University of Stavanger

**Faculty of Science and Technology**

# MASTER'S THESIS

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|---|---|
| Study program/ Specialization:<br><br>Offshore Technology<br>Marine and Subsea Technology | Spring semester, 2015<br><br>Open |
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Thesis title:

Anchor Damage Assessment of Subsea Pipelines - Optimization of Design Methodology

Credits (ECTS):
30

| | |
|---|---|
| Key words:<br><br>Offshore, Pipelines, Anchor Dragging, Pipe-Anhcor Interaction Scenario, Pipeline Response, Cross-Sectional Capacity Check, SIMLA | Pages: 118<br><br>+ enclosure: 11<br><br>Stavanger, 12.06.2015<br>Date/year |

# ANCHOR DAMAGE ASSESSMENT OF SUBSEA PIPELINES - OPTIMIZATION OF DESIGN METHODOLOGY

Master thesis/ Offshore Technology, Marine and Subsea Technology


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Spring, 2015



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## ABSTRACT

The world's energy resources on land are getting depleted, and mush attention is given to the development of offshore fields. Over the past years, new reserves located offshore have been regularly discovered. Once the hydrocarbons have been extracted, it is necessary then to transport them to the storage places, refineries or gas processing plants, and to deliver to the consumers. There are several ways of hydrocarbon transportation. One of the most cost-effective and popular means of oil and gas transportation is pipelines.

Construction and operation of subsea pipelines are known to be very hazardous and risky processes. In order to ensure reliable and safe operation of submarine lines, it is essential to design them according to the international standards and codes. However, observance of rules sometimes does not guarantee safe pipeline operation. Some undesirable events can occur from time to rime. One of such events is dragging anchor incident, which poses great threat to the subsea lines. The consequences of this incident may be huge, involving environmental pollution, asset losses and even fatality. The mitigation of these outcomes becomes problematic, expensive and impossible. That is why it is recommended to carry out relevant investigations before the mitigation measures are planned and implemented.

This work is mainly focused on the anchor damage assessment of subsea pipelines. The comprehensive discussion on a PARLOC 2001 database is done in order to determine major pipeline incidents, their causes and consequences. The questions regarding pipe-anchor interaction scenario have been studied a lot. It has been found that the extent of pipeline damage is heavily dependent on its unique properties. In addition, not only the pipeline data, but also a combination of vessel characteristics and anchoring equipment parameters has been very useful for the analyses.

Based on the results of AIS ship traffic data processing, main pipe damage criteria checks have been performed. The findings indicate that not all the anchors have potential of hooking and approaching the pipeline resting on the seafloor. Key parameters here are anchor class (size), chain length, ship speed and water depth. Moreover, the geometrical configuration of all the anchors has been taken into account as well. Not only a theoretical approach, but a model scale test has been carried out in order to understand the variation of anchor towing depth with different ship velocities. The comparison of analytical solution results with the experimental results is also included in this thesis.

Anchor pulling consequences are established in accordance with the global scale analyses performed in the FE program SIMLA for a certain number of sensitivity cases for both small (16-inch) and large (40-inch) diameter pipelines. The pipelines responses have been determined, and their cross-sectional capacities have been checked. In addition, pipelines failure frequencies have been estimated.

This work shows how critical it is to have detailed ship and equipment class data for doing pipeline integrity assessment. In accordance with the results obtained, the dragging anchor interference assessment methodology is developed.

**ACKNOWLEDGEMENTS**

I would like to express my deep gratitude to my faculty supervisor Dr. Ljiljana Djapic Oosterkamp. Her advice, meaningful assistance, patience and support helped me to complete my master thesis.

I would like to thank my external supervisor Mr. Per Rishard Nystrøm, Engineering Manager at IKM Ocean Design, who inspired me a lot during my thesis writing. I appreciate his valuable ideas and keen interest on every stage of the work.

I also thank Mrs. Kristin Sandvik and other employees at IKM Ocean Design for their kind help and guiding comments throughout the course of my thesis. They were always available for my questions.

I am very grateful to Professor Ove Tobias Gudmestad, who encouraged me to take this topic. His vast knowledge in the area of Offshore Technology has helped me to track my project in the correct path.

I would like to thank John Grønli, Laboratoriy Manager at the University of Stavanger, and members of UiS Subsea. It would be impossible to carry out an experiment without their suggestions and contribution.

Special thanks to my scientific adviser at Gubkin University, Professor Anatoly Zolotukhin, who continually supported me throughout this master program.

## LIST OF FIGURES

## LIST OF TABLES

## ABBREVIATIONS

AIS - Automatic Identification System

ALS - Accidental Limit State

BOP - Blowout Preventer

DCC - Displacement Controlled Condition

DEA - Drag Embedment Anchor

EL - Equipment Letter

EN - Equipment Number

FE – Finite Element

FLS - Fatigue Limit State

GoM - Gulf of Mexico

GRT - Gross Register Tonnage

GT - Gross Tonnage

IMO - International Maritime Organization

KP - Kilometer Point

LCC - Load Controlled Condition

LRFD - Load and Resistance Factor Design

MAOP - Maximum Allowable Operating Pressure

MMSI - Maritime Mobile Service Identity

PARLOC - The Pipeline and Riser Loss of Containment

SLS - Serviceability Limit State

SMTS - Specified Minimum Tensile Strength

SMYS - Specified Minimum Yield Stress

SPM - Single Point Mooring

ULS - Ultimate Limit State

VTS - Vessel Traffic Services

# CHAPTER 1. INTRODUCTION

## 1.1 BACKGROUND

21$^{st}$ century is a century of enormous energy consumption. The energy is arguably the spine of human life on our planet. The need for energy is insatiable and we need to constantly think of new ways to try to meet this need. However, resources on land are fast depleting, hence it is necessary to explore new reserves to extract oil and gas. Over the past couple of decades, we have seen that new reserves regularly discovered are located on offshore sites. As a result, offshore field development is receiving great interest. The new oil and gas fields on the continental shelf are fast becoming major global energy reserves. To move extracted energy resources to the storage places, refineries or gas processing plants, and to deliver them to the consumers, several means of products transportation are used. One of the most popular means is pipeline. Submarine pipelines are laid across different territories of the world. For this reason a lot of attention should be given to their monitoring, considering safety and environmental questions.

Construction and operation of pipelines are known to be very hazardous and risky processes. To mitigate the risks and to exclude the causes of pipeline failures, it is necessary to design, construct and manage the pipelines safely and in an appropriate way according to the international codes and standards. Sometimes even observance of necessary rules does not guarantee safe pipeline operation. Statistic shows that high-technology solutions and innovations help to decrease the probability of any failures. However, there are still some undesired events that cannot be completely avoided. One of such cases is pipeline anchor damage. This accident can lead to the consequences like fatality, fire, explosion, environmental pollution and asset losses. Mitigation of such outcomes becomes difficult, expensive and even impossible. Even in a best-case scenario, when the pipeline suffers minor damage, the consequences can be serious: extended pipeline shutdowns, disruption of a schedule and financial problems.

## 1.2 PROBLEM STATEMENT

In case if ship anchor is accidently dropped and dragged over the pipeline, the latter may suffer damage, lose its integrity and leak. Even though the pipeline failures and their causes are studied and discussed a lot, there are still some questions regarding anchor damage threats to submarine pipelines. An extent of damage strongly depends on pipe unique properties, vessel characteristics and anchor parameters. In addition, AIS ship traffic data with ship particularities (identification number, type, gross tonnage, equipment specifications, etc.) is to be included into the assessment as well. A combination of all these factors is of great importance for the dragged anchor interference analysis and failure frequency estimation. Based on the findings and results of the detailed investigation, risk reducing measures can be proposed and implemented if necessary. Eventually, the design methodology can be optimized and applied where appropriate for both existent and new pipeline projects.

## 1.3 PURPOSE AND SCOPE

The analysis is primarily focused on a given gas pipeline called “Pipeline 1”, which is located in the North Sea. Typical pipeline and ship traffic details are taken as a basis for the present work.

The emphasis is placed on the whole pipeline including all the KP sections and possible anchoring zones. Several sensitivity cases are distinguished along the pipeline route and selected in order to establish anchor dragging consequences and to estimate the pipeline failure frequencies. All the analyses are performed in the most conservative way, considering the worst cases.

Scope of the thesis:

1. Study of the design objectives and main aspects of pipeline route selection.
2. Pipeline hazards investigation. Detailed definition and study of the PARLOC 2001 database.
3. Analysis of the ship anchoring effect on submarine pipelines by using the corresponding theoretical approach.
4. Collection of relevant data needed for the assessment.
5. Dragged anchor interference assessment. Anchor hook/hit/damage checks.
6. Carrying out of model scale test on the variation of anchor towing depth with different towing speed. Verification of the results.
7. Establishment of pipe-anchor interaction consequences by performing global scale analysis in SIMLA finite element program. Check of large and small diameter pipelines responses and cross-sectional capacities.
8. Failure frequency estimation procedure for both large and small size pipelines.
9. Discussion and methodology description.
10. Drawing up of the conclusions with regard to the analysis and frequency estimation results.

## 1.4 THESIS ORGANIZATION

Chapter 2 presents pipeline design objectives. It points out the main factors influencing the selection of pipeline route, namely: environment, seabed features, facilities, landfall and third party activities.

Chapter 3 describes possible pipeline threats, their causes and consequences. It also defines the purpose of pipeline databases. Detailed discussion of PARLOC 2001 database is included in this chapter. The most frequently encountered incidents, involving steel and flexible lines, are studied and analyzed as well.

Chapter 4 explains the ship anchoring procedure and its effect on submarine pipelines. Comprehensive theoretical approach is presented here. The chapter defines vessel classification and its characteristics. Particularities of vessel equipment (anchor and chain) are discussed as well. In addition, the chapter provides complete description of pipeline damage criteria that is of great importance for further analysis.

Chapter 5 presents dragged anchor interference assessment. The chapter includes AIS data processing based on the typical pipeline route. Collection of missing data for different ships with respect to IMO-no, name, type, EL, GT, speed and vessel coordinates is done as well. All the information is used for the anchor hook, hit and damage criteria checks. The chapter also provides a description of model scale test on the variation of anchor towing depth with different ship velocities. The comparison of analytical solution results with the experimental results is also included. Anchor pulling consequences are established in accordance with the global scale analyses performed in finite element program for several sensitivity cases for both small and large diameter pipelines. The pipelines responses are determined, and the cross-sectional capacities are checked. In addition, anchor dragging induced frequencies estimation is presented in this chapter. In accordance with the results obtained, the dragging anchor interference assessment methodology is developed.

Chapter 6 comprises complete discussion based on the results and findings obtained from the studies, tests and analyses. All the assumptions taken for the present work are listed as well. Some recommendations for the further studies and analyses are given in this chapter.

# CHAPTER 2. PIPELINE DESIGN BASIS

## 2.1 DESIGN PHASES

In order to ensure reliable and safe operation of submarine pipelines, it is essential to design them according to the international standards, codes and practices. Pipeline design procedure mainly consists of three stages (Bai, 2001):

I. Conceptual engineering;
II. Preliminary engineering;
III. Detail engineering.

Each stage is of great importance and has a set of basic objectives which are to be given below.

*Conceptual engineering objectives:*

- Establishment of technical feasibility and constraints on the system design and construction;
- Elimination of non-viable options;
- Identification of required information for the design and construction processes;
- Preparation of the basic cost and scheduling exercises;
- Identification of interfaces with planned or existent systems.

*Preliminary engineering objectives:*

- Pipeline design: verification of pipeline size, determination of grade and wall thickness;
- Verification of pipeline against design and code requirements;
- Authority applications preparation;
- Material take-off and order of the line pipe.

*Detailed engineering objectives:*

- Route selection and optimization;
- Wall thickness and coating selection;
- Confirmation of code requirements on strength, vortex-induced vibrations, on-bottom stability, global buckling and installation;
- Detailed design and drawings preparation: pipelines, tie-ins, crossings, risers, shore approaches and subsea structures;
- Preparation of alignment sheets according to the recent survey data;
- Preparation of specifications on materials, costs, construction works (laying, survey, welding, riser and spoolpiece installation, tie-ins, structures installation) and commissioning (flooding, pigging, hydrotest, drying);
- Material take-off, procurement of materials;
- Preparation of design data and necessary information for the certification authorities.

There is a set of main pipeline design issues that is to be taken into account during pipeline design stages:

1. Environmental issues: water depth profile; weather conditions; information about currents, waves, and ambient temperature variations. Seasonal changes should be specified as well.
2. Seabed particularities: geotechnical characteristics; tectonic movement details; seabed topography data.
3. Flow issues: fluid type, flowrate, pressure and temperature information, water profile.

Specifying the issues mentioned above, it is possible to design the pipeline in an appropriate way, so that its integrity is ensured through all the pipeline system phases: from the concept development to the pipeline abandonment (Figure 1).

| Business development | Concept development | Basic design | Detail design | Linepipe | Components and assemblies | Corrosion protection and weight coating | Pre-intervention | Installation | Post-intervention | Pre-commissioning | Commissioning | Integrity management | Inspection and repair | Re-qualification | Abandonment |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***Concept*** | | ***Design*** | | ***Construction*** | | | | | | | ***Operation*** | | | | |
| ***Establich integrity*** | | | | | | | | | | | ***Maintain integrity*** | | | | |

*Figure 1: Pipeline system phases (DNV-OS-F101, 2013)*

## 2.2 ROUTE SELECTION

Route selection, being one of the objectives of the detailed pipeline engineering, is a critical aspect, affecting all the phases of pipeline project. *The pipeline route shall be selected with due regard to safety of the public and personnel, protection of the environment, and the probability of damage to the pipe or other facilities* (DNV-OS-F101, 2013). There are a lot of factors influencing the selection of the pipeline placement. These factors are mainly seabed features, geotechnical and environmental condition, seasonal changes, etc. The identification of pipe location particularities, issues and problems can be done by applying geographical information system and different route surveys techniques. As soon as all the relevant information is obtained, it becomes easier to suggest, select and develop successful pipeline route.

Typical routing is influenced by a set of factors which are presented in the Table 1 below (DNV-OS-F101, 2013).

Table 1: Factors influencing pipeline route selection

| ***Factor*** | ***Factor identification and comments*** |
|---|---|

| | |
|---|---|
| *Environment* | • archaeological sites;<br>• exposure to environmental damage;<br>• areas of natural conservation interest (oyster beds and coral reefs);<br>• marine parks;<br>• turbidity flows. |
| *Seabed characteristics* | • uneven and unstable seabed;<br>• soil properties;<br>• subsidence;<br>• seismic activity. |
| *Facilities* | • offshore installations;<br>• subsea structures and well heads;<br>• platform anchor patterns;<br>• existing pipelines and cables;<br>• obstructions;<br>• coastal protection works. |
| *Landfall* | • local constraints;<br>• 3rd party requirements;<br>• environmental sensitive areas;<br>• vicinity to people;<br>• limited construction period. |
| *Third party activities* | • ship traffic and fishing activity;<br>• dumping areas for waste, ammunition, etc.;<br>• mining activities;<br>• military exercise areas. |

### 2.2.1 Environment

Environmental and statistical data (wind, wave, tide, current, temperatures, ice, earthquake, etc.) should be determined and taken into account before the selection of pipeline route. Hydrodynamic loads induced by the *relative motion between the pipe and surrounding water* also affect the choice of pipeline routing. It is essential to take into account all the load sources, namely current, wave, etc. (DNV-OS-F101, 2013).

Arctic seas are covered with ice in different forms. Presence of such ice features as ice ridges and icebergs may cause the scouring of the seabed and increase of hydrodynamic loads. Ice gouging leads to pipeline damage and rupture. The gouging is a special hazard, requiring appropriate route selection and design to minimize the risks of pipe failures.

Geographical location is to be estimated and compared to other possible locations. Then it is necessary to assess the environmental conditions of chosen corridor: the pipeline can be divided into several sections in accordance with the water depth, seabed topography and geomorphology (DNV-OS-F101, 2013; Palmer & King, 2008).

Special focus is to be put on the seas of natural conservation interest because of tropical coral reefs, which form the ecosystem of the planet. Similar to reefs marine parks are to be protected as well. Thus, any kind of trenching or dredging works must be excluded.

### 2.2.2 Seabed characteristics

Alongside with the environmental data, it is important to utilize the seabed features. The latter should include the information about rocks, sand waves, pock marks, mud slides, mud volcanoes, and iceberg scars. Some surveys and laboratory tests are to be taken in order to obtain the list of geotechnical properties and soil parameters that are necessary for the selection of the design philosophy.

Pipeline rests on the sea bottom. Ideal seabed is represented as flat, smooth and technically uniform one, consisting of stable clay. However, the seabed is usually uneven, and due to the presence of rocks and valleys there is a probability of free spans formation. In addition, the seabed with different kinds of obstacles the cobbles and boulders poses a threat and complicates the trenching procedure a lot.

One of the challenging physical factors influencing pipeline behavior on the seabed is mobile sand waves. Since sand waves are unstable, the pipeline, resting on their crests, can lose the support of moving sand. That is why, it is recommended to avoid such territories. In case if it is impossible to evade sand waves, the route must be laid along the troughs of sand waves, and the pipeline has to be lowered in the trench below the troughs level, by using well-known *pre-sweep* method (Palmer & King, 2008).

Moreover, soil is composed of several layers, the properties of which vary with the layers' depth: the upper layer is known to be more uncertain than deeper one. Thus, both of them have to be emphasized during the pipeline design (DNV-OS-F101, 2013).

### 2.2.3 Facilities

An interaction of the pipeline with the platforms, offshore installations, subsea structures, existing pipelines and cables (power or communication) may become dangerous and challenging. In order to avoid probable pipeline damage it is better to locate the pipeline at a certain distance from such obstructions. Offshore Standard DNV-OS-F101 (2013) points out that *minimum horizontal distance of 500 m* shall be adopted in case if there are any facilities or manned areas close to the pipeline. If there is an FPSO, drilling rig or semisubmersible, it is essential to specify the size of anchor spreading or the distance of *2 km radius* (Karunakaran, 2014).

A threat may be posed by the existing pipelines and cables. Before the final decision on pipeline routing is made, some monitoring procedures are to be taken to determine the placement of existing installations. Moreover, the following should be noticed:

- The corridor shall be in a range of 50-100 meters, if it is an existing pipeline; and in a range of 20-30 meters, if the pipeline is constructed together with the new one;
- Approach angle shall be more than $30^0$;
- Size of crossing should be equal to the length of the part elevated off the seabed;

- Rock dumping is to be calculated to provide necessary protection;
- Areas with the vulnerable submarine cables are to be avoided either. Otherwise, the pipeline should be laid through the gap of severed cable. Then the cable is to be spliced and lowered back over the pipeline (Karunakaran, 2014).

### 2.2.4 Landfall

Pipeline route selection is also dependent on the construction limitations: shore and platform approaches, pipeline crossings, and trenching. With regard to the landfall, the pipeline location is chosen in accordance with the lay barge draught (in terms of the barge generation), and environmental conditions. Concerning the platform approach, the minimum clearance of the vessel to platform and sufficient corridor must be specified.

Political issues are also point of concern, especially for the export lines, interconnecting different countries or even continents. For both the design and operation of export pipelines it is important to use multiple code compliance and meet multiple reporting requirements (Karunakaran, 2014).

### 2.2.5 Third party activities

The focus of much attention is the third party activities mentioned in the Table 1. Pipelines resting on the seafloor are increasingly exposed to the loads arising due to high human activity on the sea. Deciding on a route, the inference between these activities and pipelines must be considered.

*Loads which are imposed on the pipeline system from 3$^{rd}$ party activities shall be classified as interference loads. Typical interference load include trawl interference, anchoring, vessel impacts and dropped objects.* Along with the interference loads there are also accidental loads, and the main difference between them is the probability of occurrence. If the latter is less than $10^{-2}$ throughout a year, then it can be defined as accidental load (DNV-OS-F101, 2013).

One of the evident examples of the interference load is trawl impact (Figure 2). Due to great fishing activity nowadays, the loads from the trawl gears represent a real hazard to the pipeline integrity.

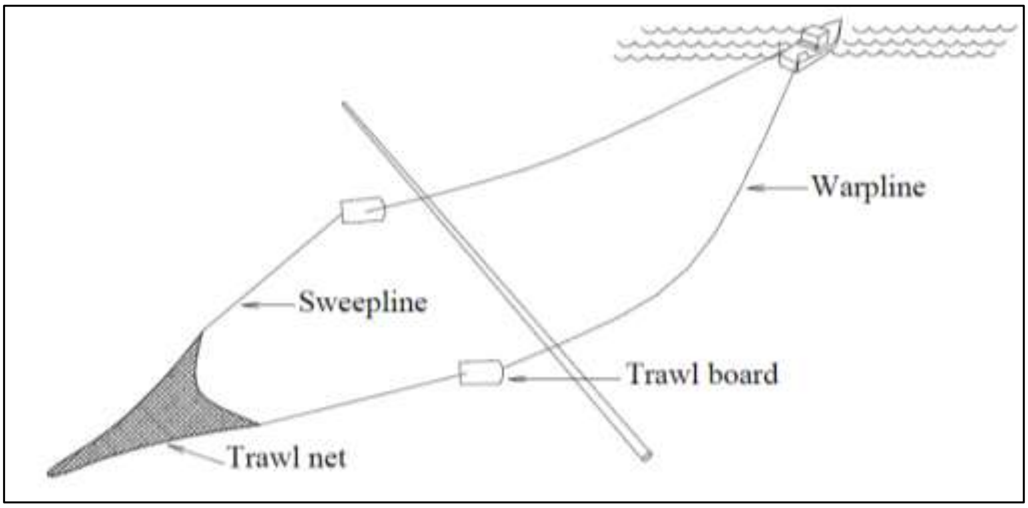



*Figure 2: Typical otter trawl gear crossing a pipeline (DNV-RP-F111, 2010)*

The trawling scenario is usually divided into three interaction phases (Table 2) (DNV-RP-F111, 2010; Bai, 2001):

Table 2: Trawling scenario interaction phases

| ***Phase*** | ***Explanation*** | ***Duration of the phase*** | ***Effect from the load*** |
|---|---|---|---|
| *Impact* | A pipeline is hit with the board, beam shoe or clump. The pipe shell is supposed to resist the impact load. | Some hundredths of second. | Local dents, damage of pipe coating. |
| *Pull-over* | A trawl board, beam shoe or clump is pulled over the pipeline. | 1-10 seconds. | Global pipeline response. |
| *Hooking* | A trawl board is stuck and wedged under the pipeline. | Several minutes. | Extreme cases, large hooking loads are imposed to the pipeline. |

**NB**. Because of its small frequency, the hooking is classified as an accidental load. The reasons for such loads may be different, and some of them are the following:

- Severe environment conditions: high wave and current loads, ice features loads;
- Emergency situations: explosions and/or fire;
- Operational failures: infrequent internal overpressure, accidental water filling;
- The impact from various items: vessel impact, dropped objects, dragging anchors, etc.

It is an era of a large amount and variety of ships (supply and construction vessels, ferries, tankers, etc.) passing different territories and performing different functions. The more these vessels are used, the greater danger is for the pipelines laid on the seabed. Dragged and dropped anchors, grounding and foundering vessels represent serious accidents the pipeline might experience. Significant consequences, such as scouring and rupture of the pipe section, subsequent leakage of the product arise out of accidental events. Thus, a lot of attention must be paid to the scenarios of pipeline routing in case of high ship traffic: pipeline shall be laid away from the harbor and shipping lanes. Ship data collection and analysis have to be taken prior to choosing the routing of the pipeline.

Another area of concern is an outcome of military activities. The presence of non-recovered and undetonated mines; navigating submarines; weapons and bombs are very problematic and dangerous. Those places must be carefully examined for location of the military action items. All the explosive devices, bombs are to be defused (Palmer & King, 2008).

In addition, there is a possibility of pipe damage due to material dumping. Ocean disposal of chemicals, nuclear wastes and obsolete equipment is a threat for both the environment and offshore pipelines. Although the disposal at sea is totally prohibited nowadays, disturbed remaining wastes may lead to undesirable and heavy consequences (Palmer & King, 2008).

## 2.3 ROUTE SURVEY

The route survey is carried out with a view to data collection for further design and construction procedures. The survey is usually conducted within the corridor of preliminary route chosen in accordance with the existing data. Later on obtained details from the sea charts, topography and ROV surveys graphs are reviewed and modified in order to fulfil all the requirements in an appropriate manner. Desk study includes the investigations of the seabed profile and geology, presence of existing pipelines and cables, obstructions and wrecks, etc. All the investigations must be performed in an accurate way for the purpose of safety during pipeline design, construction and operation. Eventually, alignment sheets are to be prepared. Alignment sheets provide information of the facilities and pipeline location, its length and key features. Those drawings are very useful for final route selection, for the production of material takeoff, and for the installation process.

*Summarizing* the part of pipeline route selection one shall understand how essential it is to obey the rules of routing design, follow the whole survey procedure sequence, define work purposes, and recognize the main features included in the alignment sheets. The more rational route is chosen, the more successful, safe and cost-effective construction, operation and management of pipeline system will be.

# CHAPTER 3. PIPELINE THREATS

Pipelines are thought to be one of the most popular and safest methods of oil and gas transportation. Otherwise, there are a lot of issues regarding design, installation and operation. As mentioned before, pipeline route selection being the first in pipeline design "chain", reflects essential and basic procedures, which are very important for the next steps of the design sequence. Factors affecting the route design are described above. Taking into account all these factors for the route selection; the safety, reliability and integrity of the pipeline will be provided. However, different problems associated with subsea lines may arise throughout their design life. *Pipeline failures* are big area of concern, and they can result in the following (DNV-OS-F101, 2013):

- *Loss of component or system function;*
- *Deterioration of functional capability to such an extent that the safety of the installation, personnel or environment is significantly reduced.*

## 3.1 DATABASE. STATISTICS

One or even several failures of the pipeline system can lead to huge incidents. Pipeline incident outcomes depend heavily on failure modes and its causes. There are different international databases and technical reports, which are commonly applied for the identification and analysis of undesired events and potential hazards. Each source may denote its own list of pipeline features, as well as failure causes and consequences correspondingly. Thus, rich information may be widely used by authorities, operating, service and other companies involved in the engineering works. The main characteristics of any database are to be defined by (Velez Vega et al., 2006):

1. *Database boundaries* that are necessary to separate the incidents relating to the pipeline, equipment, and facilities; to distinguish offshore lines from onshore ones; to point out the life cycle phases of considered activities.
2. *Database population* that presents the details of considered lines, equipment, and facilities. This information is primarily used for further statistical analysis.
3. *Incident* with the corresponding list of its *location*, *causes and consequences.*

### 3.1.1 PARLOC 2001

The most informative and comprehensive example of existing databases related to the data of offshore pipeline incidents is PARLOC 2001 document, the latest version of which was updated in the far 2003.

**NB**. The incident is defined here *as an occurrence, which directly results or threatens to result in loss of containment of a pipeline* (PARLOC 2001 Database, 2003 version).

The document contains detailed information about pipelines sitting on the seabed of the North Sea, and the description of the incidents occurring from 1960 up to 2000. All the plots, charts, tables and diagrams, presented below, are compiled manually by using the data from different chapters of this database document. An example of the datasheet is illustrated below (Figure 3).

| | | Total | Platform | Riser | | | | | Safety Zone | | | | Mid Line | Well | Shore Zone | Land | SPM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Total | Piping | Splash Zone | Subsea | Unknown | Total | Near | Far | Unknown | | | | | |
| Anchor | Ship / Supply Boat | 6 | | 0 | | | | | 6 | 1 | 4 | 1 | | | | | |
| | Rig or Construction | 0 | | 0 | | | | | 0 | | | | | | | | |
| | Other/Unknown | 2 | | 0 | | | | | 0 | | | | 2 | | | | |
| | Total | 8 | 0 | 0 | 0 | 0 | 0 | 0 | 6 | 1 | 4 | 1 | 2 | 0 | 0 | 0 | 0 |
| Impact | Ship on Riser | 0 | | 0 | | | | | 0 | | | | | | | | |
| | Trawl | 6 | | 0 | | | | | 0 | | | | 6 | | | | |
| | Dropped Object | 0 | | 0 | | | | | 0 | | | | | | | | |
| | Wreck | 1 | | 0 | | | | | 0 | | | | 1 | | | | |
| | Construction | 1 | | 0 | | | | | 1 | 1 | | | | | | | |
| | Other/Unknown | 1 | | 0 | | | | | 0 | | | | 1 | | | | |

*Figure 3: Example of datasheet from the PARLOC 2001 (PARLOC 2001 Database, 2003 version)*

The following database boundaries are identified in the PARLOC 2001 document (2003):

- Operation phase – 396 lines (248 offshore lines, and 148 fittings);
- Construction phase – 146 lines (118 offshore lines, and 28 fittings).

The PARLOC 2001 database population flowchart is illustrated below (Figure 4).

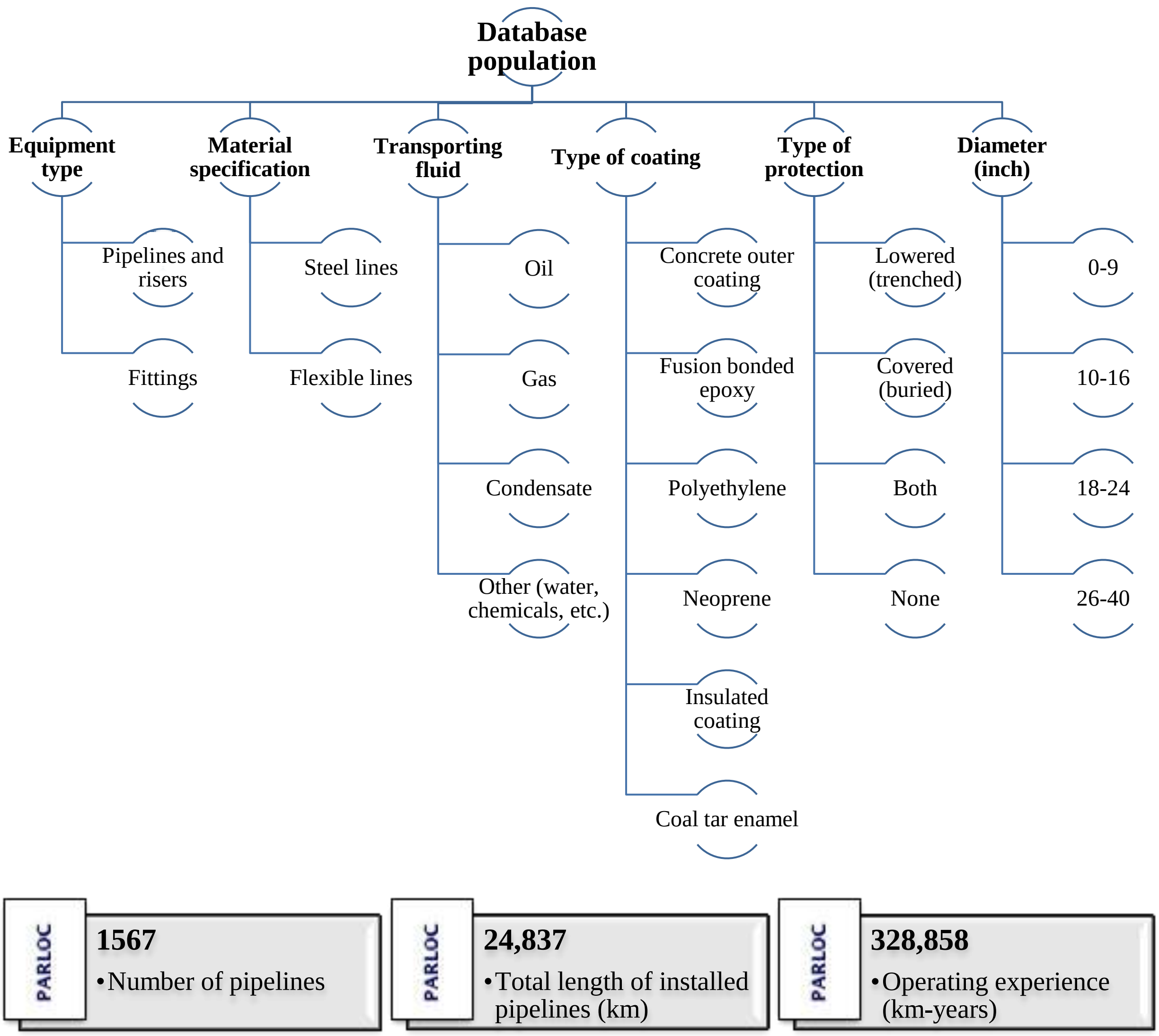



*Figure 4: Database population flowchart of the PARLOC 2001*

Regarding the last and the major part of database characterization, it should include the definition and description of incident occurrence. The latter presents a list of causes, location and consequences of the incident correspondingly. The total number of pipeline incidents and further details of the database content are given below (Figure 5).

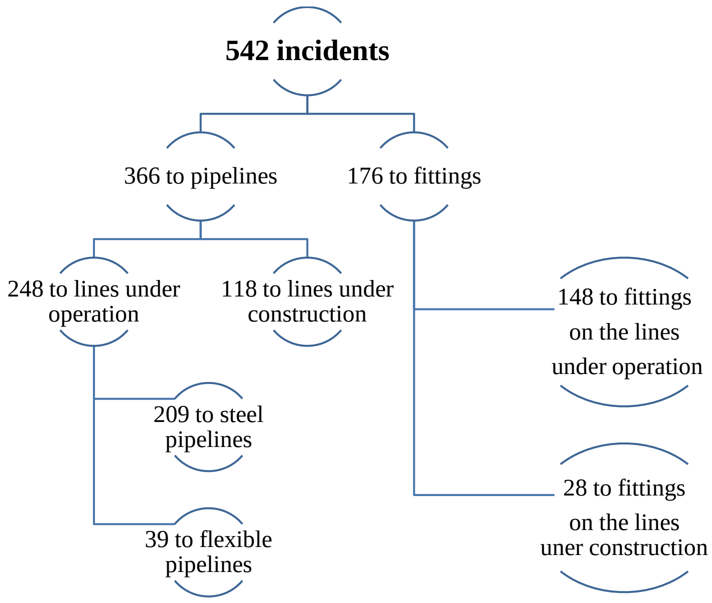



*Figure 5: PARLOC database incidents by numbers*

According to the presented flowchart, one can see that the total number of incidents is 542. There are 366 incidents involving lines, and 176 involving fittings. 248 out of 366 pipeline failures are seen during operation phase and the rest (118) are found during construction. It should be mentioned, that 209 incidents are associated with steel lines, and it represents 39% of all the 542 cases. As for the fittings, there are 148 and 28 incidents occurred on the lines under construction and operation respectively.

**NB**. Since there is no exact and full-length information about fittings incidents, proper analysis on causes and consequences of fittings failures cannot be presented.

Concerning the occurrences of failures, they are heavily dependent on failure causes. 12 main different causes may be found in that database:

- Anchoring;
- Impact;
- Corrosion;
- Material defect;
- Fire/explosion;
- Repair and maintenance;
- Natural hazards;
- Structural damage;
- Construction fault;
- Fitting fault;
- Others.

Using the data from the document, it is possible to plot the diagrams, which can be easily analyzed. As mentioned earlier, the pipelines become the subject of undesirable events two times more likely than the fittings. Furthermore, it is important to distinguish steel lines from flexible ones. That is why two diagrams are illustrated below in order to highlight their similarities and differences (Figure 6). Each diagram presents all incident causes (248) involving operating pipelines - steel (209) and flexible (39) ones.

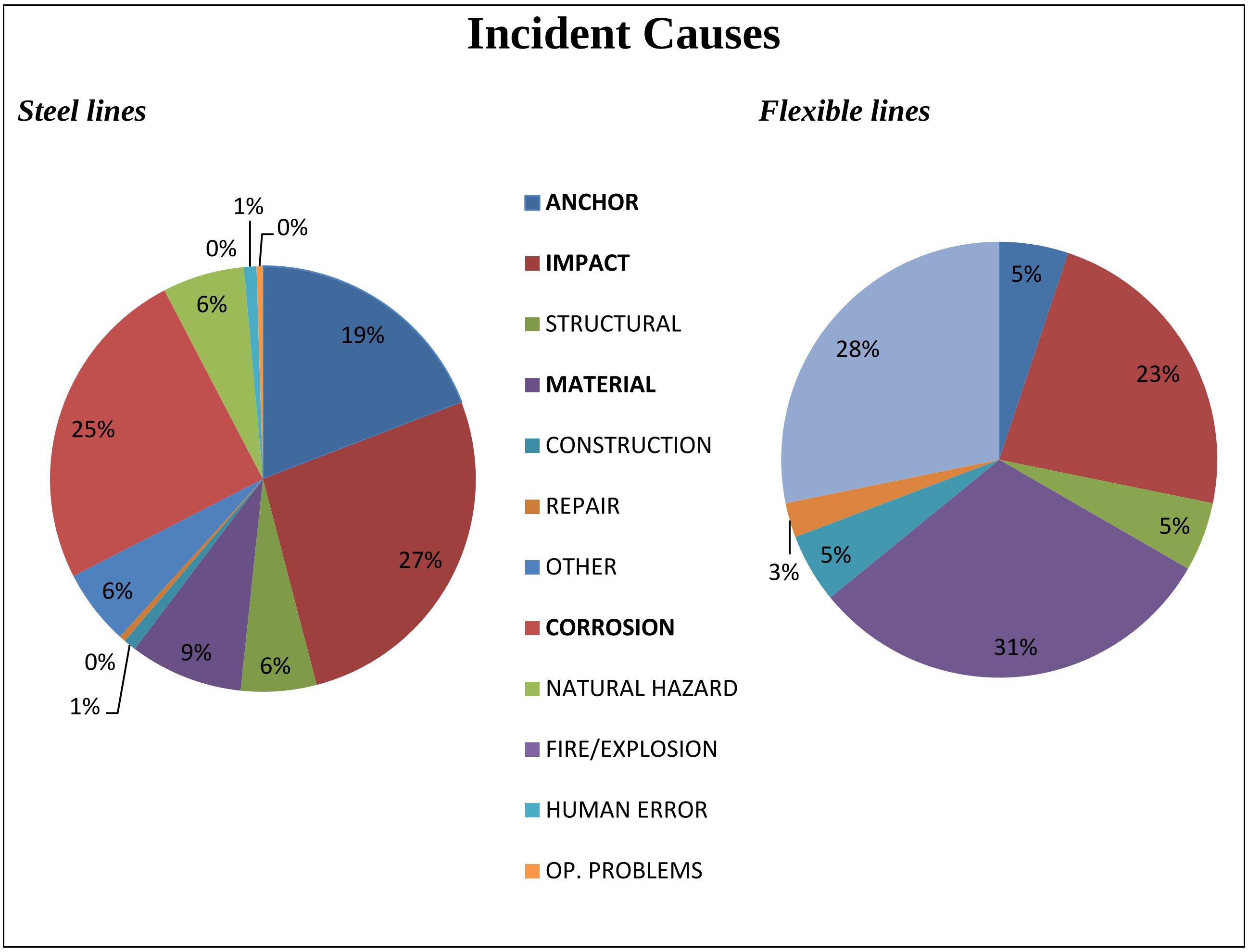



*Figure 6: Causes of incidents to operating steel and flexible pipelines*

In accordance with the diagrams above, it is seen that the most common incident causes for the rigid pipelines are impact (26.8 %), corrosion (24.9 %) and anchoring (19.1 %); while the most frequently detected incidents on the flexible lines are material (30.8 %) and impact (23.1 %).

It is also necessary to explain the consequences of all the incidents observed. All of them result in loss of system integrity, which leads to the leakages of oil and gas. As defined in the Offshore Standard DNV-OS-F101 (2013) the *pipeline integrity is the ability of the submarine pipeline system to operate safely and withstand the loads imposed during the pipeline lifecycle.* The flowchart illustrating the number of leaked and survived pipelines is presented on Figure 7.

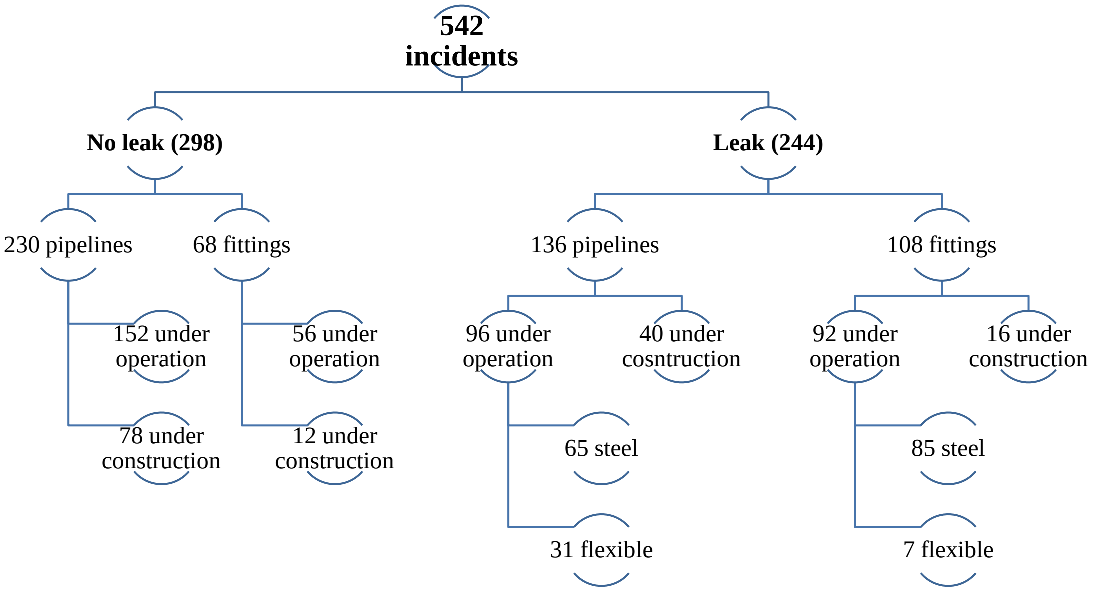



*Figure 7: Number of incidents (with and w/o loss of containment) involving pipelines and fittings*

Figure 7 points out on 244 leakage events associated with the pipelines and fittings. 188 of them are detected on the pipelines and fittings being under operation. Leaks are a big area of concern, since they poses a threat to the people, environment and assets. The leakages may be accompanied by the following ignition, fires and/or explosions.

Interesting to note that loss of pipeline containment often occurs due to the same list of damage causes (impact, corrosion, anchoring and material). This fact is confirmed by a summary table below (Table 3). The reason why there are a lot of incidents with rigid lines is probably because there are more steel lines than flexible ones. Concerning fittings, main failure reason is observed to be the fitting itself. However, there is a certain amount of fittings suffered from anchor, impact, material and corrosion. Detailed discussion on each of these issues will be given further as the text goes.

Table 3: Summary table of the main incidents causes

| ***Subject*** | ***Consequence*** | ***Cause*** | | | |
|---|---|---|---|---|---|
| | | ***CORROSION*** | ***MATERIAL DEFECT*** | ***IMPACT*** | ***ANCHORING*** |
| *Steel pipeline* | ***Damaged*** | **52** | **18** | **56** | **40** |
| | *Leaked* | 26 | 10 | 9 | 8 |
| *Flexible pipeline* | ***Damaged*** | **1** | **12** | **9** | **1** |
| | *Leaked* | 1 | 12 | 4 | 2 |

Every loss of containment event may be examined by the size of damage, which is also a part of data. PARLOC 2001 classifies different hole diameters as following:

- 0 – 20 mm;
- 20 – 80 mm;
- 80 mm and more.

In terms of the pipeline diameter, the ranges are presented in the database population (Figure 4). The relation of pipeline diameter and hole size is given below. As indicated in Table 4, both steel and flexible pipelines with 0-9 inches diameter suffer a lot as compared to the pipes with the diameters of 10 inches or even more. The same situation is evidenced with the ruptured lines. Thus, smaller diameter pipelines are more vulnerable and damageable.

Table 4: Relation of pipeline diameter and hole size

| ***Pipeline diameter (inch)*** | ***Hole size (mm)*** | ***Leaked steel pipes*** | ***Ruptured steel pipes*** | ***Leaked flexible pipes*** | ***Ruptured steel pipes*** |
|---|---|---|---|---|---|
| *0-9* | *0-20* | 26 | 0 | 18 | 0 |
| | *20-80* | 8 | 3 | 3 | 1 |
| | *>80* | 5 | 3 | 4 | 4 |
| *10-16* | *0-20* | 7 | 0 | 1 | 0 |
| | *20-80* | 2 | 0 | 1 | 0 |
| | *>80* | 9 | 5 | 1 | 1 |
| *>16* | *0-20* | 4 | 0 | - | - |
| | *20-80* | 2 | 0 | - | - |
| | *>80* | 2 | 2 | - | - |

Pipeline incident location is of great significance as well. There are 6 principle zones recognized in the database (Figure 8):

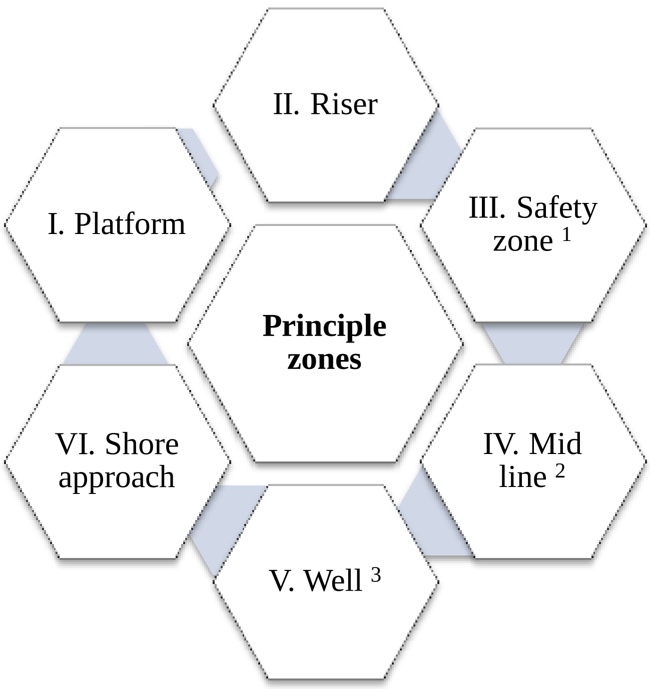



*Figure 8: Pipeline principle zones*

[1] Within a radius of 500 m from the platform;
[2] Outside the 500 m zone from the platform;
[3] Within a radius of 500 m from the well.

Summary table is compiled to show the most affected by incidents areas along the pipeline (Table 5). Table is complemented with land and SPM (single point mooring) zones.

Table 5: Affected zones of the pipelines

| ***Subject*** | ***Consequence*** | ***Total number of incidents*** | ***Zone*** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | ***I*** | ***II*** | ***III*** | ***IV*** | ***V*** | ***VI*** | ***Land*** | ***SPM*** | ***Unknown*** |
| *Steel lines* | Damaged | 209 | 1 | 60 | 47 | 84 | 10 | 4 | 1 | 2 | 0 |
| | Leaked | 65 | 1 | 12 | 18 | 27 | 6 | 0 | 0 | 1 | 0 |
| *Flexible lines* | Damaged | 39 | 2 | 5 | 2 | 15 | 12 | 0 | 0 | 0 | 3 |
| | Leaked | 31 | 1 | 5 | 3 | 9 | 10 | 0 | 0 | 0 | 3 |

Pipeline Mid Line is one of the most sensitive regions: large numbers of damages and leakages are observed there.

<u>*Summarizing*</u> the part devoted to incidents statistic in accordance with the PARLOC 2001 database, one shall understand the necessity of pipeline incidents information collection. Data may be analyzed in different ways, and the results of such analyzes may be used for various purposes during pipeline project planning, design, construction and management.

Database boundaries, population and incident occurrence are defined. Steel and flexible pipelines are distinguished and studied. Special emphasis is made on the number of pipeline incidents, their causes, location and consequences. So, damage sizes, number of leaked and ruptured pipes, as well as the area of incidents are graphically presented in tables and diagrams. The emphasis should be placed on the causes of pipeline failures, especially those, which lead to the loss of containment. That is why a detailed description of failure causes will be given in the following section of this paper.

## 3. 2 MAIN PIPELINE INCIDENT CAUSES

Discussed in a previous part pipeline incidents are characterized by their causes and consequences. Corrosion, material defect, impact and anchor damage are defined as the main reasons for loss of pipeline structural integrity (Figure 6, Table 5). That is why each of these causes is going to be discussed hereinafter.

### 3.2.1 Spontaneous hazards. Corrosion

Corrosion is one of the most leading causes of pipe failures, in particular ruptures and leakages. It is defined as *the deterioration of a material, usually a metal, which results from a reaction with its environment* (Jacobson, n.d.). Corrosion primarily affects the design life of pipelines. Pipes become weak, and they are less capable of resisting to the external forces. Two types of pipeline corrosion exist: external and internal. Once one or both of them are established, the mitigation procedures come to be more difficult. So that, corrosion process is to be controlled during design, fabrication, installation, commissioning and operation phases of pipeline life-cycle. Along with the control, corrosion protection measures should be specified as well.

*Internal corrosion* is observed inside of the pipelines because of the oil, gas or water stream. Stream characteristics (operating pressure and temperature, flow regime, fluid composition, etc.) tend to change during the design life. That is why periodic inspection, cleaning and monitoring are required.

Several mechanisms of internal corrosion are distinguished:

- Sweet corrosion (due to the presence of dissolved $CO_2$) progresses slowly in a form of pitting.
- Sour corrosion (due to the presence of $H_2S$ in the product) progresses rapidly, resulting in the cracking of pipeline steel wall.
- Corrosion due to oxygen is formed in the pipelines during water-injection, gas lift, pressure maintenance works.
- Microbiological corrosion (due to the presence of sulfate-reducing bacteria) results in the overlapping pits located on the pipe bottom (Palmer & King, 2008; Corrosion problems in production, n.d.).

*External corrosion* usually appears on the outer side of the pipeline because of corrosive ambient medium (e.g. seawater). External corrosion mechanisms may be classified as organic acid attack, oxygen or microbiological corrosion. Set of the following factors usually influences external corrosion (DNV-OS-F101, 2013):

- Temperature profile along the pipeline;
- Fabrication and installation peculiarities;
- Design life;
- Selected type of protection.

***Corrosion incidents. PARLOC 2001***

Nearly a quarter of all the incidents concerned with the operating steel pipelines occur due to corrosion: 52 out of 209 incidents. From the “Pipeline and Riser Loss of Containment” document it is seen that 24 of them are caused by internal corrosion, 22 – by external corrosion; and the reasons for the remaining 6 cases are unknown (Figure 9).

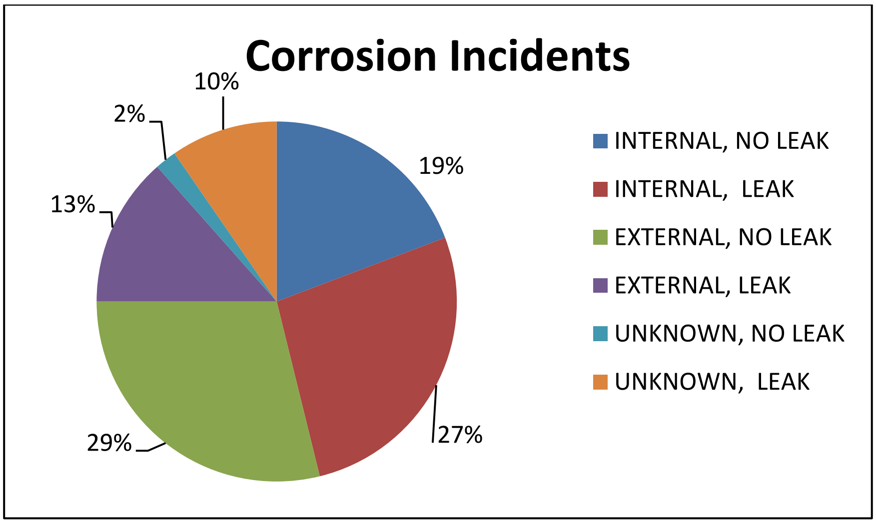



*Figure 9: Corrosion incidents involving rigid lines*

Total number of leaked rigid pipelines being under operation phase is 26. 14 and 7 cases belong to internal and external corrosion respectfully, and 5 of them are unknown (Figure 10). There are 4 incidents involving fittings. They are caused by internal corrosion, and all of them lead to pipeline loss of containment issue. Concerning the flexible pipelines, they also become subject to corrosion even if they are highly resistant to severe conditions. According to the database, only one flexible line is affected by corrosion. In terms of the fluid type, the most problematic ones are oil and water.

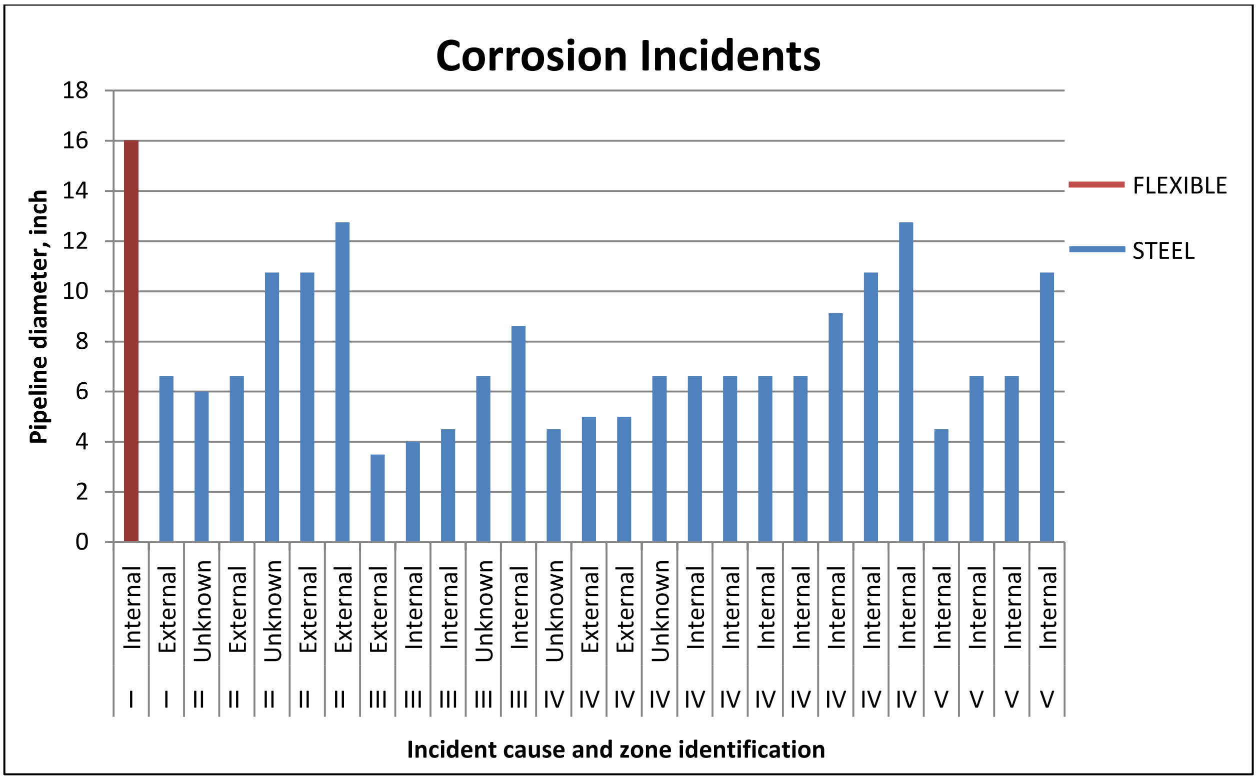



*Figure 10: Pipeline diameter (inches) and location of corrosion incidents resulted in leakage*

As seen from the Figure 10, a lot of corrosion incidents are established in II, III and IV zones, i.e. Riser, Safety Zone and Mid Line (Figure 8). Dividing the pipeline into a set of certain segments (or 6 principle zones as shown on the figure) helps to get clear understanding of degradation mechanism location and to make proper risk analysis. In addition, such kind of "pipe failed zone" information may be relevant for the selection of corrosion prevention strategies (cathodic protection and coating systems) and for pipeline inspection planning procedures. Thus, zones can dictate what and where to inspect. Nevertheless, by analyzing different failure cases, one shall not exclude the fact that every pipeline system is unique and has its own properties.

Interesting to note that smaller diameter pipelines are more susceptible to corrosion and subsequent leakage, than bigger ones. Smaller diameter pipes (3.5-16 inches) are usually used for the product gathering and distribution purposes. These lines connect subsea wells with the processing and treatment facilities. Fluid, being transported by them, is unprocessed and full of mechanical impurities. Presence of dissolved $CO_2$, $H_2S$ or bacteria in the stream may react with the pipe material. Increase of reaction rate leads to the material deterioration. Such systematic phenomena can result in loss of pipeline system integrity and other significant consequences.

In order to ensure asset integrity and to optimize pipeline monitoring and inspection costs, the following corrosion mitigation measures are to be specified during pipeline design:

- Material selection;
- Chemical and inhibitors dosing;
- Use of external and internal coatings;
- Cathodic or anodic protection.

In case of pipeline incident attributed to corrosion, the continuation of safe fluid transportation may be achieved by urgent measures. Pipeline repair, reduction of maximum allowable operating pressure (MAOP), and usage of necessary corrosion inhibitors seem to be the most indicative and useful methods in accordance with the PARLOC 2001 database. In addition to them, periodic maintenance service and monitoring are essential.

### 3.2.2 Spontaneous hazards. Material defects

Safe pipeline operation depends heavily on the type of pipe material and way of its fabrication. Despite proper material selection and line pipe manufacturing process, there are still plenty of defects that can threaten pipeline integrity. Failures may occur due to problems with the material itself (either rigid or flexible) or due to defects associated with welds.

Different impurities, oxides or trapped gas are remained in steel. The presence of them leads to the deterioration of pipe material. Eventually, formed inclusions and raised spots may affect the wall thickness and thereby reduce the value of maximum allowable pressure in the pipeline.

Pipeline manufacture procedure is an issue as well. Production of steel lines is known to be selected with or without welding (seamless pipes). Welding flaws or cracks on the pipeline wall are of common occurrence after pipe fabrication. Sometimes they become unavoidable and dangerous, because cracking size is never the same and it tends to change in time. The only way to check the pipeline for imperfections is pressure testing. At the same time, testing should be carried out carefully in order to exclude cracks size growing after several cycles of pipeline pressurization (U.S. Department of Transportation, 2014). Regarding flexible pipelines, number of all their defects is often lower than those, found on rigid ones.

***Material defect incidents. PARLOC 2001***

PARLOC database contains information about pipeline failures resulted from the material defects. There are 30 failures, where 18 are observed on steel lines, and the rest is on the flexible lines. Leakage of rigid lines happens in 10 cases out of 18, while leakage of flexible lines is found in all 12 cases. Given pie diagram (Figure 11) shows, how many mechanical failures are caused by weld and steel defects. As seen in a diagram below, steel defects represent a great danger in comparison with weld ones.

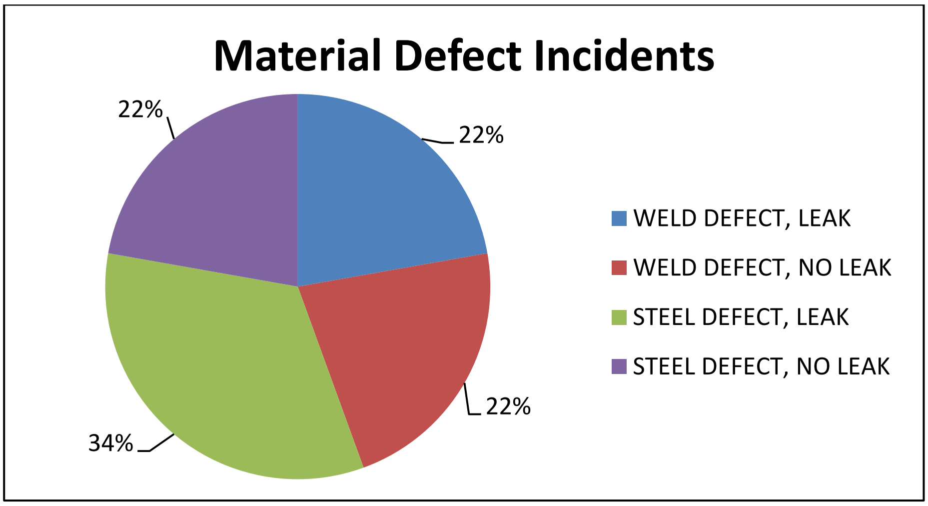



*Figure 11: Material defect incidents involving rigid lines*

Defects in material and welds also affect the weakest points of pipeline such as connections and pipe fittings. In pursuance of the database, 3 cases involving fittings are registered on the rigid lines, while just 1 is tracked down on the flexible pipe.

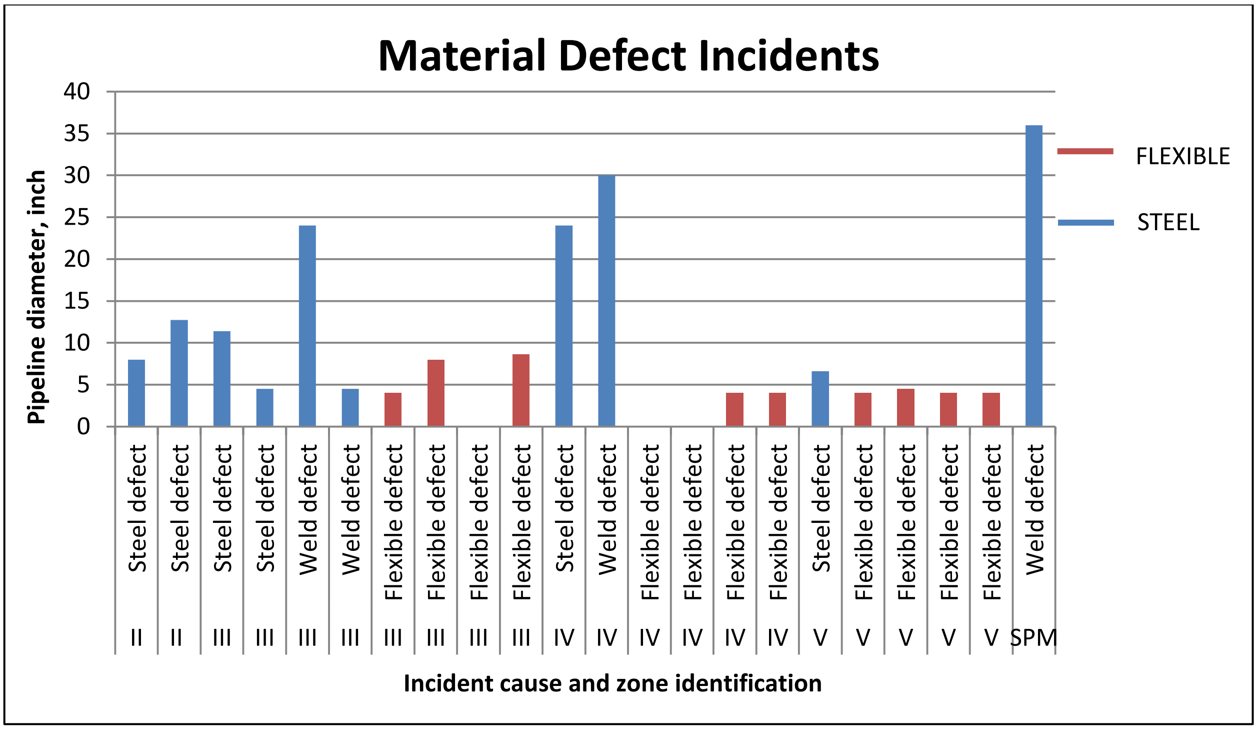



*Figure 12: Pipeline diameter (inches) and location of material defect incidents resulted in leakage*

Both small and large diameter pipelines fail due to defective fabrication and manufacturing (Figure 12). Safety Zone and Mid Line seem to be the most susceptible to defects zones of the pipeline. As for the fittings, problems with them are usually detected in a Platform Zone.

Reducing the number of mechanical failures may be achieved by implementation of appropriate pipe material procurement, fabrication, manufacture and welding processes. Improved technology and practice can have a positive effect on reduction of mechanical failures.

Hydrostatic pressure tests must be carried out periodically but in an accurate way to evade any uncontrolled and undesired events in the future.

### 3.2.3 External hazards. Impact

External hazards and harm coming from third party activities shall be taken to be the most severe incident scenarios for the offshore pipelines. These failures are usually caused by the following reasons:

1. Impacts:
   1.1. Vessel and ship impact on risers;
   1.2. Fishing and trawling;
   1.3. Dropped objects;
   1.4. Wrecks;
   1.5. Activities of construction vessel;
   1.6. Dumping;
   1.7. Accidental grounding;
   1.8. Dredging operations;
   1.9. Ice gouging.

All of them are potential consequences of activities such as pipeline, risers and modules installations; lifting procedures; subsea operations, fishing and ship traffic. A more detailed description of these reasons will be given in the next part of this paper.

*The submarine pipeline system shall be designed for impact forces caused by, e.g. dropped objects, fishing gear or collisions. The design may be achieved either by design of pipe, protection or means to avoid impacts* (DNV-OS-F101, 2013) From time to time even advanced design philosophy, optimized methods of protection and mitigation measures do not help to completely exclude the possibility of pipeline damage and later loss of containment. So, it is really important to use and refer to the incident databases, which include necessary for the analysis information of pipeline failures.

In order to describe main impact incidents causes Table 6 is drawn up and given below.

Table 6: Impact incident causes

| ***Impact incident causes*** | ***Description and mitigation measures*** |
|---|---|
| *Vessel and ship impact on risers* | It is very common when upper part of the riser is hit and damaged by various kinds of powered or drifting vessels (merchant, supply, fishing or standby vessels; shuttle tankers). For every riser vertical zone is more “attackable” than horizontal one. That part is subject to the impact from the ships and their collisions. That is why special attention shall be given to the ship traffic area around any offshore structure and platform with access to the braces in the splash zone. Some protection in a form of jackets, J-tubes or caissons is to be chosen and implemented for the upper parts of |

| | |
|---|---|
| | the risers. |
| *Fishing and trawling* | This event is the most severe among those affecting the pipeline resting on the seafloor. Scenarios and phases of interaction between the pipeline and operating trawl/fish board or gear are presented in the part devoted to the pipeline route selection (Table 2). The best way of protecting the pipeline from gear impact is to keep it buried in a trench, to use special coatings and rock cover in specified pipe sections. |
| *Dropped objects* | Drop object event is characterized by loss of any freights during lifting operation, construction activities etc. There is variety of objects that can be lost. They are classified by their shape (flat/long, box/round) and their weight (2-8 tons). Drill tubes, containers and/or huge objects like BOPs are generic examples of objects, which are able to hit both flexible and rigid lines resting on the seafloor. All the possible consequences from coating damage to pipeline exposure and product release may occur after the damage due to this undesired event. Concerning protection actions - rock filling, external coating or appropriate heavy wall thickness are to be selected. |
| *Ship grounding* | *Ship grounding is the impact of a ship on seabed or waterway side* ("Ship grounding", 2015).<br><br>Accidental grounding of the vessel may happen because of harsh weather conditions, waves and currents, incorrect vessel characteristics and parameters. All listed may affect navigation and control systems of the vessel. In case if such errors find place the ship can ground over the pipeline. After that the pipeline is moved from its initial position. In addition, pipe may be left exposed. Accurate routing design, trenching and pipe burying solution can save pipeline from the effect of grounding ship. |
| *Dredging operations* | Some pipeline failures occur during excavation activity usually taken in shallow water areas. Large equipment such as bucket dredge, suction tools, grab dredgers or stern spud can easily approach the pipeline and do much of harm to it. Some safeguards measures are quite similar to those used in other cases. In addition, marking marine chart may become useful for these purposes ("Quantitative risk assessment for submarine gas pipelines", n.d.). |
| *Ice gouging* | With great interest to the oil and gas fields located in Arctic, special attention should be paid to the pipeline transportation in these regions. High risk is driven by the presence of ice of different shape, age and physical characteristics (fast ice, drift ice, |

| | |
|---|---|
| | ridges, stamuchas, etc.) as well as icebergs. Interaction of pipeline with ice features threatens the fluid transportation process a lot. Theoretically, design philosophy for the pipelines must be done in accordance with three main factors: maximum expected gouge depth, subgouge deformation, and pipeline strain. Pipeline shall resist all possible loads from ice. Highly effective method of submarine pipe protection from the ice gouge incident is to bury it until it is placed in the safest zone below the seabed. |

***Impact incidents. PARLOC 2001***

Continuing with the impact issues, it is important to refer to the data info contained in the database. There are 56 out of 209 failures involving steel pipelines and 9 out of 39 involving flexible ones. From the diagram charts (Figure 13) it is easily seen that trawling and dropped object are serious problems for both types of lines. The fact can be proven by high fishing and trawling activities; by large amount of construction or related to that area works that require lifting of the cargo. Causes of certain number of failures are unidentified.

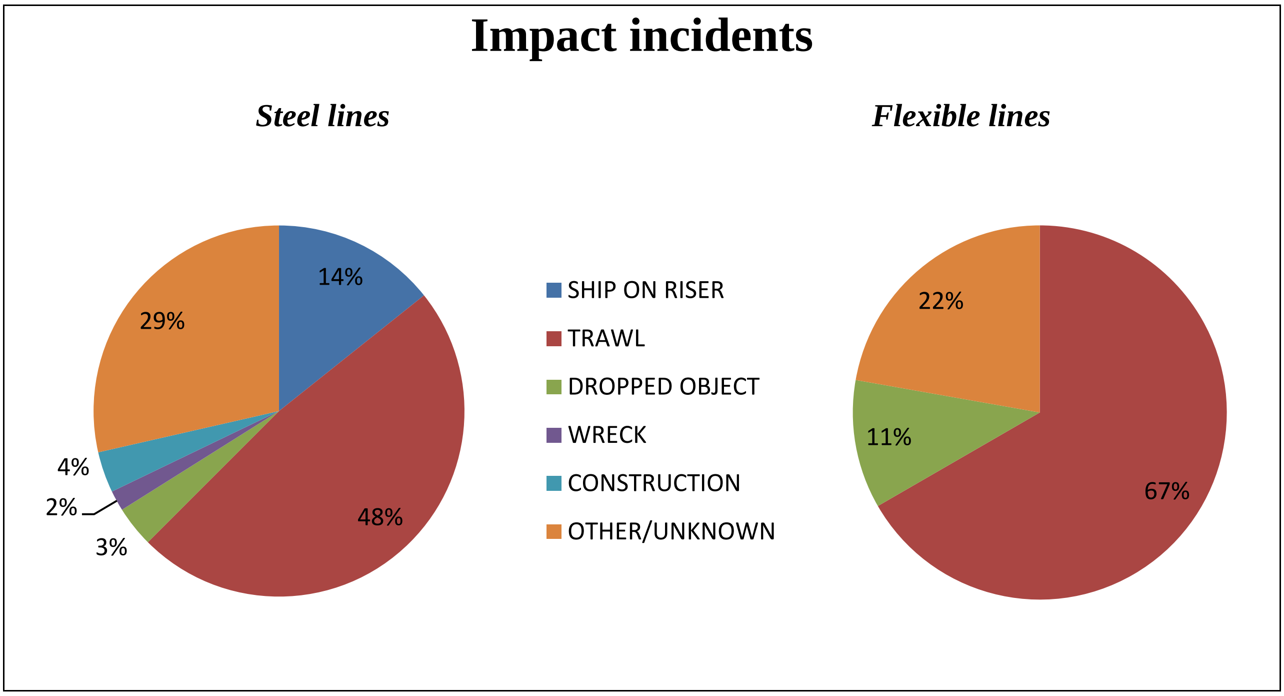



*Figure 13: Causes of impact incidents to operating steel and flexible pipelines*

Mostly, loss of containment is observed after trawl and drop object impact on the pipeline. Generally, leakage occurs in 9 cases with steel and in 4 cases with flexible lines.

6 incidents are related to the fittings: first four of them come from trawling action, the fifth one is due to snagging buoy chain and the last one is because of inaccurate anchor chain drop. Pipeline leakage over connector failure is recorded twice.

Identification of incident zone points out that Mid Line (outside the 500 m from the platform) is the most affected by impacts area among all six zones. It can be explained by the location of marine passage. In accordance with the existent standards and codes, there must be sufficient horizontal distance between ship lanes and offshore structures. That is why every marine passage commonly crosses the pipeline route sections situated in the Mid Line zone. It is also justified by the diagram (Figure 14). As to the line size, smaller diameter pipelines are more exposed to the loads from external hazards. These pipes are more vulnerable to damage than larger ones. Thus, trawl and fishing gears are able to hit and drag over them at an easy rate. Statistics shows that 2.4 and 6 inches pipes suffer a lot.

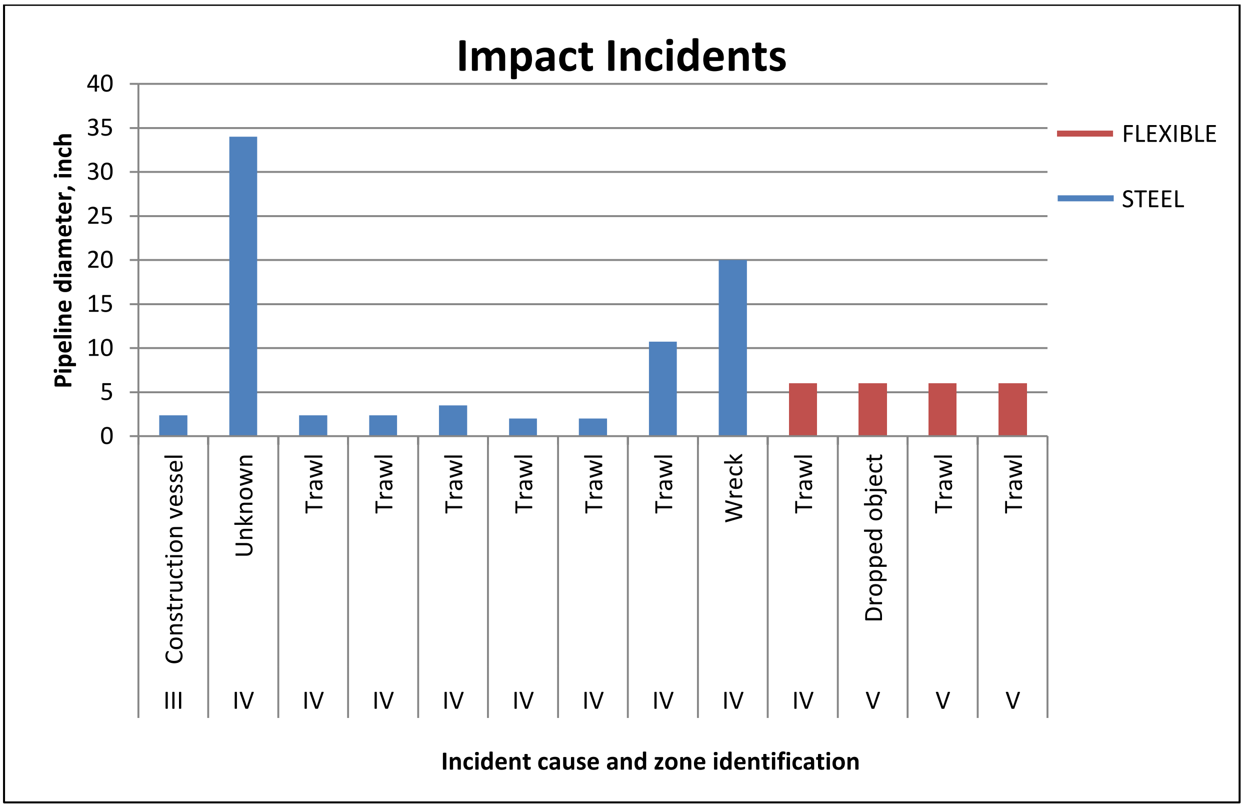



*Figure 14: Pipeline diameter (inches) and location of impact incidents resulted in leakage*

Recorded impact consequences are denting, ovalization, damaged coating, buckling, and pipeline displacement. Some of them are found on the same lines. In order to get rid of these outcomes - repair, pipe section replacement, and additional protection methods are used then. New safeguard procedures can be developed and applied as well. In addition, it is recommended to take periodic monitoring and survey along the pipeline in order to ensure its integrity and dependable service.

### 3.2.4 External hazards. Anchoring

Nowadays ship transport is getting more and more popular. It is still one of the most effective ways to carry the passengers and cargo from one place to another. Despite increasing attractiveness of sea transport, a lot of problems arise sometimes: sinking and grounding ships, collisions of vessels, incorrect ship anchoring and uncontrolled anchor drops over the subsea objects (pipelines, cables, manifolds, etc.). Several pipeline routes are crossed by ship traffic zone. So, unsuccessful ship anchoring may result in loss of pipeline integrity and other undesirable effects. Damage degree will change from case to case, depending on pipeline unique properties; type and parameters of the vessel; characteristics of anchor and anchor chain; water depth, environmental conditions and so on. Thus, a lot of attention should be paid to these factors as well as ship traffic information.

Since this part of the paper is mainly focused on the analysis of PARLOC database, more detailed discussion on vessel anchoring hazards will be presented in the next sections.

***Anchoring incidents. PARLOC 2001***

According to the data contained in the PARLOC 2001, 44 pipeline failures have occurred due to unsuccessful ship anchoring. 40 cases are recorded on the operating steel lines, 2 cases are detected on the flexible lines and remaining 2 have been found on the fittings of rigid pipelines.

Most failures are caused either by anchoring of the ship (supply boat) or construction vessel. It is shown in Figure 15 below.

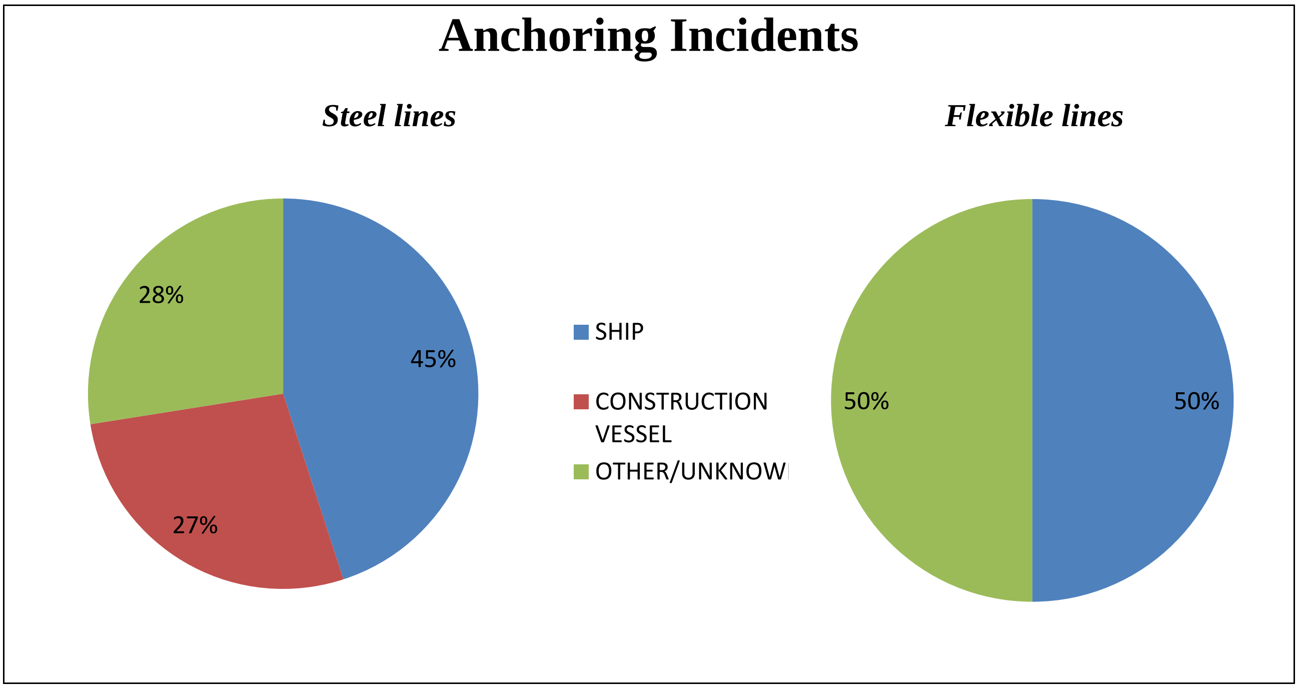



*Figure 15: Causes of anchoring incidents to operating steel and flexible pipelines*

Charts present what types of vessels have greater impact on pipeline integrity. There are 19 incidents attributed to incorrect ship anchoring (18 cases are recorded on steel pipes, and 1 case is recorded on flexible), and further 11 incidents (involving only rigid pipelines) are occurred due to anchoring procedure of construction vessels. Two fitting failure causes are not identified.

With regard to the incident location data (Figure 16), Safety Zone and Mid Line are the most exposed to the anchor damage pipeline zones. Pipeline diameter is also a point of issue. Its size is one of the major criteria for the selection of protection philosophy. For instance, the pipeline can be buried, covered with the rock or coated with concrete, etc. Protection methods help to provide some resistance against third party loads (Verley, 1994). Decision pipeline protection philosophy is usually taken from case to case depending on the unique characteristics of pipeline and environment as well. Otherwise, according to PARLOC 2001, it is seen that the largest leaked pipeline affected by an anchor is 16 inch diameter line and the smallest one is 2.4 inch diameter pipe. So in practice, smaller diameter lines (that are supposed to be protected) are more vulnerable to harm.

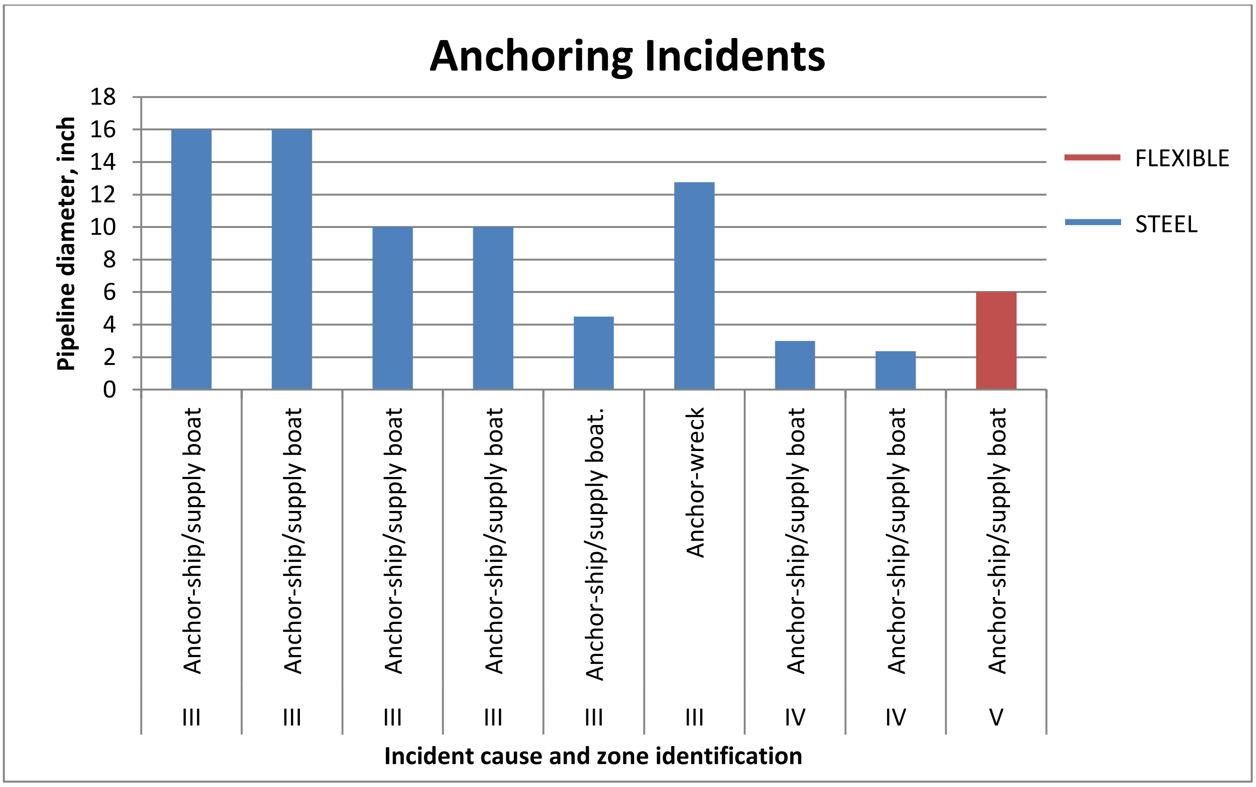



*Figure 16: Pipeline diameter (inches) and location of anchoring incidents resulted in leakage*

During anchoring activity, pipelines resting on the seafloor might be hooked and moved off from their initial position. It should be noted that theoretically not all the pipes can be hooked. Relation between pipeline diameter and geometrical parameters of anchor is quite significant. It is difficult to imagine that large diameter export line gets stuck inside the shank and flukes of 1$^{st}$ class anchor (the smallest one). Discussion on pipeline and anchor parameters will be given hereinafter.

Consequences of interaction between the anchor and submarine pipeline vary a lot: from non-visible effects defined as local to ruptures of pipe bodies and product leakages. Loss of containment is detected in 11 cases (9 in pipelines and 2 in fittings). Along with that, some rigid lines are dented, displaced, or have their concrete coating damaged. As to the flexible, one is broken, and another has external fault. Some repair procedures may be needed after such incidents, consequences of which are incompatible with future operation of pipelines.

In order to ensure safe and continuous operation of pipelines, the following solutions may be implemented, especially in areas with high ship traffic (Brown, 1972):

- Pipeline burial;
- Using of high strength concrete coating;
- Application of rock dumping;
- Using of reinforcing steel/extra steel;
- Installation of concrete sections.

Prior to implementing one or another protection system, it is important to *establish its technical feasibility*. In such a way, it will guarantee pipe safety during its design life (Brown, 1972):

*Summarizing* the part devoted to the main incident causes, namely corrosion, material defect, impacts and anchoring, one shall see how many subsea pipelines suffer from spontaneous and external hazards even in era of technology growth. Some of these incidents occur more often than other. Some of them are recorded on the same lines.

Various pie diagrams and bar charts are presented in order to illustrate the whole picture of failures consequences. These consequences are distinguished between rigid, flexible lines and pipe fittings. Special attention is given to leakages. Since the total number of steel pipelines exceeds the number of flexible lines, the leakage on steel lines is detected more often than on flexible ones. Incident cause and zone identification are determined and analyzed. The same procedure is done with regard to pipeline diameter. This kind of information is very useful for the selection of pipeline protection, which significantly reduces the extent of damage or eliminates it at all. Certain outcomes are huge and dangerous; they can result in pollution, fatality and loss of company reputation. Hereby, necessary safeguard measures for each type of incidents are to be specified during pipeline design and implemented before the start of the operation phase. In case of serious pipeline damage, some degree of repair is needed in an effort to return the pipeline to normal operational mode.

Speaking about the databases, one shall understand how important it is to use them. Statistical studies are widely used for updating of standards and design practices. Pipeline databases contain different information that helps to recognize the factors affecting the safety of existent and new lines. Moreover, statistics is needed for risk analysis procedure, which is basic for any project start.

*There will always be failures or disasters* (Spurrier, 2009). This statement may be confirmed by the bathtub curve, showing the relation between failure rate and age of the system (Figure 17).

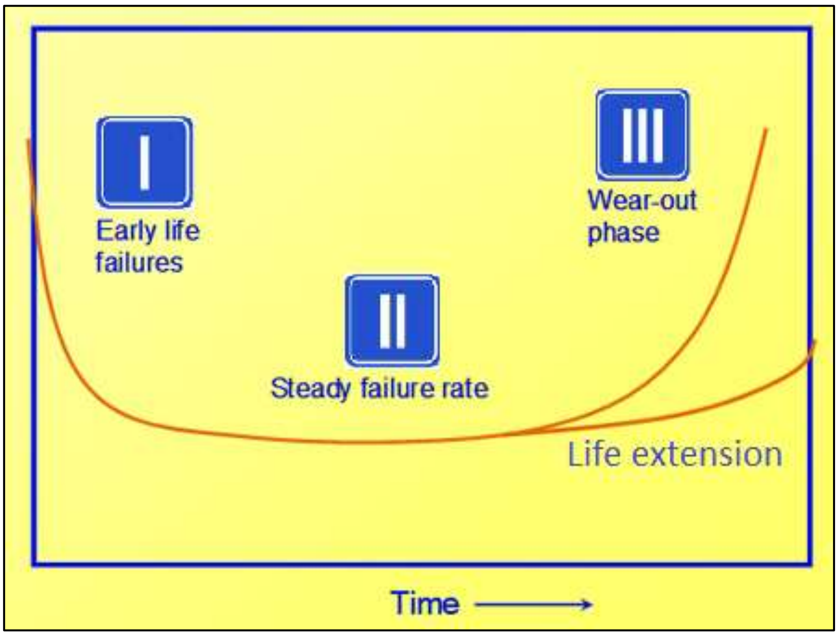



*Figure 17: Bathtub curve ("Further information on ageing and life extension", n.d.)*

As seen from the figure, bathtub curve characterizes three main phases of the system:

I. Early-life failures – decreasing failure rate;

II. Random failures – stabilized failure rate;

III. End-of-life failures – increasing failure rate.

The first phase shows the possibility of pipeline failure due to design, fabrication or construction defects. The rate is very high at the beginning, but then it starts declining. The second phase points out failures coming from the external hazards, such as anchor damage, impact or harsh weather conditions. After that the curve behavior changes again, and the rate is increasing. End-of-life failures are usually found because of pipeline ageing and wear. The most frequent causes here are corrosion, cracking, and welding issues etc. Mechanical system safety and integrity may be achieved by implementation of appropriate design, controlled manufacturing and construction works, as well as periodic maintenance and inspection. These measures also help to extend the useful life of the system (Figure 17).

All mentioned above highlight how important it is to record disasters which can occur within the whole life of the pipeline system. Collection of incidents information provides an excellent opportunity to learn from past experience and to eliminate risks in the future.

## CHAPTER 4. SHIP ANCHORING EFFECT ON SUBMARINE PIPELINES

Pipelines are the most popular mean of hydrocarbon transportation. With the expansion of pipeline network system and large amount of maritime activities, the potential damage to subsea lines increases a lot. Analyzing pipeline failure database one can determine that incorrect ship anchoring may result in huge consequences for the pipeline (rupture, leakage), environment (pollution) and people around (fatality). Even if the anchor damage is categorized as accidental event with the probability of occurrence less than the probability of occurrence of other unplanned events, it is still one of the major threats to the pipeline integrity. Not only offshore pipelines suffer from the action of anchor arrangement. Submarine cables that function as communication lines, carrying data and Internet, can be hooked, damaged and/or torn by the anchors as well.

In an attempt to show all the significance of anchor damage incident analysis, two tables (Table 7 and Table 8), containing information about worldwide offshore pipelines and submarine cables failures due to anchor hazards, have been compiled. As demonstrated, great number of accidents has occurred throughout XX and XXI centuries (Figures 18, 19). Dragged and dropped anchors are detected to be the main pipeline and cable failure causes.

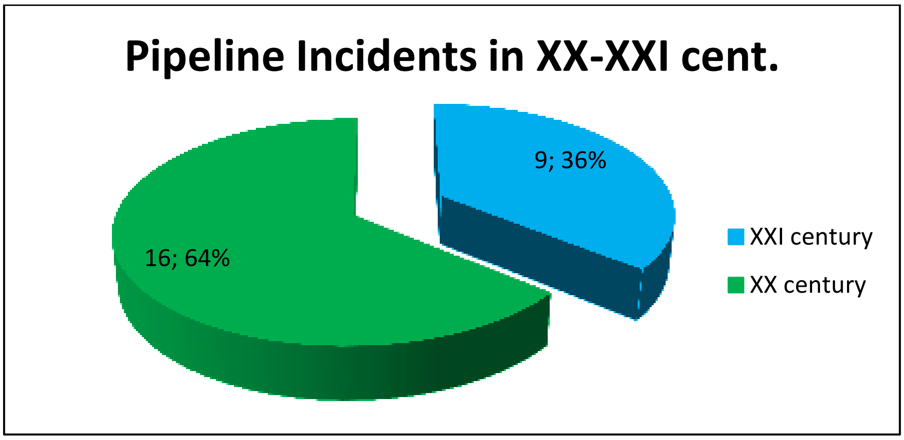



*Figure 18: Pipeline anchor damage incidents number in XX-XXI centuries*

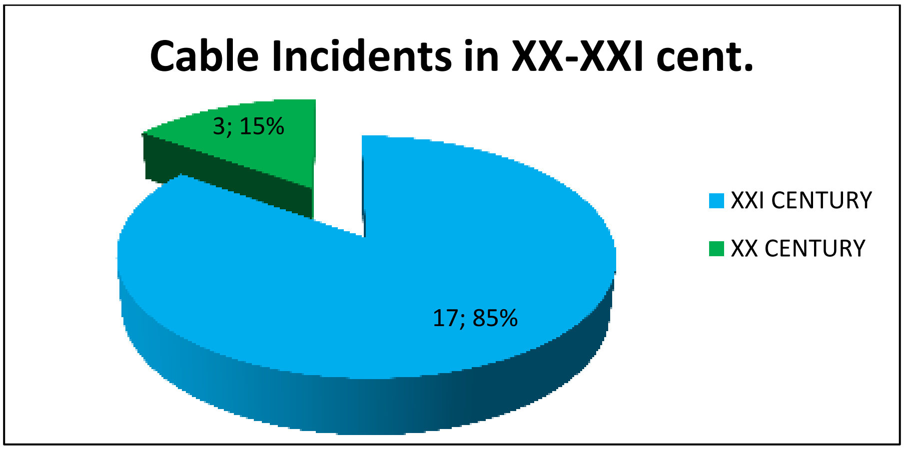



*Figure 19: Cable anchor damage incidents number in XX-XXI centuries*

Table 7: Collected data regarding to pipeline anchor damages

| ***Pipeline*** | ***Year*** | ***Location*** | ***Cause*** | ***Vessel type*** | ***Consequence*** | ***Source*** |
|---|---|---|---|---|---|---|
| *Natural gas pipeline* | 2014 | Copano Bay, Gulf of Mexico (GoM) | Dragging anchor | Boat | Snagging of the pipeline. Pipeline rupture. Fire on the water. | ("Natural gas pipeline rupture causes fire on the water in Copano Bay, Texas", 2014) |
| *West African Gas Pipeline* | 2012 | Nigeria, Benin, Togo, Ghana waters | Dragging anchor | WAGPCo vessel taken over by pirates | Damage of two pipeline sections. | ("WAGPCo loses $30m to pipeline rupture, to resume operations soon", 2012) |
| *Trans Mediterranean (natural gas pipeline)* | 2008 | The Mediterranean Sea | Dragging anchor | - | Catastrophic failure and a simultaneous l4% reduction in a parallel subsea high-pressure pipeline. | (Sim, 2010) |
| *Submarine ethane gas pipeline* | 2008 | Port Phillip, Australia | Dragging anchor | Containership "APL Sydney" | Snagging of the pipeline. Pipeline displacement. Scour marks, and some blowout craters. | (Australian Transport Safety Bureau, 2008) |
| *Kvitebjørn gas pipeline* | 2007 | Norwegian sector of the North Sea | Dragging anchor (10 ton) | Large 80 000 - 100 000 DWT vessel | A localized and sharp 17 degree dent and around half a meter of damaged coating exposing bare metal. The pipeline was dragged 53 m out of the installed position. | (Gjertveit, Berge & Opheim, 2010) |
| *Central Area Transmission System* | 2007 | UK sector of the North Sea | Dragging anchor | Motor Vessel "Young Lady" | The pipeline was lifted out of the trench and dragged 6 m laterally. Damage of outer protective layers. | (Woods, 2011) |
| *High Island* | 2006 | The Galveston | Dragging | Liberian oil | Rupture resulted in an oil | (U.S. Department of the Interior |

| | | | | | | |
|---|---|---|---|---|---|---|
| *Pipeline System (oil pipeline)* | | Lightering Area in the GoM | anchor | tanker | leakage of approximately 870 barrels. | Minerals Management Service, 2008) |
| *Canyon Chief Gas Export Pipeline* | 2005 | GoM | Dragging anchor | Semi-submersible oil rig | Hook by an anchor. The resulting damage pulled the pipeline laterally 1 500 ft from its original path. | (Alexander et al., 2014; Heallen, 2013) |
| *Equilon Pipeline Co. crude oil line* | 2000 | Louisiana, GoM | Dropped anchor (8 ton) | Ship | About 2984.12 barrels of crude oil were spilled, creating a slick (2 miles wide by 7 miles long). | (List of pipeline accidents in the United States in the 21st century, 2015) |
| *Natural gas distribution line* | 1999 | Hudson River, New York | Anchor and anchor chain, the flukes of the anchor caught the pipe | Cement barge Maria T | Gas escape from the pipe, "boiling water" effect. | (United States Coast Guard, 1999) |
| *Condensate line* | 1998 | GoM, Block EC334 | Dragging anchor during rescue operations | Service vessel | Leakage of 1 211 barrels of condensate. | (U.S. Department of the Interior Minerals Management Service, 2002) |
| *Amethyst gas pipeline* | 1997 | Humber estuar | Dragging anchor | Capella tanker | The anchor snagged on the Amethyst gas pipeline. | (United Kingdom. Marine Accident Investigation Branch, 2007) |

| | | | | | | |
|---|---|---|---|---|---|---|
| *Tennessee Gas Pipeline* | 1996 | Tiger Pass, Louisiana, GoM | Dropped stern spud (large steel shaft that is dropped into the river bottom to serve as an anchor during dredging operations) | Dredge Dave Blackburn | Rupture of natural gas steel pipeline. The pressurized (about 930 psig) natural gas released from the pipeline enveloped the stern of the dredge and an accompanying tug. | (Washington National Transportation Safety Board, 1996) |
| *Amethyst gas pipeline* | 1996 | Humber estuar | Dragging anchor | Kandilousa oil tanker | The anchor snagged the Amethyst pipeline, parted an ethylene feeder line and a power cable. The gas pipeline remained intact. | (United Kingdom. Marine Accident Investigation Branch, 2007) |
| *Chevron Corporation pipeline offshore (oil line)* | 1991 | El Segundo, California | Anchor | Ship | 1587.3 barrels of light oil spil. Wildlife was affected. | (List of pipeline accidents in the United States 1975 to 1999, 2015) |
| *Condensate line* | 1990 | GoM, Block SS281 | Dragging anchor | - | Leakage of 14 423 barrels of condensate. | (U.S. Department of the Interior Minerals Management Service, 2002) |
| *Amoco pipeline (oil line)* | 1988 | Galveston Block A-2, GoM | Anchor | Sypply boat | 15 576 barrels leakage of crude oil into the Gulf. | (List of pipeline accidents in the United States 1975 to 1999, 2015; Strating, 1981) |
| *Oil pipeline* | 1981 | GoM, Block SP60 | Anchor | Service vessel | Leakage of 5 100 barrels of oil. | (U.S. Department of the Interior Minerals Management Service, 2002) |

| | | | | | | |
|---|---|---|---|---|---|---|
| *Thistle-Dunlin (oil line)* | 1980 | North Sea | Dragging anchor | Vessel | 1000 tons of oil leakage. | (Orszulik, 2008) |
| *High pressure natural gas pipeline* | 1979 | Mississippi River Delta | Mooring spud | Crane barge | Four workers drowned attempting to escape a fire. | (Washington National Transportation Safety Board, 1980) |
| *Norpipe oil pipeline (Ekofisk to Teesside)* | 1977 | North Sea | Dragging anchor | 50 000 DWT tanker, Liberian Tanker Marion | 5-inch dent. | (Gowen, Goetz & Waitsman, 1980) |
| *Pennzoil pipeline* | 1974 | GoM, Eugen Island Block 317 | Dragging anchor | - | 19 833 barrels of oil spill. | (Strating, 1981) |
| *Oil pipeline* | 1969 | GoM, Block MP299 | Dragging anchor | - | Leakage of 7 532 barrels of oil. | (U.S. Department of the Interior Minerals Management Service, 2002) |
| *Oil pipeline* | 1968 | GoM, Block ST131 | Dragging anchor | - | Leakage of 6 000 barrels of oil. | (U.S. Department of the Interior Minerals Management Service, 2002) |
| *Humble oil pipeline* | 1967 | GoM, Block WD73 | Anchor tore a hole in a corroded pipeline | - | Leakage of 160 638 barrels of oil. | (U.S. Congress, Office of Technology Assessment, 1990; U.S. Department of the Interior Minerals Management Service, 2002) |

Table 8: Collected data with regard to cable anchor damage

| ***Cable*** | ***Year*** | ***Location*** | ***Cause*** | ***Vessel type*** | ***Consequence*** | ***Source*** |
|---|---|---|---|---|---|---|
| *Transpower and a fibre-optic communication cable* | 2015 | Cook Strait | Anchoring | Boat | Damage of cable. | ("Big fine for anchoring in zone", 2015) |

| | | | | | | |
|---|---|---|---|---|---|---|
| *Subsea fibre-optic cables* | 2014 | Off Singapore | Dropped anchor | 16,800-dwt products tanker Glory Star | Damage of cable. | (“Vietnamese tanker seized over damage to cable”, 2014) |
| *The 20,000-kilometer-long Asia-America Gateway (AAG) cable* | 2014 | Off the coast of Vietnam | Dragging anchor | Boat | Damage of cable. | (Schatz, 2014) |
| *Subsea telecommunicatio n cable* | 2014 | Off the coast of Atlantic Canada | Dragging anchor | Newfoundland fishing vessel | Cable break. | (Cuthbertson, 2015) |
| *Power submarine cable* | 2014 | Guimaras Island | Dragging anchor | Cargo vessel MV Ocean Prosperity | Cable damage. | (“Damaged power submarine cable causes blackout in Guimaras”, 2014) |
| *4 submarine cables linking East Africa to the Middle East and Europe* | 2012 | The Red Sea near Mombasa, Kenya | Dropped anchor | Ship | Damage of cables. | (Madory, 2012) |
| *Major submarine cable* | 2012 | 60 kilometers off the coast of Singapore | Anchoring | Ship | Cable damage. | (Lavallee, 2013) |
| *SEA-ME-WE 3* | 2011 | Suez canal, Egypt | - | - | Cable was cut off. | (2011 submarine cable disruption, 2013) |

| | | | | | | |
|---|---|---|---|---|---|---|
| *I2i (submarine telecommunications cable connecting India to Singapore)* | 2011 | Between Chennai, India and Singapore line | - | - | Cable was cut off. | (2011 submarine cable disruption, 2013) |
| *FALCON cable connects several countries in the Persian Gulf and India.* | 2008 | Near Bandar Abbas, Iran | Anchoring | Ship | Cable is cut off. | (2008 submarine cable disruption, 2015) |
| *SEA-ME-WE 4 and FLAG Telecom cables in the Mediterranean Sea.* | 2008 | Near Alexandria | Dragging anchor | Ship | Damage of cables. | (2008 submarine cable disruption, 2015) |
| *FALCON cable* | 2008 | Between Muscat, Oman and Dubai, UAE | Abandoned anchor weighing 5-6 tonnes | Ship | Cable is cut off. | (2008 submarine cable disruption, 2015) |
| *DOHA-HALOUL cable connecting Qatar to the United Arab Emirates* | 2008 | Between the Qatari island of Haloul and the UAE island of Das | Anchoring | Ship | Damage of cable. | (2008 submarine cable disruption, 2015) |
| *SEA-ME-WE-4* | 2008 | Near Penang, Malaysia | Anchoring | Ship | Damage of cables. | (2008 submarine cable disruption, 2015) |

| | | | | | | |
|---|---|---|---|---|---|---|
| *FLAG Telecom, SEA-ME-WE 4, and SEA-ME-WE 3 cables, linking Alexandria, Egypt, Sicily, and Malta; GO-1 cable* | 2008 | Off Sicily | Dragging anchor | Oil tanker of 244m length with a gross tonnage of 58,000 tons | Cables are cut. | (2008 submarine cable dispruption, n.d.; Green & Brooks, n.d.) |
| *6 cables: one power cable, 1 electrode cable, 1 fiber-optic cable and 3 communication cables* | 2006 | The Baltic Sea | Dragging anchor | Cargo ship | Damage of cables. | ("Cargo ship damages 6 submarine cables in the Baltic", 2007) |
| *Submarine cable* | 2005 | Between Scania and Bornholm | Anchor loss | Barge | Cable is torn in two parts. | ("Blackout on Bornholm", n.d.) |
| *4 trans-Atlantic cables* | 1986 | Off the coast of New Jersey | Dragging anchor | Cargo ship M/V Aconcagua | Damage of hot-lines between the US and the USSR. | (Burnett, Beckman & Davenport, 2013) |
| *Electric cable* | 1955 | Norway | Dropped anchor | Ship | Cable damage. | (Winiger, Koziol, Koch & Reinhard Zimmermann, 2011) |
| *Telegraph cable* | 1842 | East River, New York | Anchoring | Ship | Cable damage. | (Carter et al., 2009) |

## 4.1 SHIP ANCHORING

There are a lot of lines laid in shallow water. Some parts of their routes may be crossed by shipping lanes, and other parts may be located near to the port or harbour. (Figure 20) Such a common and controlled procedure as vessel anchoring may result in adverse effects for offshore pipelines.

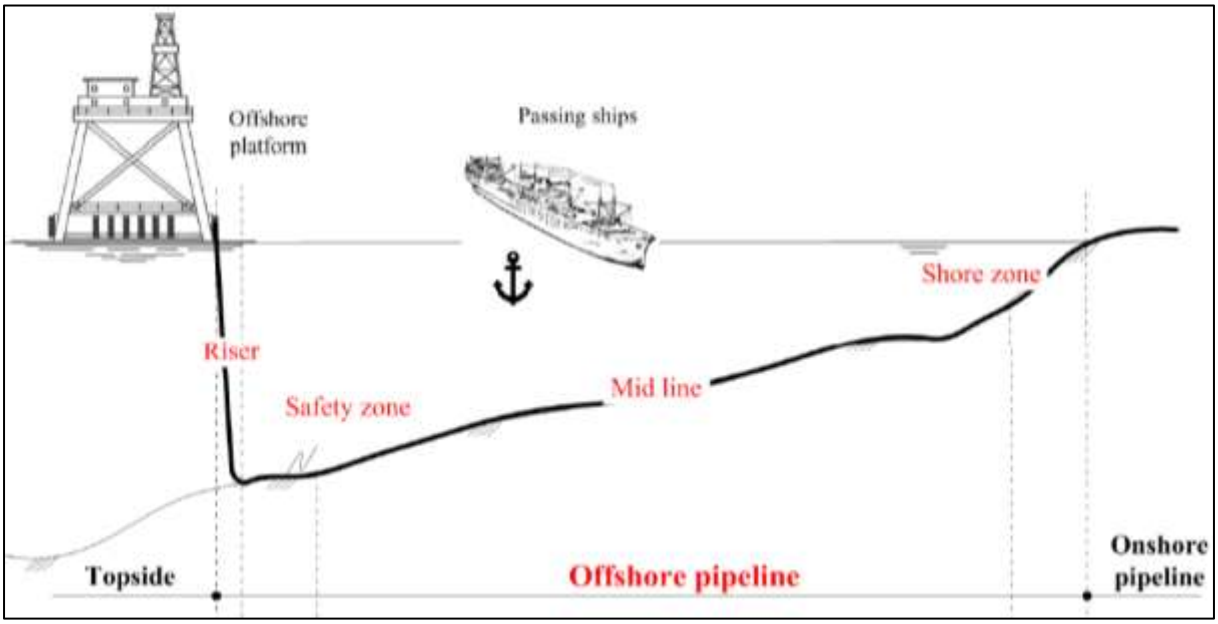



*Figure 20: Offshore pipeline zones (Liu, HU & Zhang, 2013)*

Anchoring is defined as lowering of weight (anchor, anchor chain or rope) to the sea bottom in order to hold the ship in a certain position ("Anchors and anchoring", 2012). Ship anchoring procedure is usually distinguished between two scenarios (Hvam, Bruschi, Tommez, & Vitali, 1990):

1. Ordinary (routine) anchorage is carried out in a prescribed and most suitable area, which extends 1 km on both sides of pipeline corridor. That is why ordinary procedure is not thought to be risky for the pipeline operation;
2. Extraordinary anchorage may be carried out within unpredicted zone (shipping lanes or pipe corridor) in case of emergency (engine failure, ship collision, loss of control) and dangerous situation for the surrounding vessels and installations. Thus, emergency anchoring becomes very critical for the pipelines.

Along with these two scenarios, there is also planned anchoring that is taken in the vicinity of offshore structures and pipelines during construction works. Extraordinary and planned operations need to be performed carefully and in accurate way. In spite of accumulated knowledge and experience, there are still a lot of incidents associated with incorrect and unsafe ship anchoring resulting in catastrophic damages to pipelines and submarine cables. The reasons for them may be different, but the main ones are human error, failure of navigational system, and harsh weather conditions.

It is always a challenge to deploy the anchors, when the ship is on its way. Sometimes the problem resides in unsatisfactory maintenance of anchor winch arrangement: bad condition of turnbuckle; break of the chain stopper; jerk in a chain; inadequate applications of chain lock, and band brakes (DNV Recommended Failure Rates for Pipelines, 2010). All these may lead to uncontrolled actions with three possible outcomes:

1. Anchor is dropped within 1 km. The penetration depth is not large, so the anchor is easily recovered.
2. Anchor is fully seated in the seabed. Maximum penetration and holding power are provided and it can result in chain and bitter end breaks; some problems in ship maneuvering system also arise. Anchor can be lost.
3. Anchor is not seated and dragged for some distance along the seabed until it hooks the pipeline or structure. Ship anchor drags because the external forces are greater than holding power of the anchor and chain. Anchor is lost.

Three outcomes denote that subsea pipeline may be hit from the top or displaced by dropped and dragged anchors correspondingly. In order to get a broad picture of pipeline damage, it is necessary to know key factors, particularly affecting the interaction between pipeline and anchor, namely:

- Vessel characteristics: type, identification number, length, breadth, drought, speed, and vessel movements tracks, etc.;
- Anchor arrangement parameters: anchor type, class and mass; chain type, length and diameter, etc.;
- Pipeline characteristics: route identification, seabed profile, material type (steel or flexible) and grade, diameter, wall thickness, coating thickness, type of protection, etc.

In addition to these factors, it is essential to take into account marine activity details such as ship traffic volume (intensity) and vessel population (composition). It should be mentioned that the number of emergency situations is heavily dependent on the number of ships passing the lines. Hence, the combination of these data becomes very useful.

Moreover, not only anchoring issues, but also a set of other criteria, become an actual reason for pipeline failure. Set of key factors and criteria relevant to the pipeline damage will be covered hereinafter.

### 4.1.1 Vessel characteristics

A vast number of different vessels cross over huge territories. Passing vessels vary in class and area of use. Energy Report categorizes six ship classes with the ranges of Equipment Number (EN) and corresponding values of displacement, chain length and anchor mass (Table 9).

Table 9: Ship class definition (DNV Recommended Failure Rates for Pipelines, 2010)

| ***Class*** | ***Displacement, tonnes*** | ***GRT from*** | ***GRT to*** | ***EN from*** | ***EN to*** | ***Length of anchor chain, in*** | ***Anchor mass, kg*** |
|---|---|---|---|---|---|---|---|
| I | 1500 | 100 | 499 | 280 | 320 | 179 | 900 |
| II | 3600 | 500 | 1599 | 450 | 500 | 207 | 1440 |
| III | 10000 | 1600 | 9999 | 980 | 1060 | 248 | 3060 |
| IV | 45000 | 10000 | 59999 | 2870 | 3040 | 317 | 8700 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| V | 175000 | 60000 | 99999 | 5800 | 6100 | 372 | 17800 |
| VI | 350000 | 100000 | - | 8400 | 8900 | 385 | 26000 |

All of the vessels can be attributed to a certain category that is accepted by naval architects (Ship, 2015). Several types of the ships are shown in Figure 21.

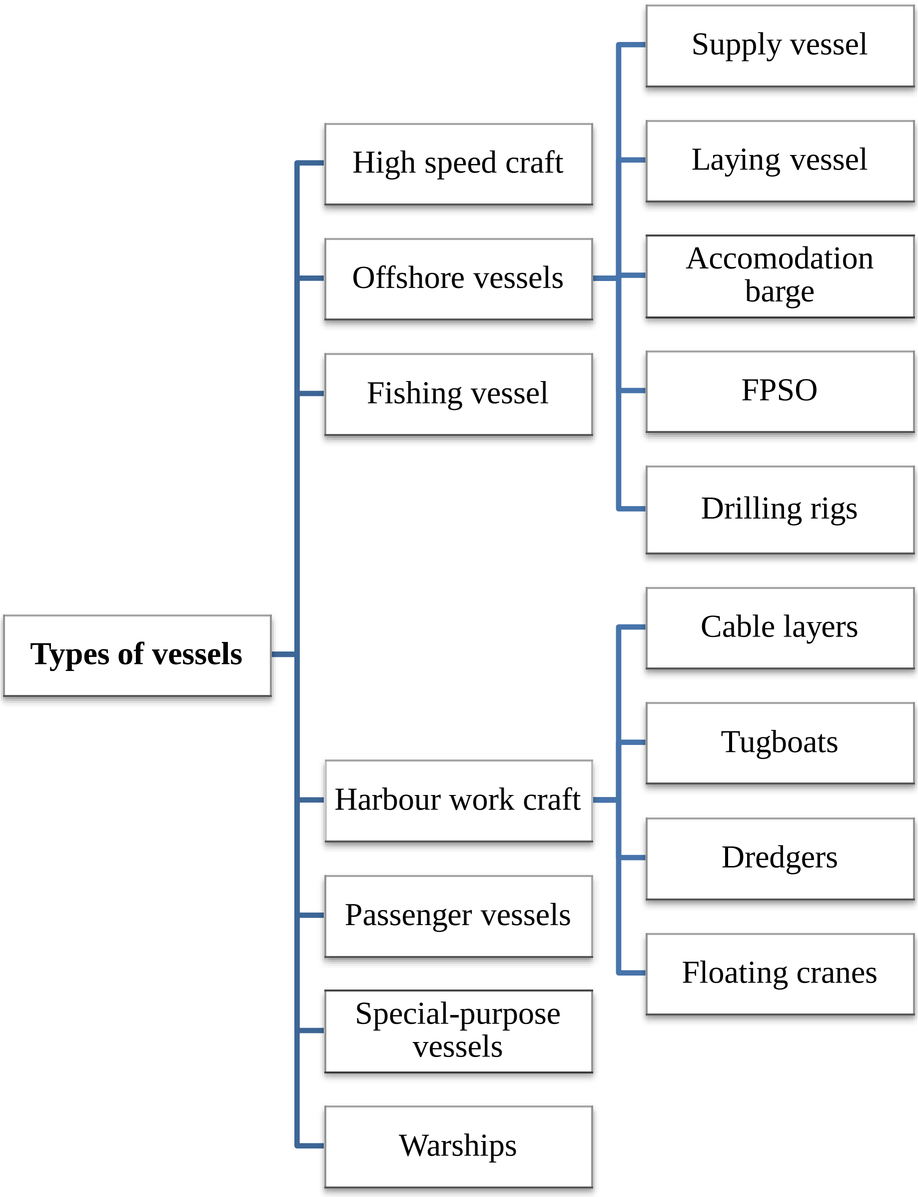



*Figure 21: Illustration of vessel types*

Each ship has its name and unique numbers like IMO (International Maritime Organization) and MMSI (Maritime Mobile Service Identity). These numbers are used to identify vessel location and set of specific parameters: tonnage, hull, cargo, and machinery, etc. Such data may be found in Vessel Register sources (for instance, DNV GL). Moreover, the identification numbers also help to determine vessels movements' details (in particular, shipping intensities and traffic composition), and tracking data, that can be retrieved from AIS (Automatic Identification System) surveys.

### 4.1.2 Anchoring equipment characteristics

***Equipment number***

Once the IMO-no is known, then it is possible to get information about anchoring equipment, which varies with the type of vessels. For the purpose of getting clear understanding of the equipment, some definitions and interpretations are taken from the DNV Rules for Classification of Ships document (DNV Rules for Classification of Ships, 2011).

*The anchoring equipment required is the minimum considered necessary for temporary mooring of a vessel in moderate sea conditions when the vessel is awaiting berth, tide, etc. The equipment is therefore not designed to hold a vessel off fully exposed coasts in rough weather or for frequent anchoring operations in open sea. In such conditions the loads on the anchoring equipment will increase to such a degree that its components may be damaged or lost owing to the high energy forces generated. The anchoring equipment required by the Rules is designed to hold a vessel in good holding ground in conditions such as to avoid dragging of the anchor. In poor holding ground the holding power of the anchors will be significantly reduced. It is assumed that under normal circumstances the vessel will use only one bower anchor and chain cable at a time.*

As noted before, each ship has its own anchoring system (anchor and its attachment to the ship), the size of which is directly dependent on the ship characteristics. To make decision on the anchor size it is needed to find an Equipment Number using specified formula from the Rules (DNV Rules for Classification of Ships, 2011):

$$EN = \Delta^{2/3} + 2 \cdot B \cdot H + 0.1 \cdot A \tag{1}$$

$H$ - effective height from the summer load waterline to the top of the uppermost deckhouse, to be measured as follows:

$$H = a + \sum h_i \tag{2}$$

$a$ - distance from summer load waterline amidships to the upper deck at side;
$h_i$ - height on the center line of each tier of houses having a breadth greater than $B/4$. For the lowest tier, $h_i$ shall be measured at center line from the upper deck, or from a notional deck line where there is local discontinuity in the upper deck;
$A$ - area in profile view of the hull, superstructures and houses above the summer load waterline, which is within $L$ of the ship. Houses of breadth less than $B/4$ shall be disregarded;
$\Delta$ – displacement.

**NB**. *The Equipment Numeral formula for required anchoring equipment is based on an assumed current speed of 2.5 m/s, wind speed of 25 m/s and a scope of chain cable between 6 and 10, the scope being the ratio between length of chain paid out and water depth* (DNV Rules for Classification of Ships, 2011).

As soon as the EN has been found, one can define what kinds of anchor and anchor chain correspond to a given vessel. Anchoring equipment may be selected according to the requirements from the Equipment Tables provided by the Rules (Figure 22).

| Table C1 Equipment, general | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Equipment number | Equipment letter | Stockless bower anchors | | Stud-link chain cables | | | | Towline (guidance) | | Mooring lines 1) (guidance) | | |
| | | Number | Mass per anchor | Total length | Diameter and steel grade | | | Steel or fibre ropes | | Steel or fibre ropes | | |
| | | | | | NV K1 | NV K2 | NV K3 | Minimum length | Minimum breaking strength | Number | Length of each | Minimum breaking strength |
| | | | kg | m | mm | mm | mm | m | kN | | m | kN |
| 30-49 | $a_0$ | 2 | 120 | 192.5 | 12.5 | | | 170 | 88.5 | 2 | 80 | 32 |
| 50-69 | a | 2 | 180 | 220 | 14 | 12.5 | | 180 | 98.0 | 3 | 80 | 34 |
| 70-89 | b | 2 | 240 | 220 | 16 | 14 | | 180 | 98.0 | 3 | 100 | 37 |
| 90-109 | c | 2 | 300 | 247.5 | 17.5 | 16 | | 180 | 98.0 | 3 | 110 | 39 |
| 110-129 | d | 2 | 360 | 247.5 | 19 | 17.5 | | 180 | 98 | 3 | 110 | 44 |
| 130-149 | e | 2 | 420 | 275 | 20.5 | 17.5 | | 180 | 98 | 3 | 120 | 49 |
| 150-174 | f | 2 | 480 | 275 | 22 | 19 | | 180 | 98 | 3 | 120 | 54 |
| 175-204 | g | 2 | 570 | 302.5 | 24 | 20.5 | | 180 | 112 | 3 | 120 | 59 |
| 205-239 | h | 2 | 660 | 302.5 | 26 | 22 | 20.5 | 180 | 129 | 4 | 120 | 64 |
| 240-279 | i | 2 | 780 | 330 | 28 | 24 | 22 | 180 | 150 | 4 | 120 | 69 |
| 280-319 | j | 2 | 900 | 357.5 | 30 | 26 | 24 | 180 | 174 | 4 | 140 | 74 |
| 320-359 | k | 2 | 1020 | 357.5 | 32 | 28 | 24 | 180 | 207 | 4 | 140 | 78 |
| 360-399 | l | 2 | 1140 | 385 | 34 | 30 | 26 | 180 | 224 | 4 | 140 | 88 |
| 400-449 | m | 2 | 1290 | 385 | 36 | 32 | 28 | 180 | 250 | 4 | 140 | 98 |
| 450-499 | n | 2 | 1440 | 412.5 | 38 | 34 | 30 | 180 | 277 | 4 | 140 | 108 |

*Figure 22: Part of the Equipment Table from the DNV Rules for Classification of Ships document*

***Anchor***

Speaking about the anchors in general, there are several types of them developed for temporary or permanent usage: gravity and drag embedment; pile and suction anchors. The most traditional one for the vessels is drag embedment anchor (DEA) designed to penetrate into the seafloor. DEA can be classified as stocked or stockless one (widely used). More detailed description of various anchor types is presented in Table 10 (Sriskandarajah & Wilkins, 2002**;** Aberdeen. Health & Safety Executive, 2009).

Table 10: Anchor types

| ***Illustration*** | ***Name*** | ***Peculiarities*** |
|---|---|---|
|   | Hook (traditional fisherman and grapnel) | • Has small fluke surface and heavy, narrow arm;<br>• Penetrates into rock, heavy kelp, eel grass, coral and hard sand;<br>• May snag unprotected (unburied) pipelines. |
|  | Plough | • May bury itself in the sea bottom;<br>• Penetrates in both soft mud and rock. |

| | | |
|---|---|---|
|  | Fluke | • Has large fluke areas;<br>• Develops very large resistance to the loads;<br>• Has less ability to penetrate;<br>• Has light weight.<br>• May threaten shallow trenched pipelines. |

***Anchor rode***

The anchor is attached to the ship by the rode, which is quite critical item of anchoring system as well. Anchor rode can be rope, chain or a combination of them. Every type has its own advantages and disadvantages: wire rope is more flexible, while chain is more robust. Nevertheless, chain is supposed to be the most applicable mode of anchor and vessel connection (Sriskandarajah & Wilkins, 2002).

One can distinguish between stud-link (for temporary purposes) and stud-less (for permanent purposes) chains (Figure 23). Each of them varies in size (diameter) and material grade, which are chosen in relation to the parameters of the anchor as shown in the Equipment Table (Figure 22).

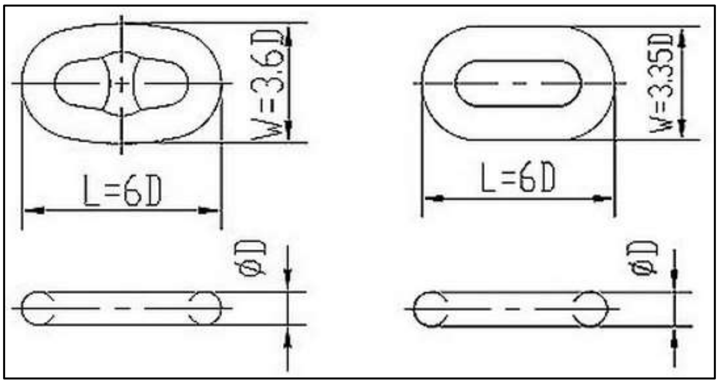



*Figure 23: Stud-link and stud-less chain configurations ("Mooring chain", n.d.)*

## 4. 2 PIPELINE DAMAGE CRITERIA

On the basis of ship, anchor and pipeline parameters it is possible then to highlight main damage criteria influencing effect of pipeline-anchor interaction. Six damage criteria are chosen to be principle for the assessment of the threats from anchors to the pipelines:

1. Chain length;
2. Anchor fluke size;
3. Anchor penetration depth;
4. Marine physical environment;
5. Applied forces from the anchor;
6. Pipeline resistance.

### 4.2.1 Anchor fluke size

It is evident that not all the anchors are capable of hooking on to the offshore pipelines. The key parameter here is the anchor fluke ("teeth") size. There are two ways (a and b) of hooking the pipeline (Figure 24). The first figure below (a) shows the configuration of pipeline being stuck between one fluke and shank of the anchor. Pipe diameter and anchor size relation for this case is as written:

$$C_{\perp} \geq d/2 \tag{3}$$

$\alpha$ - angle between fluke and shank;
$C$ - length of fluke;
$C_{\perp}$ – projected fluke length;
$d$ - outer diameter of steel pipe (w/o specifying the coating).

Another way of line hook is presented on the second figure (b). It is shown that the pipeline can be stuck between the plane of two flukes and anchor shank correspondingly. The relation here is as specified:

$$C'_{\perp} \geq d/2 \tag{4}$$

$\beta$ - angle between the plane of flukes and the shank;
$C'$ - median of flukes plane;
$C'_{\perp}$ - projected median;
$d$ - outer diameter of steel pipe (w/o specifying the coating).

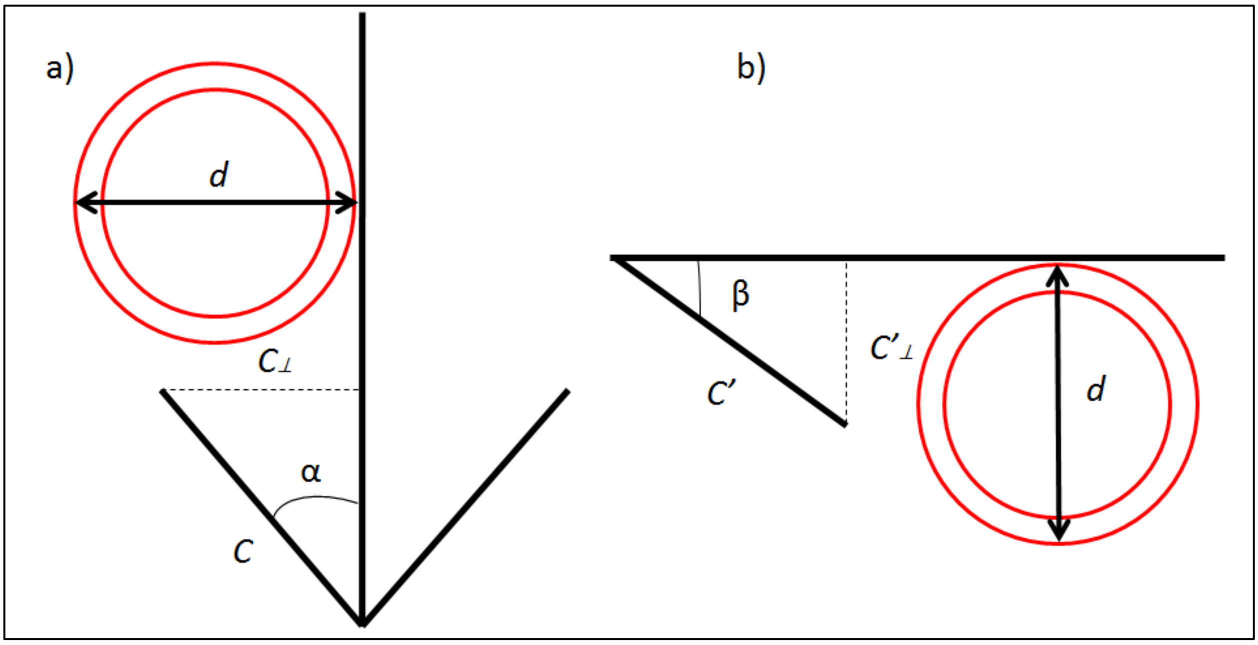



*Figure 24: Anchor size and pipeline diameter relation*

It is possible to determine the maximum hook diameter for each anchor size. Thus, pipe-anchor interaction studies are simplified a lot.

### 4.2.2 Relation between chain length and water depth

Chain length is one of the topical questions. It should be kept in mind that the relation between water depth and chain length does not equal to one. In case if ship is moving forward with the deployed anchor arrangement, the chain and anchor will never be hanging vertically. That is precisely why the chain length has to be larger than the water depth, so that the relation should be less than one (Figure 25).

$$\frac{d}{l} < 1 \tag{5}$$

$d$ – water depth;
$l$ – chain length.

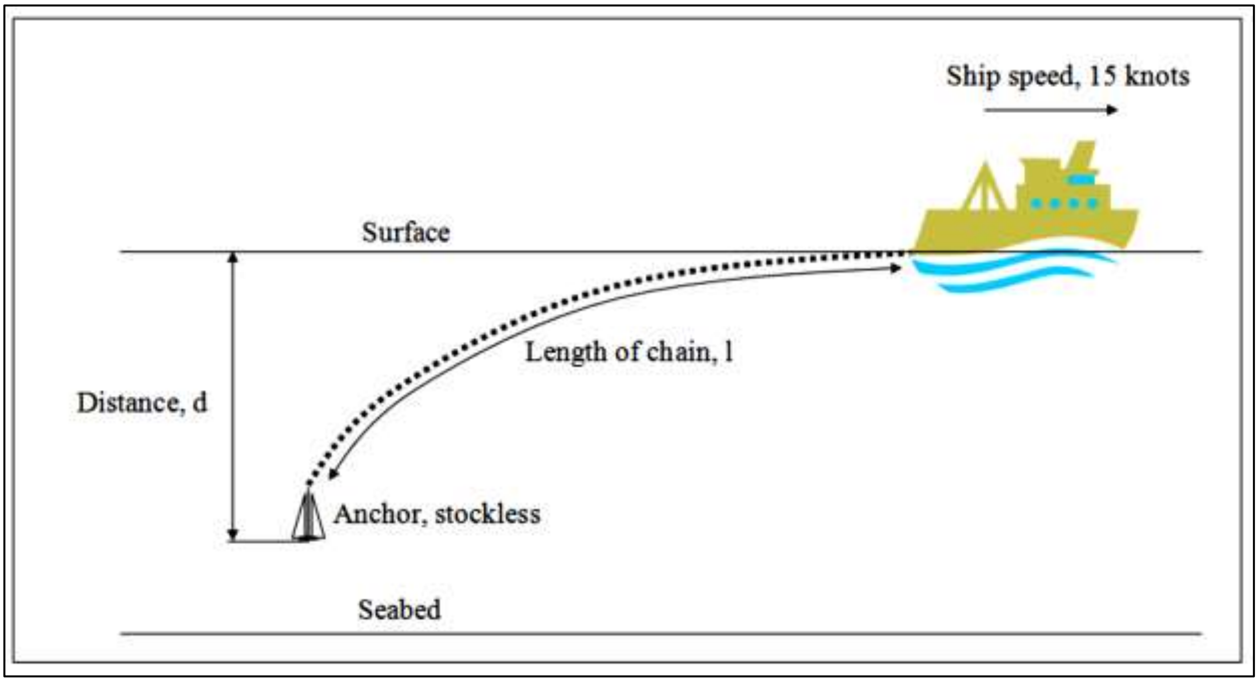



*Figure 25: Relation between water depth and chain length (DNV Recommended Failure Rates for Pipelines, 2010)*

### 4.2.3 Anchor penetration depth

Anchor parameters and soil conditions affect the anchor penetration depth. This value is significant for the damage assessment of buried lines. Since the pipeline is trenched, the anchor should penetrate deep enough to hook the pipe with its flukes.

A lot of papers on the analysis of penetration depth exist. Most of them are based on the comparison of analytical solution results with the test data. Core task here is to understand a relationship between the penetration depth, tension and drag force acting on the anchor. It is important to know how the relationship changes with different types of anchors and soil conditions. The easiest way to analyze the behavior of anchor flukes in the soil is to solve a set of equilibrium equations. One of such solutions is presented in the "Penetration and Load Capacity of Marine Drag Anchors in Soft Clay" article (1998). The equations are developed in accordance with the proposal that *anchor movement does not occur until the soil resistant forces* *are overcome* (Figure 26). The first three equations govern anchor equilibrium during its penetration, while the fourth one describes chain performance (Thorne, 1998; DNV-RP-E301, 2012).

$$M: -T_a \cdot Sin(\theta + \theta_a) \cdot S_x + W \cdot Cos(\theta) \cdot X_w + M - TDFM + T_a \cdot Cos(\theta + \theta_a) \cdot S_y + W \cdot Sin(\theta) \cdot Y_w = 0 \tag{6}$$

$$Ox: T_a \cdot Cos(\theta + \theta_a) - TDFP + W \cdot Sin(\theta) = 0 \tag{7}$$

$$Oy: T_a \cdot Sin(\theta + \theta_a) - F_n - TDFN - W \cdot Cos(\theta) = 0 \tag{8}$$

$$\theta_a = \sqrt{\frac{2 \cdot Z \cdot \bar{Q}}{T_a} + {\theta_0}^2}$$

$T_a$ – chain tension in attachment point;
$\theta$ – angle of fluke to horizontal;
$\theta_a$ – angle of chain at anchor attachment to horizontal;
$S_x$ – x-coordinate of anchor shackle;
$W$ – submerged weight of anchor;
$X_w$ – x-coordinate of anchor center of gravity;
$M$ – moment exerted on fluke by soil;
$TDFM$ – total moment of drag forces about center of fluke area;
$S_y$ – y-coordinate of anchor shackle;
$Y_w$ – y-coordinate of anchor center of gravity;
$TDFP$ – total drag force parallel to fluke;
$F_n$– normal force exerted on the fluke by the soil;
$TDFN$ - total drag force normal to fluke;
$Q$ – average normal force per unit length of chain;
$Z$ – depth from the mud line to the anchor shackle;
$\theta_0$– angle of the chain at the mud line to the horizontal.

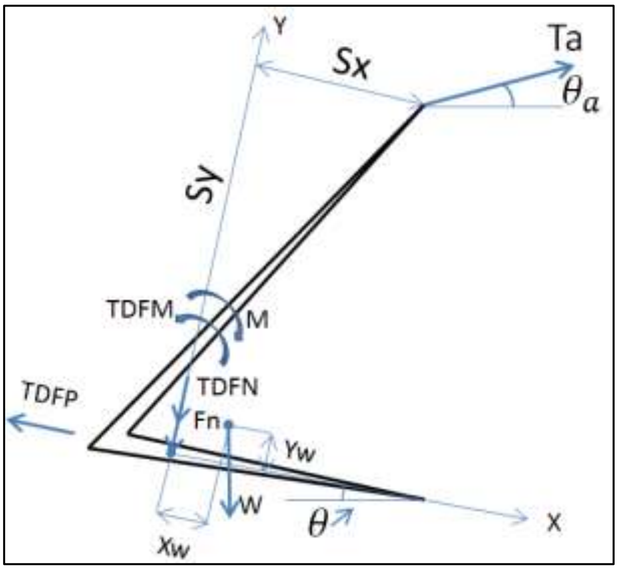



*Figure 26: Equilibrium of anchor*

Good studies results for both hard and soft soil are presented in DNV Recommended Failure Rates for Pipelines document (Table 11). Table shows the variation of anchor penetration depth and fluke length for different ship classes.

Table 11: Estimation of anchor penetration depth (DNV Recommended Failure Rates for Pipelines, 2010)

| | ***Displacement, tons*** | ***Penetration depth, m*** | ***Fluke length, m*** |
|---|---|---|---|
| *Hard soil (sand/hard clay)* | 1500 | 0.60 | 0.84 |
| | 3600 | 0.65 | 0.91 |
| | 10000 | 0.89 | 1.26 |
| | 45000 | 1.30 | 1.83 |
| | 175000 | 1.64 | 2.31 |
| | 350000 | 1.87 | 2.64 |
| *Soft soil (mud/soft clay)* | 1500 | 1.79 | 0.84 |
| | 3600 | 1.94 | 0.91 |
| | 10000 | 2.68 | 1.26 |
| | 45000 | 3.89 | 1.83 |
| | 175000 | 4.91 | 2.31 |
| | 350000 | 5.62 | 2.64 |

It is seen from the table that the maximum penetration depth of the flukes is found in soft clay and mud.

**NB**. Anchor penetration depth check is not going to be included into the analyses. In the case study it is assumed that all the anchors have already broken out of the sea bottom prior to hooking the pipe.

### 4.2.4 Marine physical environment

Action of the external forces on the vessel (sometimes exceeding the value of anchor holding power) can lead to unfavorable events. These forces are usually created by the marine physical environment. So that wind, currents and waves are capable of generating horizontal and vertical forces that give rise to various vessel motions. (Figure 27) In such cases the anchor can be broken free and then dragged along the seabed. The latter may result in huge consequences for both anchor arrangement system itself (break of the rode, loss of the anchor, etc.) and submarine pipelines and cables as well (damage, rupture, etc.) (Gudmestad, 2014).

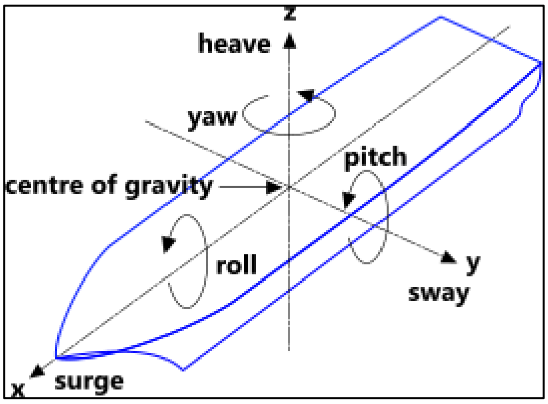



*Figure 27: Vessel motions (Gudmestad, 2014)*

### 4.2.5 Applied forces from the anchor

Mainly two anchoring operation modes characterize pipe-anchor interaction scenario. These modes are dropped and dragged anchors; and they are supposed to be the dominant causes of pipeline failure among all other external hazards.

***Dropped anchors***

Dropped from the vessel anchor is capable of hitting the pipeline vertically and causing localized deformations like coating crush and deflection of the steel shell (dent) (Figure 28). The duration of this mode is milliseconds. Assuming that all the impact energy is absorbed by the capacity of the pipeline and its protection, one shall find out that kinetic energy of the dropped anchor is very critical for the assessment of pipe local damage (Hvam, Bruschi, Tommez, & Vitali, 1990).

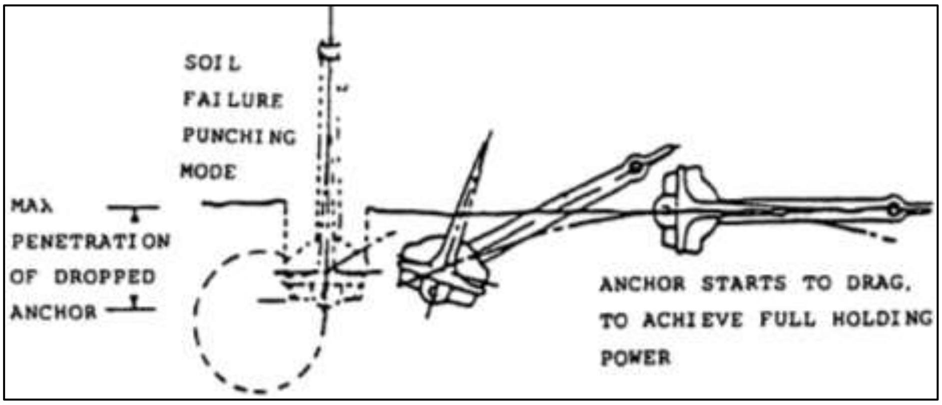



*Figure 28: Dropped anchor mode (Hvam, Bruschi, Tommez, & Vitali, 1990)*

From the basis of classical mechanics it is known that kinetic energy ($E_k$) of any object is a function of its mass ($m$) and impact velocity ($v$):

$$E_k = \frac{1}{2} \cdot m \cdot v^2 \tag{9}$$

$$v = v_T \tag{10}$$

Impact velocity is to be defined as terminal velocity of the object falling free in the water medium. The value of the terminal velocity is affected by the object shape and mass, and may be calculated from the Newton's second low:

$$(m - V \cdot \rho_w) \cdot g = \frac{1}{2} \cdot \rho_w \cdot C_D \cdot A \cdot v_T^2 \tag{11}$$

$$v_T = \sqrt{\frac{2 \cdot (m - V \cdot \rho_w) \cdot g}{\rho_w \cdot C_D \cdot A}} \tag{12}$$

$m$ – object mass;
$g$ – acceleration of gravity;
$V$ – object volume (equals to the volume of the displaced water);
$\rho_w$ – water density;
$C_D$ – object drag coefficient;
$A$ – object area in the direction of the flow;
$v_T$ – terminal velocity.

Moreover, there is an added hydrodynamic mass parameter that should be specified as well:

$$m_a = \rho_w \cdot C_a \cdot V \tag{13}$$

$m_a$ – object added mass;
$C_a$ – object mass coefficient.

Drag and mass coefficients can be taken from Table 12.

Table 12: Drag and mas coefficients for specified objects shapes (DNV-RP-F107, 2010)

| ***Shape description*** | ***Drag coefficient, $C_D$*** | ***Mass coefficient, $C_a$*** |
|---|---|---|
| *Slender* | 0.7-1.5 | 0.1-1.0 |
| *Box* | 1.2-1.3 | 0.6-1.5 |
| *Complex* | 0.6-2.0 | 1.0-2.0 |

Taking into account terminal velocity and added mass, the formula of kinetic energy of dropped object can be rewritten as following:

$$E_k = (m + m_a) \cdot v_T^2 \tag{14}$$

When the kinetic energy of the impact object is determined, then it is possible to find the size of local damage (Figure 29). It is obvious that the impact scenario consequences vary based on the type of pipeline protection (DNV-RP-F107, 2010).

- Bare pipeline:

$$E = 16 \cdot \left(\frac{2\pi}{9}\right)^{\frac{1}{2}} \cdot m_p \cdot \left(\frac{D}{t}\right)^{\frac{1}{2}} \cdot D \cdot \left(\frac{\delta}{D}\right)^{\frac{3}{2}} \tag{15}$$

$E$ - absorbed energy;
$m_p$ - plastic moment capacity of the wall;

$\delta$ - pipe deformation, dent depth;
$t$ - wall thickness (nominal);
D - steel outer diameter.

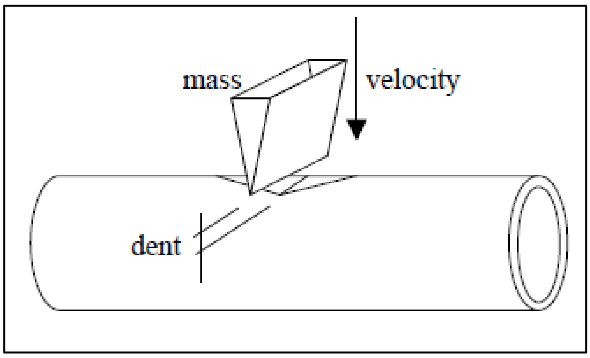



*Figure 29: Schematic view of dent prediction model (DNV-RP-F107, 2010)*

- Pipeline with the concrete coating:

$$E = \Upsilon \cdot b \cdot h \cdot x_0 \tag{16}$$

$$E = \Upsilon \cdot b \cdot 4/3 \cdot \sqrt{D \cdot x_0^3} \tag{17}$$

$E$ – absorbed energy;
$\Upsilon$ – crushing strength of concrete;
$b$ – breath of the impacting object;
$h$ – depth;
$x_0$ – penetration;
$D$ – pipeline diameter.

- Gravel cover:

$$E = \frac{2}{3} \cdot \gamma' \cdot L \cdot N_\gamma \cdot z^3 \tag{18}$$

$$E = \frac{\sqrt{2}}{4} \cdot \gamma' \cdot s_\gamma \cdot N_\gamma \cdot z^4 \tag{19}$$

$E$ – absorbed energy;
$\gamma'$ – effective unit weight of the fill material;
$L$ – length of the impacting side;
$s_\gamma$ – shape factor;
z – penetration depth;
$N_\gamma$ – bearing capacity coefficient.

***Dragged anchors***

If the vessel is moving with the deployed anchor, the latter can hit and snag the pipeline resting beneath or laid on the seafloor (Figure 30). As the result, pipeline becomes dented, bended, and/or lifted up from the bottom, and/or displaced from its initial position. In most cases pipeline loses its integrity and leaks.

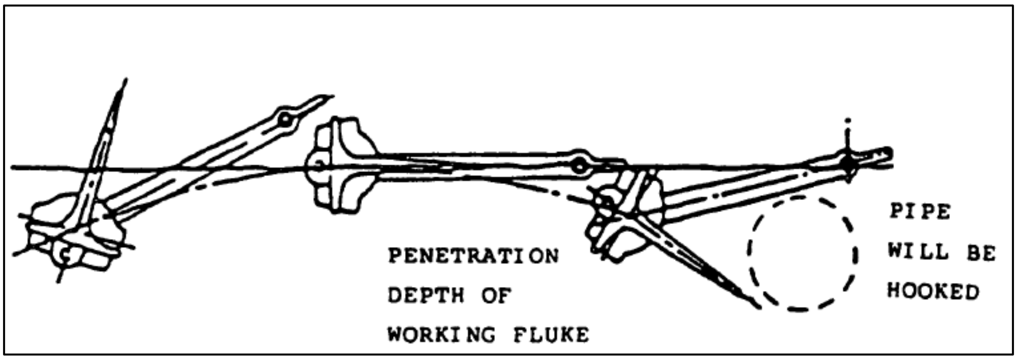



*Figure 30: Dragged anchor mode (Hvam, Bruschi, Tommez, & Vitali, 1990)*

The interaction of the pipeline with the dragging anchor can be divided into two stages. Firstly, the anchor hits the pipeline with its kinetic energy. The outcome here will be just a break of the coating, since steel pipe absorbs the impact energy. The impact energy of dragged anchor is related to the velocity of slowing down vessel. Velocity of decelerating vessels can be distinguished between different vessel sizes: for large ships it is usually in range of 0.2-0.5 m/s, and for small ships it is in range of 1.0-1.5 m/s (Hvam, Bruschi, Tommez, & Vitali, 1990).

Secondly, the anchor gets in contact with the pipeline, and applies a point load (snagging load) to it. In this case the line will be deflected, and the shell will be dented. When the line is snagged by the anchor, ship kinetic energy will be transferred to the pipeline until the rode, connecting anchor to the ship, breaks. Besides, anchor can catch the line, rotate over it and get released later. So, instead of snagging load, a pullover load will be applied to the line. The value of this load is smaller than value of snagging load. Pullover interaction may result in dents or gouges, and sometimes in line displacement. The duration of pull-over is 1-10 seconds, while the duration of anchor snagging is several minutes (Palmer-Jones, Turner, John & Nespeca, 2011).

From the basis of work-energy principle, *the work done by all forces acting on a particle (the work of the resultant force) equals the change in the kinetic energy of the particle* (Work (physics), 2015).

$$W = \Delta E_k \tag{20}$$

$W$ – work done;
$\Delta E_k$ – change in the kinetic energy.

At that time, *the work done by a constant force of magnitude F on a point that moves a displacement s in the direction of the force is the product* (Work (physics), 2015).

$$W = F \cdot s \tag{21}$$

The parameter $s$ here may be explained as a distance needed to make the vessel to stop. Interesting to note that the larger the distance traveled by the ship the larger the lateral displacement of caught pipeline will be. Once the limiting strain is exceeded, the pipeline will damage after the interaction with the anchor. Moreover, not only the force from the kinetic energy is to be considered. Another significant parameter is ship's thrust force. So, the contribution of both forces becomes a factor for the pipe damage assessment (DNV Recommended Failure Rates for Pipelines, 2010).

Furthermore, special attention should be given to the chain breaking load, which is the anchor dragging force applied to the pipeline. Checking the criteria for pipeline damage, it is safe to say that break load of the chain becomes basic parameter for the determination of damage occurrence for different cases. Breaking force value is related to the mass of anchor and varies with the diameter and material grade of the chain. The values of chain breaking load for six main ship classes are presented below (Table 13):

Table 13: Chain breaking loads for the defined ship classes (DNV Recommended Failure Rates for Pipelines, 2010)

| ***Class*** | ***Displacement, tonnes*** | ***Anchor mass, kg*** | ***Chain breaking load, kN*** | | |
|---|---|---|---|---|---|
| | | | ***Grade NV K1*** | ***Grade NV K2*** | ***Grade NV K3*** |
| I | 1500 | 900 | 368 | 389 | 476 |
| II | 3600 | 1440 | 581 | 655 | 735 |
| III | 10000 | 3060 | 1220 | 1370 | 1540 |
| IV | 45000 | 8700 | 3230 | 3610 | 3990 |
| V | 175000 | 17800 | 5720 | 6510 | 7320 |
| VI | 350000 | 26000 | - | 9030 | 10710 |

### 4.2.6 Pipeline resistance

***Limit state design***

Submarine pipelines are to be designed to withstand all the loads acting on them throughout its design life. Governing principle here is to define an acceptable limit or limit state. Once the acceptable limit is reached, the pipeline will not satisfy mandatory requirements any more.

Four categories of limit state exist (Karunakaran, 2014):

- Ultimate Limit State (ULS) involves the structural integrity or strength. The pipeline is designed to reach this limit state with very low probability.
    - Burst;
    - Collapse; local, global and propagating buckling.
- Fatigue Limit State (FLS) involves the fatigue damage coming from accumulated cyclic dynamic loads. The pipeline is designed in such a way, so that its life (considering fatigue damage) meets or exceeds its design life.
    - Currents and waves;
    - Slugging.
- Serviceability Limit State (SLS) involves the disruption of the pipeline use as planned. The pipeline is designed to be suitable for normal equipment operations.

- Extreme ovality of cross section;
- Extreme deflection or vibration.

- Accidental Limit State (ALS) involves pipeline failure due to accidental (infrequent loads).
  - Dropped objects;
  - Incidental overpressure;
  - Natural hazards;
  - Explosion and/or fire.

One of the fundamentals of Limit State Design is Load and Resistance Factor Design (LRFD) format (Figure 31) (DNV-OS-F101, 2013). The principle is to verify that the design resistance is not exceeded by the design load effects:

$$f\left(\left(\frac{L_{Sd}}{R_{Rd}}\right)_i\right) \leq 1 \tag{22}$$

$L_{Sd}$ – design load;
$R_{Rd}$ – design resistance;
$i$ – loading type.

$$L_{Sd} = L_F \cdot \gamma_F \cdot \gamma_C + L_E \cdot \gamma_E + L_I \cdot \gamma_F \cdot \gamma_C + L_A \cdot \gamma_A \cdot \gamma_C \tag{23}$$

$$R_{Rd} = \frac{R_c(f_c, t_c, f_0)}{\gamma_m \cdot \gamma_{SC}} \tag{24}$$

$\gamma_F, \gamma_C, \gamma_E, \gamma_C$ – load factors;
$\gamma_m, \gamma_{SC}$ – resistance factors;
$L_c$ – characteristic load;
$R_c$ – characteristic resistance;
$f_c$ – characteristic material strength;
$t_c$ – characteristic thickness;

- $f_0$ – out-of-roundness of the pipe.

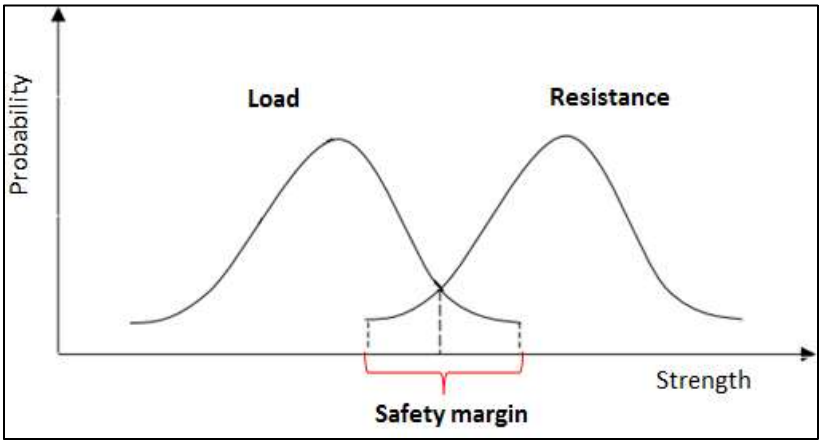


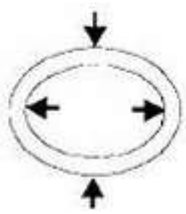

*Figure 31: Fundamentals of Limit State Design*

***Pipeline capacity***

As found above, large impact forces and snagging loads are applied to the pipeline during the interaction with the anchor. Even if the pipeline is designed properly, no one can exclude occurrence of failures due to external hazards that can introduce large forces and moments to the pipe.

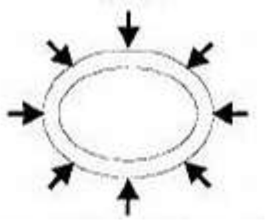
Capacity of the pipeline is heavily dependent on the amount of bending moment, axial force (tensile or compressive) and pressure (internal or external). These loads can affect the pipeline integrity singularly or in combination. Possible effects of pure loads are shown in Table 14 (Bai, 2001; Hauch & Bai, 2000).

Table 14: Pure load case description

<table>
<tr><th>Pure load and effect on the pipeline</th><th>Effect description</th></tr>
<tr><td>Bending moment<br></td><td>

- Increased ovalisation of the cross-section;
- Increased pipe wall stress;
- Cross-sectional collapse;
- Low D/t leads to failure on the tensile side of the pipe;
- High D/t leads to failure (inward buckling) on the compressive side of the pipe.

$$M_l = (1.05 - 0.0015\frac{D}{t}) \cdot SMYS \cdot D^2 \cdot t \qquad (25)$$

$M_l$– ultimate bending moment for pure bending;<br>
$M_l$ – average diameter;<br>
$t$ – wall thickness;<br>
$SMYS$ – specified minimum yield strength in longitudinal direction.
</td></tr>
<tr><td>External pressure<br></td><td>

- The deviation from circular to elliptical form;
- Total cross-sectional collapse;
- Radial displacement;
- Low D/t leads to cross-section yield;
- High D/t leads to elastic buckling.

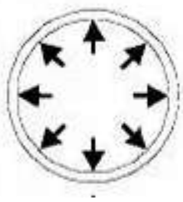
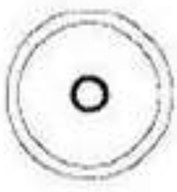
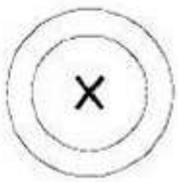
$$P_l^3 - P_{el} \cdot P_l^2 - \left(P_p^2 + P_{el} \cdot P_P \cdot f_0 \cdot \frac{D}{t_{corr}}\right) \cdot P_l + P_{el} \cdot P_p^2 = 0$$

$$P_{el} = \frac{2E}{(1-\vartheta^2)} \cdot \left(\frac{t_{corr}}{D}\right)^3 \qquad (27)$$

$$P_p = \eta_{fab} \cdot SMYS \cdot \frac{2t_{corr}}{D} \qquad (28)$$

$$t_{corr} = \frac{t-d}{1-\frac{d}{t \cdot \sqrt{1+0.8\left(\frac{L}{\sqrt{D \cdot t}}\right)^2}}} \qquad (29)$$

$P_l$ –ultimate external overpressure (collapse pressure);<br>
$P_{el}$ – elastic collapse pressure;<br>
$P_p$ – plastic collapse pressure;<br>
$f_0$ – initial out-of-roundness;<br>
$f_0$ - average diameter;
</td></tr>
</table>

| | |
|---|---|
| | $t$ – wall thickness;<br>$t_{corr}$ – corrosion thickness;<br>$d$ – defect depth;<br>$L$ - defect length;<br>$SMYS$ – specified minimum yield strength in hoop direction;<br>$E$ – Young's modulus;<br>$\upsilon$ – Poisson's ratio;<br>$\eta_{fab}$ – material strength de-rating factor. |
| *Internal pressure*<br> | • Bursting and expansion of the pipe cross-section;<br>• Wall thickness decrease.<br>$P_{burst} = 0.5(SMTS + SMYS) \cdot \frac{2 \cdot t_{corr}}{D}$ *(30)*<br>$P_{burst}$ – ultimate internal overpressure (burst pressure);<br>$SMYS$ – specified minimum yield strength in hoop direction;<br>$SMTS$ – specified minimum tensile strength in hoop direction;<br>$D$ - average diameter;<br>$t_{corr}$ – corrosion thickness. |
| *Tensile longitudinal force*<br> | • Pipe bursting;<br>• Wall thinning;<br>• Narrowed pipe cross-section.<br>$F_l = 0.5(SMTS + SMYS) \cdot (\pi - (1 - k_l) \cdot \beta) \cdot D \cdot t$ *(31)*<br>$k_l = \left(1 - \frac{d}{t}\right) \cdot \left(1 + \frac{d}{D}\right)$ *(32)*<br>$F_l$ – ultimate true longitudinal force for pure tension;<br>$D$ - average diameter;<br>$t$ – wall thickness;<br>$k_l$ – constant depending on defect size;<br>$SMYS$ – specified minimum yield strength in longitudinal direction;<br>$SMTS$ – specified minimum tensile strength in longitudinal direction;<br>$\beta$ – defect width;<br>$d$ – defect depth. |
| *Compressive longitudinal force*<br> | • Euler or local buckling.<br>Ultimate compressive force is found by the previous equation with the opposite sign. |

Along with the single loads mentioned above, the pipeline is usually subjected to the combined loading (e.g. pressure, moment, tension) as very often happens during the anchor dragging (hooking) event (Figure 32). In fact, there are a lot of analyses focused on the capacity of pipelines to resist plastic collapse and/or geometrical instabilities. Due to great numerical and experimental approach of these studies some parametric equations are developed in order to predict pipeline geometrical and mechanical behavior under different modes of combined loading (Table 15) (Kenedi, Borges & Vaz, 2009).

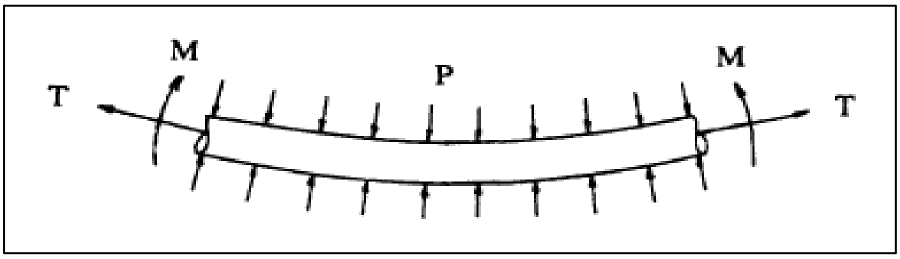



*Figure 32: Pipe exposed to the pressure, bending moment and axial force (Bai, Igland & Moan, 1992)*

Table 15: Combined load case description

| ***Combined loading*** | ***Expression for the evaluation of pipeline strength capacity*** |
|---|---|
| *Axial force – bending moment (Bai, Igland & Moan, 1993)* | $\frac{M}{M_c} - \cos\left(\frac{\pi}{2} \cdot \frac{N}{N_c}\right) = 0$ *(33)*<br>$M_c$ – ultimate bending moment capacity;<br>$N_c$ – ultimate true longitudinal force capacity. |
| *Axial force – pressure (Bai, 2001)* | $\left(\frac{\sigma_l}{\sigma_{ll}}\right)^2 - 2\alpha \cdot \frac{\sigma_l \cdot \sigma_h}{\sigma_{ll} \cdot \sigma_{hl}} + \left(\frac{\sigma_h}{\sigma_{hl}}\right)^2 = 1$ *(34)*<br>$\sigma_l$ – longitudinal stress;<br>$\sigma_h$ – hoop stress;<br>$\sigma_{ll}$ – limit longitudinal stress for pure longitudinal force;<br>$\sigma_{hl}$ – limit hoop stress for pure pressure;<br>$\alpha$ - correction factor depending on the ratio between the limit stress in the longitudinal and hoop direction correspondingly. |
| *Pressure – bending moment (Bai & Hauch, 2001)* | $\left(\frac{M}{M_c}\right)^2 + \left(\frac{P}{P_c}\right)^2 \leq 1$ *(35)*<br>$M_c$ – ultimate bending moment capacity;<br>$P_c$ – ultimate pressure capacity. |
| *Pressure – axial force – bending moment (Nozarian, 2011)* | $M = M_c \cdot \sqrt{1 - (1-\alpha^2) \cdot \left(\frac{P}{P_c}\right)^2} \cdot \cos\left(\frac{\pi}{2} \cdot \frac{\left(\frac{N}{N_c} - \alpha \cdot \frac{P}{P_c}\right)}{\sqrt{1-(1-\alpha^2)\cdot\left(\frac{P}{P_c}\right)^2}}\right)$ *(36)*<br>$M_c$ – ultimate bending moment capacity;<br>$P_c$ – ultimate pressure capacity;<br>$N_c$ – ultimate true longitudinal force capacity. |

***Design check***

One of the serious outcomes of excessive combined loading, which is often observed because of pull-over-hooking scenario, is pipeline local buckling. Local buckling occurs when loads applied to the pipeline are equal to or greater than its internal resistance over cross-section. Two design criteria for local buckling are proposed by Offshore Standard DNV-OS-F101 (2013):

- Load Controlled Condition (LCC). The pipeline response is governed by the loads.
  - *Combined loading*: internal overpressure, bending moment, effective axial force.

$$\left\{\gamma_m \cdot \gamma_{SC} \cdot \frac{|M_{Sd}|}{\alpha_c \cdot M_p(t)} + \left\{\gamma_m \cdot \gamma_{SC} \cdot \frac{S_{Sd}(p_i)}{\alpha_c \cdot S_p(t)}\right\}^2\right\}^2 + \left(\alpha_p \cdot \frac{p_i - p_e}{\alpha_c \cdot p_b(t)}\right)^2 \leq 1 \qquad (37)$$

$\gamma_m, \gamma_{SC}$ – resistance factors;
$\alpha_c$ – flow stress parameter;
$M_{Sd}$ – design moment;
$S_{Sd}$ – design effective axial force;
$p_i$ – internal pressure;
$p_e$ – external pressure;
$p_b$ – burst pressure
$S_p$, $M_p$ – plastic capacities of pipe.

  - *Combined loading*: external overpressure, bending moment, effective axial force.

$$\left\{\gamma_m \cdot \gamma_{SC} \cdot \frac{|M_{Sd}|}{\alpha_c \cdot M_p(t)} + \left\{\gamma_m \cdot \gamma_{SC} \cdot \frac{S_{Sd}(p_i)}{\alpha_c \cdot S_p(t)}\right\}^2\right\}^2 + \left(\gamma_m \cdot \gamma_{SC} \cdot \frac{p_e - p_{min}}{\alpha_c \cdot p_c(t)}\right)^2 \leq 1 \qquad (38)$$

$p_{min}$ – minimum internal pressure that can be sustained;
$p_c$ – characteristic collapse pressure.

- Displacement Controlled Condition (DCC). The pipeline response is governed by geometric displacements.
  - *Combined loading:* longitudinal compressive strain (bending moment and axial force) and internal overpressure.

$$\varepsilon_{Sd} \leq \varepsilon_{Rd} = \frac{\varepsilon_c(t, p_{min} - p_e)}{\gamma_e} \qquad (39)$$

$$\varepsilon_c(t, p_{min} - p_e) = 0.78 \cdot \left(\frac{t}{D} - 0.01\right) \cdot \left(1 + 5.75 \cdot \frac{p_{min} - p_e}{p_b(t)}\right) \cdot \alpha_h^{-1.5} \cdot \alpha_{gw} \qquad (40)$$

$\varepsilon_{Sd}$ – design compressive strain;
$\varepsilon_c$ – characteristic bending strain;
$\alpha_h$ – strain hardening;
$\alpha_{gw}$ – girth weld factor;
$\gamma_e$ – strain resistance factor.

  - *Combined loading:* longitudinal compressive strain (bending moment and axial force) and external overpressure.

$$\left(\frac{\frac{\varepsilon_{Sd}}{\varepsilon_c(t,0)}}{\gamma_e}\right)^{0.8} + \frac{\frac{p_e - p_{min}}{p_c(t)}}{\gamma_m \cdot \gamma_{SC}} \leq 1 \qquad (41)$$

In case if these criteria are not met, the pipeline will have increased ovalisation and experience collapse of its cross-section or even rupture.

***Global and local scale performance***

In order to analyze the pipeline response, it is necessary to distinguish between global and local scale performances.

- Global scale analysis is usually done to estimate the pipeline displacement while being hooked and dragged by the anchor. The emphasis here is put on recognizing the force-displacement relationship.

- Local scale analysis is performed in order to understand how severe the damage is in the area of pipe-anchor interference. The accent here is put on a strain and dent size estimation.

**NB**. A global scale analysis will be done in the following assessment study.

*Summarizing* the part about ship anchoring activity and its effect on submarine pipelines and cables one can see how many basic damage criteria and key factors are to be taken into account. Combination of vessel and anchor arrangement parameters, marine activity details and pipeline data are very helpful for the assessment of pipeline potential danger. Even if the pipeline is designed in accordance with all the standards, codes and guidelines, no one can exclude the fact that pipeline will experience a failure due to uncontrolled anchor drop and loss while the ship is in underway. Hence, it is of great importance to specify all the significant criteria that shall be met during each stage of pipeline life cycle. Moreover, different sensitivity cases are to be performed and analyzed in order to develop a generic conclusion with respect to the pipeline response and damage frequency of pipeline system. Analysis on pipeline-anchor interference scenario based on the theoretical approach written above is going to be done and presented in the following chapter.

### 4.2.7 Pipeline protection

In case if the pipeline has potential to be hooked and damaged by the dragging anchors, some pipeline protection measures can be implemented then (DNV-RP-F107, 2010):

1. Concrete coating;
2. Polymer coating;
3. Gravel dump and natural backfill;
4. Protection structures;
5. Trenching;
6. Higher wall thickness.

# CHAPTER 5. CASE STUDY - DRAGGED ANCHOR INTERFERENCE ASSESSMENT

## 5.1 SCOPE OF THE CASE STUDY

The scope of the “Dragged anchor interference assessment” case study is to present the methodology of anchor damage assessment of subsea pipelines. Several sensitivity cases are to be performed in order to gain a complete understanding of pipe-anchor interaction scenario. Detailed step by step procedure of dragged anchor interference investigation is given below.

1. AIS data processing based on the typical pipeline route: collection of data for different ship/vessel types with respect to IMO-no, name, type, EL, GT, speed and vessel coordinates.

2. Data analyzes: development of various diagrams, graphs and distribution charts for a considered pipeline route on the basis of collected data.

3. Anchor hook criteria check: relation between pipeline diameter and anchor size (2 configurations).

4. Anchor hit criteria check (MATLAB): relation between vessel speed, chain length and water depth.

5. Carrying out a model scale test on anchor towing depth: scaling of required physical values; preparation for the experiment; comparison of experimental data and analytical solution (MATLAB).

6. Establishment of anchor pulling consequences in accordance with global scale analyses performed in SIMLA; determination of pipeline response; pipeline capacity check (or anchor damage criteria) for both 40 and 16-inch pipelines.

7. Frequencies of pipe-anchor interaction modes in accordance with the criteria (hook/hit/damage) checks for 40 and 16-inch pipelines.

8. Methodology description;

9. General conclusions with regard to pipeline properties, water depth, vessel speed and EL: whether the pipeline is hooked/hit/damaged by the anchor; total frequency estimation.

## 5.2 DEFINED DATA

### 5.2.1 Pipeline data

In order to make comprehensive study on subsea pipeline damage assessment in accordance with the designated objectives, the Pipeline 1 is chosen for that purpose. The Pipeline 1 is a 40-inch gas transporting line, running through the sector of the North Sea. All the relevant information concerning pipeline design and operational characteristics are provided by Statoil Company. Generalized data of Pipeline 1 is prepared and presented in Table 16.

Table 16: Data of Pipeline 1

| ***Item*** | ***Unit*** | ***Value*** |
|---|---|---|
| *Location* | - | The North Sea |
| *Length* | km | 305 |
| *Design life* | years | 50 |
| *Nominal size* | inch | 40 |
| *Internal Diameter* | mm | 966.4 |
| *Wall thickness* | mm | 26.1 |
| *Material* | - | X-65 |
| *Transport medium* | - | Dry gas |
| *Corrosion Allowance* | mm | 0 |
| *Corrosion coating* | - | Asphalt enamel |
| *Protection and weight coating* | - | Concrete coating |
| *Density of gas* | $kg/m^3$ | 177 |
| *Density of corrosion coating* | $kg/m^3$ | 1300 |
| *Density of concrete* | $kg/m^3$ | 3040 |

The seabed profile of Pipeline 1 is shown below (Figure 33). One can see how the water depth varies with each KP section of the pipe route.

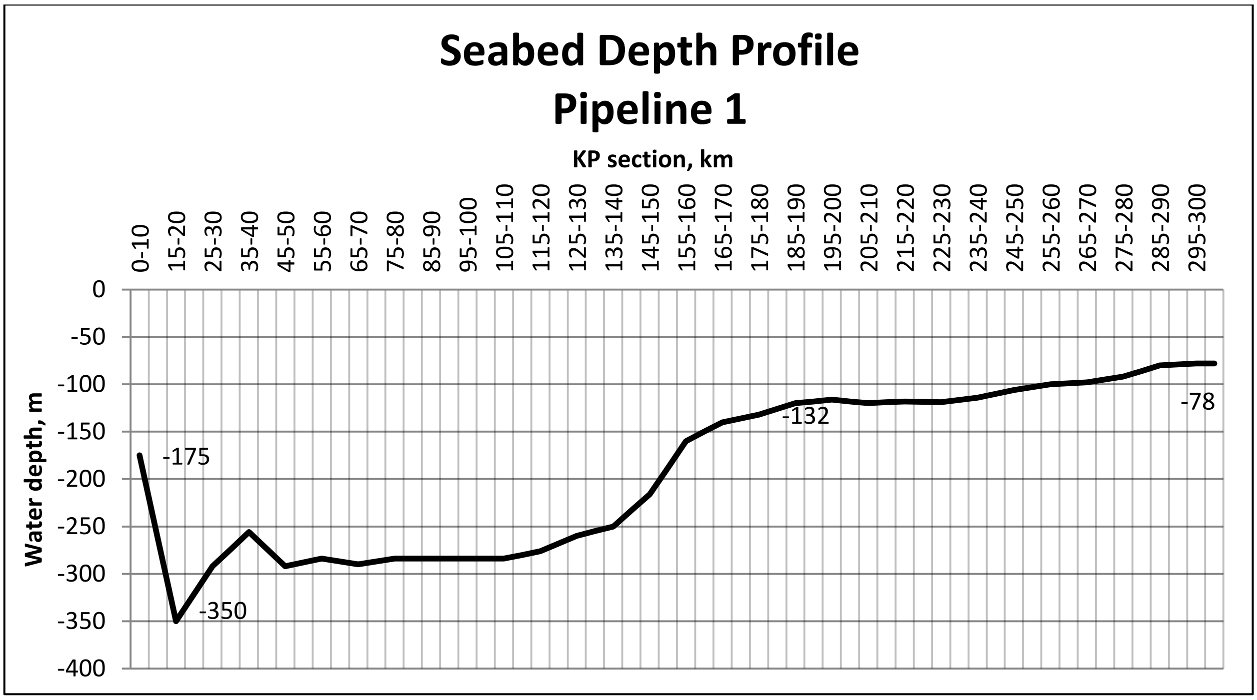



*Figure 33: Seabed depth profile of the Pipeline 1*

Part of the Pipeline 1 route and extracted AIS ship track density plot for the specified area is presented in Figure 34.

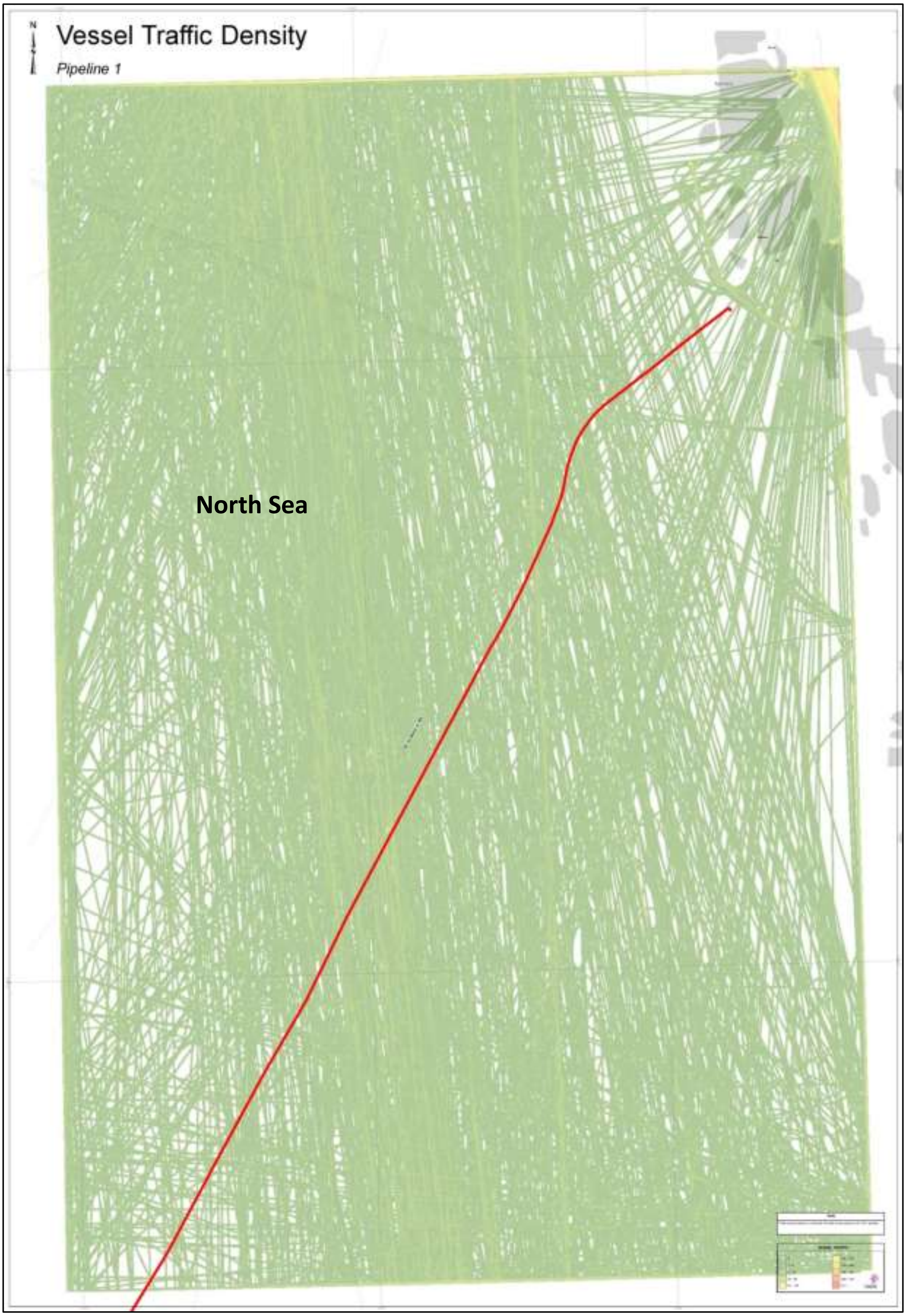



Figure 34: Part of the Pipeline 1 route and ship track density plot

### 5.2.2 AIS data

Automatic Identification System *is an automatic tracking system used on ships and by vessel traffic services (VTS) for identifying and locating vessels by electronically exchanging data with other nearby ships, AIS base stations, and satellites* (Automatic Identification System, 2105). There are a lot of services that provide a real-time and historical AIS data. Such kind of databases is very useful for the extraction of important information about ships: individual identification number, position, destination, speed, etc. As explained before, once the identification number of passing ship is known, one can get any particularities of these vessels. Moreover, ship traffic pattern around an area of interest can be obtained as well (Figure 35).

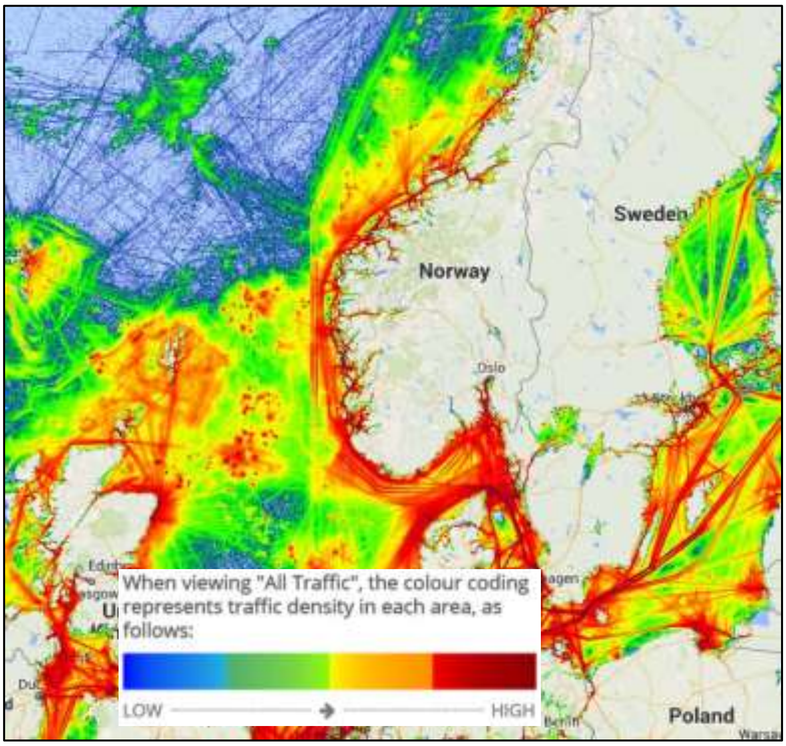



*Figure 35: Illustration of ship track density plot retrieved from MarineTraffic.com*

All the AIS data required for the assessment of pipeline-anchor interaction scenario have been provided by the Statoil Company. A total of 127006 table lines contained in the data list describe the motion of 824 vessels. For the simplification of data processing, all the information has been exported to the EXCEL sheet (Figure 36).

| | A | B | C | D |
|---|---|---|---|---|
| 1 | MMSI | SPEED | Lat | Long |
| 2 | 220628000 | 11.8 | 59,00 | 2,74 |
| 3 | 220628000 | 12 | 59,00 | 2,74 |
| 4 | 220628000 | 12.2 | 59,00 | 2,73 |
| 5 | 220628000 | 12.2 | 59,00 | 2,72 |
| 6 | 220628000 | 12 | 59,00 | 2,72 |
| 7 | 220628000 | 11.8 | 59,00 | 2,71 |
| 8 | 258366000 | 9.1 | 59,23 | 3,00 |
| 9 | 258366000 | 9.1 | 59,23 | 2,99 |

*Figure 36: EXCEL data list example*

Each vessel, crossing the route of Pipeline 1, is described by its MMSI-no (column A). Furthermore, the movement of each ship is explained by the latitude and longitude coordinates (columns C and D), and corresponding speed value given in knots (column B). As seen from above, the database does not include other significant details of passing ships. Thus, in order to get copious information, it is necessary to complete the table with missing data. Missing vessel details such as IMO-no, name and type, Equipment Letter, Equipment Number (if available), and Gross Tonnage are essential for the data analyzing process as well as future investigation work. In view of this, for every ship six additional parameters have been found and compiled manually using different online web-based sources like Vessel Register for DNV GL, Marine Traffic, Vessel Finder, etc. Full description of the ship data compilation procedure is presented in the chart (Figure 37):

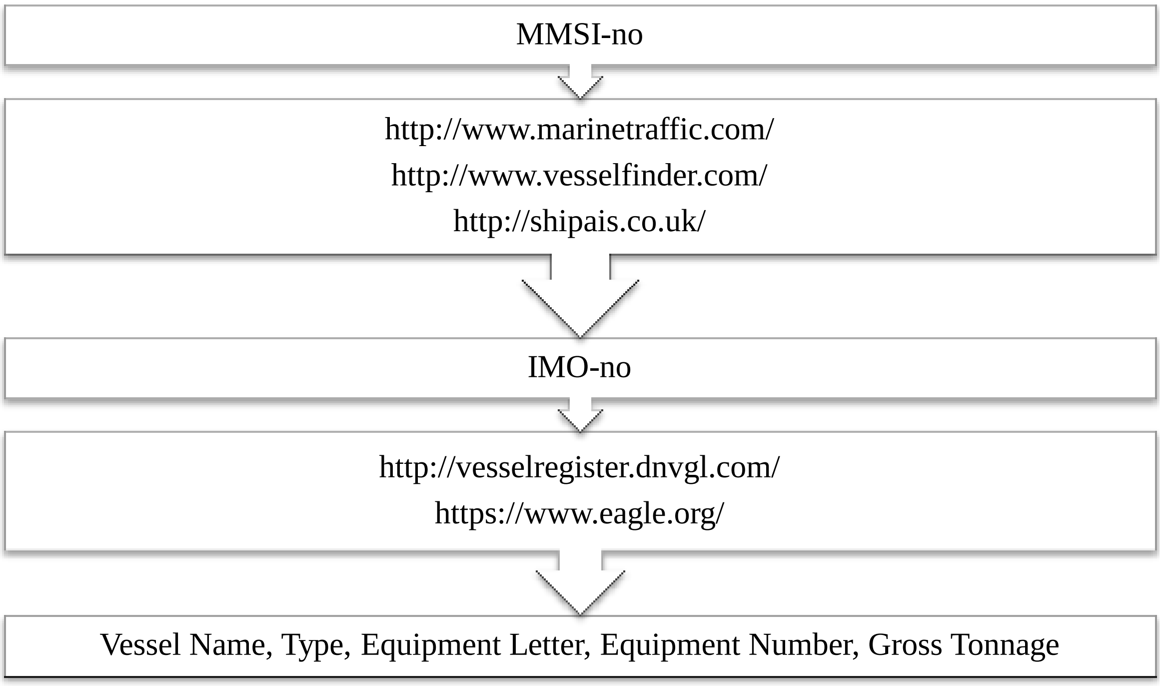



*Figure 37: Ship data collection procedure description*

**NB**. There are some vessels (22 out of 824), the information on which is not available in the vessel register books. These vessels cannot be identified by their individual IMO-no and hull classification particularities. That is why it has been decided to focus on data processing of identified ships only, the total number of which is 802. Moreover, prior to starting data analyses, it shall be noted that all the vessels are assumed to be equipped with appropriate anchoring system (anchor and chain) capable of approaching the pipeline laid on the seabed.

### 5.3 SHIP TRAFFIC DATA ANALYZES

As soon as the compilation process has been finished, the data processing is started. Firstly, the pipeline is divided into 60 KP sections, where the first section is of 10 km, and the rest 59 are of 5 km each. Thereafter, using known coordinates of the first and last KP endpoints, the coordinates of intermediate KP points can be determined by applying the Web Plot Digitizer Software. Once the new sections have been digitized, their latitude and longitude coordinates may be found after. With obtained coordinate values it is possible then to define an exact position of one or another vessel crossing over a certain section of the pipeline route. A part of the resultant ship traffic data list with determined KP sections (column K) is displayed below (Figure 38). All the following analyses are done according to this collected database.

| | A | B | C | D | E | F | G | H | I | J | K |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | MMSI | IMO | NAME | TYPE | EL | EN | GT | SPEED | Lat | Long | KP section |
| 2 | 259351000 | 6525064 | SANDSTRAND | Suction Dredger | g | | 300 | 8,4 | 60,53 | 4,79 | 0-10 |
| 3 | 258390000 | 9258442 | VIKING ENERGY | Supply Vessel | A | 1314 | 5073 | 8,9 | 60,53 | 4,78 | 0-10 |
| 4 | 231845000 | 9340738 | MOKOSICA | General Cargo | o | | 1692 | 6,8 | 60,53 | 4,77 | 0-10 |
| 5 | 259675000 | 9206334 | MEILSØ | Fishing | k | 339 | 856 | 10,1 | 60,52 | 4,76 | 0-10 |
| 6 | 258422000 | 7424762 | URTER | Fishing | m | | 1202 | 8 | 60,52 | 4,81 | 0-10 |

*Figure 38: Ship traffic data list example*

One of the important vessel parameters is its gross tonnage. The GT is an index that describes an overall internal ship volume. Gross tonnage should not be mixed up with the gross register tonnage (GRT). The latter had been used long time ago until it was replaced by the GT index. Seven GT categories are usually distinguished in order to classify the ships with respect to this parameter. The present analyses are based on the classification given in Table 17.

Table 17: Ship classification with respect to gross tonnage

| ***Class*** | ***GT range*** |
|---|---|
| 1 | <1000 |
| 2 | 1000-4999 |
| 3 | 5000-9999 |
| 4 | 10000-24999 |
| 5 | 25000-49999 |
| 6 | 50000-99999 |
| 7 | >=100000 |

In order to see the distribution of the most frequently observed ship class; the data sorting procedure is implemented. The resultant ship class pie diagram is presented below (Figure 39).

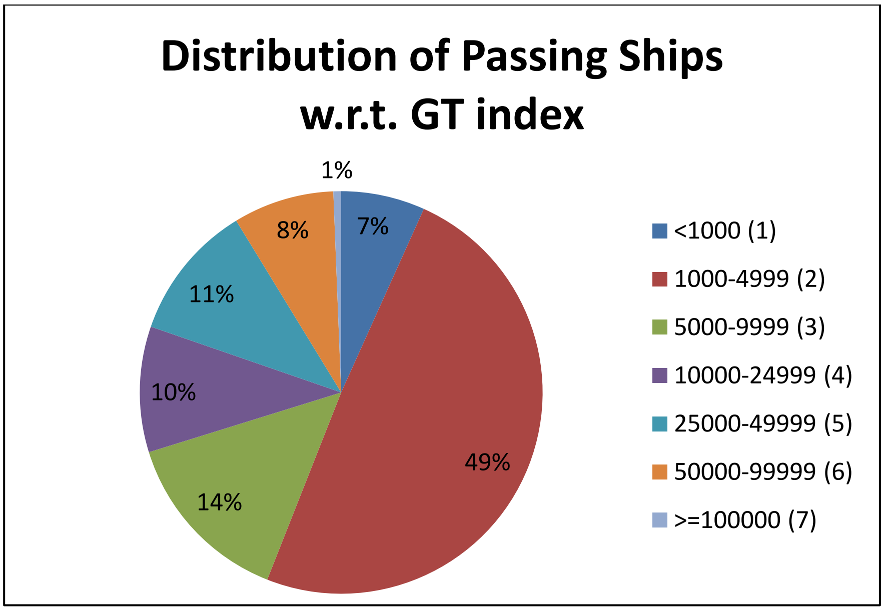



*Figure 39: Distribution of passing ships with respect to GT value*

It is visible that the most commonly encountered ship class is Class 2 (49%), the GT value of which varies between 1000 and 4999. Additionally, 14% of all the vessels fall into the Class 3. Other classes are distributed almost uniformly, except the last one that is about 1% of all the vessels passing the line.

As explained before, all the ships have their individual anchor arrangement system specified by either Equipment Number or Equipment Letter. The larger the vessel, the greater the value of the EN will be. This is quite logical, because the EN value is heavily dependent on vessel displacement and other parameters. In addition to the EN, the vessel can be characterized by the EL, which is found in accordance with the generalized Equipment Tables (Figure 22). Since compiled ship traffic database contains information about vessels' gross tonnage, it is interesting to show an illustrative case of the relation between GTs and ELs correspondingly (Figure 40).

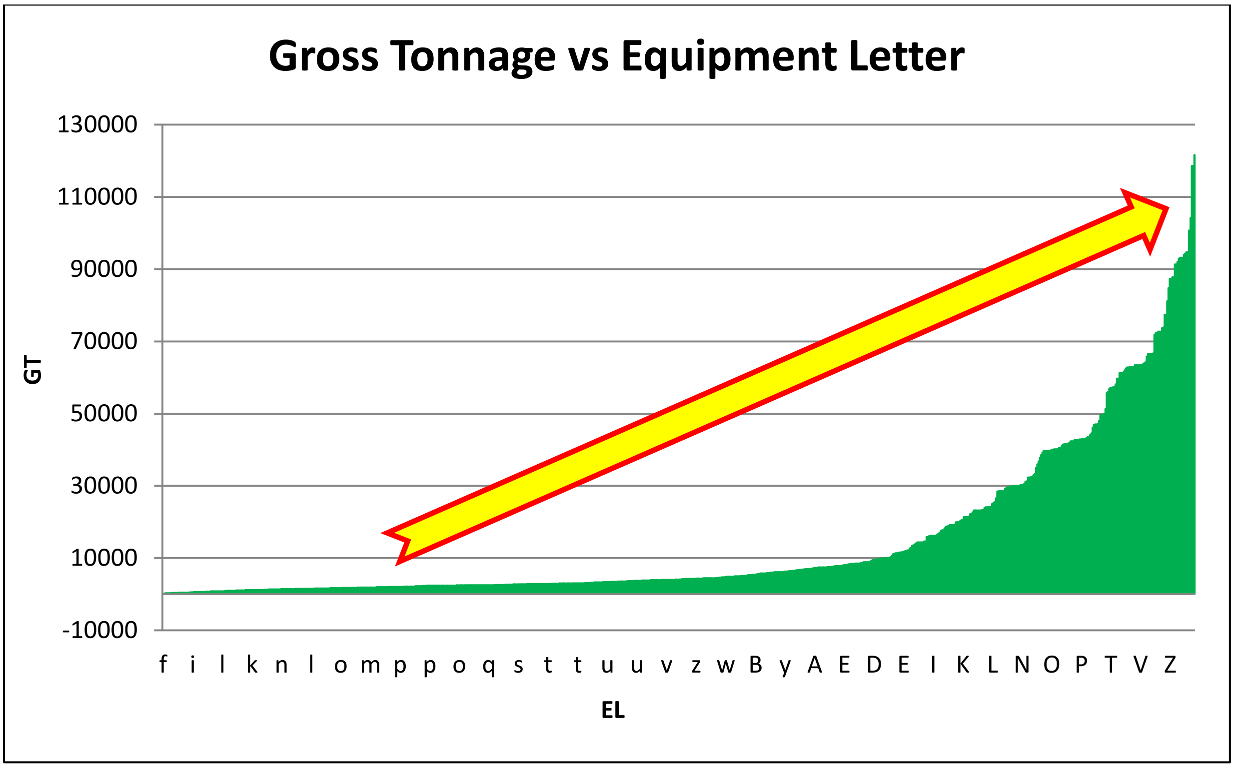



*Figure 40: Vessel GT and EL relation illustration*

The next part of this case study is devoted to the juxtaposition of every KP section with the ships classified by the GT index. Furthermore, the seabed profile is also taken into account. The water depth profile helps to understand, what kind of sections are more susceptible to anchor hitting event. Thus, Figure 41 demonstrates which vessel classes are in the majority with regard to designated KP section endpoints and proper values of the water depth.

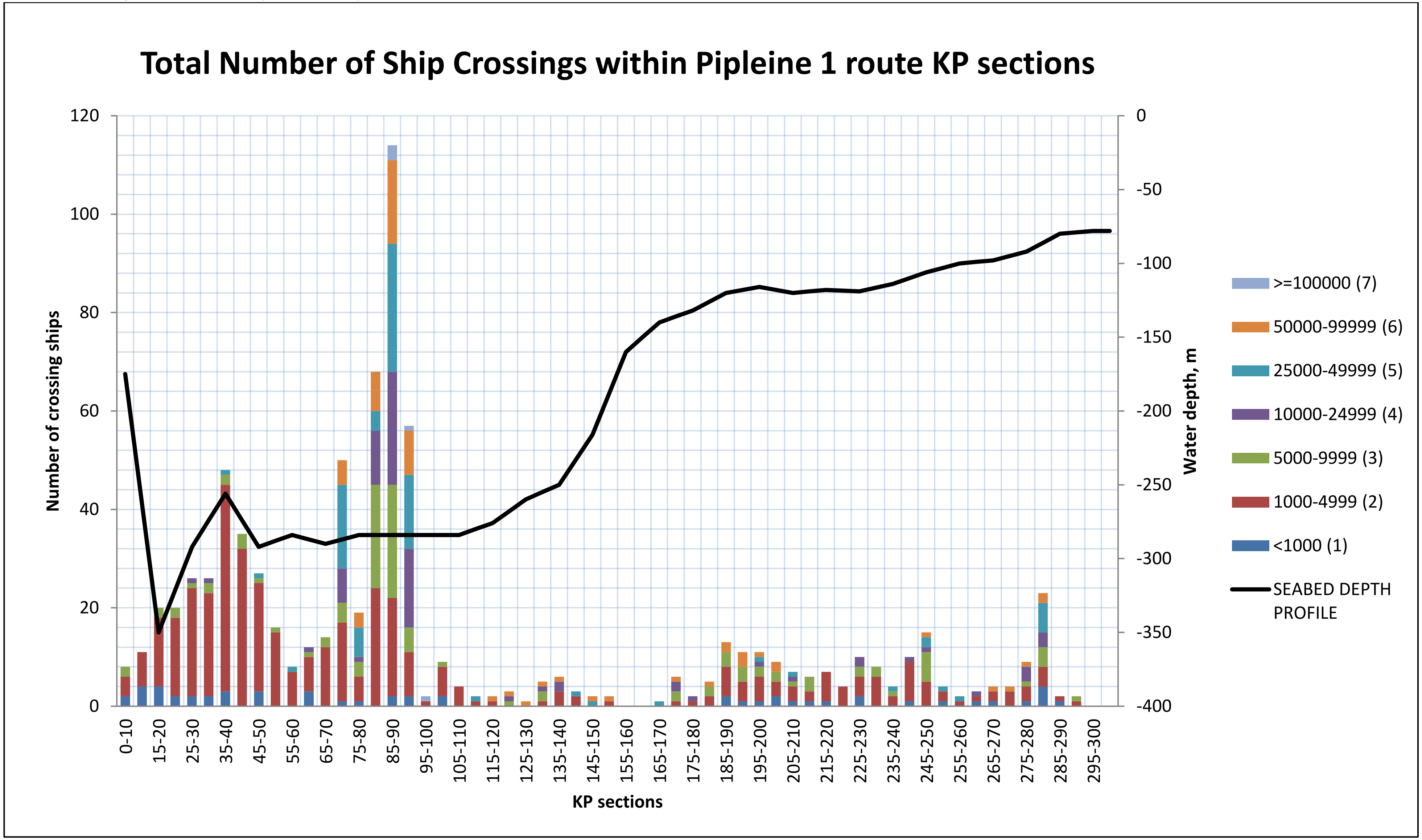



*Figure 41: Total number of crossing ships within certain KP sections and defined water depth*

Figure 41 shows that the highest marine activity falls between pipeline KP sections 0-60 and 65-95, where ship Class 2 (GT 1000-4999) is observed more often than other ship classes. According to this evaluation, the line between those endpoints may be subjected to incident coming from dragging anchor. However, these pipeline sections are situated in the deepest areas. So, at this stage no one can draw precise conclusion whether the ship anchors are capable of hooking the pipeline or not.

Not only gross tonnage is to be included into assessment, but an equipment letter shall be considered as well. The following column chart (Figure 42) points out the number of all the equipment letters assigned to the defined ships. Another significant detail here is speed value, which has been retrieved from the AIS ship database. In order to simplify the analyses, an average speed for a corresponding equipment specification is calculated and used for the following estimation work.

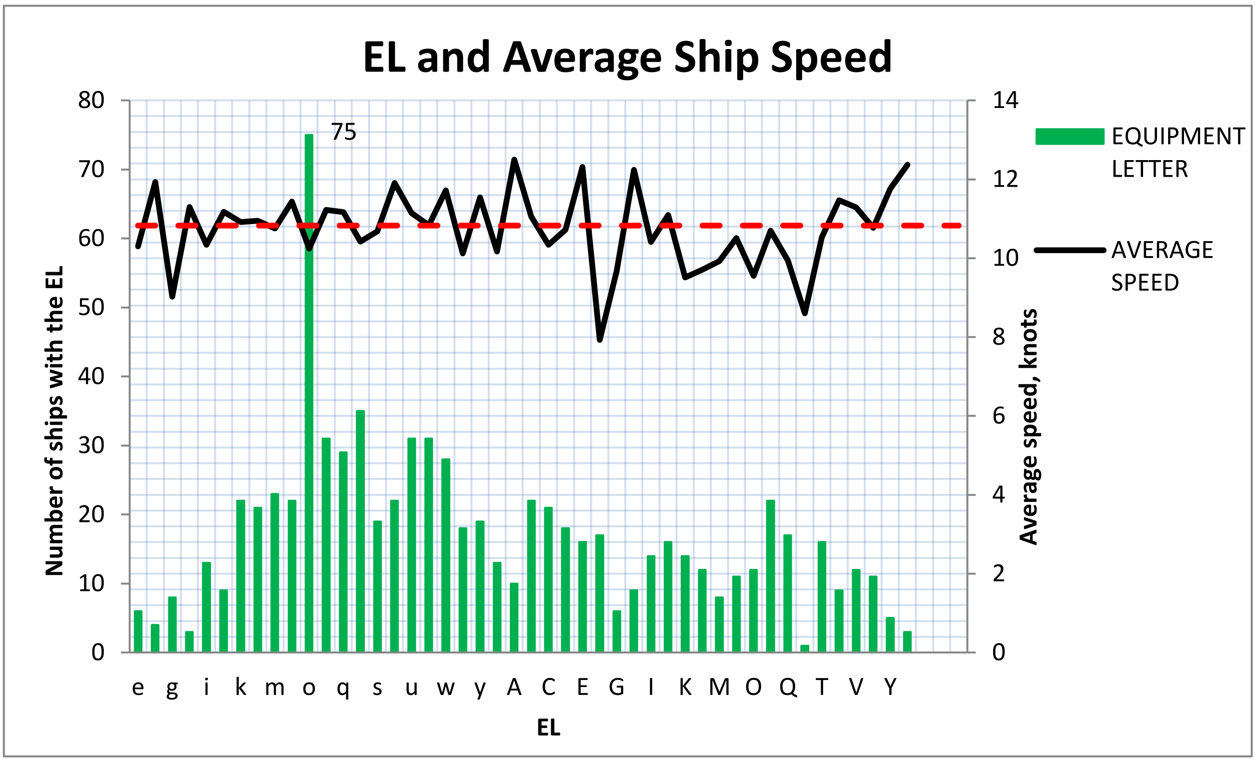



*Figure 42: Total number of various ELs with the corresponding average vessel speed value (knots)*

In general, 49 different Equipment Letters characterize given passing ships. From the Figure 42 above it is understood that the most commonly detected crossings are done by the ships with the Equipment Letter "*o*", which accounts for 9% (75 out of 802) of total number of passing over the pipe vessels. Both the variation of the average speed (black line) and medium speed (red line) are illustrated on the chart above.

There are three groups of Latin letters used for the classification of anchor arrangement. The explanation of each group is presented in the Figure 43. Small letters usually point small dimension anchors (120-3780 kg), while capital letters and letters marked with the star denote large (4050-16900 kg) and huge (17800-46000 kg) anchoring systems. Along with the anchor mass, the chain length and diameter changes as well.

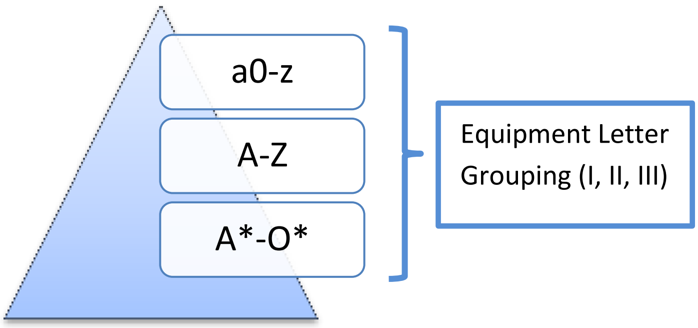



*Figure 43: Equipment Specification Letter grouping*

Development of the charts and diagrams gives a strong notion of ship distribution along the route of Pipeline 1. Along with the specified KP sections, the seabed profile is considered. The water depth values over the Pipeline 1 vary significantly, especially in 0-150 KP sectors. Additionally, the densest area in terms of the ship traffic volume is in between 0-95 KP sections. It should be mentioned, that not all the vessel types are capable of getting in contact with the pipe situated in the deepest areas: the limitation here is the length of the anchor chain and speed of the vessel. Speaking about the vessel speed, it should also be included into analysis. The combination of water depth value, chain length and speed is very important for the detailed analyses, which are going to be discussed in further parts.

Two key vessel parameters are taken as basis for the relevant ship classification algorithms, namely GT index and Equipment Letter. So that classified ships are included into distribution charts in order to show which kind of vessels cross one or another KP pipe section. The most frequently observed class of the ship is Class 2, while the most commonly encountered EL is letter "*o*".

**NB.** Additional tables used for the present analysis are included in the Appendix.

*Summarizing* this part, one shall see how many details are essential for the data analyzing process. The more particularities are taken into account during the initial steps, the more comprehensive assessment can be done hereafter.

## 5.4 ANCHOR HOOK CRITERIA CHECK

Not only the anchor mass, but its geometrical configuration is critical for the assessment of pipe-anchor interaction. It is obvious that small dimension vessel equipment is not even capable of hooking large diameter pipelines. That is precisely why hook criteria check shall be performed. As written in the previous chapter, there are mainly two ways of hooking the line. The pipeline may either stick between one fluke and anchor shank or between the plane of two flukes and shank of the anchor. Two sketches demonstrating the geometrical interpretation of hooking event are given before in Figure 24.

**NB**. For the present case study it is assumed that every moving ship is equipped with the stockless anchor, the information on which is easily found in the Rules for Ship document and relevant catalogues.

One of the most popular and conventional stockless anchor types is Spek anchor, which is widely used for the positioning of different vessels. Spek anchor is taken as basic example for the study and criteria check. The minimum size of anchor, capable of catching the Pipeline 1, can be determined for both cases by applying the formulas in the Tables 18 and 19. The formulas present the most conservative way of hook criteria check.

Table 18: I case Spek stockless anchor hook check

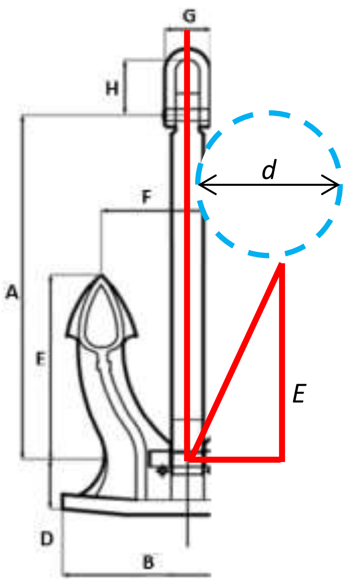
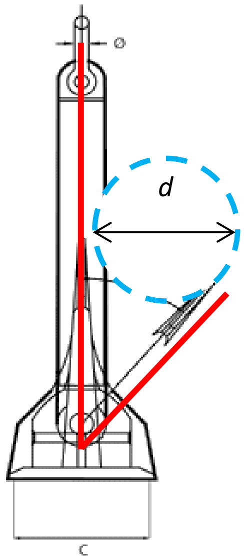
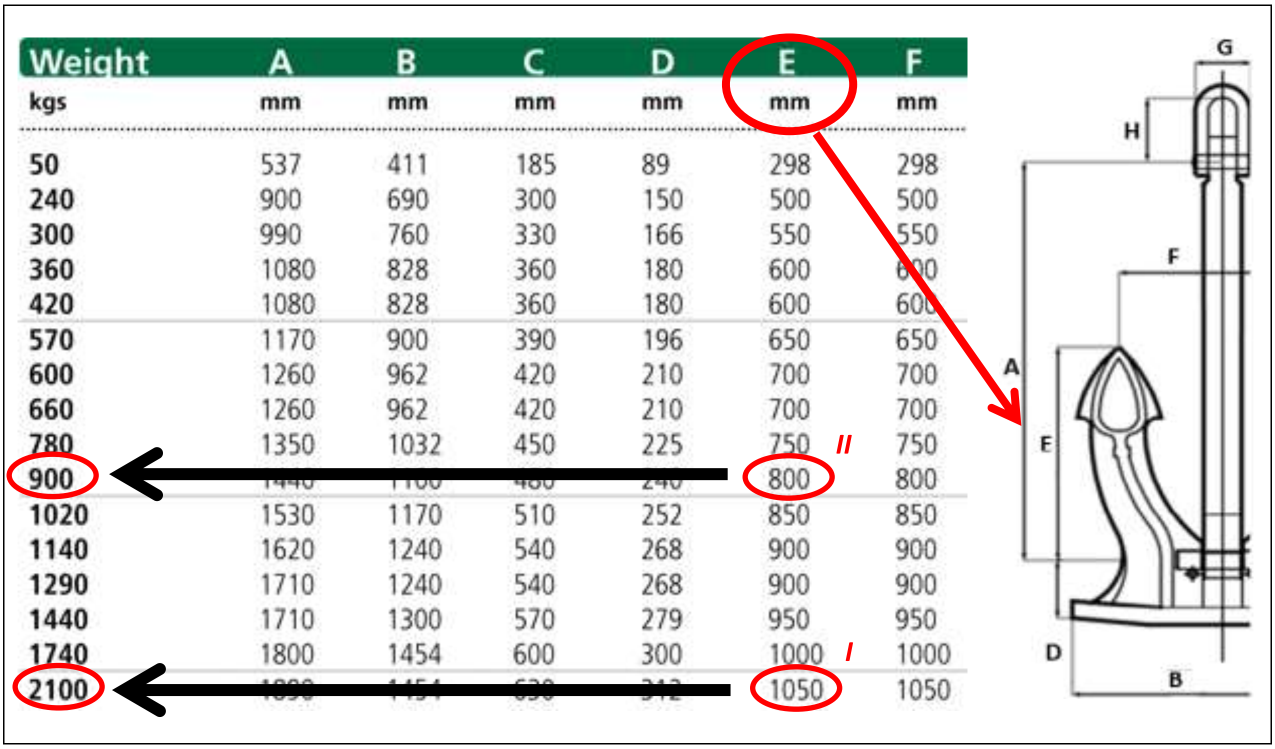
<table>
<tr><th>Formula and geometry of hook</th><th>Item</th><th>Symbol</th><th>Unit</th><th>Value</th></tr>
<tr><td rowspan="5">$C_\perp \geq d/2$   (42)<br><br></td><td>Angle between one fluke and anchor shank</td><td>$\alpha$</td><td>deg</td><td>27</td></tr>
<tr><td>Pipeline diameter</td><td>$d$</td><td>mm</td><td>1018.6</td></tr>
<tr><td>Projected fluke length</td><td>$C_\perp$</td><td>mm</td><td>509.3</td></tr>
<tr><td>Fluke length</td><td>$C$</td><td>mm</td><td>1138.8</td></tr>
<tr><td>E-parameter (Figure 44)</td><td>$E$</td><td>mm</td><td>1018.6</td></tr>
</table>

Table 19: II case Spek stockless anchor hook check

<table>
<tr><th>Formula and geometry of hook</th><th>Item</th><th>Symbol</th><th>Unit</th><th>Value</th></tr>
<tr><td rowspan="5">$C'_\perp \geq d/2$   (43)<br><br></td><td>Angle between the plane of two flukes and the shank</td><td>$\beta$</td><td>deg</td><td>40</td></tr>
<tr><td>Pipeline diameter</td><td>$d$</td><td>mm</td><td>1018.6</td></tr>
<tr><td>Projected median</td><td>$C'_\perp$</td><td>mm</td><td>509.3</td></tr>
<tr><td>Median of flukes plane</td><td>$C'$</td><td>mm</td><td>792.3</td></tr>
<tr><td>E-parameter (Figure 44)</td><td>$E$</td><td>mm</td><td>792.3</td></tr>
</table>

There is a parameter *E* that is designated to be the key one for the selection of minimum anchor size (Figure 44). According to the results from the tables above it is observed that the minimum anchor size after the 1st check falls into the value of 2100 kg, while after the 2nd check the anchor size falls into the value of 900 kg. In order to be more conservative, the value from the 2nd check is taken as the minimum size of anchor capable of hooking the Pipeline 1. Hence, all the anchors with the EL starting from the letter "*j*" can be thought dangerous for the pipe.



| Weight kgs | A mm | B mm | C mm | D mm | E mm | F mm |
|---|---|---|---|---|---|---|
| 50 | 537 | 411 | 185 | 89 | 298 | 298 |
| 240 | 900 | 690 | 300 | 150 | 500 | 500 |
| 300 | 990 | 760 | 330 | 166 | 550 | 550 |
| 360 | 1080 | 828 | 360 | 180 | 600 | 600 |
| 420 | 1080 | 828 | 360 | 180 | 600 | 600 |
| 570 | 1170 | 900 | 390 | 196 | 650 | 650 |
| 600 | 1260 | 962 | 420 | 210 | 700 | 700 |
| 660 | 1260 | 962 | 420 | 210 | 700 | 700 |
| 780 | 1350 | 1032 | 450 | 225 | 750 | 750 |
| 900 | [illegible] | [illegible] | [illegible] | [illegible] | 800 | 800 |
| 1020 | 1530 | 1170 | 510 | 252 | 850 | 850 |
| 1140 | 1620 | 1240 | 540 | 268 | 900 | 900 |
| 1290 | 1710 | 1240 | 540 | 268 | 900 | 900 |
| 1440 | 1710 | 1300 | 570 | 279 | 950 | 950 |
| 1740 | 1800 | 1454 | 600 | 300 | 1000 | 1000 |
| 2100 | [illegible] | [illegible] | [illegible] | [illegible] | 1050 | 1050 |



*Figure 44: Part of the Spek anchor characteristics retrieved from the anchor catalogue ("Spek Anchor", n.d.)*

## 5.5 ANCHOR HIT CRITERIA CHECK

When moving ship suddenly loses its anchor, the anchor-chain arrangement will stabilize after some time, but it will never be perfectly vertical due to an interaction between anchor-chain arrangement and surrounding water. The questions that have to be answered here are what a shape of the chain will take place and what a distance between the anchor and vessel itself will be (Figure 45). In case, if this distance (determined by Y-axis) is less than the water depth at the location of pipeline, it is obvious that the anchor does not have a potential to approach and hit the line.

Assuming that all the ships passing the Pipeline 1 route are moving with the constant velocity, one shall see that the steady flow will force the anchoring system in the opposite direction. Since the flow is steady one, the acceleration term becomes equal to zero. That is why an added mass and inertia terms are not considered in this case. Moreover, the drag force of the anchor is assumed to be negligible in comparison with its weight.

Consequently, the equation of the motion can be written in accordance with the 2nd Newton's Law as follows (De Silva, 2007):

$$\sum \vec{F} = m\vec{a}(l,t) = \vec{0} \quad (44)$$

$$m\vec{a}(l,t) = \frac{\partial}{\partial l}\left(T\vec{t}\right) + f_n\vec{n} + f_t\vec{t} + mg\vec{k} \quad (45)$$

$$\vec{0} = \frac{\partial}{\partial l}\left(T\vec{t}\right) + f_n\vec{n} + f_t\vec{t} + mg\vec{k} \quad (46)$$

$m$ – mass of the chain per unit length;
$g$ – acceleration of gravity;
$\vec{a}(l,t)$ – acceleration of the chain;
$l$ – coordinate along the anchor chain;
$T$ – tension force;
$f_n$ – normal drag force per unit length;
$f_t$ – tangential drag force per unit length;
$\vec{n}$ – normal unit vector;
$\vec{t}$ – tangential unit vector;
$\vec{k}$ – unit vector in the direction of gravity.

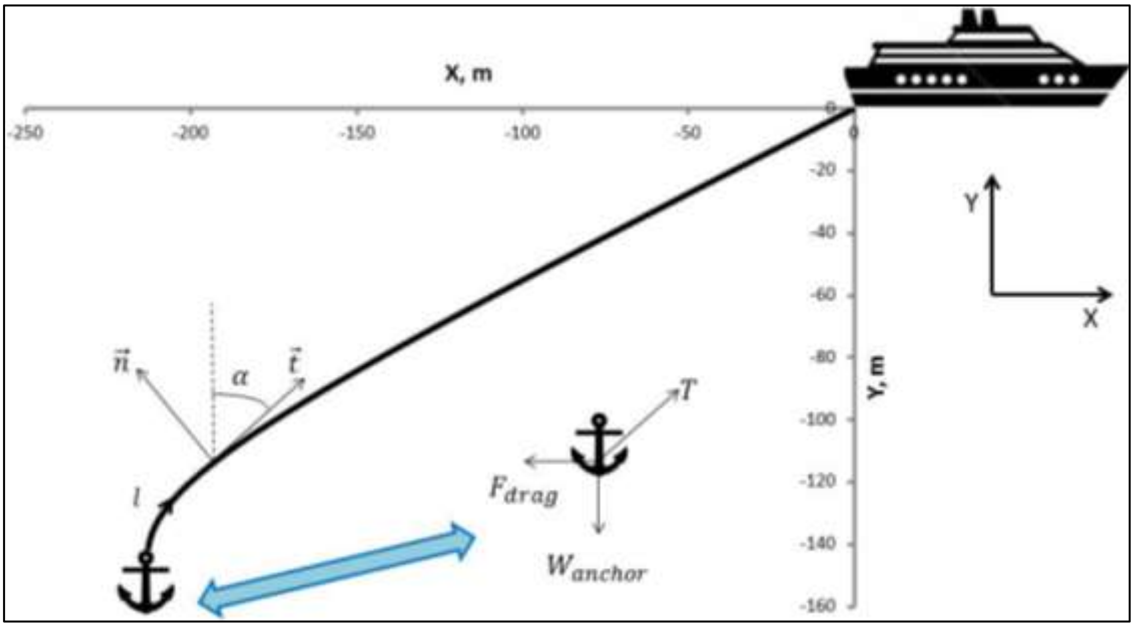



*Figure 45: Anchor-chain system configuration illustration*

As seen from the formula, there are two components of drag force: normal (dominant) and tangential. The formulas on both of them are presented below:

$$f_n = C_{Dn} \cdot \rho_w \cdot \frac{D}{2} \cdot v^2 \cdot Cos^2\alpha \quad (47)$$

$$f_t = C_{Dt} \cdot \rho_w \cdot \frac{D}{2} \cdot v^2 \cdot Sin^2\alpha \quad (48)$$

$C_{Dn}$ – normal drag coefficient;
$C_{Dt}$ – tangential drag coefficient;
$\rho_w$ – seawater density;
D – anchor chain diameter;

v – water flow velocity;
$\alpha$ – angle between the vertical axes and tangential vector.

Normal and tangential drag coefficients of the stud-link and stud less chains are given in the Offshore Standard DNV-OS-E301 (2010) (Table 20).

Table 20: Anchor chain drag coefficients

| ***Chain types*** | ***Normal drag coefficient*** | ***Tangential drag coefficient*** |
|---|---|---|
| Stud-link | 2.6 | 1.4 |
| Stud less | 2.4 | 1.15 |

To continue with the calculations needed for the criteria check, the equation of motion should be rewritten in the scalar form:

$$\begin{cases} \frac{dT}{dl} - C_{Dt} \cdot \rho_w \cdot \frac{D}{2} \cdot v^2 \cdot Sin^2\alpha - m \cdot g \cdot Cos\alpha = 0 \\ -T \cdot \frac{d\alpha}{dl} + C_{Dn} \cdot \rho_w \cdot \frac{D}{2} \cdot v^2 \cdot Cos^2\alpha - m \cdot g \cdot Sin\alpha = 0 \end{cases} \tag{49}$$

It is a system of two ordinary differential equations that can be solved numerically to find $T(l)$ and $\alpha(l)$. For that purpose, two initial conditions must be specified:

$$T(0) = W_{anchor} \tag{50}$$

$$\alpha(0) = 0 \tag{51}$$

$W_{anchor}$ – weight of the anchor in the water:

$$W_{anchor} = m_{anchor} \cdot g \cdot \left(1 - \frac{\rho_w}{\rho_{steel}}\right) \tag{52}$$

In addition to the previous system, the relation between the Cartesian coordinates and angle $\alpha$ is to be included either:

$$\begin{cases} \frac{dx}{dl} = Sin\alpha \\ \frac{dy}{dl} = Cos\alpha \end{cases} \tag{53}$$

Where the initial conditions are:

$$x(0) = 0 \tag{54}$$

$$y(0) = 0 \tag{55}$$

Thus, solving the system of four ordinary differential equations with specified set of initial conditions, it is possible to understand how an equilibrium configuration of anchor-chain arrangement looks like. Moreover, the distance between the towed anchor and the ship is determined as well. For the present case study, the anchor towing depth calculation can be done by applying MATLAB software. With this objective in view, an effort has been made to create appropriate code. An *ode-45 function*, based on an explicit Runge-Kutta formula, is included. According to the Equipment Specification Letter grouping (Figure 43) all 49 various ELs are taken for the calculation: for every EL the combination of corresponding anchor mass; chain length, chain diameter; and average speed (in m/s) are put into the prepared code. All the results have been exported to the EXCEL sheet in order to use them for the development of essential graphs and future analyses.

Obtained data helps to identify, whether the anchoring systems of given passing ships are capable of hitting the Pipeline 1 or not. The anchor towing depth variations in terms of different Equipment Letter groups are illustrated in Figures 46-48.

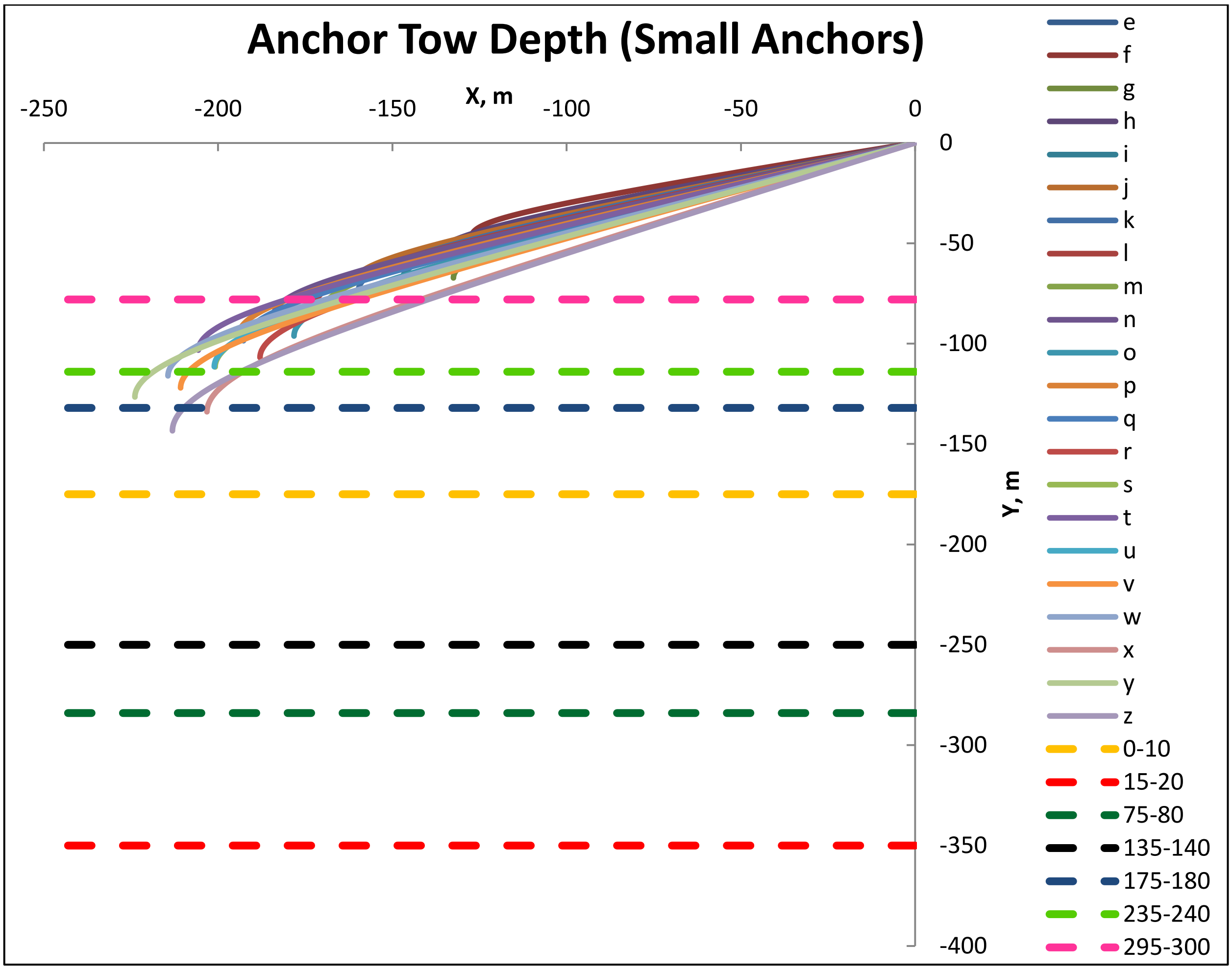



*Figure 46: Tow depth of anchors classified by Small Letters and water depth lines (dashed) of certain KP sections*

Figure 46 shows that not all the anchors classified by Small Letters will reach the sea bottom in case if passing ships lose their anchors. The majority of intersections are observed only where the water depth value is about 140 m and less.

Figure 47 demonstrates the same sort of estimation for Capital Letter class of anchors. One can see that this kind of anchors have the potential to reach even deeper sections of 250 m depth. It is quite obvious, because larger anchors have longer and heavier chains, which easily approach even deeper areas.

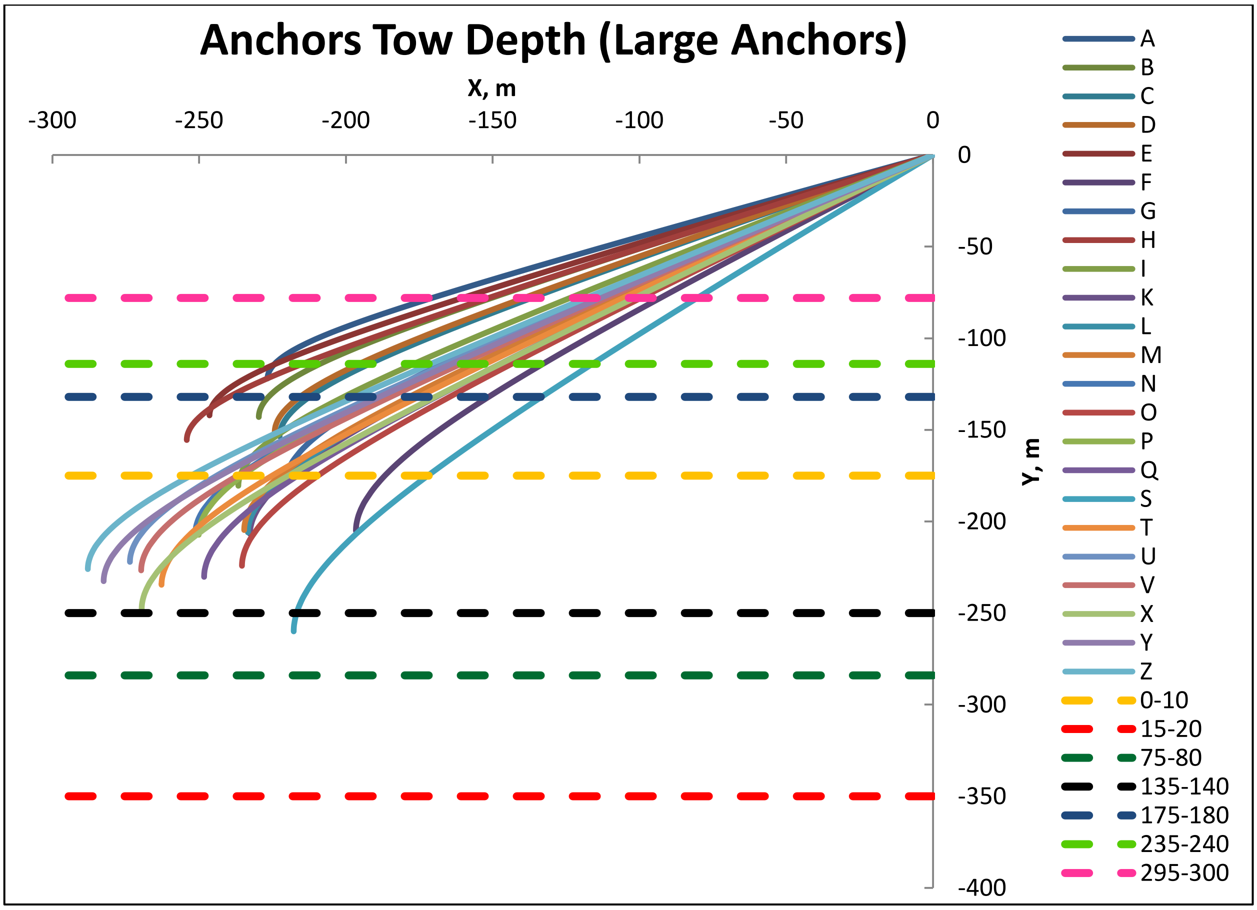



*Figure 47: Tow depth of anchors classified by Capital Letters and water depth lines (dashed) of certain KP sections*

Finally, an assessment of the 3rd anchor EL group is presented in Figure 48. In this case the anchor tow depth is increased up to 280 m. So, almost all the pipeline sections can be reached and hit by huge anchoring equipment of crossing ships.

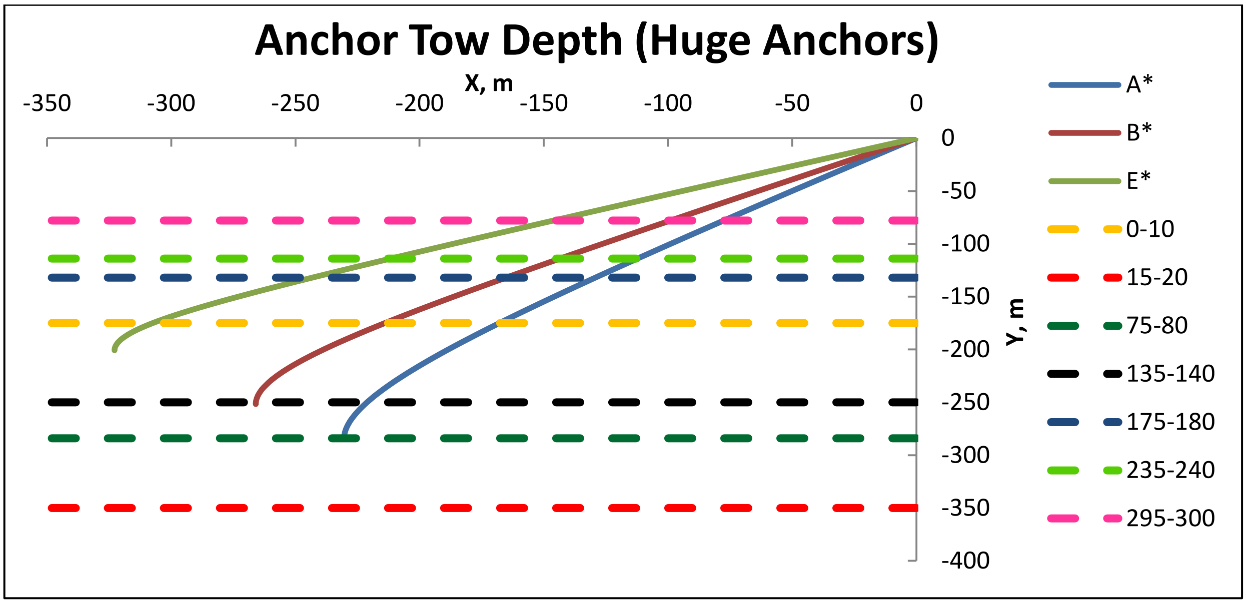



*Figure 48: Tow depth of anchors classified by Letters marked with star and water depth lines (dashed) of certain KP sections*

Summarizing the part of the hit criteria check, it should be said that all the anchors with the EL starting from "*l*" are dangerous for the Pipeline 1. Thus, not all the anchors pose threat to the pipeline resting on the seabed. The key elements here are anchor mass, chain length, and ship speed. The larger the anchor, the longer the chain will be. The anchor hanging on the longer chain has more chances to approach the seabed. Regarding vessel speed, it also affects the anchor towing depth value. In case of high velocity the anchor-chain arrangement will stabilize at less depth than in case of low velocity. A combination of anchor size, chain length, water depth and vessel speed is of great importance for the assessment of anchor towing depth while the ship is underway.

In order to verify the results of analytical solution explained above, it has been decided to take a model scale test. Detailed description of taken experiment is given hereinafter.

## 5.6 MODEL SCALE TEST

The main objective of the experimental work is to determine how the anchor towing depth changes with different values of ship velocity.

### 5.6.1 The scope of the experiment

1. Scaling of required physical values;
2. Preparation for the experiment;
3. Experiment itself;
4. Comparison of experimental data with the results of analytical solution found by using MATLAB.

### 5.6.2 Site description

An experiment has been taken in the education laboratory belonging to the University of Stavanger. One of the two tanks (Figure 49) has been chosen and used for the present test. Technical equipment like underwater lights and underwater cameras are provided by UiS Subsea team.

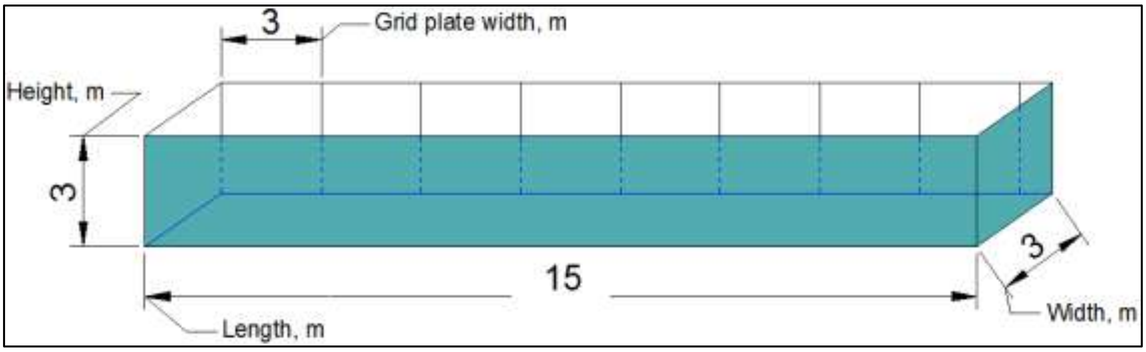
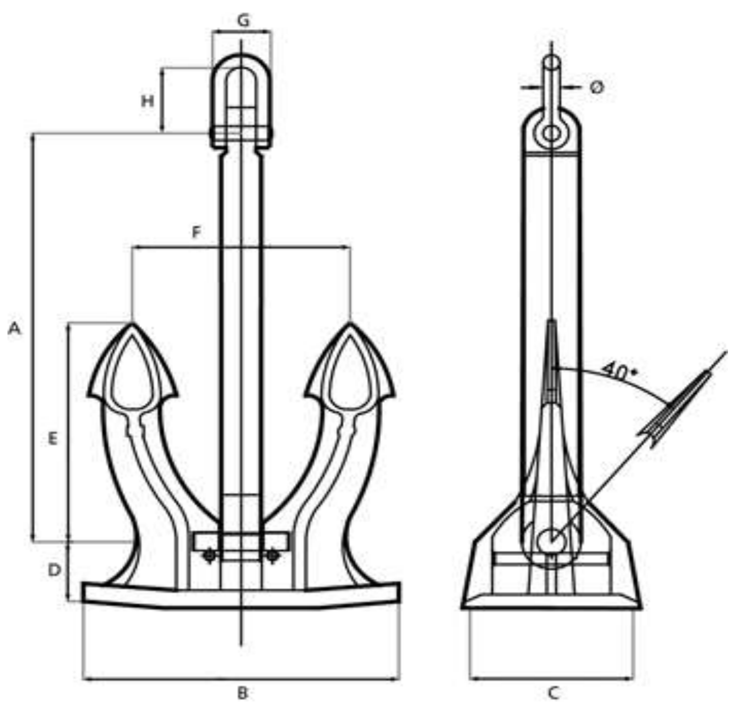



*Figure 49: The laboratory tank geometry*

### 5.6.3 Scaling procedure

Due to some limitations with the tank size it is impossible to carry out an experiment using full-scale anchor and chain. That is why it has been decided to scale down all necessary parameters of randomly chosen anchor-chain arrangement. Anchor class "z" is taken as full scale model, and scaling factor 21 is used for scale operation. Parameters of full-scale anchor and chain are presented in the Tables 21 and 22.

Table 21: Initial data of "z" class Spek anchor ("Spek Anchor", n.d.)

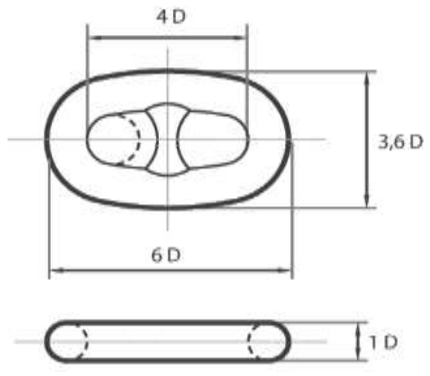



| ***Item*** | ***Unit*** | ***Value*** |
|---|---|---|
| $m$ | kg | 3780 |
| $A$ | mm | 2430 |
| $B$ | mm | 1850 |
| $C$ | mm | 810 |
| $D$ | mm | 393 |
| $E$ | mm | 1350 |
| $F$ | mm | 1350 |
| $G$ | mm | 310 |
| $H$ | mm | 385 |
| $A_{ref-a}$ | $m^2$ | 2.95 |

A rough value of anchor reference area ($m^2$) is found by using the formula:

$$A_{ref-a} = (G \cdot (A + H) + 2 \cdot E \cdot (B - F) \cdot Cos(40^0) + D \cdot B) \cdot 10^{-6} \quad (56)$$

Table 22: Initial data of the chain of "z" class Spek anchor ("Stud Link Chain", n.d.)




| ***Item*** | ***Unit*** | ***Value*** |
|---|---|---|
| $D$ | m | 0.048 |
| $L$ | m | 261.2 |
| $w$ | kg/m | 50.4 |
| $m$ | kg | 13182.05 |
| $A_{ref-c} = D \cdot L$ | $m^2$ | 12.54 |

Where the weight of the chain per meter is calculated by the following formulas ("The future of mooring", n.d.):

$$w_{stud-link} = 0.0219 \cdot D^2 \quad (57)$$

$$w_{stud\ less} = 0.02 \cdot D^2 \quad (58)$$

To scale down an anchor-chain system in appropriate way, some relevant input parameters are to be chosen. By using certain principle written below, corresponding model scale values can be obtained then (Tables 23 and 24).

Table 23: Scaling procedure for anchor (scaling factor is equal to 21)

| ***Full scale (input)*** | | | ***Formula*** | ***Model scale (output)*** | | |
|---|---|---|---|---|---|---|
| ***Item*** | ***Unit*** | ***Value*** | | ***Item*** | ***Unit*** | ***Value*** |
| $A_{ref-a}$ | m | 2.95 | $\overline{A_{ref}} = \frac{A_{ref}}{A_{ref}} = 1$ | $A_{ref}{}'$ | m | 0.01 |
| $m$ | kg | 3780.00 | $\bar{m} = \frac{m}{m} = 1$ | $m'$ | kg | 0.40 |
| $v$ | m/s | 5.23 | $\bar{v} = \frac{v}{v} = 1$ | $v'$ | m/s | 1.14 |
| $p$ | kg/m$^3$ | 1000.00 | $\bar{\rho} = \frac{\rho \cdot A_{ref}^{\frac{3}{2}}}{m} = N = 1.34$ | $p'$ | kg/m$^3$ | 1000.00 |
| $g$ | m/s$^2$ | 9.81 | $\bar{g} = g \cdot \frac{\sqrt{A_{ref}}}{v^2} = \frac{1}{Fr} = 0.62$ <br> $Fr = 1.62$ | $g'$ | m/s$^2$ | 9.81 |

Table 24: Scaling procedure for chain (scaling factor is 21)

| ***Full scale (input)*** | | | ***Formula*** | ***Model scale (output)*** | | |
|---|---|---|---|---|---|---|
| ***Item*** | ***Unit*** | ***Value*** | | ***Item*** | ***Unit*** | ***Value*** |
| $A_{ref-c}$ | m | 12.54 | $\overline{A_{ref}} = \frac{A_{ref}}{A_{ref}} = 1$ | $A_{ref}{}'$ | m | 0.028 |
| $m$ | kg | 13182.05 | $\bar{m} = \frac{m}{m} = 1$ | $m'$ | kg | 1.41 |
| $v$ | m/s | 5.23 | $\bar{v} = \frac{v}{v} = 1$ | $v'$ | m/s | 1.14 |
| $p$ | kg/m$^3$ | 1000.00 | $\bar{\rho} = \frac{\rho \cdot A_{ref}^{\frac{3}{2}}}{m} = N = 3.37$ | $p'$ | kg/m$^3$ | 1000.00 |
| $g$ | m/s$^2$ | 9.81 | $\bar{g} = g \cdot \frac{\sqrt{A_{ref}}}{v^2} = \frac{1}{Fr} = 1.27$ <br> $Fr = 0.78$ | $g'$ | m/s$^2$ | 9.81 |

All the scaling procedure has been performed as written in the paper "Similarity criteria" (Gerasimato, 2012). Special attention should be paid to the water density and acceleration of gravity, the values of which are constant. That is why such similarity parameters as $N$ and $1/Fr$ (where $Fr$ is Froude Number) are to be implemented.

$$Fr = \frac{v^2}{g \cdot \sqrt{A_{ref}}} \tag{59}$$

In the result, output mass of the anchor (0.4 kg) and output mass of the chain (1.41 kg) are taken as reference parameters. According to them, model anchor and chain, having almost the same masses, are found and bought from the car and boat shop Biltema. The final form (view) of the equipment is shown below (Figure 50).

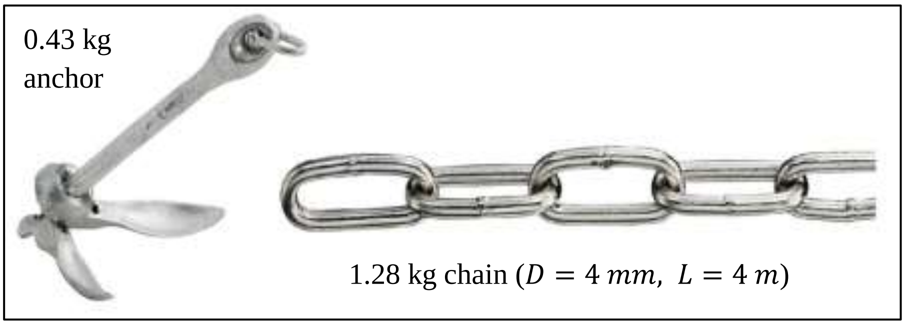



*Figure 50: Anchor and chain (stud less) chosen for the experiment*

### 5.6.4 Preparation for the experiment

Prior to carrying out an experiment, the laboratory tank should be prepared for that. It has been kind of long and routine task. Step by step description of the test preparation objectives is written hereinafter.

1. To empty and to dispose the trash and foreign objectives from the top and inside of the tank (Figure 51).

*Figure 51: Removal of steel bars from the top of the tank*

2. To clean the concrete walls and bottom with fresh water, to wait till the tank is totally dry.

3. To purchase and prepare the grid plates (1x1 m) and white material for the walls and bottom (Figures 52 and 53).

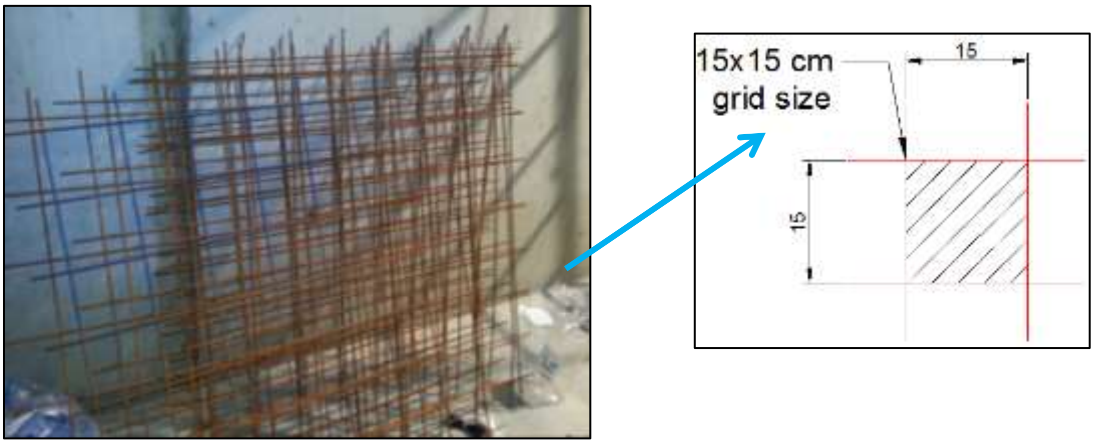



*Figure 52: 1x1 m steel mesh reinforcement and 15x15 cm grid size*

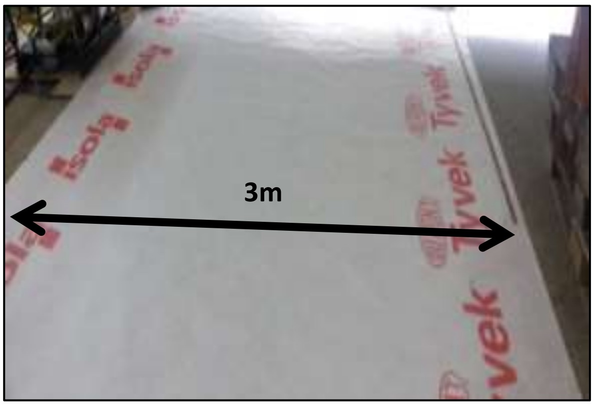



*Figure 53: Waterproof white material*

**NB.** Since all the surfaces are made of concrete, they are grey. So, it has been decided to cover them with white waterproof material, which can give more reflection from the walls and bottom during the test. Concerning grid plates, they are used to act as coordinated map inside the tank.

4. To assemble the plates so that the size of assembled mesh is three by three meters.

5. To paint the grid plates (steel mesh reinforcement) in blue color (Figure 54).

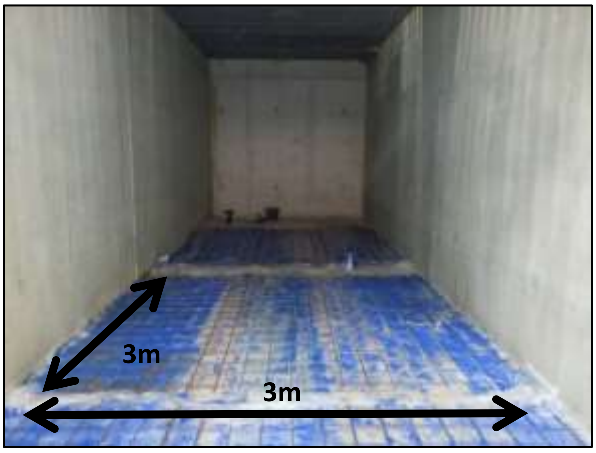



*Figure 54: Painted in blue grid plates*

**NB.** The painting is necessary here, because purchased mesh is of bad quality and can contaminate the water.

6. To cover the tank inside with white waterproof material (Figure 55).

*Figure 55: Process of covering the walls with the reflective material*

7. To install new grid plates (3x3 meters) on top of the material (Figure 56).

*Figure 56: The tank inner surface covered with material and grid plates on top of it*

8. To mark each grid inside in order to understand the position of towing anchor during the test (Figure 57).

*Figure 57: Marked with letters and numbers grid*

9. To paint the anchor and chain in yellow color (Figure 58).

*Figure 58: Painted in yellow anchor and chain*

10. To install the underwater lights and to fill the tank with water (Figure 59).

*Figure 59: Tank filled with water*

### 5.6.5 Experiment

Once the preparation stage has been finished, the main experimental part can be started then. In order to pull the anchoring system (0.43 kg anchor and 4-meter chain) in water, special electric winch has been installed for that purpose. The winch includes a high torque electric motor joined to a gear box that drives a rotating drum, so that the rode is wound onto the winch, and anchor-chain arrangement is moved across the tank. Using controller, it is possible to change the mode of towing speed. Two kinds of modes are set during the test: mode 1.5 and 2. An illustrative view of winch system is given below (Figure 60).

Drum with wound rope (a)

Fixed pulley and rope (b)


Laboratory power supply (c)

Mode controller (d)

*Figure 60: Electric winch system*

A total of 65 towing anchor runs have been done. All the experimental runs are captured on video by applying two GoPro – Hero cameras. The cameras are decided to be fixed by special tape on massive steel bars and submerged into the water, so that the shooting process is held from one of the walls. One camera has been installed at the beginning and another one in the middle of the tank. Several screenshots are taken to show how the configuration of anchor-chain arrangement changes with different speed value. The position of the anchor is visible due to marked grid acting as coordinated map. The reference table showing the distance between the tank bottom and precise letter on the grid is compiled and used for the identification of anchor towing depth value (Table 25).

Table 25: Reference table for the identification of anchor towing depth

| ***Reference letter*** | ***Position of the letter on the grid, cm*** | ***Anchor towing depth, cm*** |
|---|---|---|
| A | 285 | 7.5 |
| B | 270 | 22.5 |
| C | 255 | 37.5 |
| D | 240 | 52.5 |
| E | 225 | 67.5 |
| F | 210 | 82.5 |
| G | 195 | 97.5 |
| H | 180 | 112.5 |
| I | 165 | 127.5 |
| J | 150 | 142.5 |
| K | 135 | 157.5 |
| L | 120 | 172.5 |
| M | 105 | 187.5 |
| N | 90 | 202.5 |
| O | 75 | 217.5 |
| P | 60 | 232.5 |
| Q | 45 | 247.5 |
| R | 30 | 262.5 |
| S | 15 | 277.5 |

Using this table, one can easily see, at which letter the anchor-chain arrangement stabilizes. The most commonly observed anchor stabilization points refer to the letters K, M, O and Q; they are presented on the Figures 61-64 below.

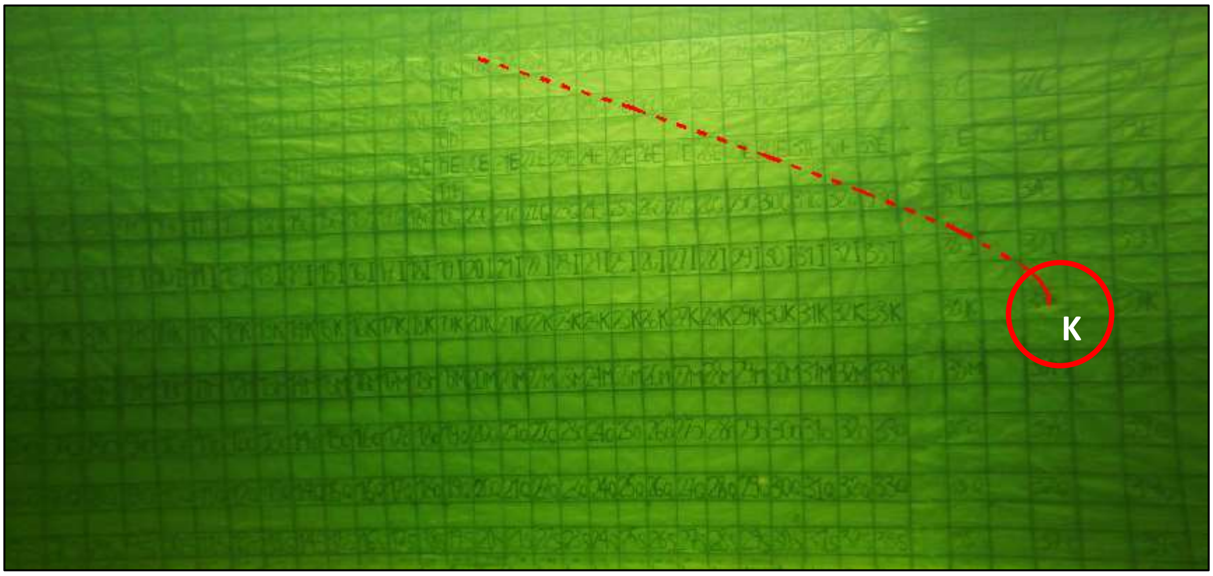



*Figure 61: Snapshot from the video: anchor towing depth – position K (157.5 cm);* $v = 2.3\ m/s$

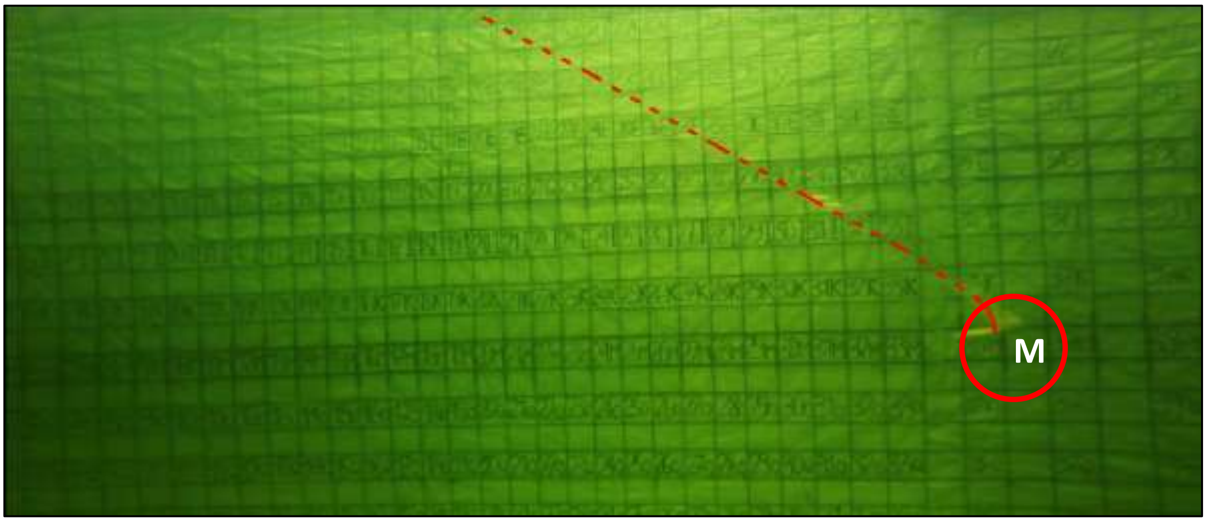



*Figure 62: Snapshot from the video: anchor towing depth – position M (185.0 cm);* $v = 1.9\ m/s$

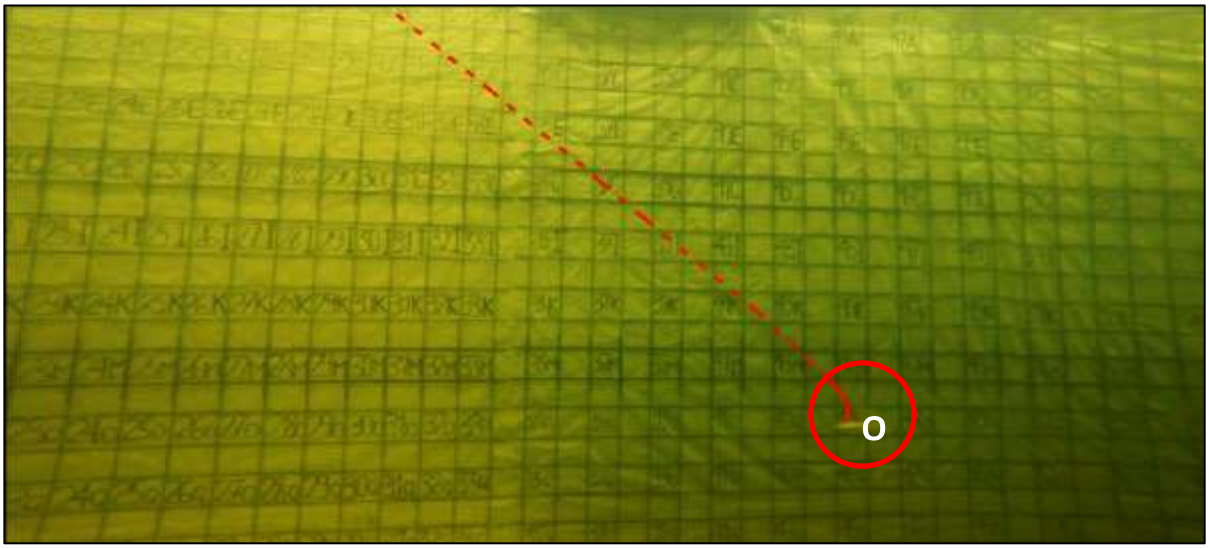



*Figure 63: Snapshot from the video: anchor towing depth – position O (217.5 cm);* $v = 1.6\ m/s$

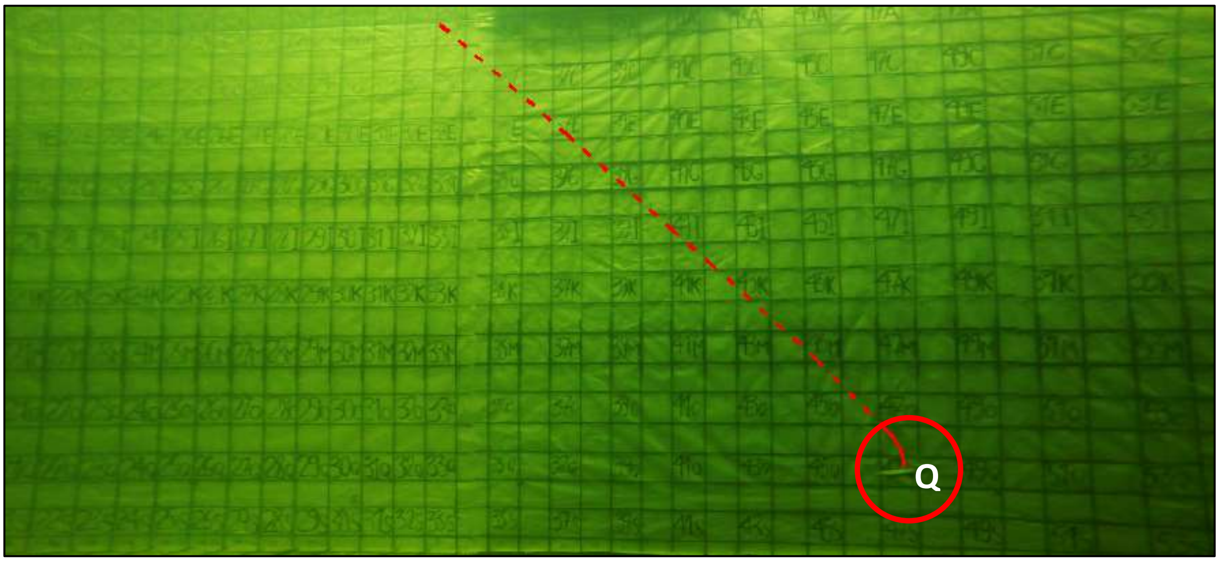



*Figure 64: Snapshot from the video: anchor towing depth – position Q (247.5 cm);* $v = 1.4\ m/s$

Every towing depth can be characterized by certain velocity value. The pulling velocity is calculated by using simple formula (Table 26):

$$v = \frac{s}{t} \tag{60}$$

Where $s$ is the distance travelled by the anchor after its stabilization, and $t$ is time in seconds measured during each anchor-chain system run.

Table 26: Anchor towing depth versus velocity

| ***Velocity, m/s*** | ***Anchor towing depth, m*** |
|---|---|
| 2.3 | 1.575 |
| 1.9 | 1.85 |
| 1.6 | 2.175 |
| 1.4 | 2.475 |

As seen from the table, anchor towing depth value increases with decreasing velocity.

### 5.6.6 Comparison of test results with the results of analytical solution

For the verification of experimental measurements, four different anchor-chain configurations (Figures 61-64) have been digitized by applying the Web Plot Digitizer Software; and obtained points have been graphed in the EXCEL application.

Concerning analytical solution, it is found by using the same principle as described in anchor hit criteria check part. Input data that are required for the present calculation is given below (Table 27). In addition, towing velocity values for 4 different cases are taken as input as well.

Table 27: Input data

| ***Characteristics*** | ***Item*** | ***Unit*** | ***Value*** |
|---|---|---|---|
| Model anchor mass | $m_a$ | kg | 0.43 |
| Chain length | $l$ | m | 4 |
| Chain diameter | $D$ | m | 0.004 |
| Normal drag coefficient of stud-less chain | $C_{Dn}$ | - | 2.4 |
| Tangential drag coefficient of stud-less chain | $C_{Dt}$ | - | 1.15 |
| Acceleration of gravity | $g$ | $m/s^2$ | 9.81 |
| Water density | $\rho_w$ | $kg/m^3$ | 1000 |
| Steel density | $\rho_{steel}$ | $kg/m^3$ | 7850 |

All the results of analytical solution are presented on the same graph (Figure 65). The absolute error of the measurements in x-direction falls between 0.003-0.059 m.

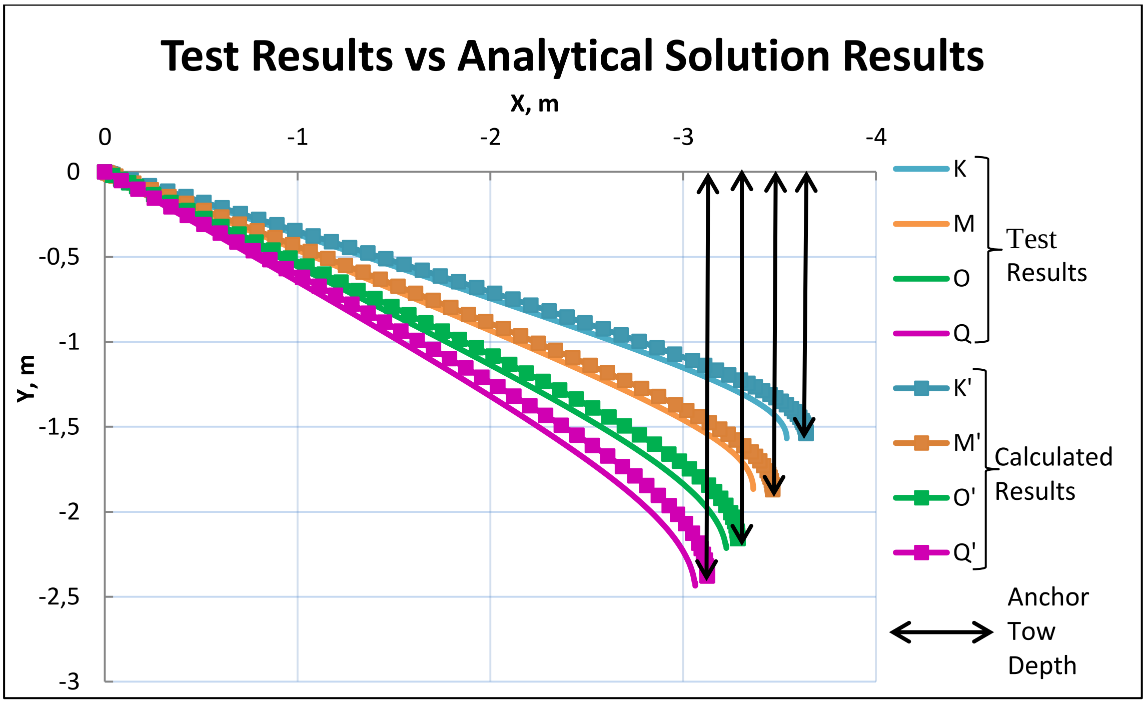



*Figure 65: Comparison of results*

*Summarizing* this part, it is safe to say that anchor hit criterion is one of the most important criteria that have to be checked and discussed in every detail prior to continuing with anchor damage performance analyses. The graph gives good answers on two major questions – the chain shape after its stabilization and anchor towing depth variations with changing velocity values. Both, analytical and experimental approaches point out that the anchor will never be hanging vertically from the bow of the moving ship. It is due to an interaction between the water and anchor-chain arrangement: there will always be the hydrodynamic drag forces acting on the system in a direction opposite to the movement of the vessel. It should be mentioned, that the drag forces are proportional to the velocity squared (as presented in the formulas above). That is precisely why the position of anchor is heavily affected by the value of ship speed. The higher the velocity, the smaller the value of anchor towing depth will be. Moreover, not only the velocity, but anchor and chain masses are significant for this investigation. It is obvious that large and huge anchoring systems (classified by Capital Letters and Letters marked with star) are very heavy, so that they stabilize at greater towing depths as compared to Small Letters anchors.

## 5.7 ANCHOR DRAGGING CONSEQUENCES

In order to investigate the response of the pipeline interacted by the anchor suddenly lost and dragged over the line, a model developed by the IKM Ocean Design in the finite element (FE) program SIMLA is used. A full access to the program SIMLA is provided by the IKM Ocean Design Company as well. Dragged anchor analysis on a given Pipeline 1 with defined parameters is done for a number of sensitivity cases.

### 5.7.1 Sensitivity cases

Based on the results obtained after the double hook and hit criteria checks, the summary column diagram is drawn up (Figure 66).

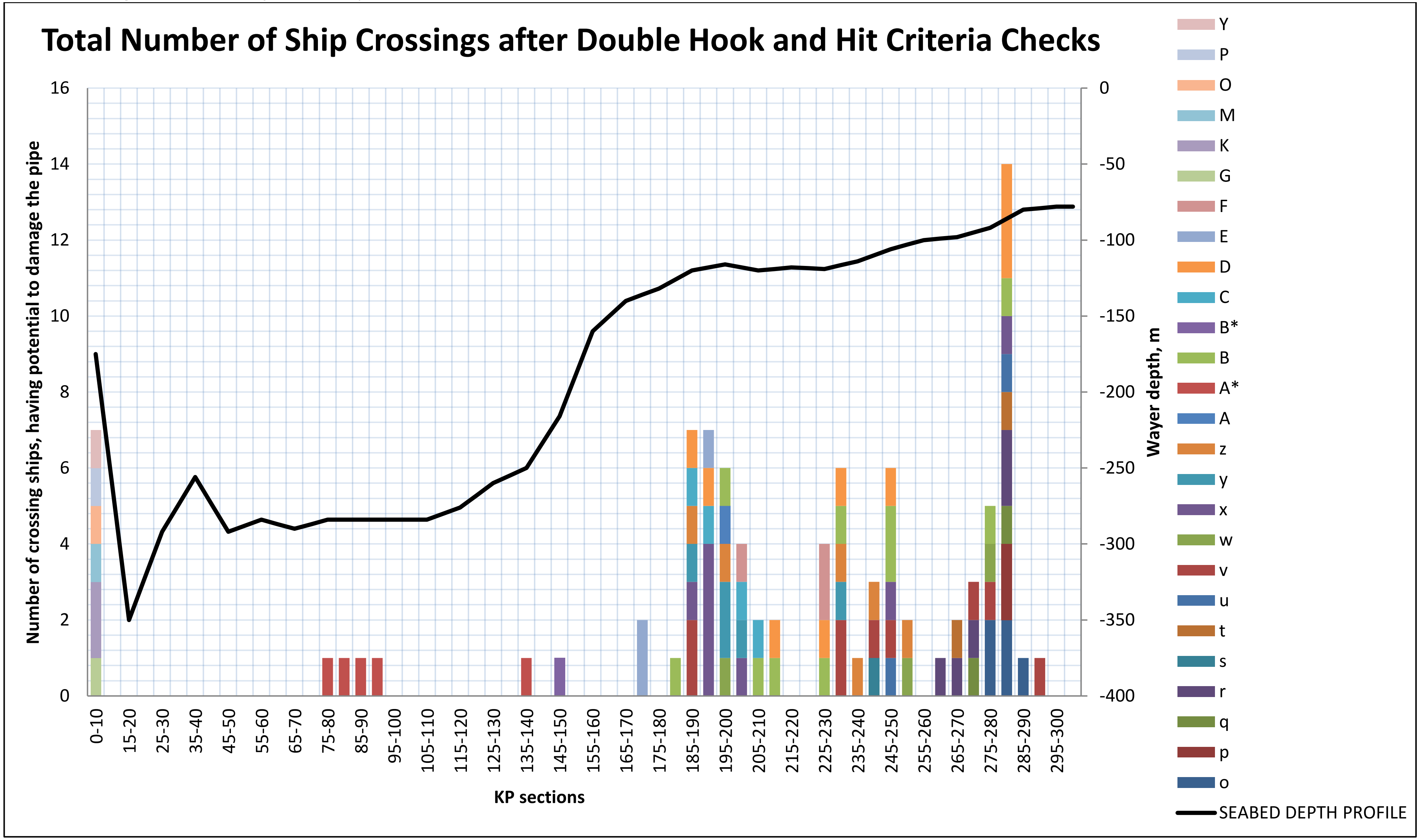



Figure 66: Total number of crossing ships within certain KP sections and defined water depth (after hook/hit criteria checks)

As seen from the diagram, the most critical Pipeline 1 KP sections are the following: 0-10, 75-95, 145-150, 170-215, 225-255, and 265-295. Each of these sections is laid at various water depths. That is why all of them are a point of interest. Every pipe segment is crossed by different number and different classes of anchoring systems (as illustrated on the legend). In view of this, several anchor types that are commonly occurred in every dangerous KP segments are selected for the anchor damage assessment procedure (Table 28).

Table 28: Selected anchors within each critical Pipeline 1 section and specified average water depth

| ***Number of critical KP section*** | ***Critical KP section*** | ***Average water depth, m*** | ***Selected anchor classes within KP section*** |
|---|---|---|---|
| 1 | 0-10 | 175 | G, Y |
| 2 | 145-150 | 224.5 | B* |
| 3 | 170-215 | 119 | E |
| 4 | 225-255 | 115.25 | z, v, F |
| 5 | 260-295 | 89 | o, x, B, D |

One can see that the number of sensitivity cases needed for the analysis of pipe-anchor interaction scenario is equal to 11. Moreover, all anchor types are chosen for the analysis: both small and large ones.

### 5.7.2 Parameters for the anchor hooking analysis

Relevant pipeline parameters essential for the analyses in SIMLA are summarized in Table 29.

Table 29: 40-inch pipeline data for FE analysis

| ***Characteristics*** | ***Unit*** | ***Value*** |
|---|---|---|
| Outer diameter | m | 1.019 |
| Wall thickness | m | 0.026 |
| Material | - | Statoil grade X-65 |
| Steel density | $kg/m^3$ | 7850 |
| Young’s modulus | GPa | 207 |
| SMYS | MPa | 450 (0.5% strain) |
| SMTS | MPa | 680 (20% strain) |
| Poisson’s ratio | - | 0.3 |
| Coefficient of linear expansion | $^0C^{-1}$ | $11.7 \times 10^{-6}$ |
| Internal temperature | $^0C$ | 50 |
| Internal pressure | barg | 170 |
| Content density | $kg/m^3$ | 177 |
| Submerged weight (empty) | kg/m | 409.17 |
| Submerged weight (operation) | kg/m | 539.00 |

Special attention should be paid to the pipeline material definition that is included into the finite element model. For the present case study a Ramberg-Osgoord stress-strain relationship is used (Figure 67):

$$\varepsilon(\sigma) = \frac{\sigma}{E} \cdot \left(1 + \frac{3}{7} \cdot \left(\frac{\sigma}{\sigma_r}\right)^{n-1}\right) \qquad (61)$$

$\sigma_r$ - Ramberg-Osgood yield parameter;
$n$ – hardening parameter.

Parameters $\sigma_r$ and $n$ are found by using this relationship, so that for the current material $\sigma_r$ is equal to 399.3 MPa, and $n$ is equal to 10.

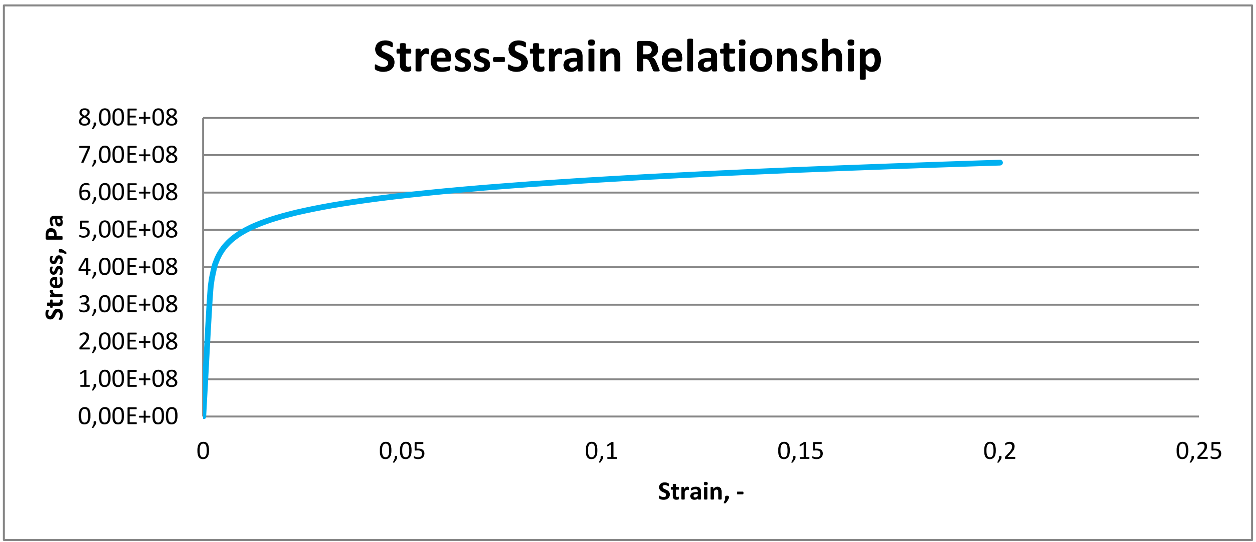



*Figure 67: Pipeline stress-strain relationship curve*

Regarding anchor and chain data, a complete table of each anchor class characteristics is given below (Table 30). All the information about vessel equipment is taken from the Rules for Ship document. Anchor pulling angle value is found during the calculations of anchor towing depth (in anchor hit criteria check part). And anchor pulling velocity is as shown on the diagram “EL vs Average Ship Speed” (Figure 42).

Table 30: Input anchor data for FE analysis

| *Case #* | *Anchor arrangement class (EL)* | *Anchor mass, kg* | *Chain length, m* | *Chain capacity, kN* | *Anchor pulling angle, deg* | *Velocity, m/s* |
|---|---|---|---|---|---|---|
| 1 | G | 6000 | 288.75 | 2770 | 33 | 4.97 |
| 2 | Y | 16100 | 371.25 | 6690 | 34 | 6.05 |
| 3 | B* | 18800 | 371.25 | 7960 | 38 | 5.70 |
| 4 | E | 5250 | 288.75 | 2430 | 25 | 6.33 |
| 5 | z | 3780 | 261.25 | 1810 | 28 | 5.23 |
| 6 | v | 2850 | 247.5 | 1400 | 25 | 5.58 |
| 7 | F | 5610 | 288.75 | 2600 | 39 | 4.07 |
| 8 | o | 1590 | 206.25 | 735 | 23 | 5.27 |
| 9 | x | 3300 | 247.5 | 1680 | 28 | 5.21 |
| 10 | B | 4320 | 225 | 1960 | 27 | 5.68 |
| 11 | D | 4890 | 225 | 2270 | 29 | 5.51 |

**NB.** Conventional stockless anchor type and the most commonly used stud-link chain (steel grade NV K3) are selected for the present analysis.

### 5.7.3 Global scale analyses

Anchor hooking analyses for all the distinguished sensitivity cases are performed by employing FE program SIMLA.

***Modeling particularities***

1. 10000-meter pipeline segment is modeled in the finite element program. By considering SIMLA element library, an element type PIPE33 has been chosen to describe elasto-plastic behavior of pipeline material. All the corresponding pipeline design and operational characteristics are also set into the computer code in SIMLA.

2. An anchor is modeled as a 3D beam, and a chain is modeled as a single beam. An element type PIPE31 is used to describe a linear elastic behavior of anchor and chain materials. Relevant input characteristics of anchor arrangement given in the Table 30 are included into the code as well. Special emphasis should be placed on the axial stiffness (in N) of the chain, which is the function of its diameter ($D$) and found by formula:

$$EA_{stud-link} = 1.01 \cdot 10^{11} \cdot D^2 \qquad (62)$$

3. The analyses are performed for several critical KP sections, which are situated at different seawater depths. The depth value has been changed for every individual case in accordance with the Table 28. SEA150 element is taken to simulate the sea properties.

4. As for the seabed, it is flat in the model. The seabed properties are described in two directions (axial and lateral) by using contact element types CONT126 in order to show the contact between the pipeline and seabed.

5. The model simulates a pipe-anchor interaction using an elastic spring connection. At a given springtime the spring (material of which is explained by the element spring137) will be activated effectively “gluing” itself to the pipeline and simulating that it hooks the line. After that the spring connection is capable of emulating the break of the chain at relevant chain breaking load. The analysis is continued until the pipeline comes to rest after being interfered by dragging anchor.

6. Global type boundary conditions are specified in the model. The pipeline is modeled with finite length and fixed ends in x- and y-directions (translation), and in torsional direction (rotation about x) as well.

Schematic illustration of the pipe-anchor interaction simulation is presented below (Figure 68).

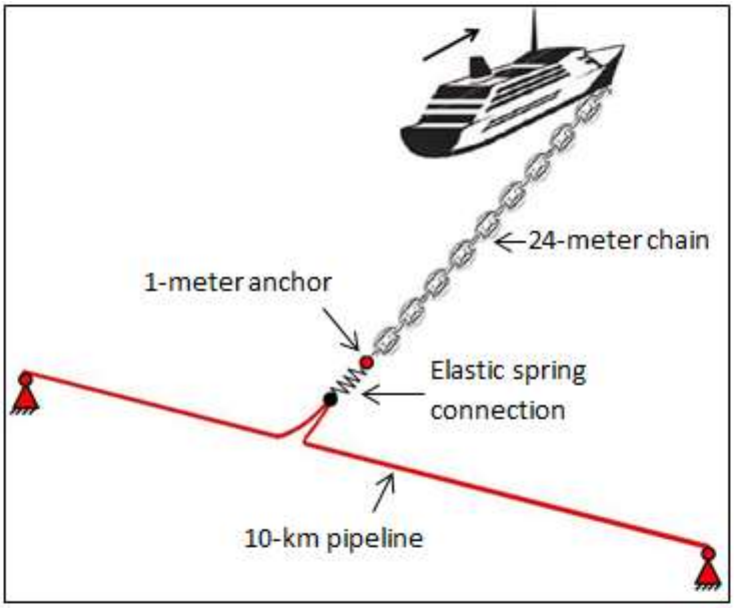



*Figure 68: Schematic view of overall pipe-anchor interaction model*

**NB**. To be more conservative the interaction between the Pipeline 1 and dragging anchor is assumed to be perpendicular.

***40-inch Pipeline 1 modeling results***

Following the main objective of the present case study, relevant SIMLA analysis input files have been prepared individually for all the sensitivity cases, a total number of which is 11. Once, every input file is run, the output data concerning moments, forces, displacements and strains are determined and exported to the individual EXCEL sheets. Using obtained data, it becomes possible to investigate 40-inch Pipeline 1 response after being hooked by the dragging anchor.

Displacements

Special attention is paid to the vertical and lateral displacements of the 40-inch pipeline. For that purpose, summarized table with the relevant values is compiled. Corresponding graphs, showing how the displacements of the Pipeline 1 changes from case to case, are developed and presented below (Figures 69 and 70).

**NB**. One shall take into account that all the parameters used for the analysis in SIMLA **are not generalized or averaged**; they are specific for every single case. So, values of the velocity, chain length and anchor pulling angle are individual and vary only with certain anchor class and water depth (Table 31).

Table 31: Resultant table

| *Anchor class (EL)* | *Vertical displacement, m* | *Lateral displacement, m* | *Ship speed, m/s* | *Anchor pulling angle, deg* | *Water depth, m* |
|---|---|---|---|---|---|
| o | 0.11 | 8.62 | 5.3 | 23 | 89 |
| v | 1.43 | 16.99 | 5.6 | 25 | 115 |
| x | 1.62 | 19.49 | 5.2 | 28 | 89 |

| | | | | | |
|---|---|---|---|---|---|
| z | 1.91 | 20.33 | 5.2 | 28 | 115 |
| B | 1.88 | 20.53 | 5.7 | 27 | 89 |
| D | 2.79 | 23.53 | 5.5 | 29 | 89 |
| E | 2.36 | 21.93 | 6.3 | 25 | 119 |
| F | 5.52 | 32.39 | 4.1 | 39 | 115 |
| G | 4.13 | 26.55 | 5.0 | 33 | 175 |
| Y | 6.61 | 49.23 | 6.0 | 34 | 175 |
| B* | 7.71 | 61.60 | 5.7 | 38 | 225 |

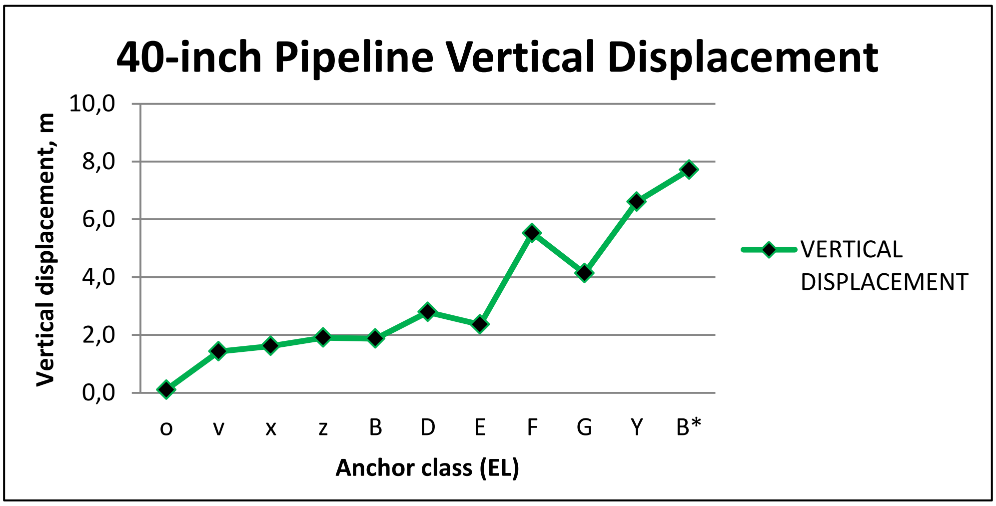



*Figure 69: Pipeline 1 vertical displacement for specified cases*

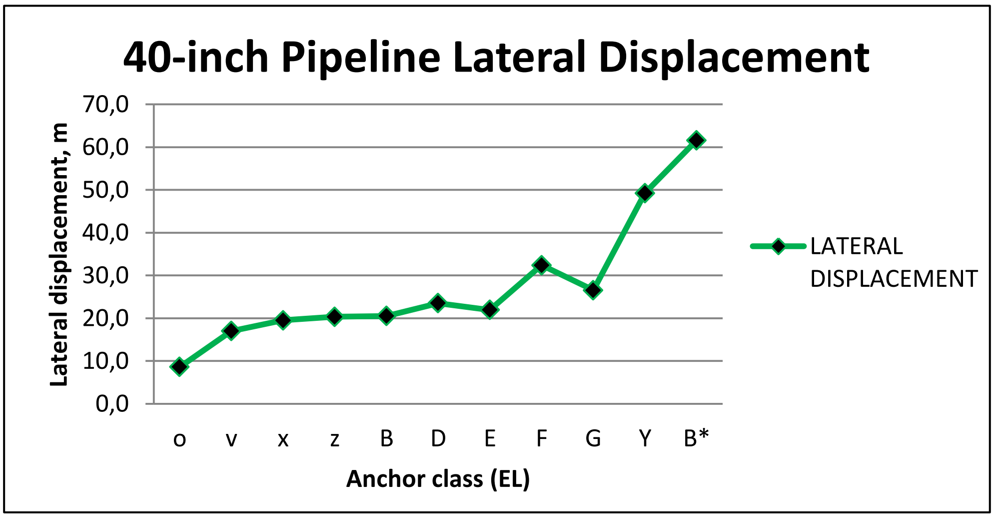



*Figure 70: Pipeline 1 lateral displacement for specified cases*

It is visible that the behavior of the graphs is quite similar. Large vertical and lateral displacements refer to the anchor classes “Y” and “B*” (Figures 71 and 72). Moreover, one can see here that the displacement values are not distributed smoothly as they are thought to be (it is observed for the “E” and “G” anchor classes). The reason for this is that not only the anchor size, but a combination of the chain length, ship speed and water depth strongly influence the value of anchor pulling angle, which greatly affects the resultant value of the pipeline displacements. In order to confirm this statement, the following table (Table 32) is compiled to show the comparison between four adjacent equipment classes: “D” - “E” - “F” - “G”.

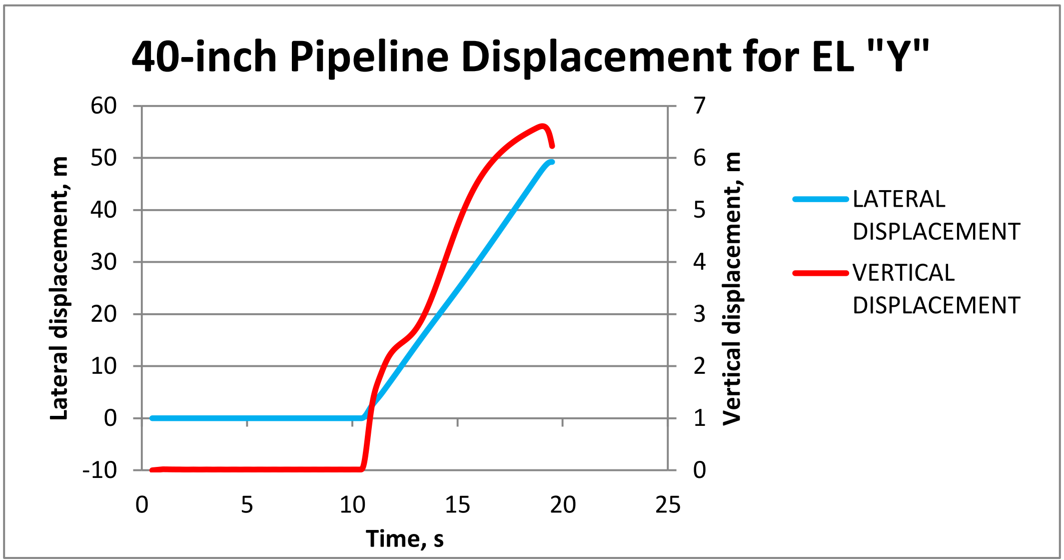



*Figure 71: Pipeline displacement in case of anchor class “Y”*

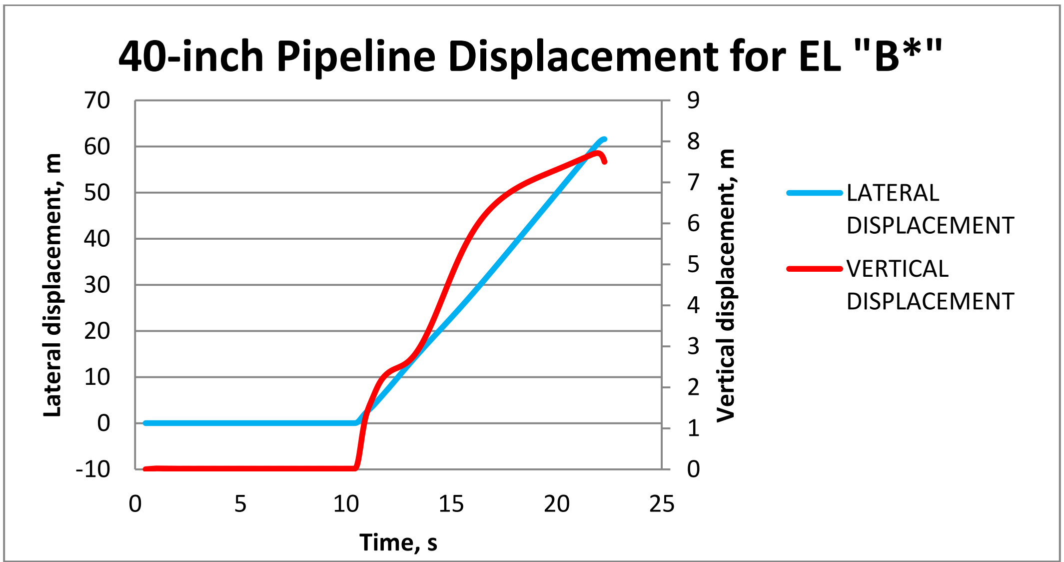



*Figure 72: Pipeline displacement in case of anchor class “B*”*

Table 32: Comparison between four adjacent equipment classes: “D” - “E” - “F” - “G”

| | ***D*** | ***Comparison character*** | ***E*** | ***Comparison character*** | ***F*** | ***Comparison character*** | ***G*** |
|---|---|---|---|---|---|---|---|
| ***Vertical displacement, m*** | 2.79 | > | 2.36 | < | 5.52 | > | 4.13 |
| ***Lateral displacement, m*** | 23.53 | > | 21.93 | < | 32.39 | > | 26.55 |
| ***Anchor pulling angle, deg*** | 29 | > | 25 | < | 39 | > | 33 |
| ***Velocity, m/s*** | 5.51 | < | 6.33 | > | 4.07 | < | 4.97 |

Strains

Along with the displacement, strain is also a point of interest while assessing the pipeline response. In the analysis 5% strain is chosen as a limit value. Once it is exceeded, the pipeline will suffer damage. The graph below presents the variation of pipeline strain with different anchor types (Figure 73).

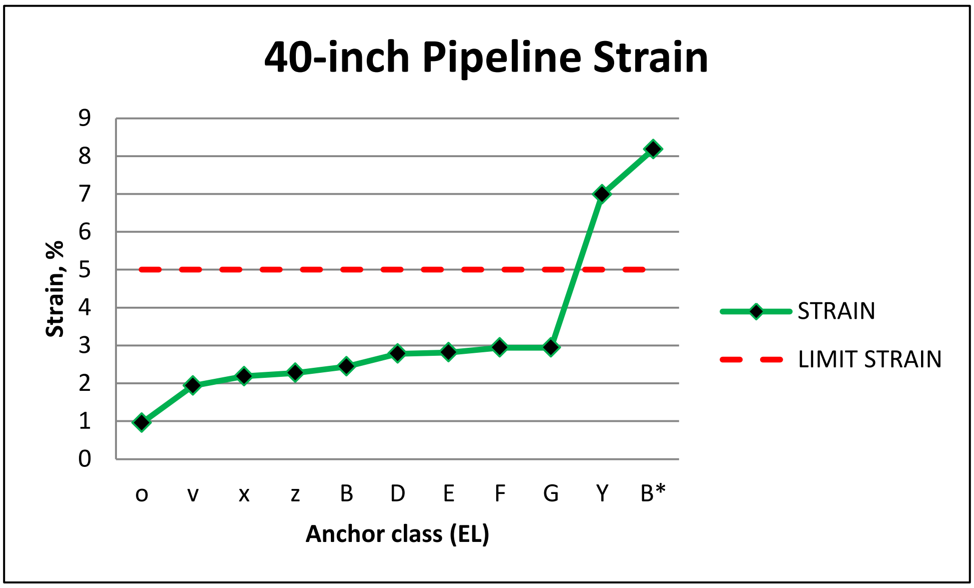



*Figure 73: Pipeline 1 strain for specified cases*

As seen from above the anchor classes “Y” (16100 kg) and “B*” (18800 kg) are very dangerous for the Pipeline 1. These classes refer to the ships, crossing KP 0-10 and 145-150.

Bending moment, axial force and internal pressure

Evaluation of cross-sectional capacity of the Pipeline 1 is to be included in the analysis as well. Being hooked by the dragging anchor, the pipeline is subjected to large axial forces and bending moments. Moreover, taking into account the fact that the pipeline is under operation, no one can exclude an effect from the internal pressure. Detailed discussion on combined loading effect has been given in the previous part (Table 15). So, an assessment of pipeline cross-sectional capacity can be performed by applying plastic interaction curves, which account for maximum combined axial force, bending moment and internal pressure. The plastic capacity curves can be gotten by solving the following equation (Vitali, Bruschi, Mork, Levold & Verley, 1999):

$$M = (D-t)^2 \cdot t \cdot \sigma_y \cdot \sqrt{1 - \frac{3}{4} \cdot q_h^2} \cdot cos\left(\frac{\pi}{2} \cdot \frac{\left(\frac{N}{N_c} - \frac{1}{2} \cdot q_h\right)}{\sqrt{1 - \frac{3}{4} \cdot q_h^2}}\right) \qquad (63)$$

$M$ – full plastic bending moment;
$N$ – axial force applied in steel;
$q_h$ - hoop stress ratio equal to $\sigma_h / \sigma_y$;
$\sigma_h$- hoop stress equal to $P_i \cdot \frac{D-t}{2 \cdot t}$;
$P_i$ - internal pressure;

$D$ - pipe outer diameter;
$t$ - pipe wall thickness;
$\sigma_y$- yield stress;
$N_y$ – yield axial force equal to $\pi \cdot (D - t) \cdot t \cdot \sigma_y$.

Once the plastic interaction curves are ready, an axial force – bending moment relationship can be plotted as well. In case, if force - moment relationship falls within the plastic interaction curve related to 5% limit strain, the pipeline is supposed to survive. Otherwise, it will suffer damage. Cross-sectional capacity (black line) of the Pipeline 1 is checked for all the anchor types specified before. Green dashed line corresponds to SMYS; red dashed line refers to SMTS; while blue dashed line is plastic capacity curve relates to 5% limit strain value. The results of this check are presented below in Figures 74-84.

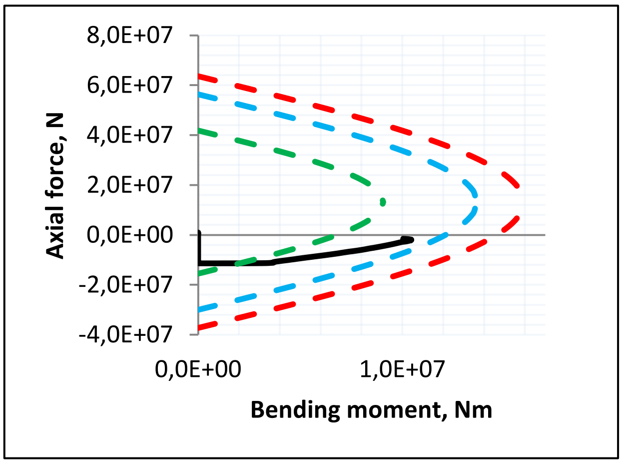



*Figure 74: Capacity check for EL "o"*

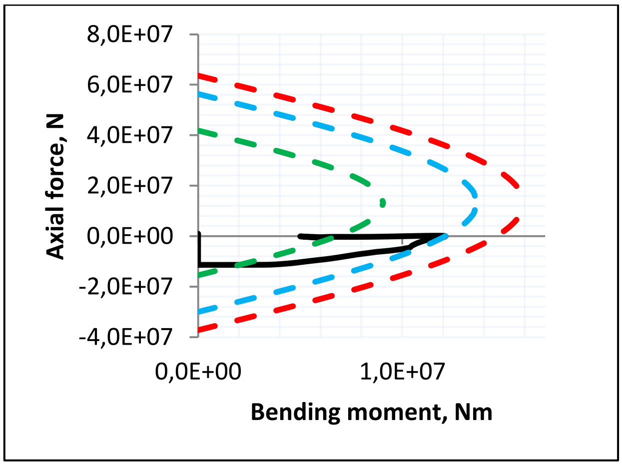



*Figure 76: Capacity check for EL "x"*

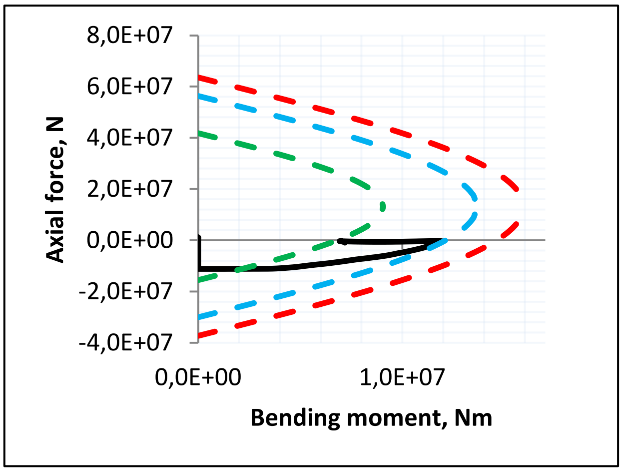



*Figure 75: Capacity check for EL "v"*

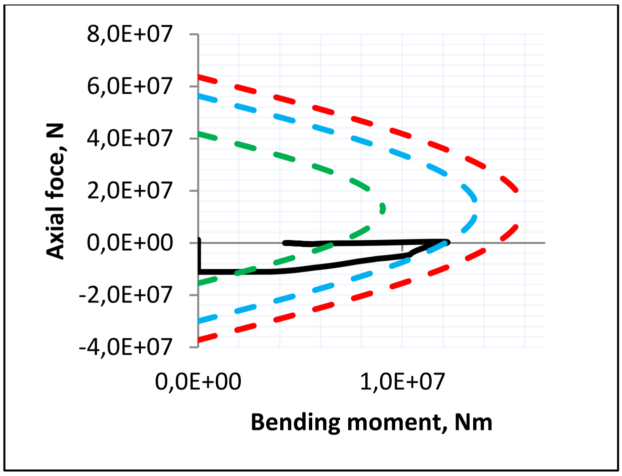



*Figure 77: Capacity check for EL "z"*

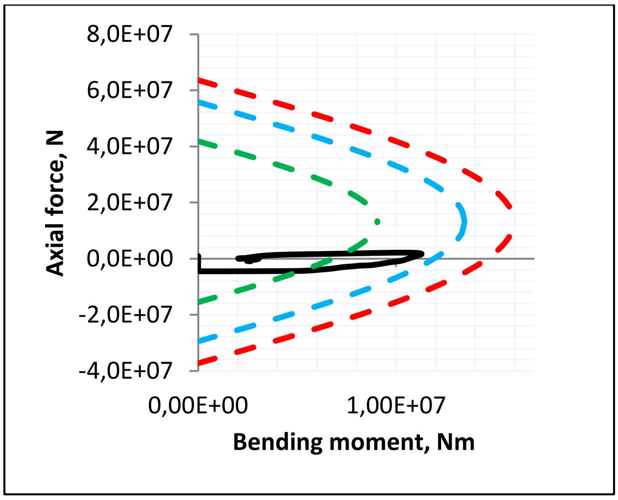



*Figure 78: Capacity check for EL "B"*

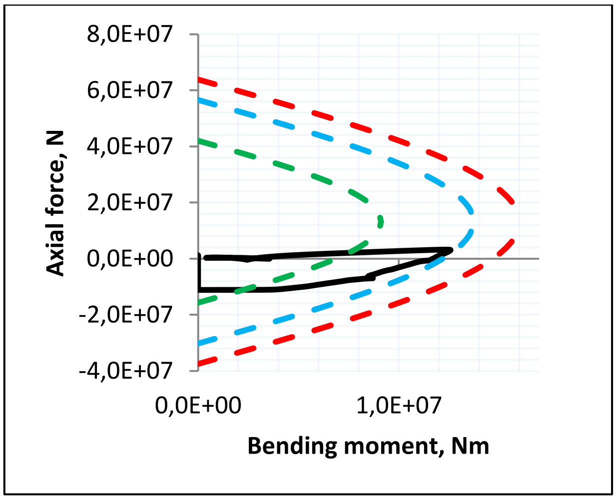



*Figure 81: Capacity check for EL "F"*

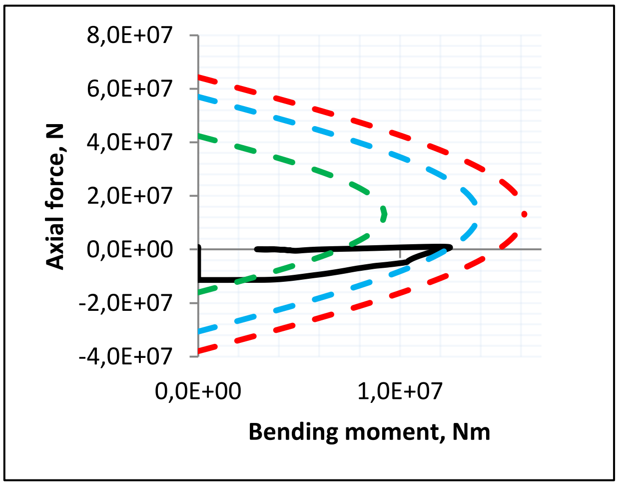



*Figure 79: Capacity check for EL "D"*

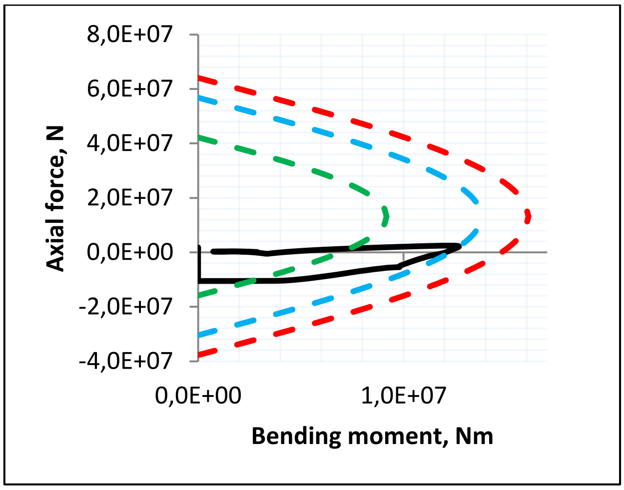



*Figure 82: Capacity check for EL "G"*

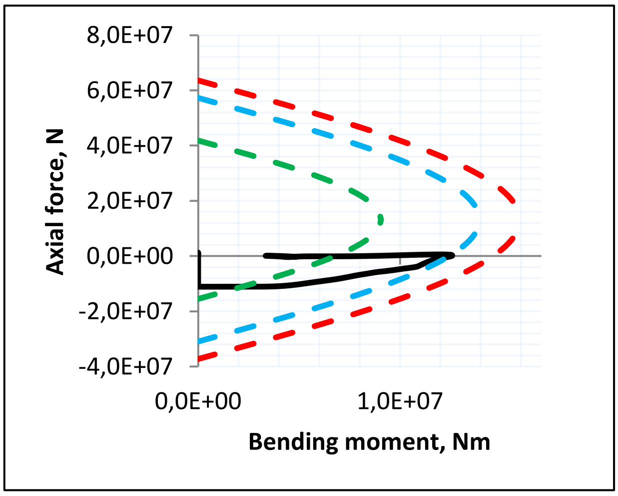



*Figure 80: Capacity check for EL "E"*

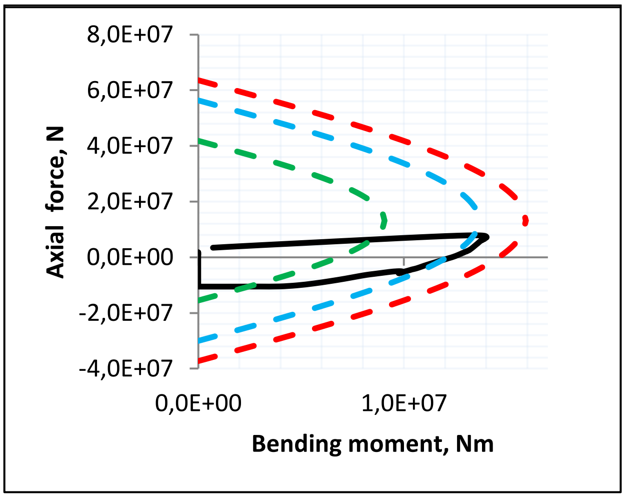



*Figure 83: Capacity check for EL "Y"*

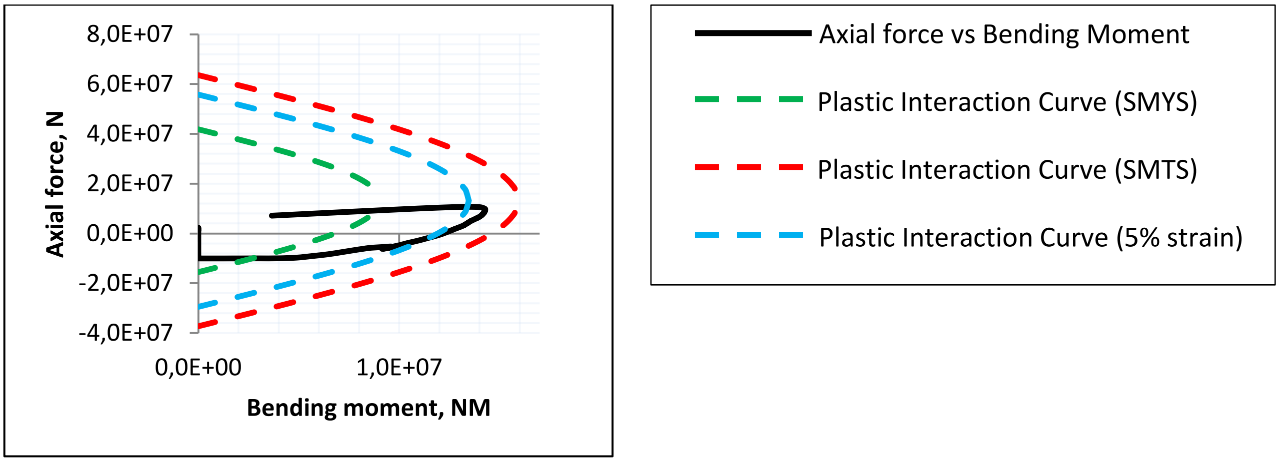



*Figure 84: Capacity check for EL "B*"*

As observed from the plots above, in case if pipeline is interfered by the dragging anchors classified by "Y" and "B*", the axial force – bending moment relationship curve intersects the plastic capacity curve corresponding to 5% limit strain (blue dashed line). So, the Pipeline 1 will suffer damage in 0-10 KP and 145-150 KP sections respectively. In order to understand, how the axial force has been changing in time until the anchor chain is broken, the following graphs are shown below (Figures 85-87).

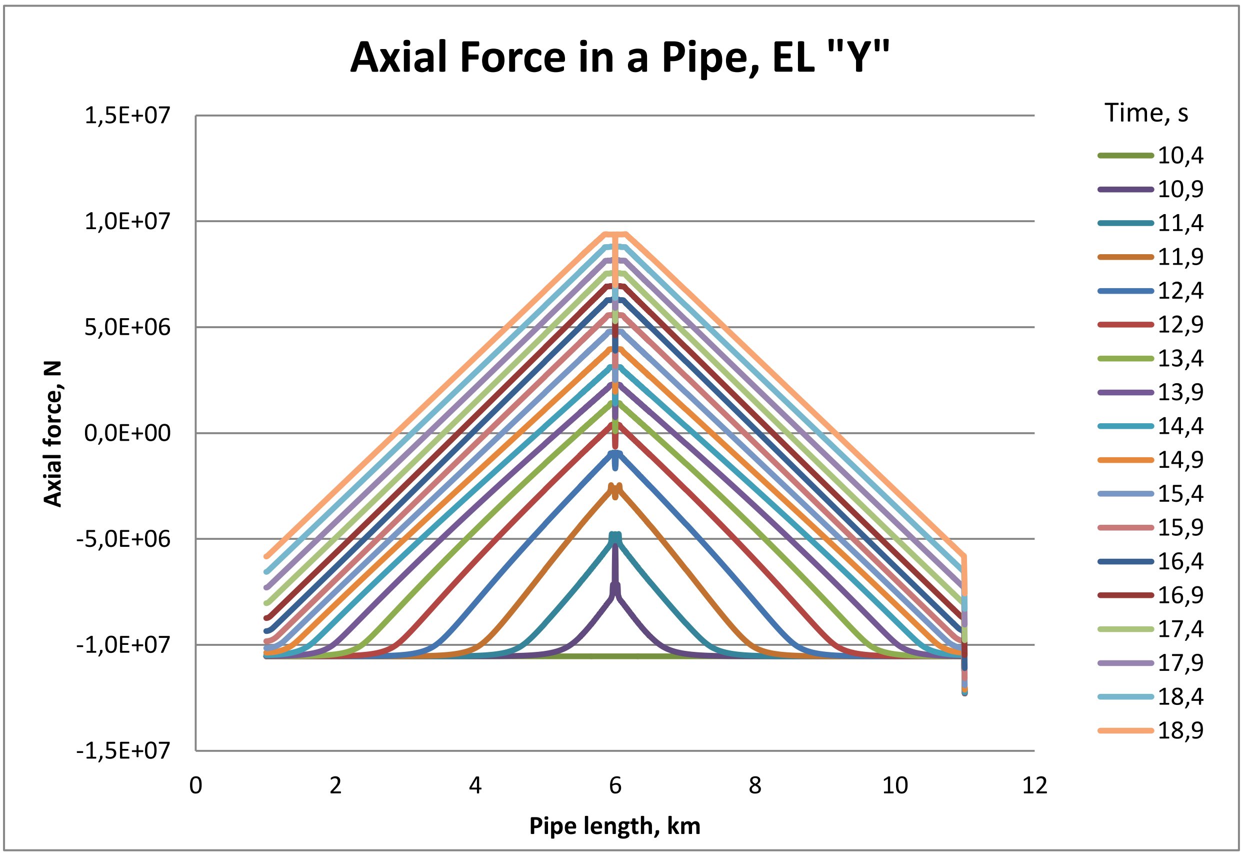



*Figure 85: Change in axial force in time, EL "Y"*

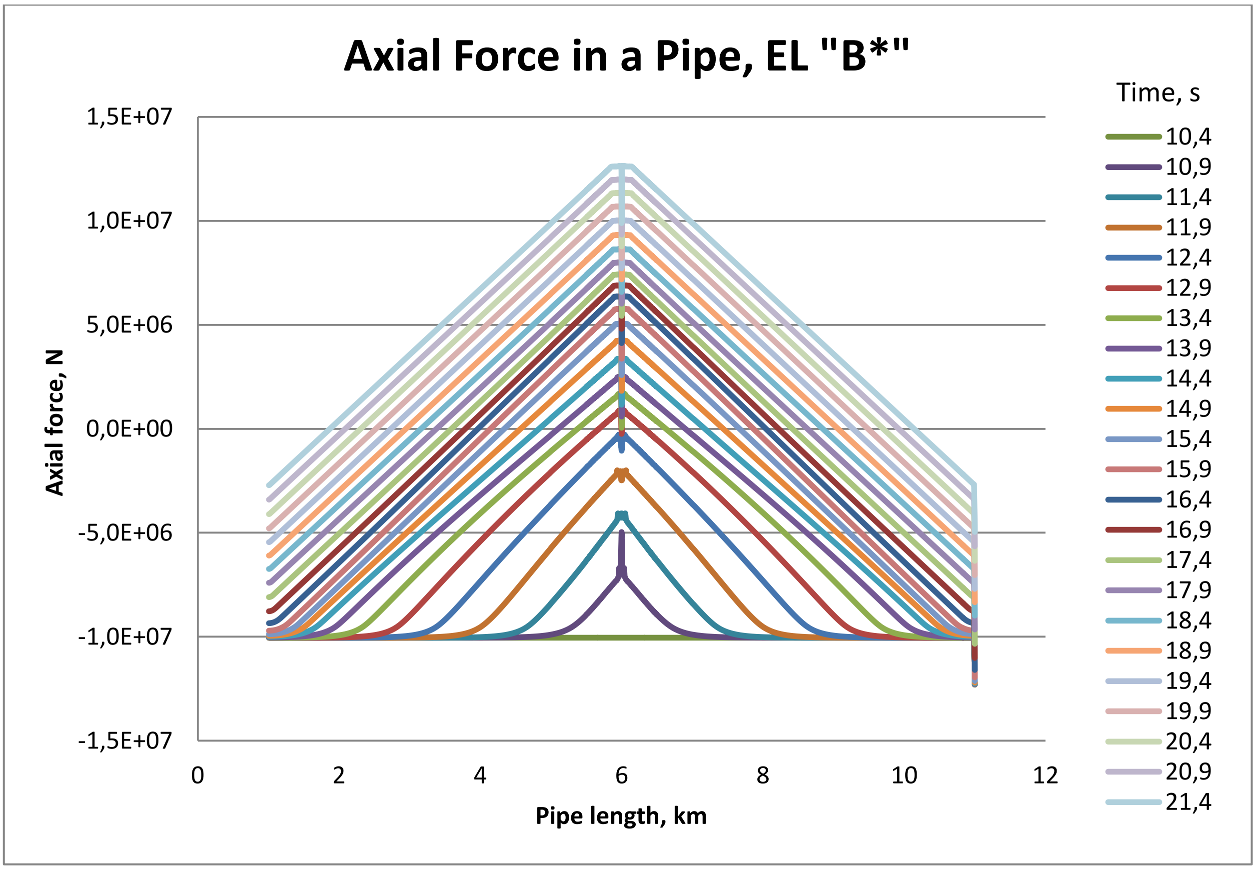



*Figure 86: Change in axial force in time, EL "B*"*

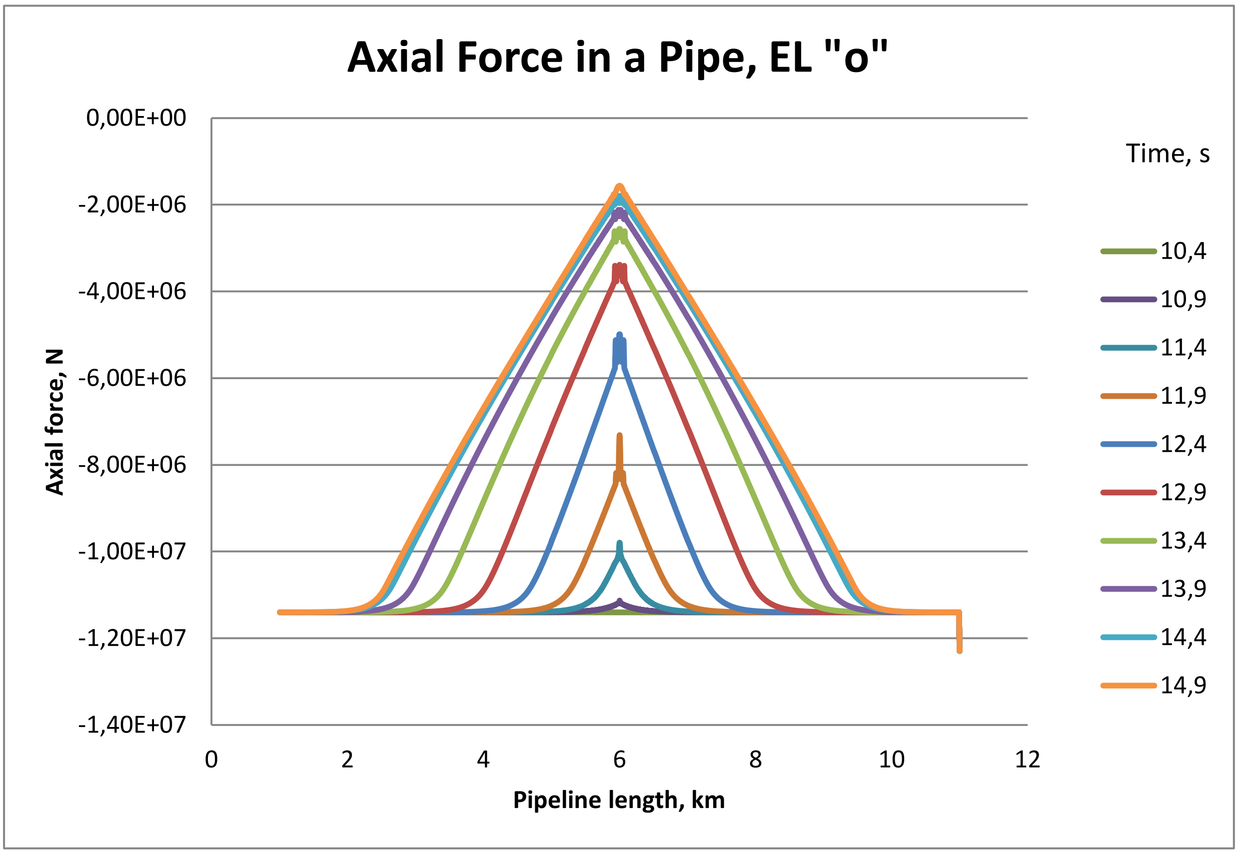



*Figure 87: Change in axial force in time, EL "o"*

In case of huge anchor interactions (“Y”, “B*”), the ends of modeled 10 km pipeline are affected by the axial force. The latter is not observed in case of small anchors (Figure 87). This phenomenon can be explained by the effect of large membrane terms in the pipeline that steadily increase until the anchor chain is broken. Hence, it is better to model longer pipeline for the assessment of its damage due to huge anchoring systems.

*Summarizing* the part about anchor pulling consequences, one shall see how important it is to perform anchor hooking analysis on a global scale. A lot of attention should be given here to the pipeline displacements and strains. The analysis shows interesting variation of vertical and lateral pipeline displacements with different anchor sizes. It is found that not only the anchor mass, but also a vessel speed becomes key parameter affecting the resultant pipeline response. The larger the velocity, the less the anchor pulling angle and the less the pipeline displacements (both vertical and lateral) will be. Regarding pipeline strain, the limit value of 5% strain is used in the present case study. The analysis indicates that the strain criterion has been exceeded in cases of anchor class “Y” and “B*”. So, 40-inch Pipeline 1 is supposed to be damaged if it is hooked by these anchors. The same results are obtained from the pipeline cross-sectional capacity check. Combined axial force, bending moment and internal overpressure are taken into account for this evaluation. Eleven plots give good demonstration on pipeline capability to survive or fail. According to them, the Pipeline 1 will not survive after the “attack” of huge anchors such as “Y” and “B*”, which are found on the ships, crossing Pipeline 1 KP 0-10 and 145-150 sections.

### *16-inch pipeline analysis*

40-inch gas pipeline response and cross-sectional capacity check are studied above for various sensitivity cases chosen on the basis of the anchor hook and hit criteria check results. It has been observed that a 40-inch line will not survive if it is “attacked” by huge anchors like “Y” and “B*”. Thus, it is interesting to see what the effect of considered dragging anchors on a smaller diameter pipeline is. By applying the same modeling and analysis procedures, a limited set of sensitivity cases is used for the damage assessment of a 16-inch gas pipeline. Relevant pipeline data is given below (Table 33). Other specific pipe parameters remain the same as for the 40-inch line.

Table 33: 16-inch pipeline data for FE analysis

| ***Characteristics*** | ***Unit*** | ***Value*** |
|---|---|---|
| Outer diameter | m | 0.406 |
| Wall thickness | m | 0.016 |
| Submerged weight (empty) | kg/m | 98.29 |
| Submerged weight (operation) | kg/m | 122.81 |

Four different classes of vessel equipment are specified for the investigation: “o”, “z”, “G”, and “B*”. The results are presented in the same way as it has been done with a 40-inch pipeline.

Displacements

Summary graphs illustrating the variation of small diameter pipeline displacements (vertical and lateral) are shown in Figures 88, 89.

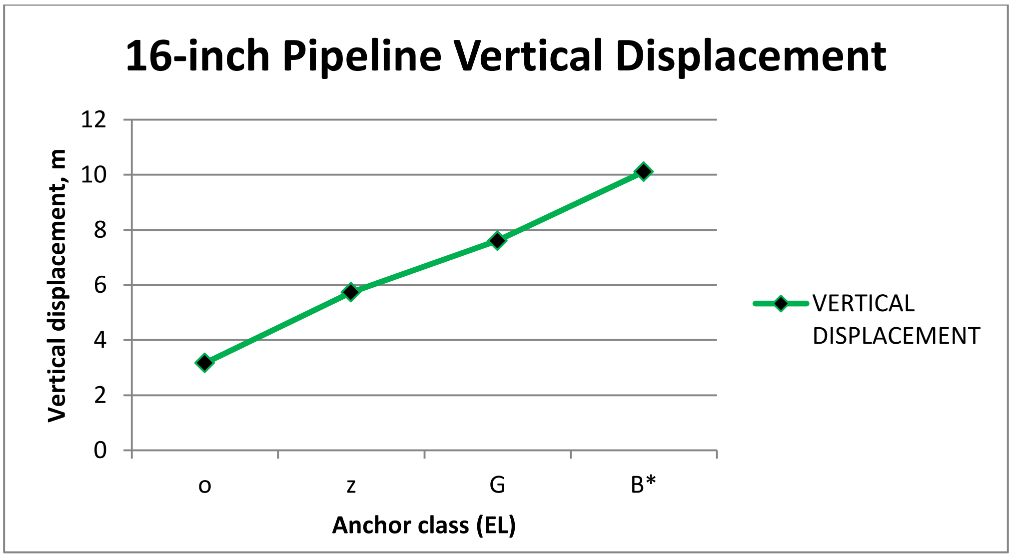



*Figure 88: 16-inch pipeline vertical displacement for specified cases*

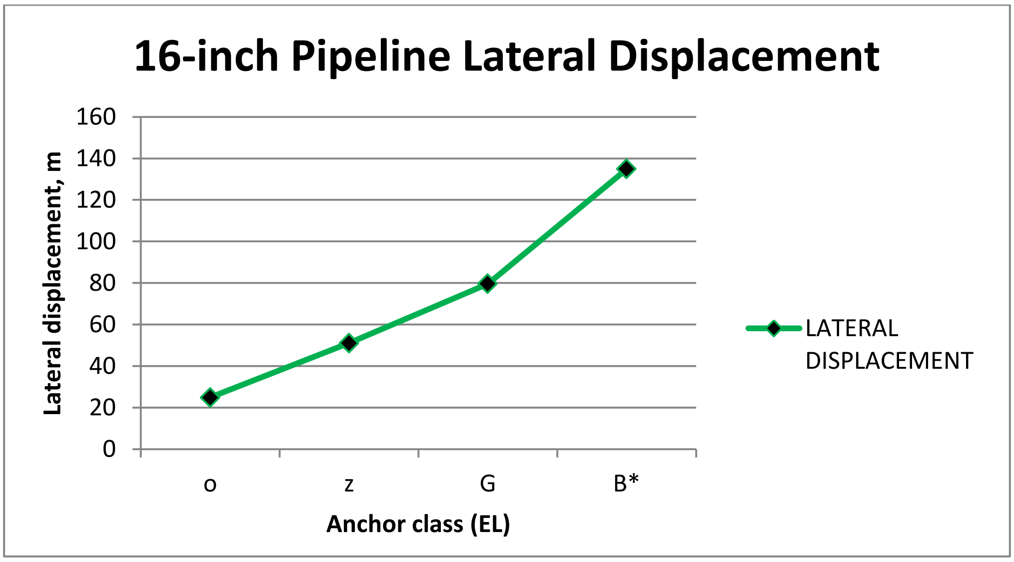



*Figure 89: 16-inch pipeline lateral displacement for specified cases*

It is obvious that the displacements will be greater as the anchor size increases: the maximum values are obtained when the line is dragged by the anchor class "B*". In addition, Table 34 is compiled to demonstrate how different the vertical and lateral displacements of 16-inch and 40-inch pipelines are.

Table 34: Comparison table for vertical and lateral displacements of 40 and 16-inch pipelines

| *Anchor class (EL)* | *40-inch line vertical displacement, m* | *16-inch line vertical displacement, m* | *40-inch line lateral displacement, m* | *16-inch line lateral displacement, m* |
|---|---|---|---|---|
| o | 0.11 | 3.17 | 8.62 | 24.80 |
| z | 1.91 | 5.73 | 20.33 | 51.02 |
| G | 4.13 | 7.60 | 26.55 | 79.59 |
| B* | 7.71 | 10.11 | 61.60 | 134.87 |

It is seen that the lateral displacements of smaller pipeline have increased approximately 2.5 times.

Strain

Strain is taken into account as well. 5% strain is chosen as a limit value. The graph below presents the variation of a 16-inch pipeline strain with 4 different anchor types (Figure 90).

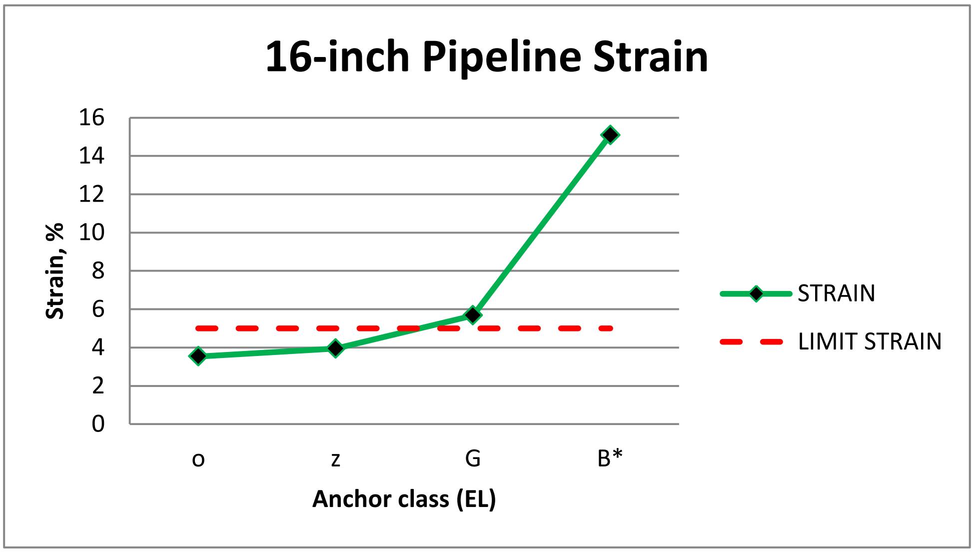



*Figure 90: 16-inch pipeline strain for specified cases*

The graph illustrates that the anchors, classified by the EL starting from “G”, have potential to damage a small diameter pipeline. Strain results for both 16 and 40-inch pipelines are presented in Table 35.

Table 35: Comparison table for strain values of 40 and 16-inch pipelines

| ***Anchor class (EL)*** | ***40-inch line strain, %*** | ***16-inch line strain, %*** |
|---|---|---|
| o | 0.9 | 3.5 |
| z | 2.3 | 3.9 |
| G | 2.9 | 5.7 |
| B* | 8.2 | 15.1 |

16-inch pipe strain values, corresponding to anchor type “G” and “*B”, have almost doubled in contrast with the same values for a 40-inch line.

Bending moment, axial force and internal pressure

Regarding combined loading effect due to bending moment, axial force and internal overpressure; it is observed that the pipeline will probably not survive after being interacted by the anchor class “G” and higher. It is proven by the graphs below (Figures 91-94), where green dashed line corresponds to SMYS; red dashed line refers to SMTS; while blue dashed line is plastic capacity curve relates to 5% limit strain value.

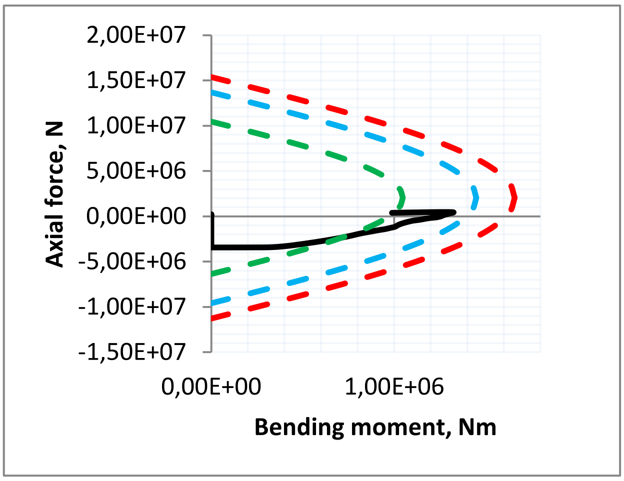



*Figure 91: Capacity check for EL "o"*

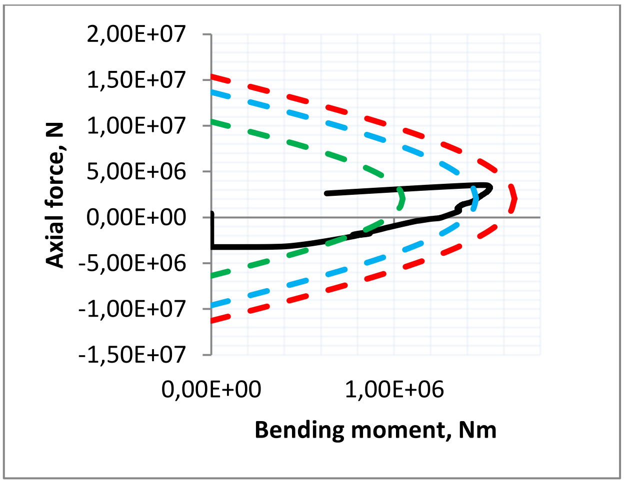



*Figure 93: Capacity check for EL "G"*

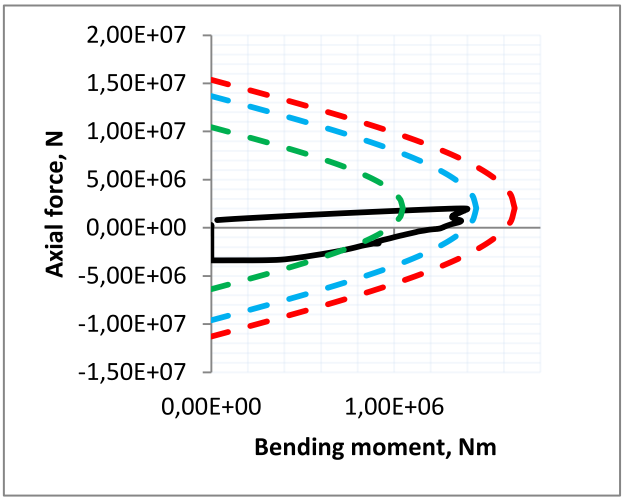



*Figure 92: Capacity check for EL "z"*

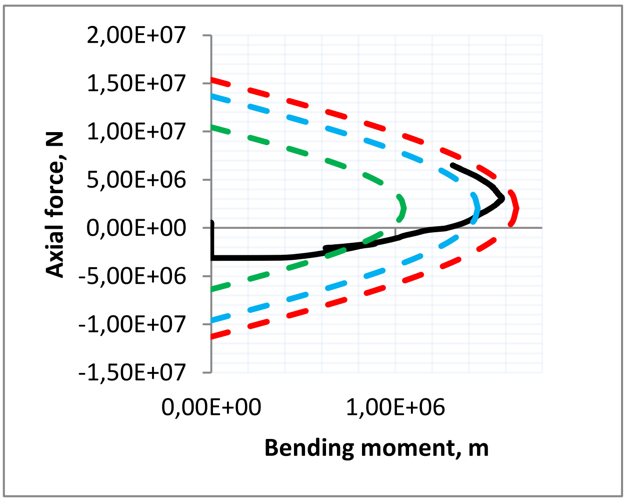



*Figure 94: Capacity check for EL "B*"*

Both predicted strain results and combined loading effect outcomes correspond to each other. Thus, it is safe to say that a 16-inch gas pipeline may suffer serious damage if it is hooked by all the anchors classified by "G" and higher. So, the pipeline KP 0-10, 75-95, 135-140, 145-150 are the most critical sections in terms of pipe-anchor interaction event.

Resultant tables indicate that the smaller diameter pipelines (especially those, which are not protected) are very vulnerable to the damages from dragging anchors. It is understandable, since thin-walled, small diameter lines are known to have negligible cross-sectional capacities in comparison with the larger diameter pipelines.

## 5.8 ANCHOR DRAGGING FREQUENCY

Prior to drawing main conclusion consistent with the results of dragged anchor analysis on a given Pipeline 1, it has been decided to estimate the pipe-anchor interaction frequencies. Frequency estimation is done in accordance with the procedure written in the Energy Report (DNV Recommended Failure Rates for Pipelines, 2010). Since all the information (namely AIS ship traffic data) is given only for the 1st quarter of 2013, the frequencies are calculated for a quarter at first. Then an assumption is taken that the same marine activity is observed for the remaining quarters of the year, and an annual failure frequency is also calculated.

### 5.8.1 Frequency estimation procedure

It is assumed that there are two incidents of anchor loss per 200 ships and year. And the frequency for this event will be equal to $1 \cdot 10^{-2}$ per ship and year, or $2.5 \cdot 10^{-3}$ per ship and quarter. Hence, the estimated frequency of uncontrolled anchor drops per vessel and quarter is as follows:

$$\frac{Accidental\ anhcor\ drops}{quarter} = \frac{Anchor\ loss}{quarter} \cdot Correction\ factor = 0.0025 \cdot 0.46 = 1.15 \cdot 10^{-3}/quarter \tag{64}$$

**NB**. Correction factor (0.46) is used, because not all the anchors are lost due to accidental anchor drop event. In addition, just a few lost anchors relate to the uncontrolled anchor drops (DNV Recommended Failure Rates for Pipelines, 2010).

An estimated frequency of accidental anchor drops per vessel and travelled distance in km is calculated in this manner:

$$\frac{Accidental\ anhcor\ drops}{km} = \frac{Accidental\ anhcor\ drops/quarter}{Travelled\ distance} = \frac{1.15 \cdot 10^{-3}/quarter}{70\% \cdot 2190\frac{h}{quarter} \cdot 15\frac{nmi}{h} \cdot 1.852\frac{km}{nmi}} = 2.7 \cdot 10^{-8}/km \tag{65}$$

Where 70% are accounted for utilization and 15 knots are taken as average vessel speed value.

The pipe-anchor interaction phenomenon may happen due to three different outcomes that are presented in the Table 36. The total frequency for this scenario is equal to the sum of the frequencies for every outcome (DNV Recommended Failure Rates for Pipelines, 2010).

Table 36: The frequency for pipe - anchor interaction scenario for different anchor drop situations

| *#* | *Anchor drop description* | *Frequency for pipe-anchor interaction per ship crossing* |
|---|---|---|
| 1 | Anchor is dropped within 1 km. The penetration depth is not large, so the anchor is easily recovered. | $2.01 \cdot 10^{-8}$ |
| 2 | Anchor is fully seated in the seabed. Maximum penetration and holding power are provided and it can result in chain break. Anchor can be lost. | $1.68 \cdot 10^{-9}$ |
| 3 | Anchor is not seated and dragged for some distance until it hooks the pipeline or structure. Ship anchor drags because the external forces are greater than holding power of the anchor and chain. Anchor is lost. | $1.66 \cdot 10^{-7}$ |

Thus, the sum of the frequencies for every outcome equals to:

$$Frequency\ of\ pipe - anchor\ interaction\ per\ ship\ crossing = 2.01 \cdot 10^{-8} + 1.68 \cdot 10^{-9} + 1.66 \cdot 10^{-7} = 1.9 \cdot 10^{-7} \tag{66}$$

This value is established to be base failure frequency per ship crossing.

Summary table, showing the failure frequency distribution for every KP section of Pipeline 1, is compiled below (Table 37). Frequency estimation procedure is done for the total number of ship crossings, and also for the ship crossings found after each criterion check:

1. Anchor hook criteria check (on the basis of geometrical configuration of vessel equipment);
2. Anchor hit criteria check (in terms of the relation between the water depth value, ship velocity and chain length);
3. Anchor damage criteria check (based on pipeline response analysis and check of cross-sectional capacity).

Furthermore, exactly the same methodology is implemented for the failure frequency estimation for a 16-inch gas pipeline case. Thus, Table 38 is compiled in order to demonstrate the total estimated failure frequency for a 16-inch pipeline.

**NB**. It is assumed that a 16-inch pipeline route is the same as for the Pipeline 1. That is why the traffic data for a 16-inch line is considered to be identical to the ship traffic data of Pipeline 1 (40-inch). Another assumption is that the results of the anchor hook/hit criteria checks remain the same as for the 40-inch pipeline. The latter will indicate how the total failure frequencies for both large and small size pipelines differ from one another.

Table 37: Failure frequency estimation for the 40-inch Pipeline 1 KP sections per 1Q

| | | ***Total ship crossings*** | | ***I criteria hook check*** | | ***II criteria hit check*** | | ***III criteria damage check*** | |
|---|---|---|---|---|---|---|---|---|---|
| ***KP section*** | ***Failure frequency per ship crossing*** | ***Total # of ship crossings*** | ***Failure frequency per KP and 1Q*** | ***# of ship crossings with potential to hook the pipe*** | ***Failure frequency per KP and 1Q*** | ***# of ship crossings with potential to hit the pipe*** | ***Failure frequency per KP and 1Q*** | ***# of ship crossings with potential to damage the pipe*** | ***Failure frequency per KP and 1Q*** |
| 0-10 | 1.9E-07 | 8 | 1.5E-06 | 8 | 1.5E-06 | 7 | 1.3E-06 | 1 | 1.9E-07 |
| 10-15 | 1.9E-07 | 11 | 2.1E-06 | 10 | 1.9E-06 | 0 | - | 0 | - |
| 15-20 | 1.9E-07 | 20 | 3.8E-06 | 18 | 3.4E-06 | 0 | - | 0 | - |
| 20-25 | 1.9E-07 | 20 | 3.8E-06 | 19 | 3.6E-06 | 0 | - | 0 | - |
| 25-30 | 1.9E-07 | 26 | 4.9E-06 | 25 | 4.7E-06 | 0 | - | 0 | - |
| 30-35 | 1.9E-07 | 26 | 4.9E-06 | 26 | 4.9E-06 | 0 | - | 0 | - |
| 35-40 | 1.9E-07 | 48 | 9.0E-06 | 48 | 9.0E-06 | 0 | - | 0 | - |
| 40-45 | 1.9E-07 | 35 | 6.6E-06 | 35 | 6.6E-06 | 0 | - | 0 | - |
| 45-50 | 1.9E-07 | 27 | 5.1E-06 | 25 | 4.7E-06 | 0 | - | 0 | - |
| 50-55 | 1.9E-07 | 16 | 3.0E-06 | 16 | 3.0E-06 | 0 | - | 0 | - |
| 55-60 | 1.9E-07 | 8 | 1.5E-06 | 8 | 1.5E-06 | 0 | - | 0 | - |
| 60-65 | 1.9E-07 | 12 | 2.3E-06 | 11 | 2.1E-06 | 0 | - | 0 | - |
| 65-70 | 1.9E-07 | 14 | 2.6E-06 | 14 | 2.6E-06 | 0 | - | 0 | - |
| 70-75 | 1.9E-07 | 50 | 9.4E-06 | 50 | 9.4E-06 | 0 | - | 0 | - |
| 75-80 | 1.9E-07 | 19 | 3.6E-06 | 19 | 3.6E-06 | 1 | 1.9E-07 | 0 | - |
| 80-85 | 1.9E-07 | 68 | 1.3E-05 | 68 | 1.3E-05 | 1 | 1.9E-07 | 0 | - |
| 85-90 | 1.9E-07 | 114 | 2.1E-05 | 112 | 2.1E-05 | 1 | 1.9E-07 | 0 | - |
| 90-95 | 1.9E-07 | 57 | 1.1E-05 | 54 | 1.0E-05 | 1 | 1.9E-07 | 0 | - |
| 95-100 | 1.9E-07 | 2 | 3.8E-07 | 2 | 3.8E-07 | 0 | - | 0 | - |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 100-105 | 1.9E-07 | 9 | 1.7E-06 | 9 | 1.7E-06 | 0 | - | 0 | - |
| 105-110 | 1.9E-07 | 4 | 7.5E-07 | 4 | 7.5E-07 | 0 | - | 0 | - |
| 110-115 | 1.9E-07 | 2 | 3.8E-07 | 2 | 3.8E-07 | 0 | - | 0 | - |
| 115-120 | 1.9E-07 | 2 | 3.8E-07 | 2 | 3.8E-07 | 0 | - | 0 | - |
| 120-125 | 1.9E-07 | 3 | 5.6E-07 | 3 | 5.6E-07 | 0 | - | 0 | - |
| 125-130 | 1.9E-07 | 1 | 1.9E-07 | 1 | 1.9E-07 | 0 | - | 0 | - |
| 130-135 | 1.9E-07 | 5 | 9.4E-07 | 4 | 7.5E-07 | 0 | - | 0 | - |
| 135-140 | 1.9E-07 | 6 | 1.1E-06 | 5 | 9.4E-07 | 1 | 1.9E-07 | 0 | - |
| 140-145 | 1.9E-07 | 3 | 5.6E-07 | 3 | 5.6E-07 | 0 | - | 0 | - |
| 145-150 | 1.9E-07 | 2 | 3.8E-07 | 2 | 3.8E-07 | 1 | 1.9E-07 | 1 | 1.9E-07 |
| 150-155 | 1.9E-07 | 2 | 3.8E-07 | 2 | 3.8E-07 | 0 | - | 0 | - |
| 165-170 | 1.9E-07 | 1 | 1.9E-07 | 1 | 1.9E-07 | 0 | - | 0 | - |
| 170-175 | 1.9E-07 | 6 | 1.1E-06 | 6 | 1.1E-06 | 2 | 3.8E-07 | 0 | - |
| 175-180 | 1.9E-07 | 2 | 3.8E-07 | 1 | 1.9E-07 | 0 | - | 0 | - |
| 180-185 | 1.9E-07 | 5 | 9.4E-07 | 5 | 9.4E-07 | 1 | 1.9E-07 | 0 | - |
| 185-190 | 1.9E-07 | 13 | 2.4E-06 | 11 | 2.1E-06 | 7 | 1.3E-06 | 0 | - |
| 190-195 | 1.9E-07 | 11 | 2.1E-06 | 10 | 1.9E-06 | 7 | 1.3E-06 | 0 | - |
| 195-200 | 1.9E-07 | 11 | 2.1E-06 | 10 | 1.9E-06 | 6 | 1.1E-06 | 0 | - |
| 200-205 | 1.9E-07 | 9 | 1.7E-06 | 9 | 1.7E-06 | 4 | 7.5E-07 | 0 | - |
| 205-210 | 1.9E-07 | 7 | 1.3E-06 | 5 | 9.4E-07 | 2 | 3.8E-07 | 0 | - |
| 210-215 | 1.9E-07 | 6 | 1.1E-06 | 5 | 9.4E-07 | 2 | 3.8E-07 | 0 | - |
| 215-220 | 1.9E-07 | 7 | 1.3E-06 | 6 | 1.1E-06 | 0 | - | 0 | - |
| 220-225 | 1.9E-07 | 4 | 7.5E-07 | 4 | 7.5E-07 | 0 | - | 0 | - |
| 225-230 | 1.9E-07 | 10 | 1.9E-06 | 9 | 1.7E-06 | 4 | 7.5E-07 | 0 | - |
| 230-235 | 1.9E-07 | 8 | 1.5E-06 | 8 | 1.5E-06 | 6 | 1.1E-06 | 0 | - |
| 235-240 | 1.9E-07 | 4 | 7.5E-07 | 4 | 7.5E-07 | 1 | 1.9E-07 | 0 | - |
| 240-245 | 1.9E-07 | 10 | 1.9E-06 | 10 | 1.9E-06 | 3 | 5.6E-07 | 0 | - |
| 245-250 | 1.9E-07 | 15 | 2.8E-06 | 14 | 2.6E-06 | 6 | 1.1E-06 | 0 | - |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 250-255 | 1.9E-07 | 4 | 7.5E-07 | 3 | 5.6E-07 | 2 | 3.8E-07 | 0 | - |
| 255-260 | 1.9E-07 | 2 | 3.8E-07 | 2 | 3.8E-07 | 0 | - | 0 | - |
| 260-265 | 1.9E-07 | 3 | 5.6E-07 | 2 | 3.8E-07 | 1 | 1.9E-07 | 0 | - |
| 265-270 | 1.9E-07 | 4 | 7.5E-07 | 3 | 5.6E-07 | 2 | 3.8E-07 | 0 | - |
| 270-275 | 1.9E-07 | 4 | 7.5E-07 | 4 | 7.5E-07 | 3 | 5.6E-07 | 0 | - |
| 275-280 | 1.9E-07 | 9 | 1.7E-06 | 7 | 1.3E-06 | 5 | 9.4E-07 | 0 | - |
| 280-285 | 1.9E-07 | 23 | 4.3E-06 | 20 | 3.8E-06 | 14 | 2.6E-06 | 0 | - |
| 285-290 | 1.9E-07 | 2 | 3.8E-07 | 2 | 3.8E-07 | 1 | 1.9E-07 | 0 | - |
| 290-295 | 1.9E-07 | 2 | 3.8E-07 | 2 | 3.8E-07 | 1 | 1.9E-07 | 0 | - |
| | **Total** | 802 | **1.5E-04** | 768 | **1.4E-04** | 93 | **1.7E-05** | 2 | **3.8E-07** |

Table 38: Failure frequency estimation for the 16-inch gas pipeline KP sections per 1Q

| ***KP section*** | ***Failure frequency per ship crossing*** | ***Total ship crossings*** | | ***I criteria hook check*** | | ***II criteria hit check*** | | ***III criteria damage check*** | |
|---|---|---|---|---|---|---|---|---|---|
| | | ***Total # of ship crossings*** | ***Failure frequency per KP and 1Q*** | ***# of ship crossings with potential to hook the pipe*** | ***Failure frequency per KP and 1Q*** | ***# of ship crossings with potential to hit the pipe*** | ***Failure frequency per KP and 1Q*** | ***# of ship crossings with potential to damage the pipe*** | ***Failure frequency per KP and 1Q*** |
| 0-10 | 1.9E-07 | 8 | 1.5E-06 | 8 | 1.5E-06 | 7 | 1.3E-06 | 7 | 1.3E-06 |
| 10-15 | 1.9E-07 | 11 | 2.1E-06 | 10 | 1.9E-06 | 0 | - | 0 | - |
| 15-20 | 1.9E-07 | 20 | 3.8E-06 | 18 | 3.4E-06 | 0 | - | 0 | - |
| 20-25 | 1.9E-07 | 20 | 3.8E-06 | 19 | 3.6E-06 | 0 | - | 0 | - |
| 25-30 | 1.9E-07 | 26 | 4.9E-06 | 25 | 4.7E-06 | 0 | - | 0 | - |
| 30-35 | 1.9E-07 | 26 | 4.9E-06 | 26 | 4.9E-06 | 0 | - | 0 | - |
| 35-40 | 1.9E-07 | 48 | 9.0E-06 | 48 | 9.0E-06 | 0 | - | 0 | - |
| 40-45 | 1.9E-07 | 35 | 6.6E-06 | 35 | 6.6E-06 | 0 | - | 0 | - |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 45-50 | 1.9E-07 | 27 | 5.1E-06 | 25 | 4.7E-06 | 0 | - | 0 | - |
| 50-55 | 1.9E-07 | 16 | 3.0E-06 | 16 | 3.0E-06 | 0 | - | 0 | - |
| 55-60 | 1.9E-07 | 8 | 1.5E-06 | 8 | 1.5E-06 | 0 | - | 0 | - |
| 60-65 | 1.9E-07 | 12 | 2.3E-06 | 11 | 2.1E-06 | 0 | - | 0 | - |
| 65-70 | 1.9E-07 | 14 | 2.6E-06 | 14 | 2.6E-06 | 0 | - | 0 | - |
| 70-75 | 1.9E-07 | 50 | 9.4E-06 | 50 | 9.4E-06 | 0 | - | 0 | - |
| 75-80 | 1.9E-07 | 19 | 3.6E-06 | 19 | 3.6E-06 | 1 | 1.9E-07 | 1 | 1.9E-07 |
| 80-85 | 1.9E-07 | 68 | 1.3E-05 | 68 | 1.3E-05 | 1 | 1.9E-07 | 1 | 1.9E-07 |
| 85-90 | 1.9E-07 | 114 | 2.1E-05 | 112 | 2.1E-05 | 1 | 1.9E-07 | 1 | 1.9E-07 |
| 90-95 | 1.9E-07 | 57 | 1.1E-05 | 54 | 1.0E-05 | 1 | 1.9E-07 | 1 | 1.9E-07 |
| 95-100 | 1.9E-07 | 2 | 3.8E-07 | 2 | 3.8E-07 | 0 | - | 0 | - |
| 100-105 | 1.9E-07 | 9 | 1.7E-06 | 9 | 1.7E-06 | 0 | - | 0 | - |
| 105-110 | 1.9E-07 | 4 | 7.5E-07 | 4 | 7.5E-07 | 0 | - | 0 | - |
| 110-115 | 1.9E-07 | 2 | 3.8E-07 | 2 | 3.8E-07 | 0 | - | 0 | - |
| 115-120 | 1.9E-07 | 2 | 3.8E-07 | 2 | 3.8E-07 | 0 | - | 0 | - |
| 120-125 | 1.9E-07 | 3 | 5.6E-07 | 3 | 5.6E-07 | 0 | - | 0 | - |
| 125-130 | 1.9E-07 | 1 | 1.9E-07 | 1 | 1.9E-07 | 0 | - | 0 | - |
| 130-135 | 1.9E-07 | 5 | 9.4E-07 | 4 | 7.5E-07 | 0 | - | 0 | - |
| 135-140 | 1.9E-07 | 6 | 1.1E-06 | 5 | 9.4E-07 | 1 | 1.9E-07 | 1 | 1.9E-07 |
| 140-145 | 1.9E-07 | 3 | 5.6E-07 | 3 | 5.6E-07 | 0 | - | 0 | - |
| 145-150 | 1.9E-07 | 2 | 3.8E-07 | 2 | 3.8E-07 | 1 | 1.9E-07 | 1 | 1.9E-07 |
| 150-155 | 1.9E-07 | 2 | 3.8E-07 | 2 | 3.8E-07 | 0 | - | 0 | - |
| 165-170 | 1.9E-07 | 1 | 1.9E-07 | 1 | 1.9E-07 | 0 | - | 0 | - |
| 170-175 | 1.9E-07 | 6 | 1.1E-06 | 6 | 1.1E-06 | 2 | 3.8E-07 | 0 | - |
| 175-180 | 1.9E-07 | 2 | 3.8E-07 | 1 | 1.9E-07 | 0 | - | 0 | - |
| 180-185 | 1.9E-07 | 5 | 9.4E-07 | 5 | 9.4E-07 | 1 | 1.9E-07 | 0 | - |
| 185-190 | 1.9E-07 | 13 | 2.4E-06 | 11 | 2.1E-06 | 7 | 1.3E-06 | 0 | - |
| 190-195 | 1.9E-07 | 11 | 2.1E-06 | 10 | 1.9E-06 | 7 | 1.3E-06 | 0 | - |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 195-200 | 1.9E-07 | 11 | 2.1E-06 | 10 | 1.9E-06 | 6 | 1.1E-06 | 0 | - |
| 200-205 | 1.9E-07 | 9 | 1.7E-06 | 9 | 1.7E-06 | 4 | 7.5E-07 | 0 | - |
| 205-210 | 1.9E-07 | 7 | 1.3E-06 | 5 | 9.4E-07 | 2 | 3.8E-07 | 0 | - |
| 210-215 | 1.9E-07 | 6 | 1.1E-06 | 5 | 9.4E-07 | 2 | 3.8E-07 | 0 | - |
| 215-220 | 1.9E-07 | 7 | 1.3E-06 | 6 | 1.1E-06 | 0 | - | 0 | - |
| 220-225 | 1.9E-07 | 4 | 7.5E-07 | 4 | 7.5E-07 | 0 | - | 0 | - |
| 225-230 | 1.9E-07 | 10 | 1.9E-06 | 9 | 1.7E-06 | 4 | 7.5E-07 | 0 | - |
| 230-235 | 1.9E-07 | 8 | 1.5E-06 | 8 | 1.5E-06 | 6 | 1.1E-06 | 0 | - |
| 235-240 | 1.9E-07 | 4 | 7.5E-07 | 4 | 7.5E-07 | 1 | 1.9E-07 | 0 | - |
| 240-245 | 1.9E-07 | 10 | 1.9E-06 | 10 | 1.9E-06 | 3 | 5.6E-07 | 0 | - |
| 245-250 | 1.9E-07 | 15 | 2.8E-06 | 14 | 2.6E-06 | 6 | 1.1E-06 | 0 | - |
| 250-255 | 1.9E-07 | 4 | 7.5E-07 | 3 | 5.6E-07 | 2 | 3.8E-07 | 0 | - |
| 255-260 | 1.9E-07 | 2 | 3.8E-07 | 2 | 3.8E-07 | 0 | - | 0 | - |
| 260-265 | 1.9E-07 | 3 | 5.6E-07 | 2 | 3.8E-07 | 1 | 1.9E-07 | 0 | - |
| 265-270 | 1.9E-07 | 4 | 7.5E-07 | 3 | 5.6E-07 | 2 | 3.8E-07 | 0 | - |
| 270-275 | 1.9E-07 | 4 | 7.5E-07 | 4 | 7.5E-07 | 3 | 5.6E-07 | 0 | - |
| 275-280 | 1.9E-07 | 9 | 1.7E-06 | 7 | 1.3E-06 | 5 | 9.4E-07 | 0 | - |
| 280-285 | 1.9E-07 | 23 | 4.3E-06 | 20 | 3.8E-06 | 14 | 2.6E-06 | 0 | - |
| 285-290 | 1.9E-07 | 2 | 3.8E-07 | 2 | 3.8E-07 | 1 | 1.9E-07 | 0 | - |
| 290-295 | 1.9E-07 | 2 | 3.8E-07 | 2 | 3.8E-07 | 1 | 1.9E-07 | 0 | - |
| | **Total** | 802 | **1.5E-04** | 768 | **1.4E-04** | 93 | **1.7E-05** | 13 | **2.44E-06** |

To sum up the results of the frequency analysis in the 1st quarter of 2013 for 40-inch gas line, a total of 802 passing ships are taken for the analysis. After the 1st criteria check, this number is reduced to 768, after the 2nd check it is dropped to 93, and after the 3rd criteria check the number of dangerous ship crossings is decreased to 2. The failure frequencies are calculated for every pipe KP section after every criterion check. Resultant damage frequency of the 40-inch Pipeline 1 for the 1st quarter of 2013 is equal to $3.8 \cdot 10^{-7}$; and an annual failure frequency is $1.5 \cdot 10^{-6}$ (assuming that the ship traffic volume has been the same in the remaining quarters of the year). In accordance with the DNV-OS-F101, the nominal target failure frequency is of magnitude $10^{-4}$ per pipeline and year. Thus, one can see that the total estimated frequency is less than the acceptance criterion for pipeline damage. Concerning a 16-inch gas pipeline, after the 3rd criteria check the number of critical crosses has decreased up to 13. So, the resultant damage frequency of smaller diameter pipeline is equal to $2.44 \cdot 10^{-6}$ per quarter, and an annual one is $9.76 \cdot 10^{-6}$, which is also less than acceptance value. The comparison of obtained frequencies for both pipelines is shown below:

$$1.5 \cdot 10^{-6} < 9.76 \cdot 10^{-6} \tag{67}$$

Consequently, the smaller the pipeline, the greater the potential for damage from dragging anchor will be.

## 5.9 ANCHOR DAMAGE ASSESSMENT METHODOLOGY

The anchor dragging interference assessment methodology is presented below (Table 40).

Table 40: Anchor damage assessment methodology

| | | |
|---|---|---|
| ***Data Processing*** | ***Pipeline Data and Characteristics*** | • General pipeline data;<br>• Operational characteristics;<br>• Material properties (steel, concrete);<br>• Seabed characteristics along the route;<br>• Seabed depth profile along the route;<br>• Segmentation of the route. |
| | ***Ship Traffic Data*** | • Total number of ship crossings;<br>• Identification number (IMO-no and/or MMSI-no);<br>• Types and/or classes of ships;<br>• Gross Tonnage index;<br>• Equipment Number and/or Equipment Letter;<br>• Vessel speed;<br>• Vessel direction;<br>• Latitude and longitude coordinates. |
| ***Screening Analyses*** | ***Anchor Hook Criteria Check*** | On the basis of anchor geometrical configuration. Two scenarios are to be analyzed:<br>• The pipeline is stuck between one fluke and anchor shank;<br>• The pipeline is stuck between the plane of both flukes and anchor shank. |

| | | |
|---|---|---|
| | | **NB**. The minimum anchor size value and corresponding equipment class should be determined from both scenarios. Lower class anchors are to be excluded from the analyses. |
| | ***Anchor Hit Criteria Check*** | On the basis of the vessel speed, water depth, and anchor class (anchor size and chain length). It allows checking if the anchor is capable of approaching the pipeline or not. The following parameters are to be found:<br>• Anchor pulling angle;<br>• Anchor towing depth.<br>**NB**. The minimum chain length value and corresponding equipment class should be determined. Lower class anchors are to be excluded from the further analyses. |
| ***Global Scale Analyses*** | ***Anchor Damage Criteria Check*** | On the basis of several sensitivity cases selected from the outcomes from anchor hook & hit criteria checks. The following is to be assessed then:<br>• Pipeline vertical and lateral displacements;<br>• Pipeline strain;<br>• Pipeline cross sectional capacity check for the case of combined loading effect (e.g. axial force, bending moment, and internal overpressure).<br>**NB**. The anchor damage assessment of the pipeline can be performed by employing the FE program SIMLA. |
| ***Frequency Estimation*** | | • Frequency estimation in accordance with the base failure frequency per ship crossing ($1.9 \cdot 10^{-7}$);<br>• Comparison of total estimated frequency for damage with the nominal annual target failure frequency for ALS ($10^{-4}$ per pipeline). |
| ***General Conclusions*** | | Which pipeline sizes (as a function of water depth, vessel size, speed etc.) will typically:<br>• Withstand anchor impact;<br>• Will be damaged. |

# CHAPTER 6. DISCUSSION, CONCLUSION AND RECOMMENDATIONS

## 6.1 DISCUSSION ON STUDY AND ANALYSES RESULTS

Prior to drawing a conclusion from the performed analyses and estimations, a complete discussion based on the results and findings from the previous chapters is presented hereinafter.

PARLOC 2001 database

A comprehensive study on pipeline failure database PARLOC 2001 is prepared in this work. The emphasis has been placed on the identification and subsequent evaluation of pipeline incidents. Database boundaries, its population and incidents occurrence are defined and highlighted. The main pipeline failures, their causes, locations and consequences have been found and analyzed. The analyses show that the most frequently observed incidents involving both rigid and flexible lines are corrosion, material defect, impact and anchoring. It has been detected that each of these hazards can cause a lot of pipeline damages, ruptures and leakages. That is why complete definition and detailed evaluation of them is presented in this paper. Corresponding graphs, diagrams and charts are prepared with the purpose of illustrating which pipeline size is the most vulnerable to damage. In addition, the location of incidents is graphically presented as well. Both spontaneous and external hazards mostly occur in the pipeline Mid Line (a lot of threats from high marine and fishing activities) and Safety Zone (a lot of threats from the dropped objects during installation works). Concerning the pipeline size, it has been found that smaller diameter lines (2.4-16 inches) are susceptible to damage a lot more since their capacity is almost negligible in comparison with the capacity of larger lines. Identified pipeline size and zones can be used for the selection of safeguard measures and pipeline protection philosophy, which significantly reduces the extent of damage or eliminates it at all. Hence, it is important to record all the threats observed throughout the whole life of the pipeline system. Collection of pipeline failures information provides an excellent opportunity to learn from every single experience and to exclude the failures in the future.

Theoretical approach

In accordance with the database study, one of the major threats to the pipeline integrity is incorrect ship anchoring. Not only the pipelines but also the submarine cables are susceptible to damage from lost and dragged anchors. All the significance of anchor damage incidents is presented in two tables (Tables 7 and 8) containing information of worldwide offshore pipelines and submarine cables failures due to anchoring hazard. Suddenly dropped and dragged anchors are supposed to be one of the main causes of pipeline and cable damages in XX and XXI centuries. The total number of incidents for pipeline and cables are demonstrated in Figures 17, 18. It is seen that the number of pipeline damages has decreased. On the other hand, the number of cable failures has increased. The latter may be explained by the widespread use of fiber-optical lines from the end of the last century to the present day. Therefore, even though there are a lot of technological developments and achievements in the sphere of marine activity control and monitoring, the incidents still occur from time to time.

A theoretical approach of ship anchoring effect on submarine pipelines is given in the present work. A comprehensive discussion on vessel anchoring procedure, its variation from case to case and explanation of different uncontrolled anchor drop outcomes are reviewed and studied as well. Along with that, the importance of main key factors such as pipe unique properties, vessel characteristics and anchor parameters is emphasized for the assessments. A combination of these factors is found to be governing for the set of relevant pipeline damage criteria, which is also discussed in this paper.

Data analyses

Dragged anchor interference assessment has been performed in order to identify potential for anchor induced damage of the 40-inch gas pipeline (Pipeline 1). Focus is placed for the entire pipeline length, including all the pipe KP sections for the analysis. Ship traffic data collection and compilation has been done by screening procedure in accordance with the steps given in the flowchart in Figure 37. Marine traffic data has been processed to develop various diagrams and distribution charts for a considered pipeline route on the basis of collected information. From the pie diagram (Figure 39) it is observed that the most commonly encountered ship class is Class 2, which accounts for 49% of total vessel crossings over the pipeline route. Regarding other ship classes, they are distributed almost uniformly, excepting the ship Class 7 that accounts only for 1% of total crossings. Anchoring equipment specification is also included for the data analysis. It is found that the equipment class (EL) "*o*" is the most common one. Furthermore, the distribution of total number of ships passing the pipe route has been included into the analyses as well. The investigation shows that the greatest marine activity (with the majority of ship Class 2) falls between the pipeline KP 0-60 and 65-95 sections, which are situated at the deepest sea area. That is why it has been decided to continue with a detailed analyses in order to draw precise conclusion whether the anchors of passing ships are capable of hooking the Pipeline 1 or not.

Anchor hook check

Three main criteria are chosen for the check. The 1$^{st}$ criterion corresponds to the geometrical configuration of the Spek stockless anchors. It is understandable that small dimension equipment is not capable of catching large diameter pipeline. The anchor hook check has been performed for two cases: when the pipeline is thought to be caught between one fluke and anchor shank (I case); or between the plane of two flukes and anchor shank (II case). It has been found that the most conservative results are obtained when the pipeline is supposed to stick between the plane of flukes and the shank. According to the outcome from the 2$^{nd}$ case check; all the anchors specified by the EL starting from "*j*" can pose threat to the Pipeline 1.

Anchor hit check

The 2$^{nd}$ criterion check is performed in terms of the relation between the ship speed, equipment class, and water depth. Following the theoretical justification presented in the corresponding part, it is proven that the anchor will never be hanging vertically after its stabilization at a certain depth. What is governing here is that there are always the hydrodynamic drag forces acting on the anchor-chain arrangement in the direction opposite to the movement of the vessel. Moreover, the drag forces are proportional to the velocity squared. Hence, it follows that the anchor stabilization point is greatly affected by the value of ship velocity. The size of anchoring equipment is also leading here: heavy anchor, hanging on long chain, will stabilize at greater depth than small dimension equipment. That is why a lot of attention should be paid to huge anchoring systems, which are generally specified by the Equipment Letters from A* to O*. In accordance with the results obtained from the analytical solution of the anchor hit criterion check, the anchors characterized by the ELs from "*l*" and higher are dangerous for the pipeline, since all of them are capable of approaching the seabed and catching the line while the ship is underway.

Model scale test

Not only the analytical approach, but also a model scale test has been applied for the identification of anchor towing depth. The test mainly focuses on the determination of anchor towing depth variations with different values of towing velocity. Every item has been scaled down; and the experimental site has been prepared for the test. Obtained results give strong notions on how the velocity affects the stabilization point of hanging anchor. The higher the speed, the larger the components of hydrodynamic forces will be, and the anchor will stabilize at less towing depth. The verification of test and analytical solution results has been done as well. The calculated absolute error in the x-direction falls in a range of 0.003-0.05 m. The errors find their place because the tests are not taken in a perfect way. For instance, the quality of most video shots is not so high, so it has become difficult to distinguish exact position of the anchor-chain arrangement in the water tank. Moreover, the velocity measurements are also not ideal, since just usual manual timer has been used for the time record of each test run.

Pipeline response and cross-sectional capacity check

After the anchor hook and hit criteria checks, the present assessment has been continued with the global analysis performed in the FE program SIMLA. Eleven sensitivity cases are chosen for the assessment. It has been decided not to generalize but to take all the parameters individually for every case. The emphasis is placed on the structural response and capacity check in terms of the axial force, bending moment and internal overpressure. An attention is given to the pipeline displacement results. What is important to notice is that the values of both vertical and lateral displacements are observed to be affected by the anchor pulling angle, greatly dependent on the value of ship velocity. Thus, the higher the ship speed, the less the pipeline displacements will be. Huge vertical and lateral displacements are found in case of "Y" and "B*" anchor classes (Figures 71, 72). Pipeline strain is also a point of interest; and 5% strain is chosen as a limit. From the graph (Figure 73) it is seen that if huge anchors such as "Y" and "B*" hook Pipeline 1, the strain values will exceed the limit, and the pipeline will not survive. The same results are obtained from the cross-sectional pipeline capacity check. Combined loading effect is included into the assessment. It should be noted that there are two dominant terms characterizing pipeline force-displacement response. The first term is bending, which is not dependent on pipeline displacements. Another one is membrane term, which increases linearly with the displacements of the pipe. In case of anchor hooking/dragging scenario, the pipeline membrane forces increase until the value of applied force reaches the value of chain breaking load. By applying plastic interaction curve accounted for 5% limit strain it is visible, that in 2 out of 11 sensitivity cases the Pipeline 1 will not survive. These cases refer to "Y" and "B*" anchor ELs. Thus, pipeline KP 0-10 and 135-140 sections have potential to be damaged by dragging anchor.

Not only the 40-inch gas pipeline but a smaller diameter line has been chosen for the investigation of pipeline response and capacity check. By using the same methodology, implemented for the modeling and analysis procedures, a pipe-anchor interaction scenario assessment has been performed for a considered 16-inch gas pipeline. 5% strain value is taken as limit as well. Based on the results from the predicted strains and outcomes from the pipeline cross-sectional capacity check, it is found that the pipeline may fail after the interaction with large anchors classified by the ELs “G” and higher. It is because thin-walled and small diameter lines have almost negligible cross-sectional capacities in comparison with the larger lines. Thus, 16-inch pipeline KP 0-10, 75-95, 135-140 and 145-150 are the most critical zones that can be interacted and damaged by the equipment of crossing vessels.

Thus, only huge anchors (classified by the Capital Letters marked with star) are capable of damaging the large diameter pipeline. Regarding a small size line, it can lose its integrity even if small dimension anchors are snagged over it.

Anchor dragging induced frequency

By using AIS ship traffic data given for the 1$^{st}$ quarter (1Q) of 2013 a pipe-anchor interaction frequency is estimated in accordance with the methodology presented in the Energy Report. The assessment results point out that the pipeline KP 0-10 and 135-140 can be damaged by the anchoring equipment of crossing ships. Focus has been placed on these sections. The frequency of pipeline failure due to dragging anchor interference is calculated based on the number of ship crossings per KP and 1Q, obtained from the anchor hook/hit/damage criteria checks. This number has been multiplied by a base failure frequency taken as $1.9 \cdot 10^{-7}$ per ship crossing. It has been found that there are only two anchors classified as “Y” and “B*”, which have potential to hook and damage the Pipeline 1. Thus, calculated annual pipeline failure frequency is equal to $1.5 \cdot 10^{-6}$. It is less than the nominal target frequency accounted for $10^{-4}$ per pipeline (DNV-OS-F101, 2013), so anchor dragging is not critical for the 40-inch Pipeline 1 for given level of ship traffic.

Regarding the 16-inch line case, it has been found that an annual failure frequency is equal to $9.76 \cdot 10^{-6}$. Since it is less than a target failure probability, small size pipeline is thought to survive.

Since the pipeline capacity checks has revealed several sections that can be damaged by passing ship anchors, potential risk reducing measures may be implemented then.

## 6.2 ASSUMPTIONS

Some assumptions have been taken during the dragged anchor interference analysis.

- The pipelines sections are supposed to be exposed in the present case study.
- All the anchors are assumed to be broken out of the seafloor prior to approaching and catching exposed lines. For that reason, an anchor penetration depth check has not been included into the analyses. However, this check can be significant for the damage assessment of trenched and/or covered lines.
- Another assumption is that every moving ship is equipped with the Spek stockless anchor and stud-link chain, the information on which is easily found in the Rules for Ship (2011) document and relevant catalogues.

- Average velocity has been taken for every ship equipped with a certain class of anchor equipment (distinguished by Equipment Letters). Thus, every EL is characterized by the corresponding value of average ship speed.
- It has been assumed that all the vessels passing the pipelines routes are moving with the constant velocity; and the flow forcing the anchoring system in the opposite direction is steady. Hence, the acceleration term is excluded; so that the anchor and chain inertia and added mass terms are not considered for the present case study. Moreover, the drag force of the anchor is assumed to be negligible in contrast to its weight.
- To be more conservative an interaction between the pipelines and corresponding dragging anchors is chosen to be perpendicular. In reality the angle between the ship's course and pipeline may be less than 90 degrees, or even equal to 0; so that the probability of pipeline damage will be less for those cases.
- For the assessment of a 16-inch pipeline, it has been assumed that its route is the same as the route of a 40-inch line. That is why the traffic data for a 16-inch pipe is believed to be identical to the ship traffic data of Pipeline 1 (40-inch). Another assumption is that the results of the anchor hook & hit criteria checks for a small size pipe are taken the same as obtained results from a large line assessment. The latter indicates how the total failure frequencies for both large and small size pipelines differ from one another depending only on the outcomes of pipelines capacity checks.
- A set of relevant assumptions for the frequency assessment procedure is taken as written in the DNV Recommended Failure Rates for Pipelines (2010) report.

Regarding the model scale test, one shall understand that its results are not 100% perfect due to some limitations encountered during the experiment. The water tank is not designed for carrying out such kind of operation, because it usually serves for concrete material tests only. That is why the experiment site preparation took a lot of time and efforts. Not only special but alternate equipment and tools were used for that purpose. Furthermore, it was quite problematic to measure the distance travelled by the anchor after its stabilization, and to record the travel time corresponding to each test run. Processing of the experimental results became very complex as well, since the identification of anchor position was limited sometimes by poor visibility inside of the tank and insufficient lighting.

## 6.3 CONCLUSION

In accordance with the anchor pulling consequences and failure frequency analyses, it can be concluded that the dragging anchor interference is not critical for a 40-inch Pipeline 1 and 16-inch line for a considered lever of marine activity (802 ships) per 3 months.

Firstly, the results of the anchor hook criteria check show that not all the anchors are capable of hooking the pipeline. The governing parameters here are pipeline diameter and anchor dimensions. It has been found that anchor classes, lower than "*g*", are not large enough to hook the Pipeline 1.

Secondly, the anchor towing depth has to be such a value as to be able to reach the sea bottom. What is important to know is that the combination of water depth, anchor size, chain length and ship transit speed dictates the value of predicted depth. The higher the vessel speed, the less the anchor towing depth will be. For the Pipeline 1 the vessels' equipment classes, lower than "*l*" have been excluded from the studies after the anchor hit criteria check.

After two criteria checks, a total number of ships capable of both hooking and approaching the Pipeline 1 have reduced from 802 to 93. Based on the information of these vessels, the anchor damage criteria have been performed. Global scale analyses results have indicated that only huge size anchors ("Y" and "B*") have potential to cause Pipeline 1 failure. The ships with such equipment type cross Pipeline 1 KP 0-10 (175 m depth) and KP 145-150 (233 m depth). An average speed of the vessels is 5.9 m/s. An attention is given to vertical and lateral pipeline displacements, strain and cross-sectional capacity due to combined loading effect (axial force, bending moment and internal overpressure). It is observed that vessel transit speed also affects the value of pipeline displacements: the higher the speed, the less the anchor pulling angle and pipeline displacements will be.

The emphasis is placed not only on a 40-inch line, but also on a 16-inch pipeline. Assuming that small pipeline route runs along the same path, the same volume of ship traffic as for the 40-inch line has been chosen for the analyses. Several sensitivity cases of crossings out of total number of threatening crossings (93) have been taken for the global scale analyses of a 16-inch pipe. The results have shown that all the anchor classes higher than "G" may pose threat to the line. It can be noted that thin-walled and smaller diameter pipelines are more vulnerable to damage from dragging anchors, because their capacity is almost negligible compared to the capacity of large size pipelines.

According to the results of pipeline response and capacity check, a failure frequency for each pipeline for the 1$^{st}$ quarter of 2013 has been estimated. Assuming the same ship traffic for the rest of the year, the total annual damage frequency for large and small diameter pipelines are $1.5 \cdot 10^{-6}$ and $9.76 \cdot 10^{-6}$ correspondingly. These values are less than the nominal annual target failure probability ($10^{-4}$ per pipeline). Thus, it is concluded that the anchor dragging event is not critical for both lines for a given level of ship traffic.

## 6.4 RECOMMENDATIONS

It would be wrong to state that the pipe-anchor interaction assessment is perfectly performed. There are still some recommendations for the future studies and assessments:

1. To specify more sensitivity cases with respect to pipeline diameter, wall thickness, internal overpressure effect, water depth values.
2. To perform not only a global scale, but also a local scale analyses in order to understand the potential for local buckling and denting, and/or fractures.
3. To give detailed study on risk reducing measures.
4. To take into account other damage criteria, e.g. anchor penetration depth.

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## APPENDIX A

Table A.1: Total number of crossing ships over the route of Pipeline 1

| Number of ships in KP | KP | GT category | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | <1000 | 1000-4999 | 5000-9999 | 10000-24999 | 25000-49999 | 50000-99999 | >=100000 | N/a | Sum |
| 8 | 0-10 | 2 | 4 | 2 | 0 | 0 | 0 | 0 | 0 | 8 |
| 15 | 10-15 | 4 | 7 | 0 | 0 | 0 | 0 | 0 | 4 | 15 |
| 21 | 15-20 | 4 | 14 | 2 | 0 | 0 | 0 | 0 | 1 | 21 |
| 20 | 20-25 | 2 | 16 | 2 | 0 | 0 | 0 | 0 | 0 | 20 |
| 26 | 25-30 | 2 | 22 | 1 | 1 | 0 | 0 | 0 | 0 | 26 |
| 27 | 30-35 | 2 | 21 | 2 | 1 | 0 | 0 | 0 | 1 | 27 |
| 50 | 35-40 | 3 | 42 | 2 | 0 | 1 | 0 | 0 | 2 | 50 |
| 37 | 40-45 | 0 | 32 | 3 | 0 | 0 | 0 | 0 | 2 | 37 |
| 28 | 45-50 | 3 | 22 | 1 | 0 | 1 | 0 | 0 | 1 | 28 |
| 17 | 50-55 | 0 | 15 | 1 | 0 | 0 | 0 | 0 | 1 | 17 |
| 8 | 55-60 | 0 | 7 | 0 | 0 | 1 | 0 | 0 | 0 | 8 |
| 12 | 60-65 | 3 | 7 | 1 | 1 | 0 | 0 | 0 | 0 | 12 |
| 14 | 65-70 | 0 | 12 | 2 | 0 | 0 | 0 | 0 | 0 | 14 |
| 51 | 70-75 | 1 | 16 | 4 | 7 | 17 | 5 | 0 | 1 | 51 |
| 19 | 75-80 | 1 | 5 | 3 | 1 | 6 | 3 | 0 | 0 | 19 |
| 71 | 80-85 | 0 | 24 | 21 | 11 | 4 | 8 | 0 | 3 | 71 |
| 114 | 85-90 | 2 | 20 | 23 | 23 | 26 | 17 | 3 | 0 | 114 |
| 57 | 90-95 | 2 | 9 | 5 | 16 | 15 | 9 | 1 | 0 | 57 |
| 2 | 95-100 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 2 |
| 9 | 100-105 | 2 | 6 | 1 | 0 | 0 | 0 | 0 | 0 | 9 |
| 4 | 105-110 | 0 | 4 | 0 | 0 | 0 | 0 | 0 | 0 | 4 |
| 2 | 110-115 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 2 |
| 2 | 115-120 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 2 |
| 3 | 120-125 | 0 | 0 | 1 | 1 | 0 | 1 | 0 | 0 | 3 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 125-130 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 |
| 5 | 130-135 | 0 | 1 | 2 | 1 | 0 | 1 | 0 | 0 | 5 |
| 6 | 135-140 | 0 | 3 | 0 | 2 | 0 | 1 | 0 | 0 | 6 |
| 3 | 140-145 | 0 | 2 | 0 | 0 | 1 | 0 | 0 | 0 | 3 |
| 2 | 145-150 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 2 |
| 2 | 150-155 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 2 |
| 0 | 155-160 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 160-165 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1 | 165-170 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 |
| 6 | 170-175 | 0 | 1 | 2 | 2 | 0 | 1 | 0 | 0 | 6 |
| 2 | 175-180 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 2 |
| 5 | 180-185 | 0 | 2 | 2 | 0 | 0 | 1 | 0 | 0 | 5 |
| 13 | 185-190 | 2 | 6 | 3 | 0 | 0 | 2 | 0 | 0 | 13 |
| 11 | 190-195 | 1 | 4 | 3 | 0 | 0 | 3 | 0 | 0 | 11 |
| 11 | 195-200 | 1 | 5 | 2 | 1 | 1 | 1 | 0 | 0 | 11 |
| 9 | 200-205 | 2 | 3 | 2 | 0 | 0 | 2 | 0 | 0 | 9 |
| 7 | 205-210 | 1 | 3 | 1 | 1 | 1 | 0 | 0 | 0 | 7 |
| 8 | 210-215 | 1 | 2 | 3 | 0 | 0 | 0 | 0 | 2 | 8 |
| 7 | 215-220 | 1 | 6 | 0 | 0 | 0 | 0 | 0 | 0 | 7 |
| 4 | 220-225 | 0 | 4 | 0 | 0 | 0 | 0 | 0 | 0 | 4 |
| 10 | 225-230 | 2 | 4 | 2 | 2 | 0 | 0 | 0 | 0 | 10 |
| 8 | 230-235 | 0 | 6 | 2 | 0 | 0 | 0 | 0 | 0 | 8 |
| 4 | 235-240 | 0 | 2 | 1 | 0 | 1 | 0 | 0 | 0 | 4 |
| 11 | 240-245 | 1 | 8 | 0 | 1 | 0 | 0 | 0 | 1 | 11 |
| 15 | 245-250 | 0 | 5 | 6 | 1 | 2 | 1 | 0 | 0 | 15 |
| 4 | 250-255 | 1 | 2 | 0 | 0 | 1 | 0 | 0 | 0 | 4 |
| 2 | 255-260 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 2 |
| 4 | 260-265 | 1 | 1 | 0 | 1 | 0 | 0 | 0 | 1 | 4 |
| 4 | 265-270 | 1 | 2 | 0 | 0 | 0 | 1 | 0 | 0 | 4 |
| 4 | 270-275 | 0 | 3 | 0 | 0 | 0 | 1 | 0 | 0 | 4 |
| 9 | 275-280 | 1 | 3 | 1 | 3 | 0 | 1 | 0 | 0 | 9 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 24 | 280-285 | 4 | 4 | 4 | 3 | 6 | 2 | 0 | 1 | 24 |
| 2 | 285-290 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 2 |
| 2 | 290-295 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 2 |
| 1 | 295-300 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| 0 | 300-305 | | | | | | | | | 0 |

Table A.2: The distribution of the ships classified by the gross tonnage index

| **<1000 (1)** | **1000-4999 (2)** | **5000-9999 (3)** | **10000-24999 (4)** | **25000-49999 (5)** | **50000-99999 (6)** | **>=100000 (7)** | **n/a** | |
|---|---|---|---|---|---|---|---|---|
| 54 | 395 | 114 | 81 | 88 | 65 | 5 | 22 | 824 |
| 6,73% | 49,25% | 14,21% | 10,10% | 10,97% | 8,10% | 0,62% | | 100,00% |

Table A.3: Total number of different anchors classified by their EL and average speed

| **EL** | **Number of EL** | **Average Speed, knots** | **Average Speed, m/s** |
|---|---|---|---|
| **e** | 6 | 10 | 5,30 |
| **f** | 4 | 12 | 6,14 |
| **g** | 8 | 9 | 4,64 |
| **h** | 3 | 11 | 5,81 |
| **i** | 13 | 10 | 5,32 |
| **j** | 9 | 11 | 5,75 |
| **k** | 22 | 11 | 5,62 |
| **l** | 21 | 11 | 5,63 |
| **m** | 23 | 11 | 5,53 |
| **n** | 22 | 11 | 5,88 |
| **o** | 75 | 10 | 5,27 |
| **p** | 31 | 11 | 5,77 |
| **q** | 29 | 11 | 5,74 |

| | | | |
|---|---|---|---|
| **r** | 35 | 10 | 5,36 |
| **s** | 19 | 11 | 5,49 |
| **t** | 22 | 12 | 6,13 |
| **u** | 31 | 11 | 5,73 |
| **v** | 31 | 11 | 5,58 |
| **w** | 28 | 12 | 6,03 |
| **x** | 18 | 10 | 5,21 |
| **y** | 19 | 12 | 5,94 |
| **z** | 13 | 10 | 5,23 |
| **A** | 10 | 13 | 6,43 |
| **B** | 22 | 11 | 5,69 |
| **C** | 21 | 10 | 5,32 |
| **D** | 18 | 11 | 5,51 |
| **E** | 16 | 12 | 6,34 |
| **F** | 17 | 8 | 4,08 |
| **G** | 6 | 10 | 4,98 |
| **H** | 9 | 12 | 6,30 |
| **I** | 14 | 10 | 5,36 |
| **J** | 16 | 11 | 5,71 |
| **K** | 14 | 10 | 4,89 |
| **L** | 12 | 10 | 4,99 |
| **M** | 8 | 10 | 5,11 |
| **N** | 11 | 11 | 5,41 |
| **O** | 12 | 10 | 4,92 |
| **P** | 22 | 11 | 5,50 |
| **Q** | 17 | 10 | 5,11 |
| **S** | 1 | 9 | 4,42 |
| **T** | 16 | 11 | 5,42 |
| **U** | 9 | 11 | 5,90 |

| | | | |
|---|---|---|---|
| **V** | 12 | 11 | 5,81 |
| **X** | 11 | 11 | 5,54 |
| **Y** | 5 | 12 | 6,05 |
| **Z** | 3 | 12 | 6,36 |
| **A*** | 6 | 9 | 4,66 |
| **B*** | 7 | 11 | 5,70 |
| **E*** | 5 | 16 | 8,25 |

Table A.4: Small Letter anchor classes capable of approaching the pipeline

| KP | WD, m | e | f | g | h | i | j | k | l | m | n | o | p | q | r | s | t | u | v | w | x | y | z |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | -52 | -47 | -67 | -57 | -68 | -70 | -73 | -80 | -83 | -86 | -96 | -96 | -99 | -107 | -112 | -103 | -111 | -122 | -116 | -134 | -127 | -143 |
| **0-10** | **-175** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **10-15** | **-262,5** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **15-20** | **-350** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **20-25** | **-321** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **25-30** | **-292** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **30-35** | **-274** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **35-40** | **-256** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **40-45** | **-274** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **45-50** | **-292** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **50-55** | **-288** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **55-60** | **-284** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **60-65** | **-287** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **65-70** | **-290** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **70-75** | **-287** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **75-80** | **-284** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **80-85** | **-284** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **85-90** | **-284** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **90-95** | **-284** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

| | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **95-100** | **-284** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **100-105** | **-284** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **105-110** | **-284** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **110-115** | **-280** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **115-120** | **-276** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **120-125** | **-268** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **125-130** | **-260** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **130-135** | **-255** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **135-140** | **-250** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **140-145** | **-233** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **145-150** | **-216** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **150-155** | **-188** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **155-160** | **-160** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **160-165** | **-150** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **165-170** | **-140** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| **170-175** | **-136** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| **175-180** | **-132** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 |
| **180-185** | **-126** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 |
| **185-190** | **-120** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 1 | 1 |
| **190-195** | **-118** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 1 | 1 |
| **195-200** | **-116** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 |
| **200-205** | **-118** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 1 | 1 |
| **205-210** | **-120** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 1 | 1 |
| **210-215** | **-119** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 1 | 1 |
| **215-220** | **-118** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 1 | 1 |
| **220-225** | **-118** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 1 | 1 |
| **225-230** | **-119** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 1 | 1 |
| **230-235** | **-116** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 1 | 1 |
| **235-240** | **-114** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 |

| | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **240-245** | **-110** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 |
| **245-250** | **-106** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 |
| **250-255** | **-103** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **255-260** | **-100** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **260-265** | **-99** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **265-270** | **-98** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **270-275** | **-95** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **275-280** | **-92** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **280-285** | **-86** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **285-290** | **-80** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **290-295** | **-79** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **295-300** | **-78** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **300-305** | **-78** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |

Table A.5: Capital Letters anchor classes capable of approaching the line

| **KP** | **WD, m** | **A -122** | **B -143** | **C -154** | **D -151** | **E -142** | **F -205** | **G -179** | **H -156** | **I -181** | **J -174** | **K -207** | **L -206** | **M -205** | **N -206** | **O -224** | **P -207** | **Q -230** | **S -260** | **T -235** | **U -222** | **V -227** | **X -248** | **Y -233** | **Z -226** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0-10** | **-175** | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **10-15** | **-262** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **15-20** | **-350** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **20-25** | **-321** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **25-30** | **-292** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **30-35** | **-274** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **35-40** | **-256** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| **40-45** | **-274** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **45-50** | **-292** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **50-55** | **-288** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **55-60** | **-284** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

| | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **60-65** | **-287** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **65-70** | **-290** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **70-75** | **-287** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **75-80** | **-284** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **80-85** | **-284** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **85-90** | **-284** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **90-95** | **-284** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **95-100** | **-284** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **100-105** | **-284** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **105-110** | **-284** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **110-115** | **-280** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **115-120** | **-276** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **120-125** | **-268** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **125-130** | **-260** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| **130-135** | **-255** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| **135-140** | **-250** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| **140-145** | **-233** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 0 |
| **145-150** | **-216** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **150-155** | **-188** | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **155-160** | **-160** | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **160-165** | **-150** | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **165-170** | **-140** | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **170-175** | **-136** | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **175-180** | **-132** | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **180-185** | **-126** | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **185-190** | **-120** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **190-195** | **-118** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **195-200** | **-116** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **200-205** | **-118** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |

| | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **205-210** | **-120** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **210-215** | **-119** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **215-220** | **-118** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **220-225** | **-118** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **225-230** | **-119** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **230-235** | **-116** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **235-240** | **-114** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **240-245** | **-110** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **245-250** | **-106** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **250-255** | **-103** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **255-260** | **-100** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **260-265** | **-99** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **265-270** | **-98** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **270-275** | **-95** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **275-280** | **-92** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **280-285** | **-86** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **285-290** | **-80** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **290-295** | **-79** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **295-300** | **-78** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **300-305** | **-78** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |

Table A.6: Capital Letters with star anchor classes capable of hooking the pipeline

| **KP** | **WD, m** | **A*** | **B*** | **E*** |
|---|---|---|---|---|
| | | **-284,928** | **-251,631** | **-200,756** |
| **0-10** | **-175** | 1 | 1 | 1 |
| **10-15** | **-262,5** | 1 | 0 | 0 |
| **15-20** | **-350** | 0 | 0 | 0 |
| **20-25** | **-321** | 0 | 0 | 0 |
| **25-30** | **-292** | 0 | 0 | 0 |

| | | | | |
|---|---|---|---|---|
| **30-35** | **-274** | 1 | 0 | 0 |
| **35-40** | **-256** | 1 | 0 | 0 |
| **40-45** | **-274** | 1 | 0 | 0 |
| **45-50** | **-292** | 0 | 0 | 0 |
| **50-55** | **-288** | 0 | 0 | 0 |
| **55-60** | **-284** | 1 | 0 | 0 |
| **60-65** | **-287** | 0 | 0 | 0 |
| **65-70** | **-290** | 0 | 0 | 0 |
| **70-75** | **-287** | 0 | 0 | 0 |
| **75-80** | **-284** | 1 | 0 | 0 |
| **80-85** | **-284** | 1 | 0 | 0 |
| **85-90** | **-284** | 1 | 0 | 0 |
| **90-95** | **-284** | 1 | 0 | 0 |
| **95-100** | **-284** | 1 | 0 | 0 |
| **100-105** | **-284** | 1 | 0 | 0 |
| **105-110** | **-284** | 1 | 0 | 0 |
| **110-115** | **-280** | 1 | 0 | 0 |
| **115-120** | **-276** | 1 | 0 | 0 |
| **120-125** | **-268** | 1 | 0 | 0 |
| **125-130** | **-260** | 1 | 0 | 0 |
| **130-135** | **-255** | 1 | 0 | 0 |
| **135-140** | **-250** | 1 | 1 | 0 |
| **140-145** | **-233** | 1 | 1 | 0 |
| **145-150** | **-216** | 1 | 1 | 0 |
| **150-155** | **-188** | 1 | 1 | 1 |
| **155-160** | **-160** | 1 | 1 | 1 |
| **160-165** | **-150** | 1 | 1 | 1 |
| **165-170** | **-140** | 1 | 1 | 1 |
| **170-175** | **-136** | 1 | 1 | 1 |

| | | | | |
|---|---|---|---|---|
| **175-180** | **-132** | 1 | 1 | 1 |
| **180-185** | **-126** | 1 | 1 | 1 |
| **185-190** | **-120** | 1 | 1 | 1 |
| **190-195** | **-118** | 1 | 1 | 1 |
| **195-200** | **-116** | 1 | 1 | 1 |
| **200-205** | **-118** | 1 | 1 | 1 |
| **205-210** | **-120** | 1 | 1 | 1 |
| **210-215** | **-119** | 1 | 1 | 1 |
| **215-220** | **-118** | 1 | 1 | 1 |
| **220-225** | **-118** | 1 | 1 | 1 |
| **225-230** | **-119** | 1 | 1 | 1 |
| **230-235** | **-116** | 1 | 1 | 1 |
| **235-240** | **-114** | 1 | 1 | 1 |
| **240-245** | **-110** | 1 | 1 | 1 |
| **245-250** | **-106** | 1 | 1 | 1 |
| **250-255** | **-103** | 1 | 1 | 1 |
| **255-260** | **-100** | 1 | 1 | 1 |
| **260-265** | **-99** | 1 | 1 | 1 |
| **265-270** | **-98** | 1 | 1 | 1 |
| **270-275** | **-95** | 1 | 1 | 1 |
| **275-280** | **-92** | 1 | 1 | 1 |
| **280-285** | **-86** | 1 | 1 | 1 |
| **285-290** | **-80** | 1 | 1 | 1 |
| **290-295** | **-79** | 1 | 1 | 1 |
| **295-300** | **-78** | 1 | 1 | 1 |
| **300-305** | **-78** | 1 | 1 | 1 |