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Underwater inspection of fixed offshore steel structures

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It was very challenging to undertake a topic concerning the offshore field, especially the underwater sector. Writing about this topic helped me to conduct a vast amount of research and spectate different aspects concerning offshore subsea structures.

RESUME

Les structures offshores sont des grandes plates-formes qui fournissent les équipements et les installations nécessaires à l'exploration et à la production en mer. Généralement ses structures sont conçues pour résister des charges environnementales telles que les vagues, les courants, le vent, les tremblements de terre et les charges opérationnelles quotidiennes. Les procédures d'inspection et de maintenance doivent être effectuées de manière à réduire le risque de fatigue et défaillance de ses structures. Ce mémoire traitera des codes et régulations nationaux-internationaux concernant les inspections des structures en mer, ainsi que les différents types d'inspection non-destructives. D'outre, nous développerons la croissance de l'encrassement biologique, l'inspection et le nettoyage de la structure sous-marine offshore. Nous présenterons également l'inspection et la surveillance correctes du système de prévention de la corrosion installé sur ces structures. Nous traiterons ensuite une stratégie d'inspection sous-marine effective sera élaboré, ce qui permet une meilleure compréhension des niveaux de risque pour la durée de vie prévue de la structure. Enfin, nous discuterons les risques que subissent les plongeurs, des limitations d'accès considérant les différents effets qui s'appliquent sur les sous-marins et le rôle d'automatisation dans ce secteur. Le but de ce mémoire est d'étudier les différents systèmes d'inspections pour pouvoir aboutir sur une méthodologie efficace qui permet de garder les structures fixe en mer (offshore) hors des cales sèches en toute sécurité.

ABSTRACT

Offshore structures are large platforms that provide the necessary facilities and equipment for exploration and production at sea. Generally, these structures are designed to withstand environmental loads such as waves, currents, wind, earthquakes and daily operational forces. Inspection procedures must be performed in an effective way to reduce the risk of fatigue and failure of these structures. This thesis will discuss international and national codes & regulations concerning inspections of offshore structures, as well as the different types of underwater non-destructive testing inspections that must be carried out at sea. Moreover, this thesis will elaborate on the marine growth development, inspection and cleaning of the underwater offshore structure. It will also present the correct implementation, inspection and monitoring of the corrosion prevention system fitted on these structures. In addition, we will develop a strategy for an effective underwater inspection, allowing a better understanding of the risk levels during the expected service life of the structure. Finally, we will discuss what risks the divers frequently face, the access limitations and the role of automation in this sector. The aim of this thesis is to study different inspection and maintenance systems to develop an efficient methodology that will keep fixed offshore structures safely out of dry-dock.

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LIST OF ABBREVIATIONS

CA: Corrosion Allowance

CP: Cathodic Protection

DCI: Decompression Illness

DMS: Diving Management System

DNV: Det Norske Veritas

DPP: Diving Project Plan

DWDI: Double Wall Double Image

DWSI: Double Wall Single Image

HAT: Highest Astronomical Tide

HSWL: Highest Still Water Level

IACS: International Association of Classification Societies

ICCP: Impressed Current Cathodic Protection

IMCA: International Marine Contractors Association

IMO: International Maritime Organisation

LAT: Lowest Astronomical Tide

LSWL: Lowest Still Water Level

MIC: Microbial Induced Corrosion

MPI: Magnetic Particle Inspection

MWL: Mean Water Level

NDT: Non-Destructive Testing

ROV: Remotely Operated Vehicle

SACP: Sacrificial Anodes Cathodic Protection

SZL: Splash Zone Lower

SZU: Splash Zone Upper

TIP: Theoretical Inspection Program

UV: Ultra Violet

General definitions

- Administration: the state under the authority of which the unit is operating
- Compton scattering: is a scattering of a photon due to contact with an electron. This effect can be improved by reducing the radiation energy (KeV) (Wikipedia, 2019).
- D: the calculated marine growth diameter
- Dc: the bare steel diameter without marine growth (diameter after cleaning)
- Divers buoyancy: is the ability of the diver to keep a proper position in water based on the mission activity: Positively buoyant by floating on the water surface, neutrally buoyant by hovering in the water and negatively buoyant by resting on the seabed.
- e: the calculated marine growth roughness
- Inspection: examination conducted by a qualified person (inspector) to define the unit structural conditions
- Inspector: the technical staff acting on behalf of the unit's operator to perform tasks of inspection duties
- k: the marine growth average peak to valley height
- Major modification: any repair or replacement of the underwater structure that might affect the unit class
- Metocean: combined word from "meteorology and oceanography", used in the offshore sector to describe the physical environment at the offshore structure area
- Minor modification: replacement or repairs of the underwater structure that will not affect the unit class
- Operator: the unit's manager or any other parties responsible to keep the unit seaworthy
- Owner: the unit's registered owner
- ROV: a robot used for underwater inspection, operated from distance
- Rules: the rules of the classification society and documents issued by the Society
- Scattering: is the change in direction of a particle due to a collision with another body (Encyclopaedia Britannica, 2019).
- Society or Class: the classification society at which the unit is classified
- Structures: offshore steel constructions used for production at sea such as gas, oil, electricity and other resources

- Survey: an inspection performed by a surveyor delegated by the Administration or Society
- Surveyor: the technical staff acting on behalf of the classification society to perform tasks of survey duties
- t: the average marine growth thickness
- TIP: the survey program followed by the unit’s operator, which was developed by the builder during the unit construction
- Unit: an offshore structure used for exploitation purposes

Chapter 1 INTRODUCTION

Subsea metal structures are progressively being used in the offshore sector. These structures are designed to withstand excessive operational and environmental loads. Accidents can cause catastrophic impact, which explains why underwater inspections of such structures are a crucial element to ensure the safety of the crew, the structure and the environment.

The offshore industry consists of many different varieties of vessels, platforms or steel structures used for exploration purposes at sea. This thesis addresses different aspects of the underwater inspection of fixed offshore structures, starting by the classification of an offshore unit and its various applicable rules and regulations. Furthermore, we will be focusing on the underwater Non-Destructive Testing (NDT) inspection and its different underwater applications.

Throughout this thesis, we handle four different types of NDT used in the underwater offshore sector: visual, magnetic particles, radiography and ultrasonic. Each method will be explained by elaborating its range of function and its pros and cons. In addition to the NDT inspections, this thesis will explain the marine growth development, thickness levels, inspection and the cleaning process on the structures. The corrosion prevention system will also be part of this research. This thesis will explain and highlight the importance of the coating and the CP system as a corrosion protection to the underwater part of the unit. Moreover, in this thesis an inspection strategy is developed in order to explain the various NDT, their scope and the inspection methods to be adopted.

This inspection strategy can be used to conduct periodic inspections on offshore structures in working conditions to ensure their structural strength, as well as on an abandoned structure in order to get an idea of its subsea structural status and to determine the further inspection process.

This thesis will also discuss the underwater diving and the limitations faced by divers while conducting subsea inspections. Furthermore, we discuss the role of automation in this sector, such as the added value of Remotely Operated Vehicles (ROV) and their role to enhance the inspection. Then, a basic approach of the ROV-diver as one team to tackle the underwater inspection is discussed. In addition, we examine different underwater diving restrictions, both technical and environmental.

The final part of this thesis is a case study of the platform Alexander L. Kielland. In this part we will describe the story and the sequences of this disaster. Then, we will describe the causes which led to this accident by examining the failed parts and explaining the lack of the underwater inspection in relation to this thesis.

Chapter 2 CLASSIFICATION & SURVEYS

2.1 STRUCTURE LIFECYCLE

The unit design life, or also known as "the unit lifecycle", is to be defined by the party applying for classification, taking into consideration the corrosion safety factor, fatigue, structural strength and marine environment on site. The owner and/or operator is required to perform the necessary environmental investigations and surveys prior to building the unit.

Structural modifications may be necessary during the operation life of the unit. In this case, the owner or operator should present an impact assessment to the Classification Society, taking into account all factors that might affect the original design life of the structure due to the modification. The Society may require a comprehensive re-assessment in the following cases (Bureau Veritas, 2016):

- The actual service life is expected beyond the design life
- If major modification took place
- based on the unit's age and condition

2.2 SITE CONDITION

Considering the offshore unit design data, the owner and/or operator shall submit a site environmental data description to be studied by the Society. The environmental data provided for a fixed unit will be in function of the estimated operation time of the unit and the predicted load accumulations caused by metocean. Furthermore, the environmental data shall at least consist of a soil study, water & atmospheric temperatures and ice formation if applicable (Bureau Veritas, 2016).

2.3 CLASS ASSIGNMENT

The class assignment can have different procedures depending on the unit's situation. We can distinguish two different scenarios, a unit under a new building procedure and a unit which has already been in-service.

In a new building procedure, a surveyor delegated by the classification society will conduct different surveys during the construction process of the unit. The surveyor will check the construction method as well as the parts and materials being used for the construction. Finally, the last survey will include a test and trials upon delivery (DNV, 2012).

If an owner is willing to switch from one class to another for a unit which has been in-service, the application procedure is different considering whether or not the unit is classified with an IACS society. The society will determine a survey program taking into consideration the unit's age, condition and operation type.
The date of build for a new constructed unit is considered as the date at which the new construction survey process is completed (IACS, 2016). After construction, some units take time to get into service; in such case the date of commissioning may also be specified. If a minor modification is carried out, the date of build remains the same. When a major modification of the unit takes place, the date of build will be associated with the date of each major modification of the unit and will be mentioned on the classification certificate (see section 2.4) (DNV, 2012). The period of Class starts either from the date of the initial classification, or from the last class renewal survey and expires at the expected next renewal survey.

2.4 CLASS SURVEYS

The surveys carried out on offshore structures intend to verify that the unit is maintained up to a specific norm. A scheduled survey program ensures that the structure meets the Class requirements during the entire Class period. Besides that, regular inspections also help to detect possible unit deficiencies in early stages, if applicable. This allows to develop an acceptable inspection and maintenance program, which suits the unit's conditions in order to maintain its structural design strength, as described in section 3.5.
After reviewing three survey programs developed by different IACS members, Bureau Veritas (2016), DNV (2012) and Polski Rejestr (2014), some of the principal surveys concerning the underwater inspection of fixed steel offshore structures are discussed below:

Class renewal survey

A renewal survey is carried out at five-year interval for the Class renewal. After this survey, a new Class period is assigned to the unit with a new Class certificate. Two types of renewal survey systems exist: the continuous and the normal survey.

In the continuous survey system, the program is maintained uninterrupted during the Class term, on a previously planned program developed by the unit's operator and the Classification Society. The owner and/or operator can request a continuous survey and inspection process, which will be considered and agreed by the Society depending on the structure life, age, conditions and metocean at the unit site. This system may apply to different survey types, specific for each Classification Society rules and regulations. The continuous survey system does not replace the periodic or occasional surveys.

In case of a normal survey system, renewal surveys are carried out in five-year interval. This system can be divided into different partial surveys in order to cover the overall underwater structure. It may commence after the fourth year of class and be completed during the following year.

Periodical surveys

We can distinguish two types of periodical surveys: the first is to be carried out annually and the second within a five-year interval which can be performed in conjunction with the class renewal survey.

The annual survey is carried out within a time window before or after the classification anniversary date, depending on each of the Society's rules (normally 3 months). The survey includes an underwater visual inspection of the hull and equipment, as described in section

The five-year periodical survey is normally performed in conjunction with the end of the classification period. This survey includes a thickness measurement, sea valves examination and NDT inspection of welded joints using one of the methods described in section 3.1 as per classification requirements.

Occasional surveys

Occasional surveys take place in unforeseen events. We distinguish first of all limited damage repairs. Due to the environmental and operational conditions, offshore units are continuously exposed to breakdowns. The owner and/or operator must directly report all damages or defects which might affect the unit's structural conditions.

In case of a modifications and/or major repairs, surveys are necessary. It shall take place if a hull, legs, columns or any other underwater structure is modified, exposed to a major repair or sustained any damage which could have an impact on the Class of the unit. The survey will focus on that specific modification and ensure that all accomplished repairs satisfy the Class standards. The Classification Society is recommended to refer to the IACS recommendations (2016) in case of a major modification and/or replacement of materials.

2.5 SURVEY & INSPECTION PROCESS

2.5.1 Prior to inspection

The underwater survey procedures are to be approved by both parties: the owner and/or operator and the classification society. The inspection plan shall consist of areas to be surveyed (suspected or non-suspected), previous damage records and their locations, hull cleaning, NDT methods and their locations (if applicable). Prior to the survey all equipment is tested and calibrated by the approved diving firm (Bureau Veritas, 2016).

The underwater survey is conducted by means of ROV's and/or divers, depending on the water visibility and the sea conditions. The underwater inspection plan should include:

- a description related to the site visibility and sea conditions
- an area accessibility description (no obstructions which might limit the diver or the ROV to accomplish the job, to reach the inspection areas or other important structures)
- a hull cleaning proof document (if required)

The unit's surfaces must be cleaned prior to the survey in order to be prepared for inspection. Moreover, if a full cleaning is required, the latter shall not be conducted just before the survey, as fouling debris will directly affect the water visibility and limit the visual structure examination.

The cleaning methodology to be followed will take into consideration the sea temperature, which affects the fouling development period (present environment compared to the unit specific structure), and the sea conditions (i.e. sea currents might clear the fouling debris faster than in calmer water). The hull cleaning process prior to a survey depends on each unit's characteristics, geographical location and the required inspection to be carried out as described in section 3.2. It is the operator's responsibility to ensure a clean hull ready for inspection, by creating a balance between both factors in order to present a clear visibility for a meaningful examination (IACS, 2016).

2.5.2 During the survey

The underwater survey shall be carried out by an approved firm (commercial diving company), suggested and approved by the classification society. A surveyor will be delegated by the classification society to be present on the unit (if possible) during the survey and attending the live broadcast video by underwater divers or ROV's. The in-water survey will determine the submerged structure's condition by providing photos and video tapes, thickness measurements, non-destructive testing results and any other test data that might be necessary to ensure the unit's fitness. It is important to consider that not all inspection techniques will be carried out at once, it depends on the survey objective and previous inspection records. During the course of the inspection, we should pay attention to few additional elements (IACS, 2016), such as:

- ensuring that the (CP) Cathodic Protection (if applicable) is maintained, well immersed and has an adequate potential measurement (based on the Society criteria). If this is not the case, the problem should be reported and a replacement procedure shall be considered.
- examining the sea connections (i.e. sea chests or the overboard discharge valves). These connections are opened and inspected from the inside once every 5 years, unless considered otherwise by the surveyor.
- inspecting the splash zone for corrosion and possible impact damage caused by the supply vessels moored alongside.

2.5.3 Post inspection

After the survey completion, the diving company must present to the Classification Society and the unit operator a detailed report including all measurements, photos, video tapes, analysed test results and any further remarks reported by the divers. The surveyor will analyse the survey outcome and compare it with the previous records.
Finally, the Society will issue a detailed report of the survey which will define the future inspection periods, maintenance & repairs describe and the underwater structure fitness. All documents should be recorded and kept on board.

2.6 SURVEYOR-DIVER CONNECTION

A direct two-way communication is to be provided between the diver and the surveyor. It is common that the diver and the surveyor assist in the inspection briefing, where the plan will be explained and approved by all parties. During the operation, a plan modification might be possible, but only if both the diver and the surveyor accept the modifications and if it will not compromise the diver's safety (IMCA, 2014).

Chapter 3 UNDERWATER INSPECTION

3.1 NON-DESTRUCTIVE TESTING (NDT)

3.1.1 General

Offshore structures have fatigue sensitive joints. Due to dynamic loading, these joints are sensible to fatigue crack growth, particularly at the welded tubular joints. Regular inspection is required to ensure that the integrity and the safety of the structure is maintained for its entire lifecycle. The following sections cover four different types of NDT inspections for underwater steel structures:

- Visual
- Magnetic particle
- Radiography
- Ultrasonic

3.1.2 Visual inspection

The visual inspection is the most common used inspection technique to obtain a general overview of the structure. This type of inspection requires clear water and adequate lighting.

A visual inspection before surface cleaning can be very useful this will lead to detect any coloration or deformation in the marine growth which may occur due to a crack in the structure below (R. Frank Busby Associates, 1978). Moreover, such a coloration detection will enhance further inspection planning and help to determine its scope.

The crack should be re-inspected after cleaning using more advanced NDT methods (such as MPI, radiography or ultrasonic inspection). The inspector shall ensure the examination of other surrounding weak spots in the structure that might be affected.

A visual inspection is also conducted to detect surface deformation and discontinuities. In addition, with the aid of a thickness gauge, metal thicknesses can be measured. These measurements are carried out on different parts of the underwater metal structure especially on the welded joints, where the diver can measure the weld profile (Hellier, 2001). This is illustrated in Figure 1.

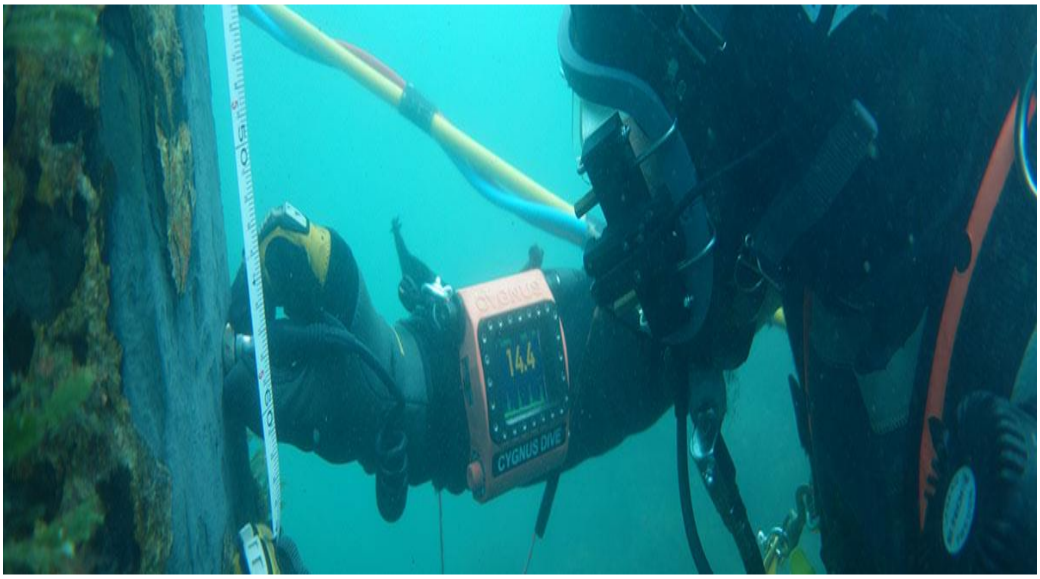

Figure 1 Underwater non-destructive testing using a micrometre depth gauge
Source: Professional Diving Services (2015)

3.1.3 Magnetic Particle Inspection (MPI)

The MPI is a frequently used NDT method in the underwater offshore sector due to its accessibility and reliability. It is used to detect defects in metal surfaces and near surface defects in ferromagnetic materials. In this method two electrical prods positioned on each side of the weld, as shown in Figure 2, which will create a magnetic field in the structure, parallel to the metal surface (if the metal is free from defects) (Hellier, 2001). In case of a crack in the metal, this magnetic field will locally leave the surface of the metal. This is called the magnetic leakage field, as shown in Figure 3.

When subsequently applying the magnet ink on the inspection surface (between the two prods), the ink will accumulate on the magnetic leakage field locations. The ink accumulation on the metal surface will make the defect location and propagation visible. UV light can be helpful to clearly visualize the ink accumulation spots. The deeper the crack in the metal, the less leakage field will be created at the surface, as shown in Figure 3. As a result, it will be difficult to detect small crack indications in subsea conditions.

The MPI method requires a high amperage (between 300 to 1600 A, depending on the prods spacing respectively from 3 to 12 inches) and a low voltage current (120 or 240 volts). It is the same current required to perform an MPI above water (NDT Education Resource Centre, 2014).

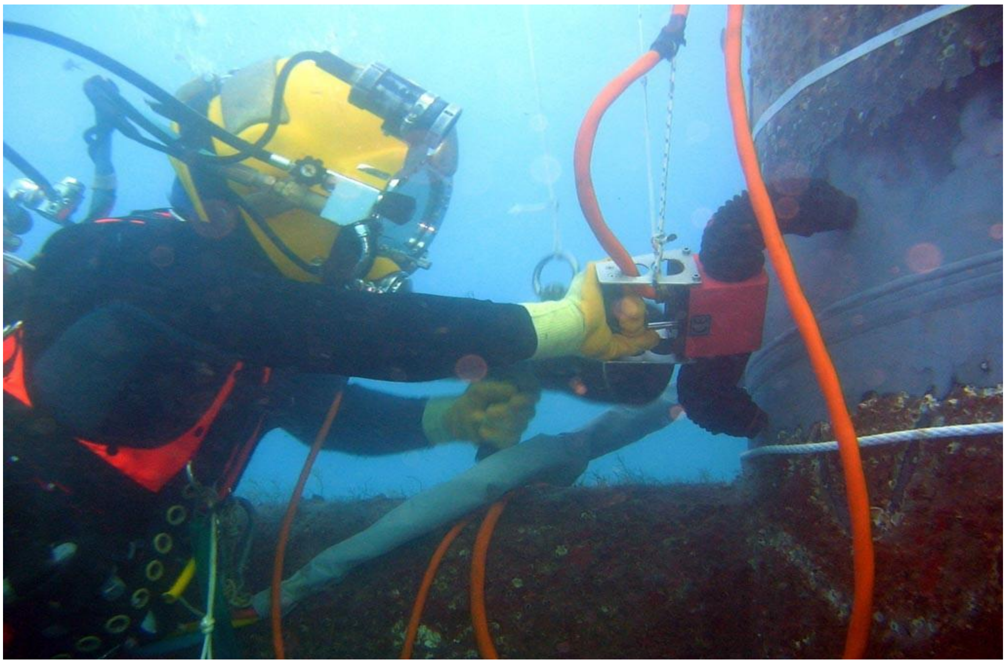

Figure 2 Underwater non-destructive testing by a diver using the magnetic particles method
Source: Impresub (2019)

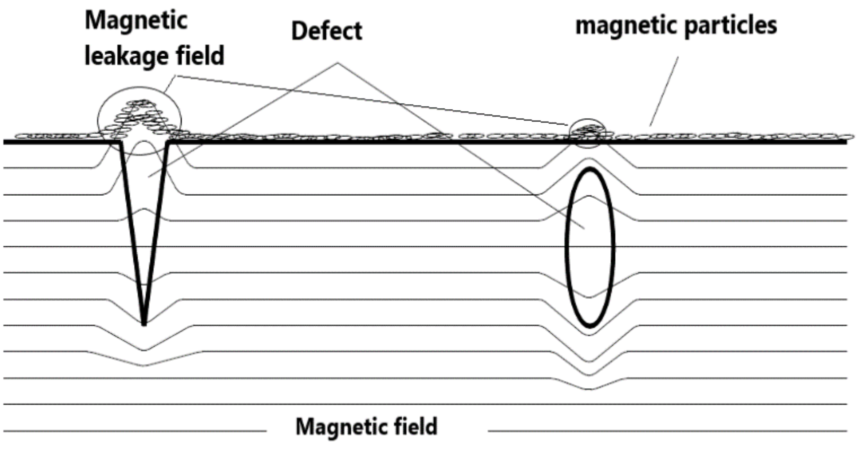

Figure 3 Shows the difference between the magnetic field created in an intact and a defected ferromagnetic material
Source: modified from Brechmann Guss (2017)

The surface to be inspected should be thoroughly cleaned to allow a good prod-metal contact. The diver shall be equipped with adequate underwater lighting equipment to allow sufficient illumination to help the diver localizing the defects.

The MPI is used above and underwater. The above water technique consists of using a dry powder containing magnetic particles, while during an underwater inspection divers use wet magnetic particles (an ink mixture containing magnetic particles) (NDT Education Resource Centre, 2014). A fluorescent particle is added to the ink which will make it clearly visible under an ultraviolet light, as shown in Figure 4.

The ink can easily spray a uniform layer of magnetic particles over the intended test surface, see Figure 5. The magnetic particles used in an ink mixture are smaller than in dry powder. Therefore, on smooth surfaces the magnetic ink can detect smaller cracks than the dry powder (smaller particles can penetrate smaller cracks), while on rough surfaces the dry powder ensures a better effectiveness than magnetic ink (the smaller particles will settle in the surface valleys) (NDT resource center, 2013).

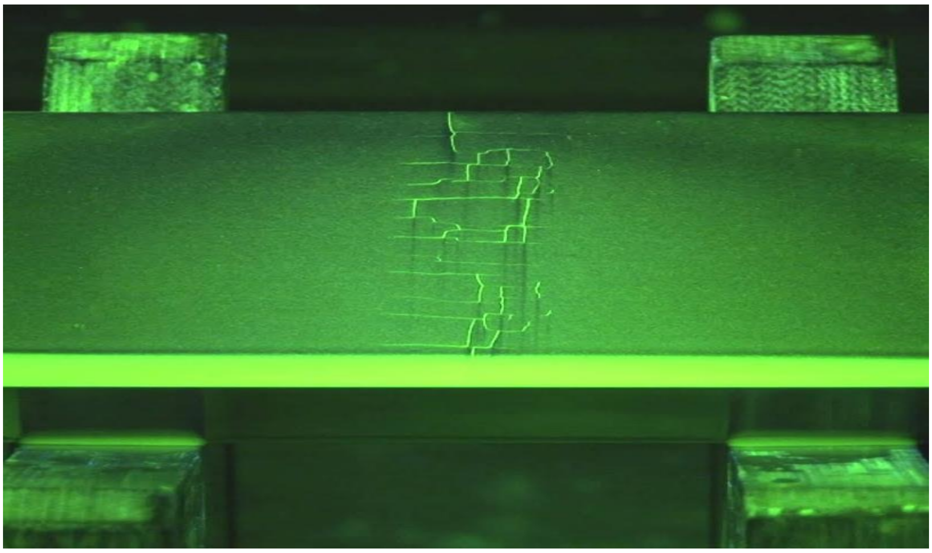

Figure 4 Photo showing a magnetic particles illumination on a metal plate under UV light in dry conditions
Source: Materials Science2000 (2014)

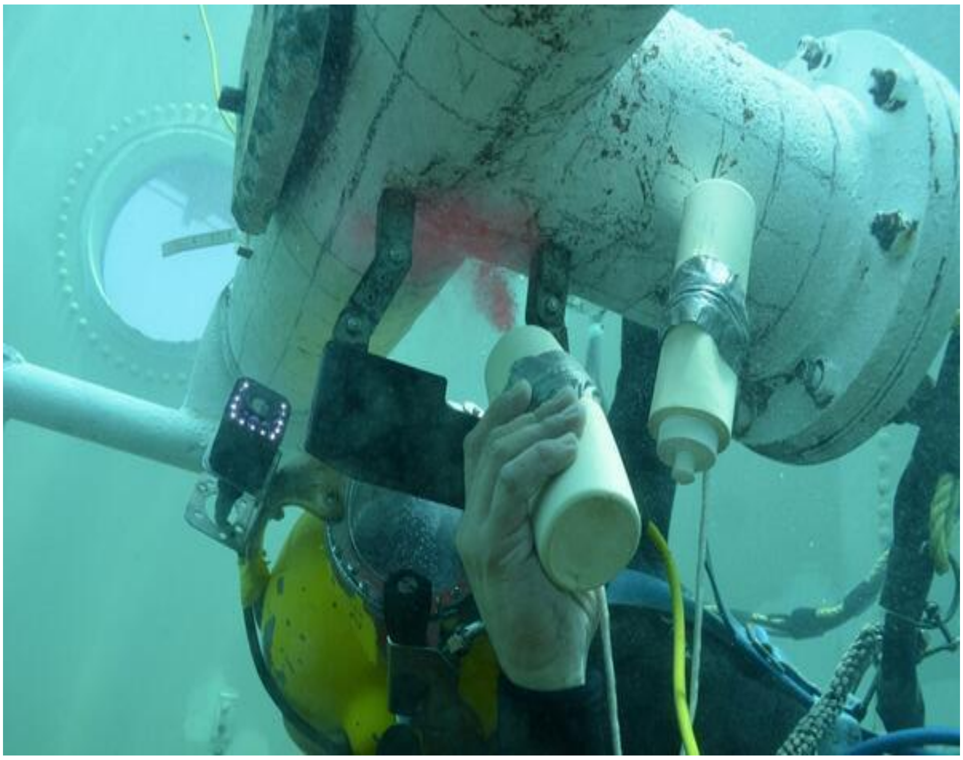

Figure 5 Diver applying magnetic ink on a steel pipeline
Source: NDT academy (2014)

A live image transmission is sometimes required to ensure that the diver has correctly followed the predefined procedure, which is also used for the record.
Divers and the diving firm shall make sure that all testing and any other underwater equipment are maintained in working condition and built to resist the hydrostatic pressure up to the test location depth (IMCA, 2014).

3.1.4 Radiographic inspection

Subsea radiography inspection is an effective NDT method. No prior surface cleaning is required. This inspection technique needs a radiation source and a detector (cassette); the latter should be covered (on the back side) by a lead sheet to protect any back-scattering photons (Hellier, 2001). In the past, it was the divers' job to operate the radiography source due to technology limitation, but nowadays and due to the automatized ROVs' underwater personnel intervention is no longer needed, see Figure 6. The use of an ROV is preferred over the use of a diver operating the radiography source. Modern ROV's can (IMCA D 054, IMCA R 020, 2014):

- improve the operation safety as it limits the diver exposure to radiation
- ameliorate the source-detector alignment which increases the image quality
- transmit a direct image to the surface control operator.

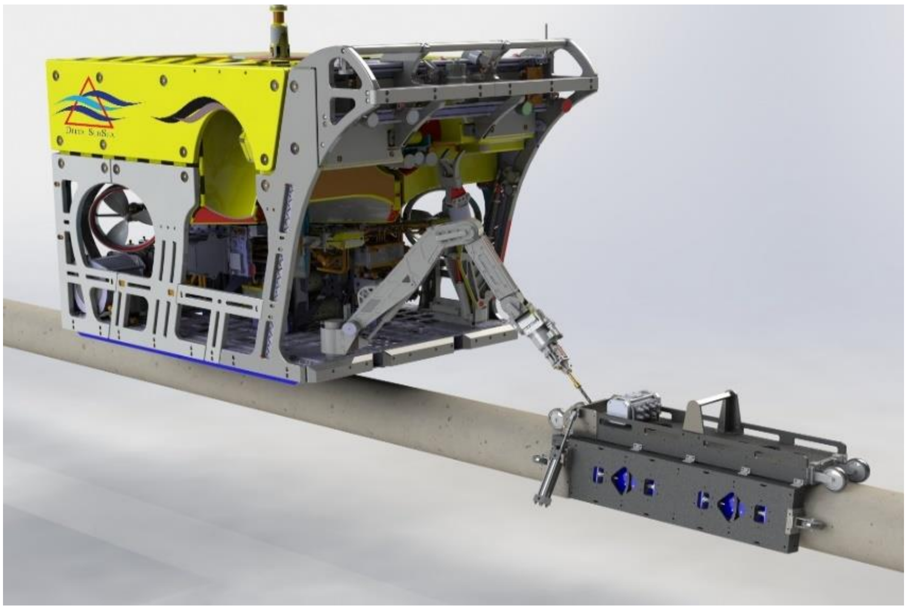

Figure 6 Subsea radiography ROV
Source: Wikipedia (2017)

The light radiation in water is highly scattering. This leads to the main difference between a normal radiographic inspection in dry air and in water. In water, the Compton scattering effect is much higher than in iron, knowing that the scattering in water starts at a low radiation energy (≈ 30 KeV) while in iron at a higher energy (≈100 KeV), (Haith, 2016). This photon scattering will significantly degrade the contrast in the radiographic image quality.

We can differ two radiographic techniques: tangential and double wall, see Figure 7. The latter is the more practical method to be used for subsea imaging (EN 16407-2, 2014). Moreover, the double wall imaging method is divided into “Double Wall Single Image” DWSI (a) and “Double Wall Double Image” DWDI (b) also illustrated in Figure 7. The main difference between both double wall methods is the distance of the radiography source to the upper side of the structure, as shown in Figure 7.

a. In DWSI, the radiography source is placed closer to the pipe side. At this angle, we can only get images of the lower pipe side due to the feature magnification over the whole detector. In addition we decrease the photons scattering effect as we reduce the source-detector distance, which means that we limit the distance of photons travelling in water (Haith, 2016).
b. In DWDI, the radiation source is placed further from the pipe. In this case both sides are shown on the detector but with a lower image quality due to the scattering effect (bigger source-detector distance).
c. In tangential imaging, the radiation source is also placed further from the pipe when compared to DWSI and the detector is shifted to the required pipe edge inspection.

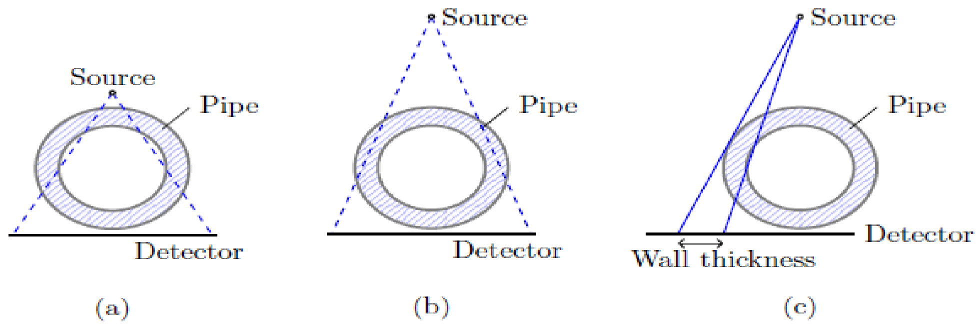

Figure 7 Radiographic imaging methods: (a) DWSI, (b) DWDI and (c) Tangential imaging
Source: Haith (2016)

The DWSI is the most commonly used subsea radiography method for non-destructive testing (API 570, 2016). The source-metal distance variation presented in Figure 8 shows an important escalation in the radiographic image sensitivity with an increasing distance. The extent of this effect was determined by using an X-ray radiation source of 2 MeV (Ship Structure Committee, 1979).

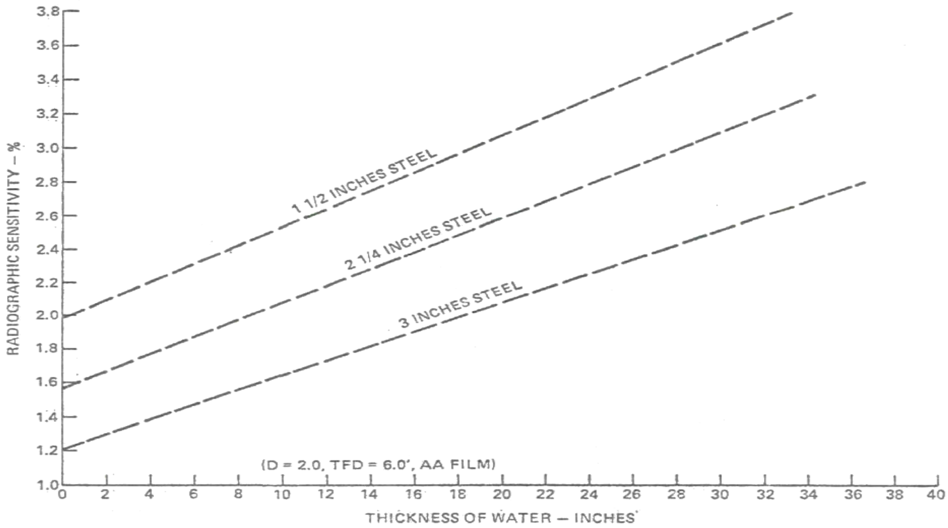

Figure 8 Radiographic sensitivity due to the metal-source distance
Source: Ship Structure Committee (1979)

The inspector should make sure to capture multiple images from different angles of the same location on the pipe, otherwise it will be very difficult to localize the defect location on the three-dimensional pipe. The image on the detector is illustrated as a cone of different possible defect locations, as shown in Figure 9; in other words, if any defect is detected it can be located at any position on that cone. However, when multiple images from different angles are carried out, then the defect range can be considerably narrowed, as illustrated in Figure 10 (Haith, 2016).

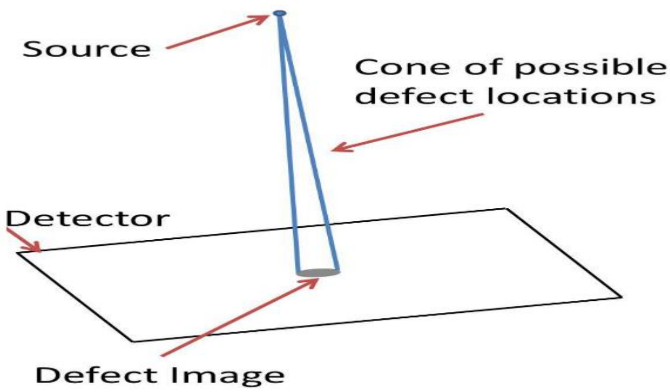

Figure 9 Illustrating the cone of possible defect locations
Source: modified from Haith (2016)

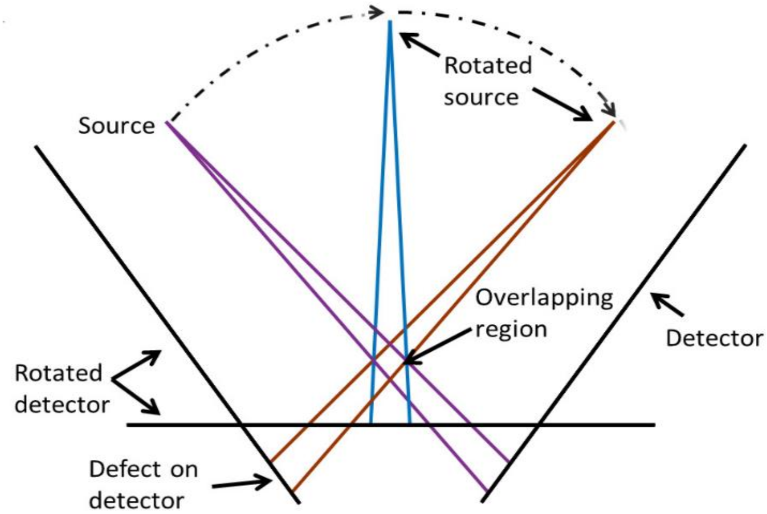

Figure 10 Multiple radiography imaging in one location
Source: Haith (2016)

3.1.5 Ultrasonic inspection

Ultrasonic inspection is an efficient underwater NDT method, which allows the detection of deep metal defects and not only near the surface. Subsea ultrasonic measurements can locate structural discontinuities or flaws and perform metal thickness measurements.
An electric pulse is produced in the main instrument and transmitted to a transducer (probe), which will convert this electric pulse into a mechanical vibration (short wavelength and high frequency) to propagate in the metal (Ayman, Outa, & Ledezma, 2015). A part of this vibration will return to the transducer receiver where it will be reconverted into electric pulses and sent back to the main instrument in order to be analysed (R. Frank Busby Associates, 1978). The interpretation of the result should be conducted by specialised inspectors. In addition, the ultrasonic instrument shall be calibrated before each use (Ship Structure Committee, 1979).

Similar to most underwater non-destructive testing, the use of ultrasounds also requires surface cleaning to ensure that the probes are applied on a bare metal surface for high result accuracy.

Ultrasound inspection can be used to detect flaws or defects in metal structures and specially in welded joints. This is done by an ultrasonic transducer placed on the metal surface. The ultrasound introduced in the structure will reflect when it hits water, air or any other interface (difference of material density) and is shown on the display, as illustrated in Figure 11. Moreover, the wave can be pointed in different angle directions into the structure to ensure a full scan.

The transducer generally transmits a higher sound frequency in metal (a range of 3.5 to 5 MHz) than in concrete and wood, which is limited to 250 KHz (R. Frank Busby Associates, 1978). In addition, when an ultrasonic inspection is done in mid-air (above water), the wave reflection by a flaw in the metal will be almost 100%. This is not the case in subsea conditions where the water is believed to transmit part of this energy. In other words, the defect will only reflect part of the wave which will be received and analysed, as illustrated in Figure 12. Experiments have confirmed that under water, the ultrasonic reflectivity is reduced to 88%, which means 12% of the energy wave is lost (NTD Education Resource Center, 2014).

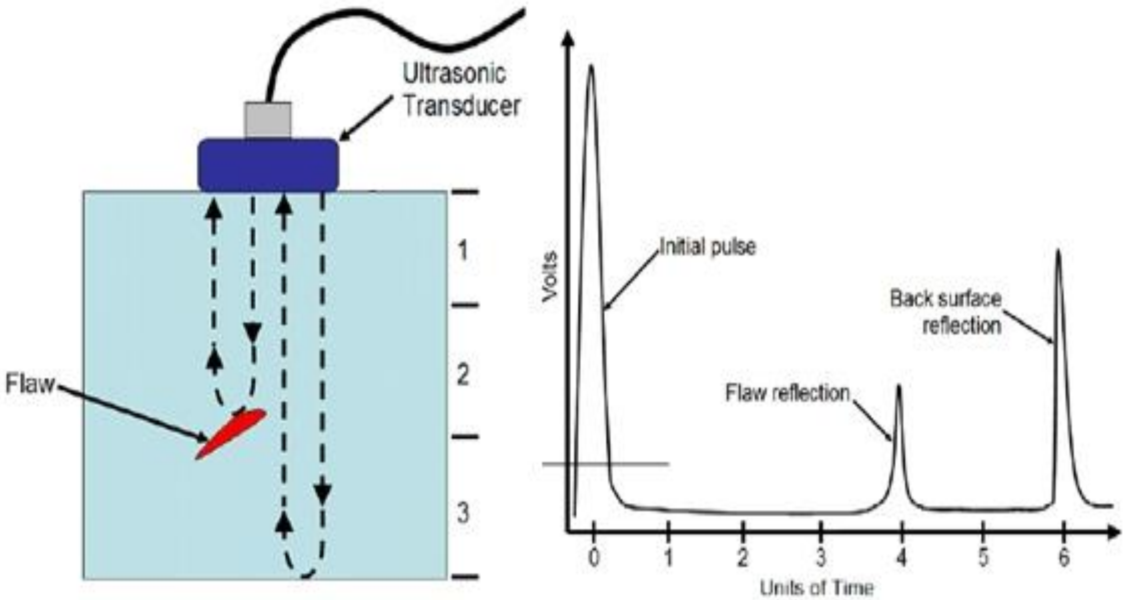

Figure 11 Ultrasonic flaw detection in metal structure
Source: Worcester NDT (2016)

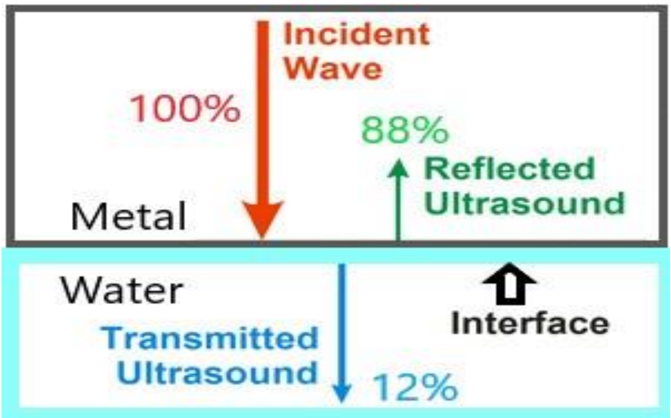

Figure 12 Ultrasound reflected by a metal-water interface
Source: modified from KARL DEUTSCH (2019)

The diver is responsible for placing or transporting the transducer (probe) as well as for ensuring a good view to the inspector and the control room through the camera and the illumination equipment. The diver is unable to obtain any output data on the transducer (see Figure 13), all data will be directly sent to be analysed and displayed in the control room (R. Frank Busby Associates, 1978).

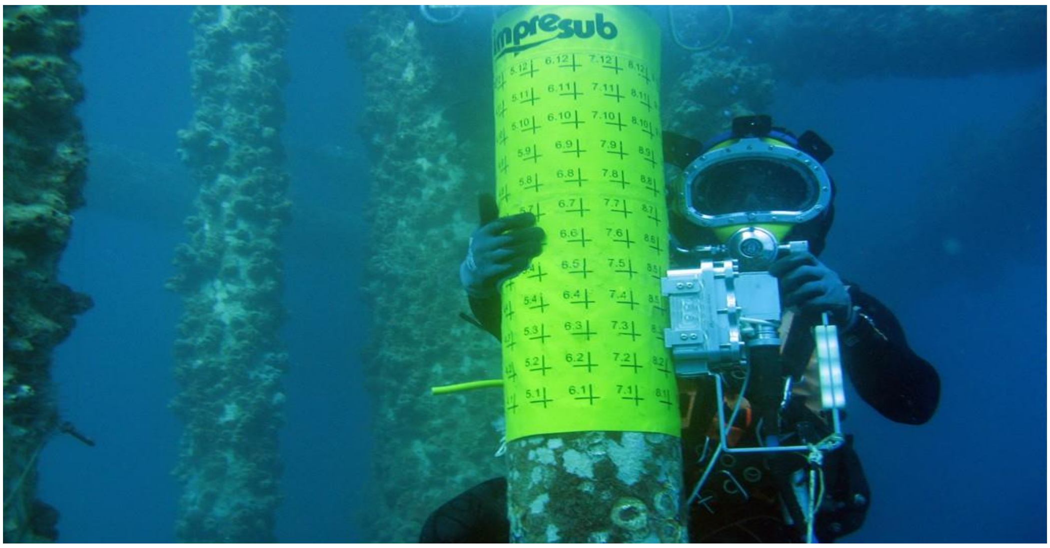

Figure 13 Diver placing the transducer on a subsea structure for an ultrasonic inspection
Source: Impresub (2019)

3.2 MARINE GROWTH

3.2.1 Marine growth guidelines and legislations

Different guidelines and legislations are set by standardisation institutes such as the Det Norske Veritas (2016) and the British Standards Institute (2005). These rules are meant to control the marine growth communities on offshore structures.

These guidelines are often set on standards derived from North Sea studies, which do not represent the marine growth development nor the activity worldwide. In addition, to overcome the latter, the IACS (2016) recommended that each unit designer and owner shall develop their own marine growth study in regards to the unit's location. The study shall be approved by the unit's classification.

The unit designer has to consider the biofouling performance at the unit's location, in order to ensure the appropriate design tolerances.

3.2.2 Marine growth development

The biofouling development can be more rapid in areas with waves and tidal differences, such as in the splash zone, when compared to total submerged areas with less active water movements (Macleod & Miller, 2016).

The offshore industry concerns can be summarised as follows, when considering the marine growth effects of the underwater structure:

a) biofouling weight added to the structure weight
b) underwater structure thickness
c) surface roughness
d) corrosion
e) impacts on sensitive points
f) inspection accessibility

Figure 14 Marine growth development on an offshore structure
Source: Shutter stock (2020)

Marine growth can considerably increase the weight of the underwater structure, which can influence the unit's physical properties in regards to buoyancy and susceptibility to fatigue. The added biofouling weight to the original structure is to be defined in advance, within the unit design's environmental studies. The difference in weight depends on the biofouling volume colonizing the underwater structure, i.e. relative proportions of hard, dense species and soft, less dense species (Macleod & Miller, 2016). The increase in the biofouling thickness will not only affect the weight, but it will also change the underwater diameter of the structure. This will directly affect the structural drag (API, 2003).

When it comes to surface roughness, the marine growth development will eventually modify the surface roughness of the underwater structure. This change will influence the dynamic loads caused by the unit operation, as well as the hydrodynamic loads caused by the water movements on the underwater structural parts. The variation in dynamic loads can directly affect the underwater drilling unit performance or any other equipment used for the underwater offshore industry.

The marine growth can influence the corrosion rates by causing a mechanical damage to the protective coating and by alerting the chemical environment at the surface of the metal.

As previously mentioned, the marine growth development will increase the loading on the underwater structure, which will enhance the corrosion fatigue process (Edyvean & Videla, 1991). In addition, the marine growth will enhance the structural corrosion through corrosion metabolites such as MIC or by damaging the activity of the corrosion protection system (see section 3.3) (ISO 19902, 2007). Additionally, the marine growth can influence the corrosion rates by causing a mechanical damage to the protective coating and by alerting the chemical environment at the surface of the metal interface (i.e. caused by MIC).

An underwater offshore unit has sensitive points which are considered to be any equipment or structure considered to be inefficient or non-functional due to the marine growth development (such as the sea chest, sensors, wet connectors, sensitive drilling equipment, etc.). The marine growth impact on sensitive points will have a negative effect on the operational properties of these equipment.

As previously stated, divers need to have clear view on the submerged part for inspection. The marine growth development will limit the divers and ROV to deliver the full image to the surface to present a clear and detailed underwater inspection. In addition, the biofilm development might be the cause or cover an existing damage on the structure.

3.2.4 Marine growth thickness levels

A. <u>The design thickness:</u>

The design marine growth thickness is included in the unit design calculations. The design thickness is the ideal thickness to maintain on the underwater structure as it represents the actual fatigue assessment plan designed for this unit. This thickness is defined as a range of t_{d1}- t_{d2}; t_{d1} being the minimal design thickness development and t_{d2} being the maximal design thickness development.

If t (illustrated in Figure 19) of the unit is calculated within the design rage, no removal is required. If t is calculated to be higher than that average (t_{d1}- t_{d2}), then the thickness will be considered excessive, see section B. The design thickness range is to be issued and approved by the unit's class (IACS, 2016).

In some cases, the unit might have a different marine growth design thickness for different locations on the structure. This can be due to multiple reasons, such as (ISO 19902, 2007):

- → coated or uncoated surface (biofouling)
- → fitted with CP or not
- → important difference in depth (less oxygen and light at greater depth)
- → higher water movements at some locations (which might affect the marine growth developments)
- → high difference in temperatures with depth

B. <u>The excess thickness</u>

The excess thickness is when the marine growth development becomes too thick and consequently too much for the structure to withstand the extra load. The latter will cause unpredicted damages to the structure which were not included in its fatigue assessment.

If cleaning is required only to reduce the thickness (mass), there is no need for a full cleaning. A partial growth removal can be conducted to reach the design thickness range t_{d1}- t_{d2}. The full cleaning will only be conducted in case a bare metal steel cleaning is required (i.e. for structure inspection purposes).

The excess thickness must be determined by the unit designer, which will be regularly monitored by the underwater inspection during the unit life service (ISO 19902, 2007).

C. <u>The stable thickness</u>

The stable marine growth is the expected accumulation thickness on the structure without the need of a cleaning process.

As described in section 3.2.5.2, a rapid development occurs during the first year. In some locations, the environmental circumstances limit the marine growth development, which will result in a maximum thickness smaller than the excess thickness level. It therefore represents a situation which will remain stable for the structure service life.
In case of a stable marine growth thickness situation, the unit designer shall include the stable thickness damages in the fatigue assessment calculation (ISO 19902, 2007).

In addition, an underwater survey will be required to inspect the stability of the marine growth. The latter will be conducted every year during the yearly underwater survey (IACS, 2016).

3.2.5 Marine growth inspection

3.2.5.1 General

Marine growth has been a major problem for the unit owner, designer and the inspectors who are deemed to ensure a complete survey to show the real underwater structure status and plan for future inspection and maintenance.

The marine growth impact on the structure dramatically affects the structural strength and other factors, as mentioned in section 3.2.2. The prevention and cleaning process shall be thoughtfully considered in the unit design and a detailed inspection plan shall be developed for the entire unit service life. Moreover, this plan is to be adapted during the unit’s lifetime if needed, based on the outcome of the inspection.

The marine growth prevention starts when the unit is being designed. The unit owner and designer have to follow the recommendations of the IACS (2016) and the unit’s classification. This will protect the underwater structure from any damage that might be caused by marine growth. The latter can be done by using specific materials, antifouling coatings and by implementing the CP system.

During the unit service life, the underwater structure has to be repeatedly inspected in order to ensure that the system is working as planned. In addition, the in-service inspection will help to analyse the current situation of the underwater structure and adapt the original plan if needed (Jusoh, 1996).

3.2.5.2 Inspection scope

Offshore metallic structures need to be built to withstand hazardous risks imposed by local conditions. The marine growth is considered to be one of the environmental factors that might endanger the unit's structural strength during its life service.

In order to overcome this possible structural damage, the designer shall include an additional environmental damage allowance calculated in regards to the expected service life of the structure and the fouling severity on the structure based on the local environmental studies (see section 3.2.1). The marine growth can be hard to predict due to study uncertainties and the difference of fouling composition due to several factors, such as seasons, depth, etc. (International Society of Offshore and Polar Engineers, 2004).

Once the unit is installed in place, the marine growth will colonize the structure. The first development will be very fast. After a year, the development will continue but at a slower rate compared to the first year. This difference in rate is highly unpredictable regarding the unit operation, the species compositions, the water movement and the temperature in addition to the adopted anti-fouling methods (ISO 19902, 2007). The reduction of marine growth developments is to be followed-up by the underwater inspection after the unit installation on site.

The first step of the marine growth inspection is to identify the general structure roughness, determined as either smooth or a rough (ISO 19902, 2007). This is performed visual as a general inspection and possibly followed by extra measurements and studies post the underwater inspection.

During the visual inspection, the diver and/or the ROV operator shall, besides the general roughness, check for the following:

- marine growth colour appearance
- damage or abnormalities in the marine growth developments
- the marine growth obstructing any equipment that is fitted or forms a part of the structure.
- marine growth abrasion

Besides visual appearances, measurements also take place:

- thickness measurements (illustrated in Figure 15)
- surface roughness (illustrated in Figure 19)
- column diameter measurements

If needed samples will be taken for later analyses in a specialised lab

Figure 15 Marine growth inspection measurements by an ROV
Source: Marine insight (2015)

The splash zone is to be inspected at all times for marine growth surveys. No marine growth surveys are not to be conducted for the structural parts below 30 meters in depth, knowing that the marine growth is limited by depth in most cases, unless otherwise proven in the pre-study conducted during the unit design (Macleod & Miller, 2016).

3.2.5.3 Inspection and cleaning limitations

An underwater inspection is more complicated and time consuming than a surface or an atmospheric inspection. The latter might require less preparation or be more easily conducted. The underwater inspection will require more advanced planning and preparations to overcome the limitations imposed on divers and ROVs below water. Many of the underwater inspection techniques require a marine growth cleaning to ensure a clean surface ready for a detailed inspection.

a. Simple cleaning

The cleaning can be done by simple means and be limited to small surfaces (i.e. manual brushing). The latter will affect the underwater visibility and limit the diver's ability to transmit clear images to the surface.

b. <u>Advanced and deep cleaning</u>

The cleaning can be done by more advanced methods such as the use of water jets, which are considered to be cumbersome and potentially dangerous to the operator (diver). In addition, the inspection shall not take place immediately after a large surface cleaning, knowing that the underwater visibility will be completely affected by the marine growth debris floating all around the structure, as illustrated in Figure 16.

Needle gun cleaning is not recommended to be used on sensitive surfaces (such as sacrificial anodes, joints, etc.). The pressure impact caused by a needle gun is considered to be high enough to damage the sensitive surfaces and to be the main reason for structural mechanical damage (R. Frank Busby Associates, 1978).

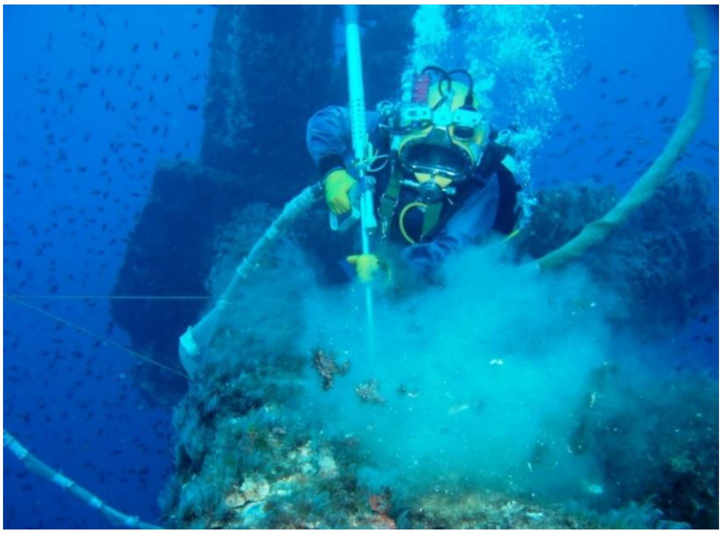

Figure 16 Underwater cleaning by diver using a needle gun
Source: Mermaid (2019)

The ideal situation for large surfaces is to be cleaned by means of automated vehicles, as illustrated in Figure 17. However, this can be challenging for offshore structures considering the complex underwater structural (tubular design) (R. Frank Busby Associates, 1978).

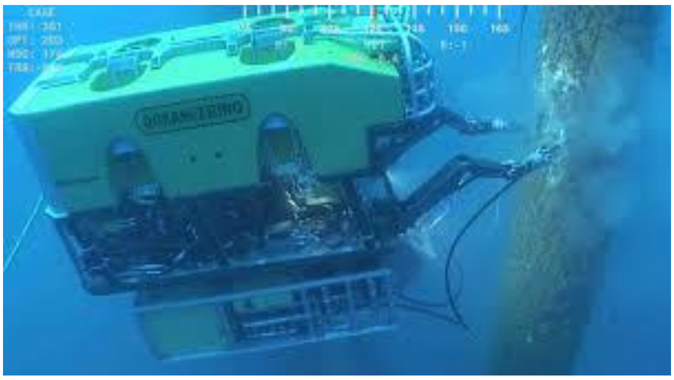

Figure 17 Marine growth cleaning by an underwater operated vehicle
Source: Restivo & Brune (2016)

c. Clean surfaces:

For NDT purposes, the marine growth cleaning of a structure always mentions the expression of a clean surface; however, it rarely defines the extent of the clean surface.

A surface can be cleaned to different extent. It can involve partial cleaning to reduce the marine growth thickness to keep the biofilm development on the structure under the design norms (see section B). The surface can be cleaned to bare metal but we can always have organisms' imprints on the structure, as illustrated in Figure 18. This will limit the inspection from detecting small damages or cracks (i.e. hairline cracks) on the inspected surface.

Figure 18 Marine growth imprints after cleaning
Source: Restivo & Brune (2016)

However, to obtain a bright clean surface, a hard cleaning is necessary which will most likely result in mechanical damage due to abrasion (R. Frank Busby Associates, 1978). The inspector and the unit operator shall have the call to promote the cleaning level to bright metal (and risking the expected mechanical damage), if they see that an advanced and detailed inspection is required.

3.2.5.4 Post underwater inspection:

The marine growth thickness is believed to be environmentally dependent. A full inspection study must be conducted by the unit designer in collaboration with the owner after the underwater marine growth inspection. This study methodology and the calculations (formulas) must be approved by the unit class (IACS, 2016).

Several marine growth inspection methods were developed to obtain a general idea about the type, composition and the severity of the species development on the underwater structure. The marine growth underwater inspection must include the following:

- species composition
- percentage of coverage
- average thickness
- surface roughness
- additional weight calculation
- cleaning strategies (if needed)

The marine growth diameter is to be calculated based on the following formula (ISO 19902, 2007):

$$D = Dc + 2t$$

→ *D*: the calculated marine growth diameter

→ *Dc*: the bare steel diameter without marine growth (or the diameter after cleaning)

→ *t*: the average marine growth thickness

The marine growth roughness is to be calculated based on the following formula (ISO 19902, 2007):

$$e = \frac{k}{D}$$

→ *e*: being the calculated marine growth roughness

→ *k*: being the marine growth average peak to valley height

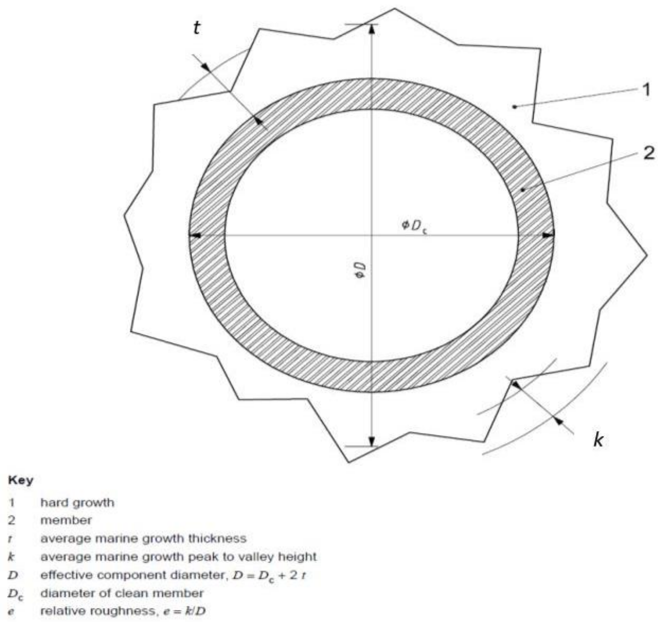

Figure 19 Definition of surface roughness height and thickness on an underwater tubular steel structure
Source: ISO 19902 (2007)

These calculations will help the unit inspector and operator to define the marine growth development rate and change in roughness and thickness. These elements will be recorded in the inspection report, which will be used to compare with previous and future underwater inspection.

3.2.6 Marine growth cleaning

3.2.6.1 General

The underwater surface cleaning depends on the development rate of the marine growth, see section 3.2.3 or the NDT inspection requirements. All methods used for non-destructive testing, except radiography, require a structure cleaning prior to inspection. Structure cleaning involves the mechanical removal of marine growth, loose paint and rust. The cleaning is a long procedure which normally takes more time than the inspection itself. Nowadays, the cleaning is mainly done by means of robots and automatized machines, in case big structure section cleaning is required.
The cleaning will be conducted based on the original design plan, in addition to the in-service inspection findings. As described above, the marine growth development depend on multiple factors, directly influencing the cleaning level and frequency (Jusoh, 1996).
For both reasons, cleaning is reduced to a minimum during the unit service life.
For the above mentioned reasons, the marine growth cleaning shall be conducted based on the cleaning plan (designed for the service life) and when required by the inspector (Kelly, 1999).

3.2.6.2 Marine growth cleaning tools

To perform an advanced underwater inspection, the marine growth has to be cleaned in order to prepare the structure for inspection (NDT). The cleaning can be done by various methods. The cleaning method is to be specified by the inspector taking into consideration the inspection requirements and area of inspection.

For simple cleaning a wire brush can be used on very small surfaces. Wire brush cleaning is believed to consume most of the diving time and the diver’s energy. Moreover, the diver is always required to carry a wire brush during the dive.

For a more advanced marine growth cleaning, which includes large surfaces cleaning, different equipment can be used (Kelly, 1999):

- Divers:
  - → hydraulic grinder
  - → high-pressure water jet
  - → cleaning machines operated by divers (illustrated in Figure 20)
- Automated vehicles; ROV equipped for cleaning purposes:
  - → manual operation: an operator conducting the vehicle from the surface
  - → automatic operation: a pre-programmed vehicle, where the machine will be self-propelled on the structure by means of integrated structure mapping in addition to the machine sensors. The self-propelled type is recommended for flat large surfaces, but not for tubular legs.

Figure 20 Cleaning machines operated by divers
Source: West Africa Marine Service Limited (2016)

3.2.7 Marine growth prevention

The marine growth development has been a massive challenge for the offshore sector. To minimise the damages resulting from the biofouling, different antifouling methods have been used such as antifouling coatings and CP systems. Throughout the years, the CP can be an effective corrosion preventive method (Eashwar et al., 1995).

In order to protect the unit against marine growth with a long term expected service life (20 to 25 years), a combination of antifouling paints and CP systems are most effective to tackle the marine growth developments' problem on the underwater offshore structure (Macleod & Miller, 2016).

3.3 INSPECTION OF THE CORROSION PREVENTION SYSTEM

3.3.1 General

To achieve the optimal design, construction and proper in-service inspection of corrosion protection systems, a clear set of technical recommendations and guidance should be applied. In addition to the inspection and maintenance programs of the corrosion protection systems during the unit's operation, corrosion control shall also include the following (DNV-GL, 2016):

- Corrosion Allowance (CA)
- Cathodic Protection (CP)
- Corrosion protective coatings
- Corrosion resistant materials

The corrosion control system in service inspection is a periodic activity to be conducted during the structure's operational life. This inspection will give the unit operator a detailed view of the physical condition and integrity of the corrosion control system. The corrosion control inspection consists of the following elements:

- visual underwater inspection of the CP system
- protective coating visual inspection
- visual underwater inspection of the structure corrosion and thickness measurements
- regular recording of data associated with corrosion control

The inspection and monitoring strategy shall take into account (ISO 19902, 2007):

- the critical and weak points of the system
- the type and severity of the corrosion environment
- the inspection and monitoring tools capabilities (limitations)
- the accessibility limitation of the area to be inspected
- the outcome of the previous inspection

The corrosion protection and consequently also inspection, depends on the structure level. Figure 21 identifies the different levels.

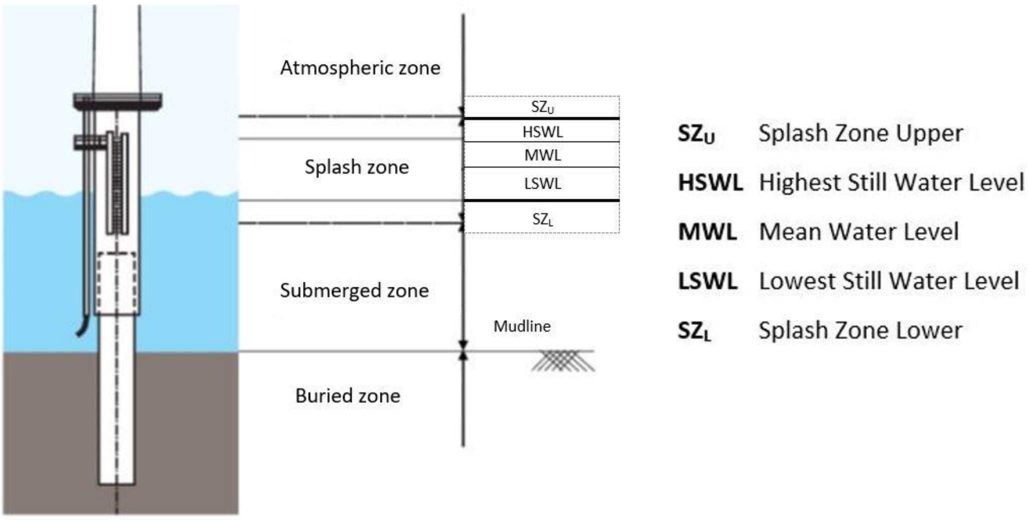

Figure 21 Schematic representation of the structure different levels
Source: DNV-GL (2016)

The splash zone is to be identified by the unit designer, based on the unit's location including the water level movements. The splash zone limitations of a structure are to be approved by the unit's class. Furthermore, the SZU-MWL distance must extend to at least one meter in order to create a splash zone (distance SZU-SZL) with two meters as a minimum (IACS, 2016).

CA is not required for the zone located below the splash zone lower SZL. The submerged zone is assumed to be protected by the CP system, see section 3.3.3.

Structural airtight compartments that are completely sealed are difficult to obtain. For example, the interiors of monopiles are accessed for periodic inspection and repair; thus, they are not considered completely sealed (Sirris, 2019). Another factor is the variation of internal water levels due to large differences in tide (location dependent).

Considering the internal structure of a brace located in the submerge zone, the CA rate is determined to be a minimum of 0.1 mm/year without the CP or the coating application. For this reason, it is not recommended to have flooded members in the splash zone (DNV-GL, 2016).

The structural designer must pay close attention to the galvanic corrosion, which occurs as a result of the combination of metallic materials with different electrochemical characteristics. Electrical insulation or CP are two actions that can mitigate this effect.

3.3.2 Coating inspection

3.3.2.1 Coating break down factor

The coating breakdown is a measurement value expressed from zero to one. If the coating breakdown is zero, this implies that the coating is 100% electrically insulating. If the coating breakdown factor increases, this implies a reduction of the coating electric insulation. Thus, a coating can be considered with no current reducing properties if its breakdown factor equals to one.

The coating breakdown is more related to the coating property and not directly related to coating damages. Additionally, a coating showing an extensive damage (such as blistering) may still retain more electric insulation than a perfectly coated surface (DNV-GL, 2016).

A mechanical damage during the unit installation or during the operational life of the unit can increase the coating deterioration, reduce the coating service life and directly affect the coating breakdown factor. Thus, the designer must take into account an initial reduction in the coating breakdown factor caused during the unit operational life, in accordance with the coating mechanical damage and ageing (NORSOK M-501, 2004).

3.3.2.2 Splash zone

The purpose of a corrosion control system shall be planned in a manner to resist the impact of the splash zone's severe environment, which may include chafing due to supply vessels and drifting ice in some areas. In addition to the impact, the sever environment also enhance the structure corrosion and fatigue. The corrosion control system protects both the external and internal surfaces of the splash zone steel structures. For external surfaces, it is mandatory to use a coating system based on manufacturer specific materials which shall be approved by the unit's class.

In the splash zone, it is assumed that a coating system based on epoxy has a useful life of up to 15 years. It is essential that this coating system meets the requirements for coating materials and quality control of both surface preparation and coating application followed by the NORSOK M-501 (2004) Coating System No. 7A (minimum dry film thickness of 600 µm). On the other hand, a coating system based on glass-flake reinforced epoxy or polyester (minimum dry film thickness of 700 µm) has a useful life in the splash zone of up to 20 years. In order to design for the proposed coating useful life, it is mandatory to pre-qualify these coating systems in accordance with a recognized standard followed by the unit's class (IACS, 2016).

The splash zone coating system and manufacturer must be selected with due consideration to the surrounding conditions of the structure, including:

- damage to structure due to chafing of supply vessels
- damage to structure due to other mechanical operations of the unit
- the metocean conditions at the location of the unit (such as currents and waves)
- damage to structure due to the ice chafing (if applicable)
- the frequency of marine growth removal

The combination of the applied coating with a CA is recommended. However, for certain applications, corrosion resistant alloys are considered as an alternative (DNV-GL, 2016).

3.3.2.3 Submerged zone

The owner and the designer of the unit shall take into account the structure steel composition and the environmental conditions of the unit location when choosing the coating composition of the submerged section. In addition to the design life, the maintenance budget and the unit operational cost must be considered.

Organic coatings are semi-permeable membranes, it protects the steel by acting as a kind of barrier to water and oxygen. This phenomenon will delay and decelerate the corrosion process of the metal if the coating is applied correctly (DNV-GL, 2016). The corrosion process will initiate from the base of holidays, bare patches and pin holes on a coated surface.

If the underwater structure should be coated, importance should be given to the inspection process to be followed of such surfaces. In particular, the coating should not include spots of the structures that require frequent inspection for fatigue and damage assessments such as weld joints and openings, among others. If this is the case, then a corrosion prevention alternative (such as a combination of coating and CP) should be applied to protect such surfaces, as described in section 3.3.6.

3.3.2.4 Splash zone internal surfaces

The internal surfaces of the splash zone structure (such as the inner tubular structure) are not mandatory to be coated (DNV-GL, 2016). The owner will decide, based on the design plan and the structure location, whether or not to coat the inner splash zone structure. The necessary CAs for these surfaces are calculated differently, as explained in section 3.3.5.

In some cases, where the structure is exposed to a limited wear, tear and UV exposure, similar to monopile internals, the lifespan of the applied coating system may be extended beyond the design lifetime. In order to determine whether the extended coating lifetime is reliable, evaluations must be conducted on a case-by-case basis following the structure design and the unit's class standards. Corrosion can still be induced by anaerobic bacteria even in complete absence of oxygen in the seawater (DNV-GL, 2016). The latter must be considered while assessing the options for corrosion control of internal compartments.
If the submerged zone compartments are not airtight, coating the internal surfaces shall be considered (DNV-GL, 2016).

3.3.2.5 Inspection scope

The underwater coating inspection is mainly performed by a general visual survey to assess the damages of the surface structure. A detailed visual examination will allow to detect any corrosion developments or coating damages of the surface (ISO 19902, 2007).

Based on the visual examination outcome, the surveyor shall develop an inspection plan to analyse the extent of the damage and its reflection on the structure integrity. The inspection plan should be based on thickness measurements and/or other non-destructive testing methods, as described in section 3.1 (NORSOK M-501, 2004).

3.3.3 Cathodic Protection (CP) inspection

3.3.3.1 General

The preferred CP technique of the underwater structure of offshore units is sacrificial anodes cathodic protection (SACP) (DNV-GL, 2016). The SACP design verification, installation and monitoring system must be performed by a qualified firm approved by the class. Moreover, in regards to documentation of personnel competence, adequate measures and certification schemes shall be according to EN 15257 (2017).

Some structures may be located in waters with strong seawater currents, such as in shallow waters with large differences between HAT and LAT. To account for the effects of seawater currents, it is recommended that the initial SACP design current (preferably specified in the unit design) be increased by 50% for all initially bare steel surfaces. Specific site considerations are advised as this value changes drastically depending on the metocean of the unit location (DNV-GL, 2016).

The SACP shall utilise Al or Zn based materials, in compliance with the applicable CP design standard issued by the owner and approved by the unit's class (ISO 15257, 2017).
The design life of the CP system must be equal to or greater than the design life of the structure, unless otherwise specified by the owner.

3.3.3.2 Splash zone

The presence of tidal actions and waves will result in an intense corrosive environment at the splash zone. It can be challenging to maintain the corrosion protection system, it is not effective to implement a CP for this zone (DNV-GL, 2016).

In areas with large tidal zones, all anodes should be located at least 1.0 m below the LAT (ISO 15257, 2017). The surface area up to HAT must be considered for CP design to calculate the initial current demand.

3.3.3.3 Submerged zone

The submerged zone of an offshore unit shall be fitted with a CP system to ensure the protection of the metal. The submerged zone is considered too large to be coated. Therefore, the CP system proved more efficient than a coating in this zone (ISO 15257, 2017).

The following aspects, considered for the distribution of anodes, are based on the calculated number of anodes required for different zones of the structure (DNV-GL, 2016):

- anodes must be uniformly distributed over the entire submerged structure.
- no anodes are to be fitted in the splash zone (higher than the SPL; or less than one meter from the MWL).
- anodes should be located as close as possible from a critical point but not closer than 0.6 meters.
- the anode shall face the centre of the structure, if it is located on a leg.
- the anodes shall be placed on the upper and lower surfaces of a diagonal structure, if more than one is required.
- the anodes shall be placed as follows on a horizontal surface:
  - → alternately facing up and down (except on the uppermost level of the structure)
  - → facing downwards on the uppermost level of the structure

The anodes' locations shall be carefully chosen. They should not to be fitted close by a structure and/or element restricting the good operation of the unit (see Figure 22).

Figure 22 Correct positioning of anodes on an underwater offshore structure
Source: Aberdeen Foundries (2020)

3.3.3.4 Underwater internal surfaces

As a backup for the coating damage on internal surfaces exposed to seawater or sediments, a CP shall be applicable. With or without a coating, CA and the use of CP have the ability to independently protect internal surfaces of the submerged zone.

The CP may be used inside the monopoles for internal protection. However, it is important to monitor the effectiveness of the SACP in the enclosed areas. The latter might weaken the system due to a difference in the pH level. A low pH level translates to a significant reduction of the current output of galvanic anodes.
The use of the ICCP systems for the internal submerged structure can ensure a controllable and flexible corrosion prevention system. Even at low pH levels, they have the potential to be designed to supply optimum protection (DNV-GL, 2016).

3.3.3.5 Buried zone

The application of SACP comes with the consideration of current drain to any buried internal surfaces like those of skirts, piles and J-tubes. With consideration to varying seabed levels due to migrating sand dunes, all anodes should be located at least 1.0 m above the seabed (ISO 15257, 2017). This is done to prevent the possibility of the anodes being covered by sand. It is important to note that corrosion may be caused by anaerobic bacteria in the uppermost buried zone, but a functional CP may prevent this.
Although corrosion protection is not needed for steel surfaces when buried in deep sediments, they will still drain current from a CP system (DNV-GL, 2016).

3.3.3.6 Inspection scope

The forces a structure undergoes during installation and operation play a vital role in the design of anode supports and their fastening to the structure. For this reason, the SACP inspection design shall at least consider an underwater survey once the structure is installed on site and regularly during the structure operation in accordance with the original SACP design calculations and its lifespan (DNV-GL, 2016).

If a SACP design is applied to a structure, the system shall be enforced and operated as soon as the structure is installed on site. A CP survey shall be conducted once the installation is completed. The latter will ensure that the CP system is not affected by the operation.
In addition, another CP survey is to be planned within a one-year period of the installation date to check and test the CP system operation and finally, to issue a one-year CP inspection report which will define the future CP inspections. Moreover, based on the one-year CP inspection report, the operator will have an indication of the system effectiveness and the CA calculations.

The underwater CP inspection is mainly performed with a general visual survey of the fitted anodes in addition to potential measurements (see section 0). Based on the visual examination and the potential measurements outcome, the surveyor shall develop an inspection plan in order to prepare a general assessment of the corrosion protection system of the structure (ISO 19902, 2007).

The CP inspection shall include monitoring of the following (Kelly, 1999):

- mechanical inspection:
  - → any signs showing the loss of anodes
  - → wear of anodes
  - → disconnected wires
  - → damage to anodes
- electrical inspection:
  - → potential measurements
  - → detection of low/high voltage

The CP inspection shall extend from the uppermost part of the submerged zone to the seabed. The inspection could be conducted by a diver, ROV or a combination of both. The latter shall only take place if the weather circumstances allow it, in order to obtain clear and exact voltage measure readings.

A. *Potential measurements*

The CP inspection shall be conducted regularly to ensure the performance of the corrosion prevention system to be functional at all times. The measurement outcome are used to analyse the effectiveness of the CP system.

i. <u>Measurement techniques:</u>

The CP system potential measurements are accomplished by measuring the potential difference between the structure and the ambient sea water. This is performed using hand-held equipment by a diver (illustrated in Figure 23) or by equipment mounted on an ROV (illustrated in Figure 24), which can accomplish the entire job without any diver assistance.

Figure 23 CP potential measurement by diver
Source: Bartuli et al. (2008)

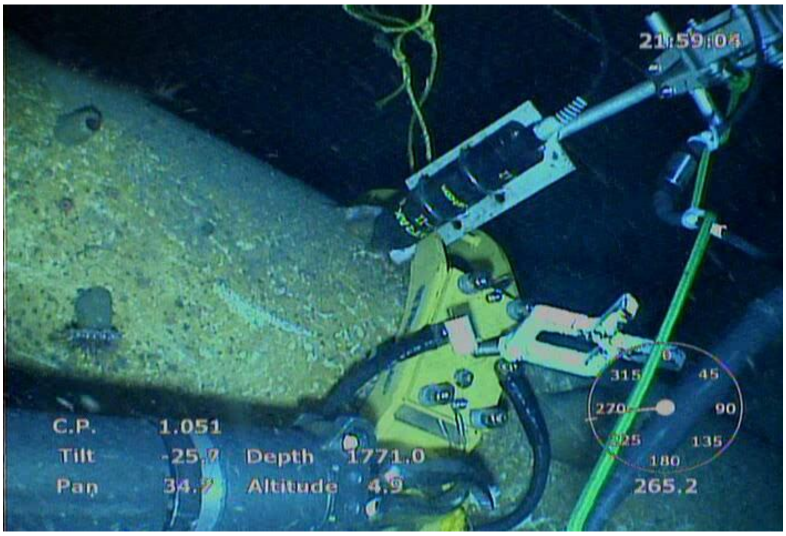

Figure 24 CP potential measurements by ROV
Source: Deepwater corrosion services (2020)

An underwater voltmeter shall be used to measure the potential of the CP system mounted on the underwater structure (Kelly, 1999). The equipment is meant to measure the potential difference and illustrate the measured figure on the equipment output to show the diver or the ROV operator the sign of a correct reading. Then, this output will be recorded with the exact time measurement. The potential measurement records are to be used for the inspection reports, as described in section 3.7. Furthermore, the inspector will issue a detailed CP measurement in regards to all the inspected locations on the underwater structure.

The measurement procedure starts by placing the probe on the surface structure, then the display outcome is checked to ensure a correct reading. Minimal cleaning of the structure is required to safeguard a bare metal contact for correct potential readings. For the underwater inspection, a double point probe is used to ensure a better surface contact.

If the measurements are conducted by means of ROV, the operation will be as follows (R. Frank Busby Associates, 1978):

- the vehicle operator will locate the measurement location.
- the inspection location will be cleaned, if required (spot cleaning).
- the probe is located in place.
- the vehicle is put on forward motion to ensure a successful probe-structure contact.
- once the potential reading is obtained, the measurement outcome as well as the time will be recorded.
- some ROV’s have their special positioning system which might be automatically synchronised with the measurement to identify the location. If this is not the case, the outcome shall be saved under the reference of the inspected location.

It is believed that it takes up to one minute to accomplish one position CP measurement (by an ROV), not including the cleaning operation possibility. The probe measurement method cannot be used on a heavy coated structure (DNV-GL, 2016).
No time records were found to represent a CP potential measurement by divers. The latter is depending on the skills and experience of the diver.

ii. <u>Measurement outcome:</u>

Table 1 Underwater CP potential measurements
Source: modified from Shawn W. Kelly (1999)

Potential measurement (V)	Description
0.0 to - 0.7	The structure is cathodically unprotected. The corrosion rate will be a factor of the surrounding environment and in consideration to the supplement corrosion protective measures applied to the structure (such as protective coating). As the potential value is high, the corrosion is considered to be active.
-0.7 to - 0.82	The structure is partially protected.
-0.83 to - 1.1	The structure is adequately protected. The corrosion prevention system is working efficiently.
- 1.1 and lower	The structure is cathodically unprotected. The structure is considered to be overprotected. The structure might be damaged due to the high potential voltages. Damages can appear in forms of coating damage or excessive formation of hydrogen bubbles.

A standard CP potential protection between -0.8 V to -0.9 V indicates an adequate functioning SACP, as illustrated in Table 1. A large uncoated structure might take up to 6 months in order to reach a steady potential conditions of -0.9 V (ISO 15257, 2017).

It has not been made aware by DNV GL (2016) that corrosion damage, including damage by bacteria, would ever be caused by a potential (IR free) in the range of -0.8 to -0.9 V. However, in this range, both the current output as well as the consumption rate of anodes is increased.

iii. <u>Measurement distance:</u>

Following the new electrodes developments, it is not necessary to position the electrode directly near the anodes, but the measurements could also be taken at a few meters from the steel surface. The distance depends on different probe efficiencies based on various manufacturers (up to couple of meters from the anode) (DNV-GL, 2016).

In addition, it is important not to position the electrode at a location where the current might be interrupted as this will result in an incorrect voltage reading (e.g. a weld can interrupt the voltage reading). During the CP potential recording, if the inspection indicated a potential less negative than -0.9 V, then an advanced CP potential inspection will be required (ISO 19902, 2007).

If a more advanced inspection is required to obtain a closer examination of the CP system performance, a detailed galvanic anode potential measurement is to be performed as part of a critical area sectional survey. The latter inspection will require to conduct a potential measurements with a maximum distance of 0.5 m from anodes (DNV-GL, 2016).

The general probe can operate up to a depth of 100 meters and at temperature of 0 to 60 ℃, with an accuracy of one mV (Aguirre-Castro et al., 2019). These figures are dependent on each equipment description and can change based on different manufacturers.

iv. Deposit layer removal:

The CP system potential measurements should always be performed before any deposit layer removal (ISO 19902, 2007). The anode and cathode potentials can be used to estimate the cathode current demand and the anode service life.

v. Coated surfaces:

In case of a heavy coated surface, a pre-defined method is to be adopted to ensure the CP potential measurements, such as a fixed connection to the bare steel metal (fitted under the coating layer) to ensure the full coverage of the underwater structure at different locations.

vi. Inaccessible surfaces:

CP measurements are only performed on the exterior part of the structure and the accessible ones. In other words, the outcome of the CP measurement inspection represents only the exterior corrosion preventative measurements of the underwater structure.

B. Anode consumption rate

In order to have an accurate and reliable outcome of the anode consumption rate, the galvanic anode inspection must be performed with a minimum interference of any deposit layers. The latter will limit the accuracy of the measurements.

If accurate consumption of anodes is required, a removal of the anodes deposit layer shall be performed (ISO 19902, 2007).

C. Fixed CP monitoring system

In some of the cases, the structure might be tailored with a fixed reference electrode recording system. The fixed system should be inspected as soon as the unit is installed in location and following with a yearly inspection to ensure its effectiveness and calibration. The calibration process will be performed by taking manual potential measurements. This is performed by an underwater intervention conducted by ROV or divers. The manual potential measurement outcome will be compared with the readings of the fixed reference recording system. Both measurements shall be performed under the same circumstances, at an approximately equal distance from the anodes and with a limited difference in time (with a maximum period interval of a couple of hours) (ISO 19902, 2007). This method ensures to have a continuous CP measurement. It also provides an immediate report after any suspected damage (such as environmental or operational) regarding the unit corrosion prevention system with no diver and/or ROV intervention.

D. CP inspection outcome

Based on the inspection results, a survey report must be issued including a potential measurement map, as illustrated in Figure 25 and Figure 26. The potential mapping will represent the entire underwater structure corrosion prevention system performance and will be used for further inspection planning.

In addition, the mapping will also serve for future comparisons of measurements to detect the critical sections of the submerged structure, indicated by an important difference in the potential measurement.

Note: the colour codes represented in the potential measurements mapping can be different from one software to another.

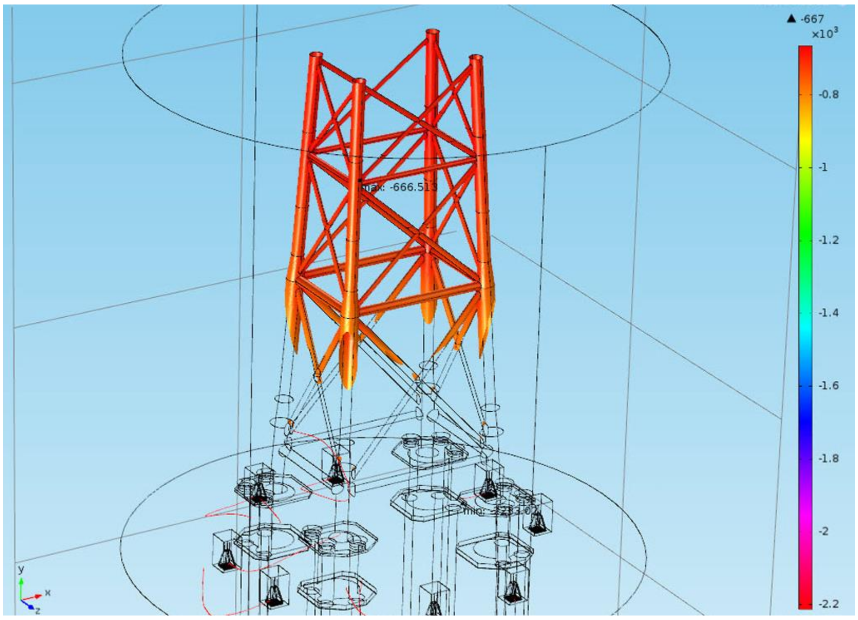

Figure 25 Potential measurements map for the upper half of the underwater structure
Source: CP modelling services (2020)

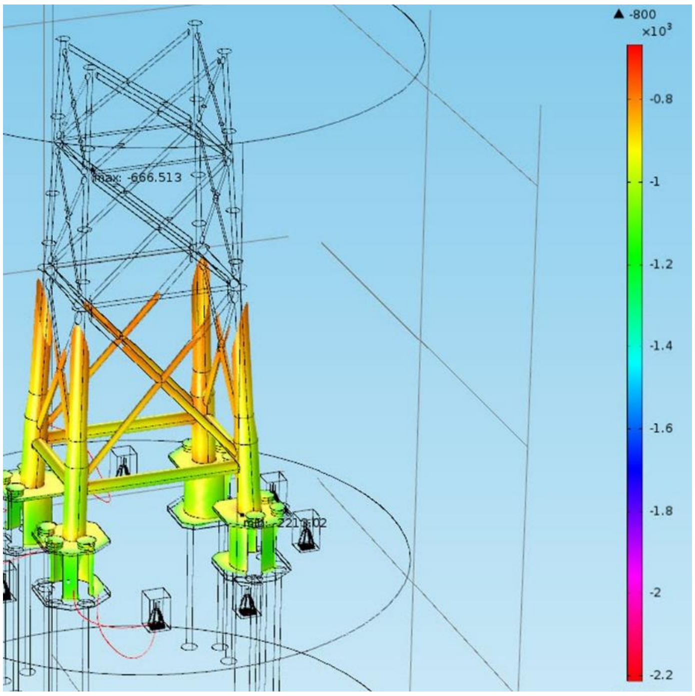

Figure 26 Potential measurements map for the lower half of the underwater structure
Source: CP modelling services (2020)

3.3.4 ICCP & SACP compared

The detailed design of an impressed current CP system (ICCP) focuses on adequate CP potential and current distribution, as well as the equipment's long-term mechanical reliability. This includes impressed current anodes, reference electrodes, cables and connectors with proper attention paid to wave forces, sea currents and other environmental parameters. Compared to SACP systems, ICCP are not as well equipped to withstand environmental and third-party damages. This is especially true for cables to anodes and the vulnerability of reference electrodes. The following factors are to be considered for the selection of SACP or ICCP, as illustrated in Table 2.

Table 2 Pros of the ICCP and SACP
Source: own collection

	Pros
SACP	• Maintains structure aesthetics and integrity • No independent source of electric power required • Limited effects on neighbouring structures • Anode connections are also protected • Correct material selection ensures no over-protection, thus avoiding metal embrittlement and coating damage • No possibility of plant damage due to incorrect connections • Straightforward to install, operate and maintain
ICCP	• Maintains structure aesthetics and integrity • Enhanced lifespan of the underwater sensitive structural surfaces • Anodes are sturdy, light and compressed • Non-destructive installation • Single installation needed for the structure

In case the ICCP anodes and reference electrodes are damaged by environmental factors or by any other causes, these elements are designed to be replaced unless the owner decides otherwise. The ICCP system must be designed with an emergency plan in case individual anodes or reference electrodes are malfunctioning or damaged. It is vital to include a contingency equivalent to at least 150% of anode current capacity based on applicable SACP (DNV-GL, 2016).

The anodes of an impressed current system shall be placed as far as practicable from one another with a minimum distance of 1.5 meters. This shall be proportional to the current magnitude. In addition, the ICCP anodes shall be fitted with dielectric shields in order to avoid over protection which help to create an adequate current distribution (DNV-GL, 2016).

3.3.5 Corrosion allowance (CA)

The CA for structures which are not protected by a CP system, such as the splash zone and the internal surfaces, can be calculated by the formula below (DNV-GL, 2016):

$$CA = Vcorr \times (Td - Tc)$$

CA: Corrosion Allowance,

V_{corr}: the expected maximum corrosion rate (see Table 3 below),

Td: the structure's design life

Tc: the coating's design useful life.

If the surface is not coated, we can assume that T_C=0.

The coating's design useful life T_C, shall be based on the manufacturer's coating specifications. The latter is achieved through relevant testing and proven operations, to finally be qualified for the coating system (NORSOK M-501, 2004).

Table 3 Minimum values for design corrosion rate (Vcorr) on primary structural parts in splash zone
Source: modified from DNV-GL (2016)

Region	V_{corr} external surface (mm/year)	V_{corr} internal surface (mm/year)
Seawater annual mean surface temperature ≤12℃	0.3	0.1
Seawater annual mean surface temperature >12℃	0.4	0.2

3.3.6 Combination of CP and coating

The CP must be applied to the surfaces of the submerged zone, which is the region below the lower limit of the splash zone. In this case, the primary intention of the optional use of the coating is to reduce the required CP capacity. In the absence of a CP, the use of a coating may reduce the dangerous effects of microbiologically induced corrosion (MIC).
The type of coating to be used in combination with the CP is to be approved by the unit class and provided by an approved manufacturer (IACS, 2016).

If the corrosion protection system includes both the application of a coating and CP, the coating to be applied shall be tested in advance to verify if it has an adequate resistance to overcome the cathodic disbondment. This might be caused by an interaction between the CP and the coating during the structure operation life (DNV-GL, 2016). If a coating is applied to the subsea structure of an offshore unit, the number of anodes to be installed for the CP system will be reduced. The determination of the number of anodes to be fitted on the structure is related to the following:

- intended structure life
- area of the bare metal (uncoated)
- coating type and thickness (if applicable)
- type of material used for the construction
- estimated corrosion rate taking into account the unit operation and the surrounding environment

The structure coating is assumed to degrade over time. The degradation rate of the coating is to be defined by the unit designer based on the type of coating and the corrosion protection used during the unit service life, in addition to the unit operation and environmental conditions. The coating degradation is defined as being the coating breakdown factor (see section 3.3.2.1).

Moreover, the coating breakdown must be considered as an important factor in the CP calculations because over time, the coating breakdown rate will increase due to more coating degradation and fatigue. The increase in rate will result in a decrease of the corrosion protection system. To overcome the coating breakdown and to maintain an acceptable corrosion protection system for the preservation of the underwater structure during its estimated lifetime period, the CP system must be enhanced.

3.4 NDT ADVANTAGES AND LIMITATIONS

The advantages and limitations for different inspection methods on an underwater steel weld are presented in Table 4:

Table 4 Showing the advantages and limitations of different non-destructive testing methods
Source: modified from Ship Structure Committee (1979)

Method	Defects	Advantages	Limitations
Visual	Surface cracks, impact damage	• Easy to interpret • Results can be photographed, live transmitted to the control room and a copy can be saved for the records • No electrical current needed	• Limited to surface defects • Surface cleaning is required for a detailed and clear metal observation
Magnetic particle	Surface cracks, laps, seams and some near-surface flaws	• Indications can be photographed, transmitted to the control room and a copy can be saved for the record	• Surface cleaning is required • Limited in the splash zone due to the weather and sea conditions • Limited to metal surface and near surface defects • Cumbersome equipment to be used by underwater divers • Electrical current is needed
Ultrasonic	Cracks inclusions, lack of fusion, incomplete penetrometer in welds and deep metal flaws	• Sensitive to cracks, • Can be used to evaluate subsurface integrity • Lightweight equipment • Result can be transmitted to the control room and saved for the record	• Surface cleaning is required • Operator skills are required • Surface roughness can affect the test result • Electric dependent
Radiography	Internal defects such as shrinks, inclusions, porosity, lack of fusion and incomplete penetration in welds	• Provides a permanent record • The most accepted method by codes and standards	• Potential health hazard • Both side access is required • Electric dependent
Corrosion potential	CP system testing by measuring the potential interface between the structure and seawater	• Easy to perform • Fast results • No sophisticated tools or equipment needed	• Marine growth cleaning is required • External potential measurements only

3.5 STRUCTURAL KNOWN DEFECTS FOR INSPECTION

3.5.1 General damages

The offshore underwater structure is known to face major types of damages if it was not inspected and maintained regularly. The general known damages of the underwater offshore structure can be described as follows:

- structural overloading
- abrasion (coating or marine growth)
- loosening of structural connections (bolts or other connections used to mount drilling equipment, if applicable)
- fatigue to joints and weak spots (such as openings, discontinuities, etc.)
- corrosion

3.5.1.1 Overloading

Offshore structures are susceptible to structural overload caused by various meteorological (such as, strong winds and high waves) and operational factors (based on the unit types of operation). The unit operation might also create a danger to the underwater structure. Other factors that might also cause overload to the underwater structure are any impact or damage to the structure due to external forces (other than weather related phenomena), such as the supply vessel impact leading to chafing at the splash zone (see Figure 27). These damages can cause structural overload and can be recognized by the formation of local deformation of the damaged section, as illustrated in Figure 28.

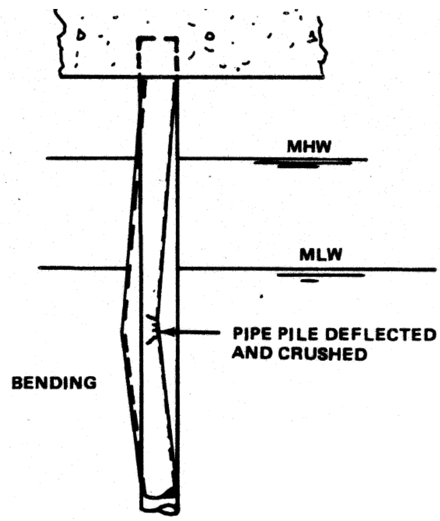

Figure 27 Structure overloading caused by collision or impact
Source: Shawn W. Kelly (1999)

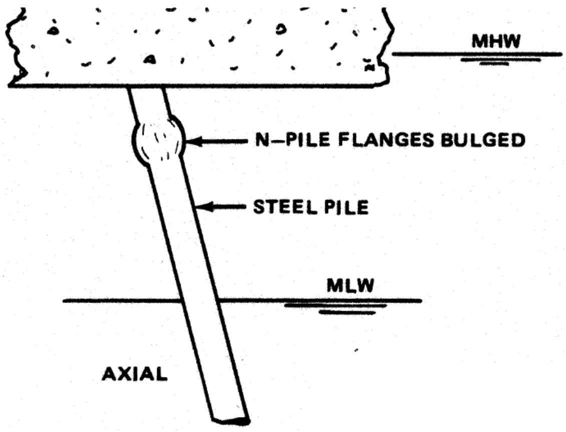

Figure 28 Structure damage caused by load accumulation
Source: Shawn W. Kelly (1999)

In some scenarios, major modifications to the unit will be conducted. These modifications can also be a complete shift in the unit operation, as mentioned in section 2.3.
In other words, it is possible that the unit will be structurally modified to operate and serve a different purpose than its original operational purpose for which it was built. In a major modification case, the new design must be approved by the unit's class and a detailed study to be provided in regards to the modification of the unit service life (IACS, 2016).

3.5.1.2 Abrasion

The abrasion can be caused by various factors, such as chafing, a powerful storm with strong waves and mechanical impact. In addition, the abrasion can be caused due to strong currents at the seabed causing sand chafing to the lower part of the structure.

The abrasion of layers that forms on the underwater structure can enhance and accelerate the corrosion process of the steel, coating damage (as illustrated in Figure 29) and sometimes even be the cause of structural damage (Kelly, 1999).

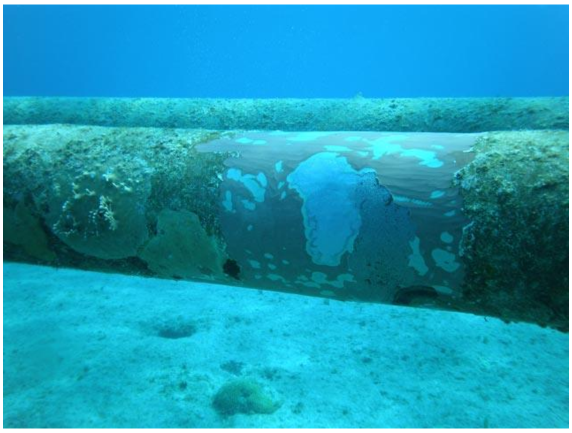

Figure 29 Marine growth and coating abrasion to an underwater offshore structure
Source: Emtedad training group (2017)

The underwater structure of an offshore unit might be protected by various means. The protection can be natural or manmade. The natural layer can be formed by the marine growth development or a protective layer of corrosion. The manmade layer on the structure can be ensured by protective coating. Both covers, natural or manmade can protect the bare streel from and reduce the corrosion rate at the surface.

3.5.1.3 Connection loosening

The underwater structure might be fitted with multiple equipment used for the unit's operation. Such equipment might be attached to the structure by means of welds, bolts or any other connection suitable for its purpose. The connections other than welding are at risk of becoming loose within the unit service life if not well inspected, maintained or replaced properly. The connections are also susceptible to corrosion (i.e. galvanic corrosion caused by the contact of two different materials). In addition, when it is exposed to the marine environment and high loads acting upon it, the corrosion of these connections will create a weak link resulting in the two following scenarios (Kelly, 1999):

- loosening of the connection
- connection breakdown

Both scenarios must be prevented; thus, early detection is ensured by regular inspections.

3.5.1.4 Joints fatigue

Fatigue is the main reason of a structure breakdown and is caused by the repetitive overload of the structure, ultimately resulting in the unit failure. The failure of a structure is primarily the result of a fracture development caused by fatigue. The fracture will start as a hairline crack in the weak spot of the structure under loading. Then, the crack will develop perpendicularly to the line of stress in the member resulting in the final breakdown of the structure (Kelly, 1999).

It is difficult to locate the small fatigue cracks which generally start at the weak spots in the structure such as joints and openings. Since fatigue fractures present extreme danger to the structure, a regular underwater inspection is to be conducted to prevent undetected structural damage.

3.5.1.5 Corrosion

Metal corrosion is an electrochemical process which converts the steel into iron oxides. It is identified by its reddish-brown colour development on the metal surfaces (known as rust). The rust can cover the metal surface or it may be removed naturally (caused by the water movement), mechanically (removed by divers or ROV) or removal can be caused by a damage to the structure by an operational impact. Undetected corrosion can cause serious damage to the unit by reducing its structural integrity and increasing the risk of the structural breakdown.

The splash zone is known to face the highest corrosion rates during the unit service life in regards to the underwater structural services, as illustrated in Figure 30 (Kelly, 1999).

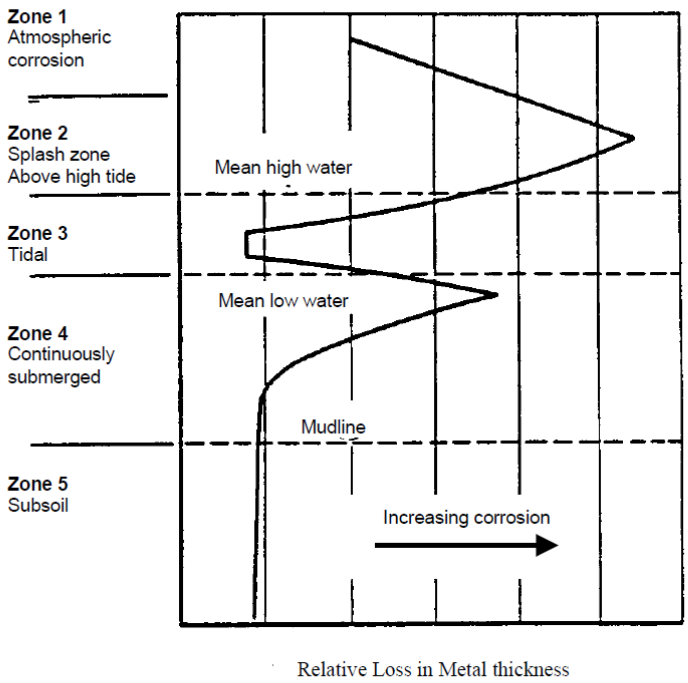

Figure 30 Corrosion rate difference on different zones of the underwater structure. Source: Shawn W. Kelly (1999)

The increased corrosion rate in the splash zone is caused by the high loads accumulated at this section, such as water movement, hydrodynamic loads, operational damage and chafing by supply vessels among others.

3.5.2 Locating the damage surfaces

To locate the critical surfaces where damages can be expected, the underwater structure mapping is important. If the latter is not possible, then a small sketch to locate the surface could be of a help. The sketch or mapping shall include the following:

- the physical features of the surface
- the exact depth at which the suspected surface is located, taking into account the tide difference
- the physical markings (if applicable). Following the previous inspections and if the damage or near damage was detected, the diver would mark the surface with a tag, print, number or any other sign to indicate the location of the damage for future inspections. The marking is to be noted in the inspection report.

ROVs are fitted with an underwater navigation system which includes a position repeater. The latter is tested to be accurate up to ± 0.5 m. Special considerations must be taken into account if the inspection will be conducted based on the positioning system equipped on the ROV in bad or limited visibility (R. Frank Busby Associates, 1978). In addition, the equipment (such as the ROV) shall be tested to operate properly with the structural material interference, i.e. the integrated compass might have an interference with steel.

3.6 Inspection Strategy and Procedure

3.6.1 General

The in-service inspection strategy shall be developed by the owner and/or operator, taking into consideration the structure's age, type of operation and environment at the structure location; in addition, to the national and international standards. An inspection strategy is developed for each specific offshore structure during or as soon as possible after the design. It must be updated and revised continuously throughout the structure service life.

3.6.2 Scheduled inspection

The scheduled inspection is a pre-planned inspection, based on the structure state, the environmental conditions and the operational conditions of the structure. Scheduled inspection can be divided into three categories: initial, periodic and special.

3.6.2.1 Initial inspection

A. General

The initial inspection takes place just after the structure installation. It is deemed to detect the initial structural status in water, transportation or installation defects and to note any additional specification not mentioned in the fabrication assessment. The installation and fabrication reports are important to define the initial survey plan and procedures.

B. Scope

The initial inspection shall take place as soon as the structure is installed and fixed in place. This inspection helps the operators to get a first impression of the structure condition in the water, which will be used to modify the Theoretical Inspection Program (TIP) if needed. The initial inspection scope shall include:

- an overall visual inspection without a structure cleaning (if applicable) (International Organization for Standardization, 2007)
- an overall visual inspection of electrodes, sacrificial anodes and any other corrosion protection (if applicable)
- monitoring the actual mean sea level, taking into consideration the tide differences and the sea conditions (IACS, 2016).

The main purpose of the initial inspection is to check the structure condition conformity with the TIP.

3.6.2.2 Periodic inspection

A. General

The periodic inspection is conducted regularly during the structure lifecycle based on a pre-defined TIP developed by the constructor. This inspection ensures an updated report of the underwater structure status to detect early defects and to check if the current inspection program (TIP) is appropriate for the structure. Based on both the inspection evaluation and the TIP, the periodic inspection scope and intervals can be modified if necessary.

B. Scope

The periodic inspection is a gradual survey strategy, as illustrated in Table 5 and Figure 31. It starts with a very general visual inspection of the overall unit and if needed, the inspector can extend the inspection level in order to obtain a better assessment of the situation and to detect the structure deficiencies. We distinguish three inspection levels: level 1 is the most general inspection (the overall area) and level 3 is the highest inspection level (a well-defined section). This levelling methodology is based on two different inspection strategies used by the International Organization for Standardization (2007) and the American Petroleum Institute (2016).

Table 5 Different periodic inspection levels scope
Source: own collection

	Scope
Level 1	• Underwater visual inspection of the entire area • Underwater marine growth visual inspection • Underwater CP inspection
Level 2	• Surface cleaning of the specific section (if required) • Detailed visual inspection of the specific section • Basic NDT depending on the extent of the damage • Underwater CP inspection (inspector's choice)
Level 3	• Surface cleaning (if required) • Advanced NDT (radiography or ultrasonic) • Underwater CP inspection (mechanical & electrical)

i. Periodic inspection level 1

During this process, a detailed visual inspection of the entire underwater structure is conducted based on the previous inspection report (if applicable). This inspection level is considered to be the basic inspection method to detect and assess a structure condition. It consists of a visual inspection program which aims to detect any existence of the following (International Organization for Standardization, 2007):

- excessive corrosion
- chafing in the splash zone
- cathodic potential measurements (if applicable)
- operational overloading
- environmental damage
- design deficiencies
- debris presence
- immoderate marine growth
- corrosion protection mechanical inspection (see section 3.3.3.6)

The periodic inspection level one, allows to build a general assessment of the underwater structure and give a clear first impression about the structure condition (if the inspection program was stopped for a while). This inspection is very efficient in determining the platform status and more importantly, the below water structure conditions (Walker & Tarantola, 2018).

This inspection level should be considered mandatory. It will help to analyse the underwater structure status after the unit installation on site. Moreover, it will also serve to detect early damages or fatigue cracks caused during the unit construction, installation and service life. The level one inspection report must be compared with the construction report to detect obvious major damages, overstress, deterioration, extensive marine growth and the CP system.

In level one inspection, the CP system will only check visually the anodes placement on the structure; thus, no readings or advanced CP inspection is required (Kelly, 1999). This inspection must first be conducted with no marine growth cleaning, knowing that the marine growth development takes part in this inspection. In case of a damage detection or suspicion of a structural damage, the inspector shall order a higher inspection level in which a marine growth cleaning might be required.

If a notable defect is detected under the visual inspection program described in section 3.1.2, a level two inspection shall be carried out to get a closer view of the specific damaged section. Finally, a detailed inspection report shall be issued.

ii. <u>Periodic inspection level 2</u>

A level two inspection is carried out to get a closer view of a selected area which was pre-identified or suspected to be damaged. The area selection is based on previous inspections and according to the TIP.

The area of inspection is to be cleaned (through marine growth removal) and made ready for inspections to have a clear view of the damaged section. Moreover, depending on the damage stage, the inspector will specify the NDT method to be used. It is most common to begin with the magnetic particles' inspection method for surface defects, see section 3.1.3 (IACS, 2016). This inspection level aims to identify and get a closer visual view of the damaged or the suspected to be damaged section.

In addition, a detailed visual inspection for structures equipped with corrosion protection equipment includes the following (International Organization for Standardization, 2007):

- the sacrificial anodes conditions and the estimated depletion percent
- a visual inspection of the impressed current system state (anodes and the reference electrodes). A complete survey is to be conducted to prevent any discontinuities.

An inspection report must be issued, specifying whether the highest level of inspection is required.

iii. Periodic inspection level 3

The level three inspection is a detailed inspection of a pre-defined surface. This inspection level consists of various and more advanced inspection techniques, such as ultrasonic and radiography inspections (see sections 3.1.4 and 3.1.5). In addition, a 100% inspection of each weld is performed in the designated section to prevent any risk of missing damaged or affected welds (API 570, 2016).

During the level three inspection, the CP system is meant to be inspected. An electrical potential measurement shall be conducted to verify the CP system performance. Moreover, the CP inspection should not only be limited to potential measurements, but an additional overall visual inspection of the structure shall be conducted (if it was not already conducted in early inspection levels). The latter inspection shall focus on the corrosion prevention method; in other words, the diver and inspector shall be searching for the areas where the CP system is not operational (Kelly, 1999).

In particular, the CP visual inspection must include the areas of known defect points of the structure (see section 3.5).

Reaching this level indicates an important matter in the underwater structure, which must be highly considered and demands maintenance and/or repair as soon as possible. The operator and/or owner shall follow a risk assessment methodology to deal with this matter while not risking the structure, the crew (if present) and the environment. In case of high risks, the structure operation must be stopped and the crew is to be evacuated.

iv. Underwater inspection intervals plan

Table 6 Inspection interval
Source: modified from ISO 19902 (2007)

Exposure level	Level 1	Level 2	Level 3
Inspection period	Annually	3 years	5 years

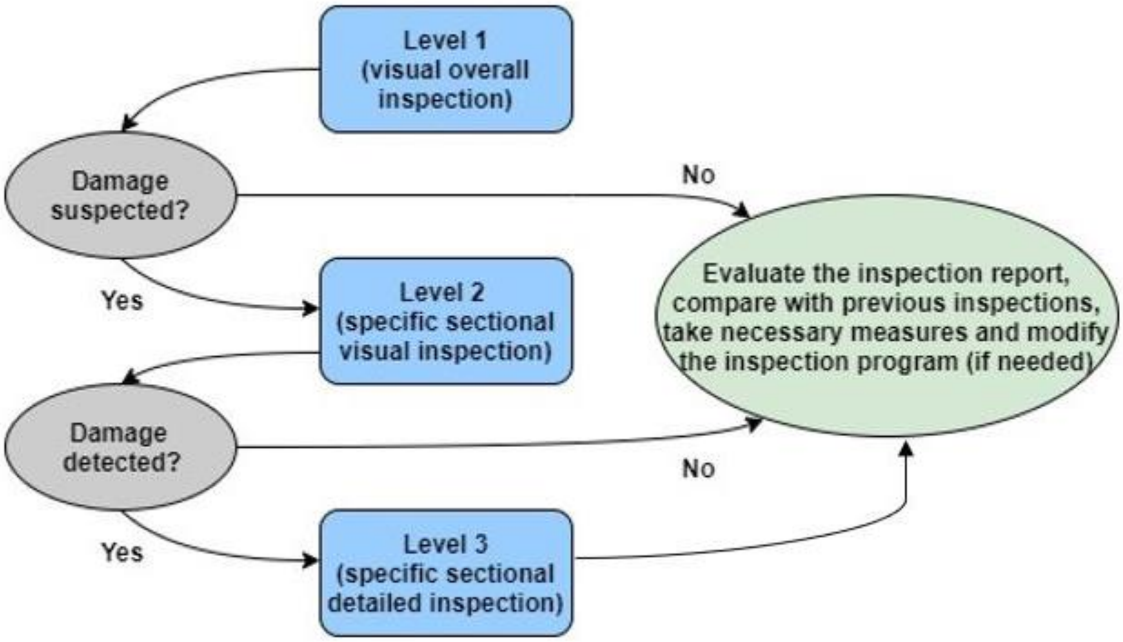

Figure 31 Periodic inspection flowchart
Source: own collection

3.6.2.3 Special inspection

A. General

The special inspection is carried out to check the previous repair status or to inspect a specified structure which is under monitoring.

B. Scope

A special inspection is conducted after one year of maintenance completion. The section must be cleaned and ready for the survey, including a marine growth cleaning. This inspection shall detect any presence of the following (International Organization for Standardization, 2007):

- structure cracking
- local corrosion
- any other defect (especially if it affects the structure fitness).

A final report is to be issued to determine the structure condition including the inspection program to be followed (if needed).

3.6.3 Unscheduled inspection

A. General

An unscheduled inspection shall take place to determine the structure condition after an incident or an environmental event (e.g. a supply vessel collision, explosion, heavy storm etc.) exceeding the initial structures' condition.

B. Scope

The inspection shall include (International Organization for Standardization, 2007):

- a visual inspection of the expected damaged section (without marine growth cleaning)
- an additional inspection extent to eliminate the possibility of skipping defected sections
- a visual inspection of electrodes, sacrificial anodes and other corrosion protection equipment, if applicable
- a visual inspection of any signs of damage (e.g. debris, missing marine growth, etc.)

A final report is to be issued including the structure condition, the inspection scope to be followed and repair measures, if needed.

3.6.4 General inspection procedures

The underwater inspection will be conducted by divers or an ROV operator. Both shall ensure to deliver the correct and clear image of the underwater situation to the inspector as well as to the engineers involved in the structure inspection procedure.

Table 7 General inspection procedure
Source: modified from Shawn W. Kelly (1999)

Steps	Description
1	The inspection is supposed to start at the splash zone where the most mechanical and corrosive damage takes place.
2	Visual inspection of the below water surfaces with no marine growth removal. Following this inspection, the diver and the inspector shall search for external damage or unusual coloration to the marine growth, rust, coating damage, etc.
3	Visual and electrical inspection of the CP system is conducted if fitted to the underwater structure. The visual inspection of a CP system involves the inspection of the anodes and the connection wires. The electrical inspection is conducted by taking potential measurements; the acceptance range for the CP protection are -0.80 to -0.90 V.
4	Check joints for fatigue cracks or any other cracks (such as original caused during construction if the unit was newly installed on site). Marine growth removal is required at this stage for a close metal steel inspection.
5	Record the depth at the bottom of the unit. The depth serves to compare the sand accumulation or reduction at the seabed. It is important that the depth is measured from a well identified water level reference (MHW; MLW etc.).
6	Inspect and record coating conditions such as peeling, blistering, erosion, etc.
7	Inspect and record the corrosion development on the structure (type, extent, affected surface, depth, etc.)
8	Conduct thickness measurements.
9	In case an advanced inspection is required, the inspector will specify the method to be used (magnetic particles, radiography or ultrasonic).
10	All measurements and outcome should to be recorded, labelled and numbered.
11	The inspector shall issue an inspection report.
12	In accordance with the unit operator and the unit designer (if needed), the inspector shall analyse the underwater structural situation, plan the future inspections and modify the inspection and maintenance plans if needed.

3.7 Inspection report

After each inspection, a final report is to be issued, concluding the structure conditions and specifying the location, type and extent of the defect(s). These are in addition to the inspection methods followed, photographs, video tapes and any additional file which might support the damage assessment (International Organization for Standardization, 2007). As soon as the inspection is completed, the inspector is required to issue the inspection report. The latter should be used to analyse the unit's current conditions to compare them with future inspections.

To facilitate the reporting system, a standard reporting form was developed, as illustrated in Figure 32. The report form shall at least include the following (Kelly, 1999):

- the water depth
- the time of the inspection in local time
- the depth of the detected damage (if any) and its specific location on the structure (an additional underwater structural mapping should be provided with the damages location if required)
- the inspection level used
- the NDT methods (if any)
- the extent of the damage and the damage dimensions
- additional comments by the divers and the inspector
- the photos and video recordings

Additional information:

- CP measurements (if applicable)
- marine growth thickness and roughness (if applicable)

<table>
<tr><th colspan="11">PILE INSPECTION RECORD</th></tr>
<tr><td colspan="4">LOCATION</td><td colspan="3">DATE</td><td colspan="4">DIVERS</td></tr>
<tr><td colspan="3">PIER NAME/No</td><td colspan="4">PILE TYPE
☐ BEARING ☐ FENDER ☐ SHEET</td><td colspan="4">PILE MATERIAL
☐ TIMBER ☐ STEEL ☐ REINFORCED CONCRETE</td></tr>
<tr><td colspan="2">WATER DEPTH</td><td colspan="2">TIME</td><td colspan="2">TIDE</td><td colspan="5">DEPTH OF DAMAGE FROM CHART DATUM</td></tr>
<tr><th rowspan="2">Bent №</th><th rowspan="2">Pile №</th><th rowspan="2">NI</th><th rowspan="2">PILE CONDITION</th><th colspan="3">DAMAGE TYPE</th><th colspan="3">DAMAGE DIMENSIONS</th><th rowspan="2">COMMENTS</th></tr>
<tr><th>mech</th><th>bio</th><th>Func.</th><th>HGT</th><th>WIDTH</th><th>PENETR</th></tr>
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</table>

Figure 32 Inspection reporting form
Source: Shawn W. Kelly (1999)

Provided images and recordings shall be attached to the inspection report and kept available for future inspections. All photographs should be dated, numbered and labelled including a brief description by mentioning the damage location and type.

3.8 UNDERWATER STRUCTURAL MONITORING

3.8.1 General

The inspection of the splash zone is considered to be the most challenging phase in the underwater section of an offshore unit. The periodical water movements of the sea surface will prevent the surveyor, as well as the diver or ROV to maintain the correct position for the inspection purposes. It is common practice to conduct the splash zone inspection preferably by means of divers, as they can easily control their buoyancy in water. However, it is believed a wrong practice to conducting a splash zone inspection by means of operated vehicle (R. Frank Busby Associates, 1978c). ROV's can be very difficult to conduct in a dynamic water, as described in section 4.4.2.4. This will affect the inspection outcome.

The submerged zone inspection also has its challenges. The deeper the water depth of the structure to be inspected the harder the inspection will get, in regards to the planning and the execution. In addition, the metocean plays an important factor to conduct this inspection.

The best way to reduce the risks caused by the underwater inspection is to limit the number of underwater entries. The latter can be achieved by conducting a structural monitoring of the unit from the surface in parallel with an underwater inspection. This monitoring method can detect an early structural damage but it cannot completely replace the underwater inspection.

3.8.2 Underwater structure monitoring

The techniques introduced for structural integrity monitoring, intend to ensure the performance and safety of the unit on site. The structural monitoring is performed by collecting, analysing and recording the data outcome of these monitors and sensors fitted on the structure.

The integrity of the underwater structure can be monitored by the following techniques:

- Acoustic emission monitoring
- Vibration analysis

3.8.2.1 Acoustic emission monitoring

Acoustic emission is a high frequency noise that is generally generated following an operational, environmental or an external impact. This technique uses the minute acoustic emissions produced by structural discontinuities in the material under stress, therefore strategically located sensors are fitted on the underwater structure (R. Frank Busby Associates, 1978).

The acoustic emission phenomena are defined by the generation of the transient elastic waves which is caused due to a rapid release of energy from a specific location in the structure (Dunegan, 1977). This system analyses the minute acoustic emissions generated by the structural discontinuity under stress in the underwater unit, as illustrated in Figure 33.

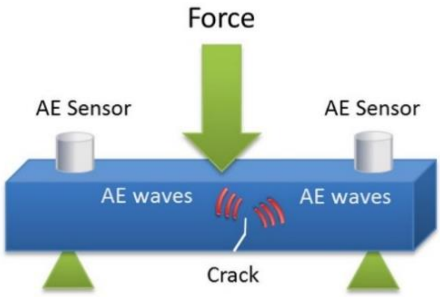

Figure 33 Acoustic emission concept
Source: PTS NDT (2017)

The equipment is based on fixed piezoelectric transducers attached to the underwater structure (represented by "AE Sensor" in Figure 33). The transducers will be connected to the surface by means of wires. This connection will serve to deliver the received signal at the connection points on the structure at all time. The data will be received, amplified and electronically conditioned then processed by a special software to identify if any damages are found in the unit (such as discontinuities).
By collecting these emissions and after their analysis, the monitoring outcome can ensure an early problem detection and prevent the unit failure or breakdown (R. Frank Busby Associates, 1978).

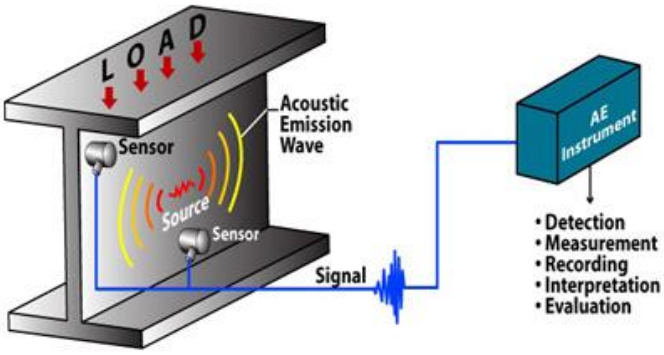

Figure 34 Acoustic emission waves on a damaged surface
Source: NDT technologies (2017)

The damage or discontinuity can be located by analysing the acoustic emission wave traveling time. Each transducer has its predefined location registered in the software with the exact traveling time needed for the acoustic emission wave time to travel through this point. Any traveling time delay will give the rise to the doubt of a structural damage. The data can also be sent to a shore-based centre for analysation by experts. The monitoring can be continuous as well as periodic with specified intervals approved by the unit's class (IACS, 2016). To prevent signal interference, it is recommended to reduce the transducers number to the weak spots of the underwater structure, such as nodes and welds. The acoustic emission signal analysis can show that a structural damage exists and can also lead to the damage location. Unlike the normal underwater inspection, the acoustic emission cannot determine the extent of the damage, neither its original cause (R. Frank Busby Associates, 1978).

A stringent maintenance level is required to keep this system working properly and efficiently. It is recommended that it is used as a complimentary monitoring system for the underwater inspection but it cannot be considered as a replacement.

3.8.2.2 Vibration analysis

Each offshore structure has its own natural vibration frequency regardless the vibration caused by the operational, environmental and external impact factors. These vibrational frequencies are to be calculated and pre-defined by the unit designer.

If the unit mass remained unchanged (if no major modification to the structure has been carried out) and the underwater structure suffered an impact which caused a stiffness reduction, the latter will affect the natural vibration characteristics. By analysing the outcome of the unit vibrational characteristics and comparing them to the pre-defined natural vibration by the designer, we can identify if the underwater structure is at a risk of breakdown.

The vibration monitoring system method does not require any underwater human or robotic intervention to ensure the structural monitoring. In addition, unlike the acoustic emission monitoring (section 3.8.2.1), the vibration analysis does not require fixed transducers fitted on the underwater structure to be connected to the surface.

The vibration monitoring takes place by measuring the current unit vibration to compare it with the unit natural vibration. The structure vibration measurement is monitored by a highly sensitive accelerometer, which will receive the vibration signature. The latter will be compared with the unit natural signature.

In case the unit structural mass changed during its service life, this will directly affect the unit natural vibration. However, if the unit mass remained constant and well controlled during the unit's operation, any shifting of the vibration characteristics will be the result of a possible damage in the structure (R. Frank Busby Associates, 1978).

Different parameters that can cause a shift to the unit natural frequency are as follows (R. Frank Busby Associates, 1978):

- excessive marine growth development (related to the marine growth density)
- corrosion
- major deck modification
- major underwater structural modification
- flooding of the underwater structure
- modification in the soil support (sand building up or sand washed away)

All the above-mentioned parameters will affect the vibrational frequency of the unit. If this is the case and the unit vibrational frequency has changed, the unit operator shall ensure to proceed with another study in order to calculate the new unit vibrational frequency. The latter shall be approved by the unit class (IACS, 2016).

This monitoring method can only prove the existence of the damage but, unlike the acoustic emission monitoring method, we cannot locate the damaged area (R. Frank Busby Associates, 1978).

3.8.2.3 Difference between Acoustic and vibration monitoring

Both monitoring systems, vibrational and acoustic are considered to be complimentary for underwater offshore structures usage. In addition, it is proven to be successful in the offshore field to deliver the full structural image of the underwater surfaces on regular basis (R. Frank Busby Associates, 1978).

These techniques are not considered adequate to provide the necessary information for an underwater inspection compared to an inspection done by a diver or an ROV (ISO 19902, 2007). A small crack might be present in the structure and under rapid development, while these monitoring techniques might not detect it. An early detection of a small structural damage can save the unit from a disaster. Outsourced vibration, such as operational or a weather storm might interact and affect the data outcome. It is believed that the sensors and transducers fitted on the underwater structure require higher maintenance than the structure itself (Sirris, 2019).

Table 8   Pros and cons of different monitoring techniques
Source: modified from R. Frank Busby Associates (1978)

	Acoustic emission	Vibration analysis
Pros	• No underwater divers or ROV required • Cracks can be detected • Crack growth can be ascertained • Crack locations can be determined	• No underwater divers or ROV required • Damaged sections can be detected (cracked or severely bent member) • Early detection of breakdown • No sensors required
Cons	• Requires high maintenance • Requires regular calibration • Expensive to install, operate and maintain • Affected by environmental impacts (i.e. storms) • Detection is limited to big cracks • Crack dimensions cannot be determined • The reason or the cause of the crack cannot be determined • Cannot replace the NDT	• Limited service life • Detection limited to big cracks • Cannot determine the reason or cause of the crack • Crack dimensions cannot be determined • Crack locations cannot be determined • Crack growth cannot be monitored

Acoustic emission is aimed to detect the transient noise in the material within the component's snaps. The latter is completed by using the timing of the transients to determine the location of the break. It is easy to operate on a simple underwater geometry design but it is complicated otherwise.

The vibration analysis technique aims to measure the long-term response to mechanical excitation of the underwater structure. The excitation may be derived through contrived methods or naturally.

It is important to regularly monitor the unit mass difference caused by excessive marine growth developments (in the case of a large underwater surface which might be the house of a big mass of biofouling).

Finally, we can assume that these monitoring techniques are meant to be used as additional means to provide a clear image regarding the behaviour of the underwater structure and cannot be considered to replace an underwater inspection.

Chapter 4 OFFSHORE DIVING

4.1 INTRODUCTION

4.1.1 General

Surveyors are delegated to conduct underwater inspections, but it is the divers’ and/or ROV’s task to transfer the underwater image to the delegated surveyor in order to define the structure’s status.

4.1.2 Underwater ROV

- <u>Deploying an ROV prior to the dive</u>

Prior to the diver water-entry, the ROV can provide the necessary images of the inspection area, identifying it to be clear from obstructions, which otherwise might put the diver’s safety in danger. In addition, the ROV can be used to detect and estimate the damaged area as a first inspection and consequently, as an aid for the dive plan.

- <u>Deploying an ROV during the dive</u>

An ROV can assist the diver’s job and reduce the dive time. Underwater operations might face serious problems which have to be solved on the spot to prevent the possibility of any dangerous situations.

If ROVs are deployed, they can give the opportunity to the operators (out of water) to assist divers by giving them solutions and intervene if needed. This can enhance the confidence of the diver where he/she is no longer left to solve the situation independently (Deep Trekker, 2016).

4.1.3 ROV’s vs diver

ROV’s can work at any water depth (considering the device limitations), limit the human error factor and limit any danger imposed on divers. However, divers can accomplish the job more efficiently than an ROV and at cheaper rates (Deep Trekker, 2016).

Commercial diving is a dangerous job, putting underwater personnel in a difficult environment where they are deemed to accomplish the job and ensure their safety at the same time.

Why not completely replace the divers - ROV team by ROV only and thus eliminate divers? Until this day, it is proven that the combination divers - ROV is an optimal team to tackle underwater jobs as illustrated in Figure 35. ROV's aren't ready yet to fully replace divers, due to the job complexity and the time consumed by an ROV to accomplish a basic underwater operation (IMCA D 054, IMCA R 020, 2014).

Figure 35 Underwater inspection operated by a ROV-diver team
Source: modified from Kirk Pyle (2014)

4.2 RULES & CODES APPLICATION

4.2.1 National

Each country can apply its own codes and regulations on all underwater jobs taking place in its territorial waters, either coastal or offshore. In addition, a nation can apply its rules and regulations on vessels conducting diving operations in open-seas, if the vessel/platform is registered in that country (i.e. flag state) (IMCA, 2014).

4.2.2 International

International organisations have developed a series of rules and regulations to be implemented, such as the codes and regulations for offshore diving operations, developed by IMO. International codes are to be applied if there are no national rules applicable, or if international rules do not influence national regulations (IMCA, 2014).

4.2.3 Classification society

Classification societies have their own standards and regulations to be applied on board structures assigned to that specific Society. The classification societies regulations cover the following (IACS, 2016):

- diving equipment (i.e. design, certification and testing)
- divers (i.e. proficiency, certification and health certification)
- equipment operator's certification (i.e. ROV's operation certification or certification of underwater equipment operated by divers)

The society should first approve the Diving Management System (DMS) of the diving firm and then make sure that they act accordingly. In addition, the firm shall develop a Diving Project Plan (DPP) for each specific operation (see section 2.5.1), which will also be reviewed by the Society. Classification Societies are recommended to refer to the IACS recommendations (2016).

4.3 THE DIVING FIRM

4.3.1 Offshore manager or diving superintendent

The diving company shall develop a DMS to define the company policy, which shall include (IMCA, 2014):

- the company personnel divisions and the responsibility distributions
- the strategy to be followed during operational planning and the plan of execution
- a plan to ensure the personnel security, health and safety

Each diving firm can have different personnel division & responsibility distributions.
The offshore manager must ensure that all the operation activities are carried out in accordance with the firm requirements, which must be adapted to the different rules and regulations to be applied (i.e. national, international and Society rules).
In addition, the offshore manager is the direct link with divers and other personnel working on site. Where he/she must ensure that all personnel are:

- certified and qualified for the specific operation
- familiar with the plan and the procedure to be carried out
- well aware of all the safety measures and precautions to be implemented
- aware of all codes and regulations.

Finally, the manager must make sure that all personnel:

- gets enough rest, (see section 4.4.4.3)
- do not exceed their permissible working time
- have enough personnel to accomplish the assigned operation.

4.3.2 Divers

In order to accomplish a successful underwater operation, divers must ensure the following (IMCA, 2014):

- have all necessary certification for that specific operation
- fully understand the operation plan and ensure that they are capable to complete the assigned task
- be aware of all applicable rules and regulations
- check all diving equipment prior to each dive
- inform the manager about any medical issue or other reasons which might prevent them from diving
- be physically and mentally ready for the operation
- be well aware of all emergency and safety procedures to be taken in case of an emergency
- report any unplanned problem faced during the operation.

4.4 Divers limitations

4.4.1 General

All different parties (owner and/or operator, diving firm and the classification society), shall combine their efforts to ensure a safe operation. A safety plan should be developed prior to the operation, which must consider all obstructions or limitations a diver might face underwater.

4.4.2 Environmental limitations

4.4.2.1 Depth

The working water depth affects the operation plans & procedures.

Commercial divers are trained and certified differently according to their levels, where junior divers cannot be assigned to deep water dives (following their certification).

Moreover, as the dives go deeper the pressure applied on divers will increase which might directly affect the breathable air mixture (i.e. breathing air with oxygen content at a depth greater than 60 meters can be toxic).

Commercial divers try to eliminate nitrogen from the air mixtures as they dive deeper, due to the nitrogen toxicity when accumulated in the human body under hydrostatic pressure. Currently, “Trimix & Heliox” or “Hydrox” are used as alternatives in the commercial diving market, i.e.:

- Trimix & Heliox: oxygen and nitrogen are replaced by helium, which eliminates the toxicity from both gases and allows longer and deeper dives. Helium breathing can cause hypothermia and has other side effects on diver’s long-term health. A Heliox dive simulation has been performed to prove that divers health is significantly affected, for example divers might face sight disorder and mental disabilities (Hou et al., 2015).
- Hydrox: oxygen and nitrogen are replaced by hydrogen which is cheaper than helium and eliminates the helium toxicity but the hydrogen is highly flammable.

Normally, commercial divers’ breathable source is an air compressor, placed well above the water surface. Obviously, as the diver goes deeper, different compressor characteristics are required.

4.4.2.2 Visibility

We can differentiate two types of limited visibility, underwater and surface visibility:

- underwater visibility directly affects divers and the image broadcasted from the ROV, if applicable. The underwater visibility can be affected by different factors, such as sea turbulence, debris in the water, mud movements near the sea bottom and traces of oil products in the water. Underwater operations can be very challenging during limited visibility, putting the diver’s safety in danger.
- surface visibility directly affects the above water personnel and diving supply vessels navigating on the surface. Surface visibility can be affected by meteorological conditions (i.e. rain, fog or pollutant gasses). Limited visibility can endanger the operating vessel and diver’s safety.

The manager must prepare a well-developed plan, which includes all necessary environmental requirements to ensure a fair visibility needed for a safe operation (IMCA D 054, IMCA R 020, 2014).

4.4.2.3 Temperature

Water temperature is an important factor to be taken into consideration, as it can directly affect divers (health, safety and efficiency) and their equipment.

4.4.2.4 Water movements (currents, waves and swell)

Water movements can affect all operation parties, above and underwater. Currents, waves and swell can limit the navigational ability of the diving supply vessel, they can also totally interrupt divers or ROV's from their job.

- divers and ROV's are very sensitive to water movements, it can disturb their buoyancy and limit them from achieving the assigned job (IMCA D 054, IMCA R 020, 2014).
- the diving supply vessel shall maintain a direct and continuous contact with divers. If the vessel is suffering from heavy weather, it can put the divers' and the on board personnel's life in danger (IMCA, 2014).

Finally, all operations must be conducted in fair weather conditions to create a safe atmosphere for the crew, vessels and environment.

4.4.2.5 Arctic conditions

Operators shall develop cold weather policies for water temperatures below 12° C (Wikiversity, 2018). They should include: the air and water temperatures, ice formation and suitable equipment for this operation. In addition, operators must ensure that divers are well trained and certified to accomplish that specific operation (IMCA, 2014).

4.4.2.6 Marine life

Divers might be confronted with dangerous aquatic life, which differs from one area to the other. It is a situation to be avoided, but divers must be trained and well aware on how to react in such a case, in order to solve the problem without putting their lives in danger. Moreover, operators must consider this aspect and include it in the risk assessment. Different research shall be conducted to study the hazards of all aquatic life living in the area during that specific season. Finally, if any suspected marine life might put the divers' life in danger, a suitable emergency or contingency plan must be developed and the appropriate safety equipment must be used such as physical protection guards (see section 4.4.3.4).

4.4.3 Technical limitations

4.4.3.1 Pollutants

The spills of petroleum products and oil fields can directly affect the dive operation, both underwater and at the surface (IMCA, 2014):

- oil traces will affect the underwater visibility, limit the diver's clear underwater view and risk the safety of the operation. In addition, diving equipment are at risk to fail if they are in contact with such products. The manager must ensure that all equipment is type approved and that it suits all requirements of that specific operation.
- surface crew might also be affected by pollutant gases, as it can disturb the surface visibility and communication transmission.

4.4.3.2 ROV's operations

An ROV might pose a risk to the diver if operated at a close distance. The diver might face different limitations when working in the vicinity of an ROV, such as: physical contact, entanglement, electric hazards, etc. Some additional safety requirements should be implemented if both divers and ROV are working in parallel, (IMCA D 054, IMCA R 020, 2014):

- the operation plan must include the safe working procedure of the ROV in water, which both divers and ROV operator shall be aware of
- a direct communication must be kept between the underwater divers and the ROV operator
- the ROV has to be certified and tested by an approved firm. This will enhance the ROV's safe operation (which includes electrical safety, thruster protection, etc.)
- the ROV operator must have all the necessary certifications and possess the experience for the assigned job
- in limited visibility situations, a minimum of 4 meters' distance is to be kept at all times between ROV and diver.

4.4.3.3 Safe use of equipment

Divers are in direct contact with electrical equipment, which must be certified, well maintained and tested for safe underwater use. It is the dive manager's responsibility to ensure that:

- the equipment is certified from an approved firm.
- the equipment is well maintained by appropriate personnel.
- divers are well trained and have enough experience to operate the equipment safely.

4.4.3.4 Water discharges & intakes

A diving work permit must be issued prior to the dive commencement. The main idea behind this step is to ensure a safe underwater environment for the personnel, which includes the platform operations (IMCA, 2014).

- Physical protection guards for divers: this is most commonly used during dangerous aquatic life hazards (see section 4.4.2.6), but it is also used to protect divers from nearby daily platform operations, if needed (i.e. sea chest water intakes or any drilling equipment). Moreover, the diving cage is also used in the offshore inspection field to lower or lift divers and their equipment in water, as illustrated in Figure 36.
- No means of physical protection: in such circumstances all underwater platform operation, which might risk the safety of underwater personnel, must be stopped. The platform crew is responsible to issue the underwater work permit in collaboration with the dive manager.

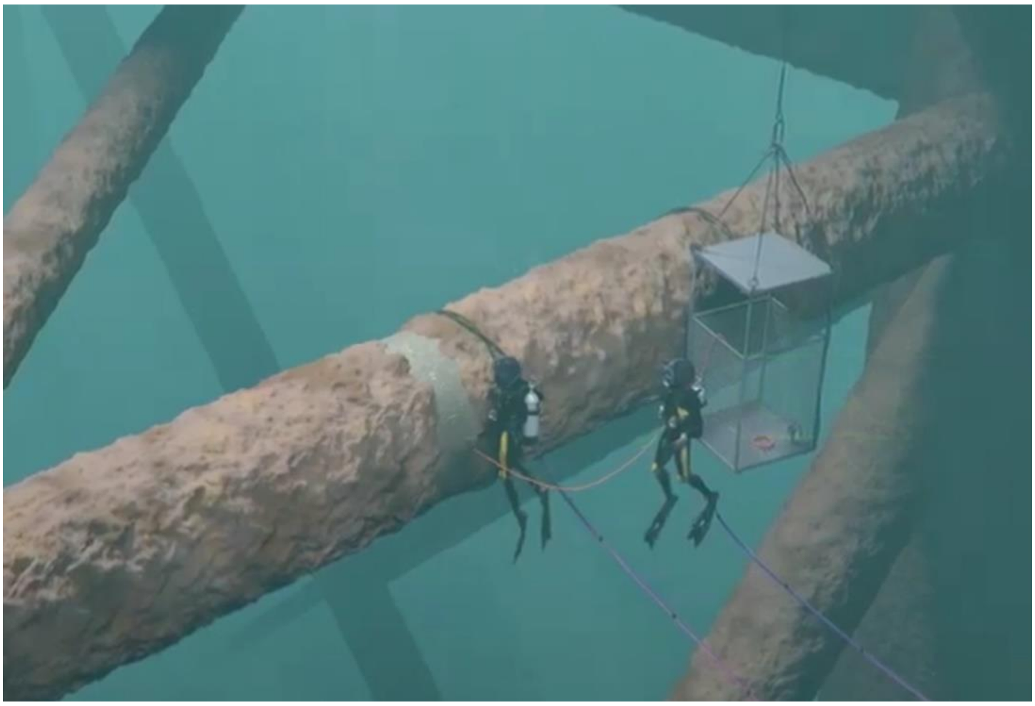

Figure 36 Divers out of their diving cage to perform an inspection
Source: TSC (2017)

4.4.3.5 Communication

A direct two-way communication system shall be established at all times with underwater personnel. The communication system must be suitable for the air mix used by the diver, i.e. helium will distort the diver's speech. Equipment requirements are described as follows (IMCA, 2014):

- the communication system must be fit with a speech processing equipment to maintain an effective and clear communication.
- divers and the dive managers (on the surface) shall be well trained and qualified for operating the communication equipment.
- all communication equipment must be certified and well maintained.
- all communication should be recorded and kept for a minimum of 24 hours.

The communication records must be retained for investigation purposes, if any incident takes place during or a couple of hours after the dive (IMO, 2016).

4.4.3.6 Corrosion prevention inspection

It is important to keep in mind the safety hazards of underwater operators (divers) once considering the inspection of the ICCP systems. Carrying out the inspection of the ICCP underwater system by divers is to be avoided due to the hazards that might endanger their safety. To tackle this problem the underwater survey shall be conducted by an ROV only in order to limit the risk.

In case of impressed current (IC) systems, the safety regulation will prohibit the diver's activity. The IC system can endanger the diver's safety due to electric shocks from a faulty equipment or from a direct contact with the anodes, which is a possibility in case of heavy water movements (ISO 19902, 2007).

If the diver's intervention is required, the following elements must be considered:

- ➢ if a close distance inspection is not required:
  - when the inspection does not involve a corrosion prevention survey, a safety distance must be kept at all times with all IC anodes in operation
- ➢ if a close distance inspection is required:
  - the IC system must be switched off before and during the dive (the timing is to be agreed between by the surveyor and the diving firm following their safety plan)
  - the use of personal protective equipment (electric insulating)
  - the use of protective equipment such as a diving protective cage (Figure 36)

4.4.4 Post diving limitations

4.4.4.1 Flying

Traveling by any means of air transportations must be avoided after a dive for a specific time (depends on each dive operation). This is due to the difference of pressure that a diver can face at high altitudes.

4.4.4.2 Decompression illness (DCI)

Recompression facilities shall be provided for emergency situations. If this is not the case, the operation plan must include an alternative solution to keep the diver safe after the dive (i.e. transfer the diver to a nearby suitable facility). The plan should include that divers cannot be evacuated by air transportation means (such as helicopters) after an underwater operation.

4.4.4.3 Rest

It is necessary for a diver to get enough rest after each dive. The divers normal schedule shall consist of 12 working hours (including different rest intervals), then at least 8 hours of uninterrupted rest period over the 24 hours. The dive manager can extend the working time from 12 to 16 hours under exceptional circumstances, only if the diver can by all means get 8 hours of unbroken rest (IMCA, 2014).

The total working hours mentioned above does not consist of the diving time, it also includes: the time spent as a standby team (on the surface) and the time for the dive preparation (planning, briefing, equipment checks, etc.).

Chapter 5 CASE STUDY: ALEXANDER L. KIELLAND

5.1 INTRODUCTION

This case was chosen since it is a practical study to the underwater inspection and can help us to implement the thesis inspection theory.

The chosen case study is considered to be a design cause of failure, but it is also directly related to the lack of inspection. More specifically, the Alexander L. Kielland platform case indicates the result of the error and wrong design in combination with the lack of inspection and monitoring, which can lead to a catastrophic failure of the structure.

5.2 THE INCIDENT

5.2.1 General

On the 27th of March 1980, the Alexander L. Kielland platform capsized during a storm at the Ekofisk oil field in the North Sea. It was a Norwegian semi-submersible drilling rig not used at the time for drilling purposes but to provide living quarters for offshore workers, a so-called flotel. At 18:30 hours, the Ekofisk Centre received the first Mayday call from the platform Alexander L. Kielland (Gjerde & Ryggvik, 2009).

Ekofisk is an oil field located 320 km southwest of Stavanger (city in southwestern Norway) in the block 2/4 of the North Sea Norwegian sector. This oil field was discovered in the 1969. Oil production is planned to continue until 2050 (Alchetron, 2017).

Figure 37 Ekofisk oil field
source: Alchetron (2017)

The flotel listed dramatically (up to 30°) due to a weld fatigue fracture in one of the braces, which are interconnecting columns that serve as platform supports. This fracture caused eventually one of the five support columns (also called legs) to rip-off and resulted in an unstable platform. Some of the crew managed to get in the lifeboats, others jumped into the sea of which only a few were wearing survival suits. The incident happened so fast and that many failed to evacuate. The platform capsized and was laying on the sea bed within 23 minutes. It was a tragic accident that left 123 people dead and only 89 survived (OFFICER OF THE WATCH, 2013).

5.2.2 Chronology of events

The Alexander L. Kielland drilling rig was anchored at the Ekofisk oil field near the Edda 2/7 C production platform and remained in this position for nine months. Originally the platform was used for drilling purposes. Later on, it was converted into a residential area for the Edda platform, located southwest of the Ekofisk Centre.

Both platforms the Alexander L. Kielland and the Edda, were linked to each other by a mobile gangway. This gangway was elevated on board the Alexander L. Kielland to keep the entire structure distant from the Edda 2/7 C platform in severe weather conditions.
In the afternoon of 27th March 1980, the weather worsened. The wind speed was about 16 to 20 m per second (31-39 knots), accompanied by waves 8 m and higher. The outside air temperature was around +4 °C to +6 °C and visibility had reduced.

At the time of the accident, the gangway to the platform Edda had been raised due to bad sea conditions and could not been used for the evacuation.

The platform was supported by a network of eight anchor cables distributed equally on columns A, B, D and E as shown in Figure 38. Columns C and D were the closest to the Edda 2/7 C platform. Column C was not anchored as it formed the bow of the Alexander L. Kielland platform directed towards Edda.

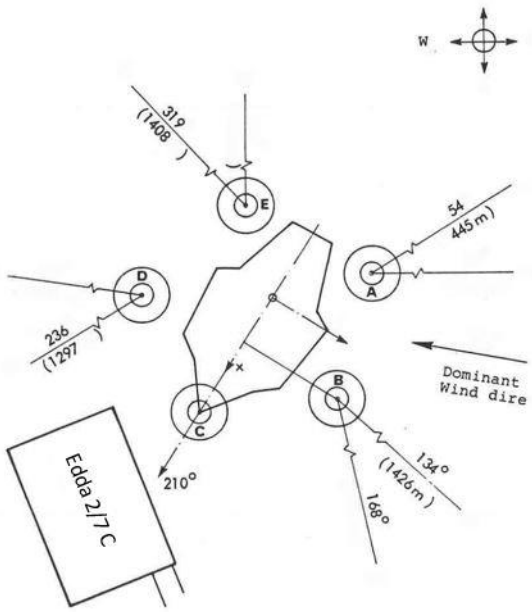

Figure 38 Location of the Alexander L. Kielland platform on the EDDA 2/7 C site at the time of the accident
Source: NOU (1981)

Fatigue of one of the lower cylindrical braces attached to column D triggered the disaster. The failure of the brace resulted in an overload of the five remaining braces connecting the platform. Subsequently they broke rapidly and successively. The progressive ruptures caused the separation of column D from the remaining platform as illustrated in Figure 40. From that moment, the Alexander L. Kielland quickly took a 30° list.

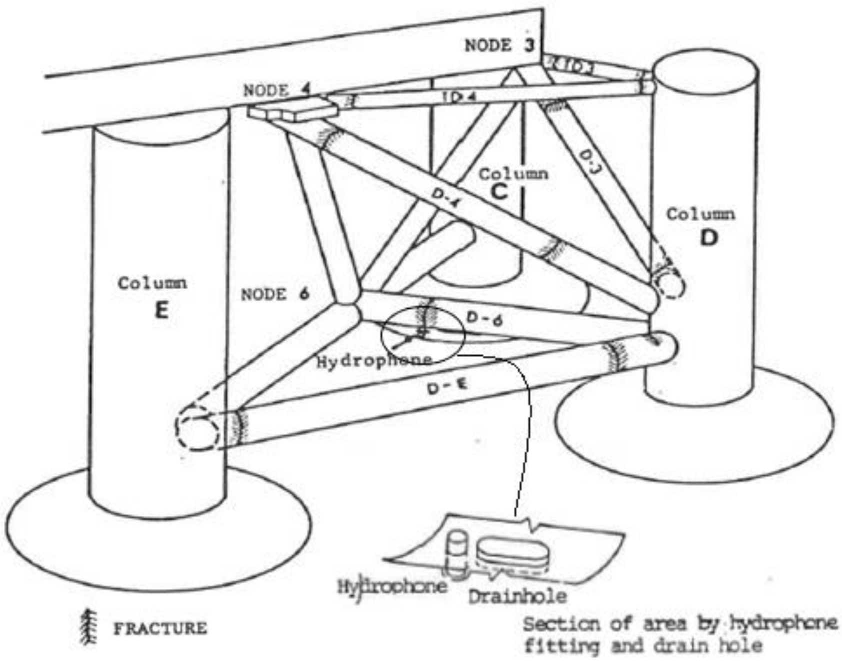

Figure 39 The hydrophone tube location and the breaks in the braces connected to column D
Source: modified from NOU (1981)

Water invaded the compartments of columns C and E as well as the decks through various openings such as doors and vents. Approximately 20 minutes later, after the last anchor cable (B) broke, the platform flipped completely. The platform continued to float upside down and only the four floating legs were visible (A, B, C and E) as the leg D was totally separated from the structure as illustrated in Figure 41. Any ballasting operation to avoid or delay the platform from overturning was impossible as the water on the bridge caused a power failure (NOU, 1981).

Figure 40 Alexander L. Kielland capsize process
Source: modified from Science Photo Library (2020)

Figure 41 The four legs of the Alexander L Kielland after capsizing, near by the Edda platform
Source: Gjerde & Ryggvik (2009)

5.3 HISTORY

Although the Alexander L. Kielland platform was designed and built as a drilling rig, instead it was used as a flotel. Its accommodation capacity was modified by building additional residential units, increasing the total occupancy from 80 to 348 people. These units were mounted in an area initially reserved for the storage of drill pipes. However, the drilling tower, weighing 200 tons at 40 m high, was left untouched (OFFICER OF THE WATCH, 2013). The Alexander L. Kielland was certified according to regulations set by the Norwegian Maritime Directorate, under the classification of Det Norske Veritas (Det Norske Veritas, 1977).

5.4 MAIN DIMENSIONAL CHARACTERISTICS

The platform was classified based on its weight of 10,105 tons. Its dimensions were 103 x 99 m with a freeboard of 40.5 m measured from the surface of the upper deck to the water level. Each of the five cylindrical columns had a diameter of 8.5 m and was supported by a 22 m in diameter base column. The columns were connected to the deck by a network of horizontal and oblique cylindrical steel braces as illustrated in Figure 42. The steel braces thickness was about 26 mm and diameters of 2.6 m and 2.2 m respectively (NOU, 1981).

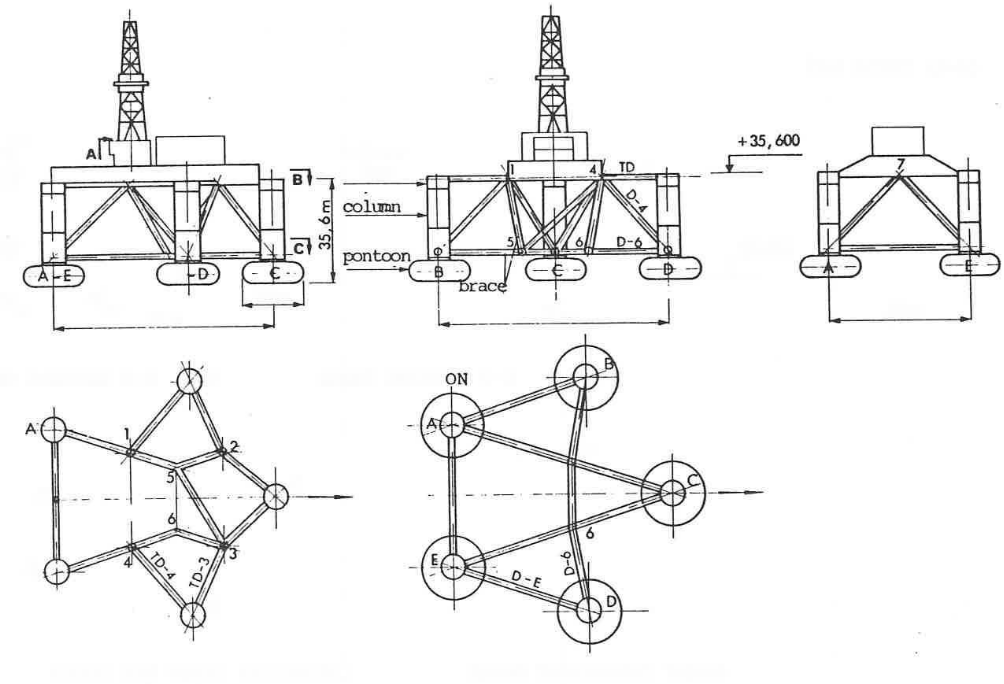

Figure 42 General architecture of Alexander L. Kielland
Source: NOU (1981)

The lower horizontal braces in sections C-D and C-B are missing as illustrated in Figure 42. These braces were eliminated in order to facilitate the movement of supply vessels near the platform (Almar-Naess, Moan, Haagensen, & Lian, 1982). The upper oblique and horizontal braces were watertight (fully enclosed columns), while the lower horizontal ones were open and filled with sea water. To make them waterproof would have involved an increase in weight and will influence the buoyancy of the platform buoyancy.

The structure was equipped with a positioning acoustic control system. This system notably included three hydrophones. The latter are microphones intended to pick up the sound waves emitted by beacons (answering machines) placed on the seabed. The three hydrophones are fitted on the structure by a welded support plate on three of the lower horizontal braces, including the collapsed D6 brace Figure 38. The installation of these hydrophones required a 325 mm diameter hole, drilled through the steel of the braces, with a thickness of 26 mm. A tube of the same diameter was welded into the opening so that it protruded by about 150 mm under the brace. The filet welds had a throat of 6 mm. (Figure 43).

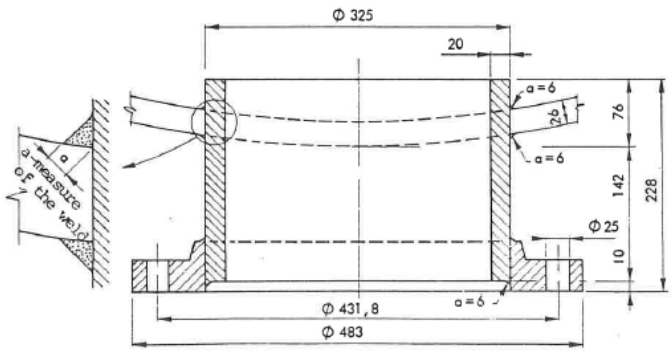

Figure 43 Nominal dimensions of the hydrophone tube fitted on the D6 brace
Source: NOU (1981)

5.5 THE CAUSES

5.5.1 Rupture of the structure

The horizontal D6 brace was the first to break due to structural fatigue. An opening was made under this brace in which one of the three hydrophone supports was welded as illustrated in the Figure 44 and Figure 45.

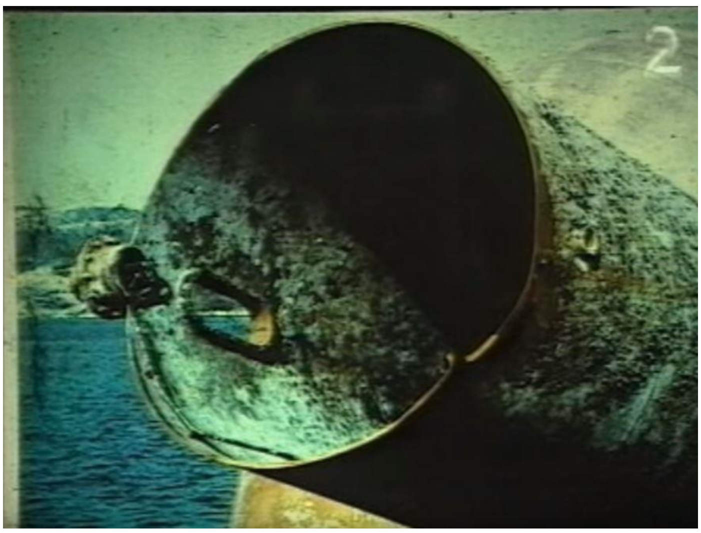

Figure 44 Breakage of the D6 brace
Source: France (2019)

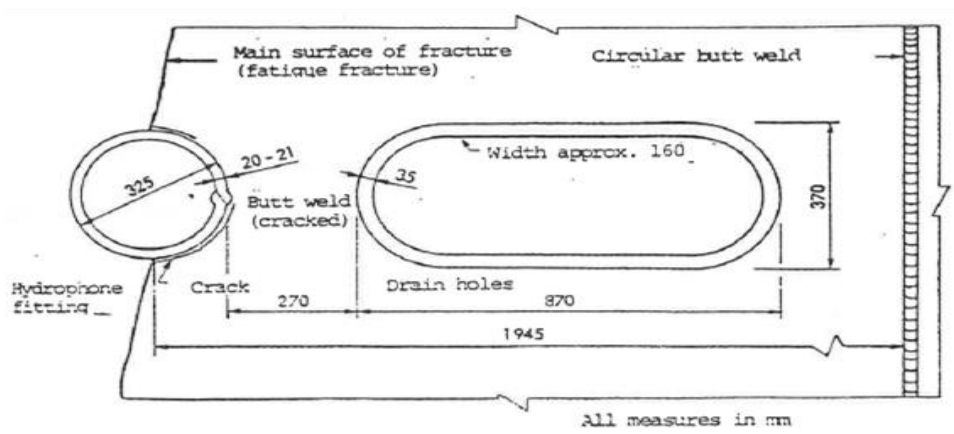

Figure 45 Breakage details of the D6 brace in relation to the hydrophone tube
Source: NOU (1981)

As described above, this process involved an internal and an external filled weld (see section 5.4). The investigation revealed that the shape of the weld beads was not standard and that the weld was not sufficiently penetrated into the hydrophone metal plate support. The laboratory examination of the samples taken from the D6 brace also revealed that a partial cracking of the welded joint between the hydrophone support and this brace had occurred well before the platform was assembled. Another detail to prove this is the discovery of paint traces on the fractured surfaces. Essentially, certain cracks were present before the application of the paint, or in other words, before the assembly of the platform (NOU, 1981).

The traces of paint came from the applications executed during construction in the Dunkirk construction sites. Meanwhile, the partial cracking was due to the low mechanical properties of the support steel (minimal strength and insufficient ductility) combined with the reduced quality of the welds in addition to the accumulation of residual stresses. Due to this cracking, a redistribution of the tensions took place in the hydrophone support as well as in the brace. Thus, two diametrically opposite points, located in the D6 brace on the circumference of the hydrophone support, sustained a higher level of tension (Figure 46 and Figure 47).

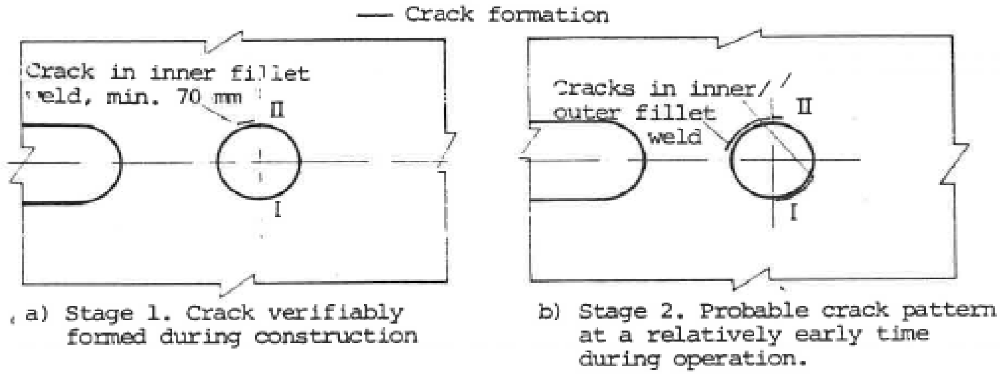

Figure 46 Probable stages of cracking progression in the welds of the hydrophone support
Source: NOU (1981)

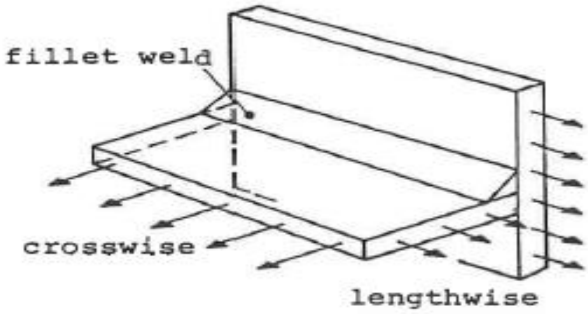

Figure 47 Stresses acting on the fillet weld
Source: NOU (1981)

These two points caused the cracks propagated by fatigue along the circumference of the D6 brace. As the cracks extended across the thickness of the brace, they quickly covered two-thirds of the circumference. The residual strength of the remaining unaffected steel became insufficient to support the load; thus, the structure final rupture took place (Almar-Naess et al., 1982).

When initially designed, the hydrophone was simply considered as an equipment. No additional sectional support was provided to enhance the strength of the opening used to mount the hydrophone. In addition, no comprehensive strength assessment had been made on the suitability of the hydrophone support mounting. The main cause of this rupture came from an inadequate design, sizing and material quality of the hydrophone support as well as its connection to the brace.

5.5.2 Examination of failed surfaces

5.5.2.1 The cracking of the corner welds on the circumference of the hydrophone support:

Examination of the mounting of the hydrophone support revealed that a part of the breaks along the circumference of the tube was older than the break in the D6 brace due to the discovery of a strong corrosion attack around the support. This could have occurred during welding operations or shortly after. During the final rupture, the crack on the double corner weld extended to over more than three quarters of its circumference (NOU, 1981). The Figure 48 schematically shows the extent of the cracking.

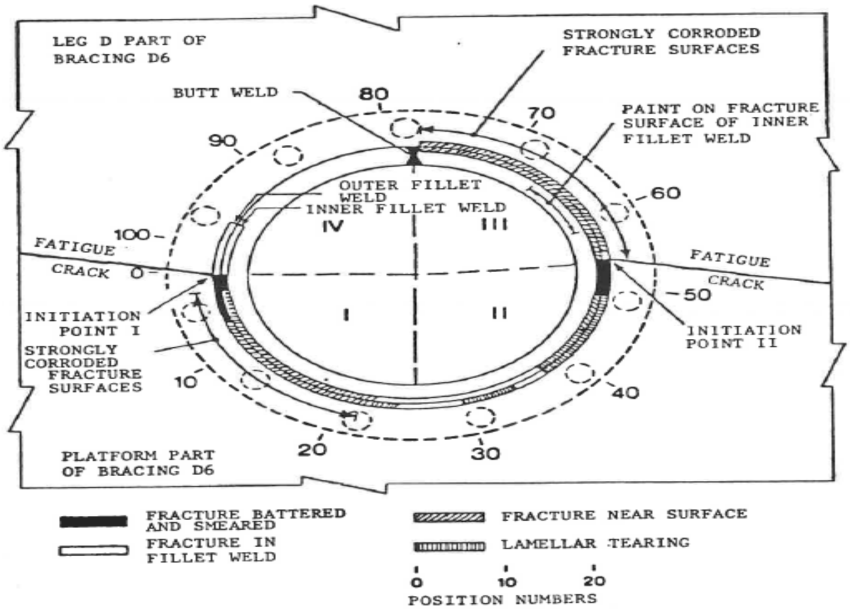

Figure 48 Extent of cracking and types of rupture in the corner welds around the hydrophone tube
Source: NOU (1981)

Certain areas of the fractured surface show signs of lamellar tearing as illustrated in Figure 49

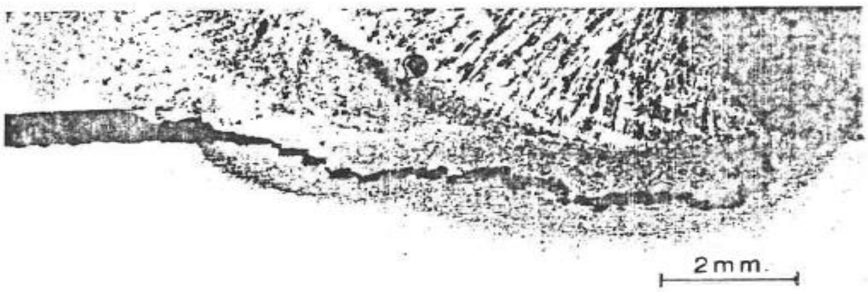

Figure 49 Lamellar tearing in the hydrophone tube
Source: NOU (1981)

Such cracks are related to the mechanical properties of the metal of the hydrophone tube. In this case, most of the affected areas around the support revealed that the cracking occurred about 1 mm below the surface of the metal of the tube, in the heat affected zone (Almar-Naess et al., 1982).

In a relatively high strength steel, such as used for the support, this type of reaction is often caused by the presence of hydrogen. Cracking begins when the bond of hydrogen with a fragile microstructure undergoes high internal stresses due to the welding.

The appearance of the impacted surfaces in quadrants I and III, shown diagrammatically in Figure 48 and Figure 50, indicated that cracking may have developed in this location much earlier than on other parts of the weld. A thick layer of corroded metal on the surface of the support between the corner welds was estimated to be equivalent corrosion exposed over a period of nine months (Almar-Naess et al., 1982).
The CP technique had worked normally until the time of the accident, suggesting that the corrosion deposit would have formed over the span of several years. This claim was reinforced by the fact that a section of the ruptured surface presented traces of paint (position 58 to 66 in Figure 48 and Figure 50); thus proving that the internal corner weld was cracked over a length of at least 70 mm when painting the D6 brace (NOU, 1981).

The cross section of the ruptured surface showed a layer of paint with a thickness of 0.5 to 0.7 mm as illustrated in Figure 48. Moreover, the quadrant IV shows that the filled weld remained practically intact (Figure 48 and Figure 50).

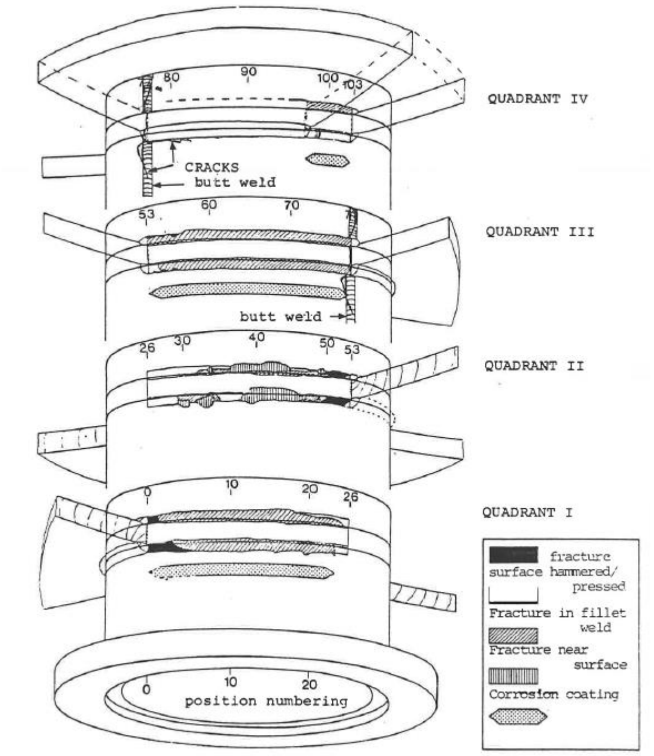

Figure 50 Characteristics of the breaking surfaces in the welds made between the hydrophone tube and the D6 brace
Source: NOU (1981)

The shape of the bead was not satisfactory because the contact angle at the edge of the weld was valued at approximately 90°. The fractured surfaces near the points where the cracking was initiated in the D6 brace were badly damaged by corrosion, friction and compression as illustrated in Figure 48.

5.5.2.2 The fatigue failure of the D6 brace

Precise measurements confirmed that the final rupture was accompanied by very little plastic deformation. As proven by the evidence in the measurement of the diameter, the overall geometry of the brace was only slightly altered. In fact, a maximum deviation of 37 mm, or barely 1.4%, was measured from the average exterior diameter of 2.6 m (NOU, 1981).

Likewise, the reduced area along the break's circumference, expressed as the value of the contraction in the thickness direction, was relatively small except in the region of the final break. The Figure 51 provides a clear representation of the value of the lateral contractions.

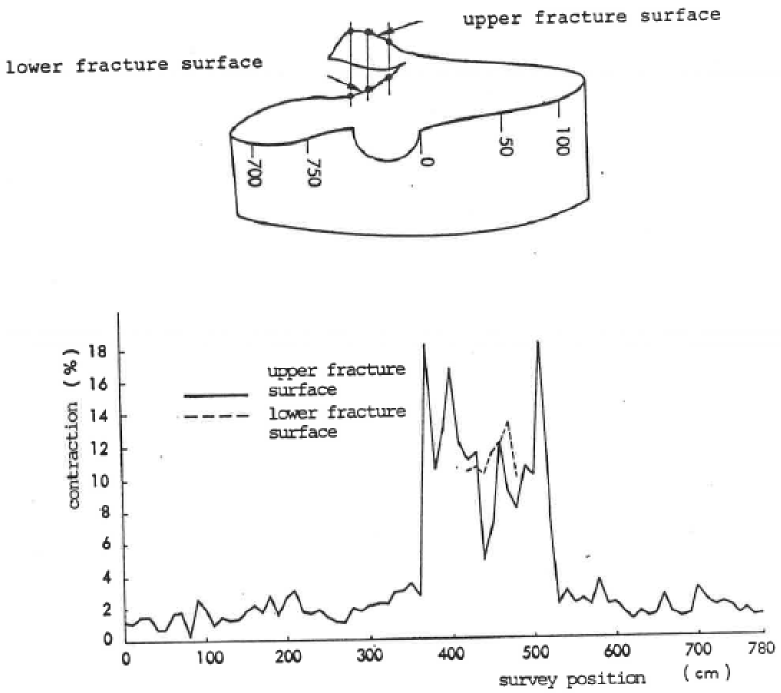

Figure 51 Contraction in the thickness direction measured on the circumference of the breakage of the D6 brace along the platform
Source: NOU (1981)

5.5.3 Lack of inspections

The fatigue break was characterized by two cracks; the first on the external corner weld of the hydrophone support and the other on the internal corner weld. These two points can be identified respectively in diagrams I and II (see Figure 48).

In addition, to an inadequate design of the hydrophone support, the investigation established that both the platform design, the monitoring during the construction stage and the inspections after platform installation, failed to expose the cracking defects.

In accordance with the regulatory requirements, as soon as the platform was put into service, the class was responsible for carrying out annual inspections (Det Norske Veritas, 1977). These should include verifying the general condition of the structure while ensuring that no permanent deformation, damages, cracks or corrosion affected the underwater structural condition.

Every four years, a special inspection takes place during calm weather conditions. This inspection was more thorough than the annual surveys and provided for the possible use of non-destructive test methods (see section 3.1).

This case proves how important it is to implement an optimal inspection program to ensure an early stage structural damage detection. In addition, it also highlights the importance of the post installation inspection (once the unit installed at sea). The latter will provide a detailed underwater image of the structure.

In this specific case, the lack of inspections caused to miss detect the damage in an early stage. This is directly related to a wrong inspection planning. In addition, the use of more accurate inspection techniques might have allowed the detection of the damage/crack propagation.

After studying and examining the causes of the accident we can conclude that the main reasons of the platform failure are as follows:

- the use of poor material and design of the hydrophone tube,
- the stress and fatigue accumulation mainly due to the switch in the platform's operation to a flotel with no serious structural study,
- the incorrect implementation of the underwater structural inspection which could've ensured the detection of the crack in an early stage.

CONCLUSION

This thesis describes different aspects of subsea offshore inspection, in particular the underwater steel structures. This project began by covering the rules and regulations applied by the classification societies on offshore units concerning the underwater surveys, then it explained the methods of non-destructive testing which are mostly applied in this sector. Moreover, a basic inspection strategy was explained to be followed by the unit's operator to keep the structure safe in open waters.
Chapter 3 handles the key aspect of this thesis where it discusses the underwater inspection specially the four NDT methods: visual, magnetic particles, radiography and ultrasonic. In addition to, the marine growth and the CP inspection of the underwater structure. Then, the advantages and limitations of each method helped to develop a gradual inspection strategy useful to detect metal defects in the underwater structure of an offshore unit. This inspection strategy can be used to conduct periodic inspections on offshore structures in working conditions to ensure its continuous structural strength, as well as on an abandoned structure in order to get an idea of its subsea structural status.

In conclusion, the inspection strategy illustrated in Figure 31 and shown in its scope in Table 5, describes the recommended program to be applied to keep the offshore structures protected out of drydock.
The first inspection level is the most elaborated inspection, as it covers the whole subsea and/or splash zone. It allows to build a general assessment of the structural conditions. In case of any damage detected in the previous level, a more detailed inspection is required in order to determine the extent of the defect. As the inspection level two is mainly sectional, where more advanced NDT can be used such as magnetic particles. At this stage a marine growth cleaning is required to allow a clear view of the metal. Moreover, if the previous inspection level wasn't accurate enough or a more detailed inspection is required to identify the damage extent, then the highest inspection level shall be carried out, where the most sophisticated inspection methods can be used such as radiography and ultrasonic.

Finally, the case of Alexander L. Kielland shows us the importance of the underwater inspection and the need of implementing a continuous and a complete inspection program, that will limit the possibility of the unit failure due to unseen structural damages. If the underwater inspection process of the structure was correctly implemented, the failure would have been avoided and lives could have been saved by an early detection of the damage.

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