# Research Activities of the Mooring Integrity Management Working Group

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***Key Words:*** *Mooring Systems, Mooring Integrity Management, RIO DE UT*

## 1. INTRODUCTION

All offshore structures are exposed to environmental loads such current, waves and wind. To avoid the drift, the floating platform must be equipped with a "mooring system", a "dynamic positioning system", or a combination of both system named "thruster assisted mooring system". In this article, we present some data regarding the mooring system gathered during the *Mooring Integrity Management Working Group* (MIM-WG) of the RIO DE UT.

The RIO DE UT (Realization of Integrated Ocean DEvelopment and Utilization system) is an endowed laboratory located in the University of Tokyo's Kashiwa campus that is sponsored by nine Japanese companies and one classification society. Among the several RIO DE UT's activities, the MIM-WG is composed by young professionals who are responsible to research the state of art regarding the mooring system, its installation, inspection and monitoring.

The first floating structures used offshore were "drilling tenders" that were anchored beside a fixed platform. Instead to build a large offshore, a small platform was built to receive the rig floor and derrick; and the floating tender received most of heavy equipment, material and living quarters (Fig. 1). Kerr-McGee was the pioneer to use this concept and drilled the first well in the Gulf of Mexico in 1947[1].

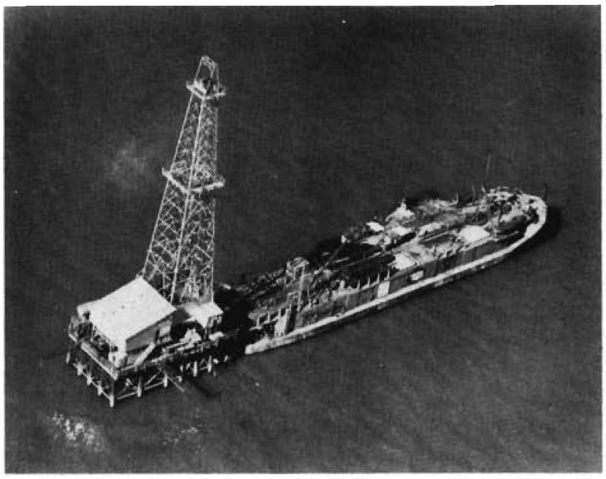

Fig. 1　Small drilling platform with the pioneer floating structure in GoM: an anchored floating tender offshore Louisiana[1].

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After the first applications in GoM, mooring systems the mooring system is widely used for the Exploration and Production (E&P) of offshore petroleum and natural gas fields worldwide. Its application includes floating platforms installed in shallow waters (<350m), deep waters (350~1500m) and ultra-deep waters (>1500m).

Another recent application of mooring system is the *Floating Offshore Wind Turbine* (FOWT). The bottom-mounted offshore wind turbines, which are installed in a very shallow water depth, are already a mature technology. However, for water depths more than 50 m, the FOWT is appropriate[2].

In Japan, the *Fukushima Offshore Wind Consortium*, funded by the *Ministry of Economy, Trade and Industry* (METI), installed the world first floating 25 MVA substation (Fig. 2) and three FOWT with generation capacity of 2 MW, 5 MW and 7 MW. Each FOWT has a different hull concept. This project aims to establish a business-model for the future commercial floating winds farms and to validate the FOWT technology[3].

Fig. 2　Floating electrical substation off Fukushima. (picture courtesy of *Japan Marine United*)

Despite the mooring technology has been used in floating structures for about 60 years, recent researches pointed out that the annual probability of failure of mooring line used in production floating platforms during the 10-year period between 2001~2011 was 30 times higher than the target probability suggested by DNV[4]. Some of new failure mechanisms have been identified. Such mechanisms are not anticipated during the design or could not be identified during inspection using ROV.

Based in this high failure probability, the MIM-WG decided to identify the state-of-the-art regarding design, installation, inspection and monitoring of mooring system. In this article, we present part of the information gathered during the last year.

## 2. RULES

In this section, we compare the two main rules for mooring system that has been widely used for the offshore E&P platforms: (i) API-RP-2SK[5)] and (ii) DNVGL-OS-E301[6)]. It is necessary to remind that these two rules cannot be applied for FOWT. For floating wind turbines, the Class NK has a specific rule[7)].

### 2. 1 API-RP-2SK

In terms of application, this rule assumes two different type mooring system featured by Table 1. The permanent mooring is assumed to have a design life of 10 years or more.

Table 1 Examples of mobile and permanent moorings.

| Type | Examples |
|---|---|
| Mobile Mooring | MODU[1], tenders, service vessels |
| Permanent Mooring | FPU (FPSO, SPAR, TLP, semi-submersible) |

This rule refers to "Stationkeeping Systems", which includes both mooring systems and dynamic positioning (the DP is out of scope of this article). Further, the rule has a review of different concepts of mooring system used so far, and several auxiliary components (shackles, buoys, etc).

In terms of analysis methods necessary for the design, API-RP-2SK has different requirement for mobile and permanent moorings (Table 2). For the mobile mooring, only a quasi-static is required for the strength design and the fatigue analysis is not required because of abuse from frequent deployment and retrieval. Thus, mooring system components may be easily inspected and such components are usually replaced before they reach their fatigue limits.

Table 2 Analysis methods required by API-RP-2SK during the design phase of a mooring system.

| Type | Analysis Method | Conditions |
|---|---|---|
| **Mobile Mooring** | | |
| Strength design | Quasi-static or dynamic | Intact/Damaged/ transient |
| Fatigue design | Not required | Not required |
| **Permanent Mooring** | | |
| Strength design | Dynamic | Intact/Damaged |
| Fatigue design | Dynamic | Intact |

For the permanent mooring, a more rigorous dynamic analysis is required for the final design. The dynamic analysis removes some of the uncertainties in the line tension prediction. Thus, the factors of safety of may be relaxed as featured by Table 3.

In terms of environmental loads, API-RP-2SK assumes a 5-year of return period for mobile mooring (10-year of return period if the vessel is located nearby another structure). For permanent mooring, it requires a 100-year return period (it can be reduced if the service life is much smaller than 20 years). In the case of a floating platform equipped with a rapid disconnection system, the maximum design condition is the maximum environment in which the platform may remain moored.

Table 3 Comparison of API-RP-2SK factors of safety for different conditions and analysis methods

| Condition | Analysis Method | Factor of Safety |
|---|---|---|
| Intact | Quasi-static | 2.0 |
| | Dynamic | 1.67 |
| Damaged | Quasi-static | 1.43 |
| | Dynamic | 1.25 |

### 2. 2 DNVGL-OS-E301

In terms of application, this rule assumes two differ classes as featured by Table 4.

Table 4 Different classes according to the DNVGL-OS-301.

| | |
|---|---|
| Class 1 | Semi-sub for drilling with riser disconnected and far from other platforms, accommodation platform located a more than 300m from other structure, Production and/or Storage platform equipped with emergency disconnection of riser and umbilical far from other platform, offshore loads buoy with no tanker moored |
| Class 2 | Drilling units with riser connected, drilling/ support/accommodation units operating at a distance less than 50m, Production and/or Storage platform equipped with NO emergency disconnection, offshore loads buoys with tanker moored. |

For the design analysis, this European rule has a different philosophy. The design criteria are based on three limit states, namely,

- ULS (Ultimate limit State): ensures that each mooring line have adequate strength to withstand the loads effects imposed by the extreme environmental actions;
- ALS (Accidental Limit State): ensures that each mooring line has adequate capacity to withstand the failure of one mooring line;
- FLS (Fatigue Limit State): ensures that the individual mooring lines have adequate capacity to withstand the cyclic loading.

The ULS and ALS shall be assessed using the same environmental conditions, while a wider range of environmental loads must be considered for the FLS. Further, the FLS must be assessed only for permanent mooring system.

DNVGL-OS-E301 suggested that the mooring analysis shall be performed by applying either a frequency domain or time domain. In case of quasi-static analysis, the safety factor shall be higher (Table 5).

DNVGL-OS-E301 also gives the corrosion allowance for distinct portions of the mooring lines (splash zone, catenary and bottom). The corrosion allowance also changes if the mooring system is located in tropical waters, Norwegian continental shelf, and if regular inspection is performed or not.

[1] MODU: Mobile Offshore Drilling Unit includes floating type drilling platforms (semi-submersible and drillship) and fixed type drilling platform (jackup).

Table 5 Comparison of DNVGL-OS-E301 partial safety factors for ULS.

| Class | Type of analysis | Partial SF on mean tension | Partial SF on dynamic tension |
|---|---|---|---|
| 1 | Dynamic | 1.10 | 1.50 |
| 2 | Dynamic | 1.40 | 2.10 |
| 1 | Quasi-static | 1.70 | |
| 2 | Quasi-static | 2.50 | |

## 3. RESEARCH & INNOVATION

In this section, we will present a review about research and innovations that has been carried out in Japan and in other countries.

### 3. 1 SR

During the late 1970’s until the middle of 1980’s, the J*apan Ship Technology Research* had carried out a comprehensive research concerning to mooring system. The section group SR179 had researched about mooring system in very shallow water; and the group SR187 had researched about mooring technology in deep water[8)].

The SR179’s research activities could be divided in: (i) study of the dynamic characteristics of an offshore structure with a box shape and (ii) study about the mooring system of an offshore structure with a box shape. This mooring research includes literature review, formulation of a methodology to calculate the static solution, formulation of a methodology to calculate de dynamic solution using the “Lumped Mass” methodology, experiments in a test basin (Fig. 3) and simulation.

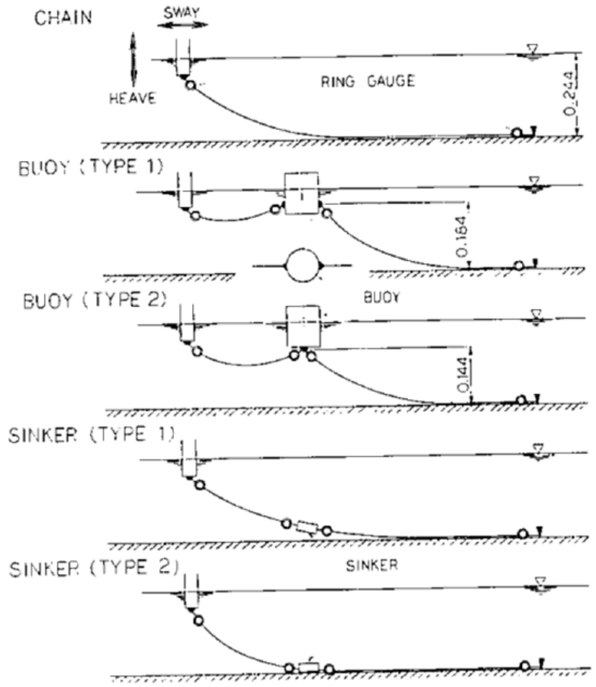


Fig. 3 Example of reduced scale mooring lines tested in basin[8)].

Next, the SR187 also had a review regarding the relationship between the water depth and mooring parameters, and about the design conditions depending the environmental loads. Then a methodology to calculate the static and dynamic behaviors of an anchored floating body including large offsets due to current, under long period oscillatory motion, composite line (chain and wire), numerical simulation. Regarding components of the mooring system, the research included the main difference between shallow water and deep water moorings, durability of wire and synthetic fiber rope, chain strength, anchor and marine life that encrusted on the mooring line. Experiments also were carried out to measure the effect of hydrodynamics forces on a chain, fatigue test for chains and wire rope.

### 3. 2 Torpedo Pile

During the 1990’s, the floating drilling platforms started to use mooring lines composed by chain and wire rope to increase the operational water depth. However, such solution required Vertically Loaded Anchors (VLA).

In the late 1990’s, Petrobras, the Brazilian national energy company, developed new concepted of free fall pile[9)]. Because such pile resembles a torpedo, it was named “torpedo pile”. In 2001, the torpedo pile T-43 (mass of 43 tons) was certified by the classification society and, in the next year, the T-43 started to be deployed to anchor drilling platforms. The new anchor was a success because it could be easily and quickly installed and matched the new requirement of vertical holding imposed by composite mooring lines.

Based on the success of the T-42, Petrobras started the development of the T-98 (Fig. 4), a much bigger torpedo pile to be used to anchor large FPSO. Table 6 features the main dimensions of the T-98.

Table 6 Main dimensions of the torpedo pile T-98.

| | |
|---|---|
| Total mass | 98 metric tons |
| Diameter | 1.07 m |
| Length | 17 m |
| 4x stiffener wings | 10 m long x 0.9 wide |

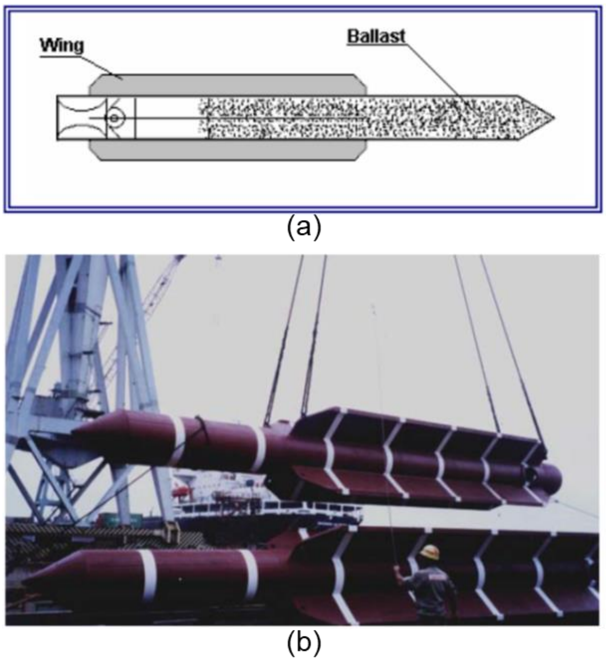


Fig. 4 The torpedo pile T-98[9)]: (a) schematic showing the ballast concentrated at the lower portion; (b) T-98 being boarded to AHV.

After a few tests, the installation method of T-98 had to be changed. Fig. 5 shows the new method that require two AHV to lower down the T-98 together. The torpedo pile is hanged about 200 m above the seafloor. Then the ROV use a rope to disconnect the connector named "pelikelo". The T-98 starts to fall and achieves a maximum velocity of 26.8 m/s.

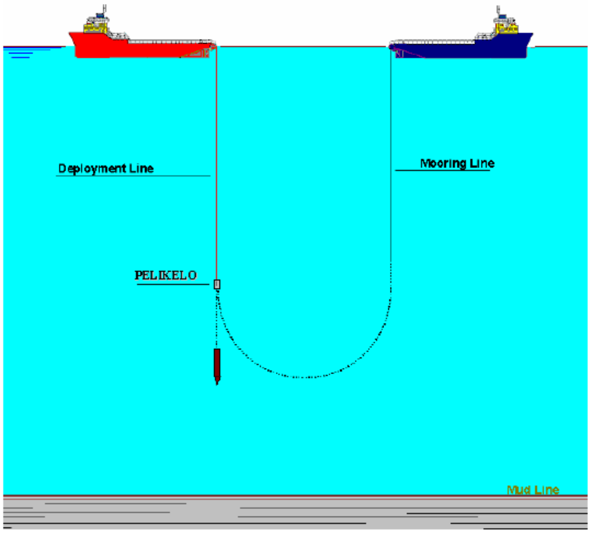


Fig. 5 Installation method of the torpedo pile T-98. Two Anchor Handling Vessels (AHV) are rquired[9].

In 2005, the T-98 was successful installed to anchor the FPSO P-50 in a water depth 1240m. The P-50 was one of the largest FPSO at that time and was anchored using 18 composites lines in an innovative lines arrangement (Fig. 6).

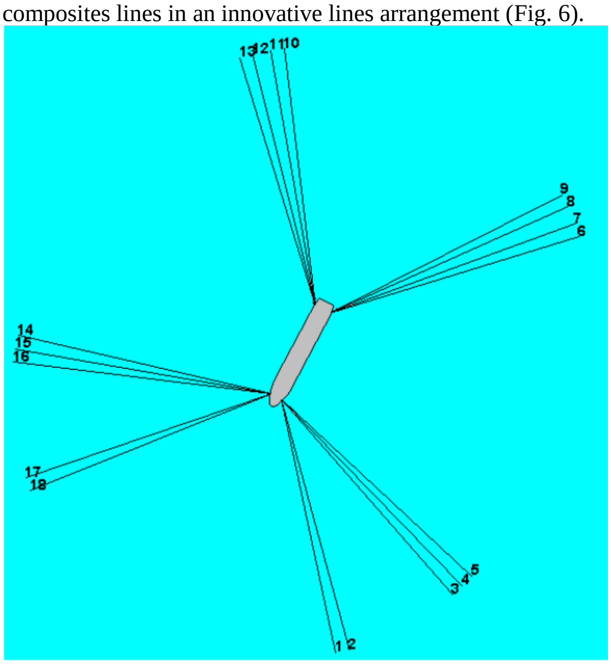


Fig. 6 P-50 mooring concept: DICAS (Differentiated Complacent Anchoring System)[9].

## 3. 3 COMPOSITE LINE WITH SUCTION PILE

In 2011, the operator *LLOG* installed the production semi-submersible to operate in the WHO DAT project. The *Delmar* was the EPCI contractor for the mooring system.

In total, 12 lines were installed in this project. The mooring line was composed of chain-polyester rope-chain, which requires vertical holding capability. Delmar chose the suction pile as anchor (Fig. 7) to attend the requirements. A special attention was paid for the design of the mooring padeye. The polyester rope was the Whittehill VETS370 (MBL 1100 metric tons; diameter of ~205 mm).

The WHO DAT project is in the Gulf of Mexico where is assumed to have hurricanes up to category 4. Delmar used the API-RP-2SK for design. The design condition assumed a 100-year return period hurricane and the survivability was checked for 1000-year return period event to ensure all safety factors were 1.0 or more.

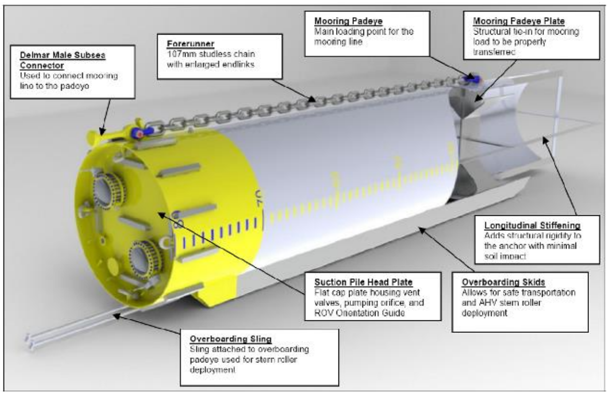


Fig. 7 Schematic of the suction pile used as anchor in the WHO DAT project[10].

## 4. INSPECTION & MAINTENANCE

### 4. 1 Inspection

As an alternative to the dry inspection of mooring line, the company *Welaptega Marine*[11] has developed an "optical caliper" that measures the *2d* distances between adjacent links. Changes in the distances indicate the wearing on the grip zone between two links. The measurement on 29 mooring system across the world showed that the highest wearing was observed at the touch down zone, followed by the upper portion of the line. The reasons for the highest wearing at the touch down zone are (i) the seabed sections of moorings can be highly dynamic and (ii) often there are trenches dug by the chain motion. Both actions may enhance the amount of abrasive material between two links increasing the wear.

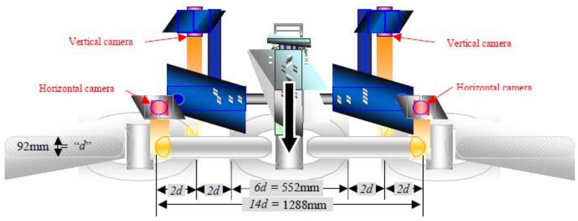


Fig. 8 Schematic of the "optical caliper" measuring the 2d distances to estimate the wearing on the grip zone[11].

Another tool developed by the same company is a rotary hammer that detects if the stud is tight or loose[11]. A loose stud can be related to crack propagation and fatigue of the link material. Fig. 9 shows the tool that is assembled on the link. A rotary hammer hit the stud and two sensors (a hydrophone and a micro-accelerometer) measure the stud response. Depending the response, the software distinguishes between "loose" and "tight" responses.

However, the accuracy and operation time of both inspection tools depends on the experiences of the ROV pilot and personnel in charge of the data recording.

The optical caliper shall receive a set of 3D cameras what could improve the visualization of the link corrosion/wearing.

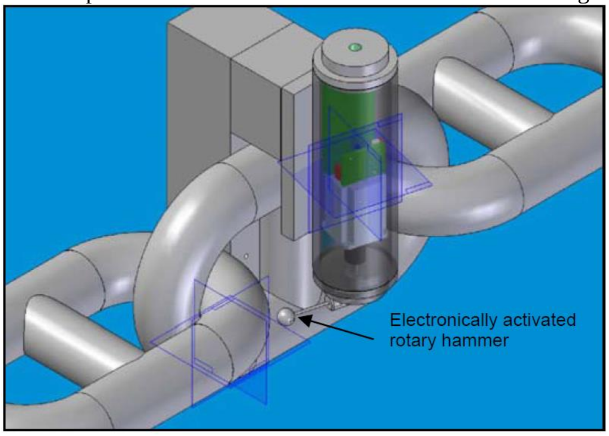


Fig. 9 Schematic of the rotary hammer that detects if the stud is tight[11].

### 4. 2 Monitoring

Assuming the floating production units operating in the North Sea, we have the following numbers[12]:

- 50% cannot monitor line tension in real time;
- 33% cannot measure offsets from the no-loads equilibrium position;
- 78% do not have a line failure alarm;
- 67% do not have mooring lines spares;
- 50% cannot adjust line lengths.

In these platforms, it may difficult to identify if a single mooring line is broken or not. Several sensors can be used or combined to indicate if there is a broken line. For instance, load cells can be installed to monitor the line tension; a reduced tension may be an indicative of broken line. Another sensor is the GPS, which measure the platform position. A large offset from the equilibrium position may indicate a broken line. But the current GPS monitoring system has a lot of false alarm because a large offset may be a strong environmental loads.

The company BMT Scientific Marine Services proposed the "Position Response Learning System" (PRLS) composed by a machine learning algorithm that "learn" the platform dynamic response based on the GPS data and environmental loads[13]. An erratic dynamic behavior means a broken a line. The advantage is that this system is constantly learning about the platform response. Even if the platform receives any major change during its service life (installation of a new module, for instance), the system learns and integrates the change to the analysis.

Another way to monitor a mooring line is measuring its inclination near to top end. The company *Pulse Structural Monitoring* developed the submersed triaxial inclinometer INTEGRIpod-AF (Fig. 10).

Fig. 10 The INTEGRIpod-AF[13].

The INTEGRIpod-AF is installed on the chain hawse of a mooring line (Fig. 11). The inclination data is transmitted acoustically to three acoustic receivers installed on the mooring the table. The inclination data is converted into tension using a developed software.

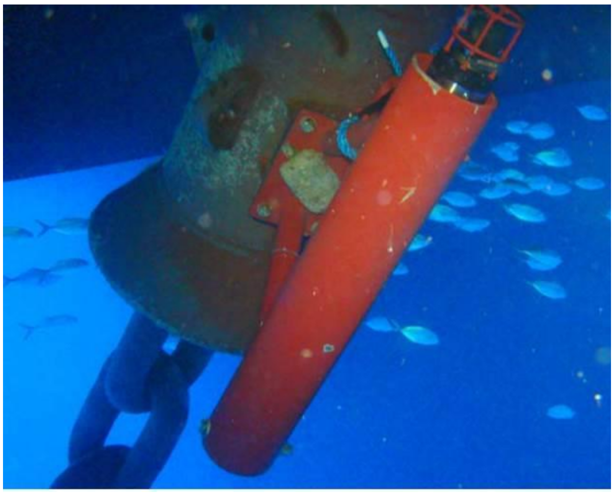

Fig. 11 The INTEGRIpod-AF installed on the chain hawse of a mooring line[13].

During the life cycle of any offshore structure, the fatigue is only assessed during the design phase. Such fatigue assessment is carried out based only in metocean data and Rules & Standards. Nobody knows if the offshore structure will withstand against the environmental loads predicted using the metocean data.

Further, it is relative common the extension of the service life of an offshore structure due to the tie back of marginal field and/or the discovery of more reservoir within the original field. In such scenario, it is very difficult to estimate if the service life can be extended or not.

## 6. SUMMARY

During the last year, the MIM-WG reviewed the state-of-the-art regarding the mooring system. Despite to be a field proven technology, recent investigations revealed a high failure probability of mooring line failure. Some of the failures are not predicted in the current rules.

Japan Ship Technology Research Association has an comprehensive research regarding mooring system in shallow and deep water that are freely available in its website.

The mooring system for deep and ultra-deep waters requires the use of composed lines (several combinations of chain, rope and wire) and anchors with vertical holding capacity (several anchors can match such requirement).

The inspection of mooring line is still dependent on ROV and the measurement of corrosion/erosion on the grip zone is possible, but it shall be a time-consuming operation.

## ACKNOWLEDGMENT

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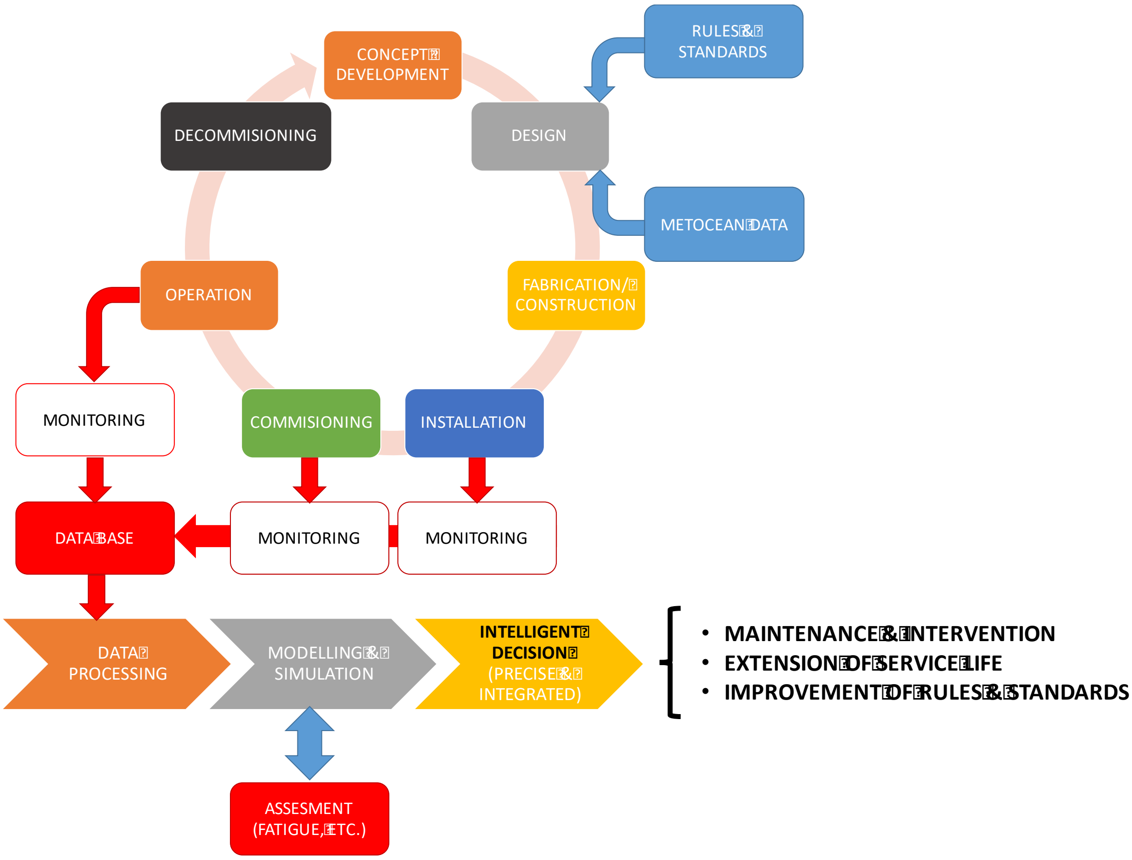


Fig. 12 Desired monitoring system to collect data during the installation, commissioning and operation phases. This data base shall be used to assess fatigue and other valuable information. All information will help the Operator to take an intelligent decision.


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