New Risk Control Mechanism for Innovative Deepwater Artificial Seabed System through Online Risk Monitoring System

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ABSTRACT:

The current offshore field development concepts (dry tree or subsea tree) have limitations for petroleum production in ultra-deep water (more than 1500 m), where the challenges are characterized by the depth of water, remoteness and harsh environmental conditions. A new alternative offshore field development solution, termed as Deepwater Artificial Seabed (DAS) system, is proposed. The new DAS system offers improved technical and commercial performance, higher levels of safety, reduced interface complexity and improved development flexibility for field development in deep and ultra-deep water. Central to the evaluation and application of the new DAS system is the inherent risk relative to the acceptance level. Hence, barriers in the new DAS system are established and maintained to prevent, control or mitigate undesired events or accidents. This paper investigates a new risk control mechanism for the innovative DAS system in accordance with the online risk monitoring and decision support principle. Firstly, main characteristics and design principle of the DAS system are presented. On this basis, the main hazards for the DAS system are identified, which includes well incident/ loss of well control, mooring system failure, ballast system failure, leak from riser, flexible jumper and subsea production facilities, and damage to riser, flexible jumper and subsea production facilities. The risk level of the identified hazards related to offshore petroleum systems already in use is analyzed and presented by the results from the risk assessment for the Norwegian Continental Shelf (NCS) in the period of 2008-2017. It has been demonstrated that the risk associated with the key sub-systems including the ballast system, mooring system, well system and external impact protection system is at a level that calls for further risk reduction. This is followed by the barrier management principles as well as a discussion of existing and potential barriers in the DAS system. Improved barrier functions in the key sub-systems are analyzed systematically and proposals for alternative barrier functions are suggested based on the online risk modelling and decision support principle. Further, a case study in regard to the DAS mooring system failure event is conducted to demonstrate how the new risk control mechanism works. The proposed new risk control mechanism could improve the safety of the DAS system and convince the offshore petroleum industry for application significantly.

Keywords: Deepwater Artificial Seabed; safety barrier; online risk modelling; risk control; ultra-deep water

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1. Introduction

In deep and ultra-deep water, oil and gas fields are currently developed by using dry tree units or subsea tree systems, or a combination of both. Nonetheless, it is recognized that both dry tree and subsea tree development concepts have drawbacks, as illustrated (the red shading) in Table 1. Aiming to overcome the demanding limitations of the current offshore field development concepts for petroleum production in ultra-deep water, where the challenges are characterized by the depth of water, remoteness and harsh environmental conditions, a new alternative offshore field development solution, termed as Deepwater Artificial Seabed (DAS) system [1-6], is proposed. Fig. 1 presents the general arrangement of the new DAS system.

It can be seen from Fig. 1 that in contrast to the geological seabed, the artificial seabed, which is positioned certain distances below Mean Water Level (M.W.L) to minimize the effects of direct loads from huge waves and strong surface currents, is established to support shallow-water rated well completion equipment and technology for the development of large oil and gas fields in ultra-deep water.

Central to the evaluation and application of the new DAS system is the inherent risk relative to the acceptance level. In particular, special challenges, such as deep waters, cold climate, remoteness and extreme environmental conditions (i.e. internal waves), expose the DAS system to additional risks while increased automation and autonomy are needed. These challenges require stronger emphasis on barriers to prevent, control or mitigate the potential major accidents.

Table 1

Features of subsea vs dry tree developments [7]

Feature	Dry tree development	Subsea development
Drilling cost	From facility	Requires MODU
OPEX cost	From facility	Requires MODU
Facilities CAPEX cost	High cost hull	Choose least cost hull
Offshore construction	Heavy lift requirements	Depends on riser system
Development flexibility	Restricted due to hull form	Minimal vessel impact
Riser/vessel interfaces	Complex interaction	Simpler interaction
Vessel flexibility	Restricted to Spar or TLP	Full range
Shut in location	In well bay close to people	Seabed isolation and offset
Flow assurance	Shortest flow path	Potentially long tie flowlines

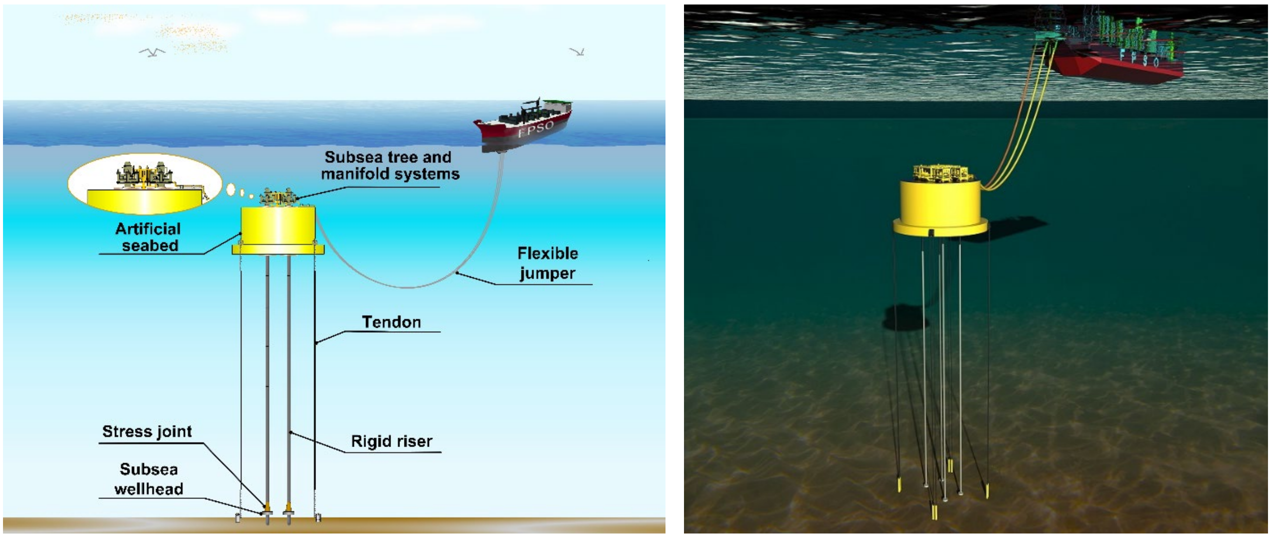

Fig. 1. General arrangement of the DAS system

In accordance with the management regulations of Petroleum Safety Authority Norway (PSAN) [8], barriers shall be established that at all times can: a) identify conditions that can lead to failures, hazard and accident situations, b) reduce the possibility of failures, hazard and accident situations occurring and developing, c) limit possible harm and inconveniences. Barrier management involves coordinated activities for establishing and maintaining barriers so that they fulfill their functions at all times [9]. Therefore, the primary purpose of barrier management is to establish and maintain barriers so as to be able to handle the risk faced at any given time. This is achieved by the established barriers whose functions are to prevent failure, hazard and accident situations occurring or restrict the consequences if they do occur.

This paper investigates the new risk control mechanism for the innovative DAS system in accordance with the online risk monitoring and decision support principle. Section 2 presents the main characteristics and design principle of the DAS system, followed by the identified main hazards and accident conditions. Section 3 gives a synopsis of the barrier management theory and principle. Existing and improved barrier functions in the DAS system are analyzed respectively in Section 4. This is followed by proposals of online risk modelling and decision support framework as alternative barrier functions for the DAS system in Section 5. Section 6 presents the detailed working principle of the new risk control mechanism by a case study with respect to the DAS mooring system failure event.

2. Main characteristics and hazards of the DAS system

2.1 Main characteristics of the DAS system

As illustrated in Fig. 2, the DAS system mainly consists of the following components.

Artificial seabed. The design and operation of the artificial seabed is critical to the DAS system since its main function is to provide a stable platform for keeping the rigid risers, flexible jumpers, subsea X-mas trees and manifold systems in-place. The submerged depth of the artificial seabed is determined by two constraints: (1) the direct loading from the surface wave and current, (2) the access for manual intervention. Hence, the optimized submerged depth of the artificial seabed varies with the area where the offshore petroleum field is located. It is also advisable to keep the submerged depth with reach of divers, even if the system is designed so that installation, maintenance and potential repair are planned without human intervention [10].

Mooring system. The DAS mooring system consists of vertically loaded tendons connecting the artificial seabed to the anchor piles. The function of the mooring system is to restrain the artificial seabed horizontally and vertically. The tendon assemblies consist of successive sections of chain and spiral strand wire rope. The anchor pile is a suction pile transferring the horizontal and vertical loads to the seabed.

Subsurface well system. The subsurface well system consists of casing programs, well completion assemblies, wellheads and X-mas trees. The casing program consists of all casing and liner strings, including hangers and cement in the subsea wellbore. The well completion assembly consists of production tubing, tubing hanger, downhole safety valve (DHSV), production packer, etc., to ensure the efficient and safe access from the artificial seabed to the reservoir. The wellhead is the subsurface/subsea termination of a wellbore in the DAS system. The subsea wellhead incorporates internal profiles for support of the casing strings and isolation of the annuli while the subsurface wellhead incorporates internal profiles for support of the rigid riser as well as isolation of the annuli. In addition, the subsurface wellhead system incorporates facilities for guidance, mechanical support and connection of the systems, which are used to drill and complete the well, such as Blowout Preventer (BOP) and X-mas tree. The subsea tree system includes a tubing hanger and a tree, which provide the barriers between the reservoir and the environment in the production phase. Basically, the tubing hanger supports the tubing string and seals off the tubing/rigid riser annulus. The subsea tree consists of an arrangement of remotely controlled valves to interrupt or direct flow for operational or safety reasons. It is noteworthy that shallow-water rated subsea trees can be utilized in the DAS system as the submerged depth of the artificial seabed will be in the scope of shallow water.

Subsurface manifold system. The manifold is a system of headers and branched piping that are used to gather and distribute fluids.

Flexible jumper. The flexible jumpers connect the manifold to the Floating Production Unit (FPU) and are in a slack catenary shape to isolate the artificial seabed from FPU motions. It is noteworthy that there exists a critical length criterion for the safe and economical design of the flexible jumper [11].

The following key advantages of the new DAS system in ultra-deep water can be envisaged:

- In place riser fatigue is low due to the location of the artificial seabed away from the surface wave zone.
- Compared with the conventional dry tree production units, light weighted FPU can be considered in service as the well completion equipment and rigid risers are all decoupled from the FPU motions.
- Direct access to local subsea wells is provided, and thus demanding flow assurance requirements can be met.
- Field layout is optimized and allows large offshore developments and unforeseen future field expansion, as a large number of subsurface wells can be supported.
- Shallow-water rated subsurface well completion technology offers improved technical and commercial performance in ultra-deep water.
- Pre-installation of the DAS system provides flexibility to the installation schedule.

2.2 Reality versus unknowns

The reality is that the proposed DAS system presents its unique and attractive potential for the industry application for petroleum production in deep and ultra-deep water. Nonetheless, prior to the true industry application, there exist various unknowns in the new DAS system. Aiming to enhance the confidence in the offshore petroleum industry, similarities can be seen in some key DAS components, which share their design with some well-proven installations in the offshore engineering practice as follows.

- The artificial seabed is designed in the same way as an anchored submerged buoy of the hybrid riser system, such as Tension Leg Riser (TLR) [12], Grouped SLOR [13]. The feasibility of the hybrid riser system has been proved by the trial well tests.
- The key design issues associated with the rigid risers are to some extent the same as Top Tensioned Risers (TTRs) for deepwater applications [14]. The feasibility of the TTR has been proved by the industry practice.
- The DAS system shares the design and application of the flexible jumpers of the hybrid riser system as well as the shallow-water rated subsea tree and manifold systems. The feasibility of the flexible jumper has been proved by the industry practice.

2.3 Main hazards and accident conditions for the DAS System in the operational phase

The main hazards and accident conditions for the DAS system in the operational phase are identified as follows.

- Well incident/ loss of well control
- Mooring system failure
- Ballast system failure
- Leak from riser, flexible jumper and subsea production facilities
- Damage to riser, flexible jumper and subsea production facilities

In order to represent risk levels of the main hazards and accident conditions for the DAS system in the operational phase, Fig. 2 presents an illustration for the certain types of hazards that can occur in similar systems in the offshore petroleum industry, i.e. the corresponding results from the risk assessment for the NCS in the period of 2008-2017, including well incident/loss of well control (DFU3), damage to platform structure/stability/anchoring/positioning fault (DFU8), leak from riser, pipeline and subsea production facilities (DFU9), and damage to riser, pipeline and subsea production facility (DFU10). DFU is a Norwegian acronym for reported hazard and accident condition. Furthermore, the main hazardous factors that may influence and result in the identified hazards and accident conditions for the DAS system in the operational phase are categorized into the following three groups.

- Degradation based hazardous factors, such as corrosion, fatigue, wear, etc.
- Event based hazardous factors, such as trawling activities, dropped objects, ROV impact, etc.
- Environment based hazardous factors, such as strong winds, huge surface and internal waves, etc.

It can be found from Fig.2 that the historical frequencies for incidents involving leak from riser, pipeline and subsea production facilities are at a fairly low level. It can also be found that the historical frequencies for incidents involving well incident/loss of well control (DFU3), damage to platform structure/stability/anchoring/positioning fault (DFU8), and damage to riser, pipeline and subsea production facility (DFU10) are at significant levels. Hence, this indicates that risk associated with well systems, mooring systems, ballast systems, and external impact protection systems is at a level where further improvements should be made.

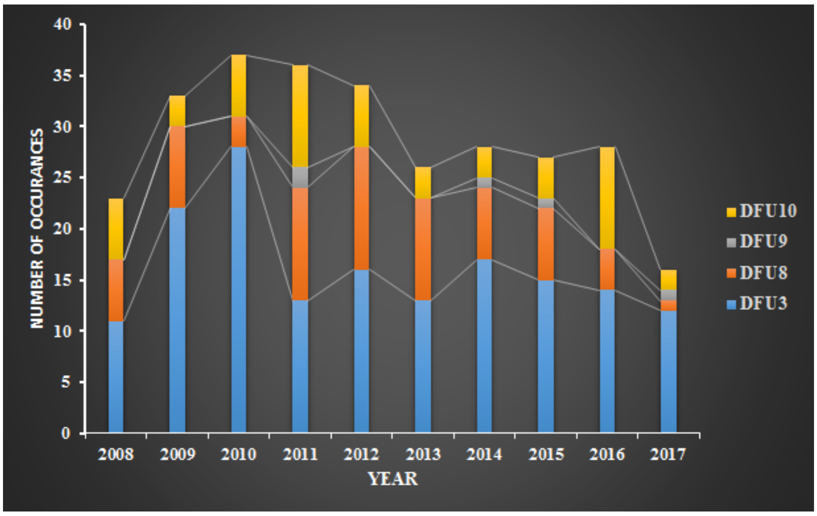

Fig. 2. Reported DFUs by categories in relation to the main hazards for the DAS system [15]

3. Fundamental principles for barrier concepts

Barrier management is defined as "coordinated activities for establishing and maintaining barriers so that they fulfill their functions at all times" by PSAN [9]. It indicates that the barrier management model is based on a process for establishing the risk picture and barriers in a planning, design or construction phase. Further, that basis must be monitored, reviewed and possibly updated during the execution or operational phase while performance measurements or verifications have to be carried out in order to achieve continuous improvement and robust barriers throughout the life cycle.

The terminology is used, involving the following levels:

- Barrier function: the task or role of a barrier.
- Barrier element (or system): technical, operational and organizational measures or solutions involved in the realization of a barrier function.
- Risk influencing factor (RIF): factors identified as having positive or negative impact on the reliability of barrier functions and the ability of barrier elements to function as intended.

The key points in barrier management are presented in Fig.3. It can be noted that barrier management starts with an understanding of the context that the barriers are intended to function in. Then, relevant failure, hazard and accident situations are identified. Aiming to protect against and combat these hazards, the necessary barrier functions are identified and established. A barrier function normally consists of several barrier elements. Further, performance requirements are defined in order to ensure that the barrier can fulfil its function. As many factors will affect the performance of the barrier elements, it is of great importance to identify the significant RIFs.

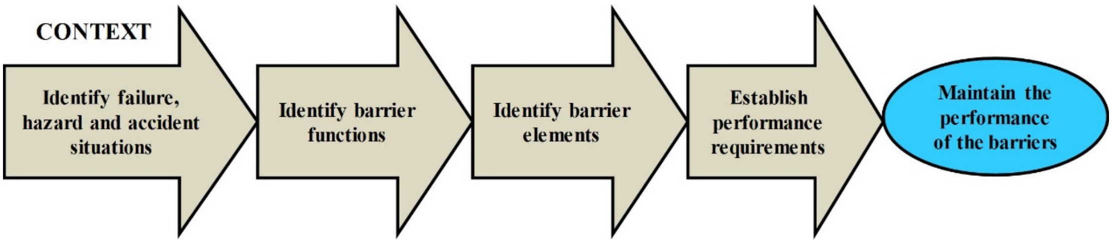

Fig. 3. Key points in barrier management [9]

4. Improved barrier functions in the DAS system

With respect to the identified main hazards and accident conditions for the DAS system in the operational phase, barrier functions in the ballast system, mooring system, well system and external impact protection system are established in this study in order to provide substantial risk reduction for the DAS system in ultra-deep water. In particular, the investigation on barrier management for marine systems [16] lays the foundation for the definition of improved barrier functions in relation to the ballast system and mooring system.

4.1 Improved barrier functions in the ballast system

In the DAS system, the barrier functions may be defined with respect to the stability and buoyancy by the ballast system of the artificial seabed as follows.

- Barrier function 1: prevent abnormal weight conditions
- Barrier function 2: control abnormal weight conditions
- Barrier function 3: prevent escalation of abnormal weight conditions

Barrier functions 1~2 are known and established in the current practice in existing offshore petroleum systems:

- Prevent abnormal weight conditions due to design capabilities as well as positions of center of gravity and displacement.
- Control abnormal weight conditions through ballast system and associated operations.

Barrier function 3 is not identified in accordance with the current practice in existing offshore petroleum systems and is a system to prevent escalation of abnormal weight conditions through a detection and advisory system. The system will be independent and work separately from the ballast system. The purpose is twofold; firstly to analyze the development of motions of the artificial seabed and its responses, and secondly to advise on how to prevent further escalation of the situation. In addition, barrier function 3 must be online and take data inputs from the motion and acceleration of the artificial seabed. The responses of the artificial seabed need to be analyzed with an online risk model of the artificial seabed, to predict the development of the artificial seabed's stability if uncorrected, as an input to advice on how to prevent further escalation. Note that it will also be important to ensure adequate independence between critical functions (control functions and safety functions) and monitoring functions.

4.2 Improved barrier functions in the mooring system

In the DAS system, the barrier functions may be defined with respect to the station-keeping by the mooring system as follows.

- Barrier function 1: prevent the initial mooring system failure
- Barrier function 2: control the initial mooring system failure
- Barrier function 3: prevent escalation of the mooring system failure

Barrier functions 1~2 are known and established in the current practice in existing offshore petroleum systems:

- Prevent the initial mooring system failure due to design capabilities and material qualities of mooring system components.
- Control abnormal weight conditions through line load management system and associated operations.

Barrier function 3 is not identified in accordance with the current practice in existing offshore petroleum systems and is a system to prevent escalation of the mooring system failure through a detection and advisory system. The system will be independent and work separately from the mooring line load management system. The purpose is twofold; firstly to analyze the development of motions and the loads on the remaining mooring system components and their responses, and secondly to advise on the load management in order to prevent further escalation of mooring system failures. In addition, barrier function 3 must be online and take data inputs from the motion and acceleration of the structure in addition to load measurement. The responses of the mooring system components need to be analyzed with an online risk model of the mooring system, to predict the development of loads and responses if uncorrected, as an input to advice on how to prevent further escalation. Note that it will also be important to ensure adequate independence between critical functions (control functions and safety functions) and monitoring functions.

4.3 Improved barrier functions in the well system

In the DAS system, the barrier functions may be defined with respect to the well integrity by the well system as follows.

- Barrier function 1: prevent uncontrolled outflow from the borehole/well to the external environment
- Barrier function 2: control the uncontrolled outflow from the borehole/well to the external environment
- Barrier function 3: prevent escalation of the uncontrolled outflow from the borehole/well to the external environment

Barrier functions 1~2 are known and established in the current practice in existing offshore petroleum systems:

- Prevent the uncontrolled release due to design capabilities and material qualities of well system components.
- Control the uncontrolled release through well integrity management system and associated operations.

Barrier function 3 is not identified in accordance with the current practice in existing offshore petroleum systems and is a system to prevent escalation of the uncontrolled outflow from the well through a detection and advisory system. The system will be independent and work separately from the well system. The purpose is twofold; firstly to analyze the development of operational pressure, and secondly to advise on the Annulus Pressure Management (APM) in order to prevent further escalation of the uncontrolled outflow from the well. According to NORSOK Standard D-010 [17], pressures in all accessible annuli shall be monitored. Barrier function 3 must be online and take data inputs from the annulus pressure monitoring. The annulus pressure of the well system needs to be analyzed with an online risk model of the well system, to predict the development of the annulus pressure if uncorrected, as an input to advice on how to prevent further escalation. Note that it will also be important to ensure adequate independence between critical functions (control functions and safety functions) and monitoring functions.

4.4 Improved barrier functions in the external impact protection system

In the DAS system, the barrier functions may be defined with respect to the structural integrity by the external impact protection system as follows.

- Barrier function 1: prevent the external impact on the DAS components
- Barrier function 2: control the external impact on the DAS components
- Barrier function 3: prevent escalation of the external impact on the DAS components

Barrier functions 1~2 are known and established in the current practice in existing offshore petroleum systems:

- Prevent the external impact on the DAS components due to design capabilities of the DAS components and setting of safety zone
- Control the external impact on the DAS components through alarms and associate operations

Barrier function 3 is not identified in accordance with the current practice in existing offshore petroleum systems and is a system to prevent escalation of the external impact on the DAS components through a monitoring, detection and advisory system. When the external impact incidents are detected, barrier function 3 must be online and take data inputs through the Condition and Performance Monitoring (CPM) program. The data from the CPM needs to be analyzed with an online risk model of the external impact protection system, to predict the integrity of the DAS system, as an input to advice on how to prevent further escalation. In addition, the new barrier function will be independent of current operations responding to the external impact. The purpose is to reduce the possibility of external impact events or limit the damage caused by such events significantly. Note that it will also be important to ensure adequate independence between critical functions (control functions and safety functions) and monitoring functions.

5. Online risk monitoring and decision support as a barrier function

Risk analysis techniques for the offshore petroleum industry have been developing for more than 30 years. Nonetheless, methods are mainly developed for the design phase and are not applied regularly in the operational phase as part of the barrier management [18, 25]. In particular, current risk analysis techniques present a static picture of the average state of the system and operation on the basis of historical data and expert judgments, which indicates that current methods do not sufficiently take the time aspect into account. In the present days, it is recognized that risk should be modelled as a function of time and hence, the need for more dynamic risk assessment techniques has been addressed [19]. This implies that risk assessment methods can provide an operational barrier function reflecting any rapid changes or incremental increases in the risk level for standard daily operations [16, 20].

As has been noted, special challenges, such as deep waters, cold climate, remoteness and extreme environmental conditions (i.e. internal waves), expose the DAS system to additional risks while increased automation and autonomy are needed. Hence, the decision support system of the DAS system requires improved functionality in safety critical software-based system, better informed operators, less manual operation and intervention, as well as longer response time if manual intervention is necessary. In addition, developments in the wireless technology as well as smaller and improved sensor technology open up for the increased use of online measurements and automation for the operator decision support [16, 20]. In particular, as ‘all subsea’ characteristic of the DAS system brings a natural gap for any direct manual operations, relevant safety operations in the DAS system are characterized by the need for rapidly understanding changes in the state of complex processes of real time data from sensors, videos and detection units.

In this scenario, an online risk monitoring and decision support framework for the DAS system is proposed, which will supply the operators with a real-time risk picture and pre-warnings of possible deviations in the DAS system. Fig. 4 presents the framework for the online risk monitoring and decision support system. It can be seen that the proposed online risk monitoring and decision support system consists of four major modules, as follows:

- Organizational management system
- Autonomous assistant system
- Online risk models
- Data collection

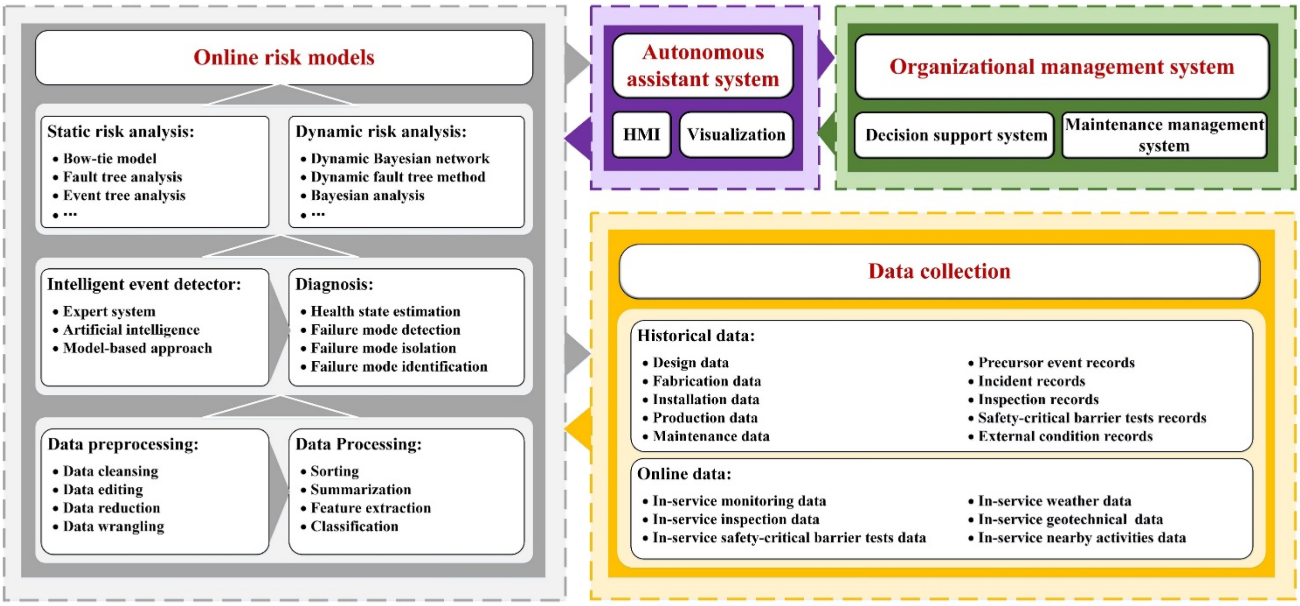

Fig. 4. Framework for online risk monitoring and decision support system

The online risk models build on the basis of data from two aspects, including historical data and online data. The historical database includes basic parameters of the DAS system and continuous data records of monitoring, routine test, inspection, and maintenance and other field data. Data from existing offshore petroleum systems can be an important supplement to the historical database for the online risk modeling. The online database collects condition monitoring data to help understand the in-service state of the whole system through real-time monitoring and transmission. The collected data serves to capture and identify potential abnormal signals through data processing, intelligent event detector and diagnosis process. The development of communication technology such as optical fiber sensing, satellite communication and microwave communication will build a solid foundation for the reliable online connection, especially as the promising application of 5G technology in various industrial scenarios including offshore petroleum industry. It can be noted that the datasets contain all available safety information with respect to DAS system. Further, the datasets gathered from diverse sources will grow rapidly, which leads to a big data volume beyond the ability of common tools to manage and process them within a tolerable elapsed time. Thus, data preprocessing and processing are indispensable and provided for the online risk models to make the datasets more relevant, non-redundant and producing meaningful information. The processed data are further handled by the intelligent event detector in accordance with the expert system, artificial intelligence and model-based approach. The intelligent event detector allows mapping the identified conditions and faults of the undesired events. This supports the diagnosis process in relation to health state estimation, failure mode detection, isolation as well as identification. The diagnosis process depends on mathematical estimators and models. The role of an estimator is to find an approximate of a variable from measurements. There are some well-known estimation methods and algorithm, e.g. Bayesian estimator [21], Kalman filter [22], Markov Chain Monte Carlo (MCMC) [23], etc. Normally, choosing and calibrating an estimator are not trivial, as it requires a combination of theoretical and practical understanding of the estimation models as well as the mathematics and process or equipment involved [24]. The aim of the diagnostic system is to detect and help explain all the deviations.

The online risk models can be developed based on the current methods for both static and dynamic risk analyses, such as bow-tie model, fault tree analysis (FTA), event tree analysis (ETA), dynamic Bayesian network (DBN), Bayesian analysis, etc. Further, the interpreted results from online risk models are presented on the visualization displays in accordance with the autonomous assistant system. Once the risk of diagnosed deviation is assessed above the warning limit, the emergency response procedure is immediately activated to start the decision-making and execution process. It has been found and recognized that for the large and complex offshore production system, vast information has to be handled and a large number of actions have to be taken to respond to the deviations in the face of major hazard risk, which may result in the information overload for the operator. Hence, some of the decision-making actions can be delegated to the autonomous assistant system by the human operators. A proper response mechanism should be established to guarantee efficient and effective response. Deviations of lower risk level can be redressed through automatic control performed by the autonomous assistant system. For deviations beyond the system authority, the autonomous assistant system must request the human operators' approval. The corrective actions and maintenance activities are then performed to redress the deviations. The redressed condition will be reassessed by online risk models. Meanwhile, a simulator is needed to train the operator in coping with various information and complex scenarios.

From the perspective of control theory, the online risk monitoring and decision support system can be regarded as a full control system. The online risk models perform as a sensor to monitor the process. The autonomous assistant system is an actuator of the corrective actions and maintenance activities. An audit or evaluation should be made by the organizational management system as a controller. The output performance of the actuator should be compared to the desired performance and finally send feedback to the actuator. Effective communications are required among these works.

Aiming to prevent, control or mitigate the hazardous events or accidents associated with the DAS system, the proposed framework emphasizes the need for exploring the potential for enhanced utilization of existing sensors, instrumentations and autonomous assistant system to improve the online decision support and the development of new monitoring solutions. Hence, an independent online risk management framework can be applied to the DAS system as an additional barrier function. Especially, the advisory functionality of the autonomous assistant system will enable the relevant operators to make right and timely decisions.

6. Case study

A case study with respect to the DAS mooring system failure event is conducted to demonstrate how the new risk control mechanism works. The mooring system failure could result in loss of stability of the artificial seabed, possibly causing damage of the rigid riser and subsurface wellhead. If the rigid riser is pressurized, hydrocarbon release or blowout may be induced further. In this case, it is required for human operators to analyze the development of the mooring system failure event as well as execute appropriate operations to prevent the major accident within a short time. Hence, the proposed online risk monitoring and decision support system is needed to be applied to the DAS system as an addition barrier function in the operational phase.

Fig.5 illustrates the working procedures of the online risk monitoring and decision support system on the DAS mooring system failure event. In the data collection phase, the primary data input consists of the historical data and online data as follows.

- *Design data*
  - Initial mooring design/analyses data
  - Mooring design upgrade/repair design data
- *In-service monitoring data*
  - Anchor position data
  - Artificial seabed motion and position data
  - Mooring line pre-tension/tension data
  - Mooring line top angle data.
- *In-service inspection data*
  - General visual inspection data on the DAS mooring components
  - Measurement data on the DAS mooring components
- *In-service environmental data*
  - Internal wave height, period and direction
  - Current speed and direction
  - Geotechnical data

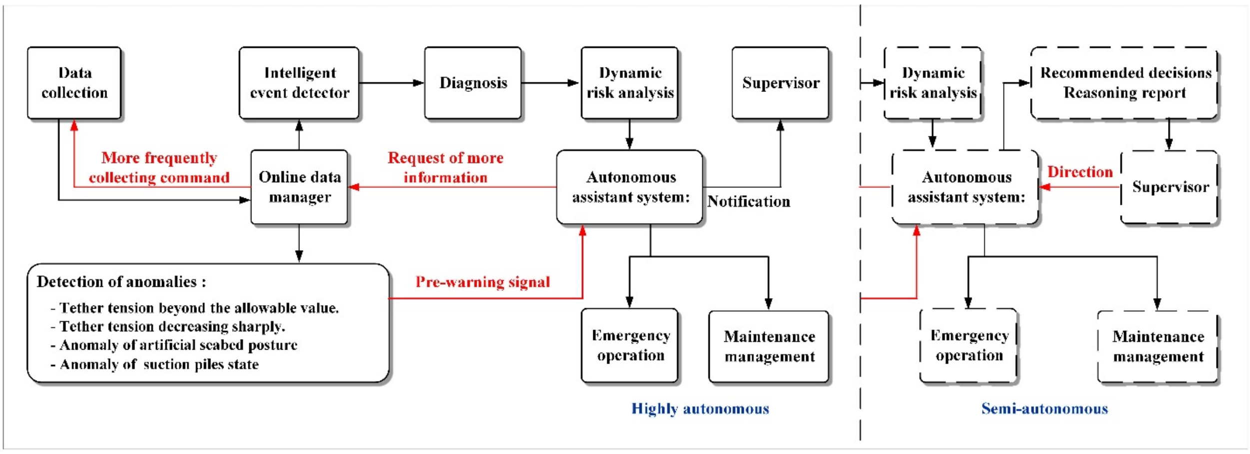

Fig. 5. The working procedures of online risk monitoring with respect to the DAS mooring system failure event

In the module of online risk models, the collected datasets are firstly preprocessed and then processed to transform the raw data into useful information. Further, the intelligent event detector deals with the processed information and detects the mooring system failures. On this basis, the relevant failure modes and potential failure causes are identified in the diagnosis phase. For instance, the potential failure causes of mooring system failure are divided into three categories, and the more detailed sample causes are listed in Table 2 [28].

- Design/Fabrication base causes. A latent defect passed through from the design, fabrication, or installation.
- Degradation based causes. Deterioration of the system.
- Individual event-based causes. Occurrence of an event-based failure.

Table 2

Sample causes of mooring system failure

Design/Fabrication base causes	Degradation based causes	Individual event-based causes
● Calculation error ● Incorrect environmental conditions ● Incorrect Geotechnical data ● Modeling error ● Fabrication error ● Drafting error ● Inadequate allowance for clashing ● Inadequate marine growth allowance ● Inadequate corrosion allowance ● Unsuitability of mooring accessories ● Inadequate consideration of mooring line movement in dynamic zone	● Wear ● Corrosion ● Failure of locking arrangements ● Fatigue ● Excessive marine growth ● Structural damage of mooring line in dynamic zone	● Installation damage ● Vessel impact ● Dropped object ● Exceeded design condition

This is followed by the dynamic risk analysis to understand the potential influence of the deviations on the DAS mooring system as well as to quantify the risk. Then, the autonomous assistant system will determine whether the mooring system is fit-for-service or not directly. In addition, control measures are also recommended to human operators. With respect to further major decision-making actions, the autonomous assistant system needs to request the approval of the human operators.

It should be noted that the autonomous assistant system also plays an important role in managing the data collection. If the deviation occurs in the datasets, a pre-warning signal will be sent to the autonomous assistant system. Then, a feedback is made by the autonomous assistant system aiming at requesting more data information to affirm the deviation.

7. Conclusions

Though the new DAS system offers attractive both technical and commercial advantages over the current offshore field development concepts in ultra-deep water, central to the evaluation and application of the new DAS system is the inherent risk relative to the acceptance level. The main intention of this study is to investigate the new risk control mechanism for the necessary barrier functions in the key sub-systems of the DAS system in accordance with the online risk monitoring and decision support principle.

In this study, the main hazards of the DAS system are identified. The illustration of risk levels on the NCS during the last ten years has demonstrated that there are concrete needs to significant risk reduction for hazards associated with the well systems, mooring systems, ballast systems, and external impact protection systems. Significant risk reduction for the new DAS system can be achieved in accordance with the establishment of additional barrier functions.

On the basis of the online risk modelling and decision support principle, proposals for additional barrier function are suggested for the well systems, mooring systems, ballast systems, and external impact protection systems of the new DAS system aiming to provide a specific detection and advisory system for the risk control.

An online risk monitoring and decision support framework for the new DAS system is proposed, which will supply the human operators with a real-time risk picture and pre-warnings of possible deviations in the DAS system. The advisory functionality of autonomous assistant system will enable the relevant operators to make right and timely decisions while the situation of information overload can be avoided. The study could improve the safety of the DAS system and convince the offshore petroleum industry for application significantly.

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Nomenclature

Abbreviations

APM	Annulus Pressure Management
BOP	Blowout Preventer
BSR	Buoy for Supporting Riser
CPM	Condition and Performance Monitoring
DAS	Deepwater Artificial Seabed
DBN	Dynamic Bayesian Network
DFU	Reported Hazard and Accident Condition
DHSV	Down Hole Safety Valve
ETA	Event Tree Analysis
FPU	Floating Production Unit
FTA	Fault Tree Analysis
HMI	Human Machine Interface
MCMC	Markov Chain Monte Carlo
M.W.L	Mean Water Level
NCS	Norwegian Continental Shelf
PSAN	Petroleum Safety Authority Norway
RIF	Risk Influencing Factor

SWC	Subsurface Well Completion
SLOR	Single Line Offset Riser
TTR	Top Tensioned Riser

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