caging[11]

Another carcass failure in a multilayer riser was observed in 2006, caused by a crack in the weld at the upper carcass ring. The investigation showed that this was due to axial loading and is an issue to be considered. Many more carcass failures were registered in late 2010 at Njord A, again infringing carcass tear due to large axial loads. Several conclusions were drawn from the report:

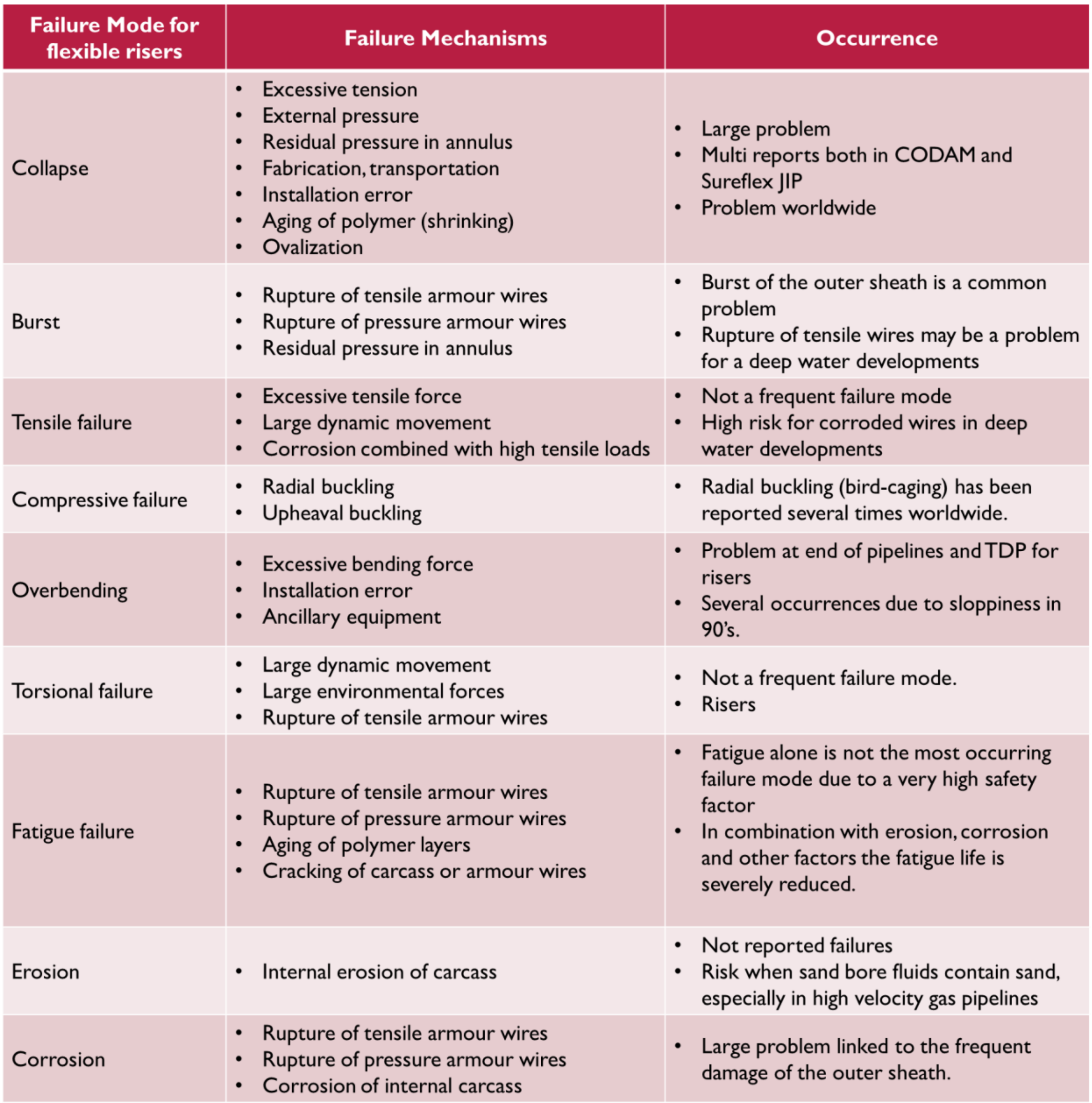
- Established operational procedures for depressurisation and hydrate plugs did not mitigate carcass failure.

- A new carcass failure caused by axial loading and tear out was observed.
- Monitoring and inspection of the carcass are recommended to mitigate risk for loss of containment, which is associated with carcass tearing.
- Development of a more robust carcass to prevent tearing and collapse in the new risers is recommended.

Additionally, several incidents in flexible risers registered in CODAM occurred due to burst; *Simonsen 2014* emphasised two events that led to burst caused by rupture of the external sheath [11]. In the first event, the rupture occurred because the annulus vent system was not working correctly, and as a result, diffused gases build up in excess of the burst resistance of the external sheath. In the second event, a leak resulted in a rupture in the external sheath, which caused an increase in pressure inside the annulus [11]. Tensile rupture represents a low percentage of CODAM, and Sureflex [1] incidents reported and is not a common occurrence [11]. Nevertheless, tensile failure could be a threat to riser integrity when it is combined with abrasion, corrosion, or other factors that affect the resistance of flexible risers[11, 22]. Torsional rupture might be caused by large dynamic movement, environmental forces and rupture of tensile armour wires; it is not considered a frequent failure mode [11].

Fatigue is a common failure mode due to the accumulation of cyclic stress in different layers of the flexible riser. In deep-water, the fatigue is mainly concentrated at the top and seabed touch down the area due to bending combined with high-pressure loads[22]. Corrosion is also a large problem linked to frequent damage of the outer sheath as both internal and external corrosion results in the gradual degradation of the pipe wall thickness[4, 11]. Overbending is considered to occur mostly at the touch-down point (**TDP**) and can affect all flexible riser layers in different ways: collapse, rupture of internal or external pressure sheath, and unlocking of carcass and pressure armour layers[11]. Erosional failure is another failure factor that can affect the internal structure of the pipe. In general, it occurs due to either the presence of sand in the production flow or to hydrates which may lead to carcass erosion and subsequent pipe leak [26]

Table 4 Summary of the most common failure modes for flexible risers, modified after [11].



Failure Mode for flexible risers	Failure Mechanisms	Occurrence
Collapse	• Excessive tension • External pressure • Residual pressure in annulus • Fabrication, transportation • Installation error • Aging of polymer (shrinking) • Ovalization	• Large problem • Multi reports both in CODAM and Sureflex JIP • Problem worldwide
Burst	• Rupture of tensile armour wires • Rupture of pressure armour wires • Residual pressure in annulus	• Burst of the outer sheath is a common problem • Rupture of tensile wires may be a problem for a deep water developments
Tensile failure	• Excessive tensile force • Large dynamic movement • Corrosion combined with high tensile loads	• Not a frequent failure mode • High risk for corroded wires in deep water developments
Compressive failure	• Radial buckling • Upheaval buckling	• Radial buckling (bird-caging) has been reported several times worldwide.
Overbending	• Excessive bending force • Installation error • Ancillary equipment	• Problem at end of pipelines and TDP for risers • Several occurrences due to sloppiness in 90's.
Torsional failure	• Large dynamic movement • Large environmental forces • Rupture of tensile armour wires	• Not a frequent failure mode. • Risers
Fatigue failure	• Rupture of tensile armour wires • Rupture of pressure armour wires • Aging of polymer layers • Cracking of carcass or armour wires	• Fatigue alone is not the most occurring failure mode due to a very high safety factor • In combination with erosion, corrosion and other factors the fatigue life is severely reduced.
Erosion	• Internal erosion of carcass	• Not reported failures • Risk when sand bore fluids contain sand, especially in high velocity gas pipelines
Corrosion	• Rupture of tensile armour wires • Rupture of pressure armour wires • Corrosion of internal carcass	• Large problem linked to the frequent damage of the outer sheath.

2.3 Risk and uncertainties

Risk assessment, according to ISO 31000 [27], is defined as "*overall process of risk analysis and risk evaluation*" in relation to an activity. Risk is defined as *"the two-dimensional combination of consequences (**C**) of an event (**A**) with associated uncertainties (**U**) about the consequences (**C**)"*[8]. Uncertainty (**U**), is defined as a lack of knowledge about unknown quantities, i.e. about **A** and **C** [28]. According to the Norwegian Petroleum Safety, risk is defined as the consequences of the activities with associated uncertainty [9]. Nevertheless, risk assessment is the first step in risk management, where risk management is defined as all measures and activities carried out to manage the risk [29]. Generally, risk management is followed by risk treatment, risk acceptance and risk communication, as showed in **Figure 9**. In the offshore industry, the activities are characterised by major risks, that require proper risk management in order to create a balance between exploring the opportunities and preventing major accidents. Therefore, Quantitative Risk Assessment (**QRA**) is used to implement risk assessment in order to prevent accidents in offshore operations [30], the main steps of QRA are presented in **Figure 9**. In the risk analysis phase, three perspectives on risk are used in general: the traditional statistical approach, the traditional Bayesian approach, and the (C, U) perspective [7]. The traditional approach will be used in this study, and it will be explained further in the next subsection.

Figure 9 Showing the main steps in risk management, adapted from [7].

2.3.1Traditional statistical approach

Traditional statistical analysis uses probability models, point estimates, confidence intervals and hypothesis testing, where risk is presented as (**A**, **C**, $\mathbf{P}_{\mathbf{f}}$) and the risk description is defined as (**A'**, **C'**, **P_{f*}**, **CI**). **A**: an event is defined as "*the occurrence of a particular set of circumstances"* according to ISO (2002) [31]; two main event categories used in **QRA**: Initiating events (**I**) and Barrier failure (**B**) [28]. Initiating events in **QRA** are referred to as unwanted or accidental events resulting in negative consequences. **A'** refers to a specific event, **P_{f*}** is estimated frequentist probability [7]. **C** refers to the consequences of an event where there are two types of consequences: physical quantities and losses [28]. **C'** refers to the consequences of a specific event **A'** [7]. **P_f** is frequentist probability and defined as "*the relative fraction of times the event occurs if the situation analysed were hypothetically repeated an infinite number of times"*[1]. In the traditional statistical approach, the uncertainty is usually represented by the frequentist probability, and it is called aleatory uncertainty since it is related to the variation of quantities, as it is linked to variation in phenomena and it's estimated. The confidence interval (**CI**) is normally used to describe the uncertainty in the **P_f**. 95% confidence interval [Y, Z] this means if an experiment is done over and over, the expected estimate will be in the interval between Y and Z in 95 out of 100 cases, where Y is the lower limit and Z is the upper limit of the interval [7]. Poisson distribution is one example of many different typical statistical distributions used in the traditional statistical approach. The Poisson distribution is defined as a statistical distribution that expresses the probability of a given number of discrete events occurring in a fixed interval of time or space. Given that these events occur with a known constant rate and independently of each other[32]. The Probability density function of a Poisson distribution with occurrence rate λ is shown in the following formula:

$$p_f(N(t) = x) = (\lambda t)^x e^{-\lambda t}/x! \qquad (1)$$

Where $N(t)$ denotes the number of incidents in the time interval [0, t] and λ represent the expected number of incidents per unit of time $\lambda = E_f[N(t)/t]$. Where E_f is defined as the average number of occurrences per unit of time when repeating the same situation and is the expectation with respect to frequentist probability. Then the estimated expected number of incidents is represented by $\hat{\lambda}$, which is equal to N(t)/t [7]. This approach is based on inputs from historical data, experience and observations, and there are variation and uncertainty associated with these inputs. Hence, the DIKW hierarchy (Data, Information, Knowledge and Wisdom) is a conceptual framework that should be reflected on in this kind of quantified risk assessment [1]. The data (D) covers the observational data, N(t) in this context, and information (I) is defined by the estimates, with an explanation of what the estimates mean by the risk analysts to the decision maker. As well, identifying assumptions which the analysis is based on

[7]. Also, the knowledge (K) in this approach is represented by the decision maker understanding of the following:

- What the true risk is for the considered activity.
- The potential threats or hazards of this activity and their consequences.
- Understanding the overall risk assessments approach, results and limitation.

Further, the wisdom (W) is linked to the decision maker and other stakeholder, where it is represented by the ability to use the result of the analysis in the right way [7].

As mentioned, aleatory uncertainty as it is related to the variation of quantities as it is linked to variation in phenomena and its estimated. It is typically used to detect and to identify a special cause variation and common cause variation in the data analyses. Hence, it is not always straight forward in some cases, e.g. leak and damage incidents, as it requires that the incidents occurred under similar conditions and circumstances in order to identify the common cause variation and, thereby, to identify the special cause variation. Two typical mistakes are usually easy to make during the analysis of the variation in the historical data:

1. Interpreting an outcome as a special cause variation, when it came actually from common causes of variation.
2. Reacting to an outcome as if it was from common causes of variation, while it represents a common cause of variation [7].

Uncertainty assessment is required to reflect the common causes, while the special cause variation should be treated separately by the following:

- Addressing the concealed uncertainties in the assumptions on which the probabilities are based.
- Addressing potential surprises relative to the beliefs and knowledge of the analysts [7].

2.4 Risk indicators

Risk indicators are developed to identify and manage hazards in order to provide support for decision making. The risk indicator is defined as a measurable quantity, which provides information about risk [33]. The Petroleum Safety Authority (**PSA**), established the Risk Level in Norwegian Petroleum Project (**RNNP**) in 1999, where the main goal of the project was to cover all aspects of Health, Safety, and Environment (**HSE**). Four main outcomes of the RNNP were addressed:

- The indicators should address a variety of incident, from irrelevant near-misses up to the most complex accident sequences.

- The potential hazard of an occurrence should be specified in addition to the actual outcome of the event.
- A combination of indicators, indicators covering a more significant scale, and indicators that reflect an individual system are required to give a better result.
- The performance indicators should reflect the importance of the incident [34].

In the offshore operation setting, lagging indicators are commonly used, often defined as the measurement of company incidents in the form of historical statistics. An example of a lagging indicator is the incident rate of hydrocarbon leaks for offshore and onshore petroleum installations [35]. There are pros and cons for using lagging indicators, which are worth mentioning:

Pros for lagging indicators

- Lagging indicators measure system failures in an observable and measurable way.
- It easily measures goal accomplishment [36].
- Hard to manipulate as it is based on the historical data [36].
- It is intuitive [36].

Cons for lagging indicators

- It does not measure what has not happened.
- There is uncertainty regarding the transparency of the reporting [36].
- The lagging indicators have been considered unsuitable on an installation level as it is based on historical data where the major incidents are too rare [36].
- It is not possible to influence what already happened [36].
- It does not give a full overview and information about the organisation’s safety culture [37].
- It does not give an overview of causes as it offers only evidence when the accidents happen [37].

Moreover, incidents and near-misses indicators are classified as lagging indicators [33] and will be presented in the next section.

2.4.1 Incidents and near-misses

Incident indicators help to create prior knowledge of accidents and the factors influencing their development. This is carried out by utilising and observing the precursors of accidents such as near-misses events and failure combined with knowledge of the event[38]. As well, kicks and hydrocarbon leaks are some examples of major hazard precursors that are rare events in a single installation [36]. Some normalisation factors are used to normalise variation in the precursor-based indicators to obtain a meaningful illustration, e.g. manhours, a number of wells drilled, and a number of installation years to be presented in the form of overall risk indicators [36]. However, the pros and cons of incidents and near-misses are presented below:

Pros of incidents and near-misses

- It provides an overview of the historical information about past accidents [36].
- It establishes the basis for the identified risk to be used further in the risk analysis [36].

Cons of incidents and near-misses

- Generally, precursor events in the offshore sector are quite rare [36].
- They are based on past data and any changes in fundamental circumstances that might have consequences for risk will not be observed until sometime later [38].
- The reporting might become imprecise due to changes in attitude to procedures for reporting where the number of reported events might be affected [38].
- Extraneous factors may affect the data [36].
- The difference in the installation complexity is not captured [36].
- There is a need for an overall incident indicator in order to identify an overall trend [36].
- There are some disadvantages related to the normalisation parameters such as:
    - A number of installations does not differentiate between less complex and more complex installations [36].

To have a better overview and classification of major incidents, 21 **DFUs** (Defined Situations of Hazard and Accident) have been developed by PSA (**Table 5**). Several criteria were used for selection of the DFUs, where the DFU should be:

- An unexpected incident/situation that has or may lead to the loss of life or other values.
- An observable incident/situation that is possible to register accurately.
- Cover all possible scenarios which can lead to loss of life.
- Important for awareness and motivation as they are applied in dimensioning and planning of the emergency procedures [33].

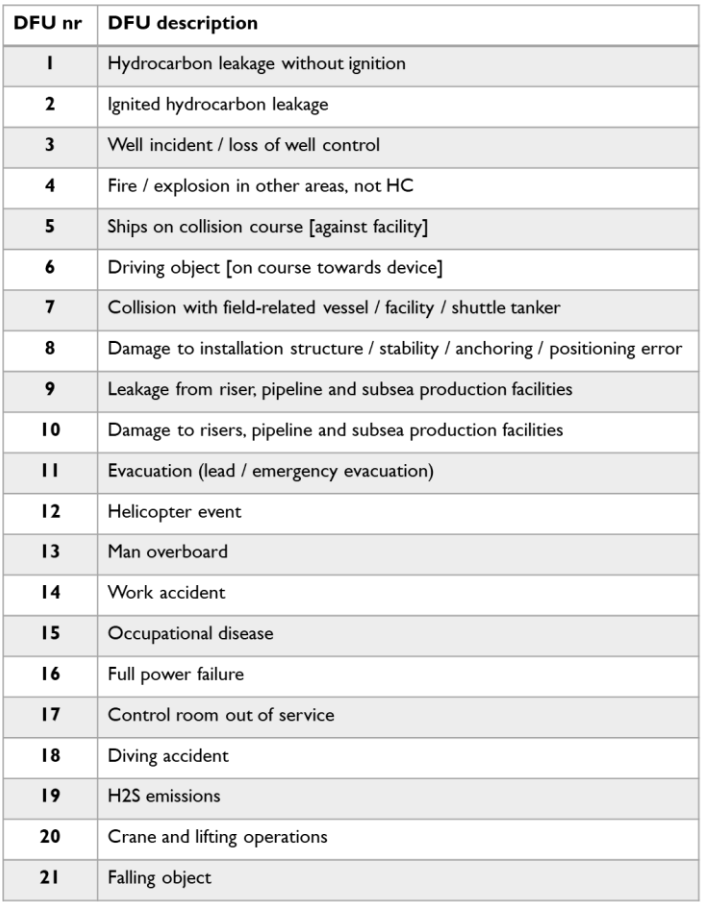
Table 5 shows that DFU 9 and 10 are related to damage to risers and leakage from the riser, where there are three categories of leakage size:

- Small leakage: 0,1-1 Kg/s
- Medium leakage: 1-10 Kg/s

- Large leakage: >10 Kg/s [39]

According to *RNNP 2015* [39], all HC leakages for DFU 9 (Leakage from risers, pipeline and subsea production plants) should be reported. However, for DFU 10 (Damage to risers, pipeline and subsea production facilities) the incident criteria should at least be defined as a major incident, corresponding to a major incident as defined in CODAM [40]. Most of the frequent flexible riser incidents that have been reported to CODAM are related to carcass incidents, abrasion/wear, and ageing [40].

Table 5 An overview of DFUs used in NCS, translated from [39]



DFU nr	DFU description
1	Hydrocarbon leakage without ignition
2	Ignited hydrocarbon leakage
3	Well incident / loss of well control
4	Fire / explosion in other areas, not HC
5	Ships on collision course [against facility]
6	Driving object [on course towards device]
7	Collision with field-related vessel / facility / shuttle tanker
8	Damage to installation structure / stability / anchoring / positioning error
9	Leakage from riser, pipeline and subsea production facilities
10	Damage to risers, pipeline and subsea production facilities
11	Evacuation (lead / emergency evacuation)
12	Helicopter event
13	Man overboard
14	Work accident
15	Occupational disease
16	Full power failure
17	Control room out of service
18	Diving accident
19	H2S emissions
20	Crane and lifting operations
21	Falling object

2.5 A comparison between Norwegian and UK sector

A comparison with UK operations was carried out in RNNP 2006, the comparison of the number of leaks > 1 kg/s is presented in **Figure 10**, and the following was noticed[41]:

- British sector,
  - From 1992-2006, 7 ignited gas leaks > 0,1 kg/s were recorded, including 1 with leakage rate >1 kg/s and another >10 kg/s.
  - From 2000-2006, 2 ignited leaks were recorded, including 1 with leakage rate <1 kg/s and another >10 kg/s.

- Norwegian sector,
    - In the Northern part (North of 59°N) from 1993-2005, only one ignited gas leak was registered in the 0,1-1 kg/s category. It was argued that the ignition source is well controlled in the Norwegian sector. Therefore, one incident is registered only in the period 1993-2005.

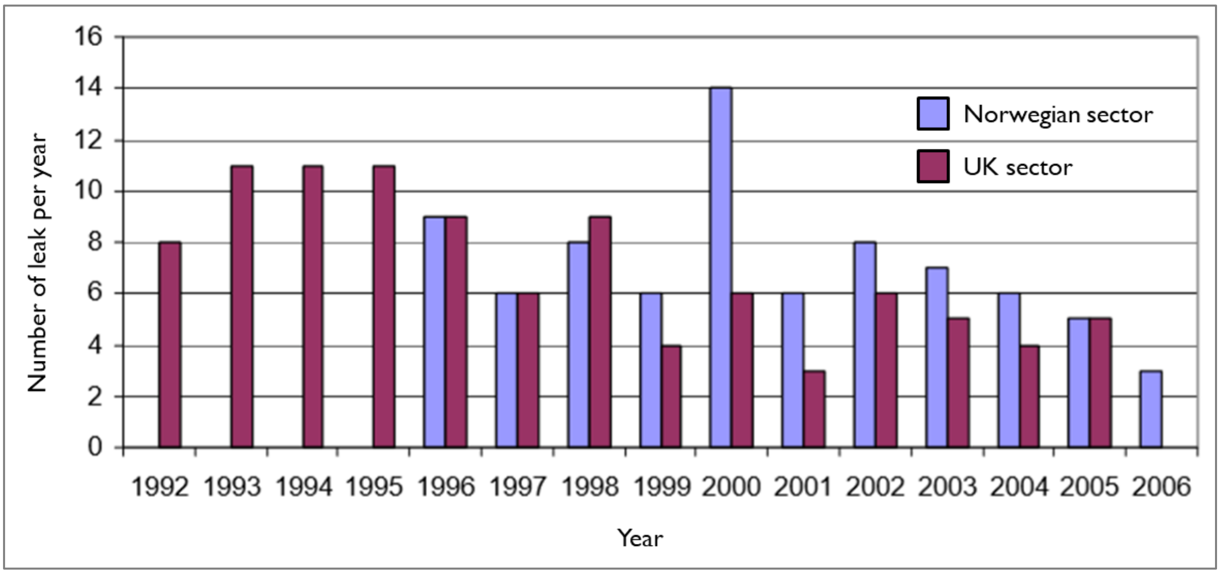


Figure 10 Comparison of a number of leaks >1 kg/s for the UK and Norwegian sectors[41].

Figure 11 represents gas leakage > 1kg/s incidents registered for the Northern part of Norwegian and British sectors per 100 installation year, and following were noticed:

- For recorded gas leakage in the period 2001-2005:
    - Norwegian sector (North for 59°N): 19 leaks and the installation year was 173, resulting in 11of leaks number per 100 installation year.
    - British sector (North for 59°N): 9 leaks where the corresponding installation year was 185, resulting in 4,9 of leaks number per 100 installation year.
- Abovementioned numbers show that the average frequency for the Northern Norwegian sector is ~2,3 times higher than its equivalent in the British sector [41].

The incidents were selected after the same criteria, and therefore, there it is less than what is shown in **Figure 11**, which is more than factor 10.

Figure 11 clearly shows a decreasing trend in both Norwegian and British historical data, but with a significant difference[41]. Also, it was noted that the HSE performs the collection of UK data, which has some additional classification criteria not used in Norwegian data collection.

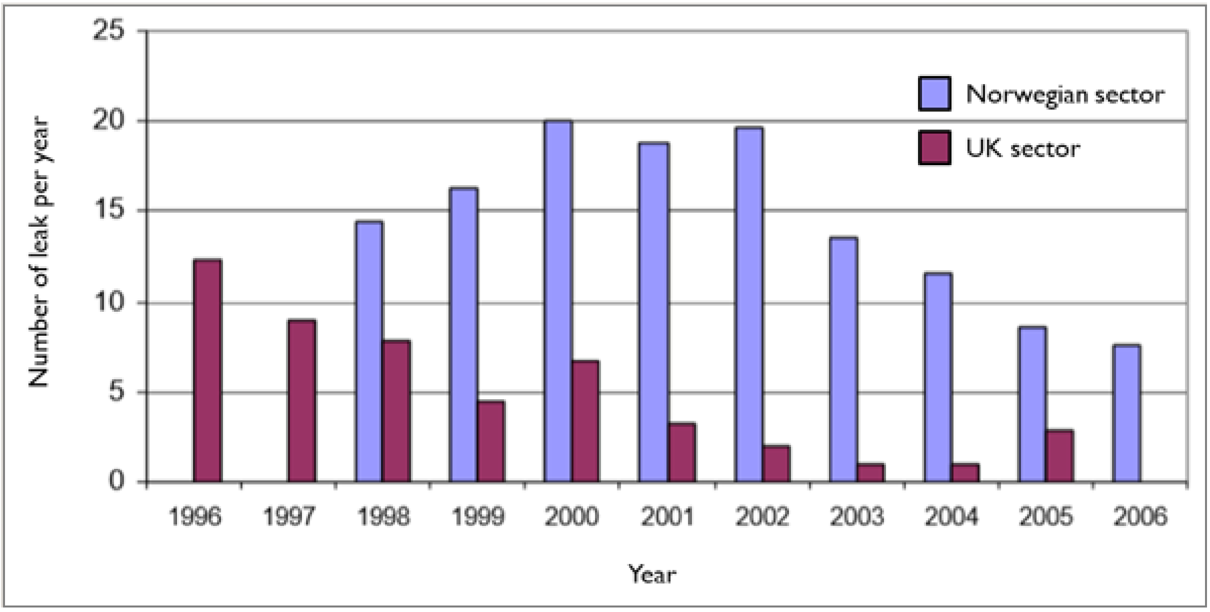


Figure 11 Gas leaks >1 kg/s for Norwegian and UK sectors per installation year, 3 years interval[41].

2.6 Preliminary work

2.6.1 Recommended failure rates for pipelines, DNV GL report

DNV GL has revised the previous report (The recommended failure rates for pipelines) [4] on behalf of Equinor ASA, where the main purpose was to provide failure frequencies for:

- Gas and oil pipelines for the offshore sector, including steel and flexible pipelines.
- Gas and oil pipelines for the onshore sector
- Static and flexible risers
- CO_2 Pipelines

Failure definition used in the report was defined as follows:

"An event is causing a failure of pipeline integrity resulting in a loss of containment and leakage. A failure excludes incidents resulting in reduced pipeline integrity, however not causing a leakage" [4].

2.6.1.1 Failure frequency

The data sources which DNV GL used are PARLOC 2012 for the UKCS in the period 2001-2012 and for the NCS for the period 2001-2017 which are presented in **Table 6**. The events from valves, flanges and pig traps were not included as they are normally counted separately in risk assessments. The following regarding the data was mentioned in the DNV GL report:

- 46 events were registered where riser material and diameter were known
- 5 events with unknown material and diameter
- 1 event with unknown riser material

- 16 events where it is unknown if they are linked to a pipe, a riser, or an umbilical.
- The riser diameter was categorised into ≤16", >16", and unknown. It was pointed out that the failure frequency for risers decreases with increasing diameter based on several factors:
    - Large diameter risers/pipelines have large wall thickness with larger load resistance against external interference.
    - Small diameter risers/pipelines are more exposed to corrosion than large diameter risers/pipelines, due to the surface area size.

Moreover, a statistical additive smoothing method was used to redistribute the unknown events where the number of riser leaks became 55,8. Thus, the remaining 12,2 events with an unknown type of pipe correspond to either umbilical or pipelines. Hence, some estimators for input were calculated:

- The best estimated leakage incidents for flexible risers with diameter ≤16" is 37,2
- The best estimated leakage incidents for steel pipe with diameter ≤16" and >16" is 17,8 and 0,8 respectively.
- The exposure (*in riser-years*) registered for flexible risers with diameter ≤16" is 10129 while for steel risers with diameter ≤16" is 16974 and for >16" is 7776.

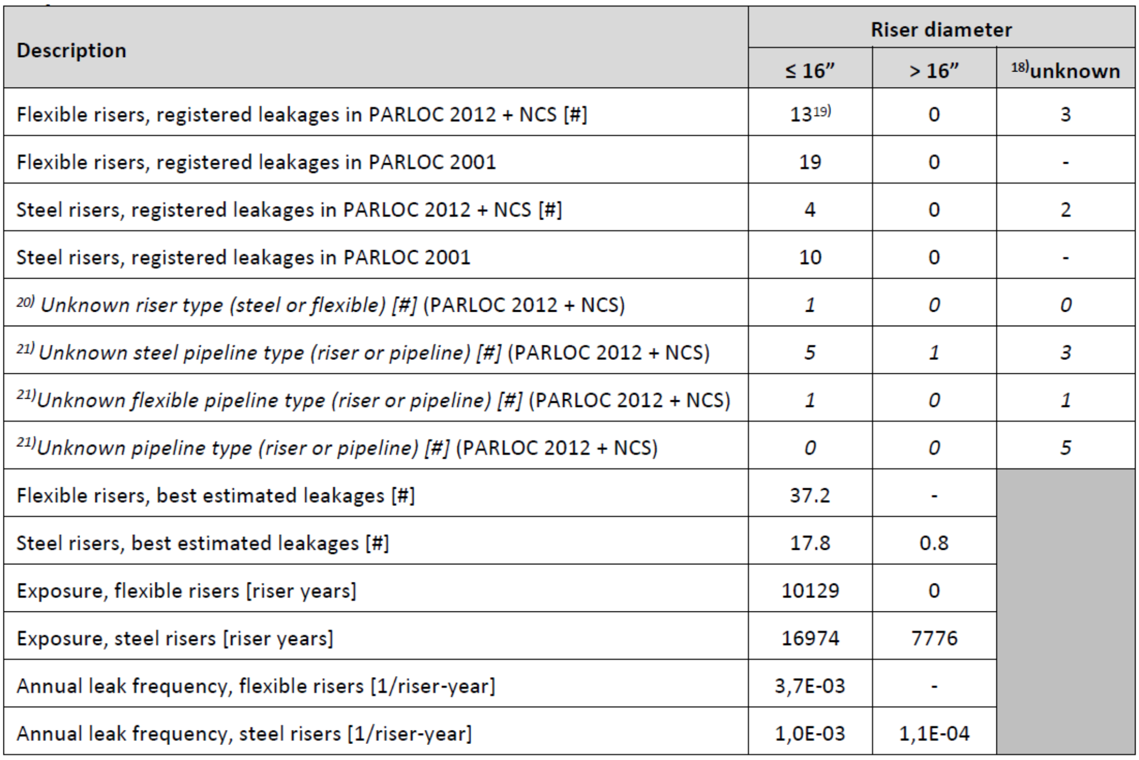
Based on these inputs, and following the same approach for failure frequency used for well stream pipelines, the annual leak frequency for risers was as follows:

- For flexible risers with diameter ≤16" is **$3{,}7 \times 10^{-3}$**.
- For steel risers with diameter ≤16" and >16" is **$1{,}0 \times 10^{-3}$** and **$1{,}1 \times 10^{-4}$**, respectively.

2.6.1.2 Hole size distribution

The information to establish a hole size distribution was not presented in the DNV GL report [4]; due to the scarcity of data information was not available for 123 out of 160 leaks. By excluding leaks from the riser body, only 13 out of 40 leaks had reported hole sizes.

Table 6 Flexible and static (steel) riser leakages and exposure data used in DNV GL, and estimated failure frequencies [4].



Description	**Riser diameter**		
	≤ 16”	**> 16”**	**[18]unknown**
Flexible risers, registered leakages in PARLOC 2012 + NCS [#]	13[19]	0	3
Flexible risers, registered leakages in PARLOC 2001	19	0	-
Steel risers, registered leakages in PARLOC 2012 + NCS [#]	4	0	2
Steel risers, registered leakages in PARLOC 2001	10	0	-
[20] *Unknown riser type (steel or flexible) [#]* (PARLOC 2012 + NCS)	*1*	*0*	*0*
[21] *Unknown steel pipeline type (riser or pipeline) [#]* (PARLOC 2012 + NCS)	*5*	*1*	*3*
[21]*Unknown flexible pipeline type (riser or pipeline) [#]* (PARLOC 2012 + NCS)	*1*	*0*	*1*
[21]*Unknown pipeline type (riser or pipeline) [#]* (PARLOC 2012 + NCS)	*0*	*0*	*5*
Flexible risers, best estimated leakages [#]	37.2	-	
Steel risers, best estimated leakages [#]	17.8	0.8	
Exposure, flexible risers [riser years]	10129	0	
Exposure, steel risers [riser years]	16974	7776	
Annual leak frequency, flexible risers [1/riser-year]	3,7E-03	-	
Annual leak frequency, steel risers [1/riser-year]	1,0E-03	1,1E-04	

2.6.2 Sureflex JIP

The Joint Industry Project (**JIP**), is a project where global data for flexible risers is collected and analysed in a non-attributable way (to maintain confidentiality) to generate an overview of:

- Quantities and types of flexible pipes in use.
- The type and number of damage/failure incidents.
- The failure modes experienced [2].

In total, 584 riser incidents were identified where 451 cases of degradation did not result in a rupture or leak, 123 cases resulted in a leak and 10 cases resulted in rupture. Incidents where risers were under, installation, commissioning, handling/transportation, and operation were included. The damage, leak and rupture frequencies for period 1976-2016 was calculated based on 5 years periods, as shown in **Figure 12**. The figure shows that the highest leak incidents occurred in the period 1991-1996, which was explained by PVDF end fitting pull-out and PA-11 ageing experience. Further, it was argued that from 1996 to 2016 a decrease in the reported incidents was due to an increase in identification of damage, obtained by an increased focus on testing, monitoring, inspection and integrity management. So, the resulting incident frequency per riser year relating to the period 2011-2016 was calculated based on the collected data. The results are as follows:

I. Damage frequency: **3.50×10^{-3}**
II. Failure-Leak frequency: **3.75×10^{-4}**
III. Failed-Rupture frequency: **1.25×10^{-4}**
IV. All damage and failure: **4.00×10^{-3}**

These frequencies do not include incidents or failure mechanisms pre-2011, which have been either updated operating procedures or been mitigated through design. Also, the frequencies for period 1976-2016 were presented in the report as follows:

I. Damage frequency: **3.68×10^{-3}**
II. Failure-Leak frequency: **1.00×10^{-3}**
III. Failed-Rupture frequency: **1.73×10^{-4}**
IV. All damage and failure: **4.85×10^{-3}**

Regarding the damage and failure causes, numerous points were highlighted when a comparison of several JIP reports was carried out:

- Sheath damage and annulus flooding experience show a large increase in incidents from the late 1990s onward due to increased monitoring and testing.
- Due to flexible riser inventory matures, a significant increase was shown in corrosion incidents between 2010-2016.
- A significant and consistent increase was noticed in carcass failure incidents, mainly caused by collapse due to multilayer sheath and effects of carcass tearing **Figure 14**.
- A small increase was observed in aged internal sheaths as the industry improved the understanding in the early 2000s, resulting in no incidents between 2002 and 2010.
- The largest number of internal pressure ageing incidents occurred in the period 1996-2001(**Figure 13**). Hence, a degradation model was developed to predict an initial acceptance criteria based on the correction of inherent polymer viscosity. Based on the gathered incidents, one leak incident was observed in the last 10 years related to this failure mechanism. From the reported incidents, it was shown that the operating temperature has either been more than the stated design temperature or/and design temperature pre-dates development in the industry. For incidents before 2000, it was observed that the temperature boundaries were routinely exceeded, the failure typically happened when the operating temperature was in the region of 100º C.

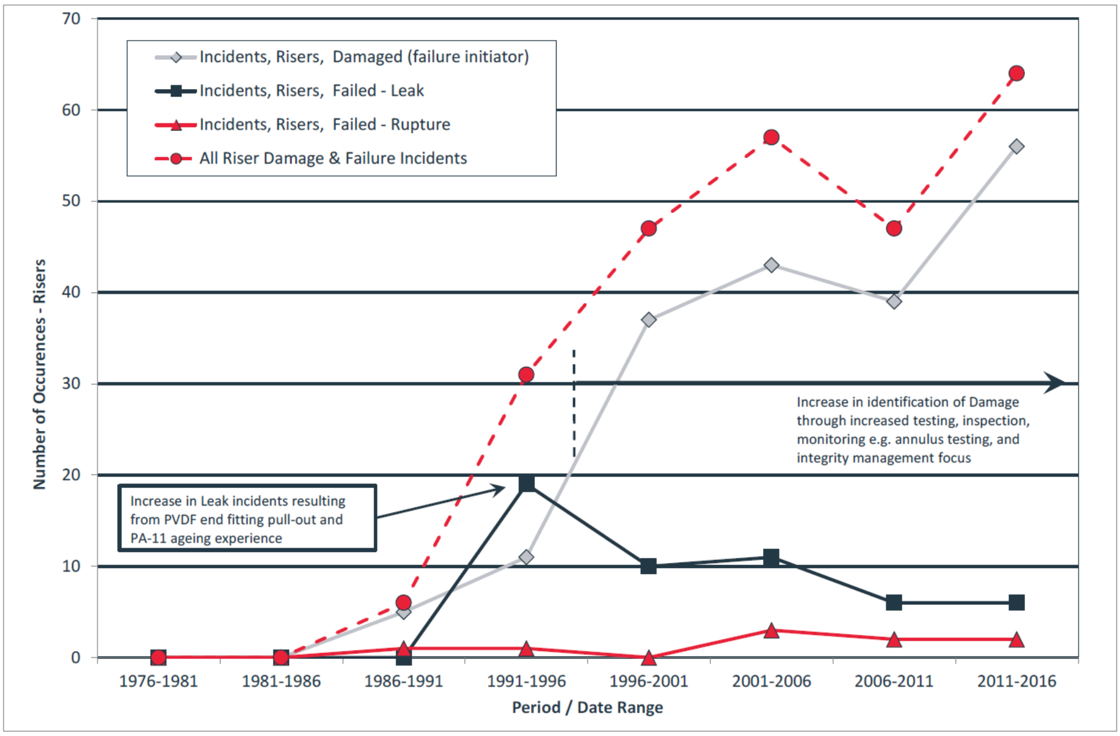


Figure 12 Damage and failure timeline for flexible riser presented in Sureflex JIP report [2].

On the other hand, carcass failure and multilayer PVDF collapse, as mentioned, show a significant and consistent increase. A total of 36 incidents were reported to be caused by this failure, only 4 of these were leak. **Figure 14** shows that the first registered incident was after 2001. Further, it was described that the carcass failure in multilayer PVDF risers has typically not exceeded the pressure designs that include sealing of more than one layer within end fitting. After 2002, riser design was modified, and only the pressure sheath layer is now sealed at the end fitting. However, if the depressurisation rates are sufficiently high, the failure mechanism can still occur [2].

A report was prepared by Wood [42] where the main aim was to extract Equinor's flexible riser data from the Sureflex report [2]. The leak frequency was estimated to be **1,0x10^{-3}** in the period 2012-2016 based on 2 reported incidents. Several key findings were highlighted:

- The leak frequency for Equinor's flexible risers is approximately 3 times higher than the leak frequency for the global population (Sureflex[2]), which is a result of the following:
  - Equinor operates mainly in a harsh environment which requires more flexible riser applicants, high temperatures and pressure endurances and large diameters.

  - The difference in the reporting regimes and regional standards in the regions in which Equinor operates, compared to the global population, may affect the results to some degree.

Figure 13 Showing the damage and failure timeline for internal pressure sheath ageing [2].

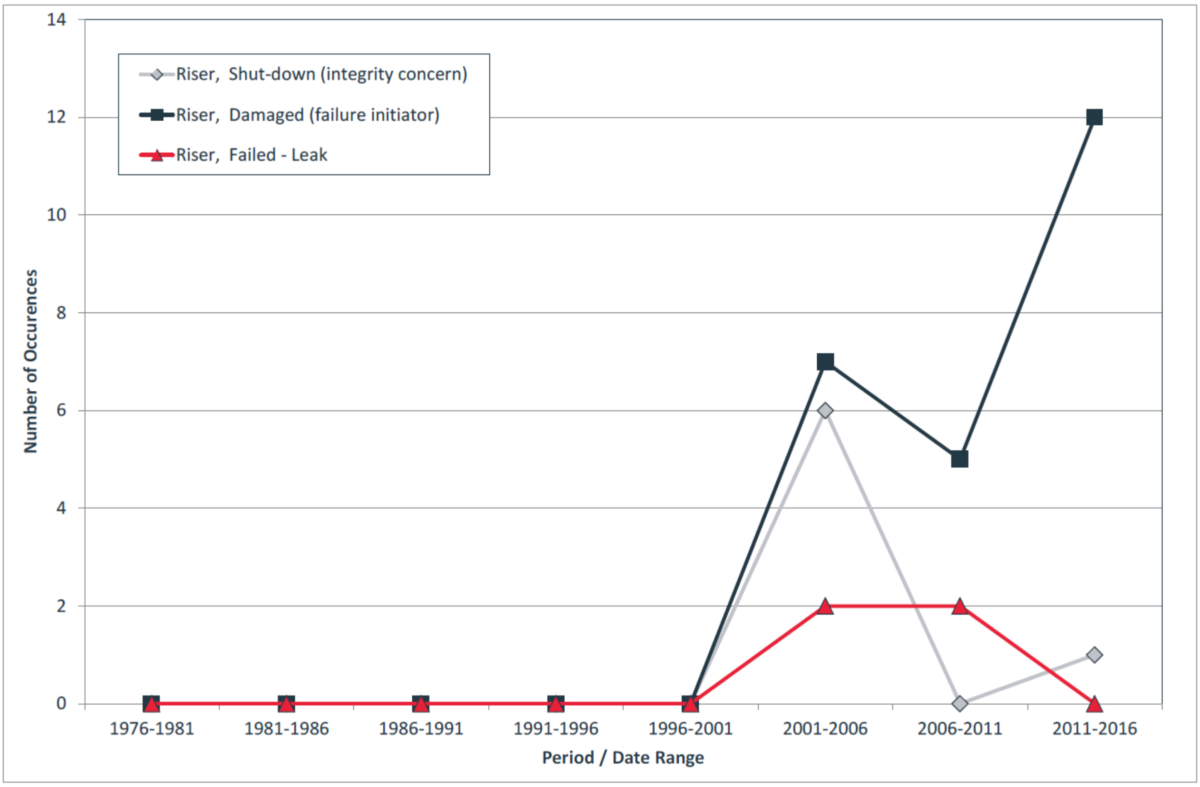


Figure 14 Showing the damage and failure timeline for carcass failure and multi PVDF collapse [2].

Chapter 3 Data analysis

The workflow of this study is based on collecting, systemising, and combining experience information on risers from different sources. In this chapter, the data used in this study will be described and presented in diagrams and tables to get a better overview and understanding of the data.

Several databases are used in this study; the primary inputs are the databases from PSA and the database from Equinor, which are listed below:

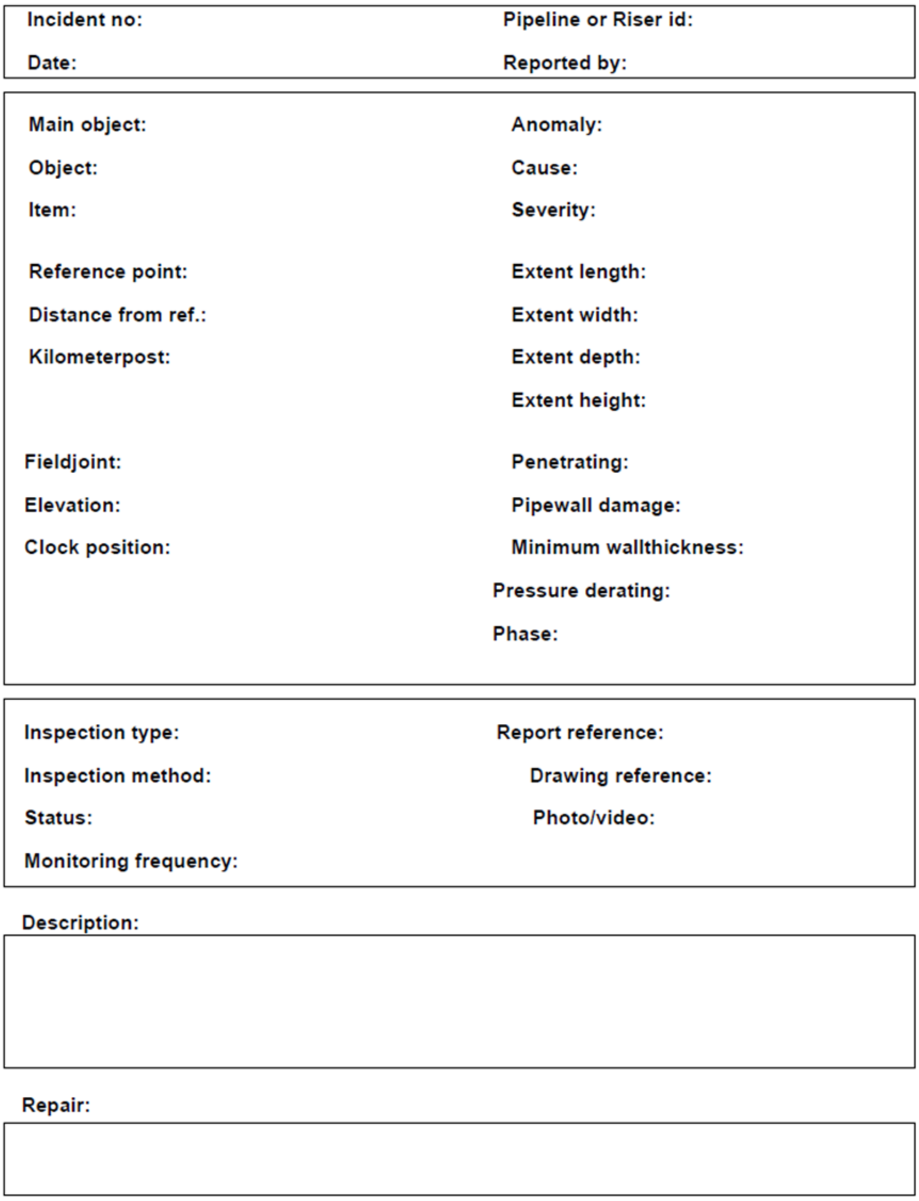
- Corrosion and Damage Database (**CODAM**) is a database of damage related to risers, including damage to the structure. CODAM covers incidents from 1974 up to 2018, mainly non-acute and near-miss events.
- Equinor's database **Synergi**, is a database used to register all types of incidents at Equinor; categories vary from personal to installation level.
- Riser master data (**SISU**) which is a population data of risers registered in the NCS.

Furthermore, the mechanism on how data is gathered into those databases and the criteria for incidents registration in both CODAM and Synergi will be presented in the next sections to understand the data and its quality.

3.1 CODAM database

Corrosion and Damage (**CODAM**) is a database for reporting incidents and damage on pipeline systems and offshore structures in the NCS and is managed by PSA; it includes data (as reported from operators) from the1970's, and structuring of flexible riser data started from 1995 onwards [40]. All operators on the NCS are obligated to report incidents to CODAM **[**The management regulations, 2012 **§36[43]]**. Hence, if riser damage or leakage occurred, a report form had to be filled in and sent to PSA via the PSA webpage. **Figure 15** shows an example of a form that was previously used in reporting before reporting was digitalised.

If the leakage or damage could result or have resulted in an accident, hazardous situation or a near-miss, additional reporting was required (**Figure 16**). In the first report form (**Figure 15**) information about the riser should be submitted such as a riser id (based on PSA's id, as each riser in the NCS is assigned an id in the population data). Information about the involved component should be included, while item description is only required if further details are needed. Additionally, reference and location information should be included, e.g. reference point, distance from reference, km post, field joint, elevation and clock position. Moreover, type of anomaly (a type of damage or incidents), cause (or possible cause), dimension measures and pressure should be filled in. If the damage was after an inspection, the inspection method and type should be described [44]. The report also includes a description box, where the reporter can describe what happened, and it should be further specified whether this is a new report or a follow up from a previous report [44].



Incident no:
Date:

Pipeline or Riser id:
Reported by:

Main object:
Object:
Item:

Reference point:
Distance from ref.:
Kilometerpost:

Fieldjoint:
Elevation:
Clock position:

Anomaly:
Cause:
Severity:

Extent length:
Extent width:
Extent depth:
Extent height:

Penetrating:
Pipewall damage:
Minimum wallthickness:
Pressure derating:
Phase:

Inspection type:
Inspection method:
Status:
Monitoring frequency:

Report reference:
Drawing reference:
Photo/video:

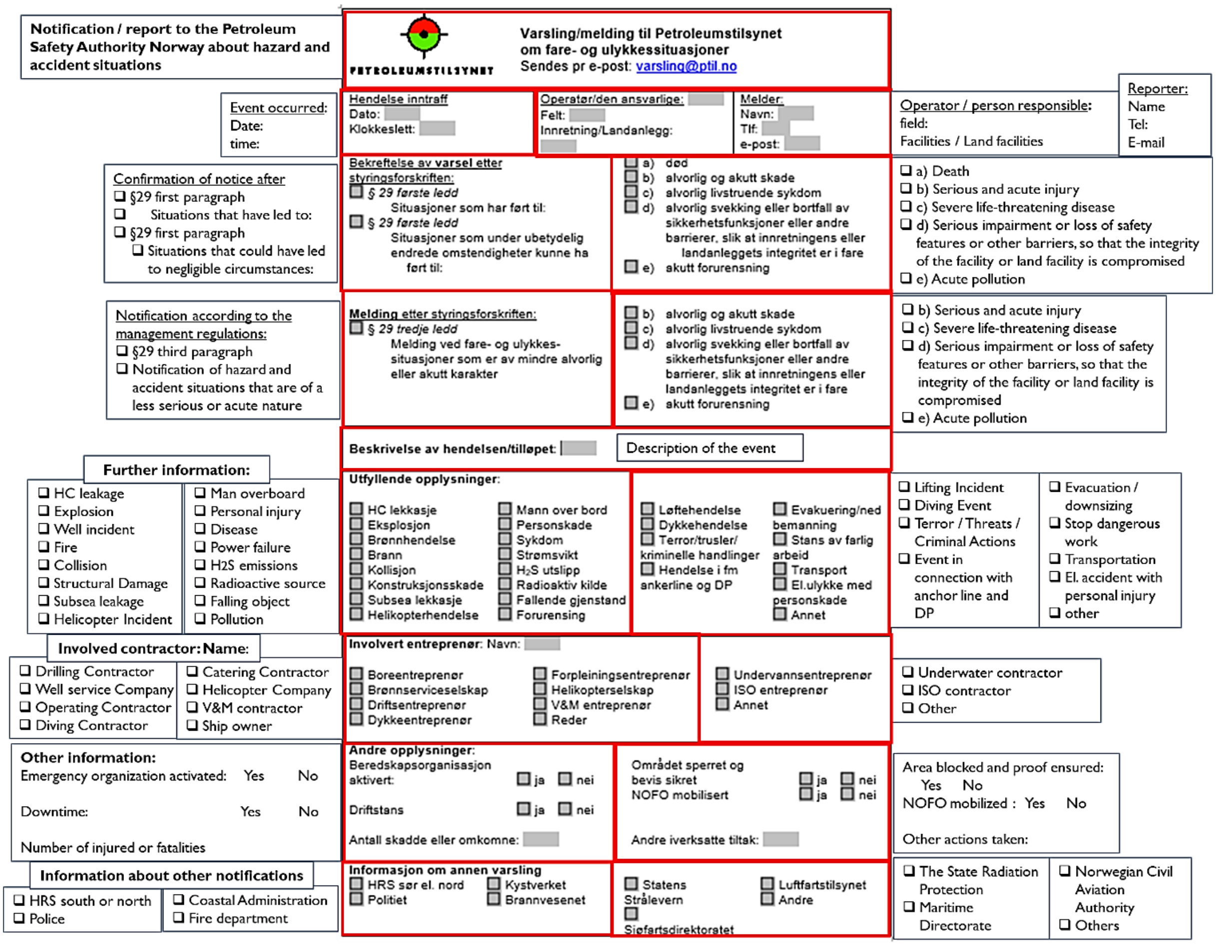
Description:

Repair:

Figure 15 A report form for the CODAM pipeline system incident reporting previously used before online reporting, PSA [44].

Severity classification, e.g. major, minor or insignificant, should also be submitted by the reporter based on how the incident might impact the integrity of the installation. Thereafter, PSA evaluates whether the incident should be investigated or not and will set the final severity degree classification, based on their evaluation and loss potential. A major incident, according to PSA, refers to high risk of injury and high risk of pollution **[40]**.

For hazard and accident situations a special report form should be submitted (**Figure 16**), where the accident should be described, and its consequences identified. If it is a near-miss, the consequences under different circumstances should be considered. The type of accident should also be chosen from the categories listed: HC leak, explosion, fire, collision, etc. The contractor involved should be chosen from the list, and it should be noted whether other authorities have been notified, the emergency organisation has been activated, and any other actions have been taken.



Notification / report to the Petroleum Safety Authority Norway about hazard and accident situations

PETROLEUMSTILSYNET

Varsling/melding til Petroleumstilsynet
om fare- og ulykkessituasjoner
Sendes pr e-post: varsling@ptil.no

Event occurred:
Date:
time:

Hendelse inntraff
Dato:
Klokkeslett:

Operatør/den ansvarlige:
Felt:
Innretning/Landanlegg:

Melder:
Navn:
Tlf:
e-post:

Operator / person responsible:
field:
Facilities / Land facilities

Reporter:
Name
Tel:
E-mail

Confirmation of notice after
❑ §29 first paragraph
❑ Situations that have led to:
❑ §29 first paragraph
  ❑ Situations that could have led to negligible circumstances:

Bekreftelse av varsel etter styringsforskriften:
☐ *§ 29 første ledd*
  Situasjoner som har ført til:
☐ *§ 29 første ledd*
  Situasjoner som under ubetydelig endrede omstendigheter kunne ha ført til:

☐ a) død
☐ b) alvorlig og akutt skade
☐ c) alvorlig livstruende sykdom
☐ d) alvorlig svekking eller bortfall av sikkerhetsfunksjoner eller andre barrierer, slik at innretningens eller landanleggets integritet er i fare
☐ e) akutt forurensning

❑ a) Death
❑ b) Serious and acute injury
❑ c) Severe life-threatening disease
❑ d) Serious impairment or loss of safety features or other barriers, so that the integrity of the facility or land facility is compromised
❑ e) Acute pollution

Notification according to the management regulations:
❑ §29 third paragraph
❑ Notification of hazard and accident situations that are of a less serious or acute nature

Melding etter styringsforskriften:
☐ *§ 29 tredje ledd*
  Melding ved fare- og ulykkes-situasjoner som er av mindre alvorlig eller akutt karakter

☐ b) alvorlig og akutt skade
☐ c) alvorlig livstruende sykdom
☐ d) alvorlig svekking eller bortfall av sikkerhetsfunksjoner eller andre barrierer, slik at innretningens eller landanleggets integritet er i fare
☐ e) akutt forurensning

❑ b) Serious and acute injury
❑ c) Severe life-threatening disease
❑ d) Serious impairment or loss of safety features or other barriers, so that the integrity of the facility or land facility is compromised
❑ e) Acute pollution

Beskrivelse av hendelsen/tilløpet:

Description of the event

Further information:

❑ HC leakage
❑ Explosion
❑ Well incident
❑ Fire
❑ Collision
❑ Structural Damage
❑ Subsea leakage
❑ Helicopter Incident

❑ Man overboard
❑ Personal injury
❑ Disease
❑ Power failure
❑ H2S emissions
❑ Radioactive source
❑ Falling object
❑ Pollution

Utfyllende opplysninger:

☐ HC lekkasje
☐ Eksplosjon
☐ Brønnhendelse
☐ Brann
☐ Kollisjon
☐ Konstruksjonsskade
☐ Subsea lekkasje
☐ Helikopterhendelse

☐ Mann over bord
☐ Personskade
☐ Sykdom
☐ Strømsvikt
☐ H_2S utslipp
☐ Radioaktiv kilde
☐ Fallende gjenstand
☐ Forurensing

☐ Løftehendelse
☐ Dykkehendelse
☐ Terror/trusler/ kriminelle handlinger
☐ Hendelse i fm ankerline og DP

☐ Evakuering/nedbemanning
☐ Stans av farlig arbeid
☐ Transport
☐ El.ulykke med personskade
☐ Annet

❑ Lifting Incident
❑ Diving Event
❑ Terror / Threats / Criminal Actions
❑ Event in connection with anchor line and DP

❑ Evacuation / downsizing
❑ Stop dangerous work
❑ Transportation
❑ El. accident with personal injury
❑ other

Involved contractor: Name:

❑ Drilling Contractor
❑ Well service Company
❑ Operating Contractor
❑ Diving Contractor

❑ Catering Contractor
❑ Helicopter Company
❑ V&M contractor
❑ Ship owner

Involvert entreprenør: Navn:

☐ Boreentreprenør
☐ Brønnserviceselskap
☐ Driftsentreprenør
☐ Dykkeentreprenør

☐ Forpleiningsentreprenør
☐ Helikopterselskap
☐ V&M entreprenør
☐ Reder

☐ Undervannsentreprenør
☐ ISO entreprenør
☐ Annet

❑ Underwater contractor
❑ ISO contractor
❑ Other

Other information:
Emergency organization activated: Yes No
Downtime: Yes No
Number of injured or fatalities

Andre opplysninger:
Beredskapsorganisasjon aktivert: ☐ ja ☐ nei
Driftstans ☐ ja ☐ nei
Antall skadde eller omkomne:

Området sperret og bevis sikret ☐ ja ☐ nei
NOFO mobilisert ☐ ja ☐ nei
Andre iverksatte tiltak:

Area blocked and proof ensured: Yes No
NOFO mobilized : Yes No
Other actions taken:

Information about other notifications

❑ HRS south or north
❑ Police

❑ Coastal Administration
❑ Fire department

Informasjon om annen varsling
☐ HRS sør el. nord
☐ Politiet
☐ Kystverket
☐ Brannvesenet

☐ Statens Strålevern
☐ Sjøfartsdirektoratet
☐ Luftfartstilsynet
☐ Andre

❑ The State Radiation Protection
❑ Maritime Directorate

❑ Norwegian Civil Aviation Authority
❑ Others

Figure 16 Interpreted report form used to report incidents to PSA, the original report from PSA (see Appendix C for a A3 size of this figure).

In general, PSA has defined the types of incidents that should be reported to CODAM [44]:

- All leakage incidents from riser regardless of size.
- The free span that exceeds the design prerequisites or if a corrective measure is implemented.
- All internal corrosion and erosion incidents; for incidents associated with a wall thickness reduction of > 40%, a full report is required.
- All areas with bare-metal should be reported.

- The external corrosion on risers where evaluation is required.
- Any corrosion or damage of the protective coating.
- Dropped objects incidents that might result in damage to the riser.
- Any damage caused by a third-party activity.
- Damage to riser clamps.

The data used in this study does not include all input information which is typically recorded, due to difficulties retrieving the data from PSA (because of the low capacity of the PSA IT department). The information received includes riser name, dimension, type of medium, field name, date of the incident, anomaly, severity, description of the incident, main object, object, cause, repair, and by whom it has been reported. Thus, not all the information mentioned above was filled out by the reporter.

3.1.1 Workflow of CODAM analysis

Major and minor reported incidents by all operators were analysed by reading the case description and all types of information that was registered or given. Hence, the selected incidents were systemised, and a comparison of reported incidents by Equinor was carried out.

Assumptions and choices were made during the analysis of CODAM

- In total, 988 incidents were reported from 1975 to 2018, where: 111 incidents were registered as major, 252 minor, and 625 as insignificant. In addition to risers, the data included incidents related to pipelines, clamps, bolts, valves, flanges and other subsea connections. *In this study, only the **riser body** will be considered. Other components (such as clamps, bolts, flanges and valves) are excluded as they normally are included in the installations leak source frequency.*
- The following definition of damage will be used to delimit which incident should be considered the damage.
    - **Damage:** "*An issue/anomaly which degrades the riser construction/performance over time. Damage tends to be a Failure Initiator, which if left undetected could progress through a Failure Mechanism, leading to an ultimate Failure condition in short to medium term. There are cases where a damaged riser may remain in operation following the identification of damage if the risk can be defined and managed/mitigated, but it is possible that the original design service life capability may be impacted. Cases, where a riser is*

unable to perform the intended design function, are normally included as damage cases, e.g. reduced capacity or blockage"[2].

- If the case description indicates or mentions a leak, the incident was considered a leakage incident regardless of medium type.
- Only incidents where the riser was in operation were considered, i.e. *incidents which occurred during transport and installation were not considered.*
- Only incidents with major and minor severity were analysed.
- Since the interpretation of incidents is based on case description, a subjective judgment was used in some cases due to the poor incident description.
- Even near-miss incidents that did not result in any serious impact, but the potential consequences of which might have been serious if the incident happened under different circumstances, were included.

3.2 Equinor database (Synergi)

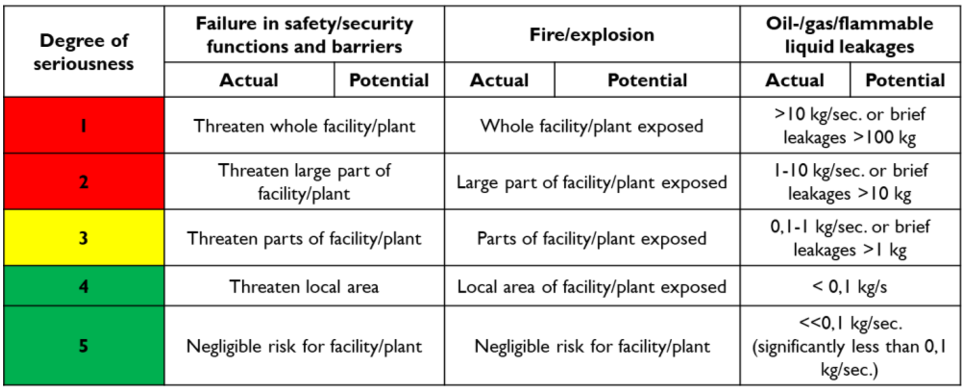
Synergi is a **QHSE** (Quality, Health, Safety, and Environment) management software used to manage risk, **HSE** (Health, Safety and Environment) non-conformities, incidents, risk analysis and improvement suggestions [45]. Equinor has been using *Synergi* for internal reporting of all HSE incidents or near-misses.

Generally, if an HSE incident occurs, it should be reported into Synergi to get reliable information on how to avoid recurrence of the incident and to monitor the risk. An HSE incident shall be categorised and classified in accordance with a matrix where the categorisation means selecting all *relevant potential and actual impacts and consequences*. Also, the classification means determining and classifying the severity of the applicable impact or consequences[46]. The classification aims to determine subsequent follow up of the incident in the form of reporting, investigation, notification, and enhancement[46]. Based on the actual and potential impact or consequences, an HSE incident shall be categorised and classified in one of five available degrees of seriousness, as shown in **Figure 17**. The highest degree of severity is red (1 and 2), followed by yellow (3) and green categories (4 and 5).

For failure in safety functions and barriers incidents, the red 1 category shall be used for an incident that is a threat for whole facility/plant, and the red 2 category shall be used for a threat that faces a large part of the facility (**Figure 17**).

Moreover, for oil, gas or flammable leakage incidents, the categorisation depends on the volume of the leakage, where the red 1 category applies to leakages > 100 kg or for leakage rate > 10 kg/s. In addition, red 2 category applies for incidents with leakages > 10 kg or leakage rate 1-10 kg/s (**Figure 17**). Likewise, for actual or potential fire/explosion the categorisation varies from red 1, whole facility/plant exposed, to green 1, the negligible risk for facility/plant. The HSE incidents should be categorised under **DFUs** (Defined situations of Hazard and accident). For incidents related to risers, typical DFUs will be:

- DFU 9: Leakage from risers, pipeline and subsea production plant
- DFU 10: Damage to risers, pipeline and subsea production facilities



Degree of seriousness	Failure in safety/security functions and barriers		Fire/explosion		Oil-/gas/flammable liquid leakages	
	Actual	Potential	Actual	Potential	Actual	Potential
🟥 1	Threaten whole facility/plant		Whole facility/plant exposed		>10 kg/sec. or brief leakages >100 kg	
🟥 2	Threaten large part of facility/plant		Large part of facility/plant exposed		1-10 kg/sec. or brief leakages >10 kg	
🟨 3	Threaten parts of facility/plant		Parts of facility/plant exposed		0,1-1 kg/sec. or brief leakages >1 kg	
🟩 4	Threaten local area		Local area of facility/plant exposed		< 0,1 kg/s	
🟩 5	Negligible risk for facility/plant		Negligible risk for facility/plant		<<0,1 kg/sec. (significantly less than 0,1 kg/sec.)	

Figure 17 Matrix used for classification and categorisation of HSE incidents at Equinor.

However, events registered before 2000 were not assigned a DFU, as DFUs were not used before 2000 and *Synergi Life* was mostly used for personal accidents reporting.

The main aim of studying reported incidents in Synergi is to evaluate the precision of the reported incidents by Equinor into CODAM, and also to make a comparison of how the same incident is reported in two different systems.

3.2.1 Synergi Analysis Workflow

The searching process in Synergi was carried out in different steps:

- First, a search by using one word at a time, e.g. *riser* and *stigerør (which means riser in Norwegian)*, so as not to miss any event by searching in combination.
    - The search resulted in~ **3700** events from the **1990**s to **2018**. Each report has a *free text box* where the incident is described. In total, 3700 free text boxes were read, and cases of damages or leaks (as it is described in the definitions) were extracted.
- Second, was a search by combination of different keywords, such as riser and leakage/ riser and damage, riser and inspection, etc.
- Finally, searching by DFU such as leakages from subsea tools.

Search results were systemised and compared to results from CODAM, i.e. the reported incidents were compared, and the similarities and differences were emphasised. The result of this Synergi analysis will be presented in the Results chapter.

Assumptions and judgments in the analysis of Synergi

- Incidents related to **riser body only** were considered and excludes components such as clamps, bolts, flanges and valves, since these are normally included in installations leak source frequency.
- Definition of damage in this study will be used to delimit which incident should be considered as damage.
- Based on case descriptions, if this indicates or mentions a leak, the incident will be considered as a leakage incident regardless of medium type.
- Only incidents for risers in operation will be considered.
- Incidents with all types of degree of seriousness (red, yellow, and green) will be analysed.
- Even incidents which did not result in serious impact, but the potential consequences of which might have been serious if it was under different circumstances, will be included.

3.3 SISU (Riser population database)

Petroleum Safety Authority (**PSA**) has a population database **SISU** (also called riser master data) for all risers that are registered in the NCS, which was made available for this study. The database includes:

- Riser diameter, medium, and material.
- Design pressure, max and min design temperature, and design life.
- Installation and start-up date.
- Wall thickness above and underwater.
- Field, operator and riser phase.

In total, **749** (excluding 4 umbilical) risers have been registered in the NCS since **1972**, where the dimension varies from 1,5" up to 42" (**Figure 58**, Appendix C). Most of the risers registered have a dimension of10", 6", 8" or 12" with a quantity of 103, 89, 65, and 57, respectively. Four categories were made for some of the risers due to the variation in dimension, which is presented in **Figure 58 (**Appendix C**).** Also, 466 out of 749 registered risers are in the service phase, 151 were decommissioned, 54 are in the installation phase, 30 were removed, and 48 registered as a future phase. *Equinor* has the highest number of risers in the NCS with 428 risers, followed by *Aker BP* with 85, and *ConocoPhillips* with 83.

While the type of riser is not included in the database, the type of material was included for 640 risers and of 109 without registered material type, 70 were registered under *Equinor*. Therefore, a classification of riser type (static or flexible) was made based on the material type, where risers with material X46, X50, X52, X60, X65, X7, 13% Cr, A333G6, Duplex, SAWL 450, AML I 450 P, and PPC 912 are interpreted to be static risers. Risers with material Coflex, Crossflex, Gammaflex, HPDE L, NKT Flexible, PA11, Polyethylene, PVDF, Rislan, and WSCflex are interpreted to be flexible risers. For risers, without material description, a correlation with Equinor's database was carried out. For the remaining 39 risers without riser material type, an assumption is made for each involved installation based on the installation type.

Excluding risers with future phase, 356 risers were assigned as a *flexible riser*, where: 43 are decommissioned, 13 under installation, 23 removed and 277 in service. 345 risers were assigned as *static risers*, where 189 registered as in-service phase, 108 decommissioned, 41 under installation, and 7 removed. While the database included the start-up and installation date for all risers, the date for the decommissioning or removing process was not included. Therefore, in corroboration with PSA, the decommissioning and removing date for 181 risers was collected and inserted manually for each riser in order to calculate *riser year*.

3.3.1 Assumptions and choices were made during analysis of population data (SISU)

- For risers without material description, a choice was made to define the riser type based on the installation type or correlate it with the majority of riser types belonging to the specific installation. This choice was taken for 39 risers out of 749 risers, 5.2% of the population. If an installation has mostly static risers, e.g. Ekofisk, then the unknown type of risers registered for Ekofisk have been registered as static.
- 4 umbilicals were excluded from the population analysis as the focus of this study is risers.
- When a riser is installed but not operational, it is exposed to other factors such as wet environment and wave movements etc. Hence, in order to capture all stressors within their correct time frame, it was decided that the date/year the riser was installed would be used, rather than start-up date, in riser year calculation.

- According to SISU registries, 58 risers were installed in the year of 1900, 36 of these are registered as future risers. The 22 risers with this incorrect installation date were given a date based on the platform installation.
- In order to correlate the final result of leakage and damage frequency with DNV GL results, the same riser dimension category was used in this study, i.e. >16" and ≤16". Thus, 353 flexible risers were categorised into ≤16", while 212 static risers were classified into category ≤16" and 133 into category >16".

Chapter 4 Results of database analysis

In this chapter, database analysis results from this study are presented and examined. A short description of the result analysis process, after data inspection, is listed below:

- The data from CODAM with major severity showed multiple reporting of some incidents. The result was presented before and after the treatment of data to address the uncertainty in the database. Thus, the multiple incidents were removed, and new tables of results are presented in section **4.2.1**.
- The data from CODAM with minor severity was analysed to make sure it was not missing any incident that might have been classified incorrectly, the result is presented in section **4.2.2**.
- The incidents registered only in Synergi were analysed and presented in section **4.3**. The aim was to show how using different data sources might impact both damage and leak frequency, as well as to examine if there is under- or over-reporting of incidents by Equinor.
- A difference in reported incidents by Equinor to CODAM and incidents registered in Synergi was observed in two ways:
    - Numerous incidents that were registered in CODAM by Equinor were not founded in Synergi.
    - Several incidents which were registered in Synergi were not founded in CODAM.

Therefore, incidents that were reported by Equinor in CODAM with major severity were combined with registered incidents in the Equinor database, Synergi and presented in section **4.4**. The main purpose was to get an overview of riser incidents for risers operated by Equinor in the NCS.

- As not all riser incidents recorded in Synergy were registered in CODAM, a combination of unreported incidents by Equinor with incidents reported in CODAM with major severity from *all operators* was carried out. The result is presented in section **4.5** and will be discussed further in the discussion chapter.
- To examine if there is a special trend in the historical data, the annual damage and leak incidents for all databases mentioned above is presented together with the annual riser year in section **4.6**.

- To examine how the use of the different database in the estimation of leak and damage frequency might impact the result, the frequency was calculated based on different databases and presented in section **4.6**.

4.1 Riser population data from PSA (SISU)

The population data was used to calculate the annual riser year and a specific riser year time-period, as well as the frequency (presented later in section **4.6)** for both categories:

- Risers operated by Equinor only
- Risers operated by all operators

An annual riser year experience for both types of risers for different categories was calculated from the **SISU** database (PSA), the date of decommissioned and removed risers was provided by PSA for this study. The first calculated annually riser year was chosen to be 1995 since flexible riser data was structured from 1995 [40]. **Figure 18** shows the riser year assessed annually for different riser types that have different operators. For flexible risers, the trend shows increasing operational experience until 2013, where replacement or removing of some risers might have happened. The riser year trend of flexible risers continued to increase from 2014 until 2015 when it started to slightly decrease into 2017. By looking at the annual riser year for only risers operated by Equinor in **Figure 19**, a similarity in the flexible riser year is perceived, where an insignificant decrease is observed in 2011 and 2013 before it increases again toward 2017.

Additionally, static riser year for both categories ≤ 16" and >16" shows staggered upward trends. Both static riser year categories show substantial decreases in 1999, 2005, and 2014, while both trends show increases in the time intervals 1999-2001 and 2008-2013.

Riser year for ≤16" static riser category shows an increase in the operational experience from 1999-2004 and keeps increasing from 2005-2007 before it showed a reduction in 2008. This is followed by an insignificant increasing trend until 2013, after which a decrease is seen in 2014 and 2016 (**Figure 18**).

The trend for ≤16" static riser year operated by Equinor shows in general increasing trend between 1995-2004 with an insignificant reduction in 2000 and a noticeable reduction in 2002 and 2005. There was also a decrease in 2008, after which the trend kept increasing until 2017.

Moreover, the trend for >16" category for static risers operated by all operators shows five increasing in operational experience intervals generally: 1995-1998, 1999-2001,2002-2004, 2005-2013 and 2014-2016. Decreases were recorded in 1999, 2002, 2005, 2014 and 2017

(**Figure 18**). The trend for >16" category for static risers operated by Equinor shows an increase in operational experience from 1995-2004 with an insignificant reduction in 1998, followed by a substantial reduction in 2005 (**Figure 19)**.

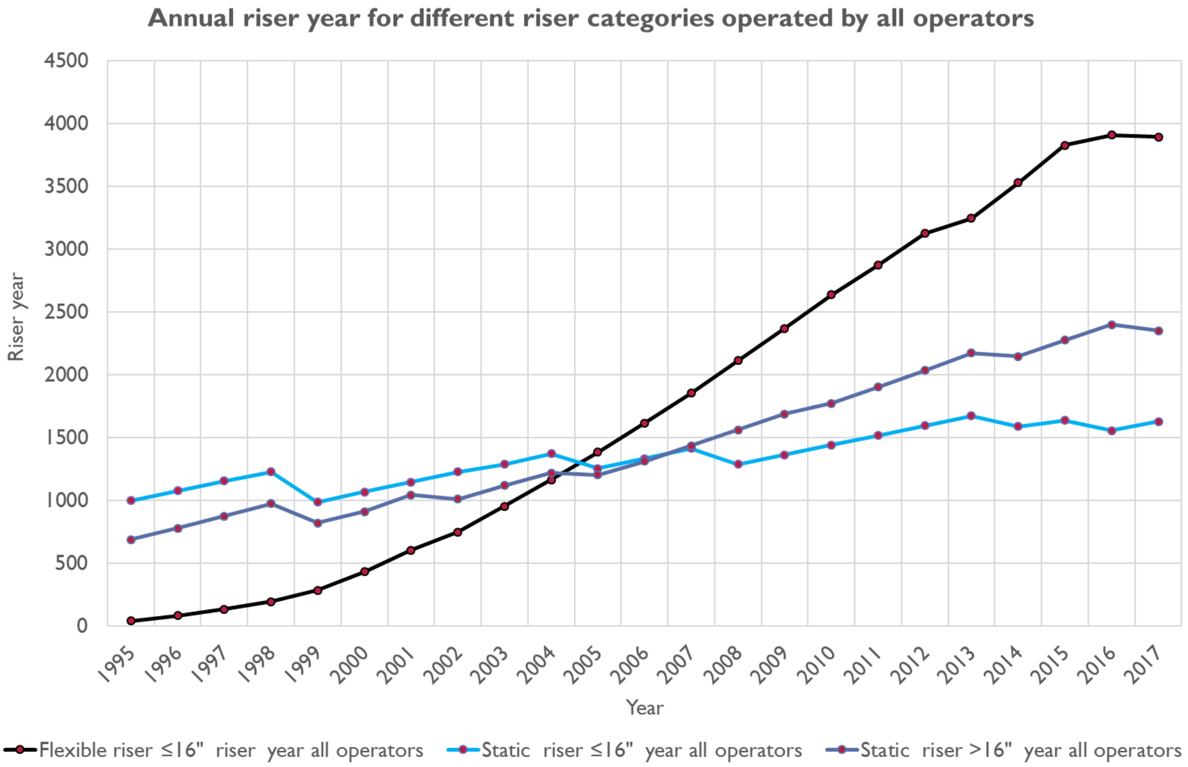


Figure 18 Annual riser year from 1995-2017 for different riser categories operated by all operators. Data from SISU.

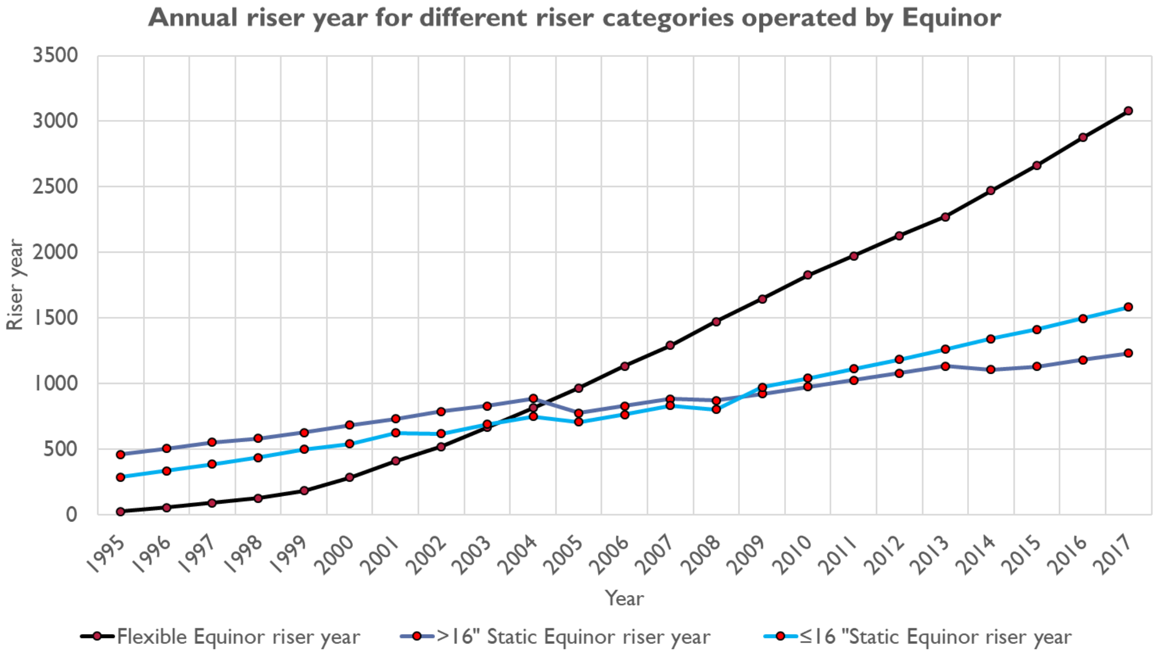


Figure 19 Annual riser year from 1995-2017 for different riser categories, which are only operated by Equinor. Data from SISU.

4.2 CODAM database

4.2.1 Major incidents reported in CODAM

Of 111 registered major incidents in CODAM in the period 1975-2016, 88 incidents were related to riser body only; 21were classified as leak and 67 as damage incidents (**Figure 59**, **Appendix C**). The following was noticed:

- The first registered damage incident was in 1975, while the first registered leak incident was in 1984 (**Figure 20**).
- The highest number of annual damage incidents occurred in 2011, 2015, and 2000 with 7, 5, and 5 incidents respectively.
- The highest number of annual leak incidents occurred in 2006 and 2011; both years recorded 4 leaks.
- **Figure 20** shows that in the time interval 1975-1995, fewer incidents occurred or were registered compared to incidents in 1996-2016.

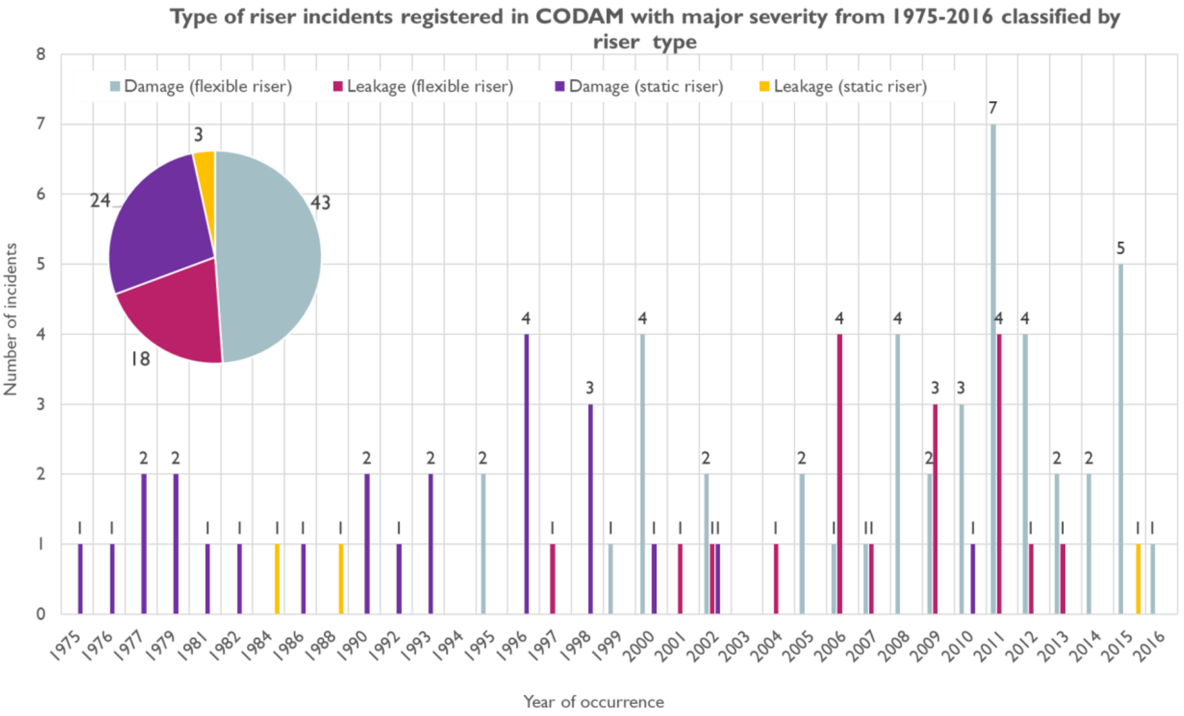


Figure 20 An overview of major incidents registered in CODAM categorised by riser type.

The type of risers involved in damage and leak incidents were assigned based on correlation with the population database SISU and the Equinor’s database. In total, 61 incidents were linked to flexible risers (43 damage and 18 leak incidents) and 27 linked to static risers (24 damage and 3 leak incidents) (**Figure 20**).

The following was perceived after looking at the annual major damage and leak incidents categorised by riser type in **Figure 20**:

- The highest annual flexible riser damage occurred in 2011 and 2015 with 7 and 5 incidents, respectively.
- The highest annual flexible riser leak incidents occurred in 2006, 2011, and 2009 with 4, 4, and 3 incidents, respectively.
- For static risers, the highest number of yearly damages occurred in 1996 and 1998 with 4 and 3 incidents, respectively.
- Three leak incidents linked to static risers occurred in total, once a year in 1984, 1988, and 2015.

The largest part of involved risers in period 1975 to 1993 belongs to the >16" dimension category while dimension category ≤16" dominates the period from 1995 to 2016 (**Figure 60**, **Appendix C**). In total, 71 of involved risers belong to ≤16", and 16 belong to the >16" dimension category (**Figure 60**, **Appendix C**).

By looking at medium type, the data shows that 28 incidents are related to oil risers, 25 gas, 19 oil/gas, 10 injections, 3 water and 2 classified as service (**Figure 61**, **Appendix C**). Additionally, 9 out of 11 incidents of oil risers which occurred in 2011 are related to 6".

The result shows that 27 of the total registered major incidents are linked to 6" dimension and 8 incidents linked to the 10" dimension. By looking into registered incidents, especially where the annual incident rate was high, several issues were addressed:

- In 2000, 4 incidents were reported from the same field: 3 with the same date and 1 registered 3 months later. Three of these are 6" oil and one 6" injection, registered on the same date as 2 others.
- In 2006, 4 incidents out of 5 were reported from the same field in November. The case descriptions indicate the leaks were detected during vacuum testing and different riser names were mentioned in the text.
- In 2008, case descriptions for two incidents reported from the same field, within 4 days of each other and where the same riser was involved, were shown to be the same incident.
- In 2009, 3 registered leak incidents were reported from the same field on the same day, where two were 6" oil and one was 6" injection where outer sheath damage was assigned as the cause of the oil risers leak.

- In 2011, 6 incidents were reported from the same field, and all were linked to the 6" oil riser with different dates and case descriptions, i.e. carcass tear, carcass collapse, carcass damage, and some were poorly described or not described at all. Of these, 5 were registered as damage incidents and 1 as a leak incident.
- In 2012, 3 damage incidents were reported from the same field where 1 incident occurred while the riser was not in operation and the remaining two seem to be same the incident.
- For 6 incidents reported in 2015, 2 of them were reported from the same field but for two different dimensions and mediums. Three of these incidents were discovered by annulus testing and one during pressure testing.

To understand the reasons for multiple registered incidents, a request was sent to PSA with a list of the presented incidents (above) to validate them within their system. The response was that an update of incidents was registered as a new incident. Hence, a new analysis was carried out where the multi-reported incidents were removed (**Figure 62**, **Appendix C**). The differences are presented below:

- In 2000: reduction of 3 flexible riser damage incidents (**Figure 21**).
- In 2008: 1 flexible riser damage was removed.
- In 2009: 1 flexible riser leak incident was removed.
- In 2011: As there were 5 reported incidents for damage and one for a leak for the same riser, it was decided to include one damage and one leak incident.
- The updated result became 4 leak and 3 damage incidents (all flexible risers) instead of 4 leaks and 7 damage incidents.
- In 2012: Two flexible riser damage incidents were removed.

The total result became: 20 leak and 56 damage incidents for both riser types, where 17 leak incidents and 32 damage incidents are linked to flexible risers. As well, 3 leak and 24 damage incidents are aligned to static risers. The updated result is presented in **Figure 21**, and the difference between registered incidents in CODAM with major severity before and after the update is presented in **Table 7**. The following was observed:

- The sum of leak incidents linked to flexible risers showed a reduction of ~5,6% when 1 incident was removed.
- Total damage and leak incidents linked to flexible risers showed a reduction of ~20 %, from 61 to 49 incidents.

- A 25,6% reduction in damage incidents of flexible risers was observed, from 43 to 32 incidents.
- The number of static riser incidents remained the same.

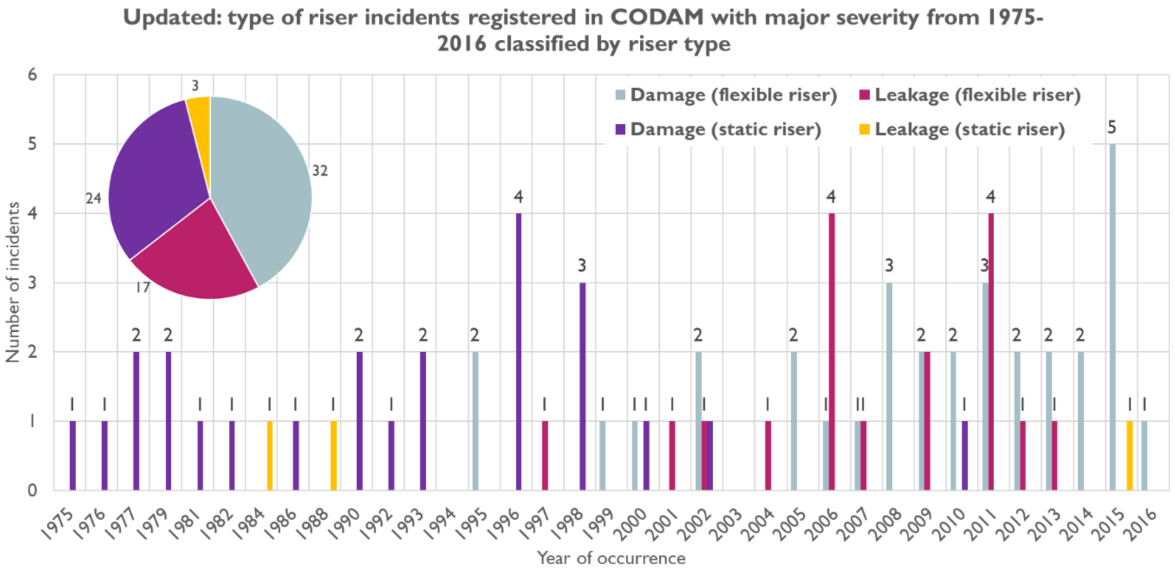


Figure 21 An updated overview of major incidents registered in CODAM categorised by riser type after removing multi reported incidents.

Distribution of dimension categories after the update is shown in **Figure 63 (Appendix C)**. Mostly risers within category ≤16" were involved in multi reported cases, even though the number of risers within this category was reduced from 71 to 60 rises, e.g. 15,5%. Only one riser was removed from category >16".

Table 7 A summary of the difference between Major incidents in CODAM before and after updating (removal of multiple reported incidents for flexible riser incidents).

Category	Type of incident	CODAM before update	CODAM after update	Difference	Difference (percentage)
Flexible riser	Damage incidents	43	32	11	~25,6%
	Leakage incidents	18	17	1	~5,6%
	Damage and leakage incidents	61	49	12	~20%
Static riser	Damage incidents	24	24	-	-
	Leakage incidents	3	3	-	-
	Damage and leakage incidents	27	27	-	-

The majority of removed risers were oil risers, as shown in the updated diagram (**Figure 64**, Appendix C): 9 oil risers were removed as well as 4 more from each category gas, oil/gas, injection and service.

The updated diagram (**Figure 64**) shows that incidents are predominantly linked to gas risers, whereas, before the removal of multi-reported incidents, oil riser incidents predominated (**Figure 61**). The new distribution of medium types for involved risers are as follows: 24 gas, 20 oil, 18 oil/gas, 9 injections, 3 water and 1 service. The majority of annual incidents related to oil risers occurred in 2011 with 4 incidents.

The highest number for incidents linked to gas risers occurred in 2006, with a total of 5 incidents; and the highest number of incidents for the majority of oil/gas risers occurred in 2015, with 3 incidents.

From 1975-1995, mostly oil/gas and gas risers were involved in registered incidents, with the exception of 1986 and 1988 where oil risers were involved. In addition, from 1996, risers with different mediums were involved, and more variation was observed (**Figure 64**). Additionally, outer sheath damage was assigned as a cause for 9 out of 17 flexible riser leaks, which is 53%, while 4 incidents were linked to carcass collapse, which is 23,5%. The remaining 4 flexible riser leak incidents were caused by wear, burst, overbending and design flaw. In addition, 3 leak incidents registered in 2006 and 2 in 2009 were caused by outer sheath damage.

4.2.2 Minor incidents reported in CODAM

In all, 153 incidents related to the riser body only were registered with minor severity in the CODAM database from 1980-2018 (**Figure 65, Appendix C**), but only139 incidents were counted because:

- In 1992: A specific incident was registered 7 times
- In 2000: A specific incident was registered 4 times
- In 2003: A specific incident was registered twice
- In 2012: A specific incident was registered 4 times

For 33 registered damage incidents in 1997, 32 of them were related to one field, linked to a specific riser and all were reported on the same date. A request was sent to PSA to validate these 32 incidents, and the response was that these events were related to different findings at different places on the riser. Therefore, it was decided to present them as they have been registered: different incidents. The case description shows that 5 out of 139 incidents were shown to be leak incidents, and the remaining 134 incidents were minor damage incidents. For 1980 up to 1998, the diagram presented in **Figure 22** shows the following:

- The highest annual incidents registration happened in 1987, 1986, and 1988 with 10, 9 and 8 incidents registered, respectively.
- By looking at riser type in the time interval 1980-1998 in **Figure 22**, all incidents were related to static risers, including two leak incidents.
- The damage incident trend started with 4 damage incidents in 1980 and then dropped to 2 incidents.
- The damage incident trend for static risers remains 4 in 1982 and 1983 before it increased to 60% in 1984.
- From 1984 onwards, the general trend showed a decrease until 1997. The next static riser incidents were registered in 2002 with one damage incident, and again in 2003, 2006 and 2007 with two damage incidents.
- For minor leak incidents linked to static risers, 2 incidents were registered in total one in 1987 and the other one in 1995.

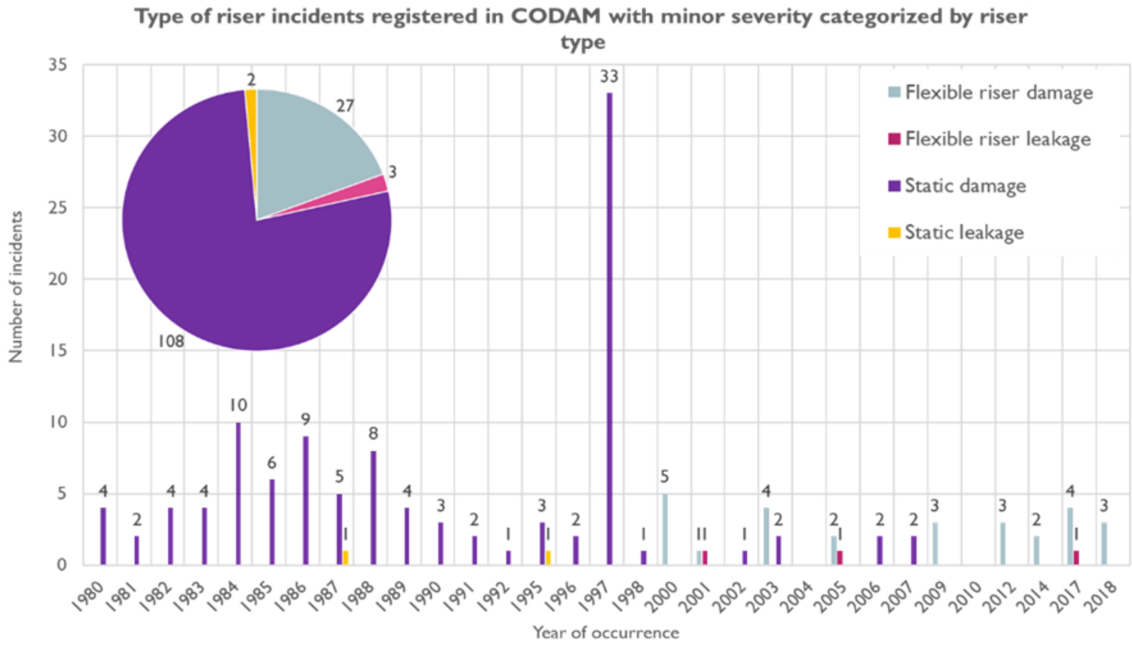


Figure 22 An overview of minor incidents registered in CODAM categorised by riser type.

In addition, **Figure 22** shows that no minor flexible damage or leakage incidents were registered before 2000. In total, 27 minor flexible riser damage incidents occurred where they were distributed within time interval 2000-20018. The yearly reported flexible riser damage incident in 2000 was 5 incidents; only 4 incidents occurred in 2003, and 2017; 3 incidents in

2009 and 2012; 2 incidents in 2005 and 2014; and one in 2001. Altogether, 3 minor leakage incidents linked to flexible risers were registered, once 2001, 2005, and 2017.

Additionally, the dimension category >16" dominate the registered incidents from 1980 up to 1996 (**Figure 66**, **Appendix C**); but the dimension category ≤16" dominates from 1997 up to 2018, which seems to be related to riser type distribution. In all, 78 minor incidents were registered in the ≤16" category and 62 in the >16" dimension category.

From 2000 up to 2018, only 6 of the registered incidents were in the >16" dimension category, where 1 was registered in each year of 1998, 2002, and 2006; while 3 of them were registered in 2003. The rest were in the ≤16" category, where 5 incidents were registered in both 2000 and 2017, and 3 incidents were registered in 2003, 2005, 2009, and 2018. Also, 2 incidents for the same category ≤16" were registered in 2001, 2007, and 2014; while 1 incident was registered in 2006 (**Figure 66**, **Appendix C**).

Moreover, the medium type distributions show that 45 of reported minor incidents were linked to gas, 36 to water (including the 32 reported incidents in 1997), 23 to gas risers, 22 to oil/gas risers and 5 to injection risers. Also, for the time interval 1980-1998, the majority of registered incidents were related to gas risers with the exception of 1997, where 32 events were related to a water riser. From 2000 up to 2018, a variation in medium type was noticed.

4.3 Equinor database, Synergi

In total, 43 incidents were found from 1992-2015 with different types of registered lose potential (**Figure 67, Appendix C**). 25 out of 43 incidents are damage incidents, and remaining18 are leakage incidents. The first damage incident was registered in 1992, and the first leakage incident was registered in 2000 (**Figure 23**).

Figure 23 shows that from 1992 to 1999, only damage incidents were registered with 1 incident a year in 1992 and 1993; and 2 for 1999. In 2000, two damage incidents were registered beside one leakage incident; while in 2001, eight incidents were registered in total: 4 leakage and 4 damage incidents. The number of damage incidents decreased to 2 incidents in 2002 and kept decreasing in 2003, where only 1 damage incident was registered. Almost no incidents were registered in 2005 while 3 damage incidents were reported in 2006. In 2010, 2011, and 2014 one damage incident was registered for each year, 2 in 2012 and 3 in 2015.

On the other hand, leakage incidents were reduced to 3 incidents in 2002, 2 in 2010, 1 in 2003 and 2005 before it increased to 4 incidents in 2011 and reduced again to 2 in 2012. Almost no incident in 2014 and 2015. By looking further into riser type for selected incidents, it shows that 23 damage incidents are linked to flexible risers while only 2 are linked to static risers (**Figure 23**); while, all of the registered leakage incidents are linked to flexible risers. The static riser damage incidents occurred in 1993 and 2001 with one incident each year. Additionally, the highest number of leakage incidents occurred in 2011, 2001, and 2002 with 6, 4, and 3 incidents, respectively. Also, 1 leakage incident was registered for each year: 2000, 2003, and 2005. 12 of the registered incidents were not assigned a type of medium, 19 were linked to oil riser, 9 to gas risers, 2 to water and 1 to an injection riser.

In addition, the cause of damage for four damage incidents in 2001 is attributed to the collision, where one incident occurred during the installation of the riser when it moved out of position and collided with a neighbouring riser. Besides this, one ship collision and one damage incident caused by collision with a trace crane were reported.

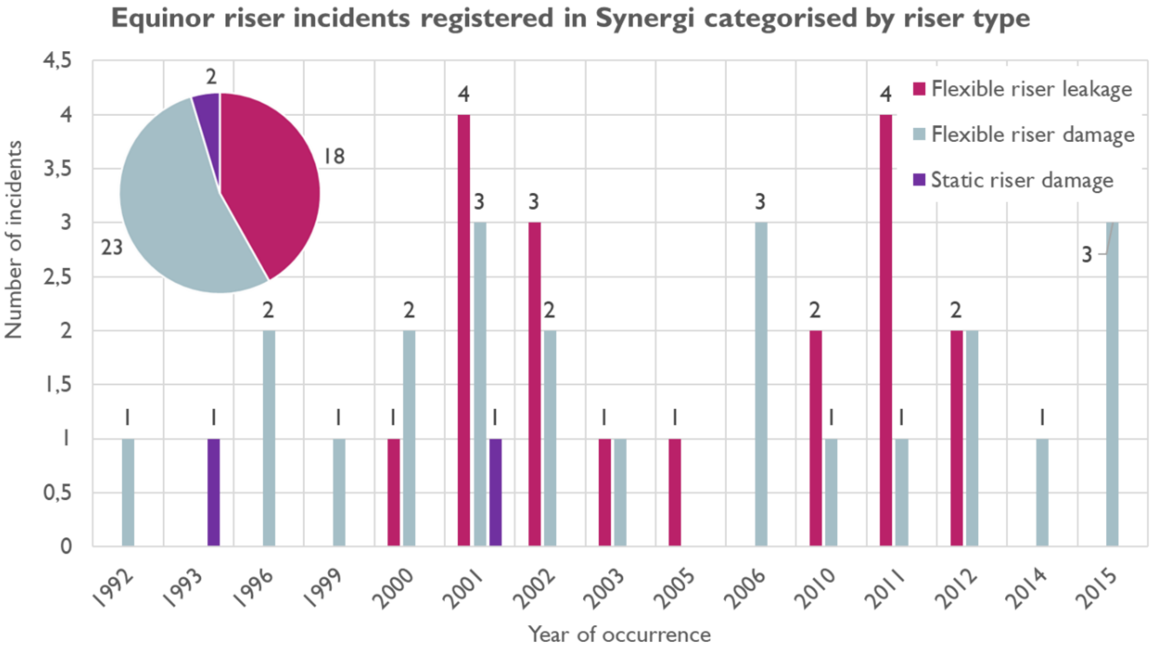


Figure 23 A diagram of selected damage and leakage incidents from Synergi database, Equinor categorised by a riser.

The loss potential classification varies among selected incidents in Synergi, where16 incidents were classified as red: 7 of them were leakages, and 9 of them represent damage incidents, all of them related to flexible risers (**Figure 24**). Moreover, 11 events are classified as yellow including 5 leakages and 6 damages (9 flexible risers and 2 static risers), and 16 events are classified as green including 6 leakages and 10 damages (all of them are flexible risers). Of 16 red registered events in the Synergi, 6 events were classified as reported to PSA, but in fact 8 of them were reported where 6 were classified as major and 2 as minor in CODAM. Also, 4 of the 11 yellow registered events supposed to be reported to PSA, 3 of them were registered in CODAM and were classified as major. For the events registered as green, 13 were registered as not reported to PSA, and for the remaining 3 the checkbox for authority notification was not included, 4 of them were found in CODAM and were classified as major.

Figure 25 illustrates the difference and similarities between:

- Reported incidents in CODAM considering incidents from Equinor.
- Reported incidents in Equinor's system
    - Reported incidents which are marked as reported to PSA
    - Reported incidents which are marked as not reported to PSA

Where the term *correlated* refers to incidents seen in CODAM and *not correlated* refers to the incidents not seen in CODAM.

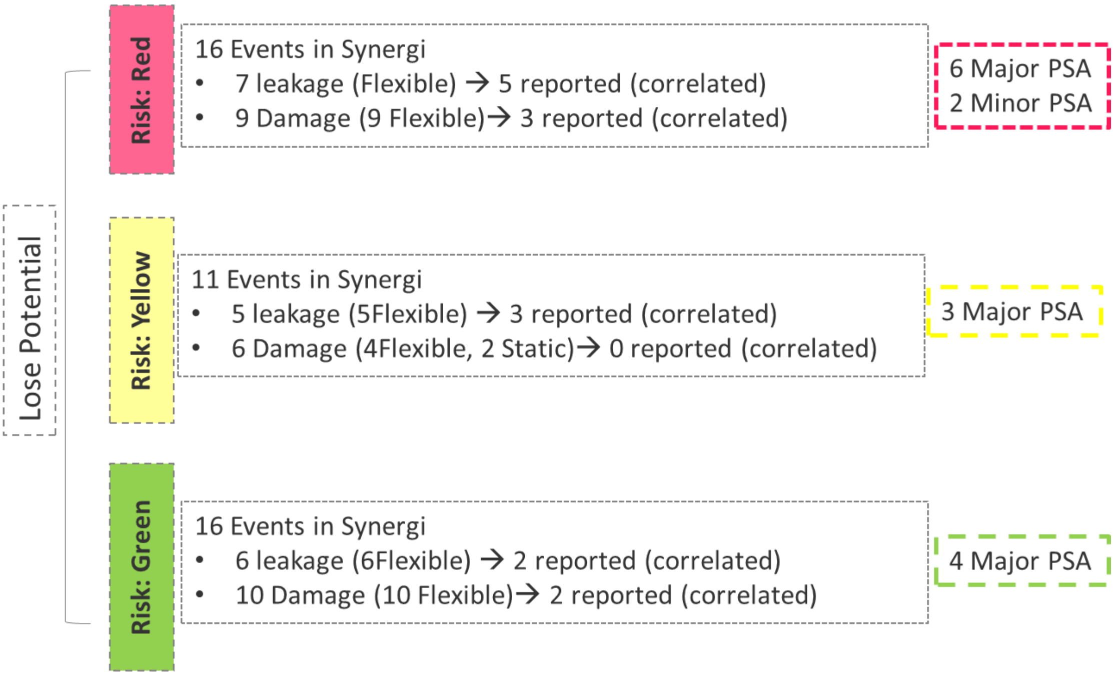


Figure 24 Result of analysis of reported events registered intern in Synergi Life, Equinor

The comparison shows that 55,6% of registered **leakage** incidents with reported status to PSA are correlated, while 16,6 are not correlated. For the **damage** incidents, only 20% are correlated, and 8% not correlated.

This revealed that by looking only at the reporting to PSA status in Synergi, the under-reporting percentage should be **27,8%** for leakage incidents and **72%** for damage incidents. By comparing and verifying the reported incidents with CODAM, the underreporting seems to be **44,4%** for leakage incidents and **80%** for damage incidents.

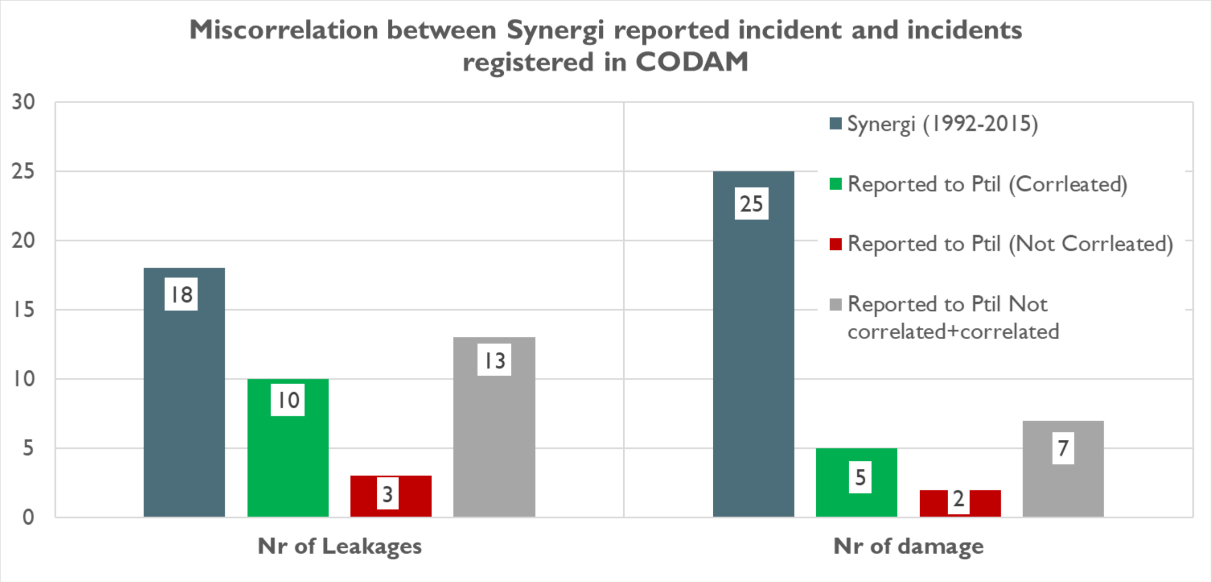


Figure 25 An overview of comparison between reported incidents in Synergi and CODAM, the term correlated refers that those incidents have been seen in CODAM and Not correlated refers to the incidents that have not been seen in CODAM.

4.4 Combination of Equinor reported incidents in CODAM and Synergi

A new analysis was carried out by combining missing incidents from Synergi into major incidents reported by Equinor only to CODAM. This was done to evaluate how the difference between reported incidents by Equinor to CODAM and incidents registered in Synergi might impact the result of frequency estimation. Thus, the type of lose potential was not considered, e.g. all missed reports were added as long as the case description matched with definitions of damage and leak used in the thesis. The result of the combination is presented in the following subsection.

The combination shows different distribution patterns and numbers of both leakage and damage incidents from 1988-2016, as shown in **Figure 68 (Appendix C)**. **Figure 26** shows that the number of leakage incidents became 28 instead of 18 only from Synergi, while the number of damage incidents became 54 instead of 25. By comparing the combination of incidents registered in Synergi and CODAM and incidents registered in Synergi only (**Figure 26**), the following was noticed:

- One leakage incident was added in 1988, 1997, 2001, 2007, and 2013.
- Two leakage incidents were added in 2009, while 4 leakage incidents were added to 2006.
- 2 flexible riser incidents in 2011 correlated with two leakage incidents registered in 2010 in Synergi, where they have been reported afterwards.

Correspondingly, for damage incidents, in total 29 incidents were added, where 3 incidents were added in each year for 2015, 2010 and 2018. Also, 2 damage incidents were added into 1995, 1998, 2009, 2011, and 2012; while 1 incident was added into the following years: 1999, 2000, 2002, 2005, 2006, 2007, 2013, 2014, and 2016.

Most added damage incidents are related to flexible risers, and 27 events were added, as shown in **Figure 26**. As well, 9 leakage incidents were added to the flexible riser leakage incident category, 1 to the static riser leakage incident category and 2 to the static damage incident category.

By looking at flexible riser leakage incidents in **Figure 26**, most of these incidents are distributed between 2000 and 2013, with the exception of 1 incident in 1997. The combined incident sources show that the highest number of annual flexible riser damage incidents was registered in 2015 with 7 incidents instead of 2004 with 4 incidents, as concluded with only data from Synergi.

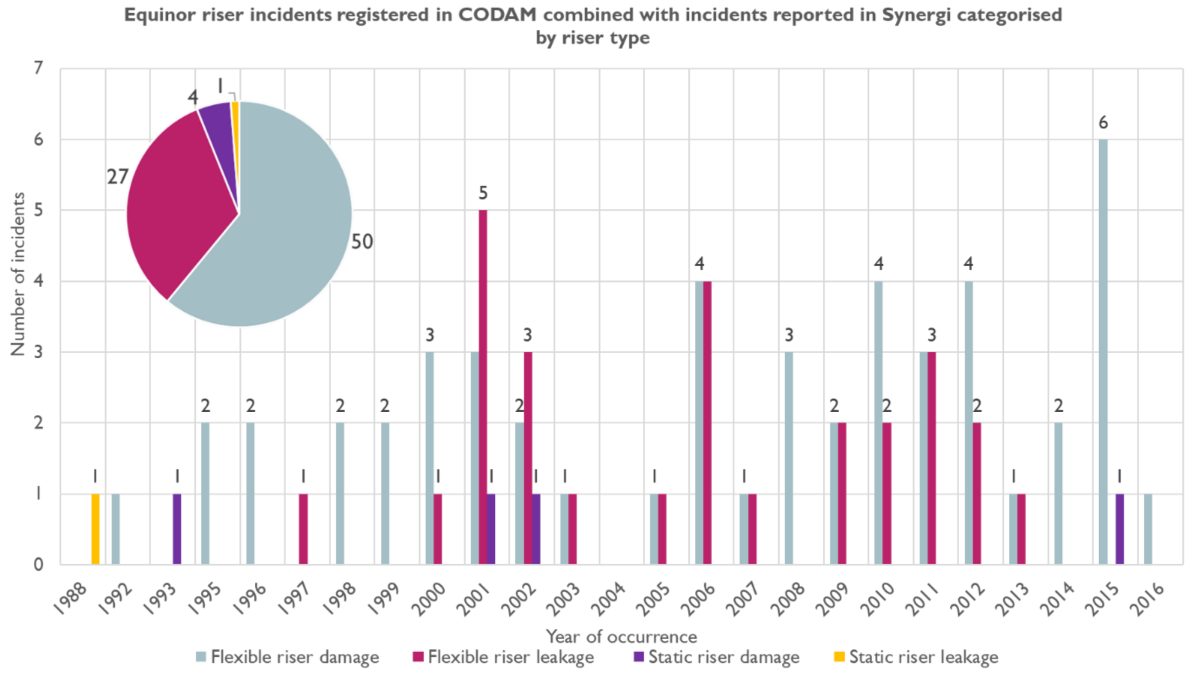


Figure 26 An overview of leakage and damage incidents after adding the missing reports from Equinor to major incidents in CODAM

In addition, 4 flexible riser leakage incidents were added to 2003 and 2 to 2009, while 3 flexible riser damage incidents were added to 2010.

For static riser damage incidents, one damage incident was added for each year, 2002 and 2015, and one leakage incident for a static riser was added in 1988. For the remaining flexible riser damage incidents: 3 incidents were added to 2008, 2 incidents were added to each year in 1995, 1998, 2009, 2010, 2011, and 2012; and 1 incident was added to 1999, 2000, 2005, 2006, 2007, 2013, 2014, and 2016 (**Figure 26**).

4.5 Combination of Equinor reported incidents in Synergi and CODAM for all operators

To get the correct number of leakage and damage incidents that have occurred on the NCS, uncorrelated reported incidents in Synergi were merged with reported incidents by all operators in CODAM where major severity was indicated. The combination resulted in 71 damage and 31 leakage incidents from 1975-2016 (**Figure 27**), where the highest annual damage incident was observed in 1996, 2012 and 2015 with 4, 4, and 7 incidents, respectively. The highest number of leakage incidents were registered in 2002, 2006, and 2011 with 4 incidents each.

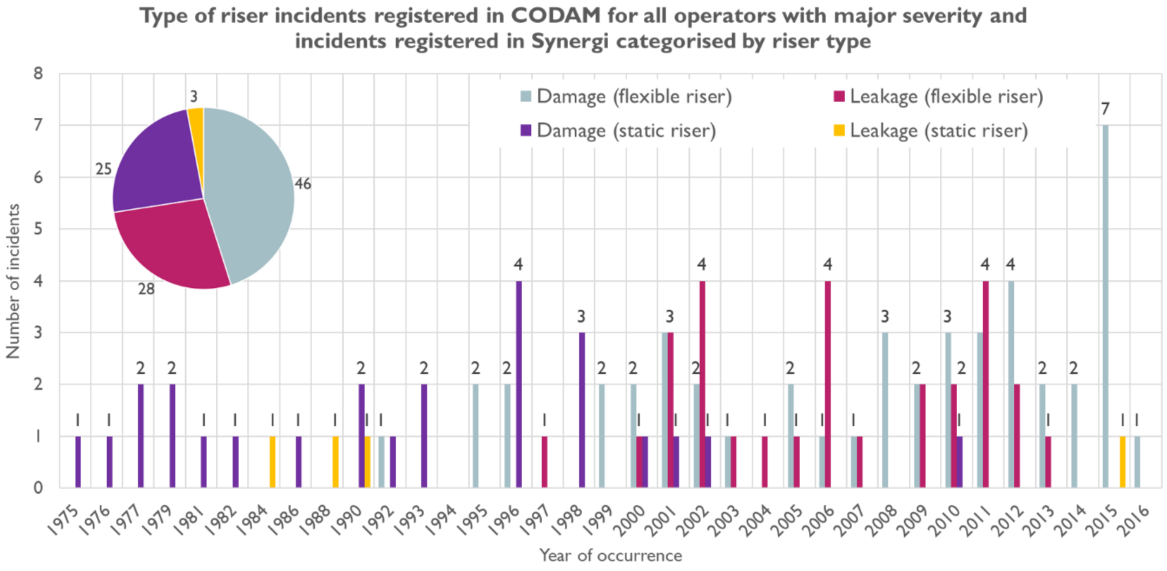


Figure 27 An overview of registered riser leakage and damage incidents with major severity in CODAM (all operators)combined with missing incidents from Equinor, Synergi categorised by riser type.

By looking at riser type distribution, the number of leakage incidents for static risers remained the same compared to incidents registered in CODAM without missing data from Equinor, while the number of damage incidents increased by one.

Moreover, the number of flexible riser leakage incidents increased by 11, and the number of damage incidents increased by 14. As shown in **Figure 27**, only in 2001 were 3 flexible riser damage, 2 leakage incidents and 1 static riser damage added. In 2003, 2 incidents linked to flexible risers were added, one leakage and one damage where no incidents were registered previously in CODAM.

In 2010, 2 flexible and 1 static damage incidents were registered in CODAM; after adding the missing data the total number became 3 flexible and 1 static damage incidents, and 2 leakage incidents linked to a flexible riser. Two flexible damage incidents were added to 2015, giving 7 incidents in total.

4.6 Damage and leakage frequencies

In this subsection, different results of incidents found in the various database will be combined with calculated riser year from population data (SISU) to see how the difference in the database used might impact the result.

4.6.1 Major incidents reported in CODAM

To understand the relationship between the annual riser year of risers and the number of incidents, a diagram of the number of incidents vs annually riser year was produced, for both damage and leakage incidents for flexible risers (**Figure 28**). The start time interval chosen was 1995 since flexible riser incidents were structured in CODAM from 1995 onwards [40].

The annual riser year was calculated from the SISU database, where the date for decommissioned and removed risers was taken into consideration together with information provided from PSA. In total, 2 damage incidents occurred in 1995 associated with 43 riser year, and 1 leakage incident occurred in 1997 associated with 134 riser year (**Figure 28**).

Moreover, one annual damage incident was registered for 1999, 2000, 2006, 2007, and 2016, where the riser year was 286, 433, 1616, 1854, and 3909, respectively. The number of damage incidents doubled in 2002 compared to 1999 and 2000; whereas, the riser year is 750, more than double that of 1999 and almost 73% higher than in 2000.

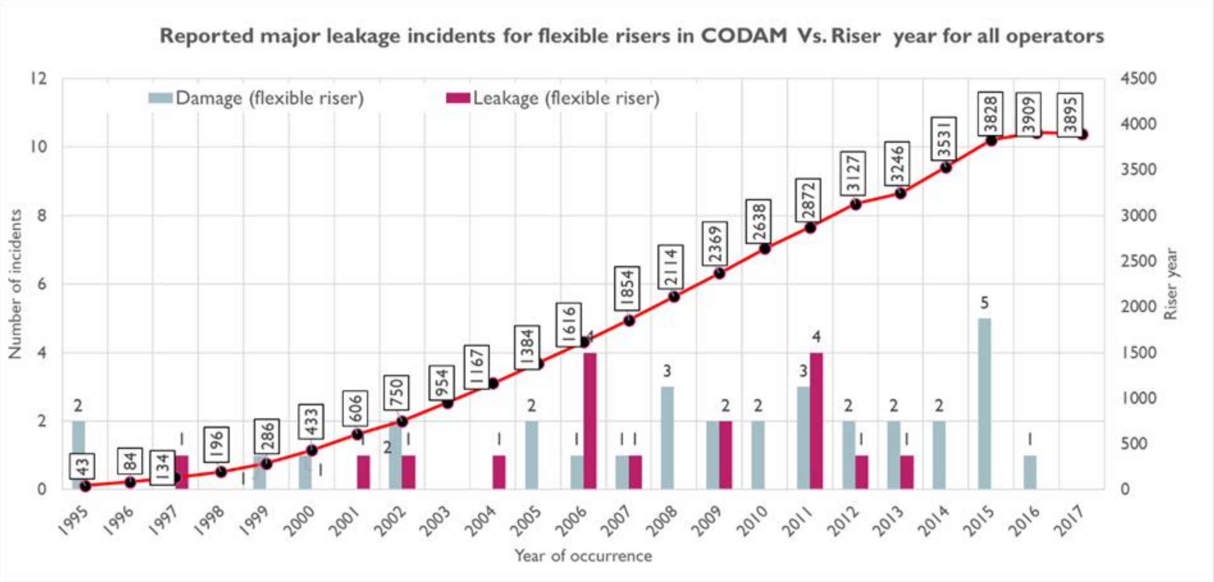


Figure 28 A diagram showing the relationship between calculated riser year from SISU and annual flexible riser damage and leak incidents with major severity, registered in CODAM.

The number of leakage incidents remained the same in 2001, 2002, 2004, 2007 and 2013 with riser year 606, 750, 1167, 1854, and 3246, respectively. The highest number of annual leakage incidents was in 2006 and 2011, with 4 incidents and a riser year of 1616, and 2872, correspondingly. The highest yearly damage incidents were in 2015, 2008, and 2011, where the riser year was 3828, 2114 and 2872, respectively. The annual leak and damage frequency for flexible risers are presented in **Figure 29**:

- The highest annual damage frequency was in 1995, which is $4{,}65\text{x}10^{-2}$.
- The lowest damage frequency is $2{,}56\text{x}10^{-4}$ in 2016, with very close values for 2007 and 2014 of $5{,}39\text{x}10^{-4}$ and $5{,}66\text{x}10^{-4}$, respectively.
- Similar damage frequency values were noticed for 2013, 2006, and 2012 with $6{,}16\text{x}10^{-4}$, $6{,}19\text{x}10^{-4}$, and $6{,}40\text{x}10^{-4}$, respectively.
- The annual damage frequency was high in 1999, 2002, 2000 with values of $3{,}5\text{x}10^{-3}$, $2{,}67\text{x}10^{-3}$, $2{,}31\text{x}10^{-3}$. Similarity in annually damage frequency was shown in 2005, 2008, and 2015 with values of $1{,}45\text{x}10^{-3}$, $1{,}42\text{x}10^{-3}$, and $1{,}31\text{x}10^{-3}$; while it was $1{,}04\text{x}10^{-3}$ for 2011.
- The highest annual leak frequency for flexible risers was recorded in 1997 at $7{,}46\text{x}10^{-3,}$ followed by 2006 with $2{,}48\text{x}10^{-3}$.
- Further, the lowest annual leak frequency was in 2013, and 2012 with $3{,}08\text{x}10^{-4}$ and $3{,}20\text{x}10^{-4}$, respectively.
- The leak frequency for 2002, 2011 and 2001 were quite similar to values of $1{,}33\text{x}10^{-3}$, $1{,}39\text{x}10^{-3}$, and $1{,}65\text{x}10^{-3}$.
- Leak frequency for 2004 and 2009 were quite similar as well, with corresponding values of $8{,}57\text{x}10^{-4}$ and $8{,}44\text{x}10^{-4}$.

There is a significant variation in the estimated annual frequencies as they are estimated over short time intervals, which can lead to a high degree of uncertainty. Besides, there is uncertainty about the date of occurrence as mentioned before. Therefore, they should be used with caution An equivalent diagram was produced for damage and leakage incidents recorded for static risers in CODAM with major severity (**Figure 30**) for the time interval 1995-2017. In 1996, 4 damage incidents occurred: 2 were linked to ≤16" where the corresponding riser year was 1077, and 2 linked to >16" where the riser year was 781. No incidents were registered in 1997.

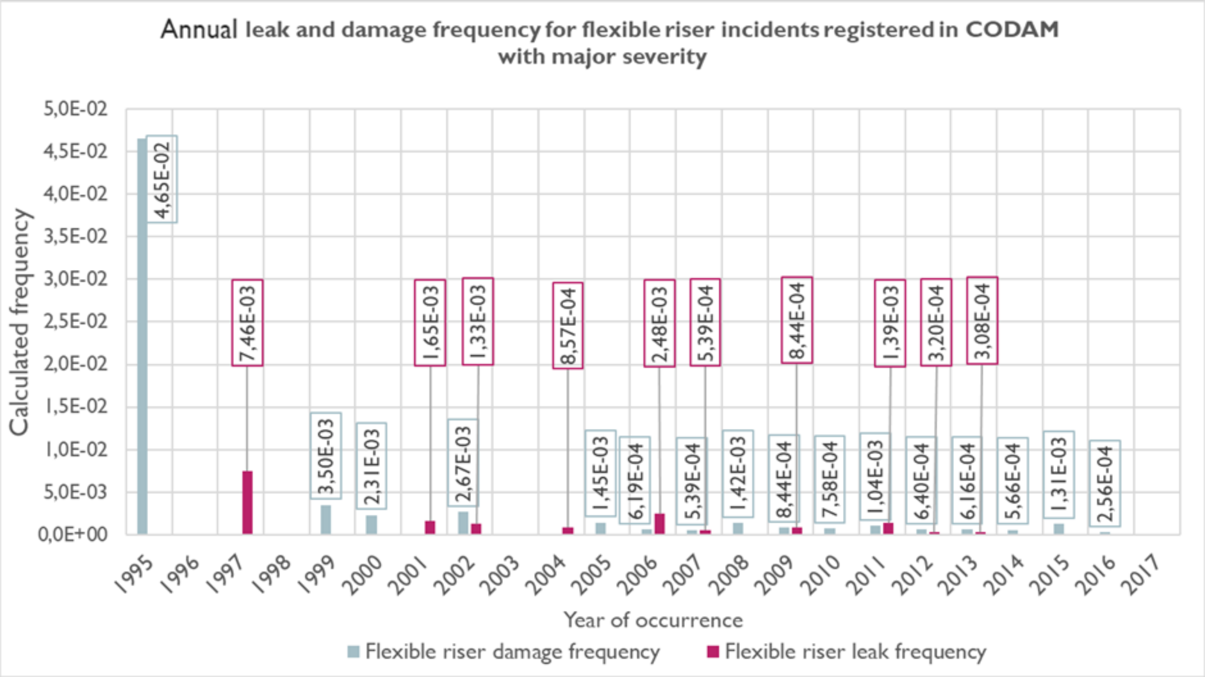


Figure 29 Annual leakage and damage frequency for flexible riser incidents registered in CODAM with major severity.

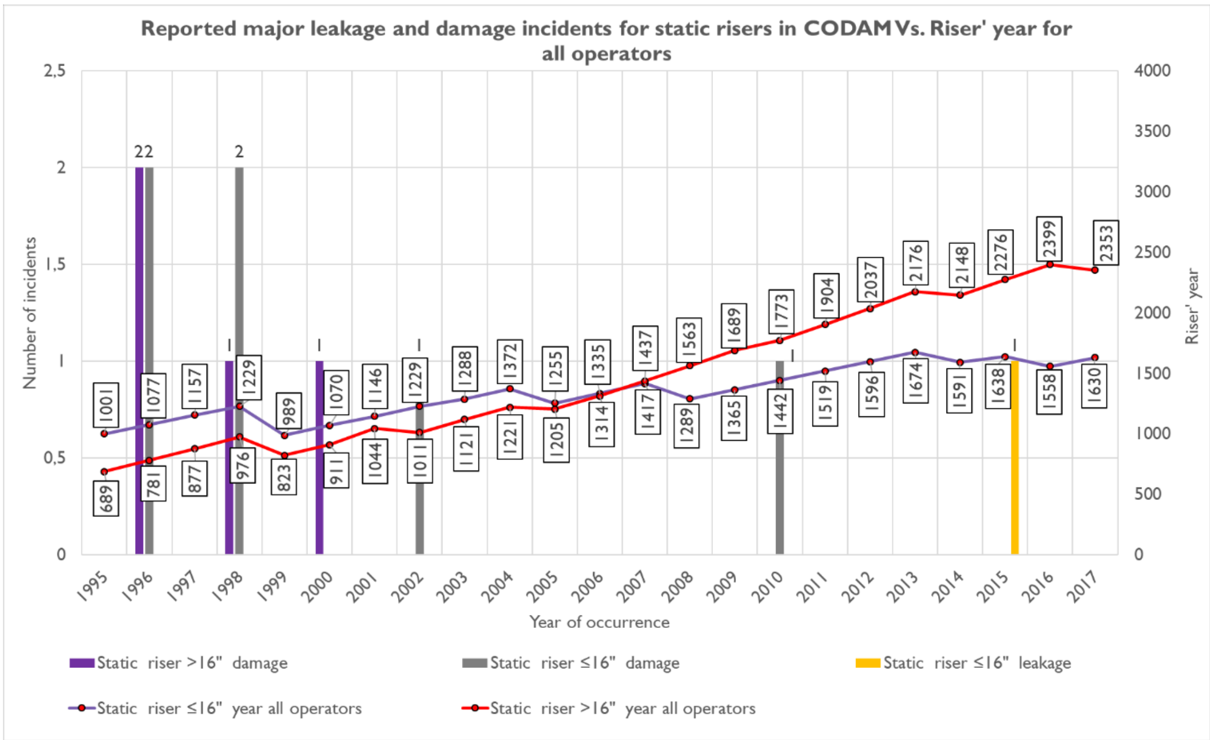


Figure 30 The relationship between the calculated riser year from SISU and annual static riser damage and leakage incidents with major severity registered in CODAM.

In 1998, 3 damage incidents occurred: 2 incidents in ≤16" category where the riser year was 1229 and one within >16" where the riser year was 976. Again, no incidents were registered in the following year, 1999. In 2000, one damage incident within >16" happened where the riser year was 911, followed by no registered incidents in 2001 and one registered incident in 2002 linked to ≤16" where the corresponding riser year was 1229. Moreover, no incidents were registered in the period from 2003-2009, and only one incident was registered in 2010 related to ≤16" where the corresponding riser year was 1773 year. No incidents were recorded from 2011 until 2015 when the first recorded leakage incident was linked to a ≤16" category where the riser year was 1638. Annual damage and leakage frequencies were calculated based on data from **Figure 30**, and the following was addressed:

- The highest damage frequency was calculated to be in 1996 for the > 16" category with a value of 2,56x10^{-3} and 1,56x10^{-3} for the ≤16" category (**Figure 31)**.
- For 1998, the annual damage frequency for static risers within the ≤16" category was 1,63x10^{-3} and 1,02x10^{-3} for the > 16" category.
- The yearly damage frequency for static riser within ≤16" category in 2010 was 6,93x10^{-4}.
- The yearly damage frequency for the > 16" category in 2000 was 1,1x10^{-3}.
- The leakage frequency for only one registered leakage incident in the period 1995-2017 is 6,11x10^{-4}, which occurred in 2015 and is linked to ≤16" category (**Figure 31**).

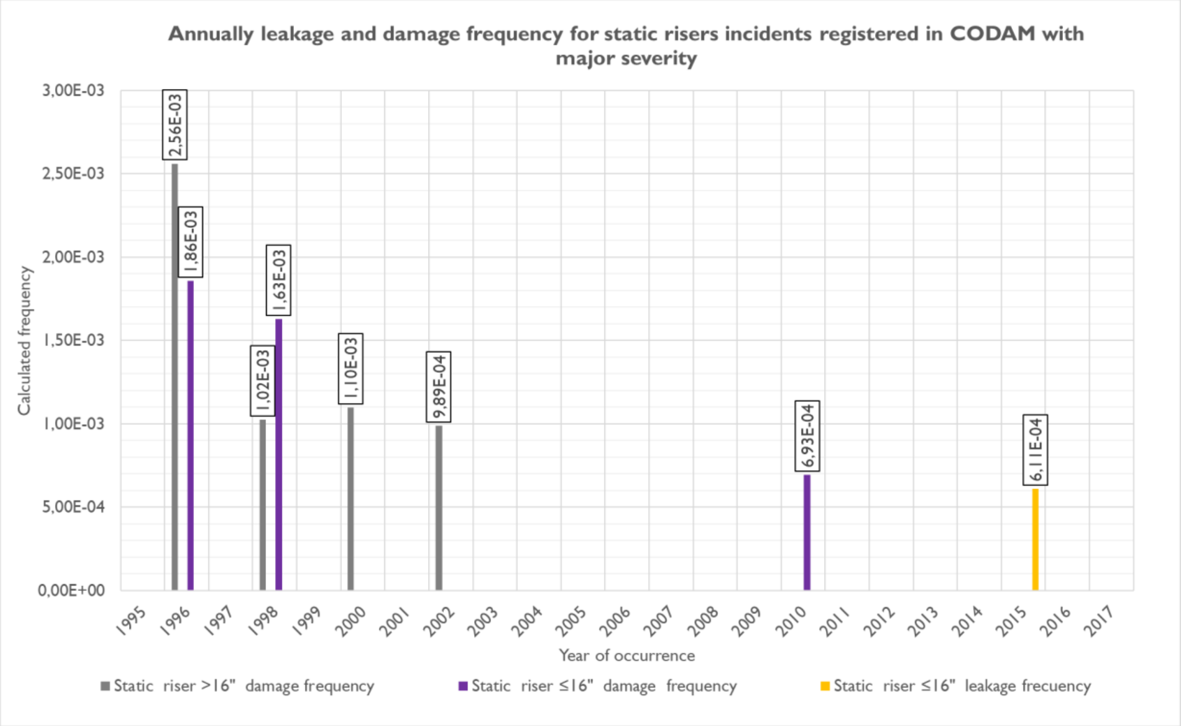


Figure 31 Annual leakage and damage frequency for static riser incidents registered in CODAM with major severity.

4.6.2 Combination of Equinor reported incidents in CODAM and Synergi

A graph of riser year for only registered Equinor flexible risers vs. number of incidents for both leakage and damage incidents, which were reported by Equinor are presented in **Figure 32,** and it shows:

- Two flexible riser damage incidents occurred, one a year in 1995 and 1996 where the riser year was 25 and 55, respectively; while, in 1997 one leakage incident occurred where the riser year was 92.
- In 1998 and 1999 two damage incidents occurred in each year where riser year was 125 and 182.
- The riser year was 1972, 408, and 1132 when the highest number of flexible riser leakage incidents were registered with 6, 5, and 4, respectively.
- The highest number of damage incidents of flexible risers were registered in 2015, 2012, 2006 correspond with riser years 2664, 2129, 1827, and 1132, respectively.
- In 2001, 5 leakage incidents occurred where the riser year was 408, followed by 3 leakage incidents the year after where the riser year was 521.
- The number of leakage incidents dropped to only 1 incident in 2003 and 2005 before it increased to 4 incidents in 2006, where riser year was 1132.
- In 2007 one leakage incident occurred where the riser year was 1292, followed by 2 leakage incidents in 2009 where the riser year was 1647.

Additionally, the annual damage and leakage frequencies for flexible riser incidents for combined Equinor incidents from Synergi and CODAM, with major severity, were calculated from **Figure 32** and are presented in **Figure 33**. There is a significant variation in the estimated annual frequencies as they are estimated over short time intervals, which can lead to a high degree of uncertainty and should be used with caution. The following was noticed:

- The annual damage frequencies for 1995 and 1996 are relatively high compared to the rest as the riser year values were registered to be 25 and 55, respectively.
- The annual damage frequency trend shows a decrease in 1998, 1999, and 2000 and a continued decrease is observed in 2001, 2002, and 2003 until 2004 as no incidents were registered.

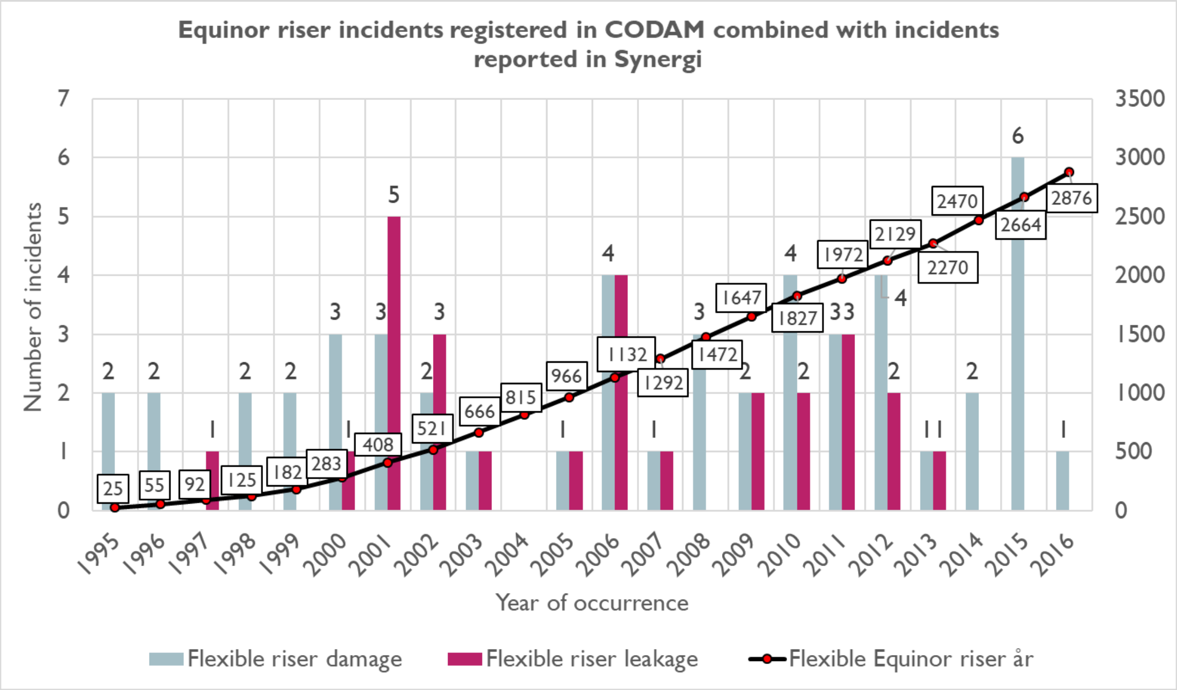


Figure 32 An overview of Equinor's flexible riser incidents from Synergi combined with missing incidents from CODAM (Major Equinor only) together with riser year for flexible risers operated by Equinor.

- The annual damage frequency was $1,04 \times 10^{-3}$ in 2005 and increased significantly in 2006 to $3,53 \times 10^{-3}$ before it dropped again in 2007 to $7,74 \times 10^{-4}$ and increased again in 2008 to $2,04 \times 10^{-3}$.
- The damage frequency trend shows a decrease from 2008 to 2009, where the annual frequency was $1,21 \times 10^{-3}$ in 2009 and increased again in 2010 to $2,19 \times 10^{-3}$.
- The reduction in annual damage frequency was observed up until 2016, with the exception of 2015, where the value was $2,25 \times 10^{-3}$ where 6 damage incidents were reported.
- For the annual leakage frequency, the first value is assigned to 1997 with $1,09 \times 10^{-2}$, followed by no registered incidents until 2000, where the annual leakage frequency was $3,35 \times 10^{-3}$.
- The highest annual leakage frequency was registered in 2001 with $1,23 \times 10^{-2}$; it then dropped to $5,76 \times 10^{-3}$ and was dramatically reduced in 2003 with $1,50 \times 10^{-3}$, zero in 2004, and $1,04 \times 10^{-3}$ in 2005.

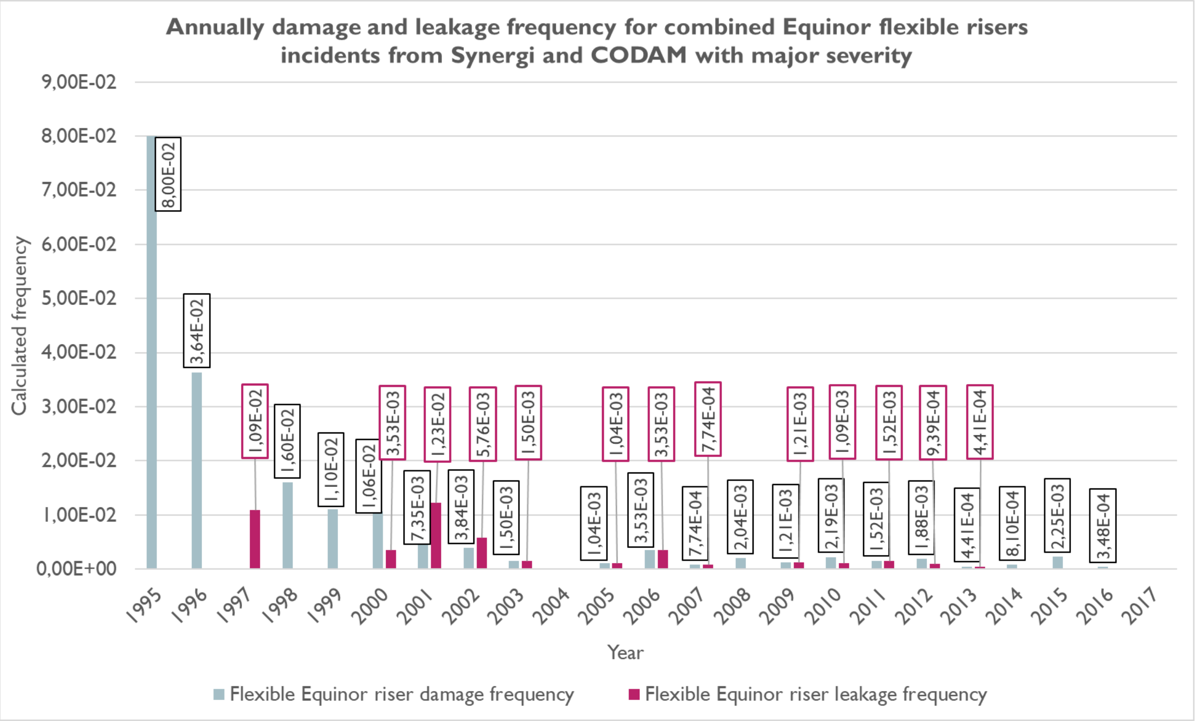


Figure 33 A diagram is showing annual damage and leakage frequency for Equinor flexible riser incidents registered in CODAM with major severity, combined with reported incidents by Equinor in CODAM.

The same type of graphs (annual damage and leakage frequency) were produced for static riser incidents as well, for **Figure 34** and **Figure 35**, the following was noticed:

- The riser year for two registered damage incidents for static risers within the ≤16" category in 2002 and 2015 was 617 and 1412, respectively.
- The riser year for the only recorded damage incident linked to the >16" category in 2001 is 731.
- The calculated annual damage frequency based on data from **Figure 34** is $1,62 \times 10^{-3}$ and $7,08 \times 10^{-4}$ for damage incidents within the ≤16" category in 2002 and 2015.
- The estimated yearly damage frequency is $1,37 \times 10^{-3}$ for damage incidents in 2000, which is linked to the >16" category.

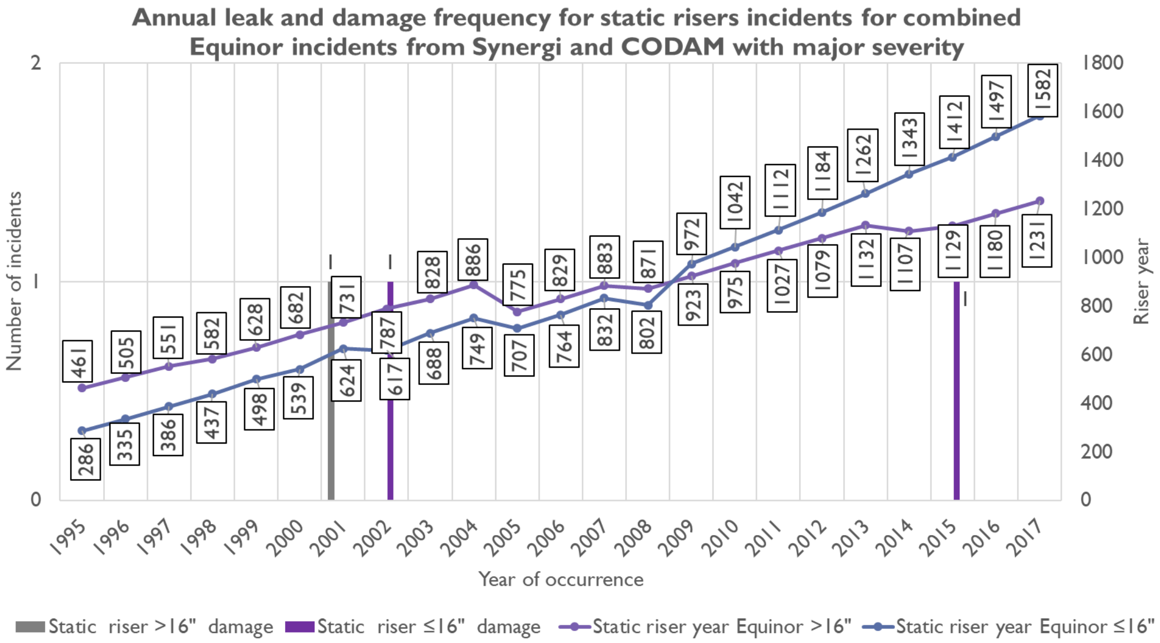


Figure 34 A diagram is showing the relationship between the calculated riser year from SISU and annual static riser damage incidents for combined Equinor riser incidents from Synergi and CODAM with major severity.

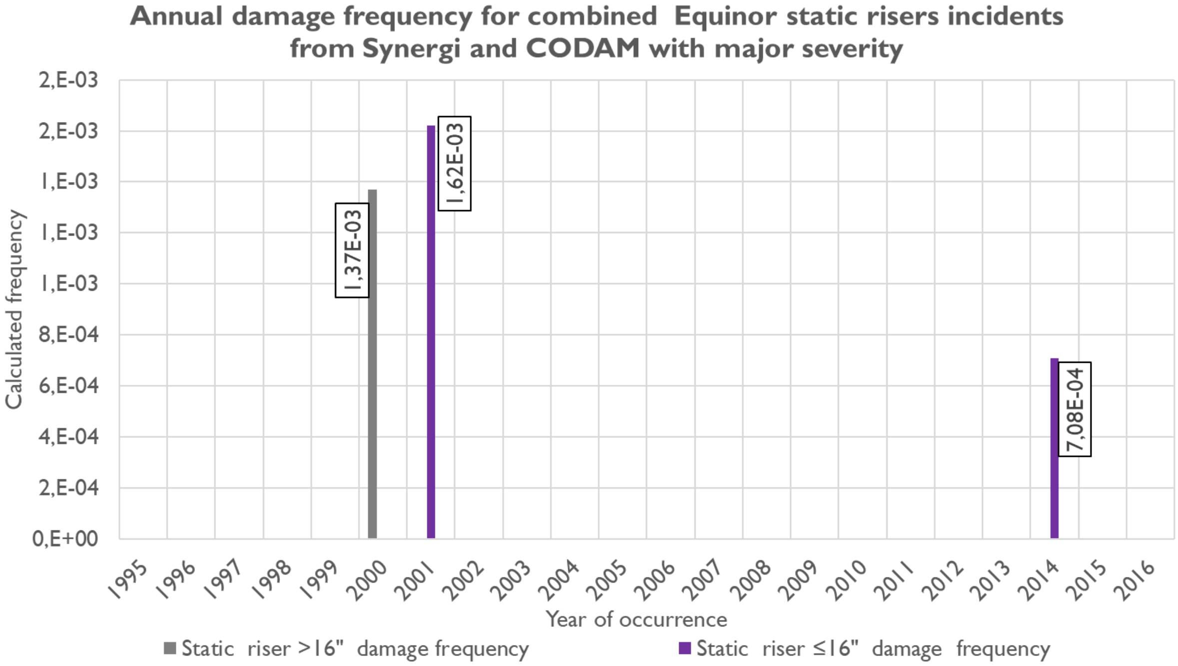


Figure 35 Annual damage frequency for Equinor static riser incidents registered in CODAM with major severity combined with reported incidents by Equinor in CODAM with major severity.

4.6.3 Combination of Equinor’s reported incidents in Synergi and CODAM (all operators)

A new graph was produced of flexible riser incidents for flexible risers operated by all operators, including missing incidents from Equinor vs. calculated flexible riser year for all operators (**Figure 36**). **Figure 36** shows the following:

- In 1995 and 1996, two damage incidents occurred where the riser year was 43 and 84, respectively.
- One leakage incident occurred in 1997 where the riser year was 134.
- Two damage incidents occurred in each year 1999 and 2000, and one leakage incident in 2000, where the riser year was 286 in 1999 and 433 in 2000.
- In 2001, 3 leakage and 3 damage incidents were registered where the riser year was 606. The number of damage incidents decreased by one in 2002.
- The leakage incidents increased by one where the riser year was 750. In 2003, two incidents were registered, 1 leakage and 1 damage incident where the riser year was 954.
- In 2004, no damage incident was registered, and only one leakage incident was registered; the riser year was 18,25% higher than in 2003
- In 2005, 2 damage incidents and 1 leakage incident were registered, and the riser year was ~220 % higher than 2000, where similar types of incidents occurred.
- The number of leakage incidents increased in 2006 to 4 incidents where the riser year was 1616, which is 115,5% higher than what it was in 2002, where the same number of leakage incidents occurred.
- The number of damage incidents increased to 3 in 2008 where the riser year was 2114, which is 249% higher than in 2001, where the same number of damage incidents occurred.
- The same number of damage incidents is registered in 2010 and 2011 where the riser year was 2638 and 2872, compared to 606 in 2001 and 2114 in 2008.

It was decided to further emphasise the calculation of the leakage and damage frequencies for the time interval 2000 and onwards. This will be explained and discussed afterwards.

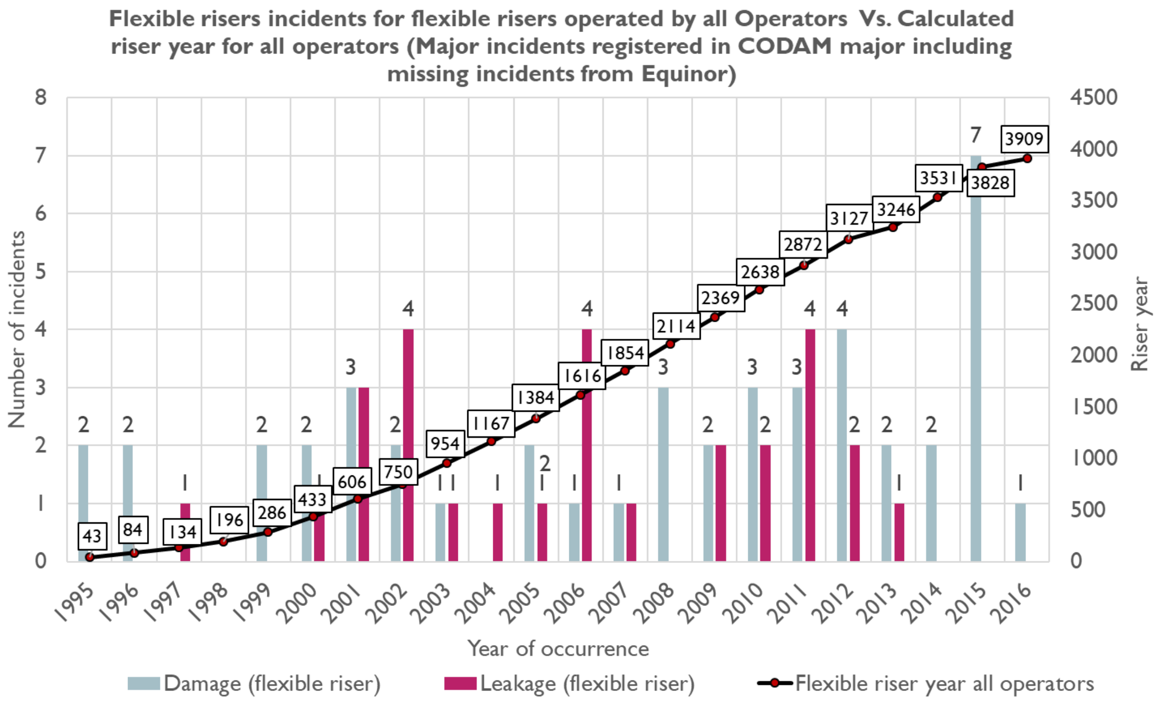


Figure 36 A diagram of flexible riser incidents for risers operated by all operators and calculated riser year for all operators, including missing incidents from Equinor.

The annual damage and leakage frequencies for flexible risers based on input from **Figure 36** were calculated and presented in **Figure 37** for the time interval 2000 and onwards. The main aim was to examine if there is any trend or difference in the time interval 2000-2016. The results of the annual frequency for damage and leakage in **Figure 37** shows the following:

- The highest annual damage frequency is represented by 2000, 2001, 2002, and 2015, where the annual damage frequency is 4,62x10^{-3}, 4,95x10^{-3}, 2,67x10^{-3} and 1,83x10^{-3}, respectively.
- In 2004, no annual damage frequency was registered as no incidents were recorded. For 2005, 2008, and 2012, the yearly damage frequency shows a relatively similar trend for 2003, 2010, and 2011.
- The annual damage frequency is almost the same for 2006 and 2013, while in 2007 and 2014 yearly damage frequency shows similarity as well.
- Further, the annual damage frequency for 2009 was the same as the leakage frequency in the same year, 8,44x10^{-4}; and, the lowest annual damage frequency is recorded in 2016 with 2,56x10^{-4}.
- For the yearly leakage frequency, the highest value is recorded in 2002, 2001, 2006 and 2000 with values of 5.33x10^{-3}, 4,95x10^{-3}, 2,48x10^{-3} and 2,31x10^{-3}, respectively.

- The annual leakage frequency dropped significantly in 2003, 2004, and 2005 and increased substantially in 2006; it decreased again in 2007, followed by no recorded leakage incident in 2008.
- The yearly leakage frequency in 2009 was 8,44x10^{-4} and decreased to 7,58x10^{-4} the following year in 2010
- The yearly leakage frequency increased to 1,39x10^{-3} in 2011 before it continued decreasing in 2012 and 2013 to 6,40x10^{-3} and 3,08x10^{-4}, respectively.
- No leakage frequency was recorded for 2014, 2015 and 2016.

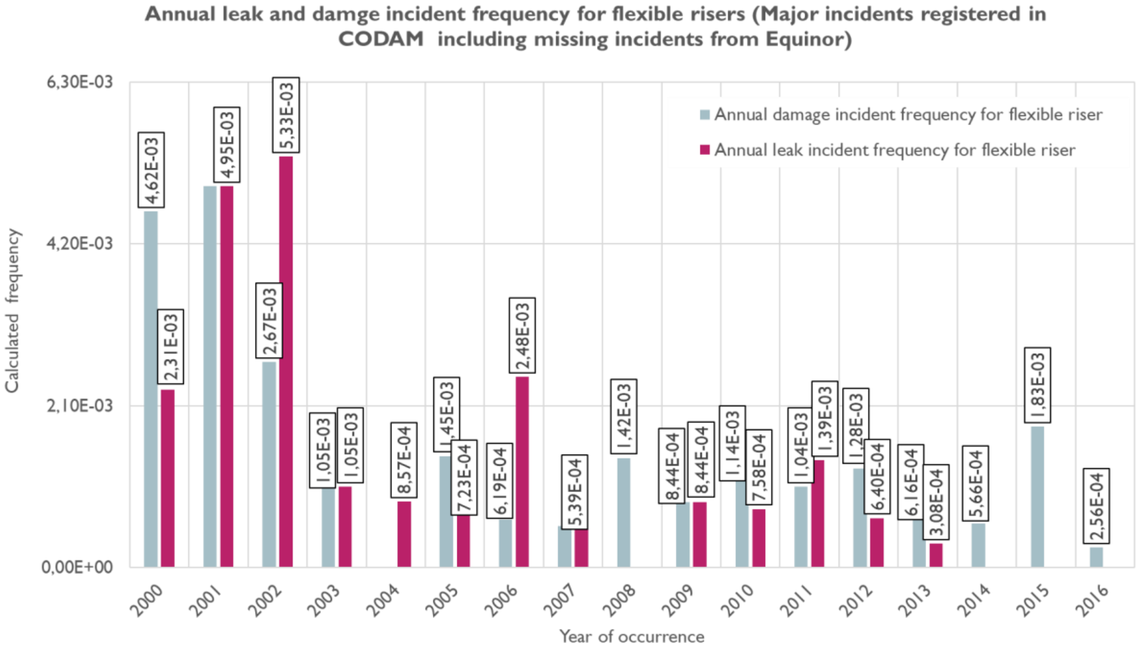


Figure 37 An overview of annual flexible damage and leakage frequencies based on damage and leakage incidents registered in CODAM with major severity and missing incidents from Equinor

Additionally, a graph was produced (**Figure 38**) for annual static riser leakage and damage incidents for all operators including missing incidents from Equinor vs. calculated annual static riser year for static riser operated by all operators.

- In the period from 2000 up to 2016, 4 incidents linked to static riser are recorded were 1 damage incident in 2000 belongs to the >16" category where the riser year was 911.
- Three damage incidents for static risers which belong to the ≤16" category, where 1 incident occurred in each year in 2001, 2002 and 2010 where the riser year was 1146,1229, and 1442 correspondingly.
- The only recorded leakage incident of the static riser in period 2000-20016 belongs to the ≤16" category and occurred in 2015 where the riser year was 1638.

- The annual leakage and damage incident frequency for static risers graph (**Figure 39**) shows that the annual damage frequency decrease from 2001 to 2002 from 8,73x10^{-4} to 8,14x10^{-4}, while it decreases significantly in 2010 to 6,93X10^{-4}.
- Also, the annual leakage frequency for static risers, which belongs to ≤16" category in 2015 was 6,11x10^{-4}, and the damage frequency for static riser within > 16" category is 1,10x10^{-3}.

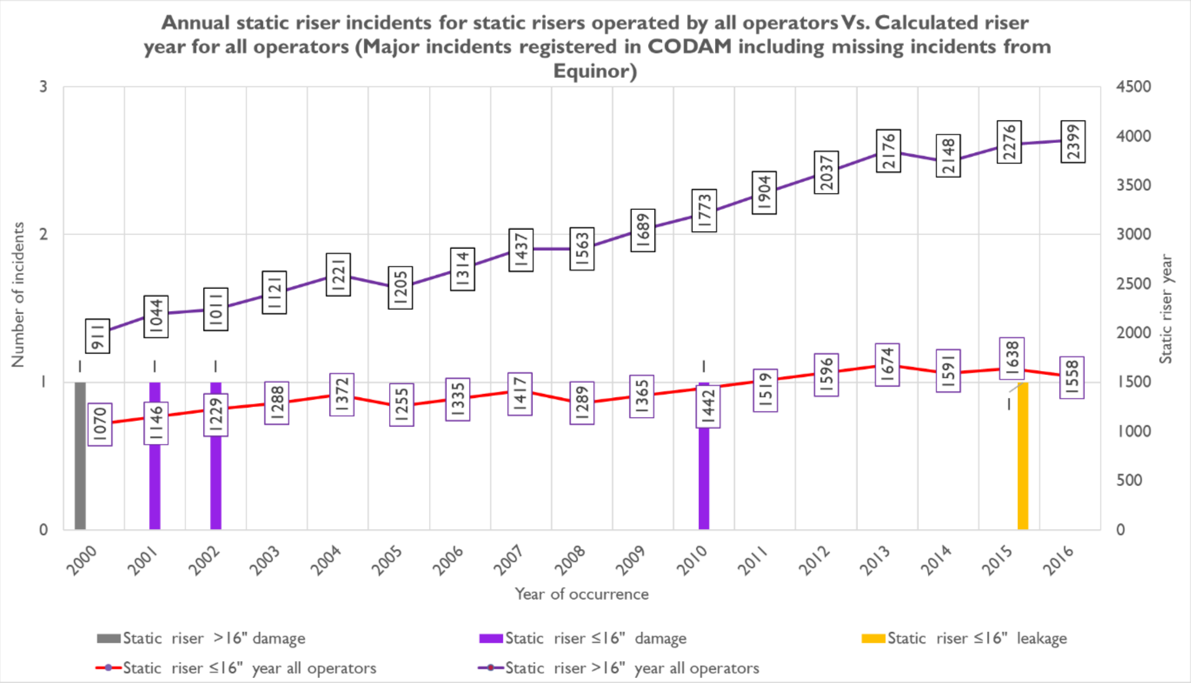


Figure 38 A diagram of static riser incidents for risers operated by all operators and calculated riser year for all operators, including missing incidents from Equinor.

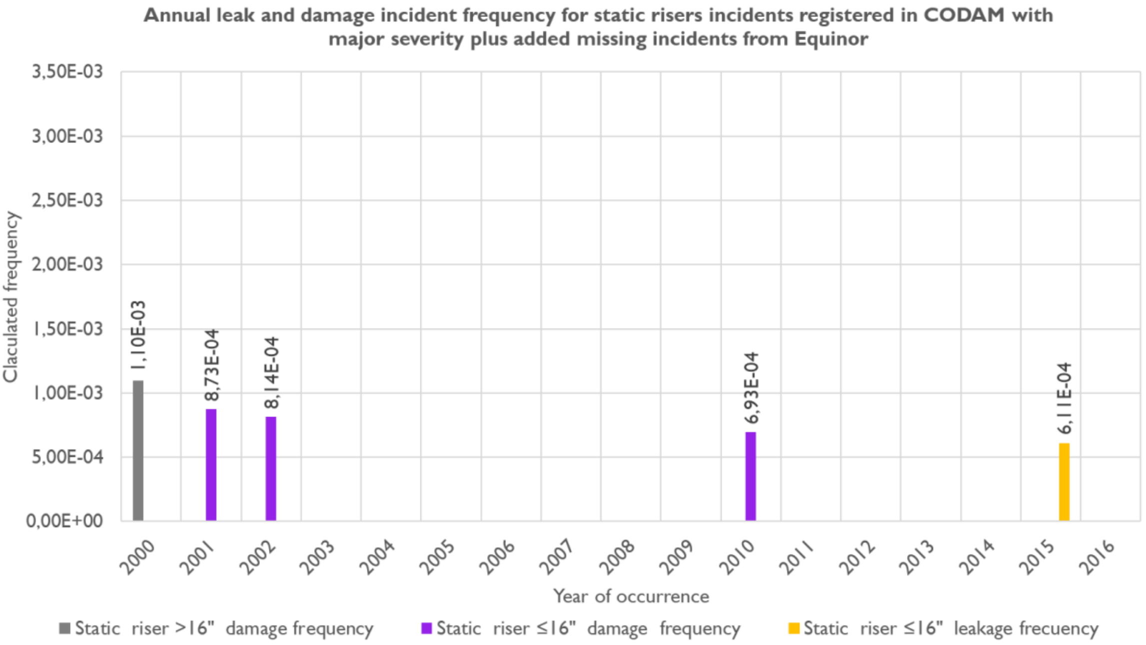


Figure 39 An overview of annual static damage and leakage frequencies based on damage and leakage incidents registered in CODAM with major severity and missing incidents from Equinor.

The damage and leak frequencies for flexible and static risers were estimated from 2000 and onwards for different databases and their combinations by dividing the number of incidents by riser year (**Table 8**):

- Incidents registered in CODAM with major severity after updating.
- Incidents registered in CODAM combined with missing incidents from Synergi.
- Incidents registered in the Equinor system, Synergi.
- A combination of major and minor incidents in CODAM.

Table 8 The main inputs used to estimate the frequency from different databases for different riser categories, boxes in pink represent the riser year used in the estimation for that specific category

Riser type and database	Riser year				Number and type of incidents		Estimated frequencies	
	2000-2015	2000-2016	2000-2017	2000-2018	Leakage incidents 2000-2018	Damage incidents 2000-2018	Damage frequency	Leak frequency
Flexible all operators (only CODAM major)2000-2016	4046	4351	4636	4984	16	29	**6,67E-03**	**3,68E-03**
Static ≤16" (only CODAM major)2000-2016		2234	2377	1501	1	2	**8,95E-04**	**4,48E-04**
Static >16" all operators (only CODAM major)2000-2016	1285	1357	1429	1501		1	**7,37E-04**	
Static ≤16" Equinor (CODAM major+Synergi)2000-2016	1176	1261	1352	1445	0	2	**1,59E-03**	
Static >16" Equinor (CODAM major+Synergi)2000-2016	864	915	966	1017	0	1	**1,09E-03**	
Flexible Equinor (CODAM major+input fraEquinor)2000-2016	2779	2997	3214	3446	26	41	**1,37E-02**	**8,68E-03**
Flexible all operators (only CODAM major+input fraEquinor)2000-2016	4046	4351	4636	4984	27	39	**8,96E-03**	**6,21E-03**
Static >16 " all operators (only CODAM major+input fraEquinor)2000-2016	1285	1357	1429	1501		1	**7,37E-04**	
Static ≤16 " all operators (only CODAM major+input fraEquinor) 2000-2016	2090	2234	2377	2522	1	3	**1,34E-03**	**4,48E-04**
Flexible onlyEquinor (Synergi) 2000-2015)	2779	2997	3214	3446	18	19	**6,84E-03**	**6,48E-03**
Static ≤16 " onlyEquinor (Synergi) 2000-2015)	1176	1261	1352	1445		1	**8,50E-04**	
Flexible all operators (CODAM major+minor)2000-2018	4046	4351	4636	4984	19	67	**1,34E-02**	**3,81E-03**
Static ≤16" all operators (CODAM major+minor)2000-2018	2090	2234	2377	2522	1	7	**2,78E-03**	**3,97E-04**
Static >16" all operators (CODAM major+minor)2000-2018	1285	1357	1429	1501	0	3	**2,00E-03**	
Flexible (CODAM before modification 2000-2016	4046	4351	4636	4984	17	40	**9,19E-03**	**3,91E-03**

The pink boxes in **Table 8** highlight the riser year used for each category. The result is categorised and presented in the next subsections together with different results from different sources, as DNV GL and Sureflex and will be compared in the next subsections for each riser category.

4.6.3.1 Flexible riser damage and leak frequencies

4.6.3.1.1 Damage frequency for flexible risers

In total, five damage frequencies for flexible risers were estimated and presented in **Table 9** where he following observations were made:

- The *highest* damage frequency was observed to be **1,37x10^{-2}**, which is estimated by using only Equinor incidents in CODAM (major) and missing incidents from Synergi within the time interval 2000-2016.
- The damage frequency estimated from the combination of incidents registered in CODAM with minor and major severity is **1,32x10^{-2}** for the time interval 2000-2018.
    - It is very similar to the damage frequency estimated from Equinor incidents only registered in CODAM (with major severity) combined with incidents registered in Synergi.
- The *lowest* damage frequency estimated from incidents registered in CODAM only with major severity is within the time interval 2000-2016 is **6,67x10^{-3}**.
- The estimated damage frequency from Synergi for the period 2000-2015 is **6,84x10^{-3}**.
    - The value is very close to the damage frequency estimated from CODAM only (with major severity) for the time interval 2000-2016, which is **6,67x10^{-3}**.
- The estimated damage frequency from the combination of the maximum amount of available reported incidents, CODAM major for all operators with missing incidents from Synergi, is **8,96x10^{-3}** for the time interval 2000-2016.

Table 9 Estimated damage and leak frequencies for flexible risers from different databases used in this study.

	Database	**Damage Frequency**	**Leaka Frequency**
Flexible riser	CODAM Major incidents all operators (**2000-2016**)	6,67E-3	3,68E-3
	CODAM Major all operators +Synergi (**2000-2016**)	8,96E-3	6,21E-3
	Only Equinor incidents (combination of CODAM major and Synergi **2000-2016**)	1,37E-2	8,68E-3
	Synergi only (**2000-2015**)	6,84E-3	6,48E-3
	CODAM Major + Minor incidents all operators (**2000-2018**)	1,32E-2	3,81E-3

4.6.3.1.2 Leak frequency for flexible risers

Overall, five leak frequencies for flexible risers were estimated and presented in **Table 9**, where the following observations were made:

- The *lowest* leak frequency, **3,68x10^{-3}**, for flexible risers was estimated from incidents reported by all operators and registered in CODAM with major severity in the time interval 2000-2016.

- The *highest* leak frequency for flexible risers was **$8{,}68\times10^{-3}$**, estimated from incidents reported by Equinor only combined with incidents registered in Synergi in the time frame 2000-2016.
- The leak frequency estimated from only major incidents from CODAM is **$3{,}68\times10^{-3}$** in the time frame 2000-2016.
- The leak frequency estimated from minor and major incidents registered in CODAM by all operators is **$3{,}81\times10^{-3}$** for the period 2000-2018.
- The leak frequency estimated from major incidents registered in CODAM is **$3{,}68\times10^{-3}$** for the time interval 2000-2016.
- The estimated leak frequency, from registered major incidents in CODAM combined with missing incidents from Equinor, is **$6{,}21\times10^{-3}$** for the time interval 2000-2016.
    - It is almost the same as leak frequency estimated from the Synergi database only for the time frame 2000-2015, which is **$6{,}48\times10^{-3}$**.

The relationship between the leak and damage frequency for flexible risers estimated from different databases, in combination with estimated frequencies from previous studies, will be discussed in the Discussion chapter.

4.6.3.2 Static riser ≤16" damage and leak frequencies

4.6.3.2.1 Damage frequency for static risers within category ≤16"

In all, 5 damage frequencies from different databases and their combination for static risers within the ≤16" category were estimated in this study and presented in **Table 10**:

- The *lowest* estimated damage frequency is **$8{,}50\times10^{-4}$** for the time interval 2000-2015, from incidents registered in Synergi only.
    - This damage frequency was close to the damage frequency estimated from major incidents registered in CODAM for all operators for the time interval 2000-2016 with a value of **$8{,}95\times10^{-3}$**.
- The highest estimated damage frequency is **$2{,}78\times10^{-3}$** for the time interval 2000-2018, which is estimated from combinations of major and minor incidents registered in CODAM by all operators.
- The damage frequency estimated from incidents registered in CODAM with major severity by all operators, including the missing incidents from Synergi is **$1{,}34\times10^{-3}$** for the time interval 2000-2016.

  - This damage frequency is close to the damage frequency calculated from Equinor incidents only from CODAM with major severity and missing incidents from Synergi, which is **1,59x10^{-3}** (2000-2016).

Table 10 Estimated damage and leak frequencies for static risers within the ≤16" category from different databases used in this study.

	Database	Damage Frequency	Leak Frequency
Static riser ≤16"	CODAM Major incidents all operators (**2000-2016**)	8,95E-04	4,48E-04
	CODAM Major all operators +Synergi (**2000-2016**)	1,34E-03	4,48E-04
	Only Equinor incidents (combination of CODAM major and Synergi **2000-2016**)	1,59E-03	-
	Synergi only (**2000-2015**)	8,50E-04	-
	CODAM Major + Minor incidents all operators (**2000-2018**)	2,78E-03	3,97E-04

4.6.3.2.2 Leak frequency for static risers within category ≤16"

Four leak frequencies for static risers within ≤16" category were calculated and presented in **Table 10** and show the following:

- The *lowest* leak frequency was estimated from the combinations of major and minor incidents registered in CODAM, which is **3,97x10^{-4}** for the time interval 2000-2018.
- The *highest* leak frequency is **4,48x10^{-4}** that is estimated from the combination of CODAM (major) and missing incidents from Synergi. Hence, it is the same for major incidents only from CODAM, as there were no registered leak incidents for static risers within category ≤16" in Synergi.
- Leak frequency for incidents registered in Synergi only and for Equinor incidents from both CODAM (major) and Synergi were not estimated due to the absence of incidents recorded in the abovementioned databases.

4.6.3.3 Static riser>16" damage and leak frequencies

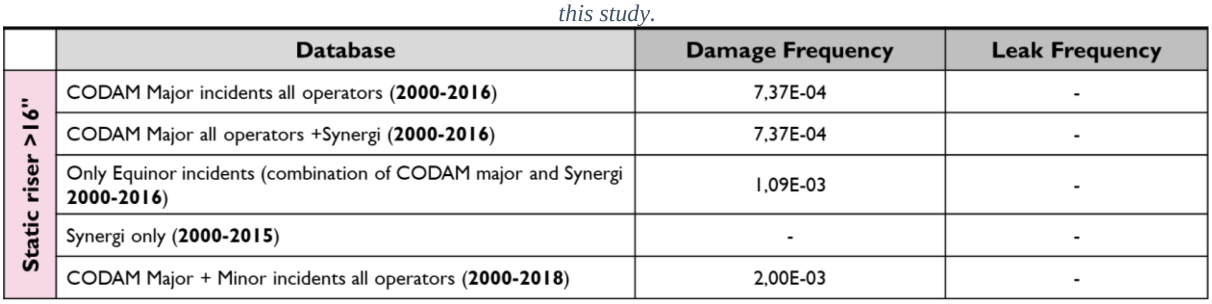
4.6.3.3.1 Damage frequency for static risers within category >16"

In total, four damage frequencies for static risers within the >16" category were estimated and presented in **Table 11**:

- The *lowest* damage frequency was similar for both categories; CODAM major incidents for all operators and CODAM major incidents for all operators combined with incidents from Synergi is **7,37x10^{-4}** for the time interval 2000-2016.
- The *highest* damage frequency extracted from only Equinor incidents from both Synergi and CODAM (major) for the time frame 2000-2016 is **1,09x10^{-3}**.

- The damage frequency estimated from a combination of both major and minor incidents registered in CODAM within the time interval 2000-2018 is **2,00x10^{-3}**.
- As there were no registered damage incidents for static riser within >16" category in Synergi, no damage frequency for this category is estimated.

Table 11 Estimated damage and leak frequencies for static riser within the >16" category from different databases used in this study.



	Database	Damage Frequency	Leak Frequency
Static riser >16"	CODAM Major incidents all operators (**2000-2016**)	7,37E-04	-
	CODAM Major all operators +Synergi (**2000-2016**)	7,37E-04	-
	Only Equinor incidents (combination of CODAM major and Synergi **2000-2016**)	1,09E-03	-
	Synergi only (**2000-2015**)	-	-
	CODAM Major + Minor incidents all operators (**2000-2018**)	2,00E-03	-

4.6.3.3.2 Leak frequency for static risers within category >16"

The leak frequency for static risers within the >16" category was not estimated as there were no registered leak incidents for this category in any of the databases that were used in this study.

4.7 Damage and leak frequencies of various hole sizes

In all, 5 incidents of the reported leak incidents linked to flexible risers were registered with an estimated hole size (**Table 12**). Only 2 of these had information about duration, total flow amount and rate, and only one with pressure information. Also, for six leak incidents, no hole information was provided, and three of these also did not include flow rate input. The pressure parameter was provided for only four leak incidents and only of these had hole size information. The total flow amount was provided in only eight of the incidents, only two of which had information about the hole size.

For the only reported static riser leak incident in CODAM with major severity in the time interval, no information regarding the hole, flow rate, etc. was provided.

Based on the scarcity of available information (for hole size, flow rate, pressure, etc.) it was concluded, with experts at Equinor, that the frequencies for various hole sizes for static risers would not be calculated as there is not enough defensible data. The same was concluded for flexible risers, as there are different layers in the flexible risers, and the hole sizes will not be the same through all these layers.

Table 12 An overview of leak incidents of flexible riser associated with available information of medium type, hole size, flow amount, pressure and flow rate (from both CODAM and Synergi).

Riser type	Year	Dimension	Medium	Hole info	Duration	Total flow amount	Flow rate (Kg/s)	Pressure
Flexible	2001	11	Water injection	Length 1 m Width ~10cm	-	-	-	-
	2009	6	Injection	1 cm	-	-	-	-
	2009	6	Oil	1 cm	-	-	-	-
	2011	6	Oil/Gas	2,65 mm	174 min	1947 kg gas 10 L oil	0,09	-
	2011	6	Oil	2,7 mm	540 min	2532 Kg	0,1	1,5 bar
	2001	9	Oil	-	45 min	12000	5	-
	2002	6	Water injection	-	180 min	9072	0,84	-
	2002	-	Oil	-	19 min	122 L	0,17	-
	2005	6	Oil	-	15 min	2 L	-	80 bar
	2011	2	Gas	-		600 m3	-	0,5 bar
	2012	9	Oil	-	8280 min	1300 L	-	40 bar

Chapter 5 Discussion

Several decisions were made regarding the selection of databases, data analyses, and the way results were obtained. This chapter will cover two main aspects: the discussion of basic assumptions, and the discussion of the results of this study.

5.1 Discussion of basic assumptions

In this subchapter, the reasons behind the selection of different databases, categorisation, classification, and the methods used will be discussed and later compared to previous studies, which were presented in section 2.6.

5.1.1 Selection of databases

As mentioned previously, DNV GL [3] has used data combined for PARLOC 2012 for UKCS in the period 2001-2012 and for the NCS for the period 2001-2017. In addition, incidents for static and flexible risers from PARLOC 2001 were also included.

The regulation (how operators should operate), and how the government follows up the operator's activities, are different from one country to another. Also, the operational circumstances and conditions vary from one operator to another and from one installation to another. The operational condition is a source of uncertainty, as it is difficult to consider due to the uniqueness of each operation. Yet, there is a distinct difference between individual companies and the operational circumstances, i.e. installation regarding the design, maintenance, inspections, age of the installation and risers (mentioned above). Nevertheless, the comparison which was carried out in RNNP 2006 (section 2.5) showed that the average frequency for the Northern Norwegian sector is ~2,3 times higher than its equivalent in the British sector[41]. Also, there is a significant difference in decreasing trends of gas leaks >1 kg in the Norwegian and British sectors. Besides this, different classification criteria were used for the collection of both NCS and UKCS data. Hence, it is believed that including data from different countries will result in data inconsistency. Therefore, the task of this study was limited to static and flexible risers in offshore operations at the NCS, from all operators.

The main assumption in the leak and damage frequencies estimation is that the historical data used is representative for the future and incidents would have occurred under similar conditions. Hence, the corresponding uncertainty factor is the degree to which the historical data used is representative for the future and how similar the conditions are. For the timeline of failure, a bathtub curve is often taken as normal in the start-up phase, since the probability for early failure is high (infant mortality) as shown in **Figure 40**. During this normal operation phase, only random failures occur (in the riser incident context, the corrosion failure is not random, and it develops over time), and the failure rate is mostly quasi-constant; while, for the end of life the failure rate normal increases. Previously, it was mentioned that from 1998-2001, carcass collapses were observed in several flexible risers due to a new failure mode. In comparison, after gaining experience and knowledge about the typical new failure modes in general, the incidents which occurred in the first phase decreased. Then, due to the ageing the robustness of risers decreases, resulting in increases in damage and leak incidents. Also, in one specific installation 4 flexible risers experienced carcass collapse after 1 year of installation and 2 flexible risers experienced the same failure mechanism after 3 years of installation. Hence, the bathtub curve might represent a good timeline of failure for the risers. The ageing factor is a critical factor, and in this study, it was not taken into consideration; therefore, it represents an uncertainty source. The historical data represents both new and old risers, but by this year the riser's operational experience will not be the same as in 2000, i.e. the riser will be 19 years older than it was in 2000. Also, many risers were installed, replaced, and removed. Therefore, it would be a complicated procedure, and the database would be too limited if the risers were grouped into smaller sets. Moreover, in a specific installation, the age of installed risers varies even if the operational conditions, maintenance, and inspections are the same.

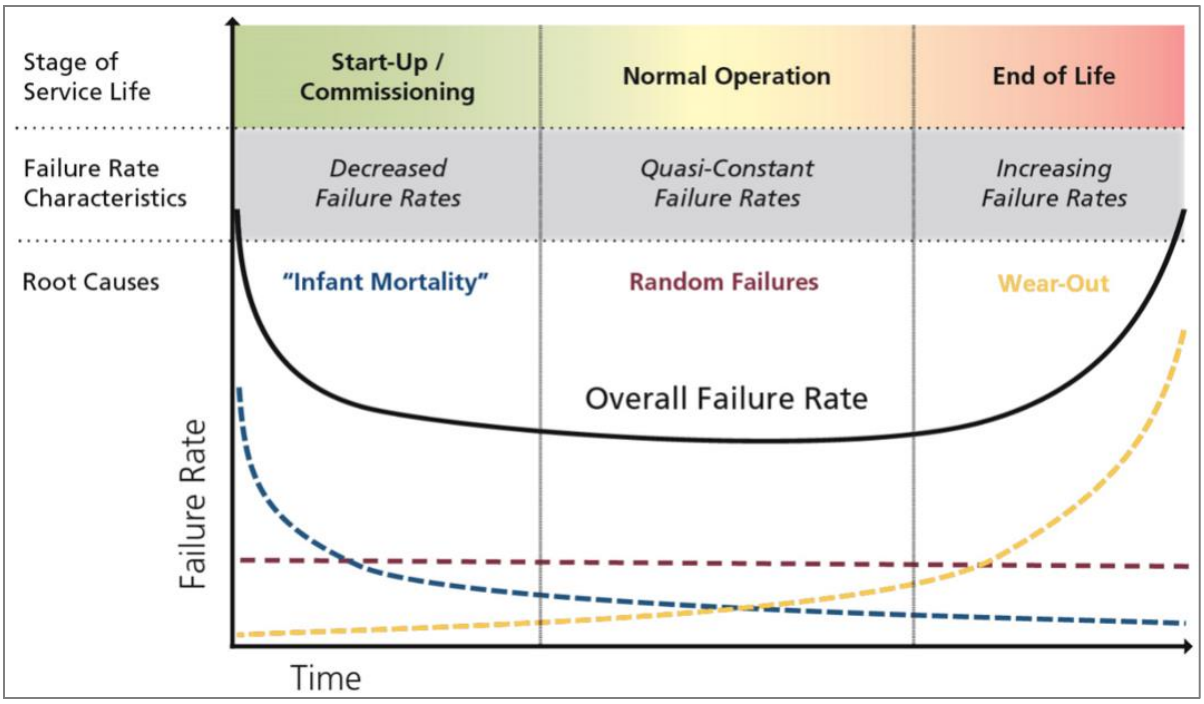


Figure 40 Showing the bathtub curve, a timeline of failure (Courtesy OsiHardware).

5.1.2 Riser categorisation and classification

In most of the cases, riser type was provided, and for the cases where it was not provided with a correlation with another database was made, such as SISU and internal systems at Equinor for Equinor's risers. The riser type for registered risers in SISU was assigned, as mentioned before, based on the material type and the installation type.

The categorisation of risers based on the medium type was not considered in this study, as the amount of data available is limited. The main purpose was to estimate the leak and damage frequencies for all risers.

5.1.3 Selection of time frame

The leak and damage frequencies, which were calculated from different databases used in this study, were chosen for the period 2000 and onwards. The background reasoning for this decision is based on the following:

After discussion and consultation with experts at Equinor within Pipelines/ risers and risk assessment, it was concluded that time interval from 2000 and onwards would be chosen. The reasons for not excluding the high annual damage and leak frequencies for flexible risers in 2000, 2001 and 2002 were that these were believed to be a special cause variation as follows:

- A small riser year would give high frequency even if two damage incidents and only one leak incident were registered in 2000. The riser year for flexible risers was 433 then, compared to the same situation in 2005 where the same type and quantity of incidents occurred the frequency was considerably lower.
- Equinor has experienced failure in several flexible risers related to carcass failure such as collapse, tearing and overload, from 1998-2001. This type of failure is still common:
    a. Two damage incidents that occurred in 2005 were caused by carcass collapse.
    b. Four of the leak incidents that occurred in 2006 were caused by a hole in the outer sheath, which has been mentioned before. Most of the failures seen in multi-layer PVDF risers originated from damages to the carcass in the form of un-spiral and collapse of carcass profiles [25].
    c. For 2008, 2 out of 3 damage incidents were caused by carcass collapse.
    d. All three damage incidents occurring in 2011 were caused by carcass collapse.
    e. Two damage incidents which occurred in 2015 were linked to carcass collapse.

- Considering that there is constant development in technology, there will always be new challenges and problem to solve. On average, one new failure mechanism linked to flexible risers is discovered yearly according to a flexible riser expert at Equinor.
- There is uncertainty about the precision of the date of reported incidents, i.e. two leak incidents occurred in 2010 but were reported 1.5 years later.

Hence, it was shown that the perceived special cause variations were common cause variations. Therefore, no reason was found to exclude these frequencies and the time interval of 2000 and upwards is widely used in related risk assessment at Equinor.

On the other hand, the upper limit of the time frame for the combined database (Equinor and CODAM with major severity) was chosen to be 2016, due to:

- The last registered incident in the combined database was in 2016.
- As presented previously in the Results chapter, a case exists where an incident was registered 1,5 years later than the actual date of occurrence.

Hence, to reduce the uncertainty regarding improper incident registration 2016 was chosen as the upper time interval limit for this database. A sensitivity analysis was carried out to gauge the impact of the timeframe selection on the decision (**Table 13**). The sensitivity analysis shows that for flexible riser leak frequency is 5,82x10^{-3} in the timeframe 2000-2017 and 5,24x10^{-3} in 2000-2018 while the presented result in this study is 6,21x10^{-3} for 2000-2016. Moreover, the damage frequency for flexible riser is 8,41x10^{-3} and 7,81x10^{-3} for timeframe 2000-2017 and 2000-2018, respectively.

For the static riser within the ≤16" category, the damage frequency is 2,10x10^{-3} and 2,00x10^{-3} for 2000-2017 and 2000-2018, respectively. Also, the leak frequency for the same category is 7,00x10^{-4} and 6,66x10^{-4} for the time frame 2000-2017 and 2000-2018, respectively.

For the static riser within the >16" category, the damage frequency was shown to be 4,21x10^{-4} for 2000-2017 and 3,97x10^{-4} for 2000-2018.

The differences within the sensitivity analyses results for both damage and leak frequencies for flexible risers is insignificant as the number of reported incidents seems to be a representative data sample.

On the other hand, as the number of reported incidents for static risers (both categories) is scarce, the estimated frequencies are highly sensitive to any change in the size of data and the riser year. Still, there is the possibility of missing incidents which have not been recorded yet, and in the sensitivity analysis, the number of incidents was considered to be the same as in the timeframe 2000-2016.

Table 13 A sensitivity analysis of timeframe impact on the leak and damage frequencies.

		This study			Unit
	Time interval	2000-2016	2000-2017	2000-2018	Year
Leak incidents	Flexible risers ≤16"	27			Number
	Static risers ≤16"	1			
	Static risers>16"				
Damage incidents	Flexible risers≤16"	39			
	Static risers ≤16"	3			
	Static risers >16"	1			
Riser years	Flexible risers ≤16"	4351	4636	4984	Riser year
	Static risers ≤16"	2234	1429	1501	
	Static risers >16"	1357	2377	2522	
Leak frequency	Flexible risers ≤16"	6,21E-03	5,82E-03	5,42E-03	Per riser year
	Static risers ≤16"	4,48E-04	7,00E-04	6,66E-04	
	Static risers >16"				
Damage frequency	Flexiblerisers ≤16"	8,96E-03	8,41E-03	7,83E-03	
	Static risers ≤16"	1,34E-03	2,10E-03	2,00E-03	
	Static risers >16"	7,37E-04	4,21E-04	3,97E-04	

5.1.4 Challenges and uncertainties related to databases

5.1.4.1 Accurateness of reported incidents

Generally, all reported damage and leak incidents are reported by operators based on their selective judgment that is based on their certain frame of a reference. The frame of reference is different from one operator to another, and also from one individual to another within the same operator group. Besides, how individuals interpret and evaluate information and data varies greatly.

This issue was noticed among the reported incidents in both databases, CODAM and Synergi, where variation in the way a case was described was noticed:

- Empty case description
- Few words for describing the incidents
- Full and detailed case description

The empty and briefcase descriptions are a source for uncertainty where it is not ensured that a full picture of the incident is captured based only on anomaly or cause specifications. As mentioned, there is a variation of in frame of reference from which the selective judgment is constructed. As the registration criteria were imprecise in many cases, an evaluation had to be carried out together with experts at Equinor.

Additionally, misspelling of some keywords was observed in some cases, e.g., instead of writing carcass the word **carkass** was used, and it was difficult to detect by searching if another keyword was not used in combination.

In addition, searching by DFU resulted in few cases, as some cases were registered as a deviation instead of an HSE event and, moreover, the DFU has only been used recently. This underlines the uncertainties and challenges related to incidents of data gathering and classification in an appropriate way. The selective judgement is an important factor which is difficult to address in some cases. The variation in the case description quality will affect the quality of any data gathering. Even though, several cases were described in full detail, when combined with a summary of other cases with poor description, the quality of the data will decrease.

Also, misspelling can be a real challenge as any general search in the database will not be good enough to cover all registered incidents, especially for those incidents which were not assigned a DFU. As mentioned before, some incidents were classified as deviation instead of HSE incidents, which was surprising. This revealed the amount of uncertainty which is associated with the searching process. The severity classification difference between common reported incidents in Synergi and CODAM can further contribute to differences in the number of incidents registered in each category, and thus, a difference in the background for decision making.

5.1.4.2 Reliability of the database

A difference was observed in the number and type of incidents registered in different databases. In order to discuss the difference between the data sources, a graph was produced and is presented in **Figure 41.** These differences will be highlighted and discussed in the next subsections.

Equinor’s incidents

As shown in **Figure 41**, the Synergi database does not have a full overview of all riser incidents which are operated by Equinor. The difference can be perceived after comparing Equinor incidents only from both Synergi and CODAM (with major severity) as follows:

In Synergi, 25 damage riser incidents were registered (23 linked to flexible and 2 to static riser), while only 18 leak incidents were registered (all of which linked to flexible risers). The second column set in **Figure 41** represents incidents reported by Equinor into CODAM with major severity for the period 1988-2016.

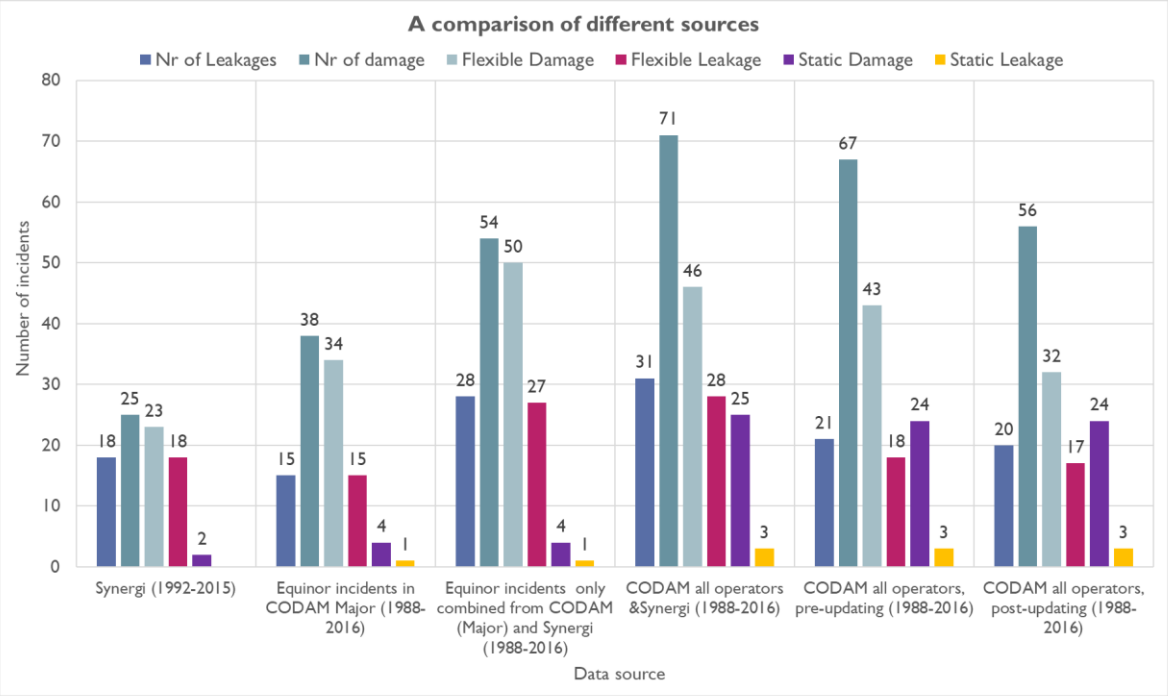


Figure 41 A comparison of different data sources and their combinations used in this study.

It shows that 38 damage incidents were reported (34 related to flexible and 4 to static risers), while only 15 leak incidents were reported (all linked to flexible risers).

As mentioned earlier, to get a more accurate overview of all possible incidents reported by Equinor across the different databases, these databases were combined. The result shows that in total 54 damage and 28 leak incidents were reported by Equinor in different databases, none of which had a full overview of the total number of incidents. **Figure 41** shows that there are more reported incidents in CODAM by Equinor than are registered in Synergi, and also that some incidents were not reported into CODAM. The following can be inferred:

- For leak incidents, Synergi has information for about 64% of total incidents for risers operated by Equinor, while CODAM (major) has only 54% of total incidents.
    - Synergi has 67% of flexible riser leak incidents and none of static.
    - CODAM has 56% of flexible riser leak incidents and 100% of static.
- For damage incidents, Synergi has only 46% of total damage incidents, and CODAM has 70% of total incidents for risers reported by Equinor.
    - Synergi has 46% of flexible riser damage incidents and 50% for static risers.
    - CODAM has 68% of flexible riser damage incidents and 100% for static risers.

The most intriguing observation from the database comparison is that there is no complete overview of total occurred incidents for risers operated by Equinor in any one database.

Notably, the Equinor database does not have registered all incidents which are registered in CODAM, which was surprising.

After talking to experts at Equinor in the safety department, the following possible explanation was given:

Reporting of riser leak and damage incidents internally was not a part of reporting culture earlier in Equinor, even if the system was available. Hence, CODAM was mainly used to report these kinds of incidents.

On the other hand, Synergi was mainly used to report personal accidents and work-related incidents in the beginning; riser incidents reporting began to be more organised recently.

The difference is a significant source of uncertainty as none of the above-mentioned databases has a complete representation of the actual number of incidents. Mainly, if any analysis was carried out using one of these databases assuming that it has a complete overview, then an incorrect risk picture will be drawn.

To reduce the uncertainty in this study, a combination of the abovementioned databases was carried out to get a full picture of incident quantities.

However, the validity of incidents reported by other operators was not easy to assess since there was no access to this information; even though requests were sent requesting permission, no reply was received. Hence, it is another uncertainty factor which should be addressed in order to get a better overview.

CODAM (Major) database

In section 4.2, issues related to the CODAM database were highlighted concerning multiple reporting of incidents instead of updating them. The difference is presented in two last column sets in **Figure 41**, as well as in **Table 7**. The number of registered incidents with major severity in CODAM prior to updating is higher, especially for incidents related to flexible risers. As **Figure 41** shows the result of sorting out the multi reported incidents gives a reduction of 1 leak incident and 11 damage incidents in total. The reporting and registration criteria are imprecise, and the following points were observed:

- Missing information on some reported events, where some information fields were empty.
- Riser type was not assigned at all, and as mentioned before, it was constructed from the material and installation type.
- Information about leak rate or hole size was not assigned for most of the leak incidents.
- The case description was poorly described or even emptied in several cases.

Additionally, the uncertainty related to the selective judgment and the classification of the severity are important to consider.

These uncertainty factors are important to address in order to get good data quality and to be acceptable for further use in risk assessment.

Population database (SISU)

Several assumptions needed to be made while analysing the population data, as mentioned in section 3.3.1, which can be factors for uncertainties.

The correlation approach, which was used, was assumed to be the best suitable way to reduce the uncertainty based on the timeframe of the thesis. More detailed work concerning validation of the population data could be important to do in the future, as the riser year is an important factor in the estimation of the frequency.

Discussion of results obtained from the databases before improvements

As mentioned previously, most of the duplicated events in CODAM major (before the update) were linked to flexible riser damage incidents. In total, 40 damage and 17 leak incidents were registered, which gave **$9{,}19\text{x}10^{-3}$** in damage frequency and **$3{,}91\text{x}10^{-3}$** in leak frequency. The result after updating is **$6{,}67\text{x}10^{-3}$** for damage frequency and **$3{,}68\text{x}10^{-3}$** for leak frequency. There is a significant difference within the damage frequency as there is a difference of 11 incidents, that resulted in a difference of $2{,}52x10^{-3}$. Likewise, for leak frequency, a difference of 1 leak incident resulted in $0{,}23x10^{-3}$. Comparing the result of damage frequency obtained from the combination of CODAM major and Synergi, which is **$8{,}96\text{x}10^{-3}$,** the difference calculated is $8{,}07x10^{-3}$. The result showed that the CODAM database does not have a full overview of all Equinor's incidents and underreporting occurs (**Figure 25** and **Figure 41**). Hence, a good portion of data is missing and considered to be incomplete and unreliable.

As mentioned earlier, the Synergi database does not have a complete overview of all Equinor's incidents (**Figure 41**). Synergi has 48 recorded incidents out of 72 (sum of leak and damage incidents). A significant number of incidents is missing. Therefore, the Synergi database is also considered to be unreliable. By adding missing data from Equinor, the uncertainty related to underreporting has been reduced, and the combination dataset represents a better database than before. Nonetheless, there is still uncertainty regarding how definite it is that all incidents by Equinor are registered in CODAM or Synergi. Also, validation of incidents by other operators was not possible due to data inaccessibility. Hence, it is considered that by combining Synergi and CODAM, this results in a reliable database for flexible riser incidents.

5.2 Discussion of the result

In this subsection, a discussion of the result of this study will be presented combined with a comparison to previous studies.

5.2.1 Flexible risers damage and leak frequencies

In DNV GL report [4], no damage frequency was presented as they have focused on failure frequency in their report, which is defined to be *a subset of an incident resulting in loss of containment and leakage* [4]. On the other hand, the damage definition used in this study is in line with the damage definition used in Sureflex JIP for flexible risers, except the assumption used in this study is that only riser in operation was considered [2].

Two damage frequencies were introduced in section 2.6 from Sureflex JIP[2], **$3{,}50\text{x}10^{-3}$** and **$3{,}68\text{x}10^{-3}$** for the time interval 2011-2016 and 1976-2016. By comparing this with the lowest estimated damage frequency in this study, which is **$6{,}67\text{x}10^{-3}$** for incidents registered in CODAM (2000-2016) with major severity, the difference is $3{,}17x10^{-3}$ and $3{,}01x10^{-3}$. On the other hand, the result from the combined databases (Equinor and CODAM with major severity) is $8{,}96\text{x}10^{-3}$, almost 2,5 times higher than the leak frequency from Sureflex for the period 2011-2016, which is $3{,}50\text{x}10^{-3}$ (**Table 14**). Also, it is nearly 2,4 times higher than the damage frequency from Sureflex for the period 1976-2016, which is $3{,}68\text{x}10^{-3}$. The result from Wood report [42], where the leak frequency for Equinor was estimated to be 3 times higher than the leak frequency for the global population (Sureflex [2]) correlates approximately with the fraction provided here, 2,5. Even if the result provided for Equinor only, there are two possible reasons:

- The data was provided to Sureflex from different operators, which was not provided in this study, and the difference in 0,5 could be linked to the incidents from other operators, which are not reported to CODAM.
- As mentioned earlier, Equinor operates most of the risers in the NCS, and the frequency estimate based on the inputs from all operators, including Equinor, will mainly be affected by the input from Equinor.

To be able to discuss the difference in the leak frequency provided in the Wood report [42] for Equinor's flexible riser incidents only, a leak frequency for the period 2012-2016 was estimated. The leak frequency was estimated base on 3 leak incidents registered in the period 2012-2016, where the calculated riser year was 1045 for Equinor's flexible risers only.

The estimated flexible riser frequency is $2{,}87\text{x}10^{-3}$ and the difference shown to be $1{,}87\ \text{x}10^{-3}$.

The differences in the results are related to the difference in a number of incidents, database, riser year and assumptions used in Sureflex compared to this study.

Table 14 Result comparison of results presented in this study (a combination of Equinor's database and CODAM with major severity) and previous studies.

	Source	**DNV's report**	**Sureflex**	**Sureflex**	**This study**	**Unit**
	Time interval	2001-2017	1976-2016	2011-2016	2000-2016	Year
Leak incidents	Flexible risers ≤16"	37,2	63	6	27	Number
	Static risers ≤16"	17,8			1	
	Static risers>16"	0,8				
Damage incidents	Flexible risers≤16"		231	56	39	
	Static risers ≤16"				3	
	Static risers >16"				1	
Riser years	Flexible risers ≤16"	10129	51940	15982	4351	Riser year
	Static risers ≤16"	16974			2234	
	Static risers >16"	7776			1357	
Leak frequency	Flexible risers ≤16"	3,70E-03	1,00E-03	3,75E-04	6,21E-03	Per riser year
	Static risers ≤16"	1,00E-03			4,48E-04	
	Static risers >16"	1,1E10-4				
Damage frequency	Flexiblerisers ≤16"		3,68E-03	3,50E-03	8,96E-03	
	Static risers ≤16"				1,34E-03	
	Static risers >16"				7,37E-04	

For the period 1976-2016, 231 damage incidents were used in the Sureflex [1] study compared to 39 in this study, which is almost 6 times higher. The riser year used in Sureflex is 51940 while it is 4351 in this study, almost 12 times higher. For the period 2011-2016, 56 damage incidents were registered in Sureflex, which is around 1,4 times the number of incidents in this study. Further, the riser year used is almost 3,7 times higher than the riser year used in this study. The following reasons can be highlighted:

- The Sureflex report is based on global data for flexible risers collected from different industry members; whereas, in this study, only incidents which occurred in the NCS are included.
- The time frame is different; this applies for both time intervals from Sureflex, 1976-2016 and 2011-2016, compared to the time interval used in this study, 2000-2016.
- The assumption used is different; in this study, only, incidents where the riser was in operation, are included, while Sureflex also included incidents where the riser was not in operation.

Therefore, the number of incidents and the riser year is much higher compared to the number of incidents and riser year presented in this study.

A comparison with DNV GL [3] leak frequency **$3{,}7\text{x}10^{-3}$** in the time interval 2001-2017 shows the following:

- Leak frequency estimated from only major incidents in CODAM within the time frame 2000-2016 is **3,68x10^{-3}**, which is very close to the leak frequency from DNV GL. But, by looking at inputs behind these values, the following is noticed:
  - The number of leak incidents registered in CODAM with major severity is 16, while it is 37,2 in DNV GL report. Nevertheless, the riser year used for CODAM is 4351 and 10129 in DNV GL report.

    This is an example of how the use of frequency only cannot show the knowledge beyond it or the quality of data used in the calculation. As shown in the Result chapter in section 4.3 and discussed in section 5.1.4, CODAM database is not complete, and under-reporting seems to be 44,4% for leakage incidents and 80% for damage incidents.
- Leak frequency estimated from a combination of major and minor registered incidents in CODAM has a value of **3,81x10^{-3}** and is very close to the leak frequency from DNV GL report. This is due to the following:
  - The number of leak incidents registered in CODAM with minor severity is 19 while it is 37,2 in DNV GL report. Nevertheless, the riser year used for CODAM is 4984 and 10129 in DNV GL.
- The estimated leak frequency from reported major incidents from all operators in CODAM combined with missing data from Synergi is *almost* twice the value from DNV GL. The same for leak frequency estimated from incidents in Synergi only is **6,21x10^{-3}**. The differences can be linked to the following:
  - The number of leak incidents registered in the DNV GL report is 37,2, which is almost 1,4 higher than leak incidents presented in this study, which is 27 (**Table 14**).
  - The riser year used in the DNV GL report is 10129, which is almost 2,3 higher than that used in this study, which is 4351.

  As mentioned previously, DNV GL has used data from UCKS, which explains the significant difference in both the number of incidents and riser year.
- The estimated leak frequency from only Equinor incidents combined from both Synergi and CODAM (**8,68x10^{-3}**) is very **high** compared to the DNV GL leak frequency. The differences can be linked to the following:

- The number of leak incidents registered in the DNV GL report is 37,2, which is almost twice as high than leak incidents presented in the Equinor database, which is 18.
- The riser year used in the DNV GL report is 10129, which is almost 4,5 higher than that used in this database of 2279.

As mentioned previously, DNV GL has used data from UCKS, and data from Synergi represents the registered incidents in the Equinor system only. Thus, it was shown that this database is incomplete, and a number of incidents are missing.

5.2.2 Static riser ≤16" damage and leak frequencies

There is no damage frequency for static riser presented from previous works such as DNV GL [3]; as mentioned before, the focus of their report was failure frequency (leak frequency). Also, Sureflex [1] focused on leak and damage frequencies for flexible riser incidents only.

The estimated damage frequency from the combination of CODAM major and Equinor databases is **$4{,}48 \times 10^{-4}$**, while the presented damage frequency by DNV GL for the same category is **$1{,}0 \times 10^{-3}$**, for the time interval <u>2001-2017</u>. The significant difference between these frequencies is related to the differences in the input: 17,8 leak incidents registered in the DNV GL report compared to only 3 leak incidents found in the combination of CODAM major and Equinor databases. The riser year shows a substantial difference as well, 16974 for DNV GL and 2234 for the combined database.

5.2.3 Static riser>16" damage and leak frequencies

As presented in the Result chapter, no leak frequency was calculated as no leak incidents were found for this category in the period from 2000 onwards. The only frequency that is presented from the previous study is the leak frequency from DNV.GL Thus, the difference cannot be discussed or highlighted for both damage and leak frequencies.

In total, only one damage incident was recorded for all three databases, i.e. CODAM (all operators with major severity), Equinor's incidents (combined from CODAM major and Synergy) and the combination of CODAM (Major severity) and missing incidents from Equinor. For the combination of incidents registered in both the major and minor severity category in CODAM, 3 incidents were recorded.

5.2.4 Uncertainty estimation of the results

The Poisson distribution was chosen to account for uncertainty when estimating the failure rate of different riser categories. In addition, the confidence intervals for the estimated failure rates are presented in **Table 15** according to a 95% confidence that the true value for the failure rate $(\hat{\lambda})$ will be within the corresponding interval given the following conditions:

- The discrete nature of the failures for risers, whether they are damage or leakage.
- Feasibility to approximate the confidence interval to a Normal distribution when relatively few data is available.

The mathematical expression for the confidence interval of the Normal approximation is shown in formula [47]:

$$p\left(\hat{\lambda} - Z_{\frac{\alpha}{2}}\sqrt{\frac{\hat{\lambda}}{n}} < \lambda < \hat{\lambda} + Z_{\frac{\alpha}{2}}\sqrt{\frac{\hat{\lambda}}{n}}\right) = (1-\alpha) \qquad (2)$$

Where n represents the total number of events per category of riser failures in the time interval, λ is the true value for the failure rate, $\hat{\lambda}$ represents the estimated failure rate per category, $Z_{\frac{\alpha}{2}}$ is the critical value of the standard normal distribution and α the degree of confidence in percentage to determine the confidence intervals.

To calculate the confidence interval, it is also necessary to normalise the values (upper and lower limits), dividing them by the number of average riser year per category. Otherwise, the obtained results would be too small, and this is problematic for parameter values that are close to zero. The following steps indicate how to calculate the confidence intervals for all categories of failure risers.

1. Calculate the failure rate $\hat{\lambda}_{category}$ for the failure of riser's category by taking the mean of failures in the fixed interval of years (**Table 15**).
2. Choose a value for the degree of confidence α.
3. Obtain the critical value of the standard normal distribution $Z_{\frac{\alpha}{2}}$ for the selected α.
4. Calculate the upper and lower intervals of the confidence intervals, given the estimated frequency of events per riser year by subtracting and adding the term $Z_{\frac{\alpha}{2}}\sqrt{\frac{\hat{\lambda}}{n}}$ to the parameter.
5. Verify that the obtained values are symmetrical to the estimated parameter $\hat{\lambda}$ by comparing the difference between $\hat{\lambda}$ and $Z_{\frac{\alpha}{2}}\sqrt{\frac{\hat{\lambda}}{n}}$.

Table 15 presents a summary of confidence intervals of the estimated parameters for failure rates in the different categories of risers. The default degree of confidence is 95%, thus, $Z_{\frac{\alpha}{2}}$ has a fixed value of 1,96. By following the previous steps to calculate confidence intervals, for the damage incidents in the flexible riser category, the results are:

1. $\hat{\lambda}_{category} = 2{,}29$
2. $\alpha = 5\%$
3. $Z_{\frac{\alpha}{2}} = 1{,}96$
4. $+Z_{\frac{\alpha}{2}}\sqrt{\frac{\hat{\lambda}}{n}} = 8{,}79x10^{-04}$ and $-Z_{\frac{\alpha}{2}}\sqrt{\frac{\hat{\lambda}}{n}} = 9{,}14x10^{-04}$
5. $\hat{\lambda} - Z_{\frac{\alpha}{2}}\sqrt{\frac{\hat{\lambda}}{n}} = 1{,}72x10^{-04}$ and $\hat{\lambda} + Z_{\frac{\alpha}{2}}\sqrt{\frac{\hat{\lambda}}{n}} = 1{,}79x10^{-04}$

The confidence interval shows the statistical uncertainties only, assuming the data used is representative and does not reflect the uncertainty in the assumptions and other uncertainty factors. Several factors can affect how representative the historical data is, these factors will be highlighted in section 5.3.

Table 15 Showing the input parameters for estimation of the upper and lower frequency for each frequency category in this study using Poisson distribution.

	Static riser >16" damage	**Static riser ≤16" damage**	**Static riser ≤16" leakage**	**Flexible riser damage**	**Flexible riser leakage**
Number of incidents (2000-2016)	1	3	1	39	27
λ (mean)	5,88E-02	1,76E-01	5,88E-02	2,29	1,59
Estimated Frequency	7,37E-04	1,34E-03	4,48E-04	8,96E-03	6,21E-03
Year	17	17	17	17	17
SQR(λ /n)	6,58E-03	8,88E-03	5,13E-03	2,30E-02	1,91E-02
Z $\alpha/2$	1,96	1,96	1,96	1,96	1,96
Lower interval	4,59E-02	1,59E-01	4,88E-02	2,25E+00	1,55E+00
Upper interval	7,17E-02	1,939E-01	6,89E-02	2,34E+00	1,63E+00
Average riser year	7,98E+01	1,31E+02	1,31E+02	2,56E+02	2,56E+02
Estimated frequency lower interval	5,75E-04	1,21E-03	3,71E-04	8,79E-03	6,06E-03
Estimated frequency upper interval	8,99E-04	1,48E-03	5,24E-04	9,14E-03	6,35E-03
Frequency	7,37E-04	1,34E-03	4,48E-04	8,96E-03	6,210E-03
Difference from estimated frequency to the lower interval	1,62E-04	1,30E-04	7,69E-05	1,72E-04	1,51E-04
Difference from estimated frequency to the upper interval	1,62E-04	1,35E-04	7,62E-05	1,79E-04	1,42E-04

5.2.5 Robustness analysis of the results

A difference was noticed for estimated damage frequency for static risers within the ≤16" category, between CODAM major and the combination of CODAM and Synergi. Also, the difference of single registered damage incident changed the result from **$8{,}95\text{x}10^{-4}$** to **$1{,}34\text{x}10^{-3}$**, which makes *$4.45\text{x}10^{-4}$* in difference.

Overall, there is one static damage incident within the ≤16" category was missing from Equinor, but there is a possibility of missing incidents from other operators especially, those who have operated mainly with static risers. However, there is no means to confirm or invalidate this possibility without access to the databases of the other operator. Even so, riser year for this category shows that risers operated by Equinor have 1261 riser year for the time interval 2000-2016, compared to 2234 for all operators including Equinor in the same time interval. There is still uncertainty as 44% of riser year belongs to other operators.

The leak frequency calculated for the static riser within the ≤16" category ($4{,}48\text{x}10^{-4}$) is considered to be highly sensitive to any change as it is estimated based on one incident, i.e. if one incident was not reported the frequency would double. Hence, the database for static riser has weak robustness as a small change is required to alter the conclusion.

Based on the quality of database and robustness classification of the results obtained from different databases, a matrix of the database quality and robustness is presented in (**Figure 42**). The following was assigned:

- The damage and leak frequency for both static and flexible risers estimated from the CODAM database (with major severity, after update) are assigned medium quality and weak robustness.
- The damage and leak frequencies estimated from the Synergi database for both static and flexible risers are assigned low quality and weak robustness.
- The damage and leak frequencies for flexible risers estimated from the combination of CODAM (with major severity after update) and Synergi are assigned high quality and moderate-high robustness.
- The damage and leak frequencies for static risers estimated from the combination of CODAM (with major severity after update) and Synergi are assigned medium quality and weak robustness.

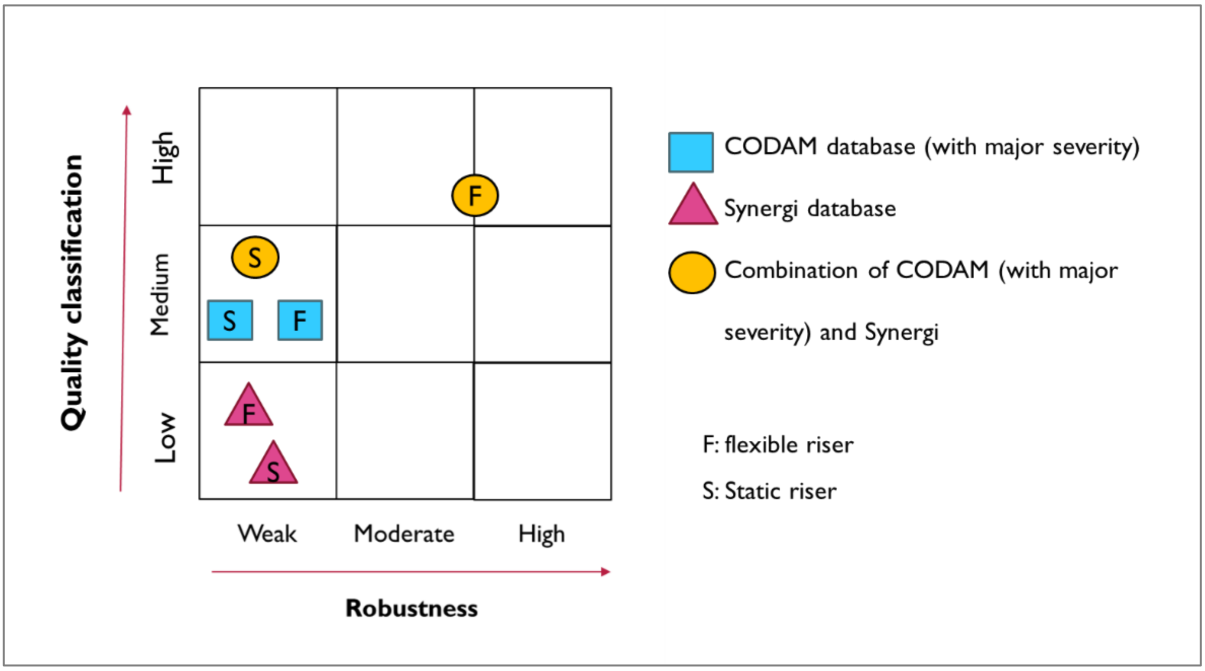


Figure 42 Classification of database quality and robustness aspects of the obtained results in this study in a simplified 3x3 matrix, modified after [48].

The uncertainty factors which have been highlighted in this chapter are listed in **Table 16** together with assigned assessor's degree of uncertainty for each factor and the impact of each uncertainty factor on the precision and quality of the frequency estimation. Five categories were defined, where 1 represents very low and 5 very high, to better reflect the assigned degree of uncertainty.

It is important to emphasise that the degree of assigned uncertainty is a selective judgment based on the background knowledge obtained during this study. Thus, the result of the degree of uncertainty for each factor and their impact on the frequency estimation in **Table 16** is presented in a 5x5 matrix in **Figure 43**. The matrix shows several factors have a high impact on the estimation of the damage and leak frequencies and the highest score for both the degree of uncertainty and the impact on the frequency estimation was assigned to (d), (c), (r), (n) and (q).

Thus, the maintenance, inspection, operational conditions, the precision of riser population data, considering the same conditions for all risers such as ageing and position in failure timeline, are believed to have the highest influence on the quality of the frequency estimation.

Nevertheless, the quality of reported incidents and the way they have been reported and described, including the selective judgment (h, f) and the variation of the installations type and their age (b), as well as a scarcity of static riser historical data (q) are important factors to assess.

In general, a reduction or increase in estimated frequencies is normally used based on different indicators and the historical data. If the historical data is believed to be unrepresentative of the future due to the learning of incidents and development in the technology, the frequency will usually decrease taking into consideration the reduction of the historical trend. Likewise, if the historical trend shows an increase, a conservative approach will be taken in order to be on the safe side. However, it is not always the best solution to be conservative as in the risk assessment process. This approach might impact the prioritisation and ranking due to the scarcity of the resources.

However, the historical data used in this study does not reveal any clear trend due to high incident rates in different years. The arguments for and against the reduction of the estimated frequencies are presented in **Figure 44** where several reasons were addressed to not lower the estimated frequencies due to many uncertainty factors. Hence, a more detailed study is required in order to reduce the uncertainty in the different aspects mentioned in **Figure 44.**

Table 16 An overview of important uncertainty factors associated with analysis of data and frequency estimation and their impact on the precision and quality of frequency estimation. 1 stands for very low and 5 stands for very high.

	Procedure	**Uncertainty factor**		**Degree of Uncertainty**	**Impact of the uncertainty factor on the precision and quality of frequency estimation**
Data analysis	Database selection (CODAM and Synergi)	**(a)**	The data used is representative for the future.	**3**	**4**
		(b)	The type and age of the installation was not taken into consideration.	**3**	**5**
		(c)	Operational conditions were not taken into consideration.	**5**	**4-5**
		(d)	Maintenances and inspections of the risers were not taken into the consideration.	**5**	**4-5**
	Incidents mining	**(e)**	Selection of definition for damage and leak (selective judgment for each case description)	**2**	**5**
		(f)	Quality of the search results and case description	**3**	**5**
		(g)	Considering incidents where the riser was in operation only	**2**	**5**
		(h)	The precision of the date of the reported incidents	**4**	**4**
	Categorisation and classification	**(i)**	Only riser body was taken into the consideration.	**1**	**5**
		(j)	Riser type was assigned for 39 risers from the population data (5,2% of the population).	**1**	**2**
		(k)	Categorisation based on mediums type was not taken into the consideration	**2**	**3**
		(l)	Categorisation of the risers based on dimension	**2**	**4**
		(m)	Categorisation of risers based on the type and use of other data sources (SISU and internal Equinor system)	**1**	**5**
		(n)	Considering the same conditions for all risers (ageing and where each riser in failure time is not considered)	**4**	**5**
Frequency calculation	Selection of time frame	**(o)**	Assuming the timeframe (2000-2016) is representative for frequency estimation	**2**	**5**
	Number of incident	**(p)**	Number of flexible riser incidents reported in 2000-2016	**3**	**5**
		(q)	Number of static riser incidents reported in 2000-2016	**3-4**	**5**
	Riser year calculation	**(r)**	The precision of registered date for installation, decommission and removing of risers	**4**	**5**

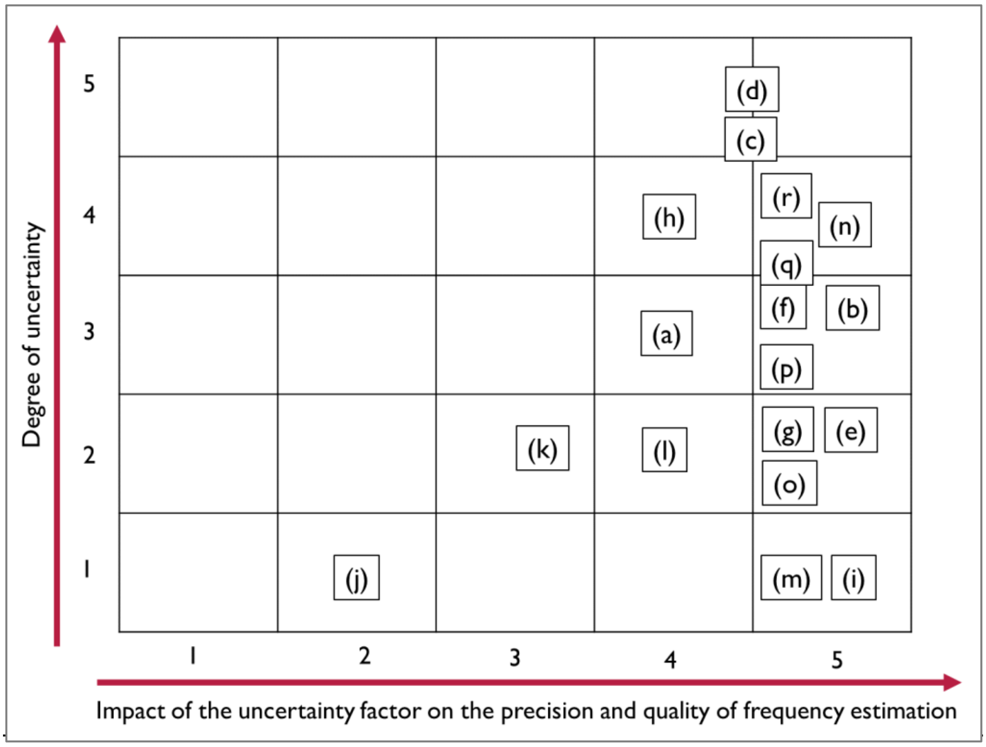
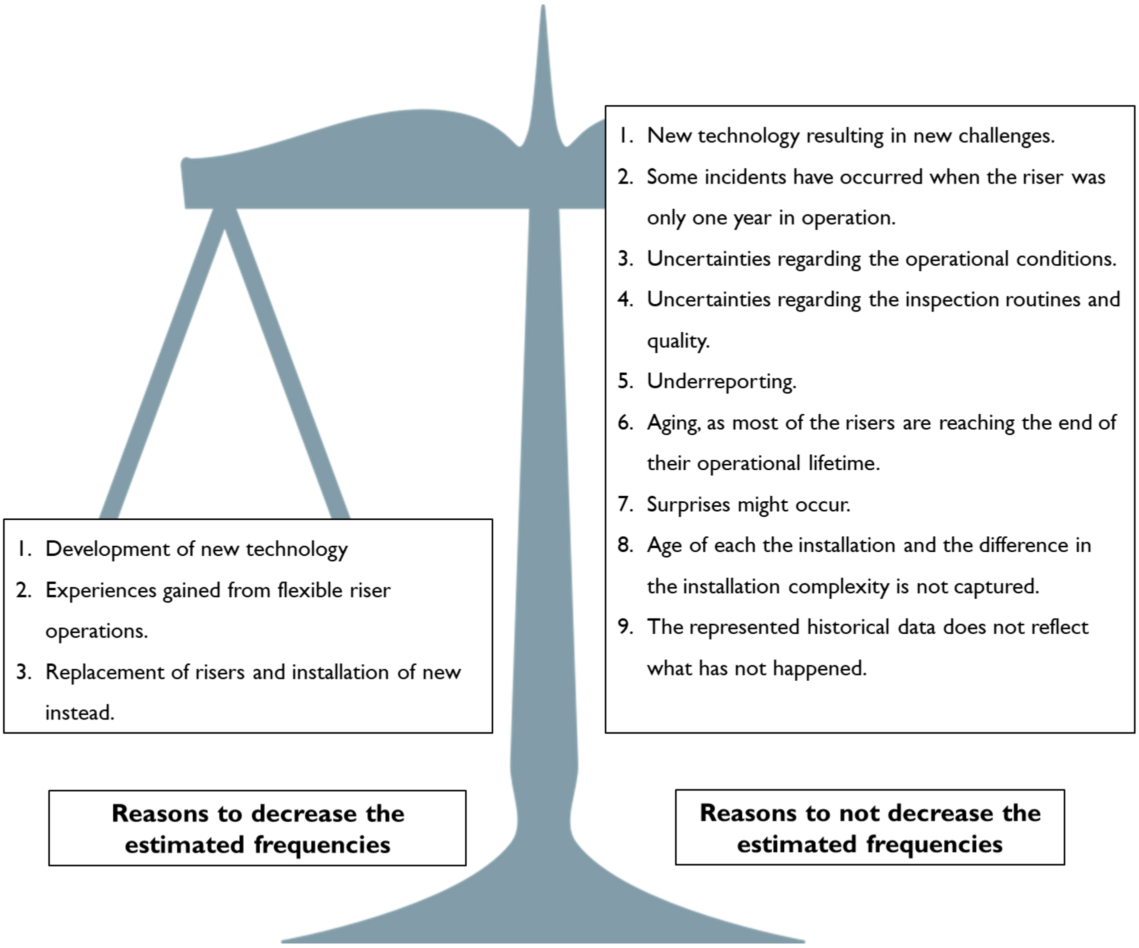


Figure 43 5x5 matrix showing the degree of uncertainty associated with data analysis and their impact on the precision and quality of the frequency estimation from Table 16.



1. New technology resulting in new challenges.
2. Some incidents have occurred when the riser was only one year in operation.
3. Uncertainties regarding the operational conditions.
4. Uncertainties regarding the inspection routines and quality.
5. Underreporting.
6. Aging, as most of the risers are reaching the end of their operational lifetime.
7. Surprises might occur.
8. Age of each the installation and the difference in the installation complexity is not captured.
9. The represented historical data does not reflect what has not happened.

1. Development of new technology
2. Experiences gained from flexible riser operations.
3. Replacement of risers and installation of new instead.

Reasons to decrease the estimated frequencies

Reasons to not decrease the estimated frequencies

Figure 44 Showing arguments for and against the reduction of the estimated frequencies.

Chapter 6 Conclusion

The following can be concluded based on this study:

- The combination of incidents reported by all operators in CODAM (with major severity) combined with the missing incidents, is considered to be the best available database.
- The estimated frequency in the time interval 2000-2016 for flexible risers, based on the combination of CODAM (with major severity) and missing incidents from Equinor, is as following:
    - Leak frequency is estimated to be 6,21x10^{-3}.
    - Damage frequency is estimated to be 8,96x10^{-3}, which is 1,4 times higher than the leak frequency.
- The estimated leak and damage frequencies in the time interval 2000-2016 for static risers for both categories ≤ 16" and >16" are estimated based on few incidents, which results in high sensitivity of the provided frequency. The uncertainties related to these frequencies have to be reduced by combining databases from other operators to provide possible frequencies.
- The estimated leak frequency from major incidents in CODAM, without including missing incidents from Equinor, within the time frame 2000-2016 shows an almost identical frequency compared to DNV GL leak frequency. This reveals how important it is to see beyond the frequency values as the numbers alone do not reflect the knowledge and data quality behind it.
- The comparison between the damage frequencies from this study with DNV GL was not possible, due to lack of damage frequency in the DNV GL report.
- The NCS has higher leak and damage frequencies than the UKCS, and by including incident data from UCKS, the frequencies will become lower and conceal the real risk picture. Nevertheless, there were differences in the environment, operational conditions, and the way the incidents were reported and collected. Variation in these factors will result in an increase of the uncertainties.
- Due to the difference in assumptions, incident selection criteria, and time intervals used in this study and Sureflex JIP, the results are not comparable.
- An improved basis for estimating the damage and leak frequencies of various hole sizes was not provided because of the scarcity of data.
- Collection, systemising, and combination of different databases in this study have enhanced the quality of the studied database in several aspects:

1. <u>CODAM database (with major severity):</u> multi reported incidents in the CODAM database were removed, ~25,6% of damage incidents and ~5,6 of leakage incidents for flexible riser. Missing incidents from Equinor were combined with the updated CODAM database with major severity.
2. <u>SISU:</u> classification of risers based on material types was carried out by studying several databases, including the internal system in Equinor.
3. <u>Synergi:</u> weaknesses of the Synergi database were highlighted.

Different conditions will give different consequences and results, as the estimated numbers are based on historical data that had its conditions and circumstances, i.e. these numbers should be used with caution as many possible scenarios are not covered in the historical data and surprises can occur. Hence, more studies are required in order to reduce the uncertainty factors and to combine different aspects, such as maintenance, inspection, age and operational conditions, as these aspects represent the highest uncertainty factors in the data.

6.1 Recommendation for further work

- To gather incident data, especially for static risers from other operators.
- To check and validate the riser year.
- Improvement and quality check of registered incidents in both Synergi and CODAM databases.
- Enhance the quality of the reporting process.
- A combination of all incidents in one database is important in order to increase the quality of the database and to reduce the uncertainty associated with the use of these databases.
- Multiple reported incidents should be removed from CODAM, or to be marked as an update if they are not removed. The multi reporting can be misleading and could give an unreal risk picture, which can affect the prioritising of which type of risk should be assessed.

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Appendices

Appendix A Different configuration of flexible risers

A.1 Free hanging catenary

It is considered to be the simplest configuration and installation for a flexible riser, where minimal subsea infrastructures are required (Figure 45). Some challenges are related to free hanging catenary design, such as over bending and compression near Touchdown Point (**TDP**) and hang-off tension for both static and dynamic [6]. This configuration is not common in the North Sea due to the harsh environment. Hence, there is a need for a more flexible configuration [15].

A.2 Lazy wave

The configuration of a lazy wave consists of a flexible riser fitted with buoyancy (Figure 46) in order to withstand vessel motion and harsh environment [6]. Advantages related to lazy wave configuration are: reduction in top tension and TDP loads, simple/moderate installation complexity, and high floater offset tolerance [6].

Nevertheless, there are some challenges related to the lazy wave design in deep-water, such as, interference, hang-off tension, loss of buoyancy, over bending near TDP and hang-off [6].

A.3 Steep wave

In the steep wave configuration, the riser is connected vertically to the riser base on the seabed, and it is a variation of the lazy wave (**Figure 47**). This kind of configuration can decrease the interference problems, but at the same time, it may result in higher tension on the riser base, both during the operation and installation [6].

There are two extra advantages for steep wave besides the same advantages for lazy wave configuration: moderate hog bend movement, and moderately sensitive to content density variation. The challenge for steep wave configuration in the deep-water is that it is more complicated than required in a moderate environment [6].

A.4 Lazy S

Lazy S configuration is obtained by using Mid Water Arch (**MWA**) where many risers can be path over the same subsea buoy, and the interference will be less. The primary disadvantage might be the effect of risers weight on buoy instability, while design challenges for deep-water are buoy stability and hydrodynamics [6].

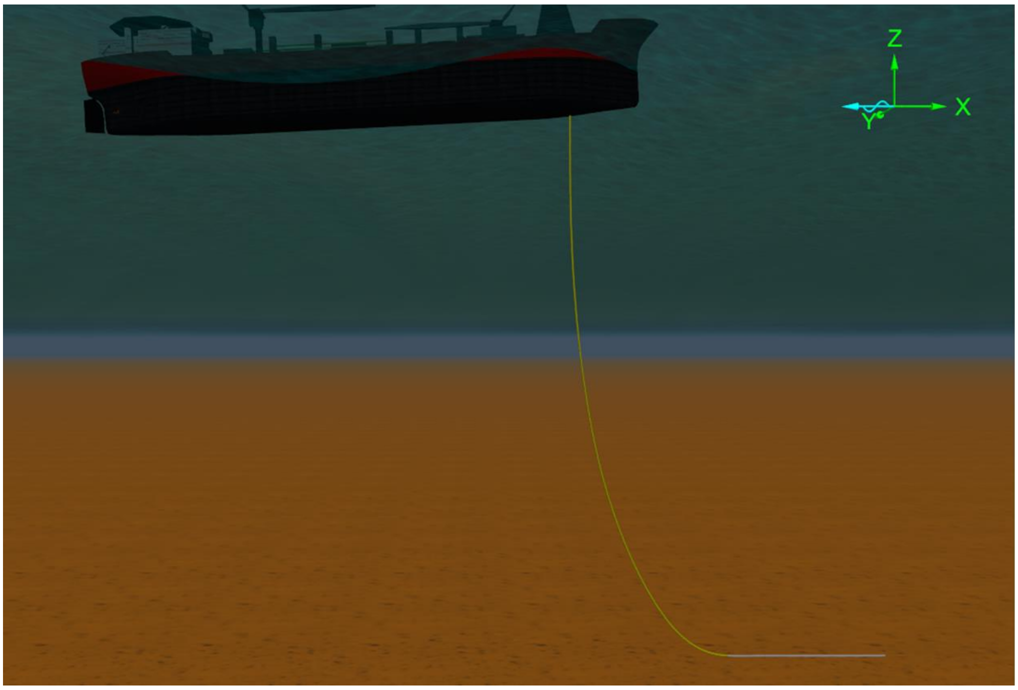


Figure 45 Free hanging riser configuration [49].

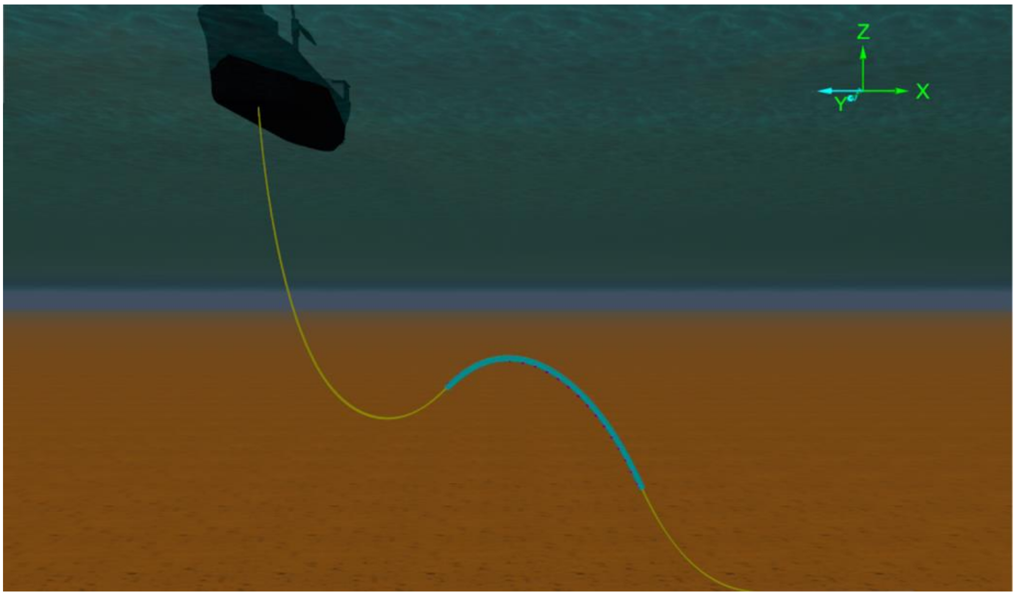


Figure 46 Lazy wave riser configuration [49]

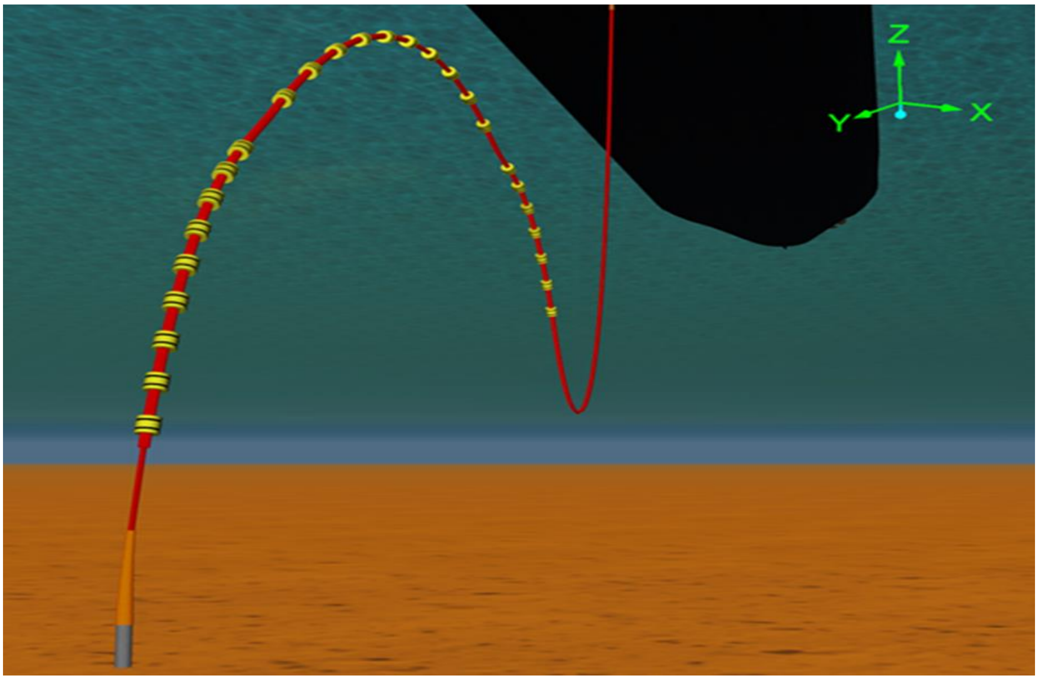


Figure 47 Steep wave riser configuration [49].

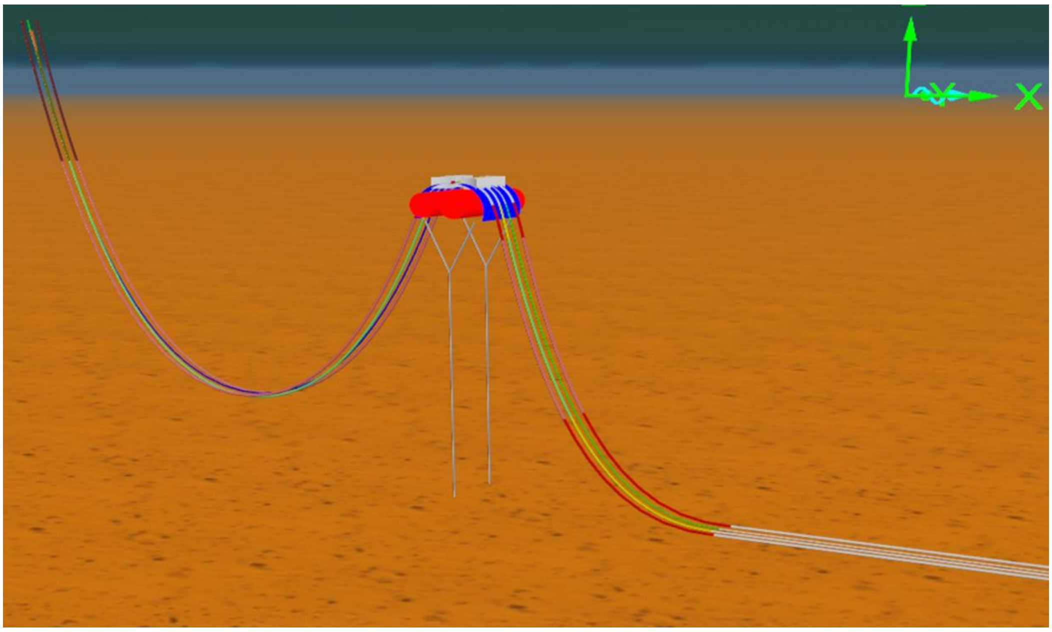


Figure 48 Lazy S configuration [49].

A.5 Hybrid Riser

Hybrid risers were developed to allow the riser system to be installed during or after the installation of a host platform to reduce the weight effect of the risers on the host platform and to help in reducing the effect of the host platform motion. It consists of a jumper that is an upper catenary section of flexible pipe and a lower vertical steel section which is under tension (**Figure 49**) and supported by submerged buoy[5, 16]. Free standing hybrid risers can be deployed both in a single line and bundle arrangements [16]. The role of Buoyancy/air can is to supply tension to the vertical steel section and to carry a part of the jumper's weight, and it often consists of one or more buoyancy tanks[5].

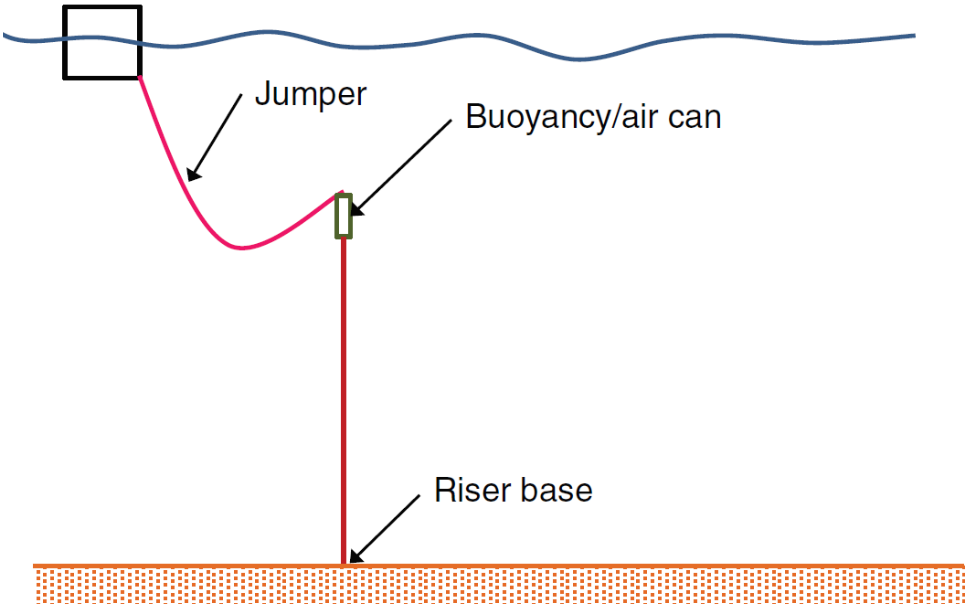


Figure 49 Hybrid riser configuration [5]

Appendix B Common failure mechanism for risers

B.1 Collapse failure

Riser collapse is a complicated phenomenon as it is associated with surface topography, the geometry of pipe, material properties[50]. Based on the historical data, the flexible risers have experienced two types of collapse, carcass and pressure liner collapse in rough bore pipes, and the collapse of internal pressure liner in smooth bore pipes [26].

Pressure liner collapse often occurs in water injection pipes as a result of vacuum entry during shut down to the bore due to flow effect [26]. The carcass collapse is caused by a difference in the external pressure and the pressure capacity of the carcass (**Figure 3**)[11].

B.2 Burst failure

Burst develops due to excessive forces or internal pressure where the material will rupture outwards, and it is the opposite of collapse (**Figure 50** and **Figure 51**). The typical failure mechanism for burst are: rupture of tensile or pressure armour due to excessive internal pressure, and rupture of the external sheath which may lead to the loss of pipe integrity [11].

Figure 50 Rupture of external sheath due to leak in end fitting [51].

Figure 51 Rupture of the external sheath due to blocked vent tubes[19].

B.3 Tensile failure

The tensile failure is common for both flexible and static risers as they are subjected to excessive tensile forces. The consequences may be a rupture in the tensile armour if a combination with other factors occurs, such as corrosion, fabrication or other anomalies which might result in resistance reduction[11]. **Figure 52** shows an example of how fatigue can cause rupture of tensile wires; abrasion as well can wear down the external sheath and some of the tensile wires which might cause the entire pipeline to rupture (Figure 53) [11].

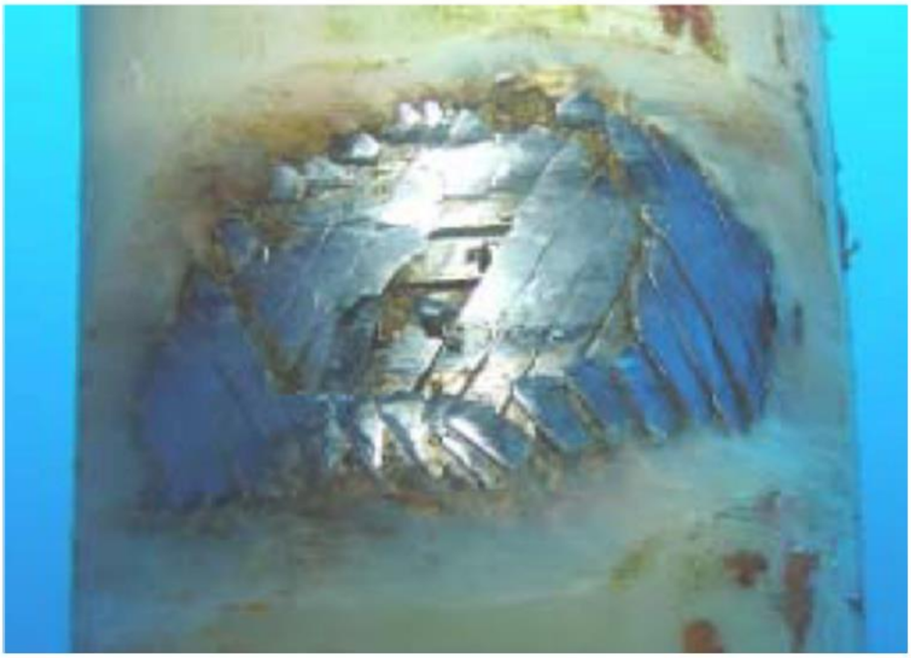


Figure 52 Tensile armour wire rupture due to abrasion [52].

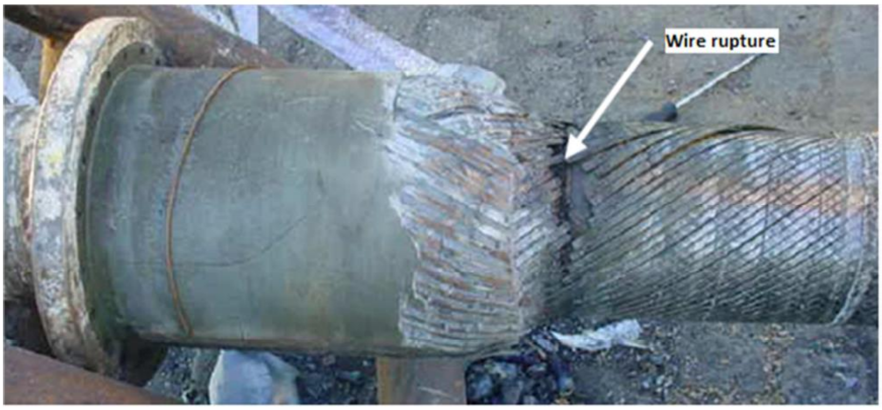


Figure 53 Rupture of tensile armour wire due to fatigue [52].

B.4 Compressive Failure

Compressive failure is due to the difference in the temperature between the ambient water and the riser material after starting production because of the introduction of warm gas and fluids. Consequently, the material in the risers will expand and compression forces will develop resulting in overbending and buckling[11]. Furthermore, numerous buckling modes have been seen in a flexible pipe that applies, as well, for flexible risers:

- **Lateral buckling due to elastic instability:** For a pipe with a damaged outer sheath that is subjected to axial compression combined with bending [26].

- **Lateral buckling due to overstress:** For a pipe with a undamaged outer sheath in deep-water, where frictional forces prevent the wires from moving until the critical bend is reached [26].
- **Radial buckling (bird-caging):** occurs mostly due to: yield failure of wires, elastic buckling without tape failure, and failure of the supporting layer as a result of high pressure from the layer beneath [53].

Figure 54 Shows an example of radial buckling (bird-caging)[54].

B.5 Overbending failure

Overbending is common in touch down point (TDP) and for flowlines as a result of buckling, where compression can occur on one side of the pipe due to bending while tension occurs on the other side. Consequently, collapse or rapture may occur because of the compression force and also reduction of the collapse resistance due to the ovalisation [11].

B.6 Torsional failure

The tensile armour wires are subjected to compression or tension as the riser is twisted due to the helical configuration of the tensile armour wires. Rupture of one or several wires might occur due to twisting as a result of excessive tension loads (**Figure 55**). The constant motion of floating production facilities due to wind, waves, and currents are the main source for torsion load [11].

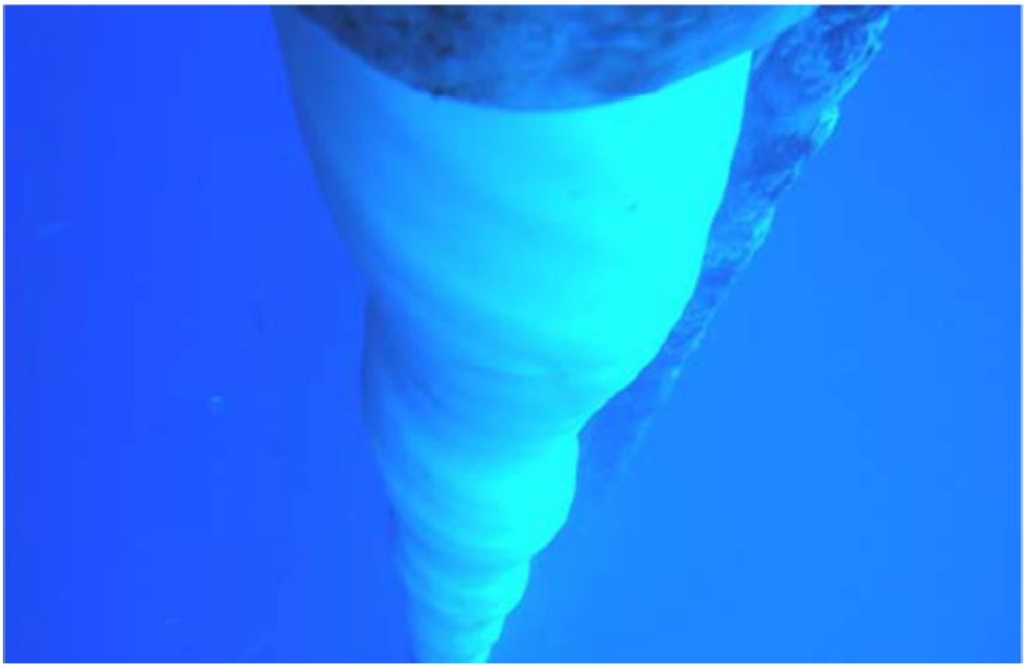


Figure 55 Shows torsion at the top of a riser due to ruptured armour wires[52]

B.7 Fatigue failure

All components used in the flexible riser cross-section may be exposed to mechanical fatigue, such as steel components[26]. Also, the effect of temperature cycle induced fatigue in PVDF should be taken into consideration under the investigation progress of damages within the flexible riser cross section [26].

Different types of fatigues in the material used in the flexible riser was experienced, such as carcass fatigue. Carcass fatigue occurred due to inaccuracies in fabrication or load conditions changing the carcass performance. Previous experience shows that when the flexible riser is interacting with arch structures, the carcass may experience significant stress levels. Hence, a pipe failure may result due to failed carcass [26].

On the other hand, the fatigue in the pressure and tensile armour did not contribute to pipe failures in operation. Design analysis was performed where the result shows that the fatigue failures are unlikely as the oldest flexible riser in the Norwegian water is older than ten years. Moreover, the assumption that the risers were located in an annulus dry environment was made for the design analysis. Nevertheless, experience shows that almost all production risers will fill the riser annulus with condensed water and the difference will be related to different pressure barrier material, temperature, well fluid etc. [26].

B.8 Erosion failure

In the flexible risers, erosion occurs due to the friction of particles in the produced fluids with the internal wall of the carcass resulting in degradation of the wall over time. Besides, hydrates development in a flexible riser may cause erosion problems. The high-velocity gas production may result in high risk for serious erosion [11].

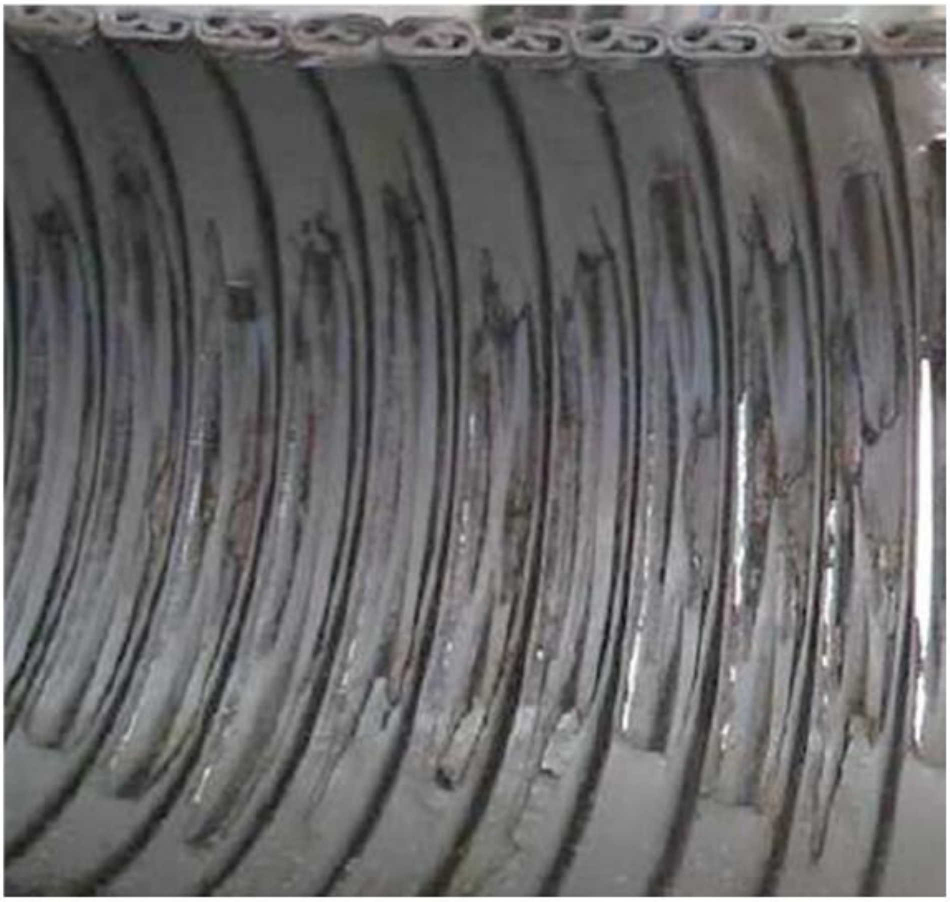


Figure 56 Shows internal erosion of carcass[19]

B.9 Corrosion failure

External and internal corrosion of risers is a common failure mechanism in the offshore industry. Both internal and external corrosion might result in the gradual degradation of the pipe wall thickness[4].

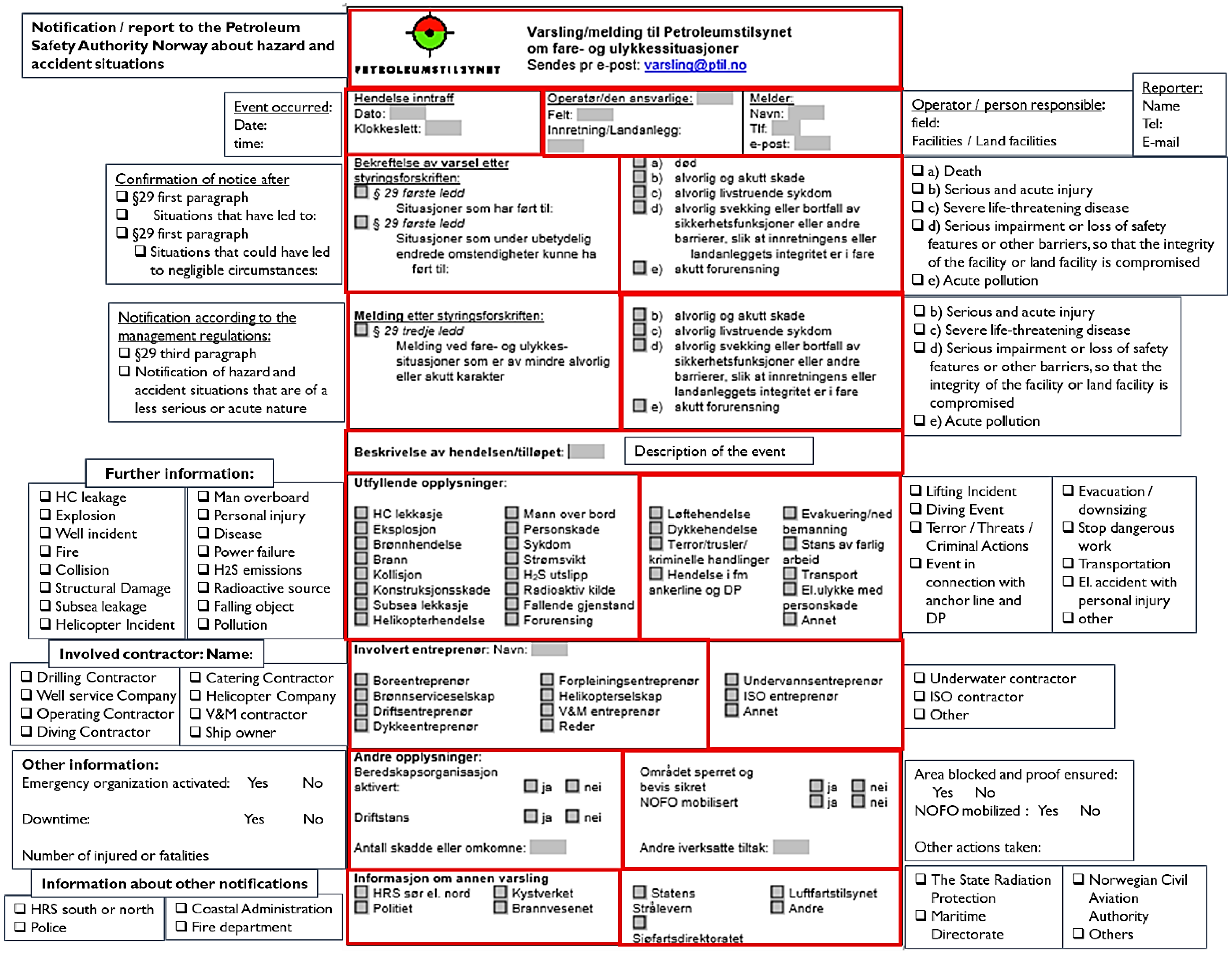
The corrosion fatigue in the flexible riser is linked to the flooding of pipe annulus, which is started either by the damage to outer or the inner shealf and may lead to tensile armour wire corrosion [11, 55]. The inner shealf damage is caused by the high pressure inside the pipe after the transportation of condensed water, while the outer shealf damage can result in ingress of seawater into the annulus[55]. Both environments are exposed to gases, such as CO_2 and H_2S

beside cyclic wave loading on the flexible riser all these factors can contribute to corrosion fatigue in flexible risers [55].

In addition, the internal corrosion depends on the existence of water in liquid form, which may originate either from gas condensing into liquid water under certain pressure or the liquid from the process. Nevertheless, the internal corrosion is considered to be a local issue as it will be for a specific pipeline, and it often occurs a few kilometres downstream from the pipeline starting point due to the change in the pressure and temperature[4]. In the case of the external corrosion, mounted anodes are used to prevent the corrosion or to avoid the corrosion reaching a critical level [4].

Figure 57 Shows corroded tensile armour wires due to a breach of outer sheath [19]

Appendix C



Notification / report to the Petroleum Safety Authority Norway about hazard and accident situations

PETROLEUMSTILSYNET

Varsling/melding til Petroleumstilsynet om fare- og ulykkessituasjoner
Sendes pr e-post: varsling@ptil.no

Event occurred:
Date:
time:

Hendelse inntraff
Dato:
Klokkeslett:

Operatør/den ansvarlige:
Felt:
Innretning/Landanlegg:

Melder:
Navn:
Tlf:
e-post:

Operator / person responsible:
field:
Facilities / Land facilities

Reporter:
Name
Tel:
E-mail

Confirmation of notice after
☐ §29 first paragraph
☐ Situations that have led to:
☐ §29 first paragraph
☐ Situations that could have led to negligible circumstances:

Bekreftelse av varsel etter styringsforskriften:
☐ *§ 29 første ledd*
Situasjoner som har ført til:
☐ *§ 29 første ledd*
Situasjoner som under ubetydelig endrede omstendigheter kunne ha ført til:

☐ a) død
☐ b) alvorlig og akutt skade
☐ c) alvorlig livstruende sykdom
☐ d) alvorlig svekking eller bortfall av sikkerhetsfunksjoner eller andre barrierer, slik at innretningens eller landanleggets integritet er i fare
☐ e) akutt forurensning

☐ a) Death
☐ b) Serious and acute injury
☐ c) Severe life-threatening disease
☐ d) Serious impairment or loss of safety features or other barriers, so that the integrity of the facility or land facility is compromised
☐ e) Acute pollution

Notification according to the management regulations:
☐ §29 third paragraph
☐ Notification of hazard and accident situations that are of a less serious or acute nature

Melding etter styringsforskriften:
☐ *§ 29 tredje ledd*
Melding ved fare- og ulykkes-situasjoner som er av mindre alvorlig eller akutt karakter

☐ b) alvorlig og akutt skade
☐ c) alvorlig livstruende sykdom
☐ d) alvorlig svekking eller bortfall av sikkerhetsfunksjoner eller andre barrierer, slik at innretningens eller landanleggets integritet er i fare
☐ e) akutt forurensning

☐ b) Serious and acute injury
☐ c) Severe life-threatening disease
☐ d) Serious impairment or loss of safety features or other barriers, so that the integrity of the facility or land facility is compromised
☐ e) Acute pollution

Beskrivelse av hendelsen/tilløpet:

Description of the event

Further information:

☐ HC leakage
☐ Explosion
☐ Well incident
☐ Fire
☐ Collision
☐ Structural Damage
☐ Subsea leakage
☐ Helicopter Incident

☐ Man overboard
☐ Personal injury
☐ Disease
☐ Power failure
☐ H2S emissions
☐ Radioactive source
☐ Falling object
☐ Pollution

Utfyllende opplysninger:

☐ HC lekkasje
☐ Eksplosjon
☐ Brønnhendelse
☐ Brann
☐ Kollisjon
☐ Konstruksjonsskade
☐ Subsea lekkasje
☐ Helikopterhendelse

☐ Mann over bord
☐ Personskade
☐ Sykdom
☐ Strømsvikt
☐ H_2S utslipp
☐ Radioaktiv kilde
☐ Fallende gjenstand
☐ Forurensing

☐ Løftehendelse
☐ Dykkehendelse
☐ Terror/trusler/ kriminelle handlinger
☐ Hendelse i fm ankerline og DP

☐ Evakuering/nedbemanning
☐ Stans av farlig arbeid
☐ Transport
☐ El.ulykke med personskade
☐ Annet

☐ Lifting Incident
☐ Diving Event
☐ Terror / Threats / Criminal Actions
☐ Event in connection with anchor line and DP

☐ Evacuation / downsizing
☐ Stop dangerous work
☐ Transportation
☐ El. accident with personal injury
☐ other

Involved contractor: Name:

☐ Drilling Contractor
☐ Well service Company
☐ Operating Contractor
☐ Diving Contractor

☐ Catering Contractor
☐ Helicopter Company
☐ V&M contractor
☐ Ship owner

Involvert entreprenør: Navn:

☐ Boreentreprenør
☐ Brønnserviceselskap
☐ Driftsentreprenør
☐ Dykkeentreprenør

☐ Forpleiningsentreprenør
☐ Helikopterselskap
☐ V&M entreprenør
☐ Reder

☐ Undervannsentreprenør
☐ ISO entreprenør
☐ Annet

☐ Underwater contractor
☐ ISO contractor
☐ Other

Other information:
Emergency organization activated: Yes No
Downtime: Yes No
Number of injured or fatalities

Andre opplysninger:
Beredskapsorganisasjon aktivert: ☐ ja ☐ nei
Driftstans ☐ ja ☐ nei
Antall skadde eller omkomne:

Området sperret og bevis sikret ☐ ja ☐ nei
NOFO mobilisert ☐ ja ☐ nei
Andre iverksatte tiltak:

Area blocked and proof ensured: Yes No
NOFO mobilized : Yes No
Other actions taken:

Information about other notifications

☐ HRS south or north
☐ Police

☐ Coastal Administration
☐ Fire department

Informasjon om annen varsling
☐ HRS sør el. nord
☐ Politiet

☐ Kystverket
☐ Brannvesenet

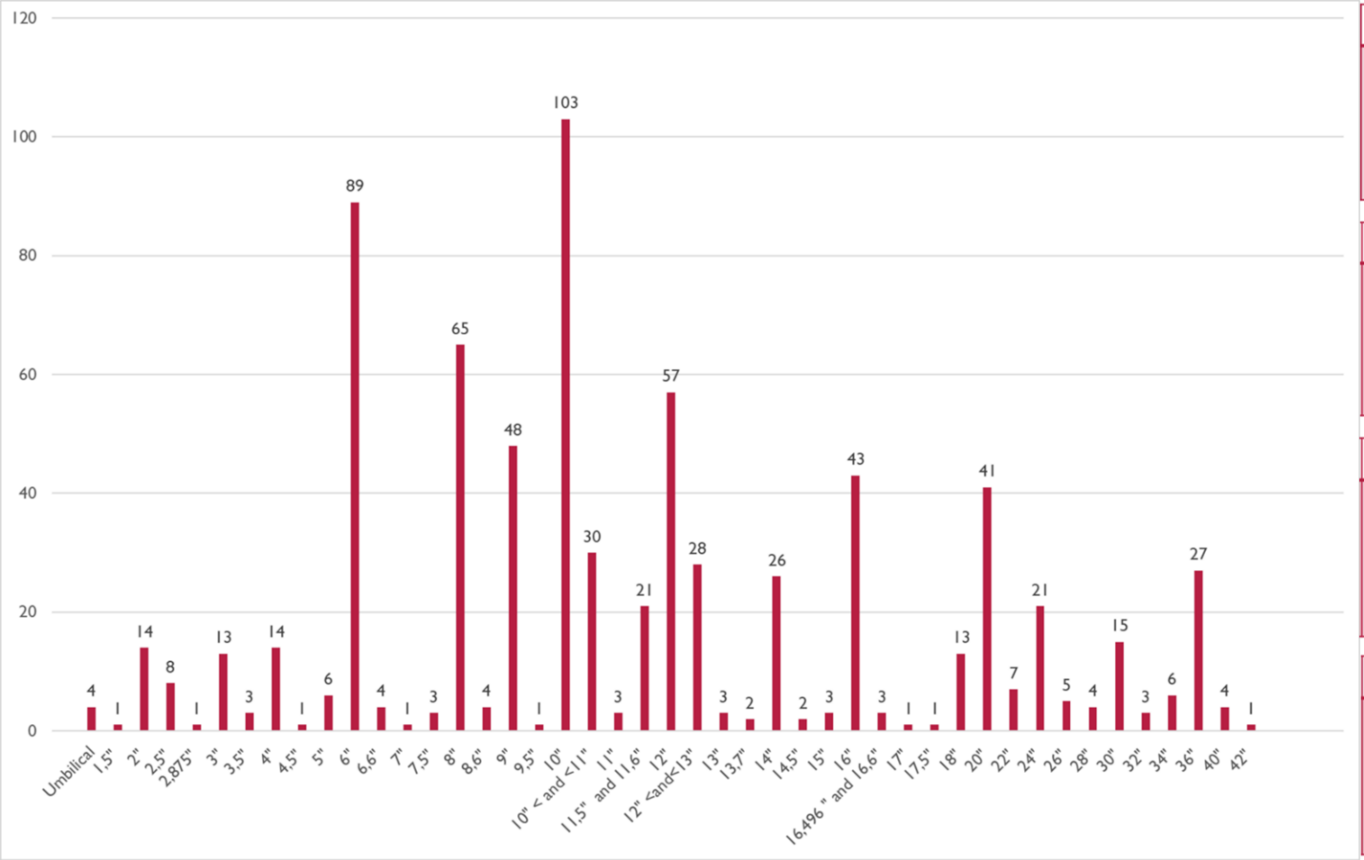
☐ Statens Strålevern
☐ Sjøfartsdirektoratet

☐ Luftfartstilsynet
☐ Andre

☐ The State Radiation Protection
☐ Maritime Directorate

☐ Norwegian Civil Aviation Authority
☐ Others

Figure 16 Interpreted report form used to report incidents to PSA, the original report from PSA



10"<and <11": 30 risers

1 with dimension of 10,3"
6 with dimension of 10,5"
1 with dimension of 10,744"
2 with dimension of 10,748"
19 with dimension of 10,75"

11,5" and 11,6": 21 risers

11 with dimension of 11,5"
10 with dimension of 11,600004"

12"<and<13": 28 risers

23 with dimension of 12,75"
3 with dimension of 12,717"
2 with dimension 12,953"

16,496" and 16,6": 3 risers

1 with dimension 16,4960003
2 with dimension of 16,600004

Figure 58 An overview of riser dimension and the quantity. Data from SISU.

Major incidents reported in CODAM

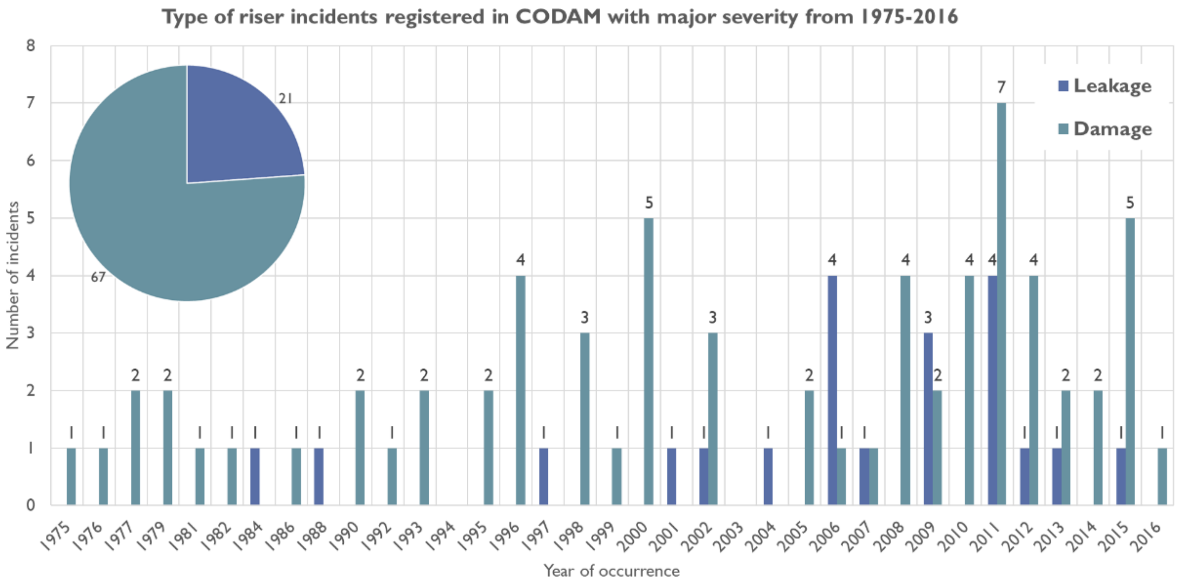


Figure 59 A diagram shows type of registered incidents registered as major in CODAM, the classification was made based on the definition of damage and leak used in this study.

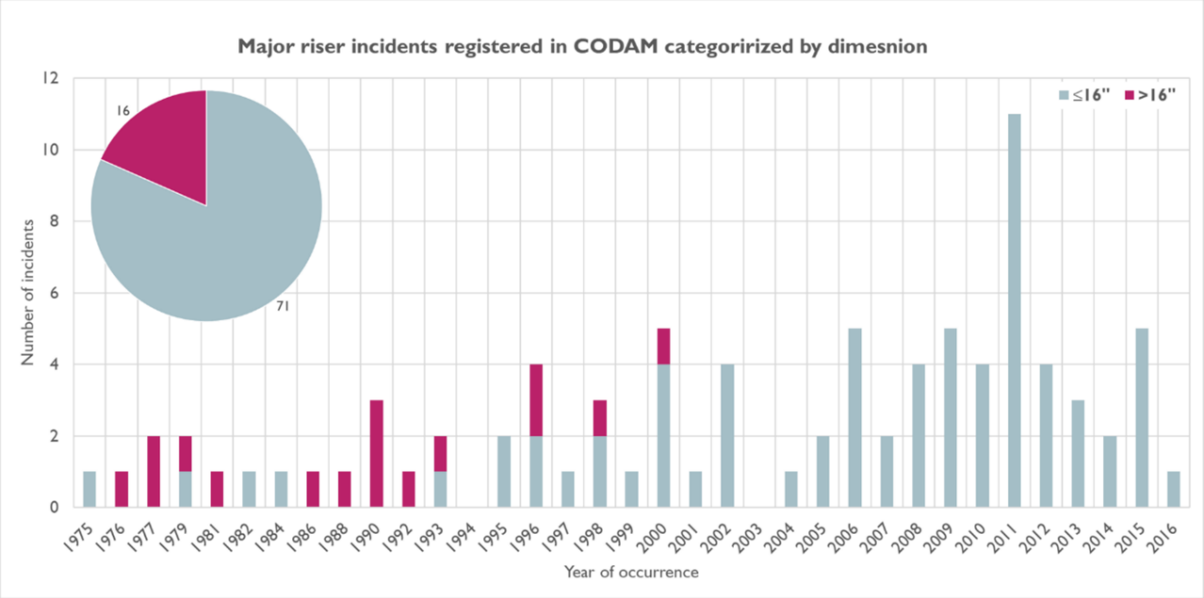


Figure 60 A diagram shows major registered in CODAM categorised by riser dimension.

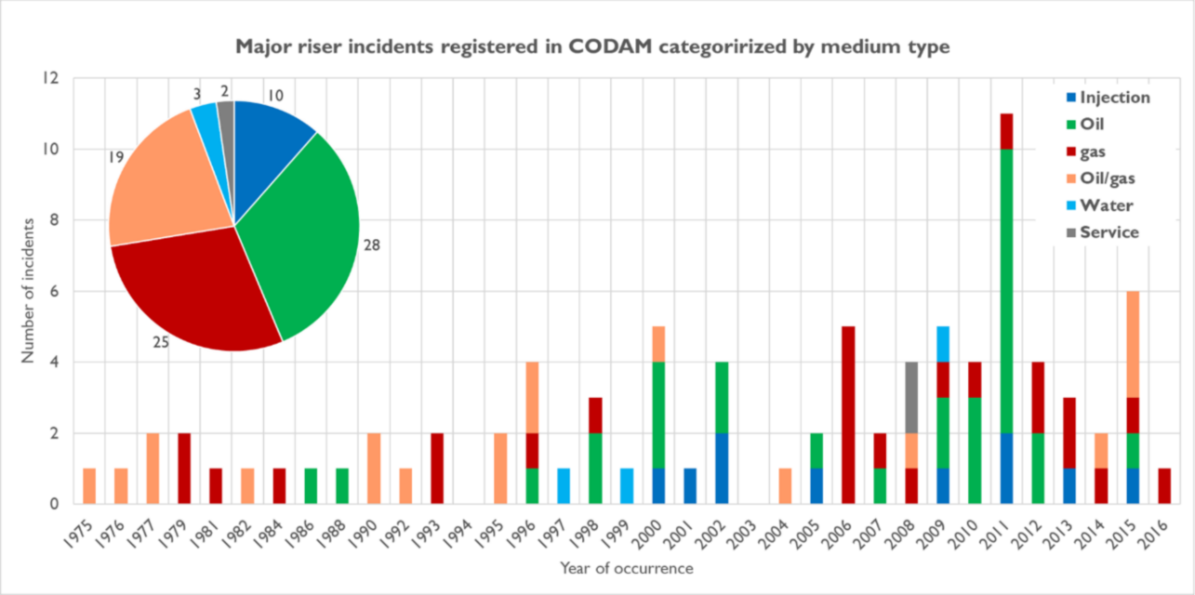


Figure 61 A diagram shows risers major incidents registered in CODAM categorised by medium type.

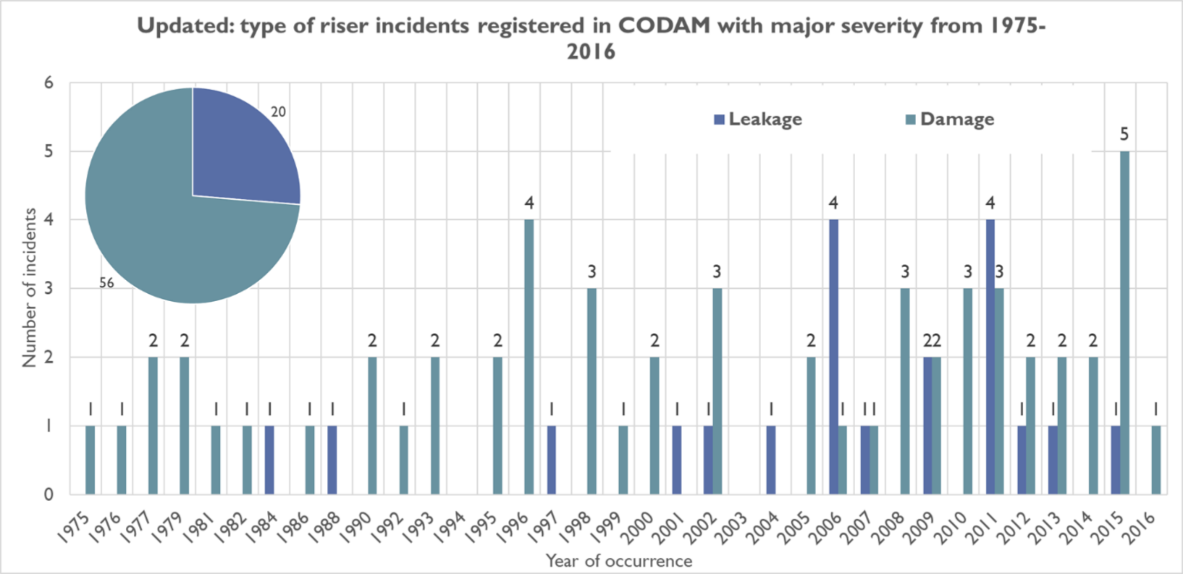


Figure 62 An updated diagram from Figure 59 shows type of registered incidents registered as major in CODAM, where the multi reported incidents were excluded. The classification was based on the definition of damage and leak used in this study.

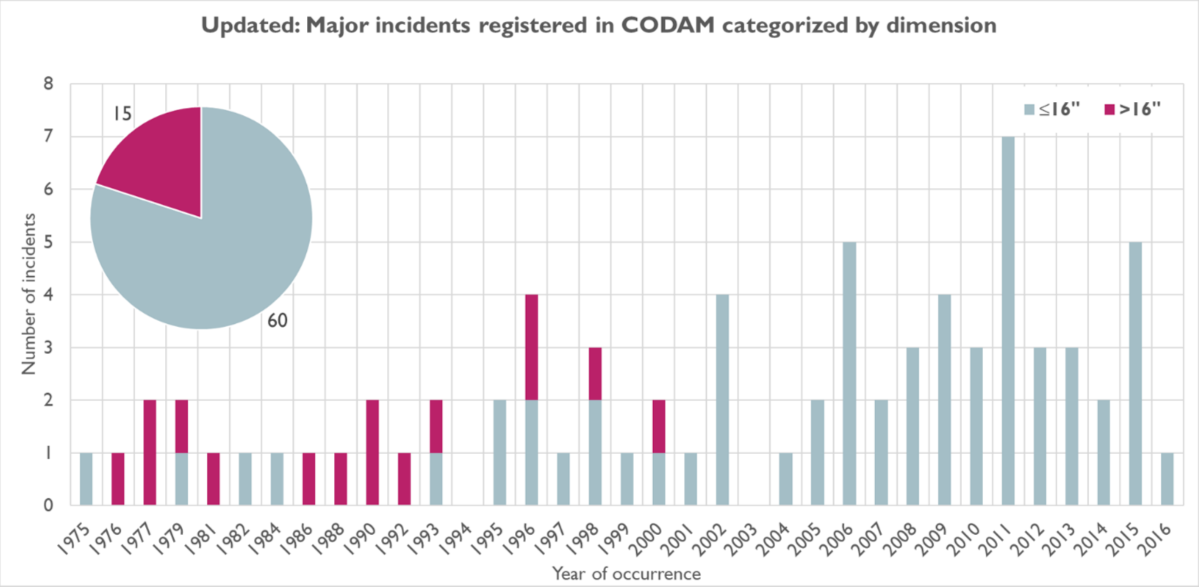


Figure 63An updated diagram shows major incidents registered in CODAM categorised by riser dimension.

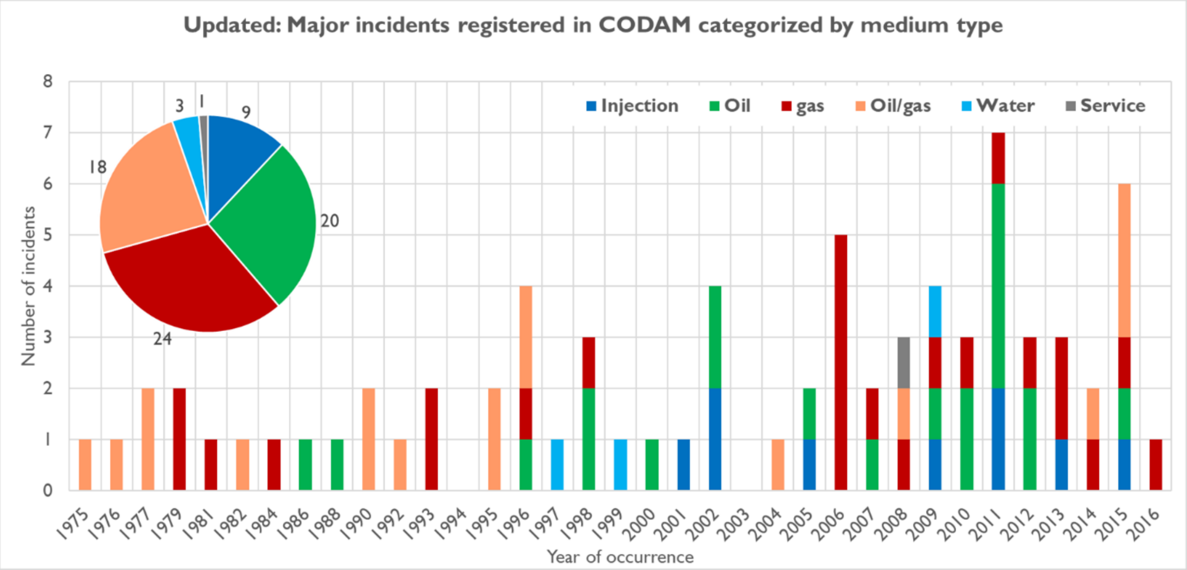


Figure 64 An updated diagram shows risers major incidents registered in CODAM categorised by medium type

Minor incidents reported in CODAM

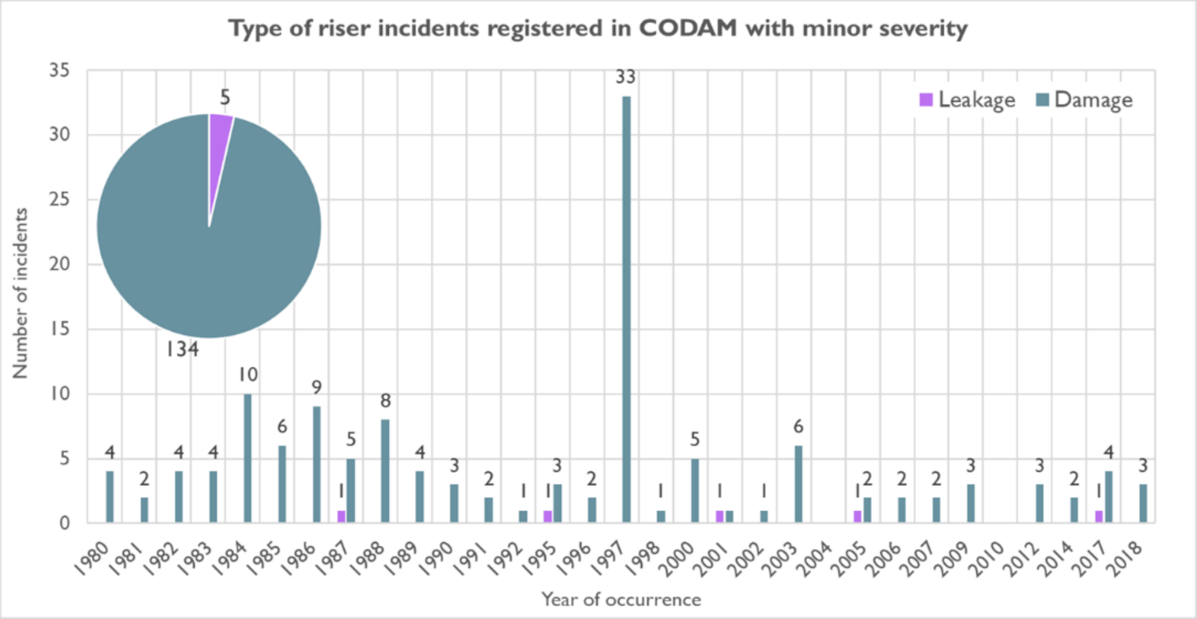


Figure 65 A diagram shows an overview over registered riser incidents in CODAM with minor severity.

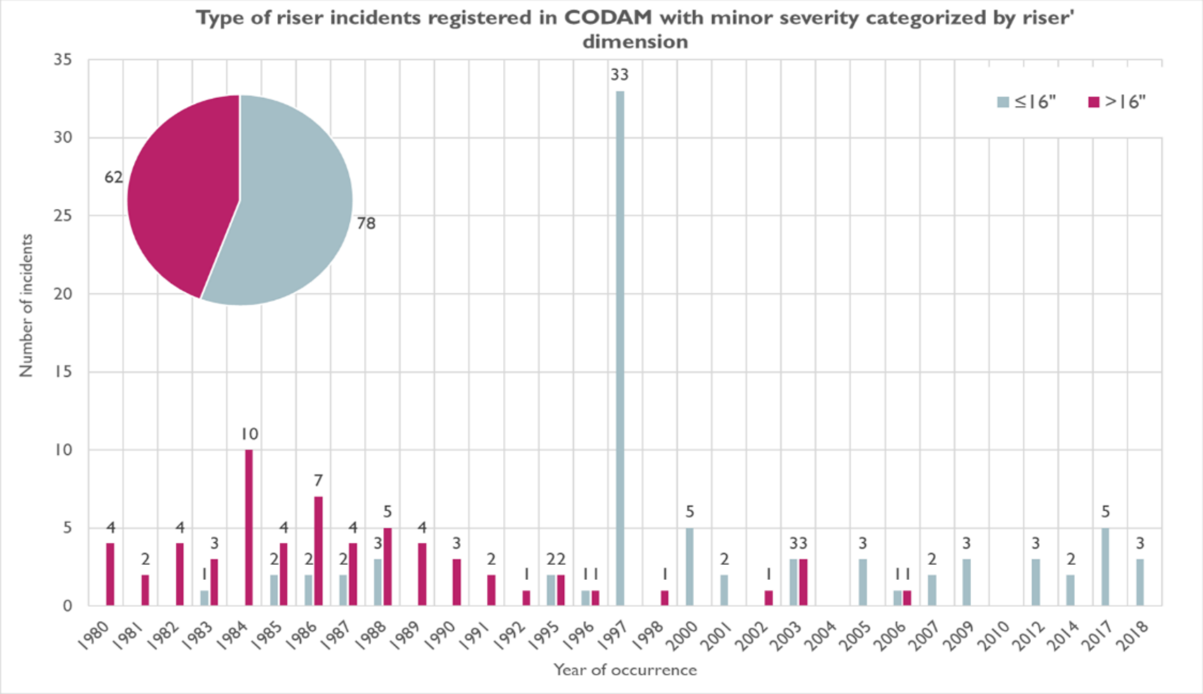


Figure 66 An overview of minor incidents registered in CODAM categorised by riser dimension category.

Equinor’s database, Synergi Life

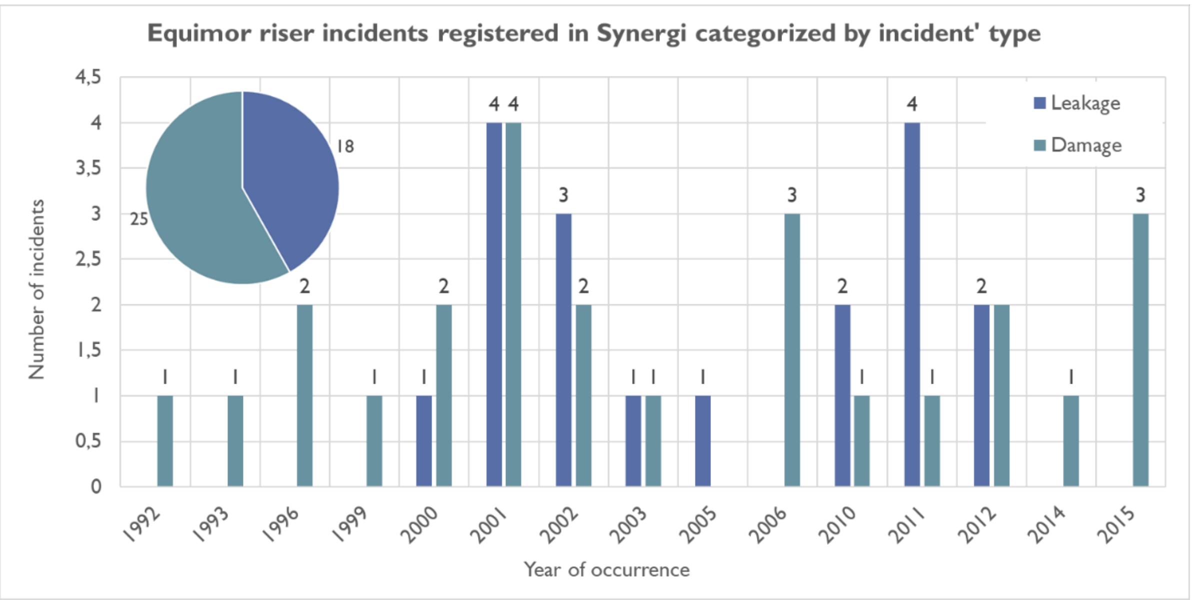


Figure 67 An overview of search results of leak and damage incidents in Equinor's database Synergi.

Combination of Equinor reported incidents in CODAM and Synergi

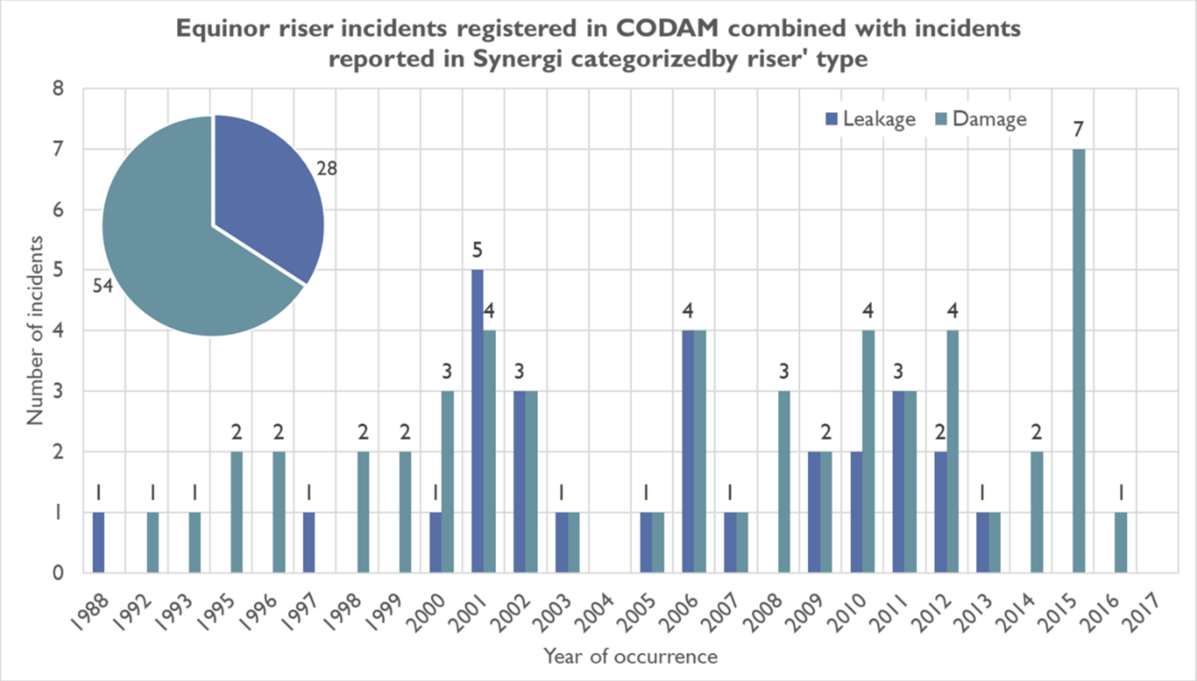


Figure 68 An overview of the combination of registered incidents in Synergi and reported incidents by Equinor (which are classified as major) in CODAM.