PETROLEUMSTILSYNET

Investigation report

Report	
Report title Investigation of an incident with fatal consequences on *COSLInnovator*, 30 December 2015	Activity number 418005005

Security grading		
☑ Public	☐ Restricted	☐ Strictly confidential
☐ Not publicly available	☐ Confidential	

Summary

Mobile drilling unit *COSLInnovator* was struck by a wave at 16.38 on 30 December 2015. The impact occurred forward on the port side, and the unit suffered extensive damage. One person died and four were injured. The damage was confined to part of the living quarters.

Involved	
Main group Supervision - Mobile facilities and drilling contractors	Approved date 6 July 2016
Members of the investigation team Irja Viste-Ollestad, Terje L Andersen, Narve Oma and Sigvart Zachariassen	Investigation leader Irja Viste-Ollestad

Contents

1 Summary

Statoil received a consent from the Petroleum Safety Authority Norway (PSA) on 6 June 2012 to pursue well operations on the Troll field with the semi-submersible offshore drilling unit *COSLInnovator* (CI). This facility has operated for Statoil on Troll since January 2013.

At about 16.38 local time on 30 December 2015, part of the forward topside (box girder/ superstructure) on CI was struck by a large wave. The unit was disconnected from the well at the time and raised to its survival condition.

The wave struck CI on the port side of the front bulkhead of the forward box girder and smashed 17 windows: six on the lower deck and 11 on the mezzanine deck. Water intrusion caused extensive damage to cabins on these two decks. One person was killed and four others suffered light injuries from the damage which followed the wave's impact with the unit. The wave also caused deformation to the forward bulkhead on the box girder.

Had the incident occurred at a time when more of the people on board were in their cabins, more lives could have been lost.

The alarm was activated on CI, the emergency response organisation mobilised and the crew mustered. Search and rescue, damage limitation and life-saving first aid were then initiated. Both COSL and Statoil established second-line emergency response on land. Activities in the acute phase were largely conducted in accordance with procedures, but it took about 40 minutes to establish a full overview of personnel on board (POB). Injured people were flown by helicopter to hospital. Non-essential personnel were evacuated by helicopter. After the incident, the unit sailed for land under its own power.

The HSE regulations for the petroleum industry specify requirements for the air gap – the distance between the underside of the lowest deck and the highest wave crest – if its superstructure is not dimensioned to resist wave slamming. The strength of structures is calculated in accordance with the regulations drawn up by the classification society. Attention in the investigation has concentrated on how wave slamming on the forward bulkhead of the box girder (superstructure) could occur. The design basis and the analyses carried out in the design phase to clarify the air gap have therefore been prioritised in this investigation.

Various air gap calculations exist for CI, with different results, as well as a model test. The PSA considers that inadequate attention was paid to two of the analyses performed. This circumstance could have been significant for the extent of the damage sustained in the incident.

Wave characteristics have been calculated after the incident on the basis of weather observations. The possibility of a negative air gap arising as a result of the unit's motion and wave crest heights has been considered, and assessments made of horizontal hydrodynamic pressure on the basis of the damage to the unit. Given the data available, the PSA has concluded that the wave was steep, but that the weather conditions on 30 December were probably within the limits which the unit was designed for. In the PSA's view, the greatest uncertainty related to the description of the incident lies in the relative positions of wave and unit at the moment of impact.

Topsides must be dimensioned to resist wave loads if a unit has a negative air gap. Set by both the Norwegian Maritime Authority (NMA) and DNV,[1] this requirement does not distinguish specifically between vertical and horizontal wave slamming (related to the box girder's underside and forward bulkhead respectively). The PSA has observed that horizontal wave slamming was disregarded, even though a negative air gap was identified in analyses performed by both DNV and Grenland Group (GG). The work carried out during the design period was largely in line with experience and industry practice for mobile offshore units at the time the project was pursued.

Various owner constellations and different engineering companies were involved during development of the design from 2005 to 2008. Disagreements and inadequate information existed between the players, particularly when weight increases occurred during the construction process. Not all documentation was transferred at once when the engineering company changed. It is therefore unclear who had access to what documents at given times.

The windows on the unit were not designed to resist wave loads. It was found that bolts with a lower strength grade than the supplier's specification had been extensively used to attach windows. Observations have revealed that the attachments (bolts) had roughly the same breaking strength as the glass. The PSA has therefore concluded that the use of bolts with a lower strength grade was not determinative for the extent of the damage.

The following observations have been made by the investigation.

- The superstructure with windows of the unit (CI) was not dimensioned at the time of the incident to resist horizontal wave loads, even though the unit did not have a positive air gap.
- Analyses and a model test were conducted during the design process to determine the air gap. Some of this documentation indicates a negative air gap. The final analysis, which formed the basis for building and commissioning the unit later in the process, led to a conclusion that the unit had a positive air gap.
- The system for counting personnel during mustering did not function satisfactorily.
- The correct quality of bolts was not used for attaching windows.

2 Introduction

CI was struck by a wave at 16.38 on 30 December 2015. The impact occurred on the forward port side, and the unit suffered extensive damage. One person died and four were injured.

2.1 COSLInnovator

CI is a semi-submersible mobile offshore drilling unit designed for dynamic positioning, mooring and combined operation with mooring and thrusters (Posmoor ATA). The basic hull design (GM4000) was developed by Global Maritime (GM) for drilling with the notation GM4000-D, and further developed (GM4000-D w/S&B) with extra buoyancy elements[2] by Grenland Group (GG) to achieve additional load-carrying capacity.

[1] DNV is used for DNV GL since a number of conditions covered in this report predate the change of name.

[2] Buoyancy elements are called sponsons on pontoons and blisters on columns, abbreviated to S&B.

CI is operated by COSL Drilling Europe AS in Stavanger, a subsidiary of China Oilfield Services Limited (COSL) of Beijing, China. It was built by CIMC Raffles Shipyard[3] at Yantai, China, from 11 April 2008 to 28 November 2011. Singapore is the flag state. The unit is classed by Det Norske Veritas (DNV) (now DNV GL) with the following class notation:[4, 5]

✠1A1 Column-stabilised Drilling Unit(N) Well Intervention Unit 2(N) Crane(N) DRILL(N) DYNPOS-AUTRO E0 HELDK-SH POSMOOR-ATA

2.2 The PSA's investigation

The PSA decided on 31 December 2015 to investigate the incident and established an investigation team with the following composition (see appendix A for its mandate):

- Irja Viste-Ollestad, logistics and emergency preparedness - investigation leader
- Terje L Andersen, structural integrity
- Narve Oma, structural integrity (did not participate on the unit)
- Sigvart Zachariassen, occupational health and safety.

The team conducted verifications and interviews on CI from 1-3 January 2016. It had further interviews with COSL to acquire information throughout its investigation. Meetings were held with GM, Kongsberg Maritime, Kongsberg Seatex, Wood Group Mustang Norway (formerly GG and Agility Group), DNV GL, Statoil and IMS.

During the investigation, the PSA used Sverre Haver and Carl Trygve Stansberg as its own consultants for verification and assessment of documents related to air gap calculations and the model test. The Norwegian Meteorological Institute (NMI) contributed weather data and assessments of wind and wave conditions.

The PSA has acquired and reviewed information covering the period from design development until the incident occurred.

3 Overview of players and relationships

Many players were involved from the design development stage until the unit became operational. An overview is provided below. See also Figure 1.

2005

- GM begins developing GM4000-D.
- GM enters into a contract with DNV for approval of the GM4000-D design.
- OffRig is created as a vessel owner to bring GM4000-D to market.
- OffRig enters into a contract with Yantai CIMC Raffles Offshore Ltd (Yantai) on the construction of the first unit (*WilPioneer*).

2006

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[3] http://www.cimc-raffles.com/en/enterprise/raffles/company/overview/introduction/.

[4] Det Norske Veritas classification certificate for *COSLInnovator,* dated 14 January 2013.

[5] https://exchange.dnv.com/Exchange/main.aspx?extool=vessel&subview=summary&vesselid=27625.

- OffRig enters into a contract with Yantai on building *WilInnovator*, later CI.
- Yantai enters into a contract with DNV for class inspection at the yard.
- Awilco acquires OffRig on 27 December 2006. Key OffRig personnel transfer to the new company.
- Norsk Hydro assesses the GM4000 rigs for use on Troll.
- BP charters *WilPioneer* for use on Skarv.

2007
- May 2007: Norsk Hydro enters into charters with Awilco for two units – *WilInnovator* and *WilPromoter* – to start work on Troll in the autumn of 2009.
- Norsk Hydro does not conduct its own analyses of the rig's air gap.
- Statoil and part of Norsk Hydro merge as StatoilHydro. Statoil (from 2009) coordinates follow-up of mobile newbuildings.

2008
- Awilco is acquired by COSL Drilling Europe (COSL). The units change their names to *COSLPioneer, COSLInnovator* and *COSLPromoter*.
- GM exits from the project.
- GG takes over as the engineering company and further develops the design to GM4000-D w/S&B. Holds contract from Awilco for design development and for yard-related design at Yantai.
- TeamTec (from 2010 IMS) enters into a contract on the delivery of windows with an agent who is under contract to Yantai.

2011
- COSL applies to the PSA for an acknowledgement of compliance (AoC) for CI, and receives this on 30 March 2012.

2012
- Statoil applies to the PSA for consent to use CI on Troll, and receives this on 6 June 2012.

2013
COSL puts CI into operation on Troll in January 2013.

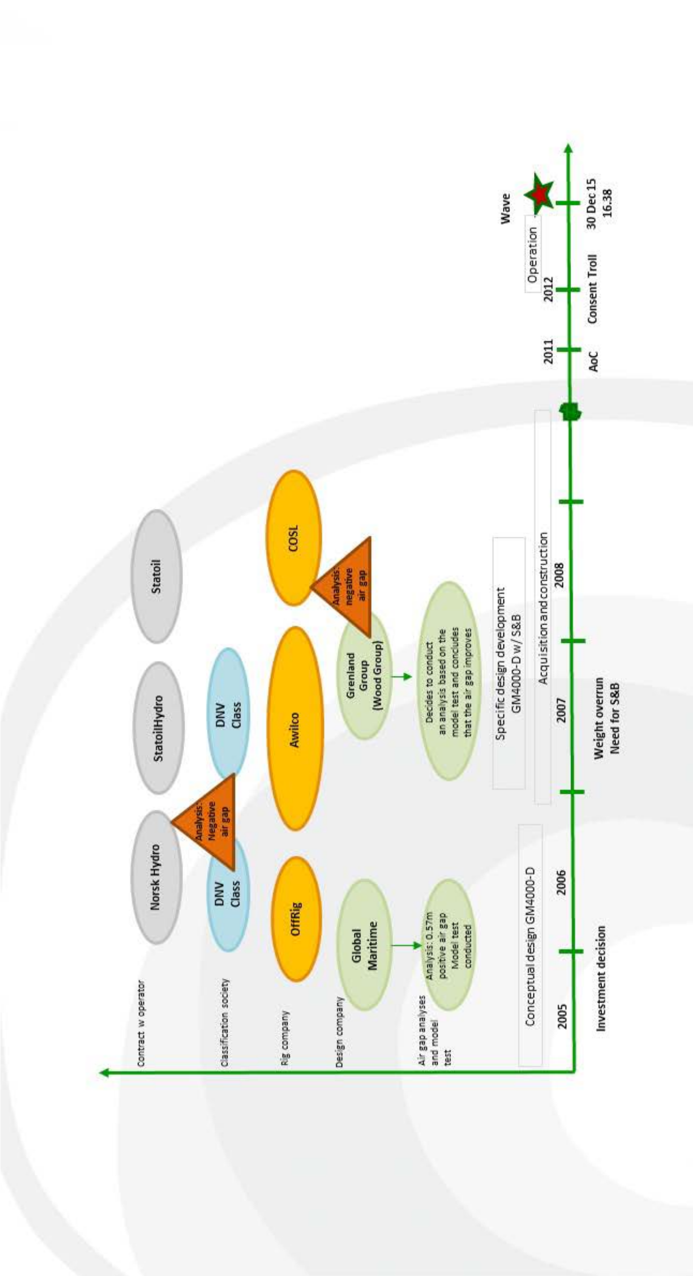

Figure 1 Overview of players and relationships.

4 Course of events on the Troll field, 30 December 2015

4.1.1 Before and during the incident

Planned maintenance work was carried out on the BOP[6] between Christmas and the New Year, which meant the unit was disconnected from the well. Owing to strong winds, the deck was shut for work from the morning of the incident day. It had also been shut the day before.

The weather forecast on the morning of 30 December showed that significant wave heights (Hs) were expected to exceed nine metres, the operational criterion for raising the unit to its survival condition. At the daily morning meeting, the offshore installation manager (OIM) accordingly announced that the unit was to be raised to this condition, starting around 12.00 when the BOP maintenance team was at lunch. The OIM was in contact with sister unit *COSLPromoter*, which was also located on Troll. Experience with the motion characteristics for both units in survival condition was discussed.

Between 12.00 and 13.00, the unit was raised from its operational condition (draught 17.75 metres) to its survival condition (draught 15.75 metres). About 100 tonnes of water-based drilling mud was dumped to the sea because the planned deballasting would create a high centre of gravity (CoG). Drilling fluid was also transferred to the tanks in the columns to lower the CoG. That operation provided a weight margin of about 120 tonnes in accordance with the requirement specified in the stability manual. The unit was positioned with the wind slightly from port (about 10 degrees), waves slightly from starboard (about 10-15 degrees) and a forward trim of about 1.5 degrees[7]. The crew felt that the unit was “performing well” both before and after it was raised to survival condition.

The crew experienced rough weather, but nothing of concern or beyond earlier experience. When the wave struck, a number of people in the living quarters heard a bang followed by pressure in their ears. Those in offices on the main deck saw large quantities of white water wash over their windows. Three drill floor workers in the coffee room by the derrick had a view of the helideck and saw sea spray overtopping it, but felt neither impact nor motion. They noted that water struck the wall, and afterwards flowed down onto the container roof. The dynamic positioning operator (DPO) and engine room operator sitting in the control room on the bridge heard a bang and felt their ears “popping”, followed by sea spray on the windows. It was dark at the time, so they did not see the wave before it struck. A number of alarms were activated in the control room.

The OIM was sitting in a recreation room on the mezzanine deck close to the damage site. He felt a hard thud followed by vibrations which lasted longer than normal, and went immediately to the bridge. In the corridor outside the recreation room, he saw that there was water on the floor and that the forward air-assisted weathertight sliding door was open.

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[6] Blowout preventer.

[7] Mean angle of inclination (around a transversal axis) of the hull because the ballasted draught differs fore and aft.

4.2 Weather on the incident day

The unit is approved for weather conditions with waves up to Hs = 17.3 metres and mean wave periods of 15 seconds, and a wind speed up to 51.5 metres per second (one-minute mean at the 10-metre level)[8]. On the incident day, the weather was better than these criteria. The following main weather parameters prevailed at the incident time:[9]

- significant wave height: Hs = 8.5-9.5 metres
- wave spectrum peak period: Tp = 12-14 seconds
- wind speed: 24-26 m/s (10-metre level, 10-minute mean time)
- wave direction: 170-180 degrees (from south)
- wind direction: 150 degrees (from south-south-east)
- current speed: 0.5-0.7 m/s
- current direction:[10] 20 degrees (towards north-north-east)
- swell:[11] Hs = 2 metres from 231 degrees (from south-west).

The unit had a heading of about 160 degrees.

These weather data describe stationary conditions over a given period. They can be used in combination with statistical models to estimate the probability of a given extreme wave height or crest.

The NMI[12] notes that the sea state on the incident day has a return period of four years if wave direction is ignored. Including direction, the return period is 25 years. Figure 2 presents a view of the sea taken earlier on the incident day at a lower sea state.

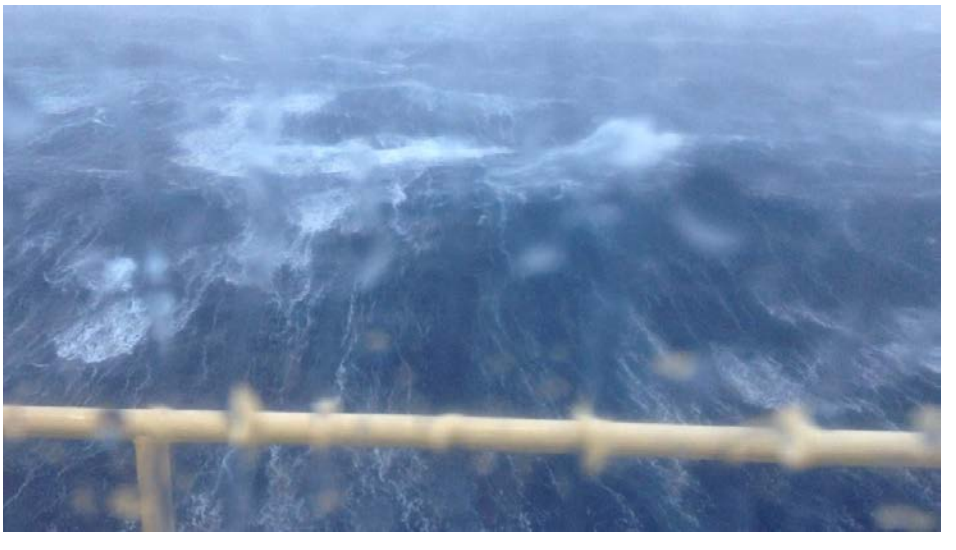

Figure 2 Image captured from a video shot from CI at 14.24 on the incident day, 30 December 2015 (shot by safety officer).

More detailed information on the sea state is provided in chapter 8.

[8] Appendix to classification certificate, DNV Høvik, ID no 27625, dated 18 October 2012.

[9] *COSL Innovator* Incident – Metocean Conditions, Statoil memo, Metocean ME2016-002, Rev 2, dated 12 January 2016.

[10] Email from COSL dated 6 January 2016, item 14.

[11] Weather forecast from StormGeo Weather Forecast for Troll C, 30 December 2015, 12.00 UTC.

[12] *Weather conditions…*, Norwegian Meteorological Institute, ISSN: 2387-4201.

4.3 After the incident

The OIM activated a general alarm around 16.40, followed by an announcement that all personnel should muster in the day room on the main deck. He reported that his first thought was to turn the unit. But reports of extensive damage made him uncertain whether it could withstand the motion, which would increase somewhat with the change of heading. Furthermore, the unit's engines and engine air intake were aft, and the OIM feared that a similar wave could cause water intrusion and loss of power. He accordingly opted not to turn the unit. To prevent further damage from new waves and to shield the damaged area, the heading was changed somewhat towards port. The marine section leader, who was the on-scene commander, led the search and rescue and technical teams.

Extensive damage and many physical obstacles made it difficult to search for personnel. Two lightly injured people reached the sick bay under their own steam and with some help from colleagues, and were treated. The deceased was found just before 17.00 in the corridor outside his cabin on the lower deck. He was moved to a dry area, where the medic and the first-aid team attempted cardiopulmonary resuscitation (CPR) until about 19.00. His death was then confirmed. A full POB overview was established around 17.20.

Wind and rain entered the mezzanine deck from the forward door. Personnel reported that the water was knee-deep, and an odour of electrical short-circuits could be smelt. This door and its equivalent on the lower deck were probably forced open by the action of the wave striking the pushbuttons for air-assisted opening. The wave impact also damaged the air supply for local operation of the doors, which accordingly remained open. The technical team quickly wedged the doors shut, and also emptied water from the corridors by opening the watertight doors in the port and starboard bulkheads respectively in time with the unit's motion. In addition, the team sealed internal water and air leaks and cleared the helideck of loose objects.

The OIM decided around 17.30 that non-essential personnel should be evacuated. This operation began at about 20.30 and was accomplished by hoisting into helicopters. A total of 46 people were voluntarily evacuated, including two with injuries. The remaining personnel and the deceased accompanied the unit into the CCB base outside Bergen.

5 Potential of the incident

5.1 Actual consequences

One person was killed. He was in his cabin on the lower deck and died instantly[13] when the wave smashed in the cabin window. Four people were also lightly injured. Two of them suffered cuts and head injuries, and were hospitalised. They had been in their cabins.

CI suffered extensive damage to a total of 17 cabins as well as corridors on two decks forward on the port side. Six windows on the lower deck and 11 on the mezzanine deck were driven in. See Figure 3.

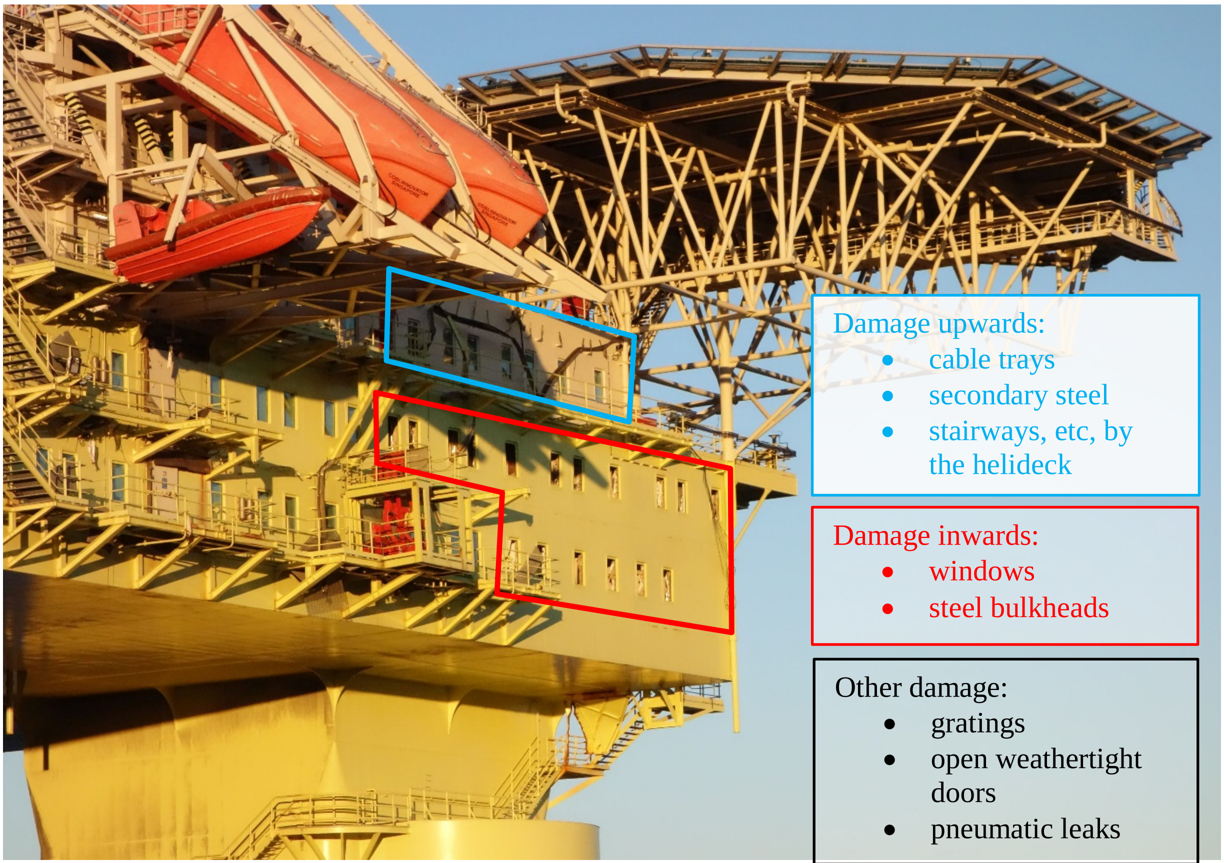

Figure 3 Forward bulkhead of the CI berthed at CCB after the incident. The scale of the damage can be seen from the broken windows and fastening brackets for cable trays.

[13] Press release from the police.

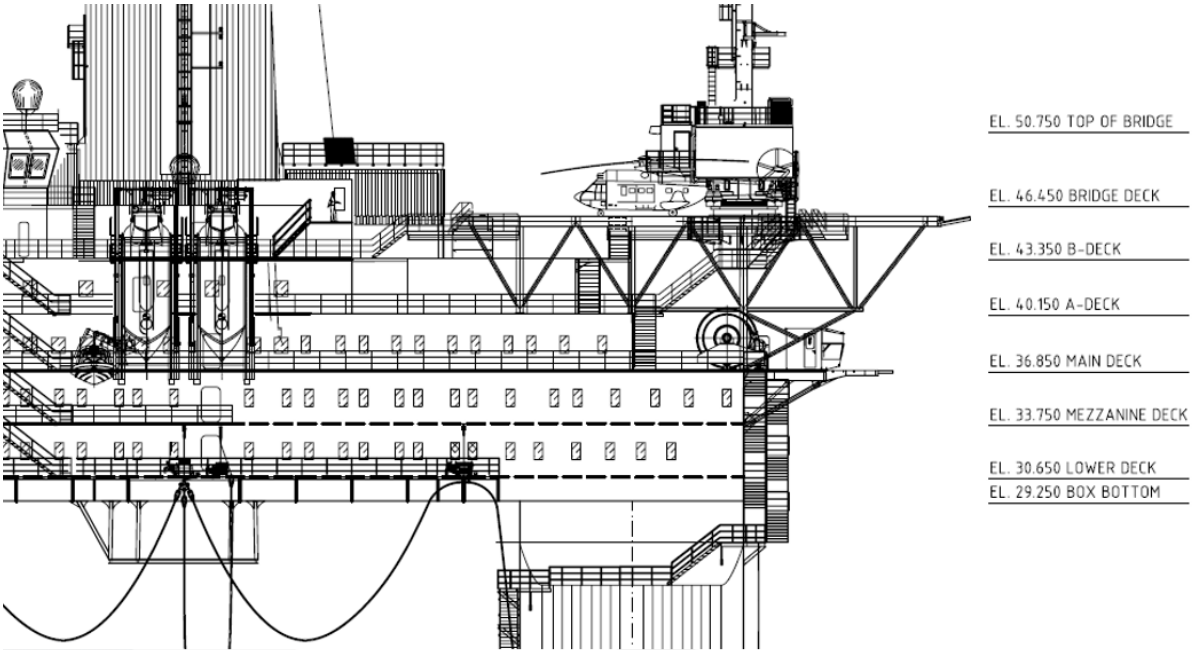

Figure 4 Overview of deck levels.

The PSA noted the following main features of the damage.

- Below the main deck level, damage to windows and steel bulkheads was directed inwards, with some displacement of grating panels. No structures (gangways and the like) were present immediately forward of and below damaged windows on the outside of the bulkhead.
- Above the main deck level, damage to grating panels, cable trays and secondary structures was directed upwards.
- Towards the centre of the box girder's forward face and above A deck level, damage to glass, grating panels, weathertight doors, cable trays, equipment cabinets and so forth was on a smaller scale and oriented in various directions – both inwards at the midships doors and upwards in the helideck area.

5.2 Potential consequences

Given the scope of material damage in the affected cabins and adjacent corridors, the loss of human life or personal injuries could have been greater under slightly different circumstances. The incident occurred at a time when few people were present in the damaged area. Those who were injured could also have suffered more serious personal injuries or been killed had circumstances been slightly different.

6 Regulations applying to the unit

6.1 General

CI is a Singapore-registered mobile offshore drilling unit classed by DNV GL. In those areas where it is entitled to do so, the owner has utilised section 3 of the framework regulations (FR) concerning the application of maritime regulations in the offshore petroleum activities,[14] rather than applying the corresponding requirements specified in the facilities regulations. Section 3 of the FR makes sections of the rules and regulations established by the NMA and DV-GL also applicable as regulations for the petroleum activities (which is the PSA's area of authority), through the process known as the adoption of requirements. As a result, these requirements (set by others than the PSA) also become de facto the PSA's requirements.

The following provides a brief overview of the relevant rules and regulations related to the air gap on a semi-submersible mobile offshore unit.

6.2 NMA regulations

Section 10 of the construction regulations[15] sets specific requirements for the air gap.

Sub-section 1.1.3 states: "By means of model tests or by calculation it shall be shown that the unit has a safe movement and immersion characteristic in all probable wave spectra and up to wave heights being at least 10% higher than the maximum wave height for which the unit is designed. If the unit with superstructures, deckhouses, etc. has not been designed for wave forces, there shall be a distance of 1.5 m between the lower deck and the maximum wave crest elevation."

Section 6 of the construction regulations[15] specifies requirements for strength calculations.

Sub-section 6.2.3 states: "The calculations shall be carried out in accordance with the design criteria and calculation methods in force at any time of a MOU classification society."

6.3 DNV GL classification rules and associated standards

CI was issued on 29 November 2011 with a class certificate based in part on the following regulations and standards.[16]

[14] Section 3 of the framework regulations specifies that, for mobile facilities registered in a national ships' register, and which follow a maritime operational concept, relevant technical requirements in the NMA's regulations for mobile facilities and with supplementary classification rules provided by DNV can be applied.

[15] Regulations of 4 September 1987 no 856 on construction of mobile offshore units.

[16] DNV: Appendix to classification certificate column-stabilised unit – COSLINNOVATOR, DNV ID no 27625, dated 18 October 2012.

Reference	**Title**	**Year**
DNV-OSS-101	Rules for Classification of Offshore Drilling and Support Units	April 2004
DNV-OSS-201	Verification for Compliance with Norwegian Shelf Regulations	July 2003
DNV-OS-A101	Safety Principles And Arrangements	October 2002
DNV-OS-B101	Metallic Materials	January 2001
DNV-OS-C101	Design of Offshore Steel Structures, General (LRFD Method)	April 2005
DNV-OS-C103	Structural Design of Column Stabilised Units (LRFD Method)	April 2005

Of these references, DNV-OS-C103 (later DNVGL-OS-C103) refer to the air gap. Requirements for the air gap in this standard are as follows.[17]

D. Air Gap

D 100 General

101 In the ULS condition, positive air gap should in general be ensured for waves with a 10^{-2} annual probability of exeedance. However, local wave impact may be accepted if it is documented that such loads are adequately accounted for in the design and that safety to personnel is not significantly impaired.

102 Analysis undertaken to check air gap should be calibrated against relevant model test results when available. Such analysis should take into account:

— wave and structure interaction effects
— wave asymmetry effects
— global rigid body motions (including dynamic effects)
— effects of interacting systems, e.g. mooring and riser systems
— maximum and minimum draughts.

103 Column "run-up" load effects shall be accounted for in the design of the structural arrangement in the way of the column and bottom plate of the deck connection. These "run-up" loads shall be treated as environmental load component, however, they should not be considered as occurring simultaneously with other environmental loads.

104 Evaluation of sufficient air gap shall include consideration of all affected structural items including lifeboat platforms, riser balconies, overhanging deck modules etc.

These requirements are unchanged between the editions of DNV-OS-C103 when class and the AoC were awarded (29 November 2011 and 30 March 2012 respectively) and at the date of the incident (30 December 2015).

The DNV-OS-C103 standard (later DNVGL-OS-C103) also refers to the following documents for recommended design practice.

- DNV-RP-C103 column-stabilised units.
- Classification note 30.5 (later DNV-RP-C205) on environmental conditions and environmental loads.

[17] Offshore standard DNV-OS-C103, Structural design of column stabilised units (LRFD method), April 2004, amended April 2005.

DNV's recommended practice documents (DNV-RP) are not listed in the appendix to the class certificate, and accordingly do not form a direct basis for awarding the latter. DNV confirmed that the RP text should be followed or that an alternative technical solution of equal status should be used.[23] Relevant design practice related to air gap is stated as follows in DNV-RP-C103.[18]

> **2.3.6 Asymmetry factor in air gap calculation**
>
> Generally a wave asymmetry factor of 1.2 should be applied in the air gap calculations unless model tests are available. In this case the air gap shall be calibrated against the model tests.
>
> Calculations for sufficient air gap is further referred to in 6.3.

> **6.3 Air gap**
>
> Requirements for sufficient air gap are specified in DNV-OS-C103 Sec.4 D100.
>
> In the ULS condition, positive clearance between the deck structure and the wave crest, including relative motion and interaction effects, should normally be ensured. Localised, negative air gap may be considered as being acceptable for overhanging structures and appendages to the deck structure. In such cases full account of the wave impact forces is to be taken into account in the design. The consequence of wave impact shall not result in failure of a safety related system (e.g. lifeboat arrangements).
>
> The wave asymmetry factor in air gap calculations is given in 2.3.6.
>
> It is recommended, in the design phase, to consider operational aspects, including requirements to inspection and maintenance, which may impose criteria to air gap that exceed minimum requirements.
>
> In the context of DNV-OS-C103 Sec.4 D103, column run-up load effects are not considered as resulting in negative air-gap responses.

No differences exist in DNV-RP-C103 between the editions prevailing when awarding the class certificate or the AoC, or when the incident occurred, apart from:

- the following has been changed in the July 2015 edition from the two previous versions:
  - the wave asymmetry factor in point 2.3.6: "When the extreme response is calculated as 90% percentile using short-term statistics, wave asymmetric factor of 1.1 may be used". The earlier editions referred only to a wave asymmetric factor of 1.2.
  - the word "normally" is deleted in point 6.3, where it refers to the air gap.

Classification note 30.5[19] gives no direct guidelines on the air gap, but provides guidance on the steepness of waves and on calculating wave slamming.

[18] DNV-RP-C103, Structural design of column stabilised units (LRFD method), February 2005.

[19] DNV classification notes no 30.5, Environmental conditions and environmental loads, March 2000.

DNV-RP-C205[20] provides direct guidelines on calculation methods for the air gap, and expanded guidance on wave description and calculation of wave slamming. It also provides guidance on performing hydrodynamic model testing.

The asymmetry factor will be discussed below, since this is important for calculating the air gap. A low asymmetry factor will increase the calculated air gap.

[20] DNV-RP-C205, Environmental conditions and environmental loads, April 2007.

7 Causes in the design process

Direct causes for the accident are that

- the unit was struck by a steep wave
- windows with attachments were unable to resist the pressure from such a wave.

The underlying causes are reviewed below.

7.1 Decision basis for the design with regard to the air gap

Hydrodynamic calculations[21] and a model test[22] were performed in 2006 to assess motion characteristics and the air gap. This work was originally carried out by GM for the conceptual design of the GM4000-D hull. The analysis[21] calculated the minimum positive air gap at 0.57 metres. The model test[22] concluded that a zero air gap was recorded for all tested wave directions except for transverse seas, where a positive gap was identified. However, the report's air gap conclusions were not clear.

GM had contracted with DNV for approval of the GM4000-D's conceptual design. DNV carried out an independent analysis which showed a negative air gap of about four metres.[23] This was communicated to GM by letter,[30] and included as a class comment until September 2007.[34]

GG carried out new air gap analysis in 2008 in connection with design modifications which incorporated additional buoyancy elements to compensate for increased weights in the construction period. The modified design with sponsons and blisters was thereafter called the GM4000-D w/S&B. GG's analysis shows that the design had a negative air gap of about four metres[24] in survival condition.

Following discussions between Awilco, GG and DNV, it was decided to apply the conclusions from the model test and to pay minor attention to GG's analysis[24] during the rest of the design process[25]. DNV has not confirmed its involvement in this discussion.

A new linear air gap analysis was therefore conducted by GG. The results were incorporated as an update to an existing GG report on motion characteristics[26] for the GM4000-D w/S&B. The revised report[27] specified changes following from the upgrade (w/ S&B) measured in relation to a zero air gap level, where the 2006 model test report was used as the zero reference. The report concluded that the upgrading had achieved an improvement.

According to DNV,[23] GM was informed in 2007 that DNV's own analyses indicated that the GM-4000D design had a negative air gap of about four metres. DNV reported that its own air gap analysis had been used as a reference throughout the class approval process. The comment on a negative air gap in DNV's approval process was closed in 2007. DNV could

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[21] Air gap analysis, Global Maritime A/S, doc no. 910-003-N-201-CA-004, dated 10 February 2006.

[22] Oceanic: Experimental performance evaluation of the semi-submersible *OffRig Pionee*r, doc no: ORS001-01, dated 8 December 2006.

[23] Interview with DNV incident task force, 18 February 2016.

[24] Airgap analysis, Grenland Group Technology, doc no 10113049-0072-ANL, dated 12 September 2008.

[25] Interview with Wood Group Mustang Norway (formerly Grenland Group), 12 February 2016.

[26] Motion comparison analysis, GM4000 upgrade, Grenland Group, doc no 10113049-0019-ANL, dated 16 May 2008.

[27] Motion comparison analysis, GM4000 upgrade, Grenland Group, doc no 10113049-0019-ANL, dated 18 November 2008.

not clarify the basis for closing the comment, but confirmed that CI could handle a negative air gap of four metres with regard to vertical slamming below the topside. As a basis for this assessment, DNV referred to its approval process for another sister unit (*Island Innovator*). According to DNV, it was not normal practice to include horizontal slamming on the topside structure in analyses, even though a negative air gap was identified. The box girder on CI was therefore not designed to resist forces from horizontal wave slamming.

The forward bulkhead of the box girder was dimensioned on the basis of its global strength and to resist water pressure pursuant to the stability requirements. Windows with attachments were therefore specified only to resist hydrostatic pressure, not horizontal wave slamming.

7.2 Technical design basis with regard to the air gap

A review of the reports dealing with the air gap is provided below. Much of the documentation for CI, as for the other units with the GM-4000 hull, is based on that produced for the first unit (*COSLPioneer*). Table 1 provides key construction dates for the three COSL facilities.

Table 1 Milestone dates for the three sister units Pioneer, Innovator *and* Promoter.

Construction period[28]	Yard contract	Keel laid	Delivered from yard	Operation	DNV ID no
COSLPioneer	7 Nov 2005	28 Sep 2007	15 Nov 2010	Statoil, Aug 2011	26952
COSLInnovator	28 Aug 2006	11 Apr 2008	28 Nov 2011	Statoil - Troll, Jan 2013	27625
COSLPromoter	20 Mar 2007	29 Aug 2009	14 May 2012	Statoil - Troll, Apr 2013	28127

7.2.1 Air gap analysis, GM

Air gap analysis, Global Maritime A/S, doc no 910-003-N-201-CA-004, dated 10 Feb 2006
Hydrodynamic calculations were performed by GM in 2006 to assess the air gap for a set of locations which partly represented the outer limits of the GM4000-D topside. The analysis report indicated a minimum positive air gap of 0.57 metres in survival condition with an associated draught of 15.75 metres. The report also specified a minimum positive air gap of 2.25 metres in operational condition with a corresponding draught of 17.75 metres[29]. This was a linear analysis using Moses software.

The PSA's comments on this analysis:

- it takes no account of the interaction between waves and hull (which must include the local wave amplification)
- a significant wave height of Hs = 16.8 metres in used in survival condition, which is 0.5 metres lower than the figure used for DNV's approval, see chapter 4.2.
- it was not subsequently calibrated with the model test conducted later – the PSA investigation has not received documentation about any possible evaluation of the agreement between analysis and tests in the design period.

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[28] DNV on-line vessel info.: https://exchange.dnv.com/Exchange/main.aspx (information acquired on 10 March 2016).

[29] According to GM's air gap report, operational condition is limited to a sea state of Hs ≤ 9 metres.

- it does not include at this point the additional buoyancy elements (sponsons and blisters) first introduced to the design in 2008
- it contains relatively few reference points for checking a negative air gap[54]
- it does not address the NMA's requirement[14] for a positive air gap of 1.5 metres if the superstructure is not dimensioned for wave forces.

DNV had a contract with GM to approve the GM-4000D's conceptual design. Its own independent analysis showed a four-metre negative air gap. This was communicated to GM by letter[30], and the latter responded[31] on 30 March 2006 to request guidance on conducting the analyses with disturbed waves (wave-structure interaction[32]) to meet DNV's requirements.

7.2.2 Model test

Oceanic: Experimental performance evaluation of the semi-submersible *OffRig Pioneer*, doc no: ORS001-01, dated 8 December 2006

Hydrodynamic model tests in waves were conducted by Oceanic in the summer of 2006 at IOT's[33] 32x75 metre Offshore Engineering Basin in St Johns, Canada. The client was OffRig. A final report on the tests was submitted in December 2006. Testing was done in both regular and irregular waves. A total of 14 regular waves with various periods and heights were used to determine transfer functions. Eight test conditions in all were conducted for irregular waves in operational and survival conditions. All operational conditions were tested with wave spectral peak periods (Tp) of about 9.5 seconds and Hs around seven-eight metres. All the periods for survival condition were about 19 seconds and the Hs was around 16-17 metres. The scale was 1:40, with mooring included for irregular seas.

The PSA's comments on the model test:

- it does not include sponsons and blisters, and is therefore not fully representative for the GM-4000D w/S&B
- as far as can be seen, it only contains one realisation for each sea state
- survival conditions are not tested with the steepest waves to be expected (given the knowledge available in 2006)
- in practice, only one sea state is assessed for operational and survival conditions respectively, but with different directions
- a fully developed sea state is not achieved for survival condition in some of the tests
- the report's conclusion is unclear with regard to information on negative air gap measurements in its appendix J. The significance of the negative air gap measured is not clearly communicated in the report.

GM refers to the model test report in its consideration[34] of the negative air gap with DNV. The latter asked for the report[34] (18 September 2006) to review wave slamming and run-up, but commented only on that part of the report which concerned mooring.[35]

[30] DNV: D26952-J-90,5894830/DNV.

[31] GM: 910-003-DNV-L-010, dated 30 March 2006.

[32] This means that the structure will affect the wave, whose crest is thereby higher close to the structure.

[33] National Research Council – Institute for Ocean Technology.

[34] Chronological summary of the approval work related to air gap and slamming under the deck box bottom on COSLInnovator. DNV, 23 February 2016.

[35] DNV: D26952-J-1040, dated 19 March 2007.

DNV later closed comments and established new comments in its consideration[34] of slamming and negative air gap. One comment was closed on 23 May 2007 (after a meeting at Yantai) and the other was given information status on 2 September 2007 (after a meeting with GM on 25 June 2007). No explanation has been given on the background for changing the status of the comments, nor does one emerge clearly from the minutes of these meetings received by the PSA during its investigation.

COSL has not been able to produce an order and associated job description for the model test.

7.2.3 Airgap analysis, Grenland Group Technology

Airgap analysis, Grenland Group Technology, doc no 10113049-0072-ANL, dated 12 September 2008

GG conducted new air gap analyses in connection with modifications to the design which introduced additional buoyancy elements to compensate for increased weights during the construction period. The modified design is thereafter called the GM-4000D w/S&B. GG's analyses show that the design has a negative air gap in the order of four metres.

The PSA's comments on this analysis:

- in the PSA's view, this is the most complete analysis it has been given access to for the three COSL units
- it contains sponsons and blisters
- it contains many reference points to check for a negative air gap
- it takes account of wave-structure interaction (disturbed wave)
- no references are provided to earlier reports and, although the analysis does refer to earlier studies, it does not clearly specify which these are
- the analysis is not subsequently calibrated with the model test
- it reports on a negative air gap in operational condition (for disturbed waves) and in survival condition (for both undisturbed and disturbed waves).
- the analysis concludes that upgrading with the new buoyancy elements has led to some improvement in the air gap compared with the original geometry.

GG says that the analysis results were discussed with Awilco and DNV[25]. The results were disregarded, and GG considered this to be an unofficial report. The company cannot fully explain the basis for that decision today. GG decided to carry out a new analysis, based on the results from the original design[36]. This analysis is addressed in section 7.2.4.

GG confirms that it has not conducted a critical review of the model test report with appendices.

7.2.4 Motion comparison analysis, GM4000 upgrade, GG

Motion comparison analysis, GM4000 upgrade, Grenland Group, doc no 10113049-0019-ANL, dated 18 November 2008

[36] GG: memo 8 September 2008. Subject: notes from meeting with DNV/Dr Techn Olav Olsen, 5 September 2008.

GG carried out a new analysis of the air gap in 2008 in connection with the modification involving extra buoyancy elements. It chose to base this analysis on the conclusions from Oceanic's model test, which had not registered a negative air gap. On that basis, the company opted to compare the results from the new analysis with a reference for a zero air gap. GG did not conduct a critical review of the actual model test report with associated appendices. The conclusion of the analysis was that new buoyance elements improved the air gap position.

The existing report – motion comparison analysis, GM4000 upgrade, Grenland Group, doc no 10113049-0019-ANL, dated 16 May 2008, rev 02 – was updated with results from the new air gap analysis in revision 03 of the document (dated 18 November 2008).

The PSA's comments on this analysis:

- the report was issued with the project title GM4000 upgrade – global analyses scantling design (in other words, it was not specifically for CI)
- it uses the conclusion from the model test report as a zero level for the air gap, and includes this report as a reference
- the hydrodynamic calculation model includes sponsons and blisters, as well as a comparative model without them
- it contains many reference points for checking the air gap
- it takes account of wave-structure interaction (disturbed wave)
- it only reports results for survival condition
- it concludes that upgrading improved the air gap compared with the original geometry
- the report does not comment on the NMA's requirement[14, 15] for 1.5 metres of positive air gap if the superstructure is not dimensioned for wave forces.

DNV confirmed[37] to GG that the report was received for information, without further comment.

This report was specifically reissued by GG in 2011 for CI as motion comparison analysis, Grenland Group, doc no 10113217-ANL-N-0010, dated 4 July 2011. It was sent to DNV as part of the documentation for CI. DNV has confirmed to the PSA[23] that the report was received for information without further comment.

7.2.5 Observations related to the air gap

The PSA's attention has concentrated on how wave slamming on the forward bulkhead of the box girder could occur. At the centre of interest here has been the design basis for the unit's air gap (see also section 8). The analyses conducted during the design process in order to clarify a possible negative air gap are central to observations made below.

The PSA's comments on the above-mentioned analyses are as follows.

- The conclusions in Oceanic's model test report were cited as a reference in the final documentation submitted by both GM and GG[34]. The latter confirmed that it has not quality-assured the text and appendix dealing with the air gap. DNV requested the report in connection with its comments on the air gap, but commented only on mooring issues.

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[37] DNV: D29492-J-104, dated 16 December 2008.

- All the reports specify that the analyses were conducted with a wave asymmetry factor of 1.1. This was combined with the 90 per cent percentile of the extreme-value distribution of the response. That was the recommendation from DNV.[38] DNV-RP-C103 had a reference to an asymmetry factor[39] of 1.2 at this time. DNV-RP-C205 also refers generally to an asymmetry factor[20] of 1.2. This factor is incorporated in a simplified calculation method. It is also specified that the simplified method cannot be applied close to columns. The most severe on the incident day was sustained immediately ahead of the unit's port forward column (see also section 12.4).

- A negative air gap was the result obtained by independent analyses conducted between 2006 and 2008 (by DNV and GG). According to DNV, it was not usual practice to include horizontal wave slamming on the topside structure in analyses, even though a negative air gap had been identified.

- According to DNV,[23] attention in the design process was directed at vertical slamming under the deck if analyses or model tests showed a negative air gap. The effect of horizontal slamming on the topside structure was not normally assessed. Damage suffered in the incident was caused by horizontal pressure from the wave. The significance of horizontal slamming appears to have been undercommunicated in the design process.

In the PSA's assessment, the above-mentioned conditions are underlying causes of the accident.

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[38] DNV Memo no D26952-J-24, dated 9 January 2006.

[39] DNV-RP-C103, February 2005.

8 Wave conditions and the unit's motions

The air gap is 13.5 metres when the unit is in survival condition and the sea is calm (still-water air gap, a0). This gap is thereafter influenced by both wave crest and unit motion (roll, pitch and heave).

The distance from the underside of the box girder to the main deck is 7.6 metres. The uppermost smashed windows are about six metres above the box girder's base plate.

When the incident occurred, CI was forward trimmed by about 1.5 degrees, which meant that the draught was larger at the forward columns than the aft ones. This helped to reduce the gap from still-water level to the underside of the forward box girder. The effect of a 1.5-degree trim is a reduction of about 1.2 metres in the air gap at the outermost edge of the box girder.

8.1 Estimates of wave crest during the incident

The weather on the incident day was specified by the main parameters listed in section 4.2. Using these data, Statoil has estimated extreme wave crests (above still-water level) for a 12-hour storm based on a Forristall wave crest distribution.[9] Table 2 presents estimates from Statoil and independent estimates from Haver.[40] Agreement between the estimates for undisturbed crests is good. Haver has also made a simplified estimate of the disturbed wave crest (wave-structure interaction), which shows a big additional effect on the crest when it strikes CI. Stansberg[46] has performed an independent assessment which confirms the order of magnitude of Haver's estimate for a disturbed wave crest close to the unit.

Table 2 Statistical wave height estimates for sea state on 30 December 2015 with Hs = 9.5 metres and a 12-hour duration.

Probability of not exceeding specified wave crest	Statoil, undisturbed wave crest	Haver, undisturbed wave crest	Haver, disturbed wave crest
[%]	[m]	[m]	[m]
50	11.1	11.2	15.8
90	12.3	12.5	17.1
99	13.7	13.9	18.5

An assessment of the probability of experiencing a negative air gap can be based on the estimates for disturbed wave crests and the unit's motion.

Kongsberg Maritime has combined simultaneous measurements[41] of the unit's pitch, roll and heave from the DPS-4D system. However, the exact time the wave struck is not known. No relationships has therefore been established on the way the unit responded (heave[42], pitch[43] and roll[44]) to the wave's position at the moment of the incident. Kongsberg Maritime has tried to synchronise information from the DPS-4D system and audio recordings from the marine

[40] *Beregning av høyde av bølgetopp relativt til plattformen ved skade,* S Haver, dated 21 February 2016.

[41] Kongsberg Maritime report on DPS-4D data. 24 January 2016, revision 1.4.

[42] Vertical position for the motion of the unit's CoG, in metres.

[43] Motion of the unit up/down forward and aft around its transverse axis, in degrees.

[44] Rolling of the unit from side to side around its longitudinal axis, in degrees.

black box (MBB) in order to identify exactly the time of the accident. Timing in these two systems has proved to be unsynchronised.[45]

Stansberg[46] believes that the wave is most likely to have struck at 15.38.10 UTC, according to the time registration in the DPS-4D (corresponds to 16.38.10 local time).

Based on the measured motion of the unit, the investigation team has produced estimates for the influence of motion on the still-water air gap at various times around the incident time. Appendix B and Table 3 present the effect of the unit's motion on the still-water air gap. Haver and Stansberg have carried out corresponding assessments on a generic basis (Table 4).

Table 3 Effect on the still-water air gap of the registered simultaneous degrees-of-freedom motion for selected times close to the incident (based on measurements stored in the Kongsberg DPS-4D system).

	Time UTC DPS-4D	Still-water air gap (nominal)	Heave change in centre	Pitch effect forward @ 40.5 m	Roll effect port @ 32.5 m	Resulting still-water air gap forward port
		(a_0)	(a_H)	(a_S)	(a_R)	$(a=a_0+a_H+a_R+a_S)$
		[m]	[m]	[m]	[m]	[m]
A (+)	15:38:06.9	+13.5	-2.2	-3.2	+0.0	8.1
B (◊)	15:38:08.7		-3.8	-2.4	-1.0	6.3
C (o)	15:38:10.0		-3.6	-0.9	-1.6	7.4
D (+)	15:38:18.5		-0.6	-5.6	+1.5	8.8

Table 4 Air gap estimates by Haver[40] (SH) and Stansberg[46] (CTS) for the time around the incident.

	Haver/Stansberg	Heave	Pitch	Roll	Resulting still-water air gap forward port
		[m]	[°]	[°]	[m]
SH1	"pessimistic" estimate	0	-4.25	0	10.5
SH2	"optimistic" estimate	0	0	0	13.5
CTS	"scenario"	0	-2	-2	11.5 ± 1

Comparing the values for the unit's motion from Table 3 and Table 4 with the estimated statistical wave crest values in Table 2, it is reasonable to assume that a negative air gap incident could occur in the reported sea state if the unit's motion failed to follow the wave motion (right itself in time). Table 3 and Table 4 show that several conditions exist where waves estimated in Table 2 could produce a negative air gap of the same order of magnitude as the one on the incident day.

The above-mentioned conditions are based on calculated Hs at the relevant time from the Miros wave radar on Troll. The NMI has made an independent assessment of weather conditions on the incident day, and concludes that the Miros data may underestimate the sea state under given conditions. This is also confirmed by Haver[40]. The NMI provides a higher estimate than Statoil for the sea state (Hs > 9.5 m) at the time of the incident. See section 4.2.

[45] Email from Kongsberg Maritime 22 February 2016

[46] *Vurdering av hendelse på COSLInnovator 30/12-15*, C T Stansberg, report 002, dated 03 March 2016

Haver[40] assesses the possibility of freak waves at the incident time, and concludes: "I would define freak waves as crests which significantly exceed the 99 per cent value for the extreme value distribution ... based on a height of 14-15 metres [undisturbed], no reasons exist to conclude that the wave crest was a freak."

Stansberg[46] assesses the possibility that there could have been a breaking wave, and concludes: "The slamming pressure on vertical walls could then have been much higher ... But the observations do not suggest such an event."

On the basis of the available data, the PSA's assessment is that the wave was steep but that the weather conditions on 30 December were within the limits the unit was supposed to be designed for.

8.2 Estimate of wave loads and the strength of window attachments

Estimates for horizontal pressure from the slamming wave which caused the accident are:

- Stansberg:[46] 200-300 kPa
- Wood Group Mustang Norway:[47] 250-300 kPa (based on deformed bulkhead plate and stiffeners)
- DNV:[23] 350 kPa

Stansberg[46] specifies that that the loads from the slamming wave were "both vertical and horizontal" and that "the water speed is estimated at 15 m/s".

Wave pressure in the incident, estimated above, is significantly higher than the static water pressure from damage waterlines stated in the applicable stability regulations. Static pressure formed the design basis for specifying the windows supplied by TeamTec, now IMS. The windows were delivered with 15 millimetres of pressure-resistant glass. IMS confirms that they should resist a pressure of 5.8 metres of water column (corresponding to 58 kPa). The requirement for the windows is that they must be tested to three times the relevant water pressure.[48] In other words, they should be expected to resist about 180 kPa. The windows, including their attachments, were thereby not designed for the pressure from the wave.

It was found that bolts with a lower strength grade than the supplier's specification had been extensively used to attach windows. Observations have revealed that attachments with the weakest bolts had roughly the same breaking strength as glass.[49] The PSA has therefore concluded that the use of bolts with a lower strength grade was not determinative for the extent of the damage.

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[47] Capacity of forward bulkhead – ALS slamming loads, Wood Group Mustang Norway, doc no 10113778-N-241-CA-002, dated 25 January 2016.

[48] Section 34, sub-section 3 a), regulations of 20 December 1991 no 878 on stability, watertight subdivision and watertight/weathertight means of closure on mobile offshore units.

[49] Interview with IMS, 16 February 2016.

9 Observations

The following nonconformities and improvement points in relation to the HSE regulations have been identified in the investigation process.

9.1 Nonconformity with requirement for POB check

Description
The system for POB registration on board during mustering did not function satisfactorily

Grounds
The responsible party must ensure that personnel can be located and rescued as soon as possible. The emergency response plan for CI requires a POB check to be completed within 10 minutes in the event of a hazard or accident, in part to ensure that personnel can be rescued as quickly as possible in such conditions.

A number of people were registered as missing at one point during the incident, even though they had in fact mustered. This was partly because lifeboat crew registered the number of people arriving and failed to note their names.

The POB check first became available to the emergency response leadership about 40 minutes after the general alarm was sounded. As a result, the search and rescue team was sent out on a second sweep and was thereby unnecessarily exposed.

Requirement
Section 77, letter c) of the activities regulations on handling hazard and accident situations.

9.2 Improvement point concerning quality assurance

Description
The right bolt quality was not used to attach windows.

Grounds
A number of bolts used to attach windows did not accord with the design specification. The specification from the window manufacturer referred to bolts in strength grade 8.8 (yield strength 640 MPa). Following the incident, bolts were found in two strength grades, 8.8 and 4.8 (yield strength 320 MPa). The design drawings for window attachments specify one washer per bolt. Up to three washers were observed on some attachment points after the incident. According to the window manufacturer, three washers would leave insufficient thread grip. Both the use of bolts in strength grade 4.8 and the erroneous installation of windows have reduced the strength of the attachment. This is considered to have been of minor significance for the extent of the damage.

Requirement
Section 3 of the framework regulations on application of maritime regulations in the offshore petroleum activities, see the section 34, sub-section 3.a. on requirements for dimensioning and testing in the stability regulations.

10 Barriers which functioned

A description of barriers which functioned is provided below by the investigation team.

10.1 Barriers related to structural integrity

The operation manual[50] sets limits for operating the unit and specifies how safe operation of the unit will be achieved and maintained when bad weather is expected and experienced. This means in practice that the unit's draught is changed from 17.75 to 15.75 metres in order to secure a larger air gap in high sea states. According to the operation manual, that change must be made when Hs exceeds nine metres. On the incident day, this operation was planned at the morning meeting and executed from 12.15 to 13.00. The weather forecast[51] at the morning meeting indicated a maximum Hs of about 7.7 metres at 12.00, rising to roughly 9.3 metres by 18.00. Deballasting to survival condition was done in good time before the operational criterion for Hs was exceeded, which probably helped to limit the extent of the damage. Deballasting to survival condition is meant to establish a barrier to ensure an adequate air gap.

Stability of the unit is monitored using the Lodic[52] stability computer. The stability printout after deballasting at 12.14 UTC shows positive margins with regard to intact stability in survival condition. A positive weight reserve of 114 tonnes is calculated (when placed one metre over the main deck and compensated for by a corresponding reduction of ballast in the pontoons). The PSA investigation team has requested COSL's stability calculations after the incident. Some uncertainty prevails over these calculations. See chapter 12.6. However, the incident did not develop into a stability event after the damage caused water to enter and fill parts of the box girder. This confirms that the unit's initial stability margin functioned as an adequate barrier against capsizing in the actual course of events.

The topside structure is dimensioned for global loads which represent a combination of still-water and wave loads (hydrostatic and dynamic response from the hull), combined with functional and permanent loads in the actual box girder. In addition, the topside is dimensioned for accidental loads (hydrostatic pressure) caused by accidental listing. The dimensioning principles contain margins for both load and material resistance, and are normally to be regarded as robust. An important barrier is that structural elements are assembled and dimensioned in a way which provides damage tolerances to prevent total collapse (major accident) being caused by limited damage. The incident led to the loss of a human life and the structure suffered local damage to the forward bulkhead, but damage tolerance prevented a total collapse of the forward bulkhead and the forward part of the box girder. This confirms that the unit's damage tolerance functioned as an adequate barrier to structural collapse (and a major accident) in the actual course of events.

10.2 Barriers related to emergency response

CI's emergency preparedness manual[53] describes how an accident should be handled on the unit with a view to limiting its consequences. A general alarm was sounded, with subsequent announcements, soon after the wave struck. This mean that (despite the challenge of

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[50] Operating criteria/adverse weather procedure, COSL, doc no L3 - MAR – 34830, dated 9 March 2015.

[51] Weather forecast for Troll C (lat: 60.64°/long: 3.73°), 06.00 UTC forecast issued by meteorologist at 04.49 UTC. StormGeo.

[52] Ballast and stability software for planning and operating ballast systems. Delivered by Kongsberg Seatex.

[53] Emergency preparedness manual/L4-HSE-*COSLInnovator* – 89875.

establishing a POB overview) personnel mustered in a safe area. Furthermore, search and rescue activities were conducted to locate people in the affected area, and the medic dealt with the injured. Personnel were mustered in a safe area, a search was conducted for missing people, and medical treatment was provided.

The technical team conducted damage limitation by identifying and isolating damage. That included wedging weathertight doors and isolating the fresh water and air systems. Water was eventually emptied out by opening the watertight doors in line with the unit's motion. That gave the emergency response leadership an overview of and control over actual damage, and an overview of any possibilities for escalation. Damage limitation and the provision of information on the actual damage to the emergency response leadership are barriers which reduce the consequences of an incident.

Some important decisions taken by the OIM may have reduced the consequences. He initially wanted to move the unit so that the damaged area was protected from the weather, but decided that this operation would in itself be too uncertain with regard to stability in relation to the extent of the damage. He was also aware that a possible new wave of the same size could damage the engines if the unit were turned.

Given the unclear and uncertain conditions, the OIM decided to evacuate non-essential personnel. Had the incident developed further, this evacuation would have helped to limit the numbers involved. Furthermore, several resources such as ships and helicopters were established in the area and ready to render assistance had the incident developed further.

11 Assessment of the investigation report from the players

COSL, Statoil and Aker Solutions established a joint team under COSL's leadership to investigate the wave incident. The report of this team was presented on 1 March 2006, and shows that detailed technical and analytical work has been done to understand elements of significance. The report provides a basis for learning from the incident. It has mainly identified the same causes as the PSA.

COSL, Statoil and Aker Solutions provide supplementary details in their report on what happened immediately before and after the incident. The investigation work does not discuss the possible significance of changes in the players, lack of clarity related to exchanging information and so forth.

12 Uncertainties related to the incident

The investigation has focused on how slamming on the forward bulkhead of the box girder (superstructure) could occur. Work has accordingly been concentrated on the design basis, analyses and decisions taken in the design phase. Documentation has been sought as far as possible on these conditions, but not everything has been available or possible to check within the team's mandate. This chapter describes uncertainties which may have been significant for the extent and course of the incident.

12.1 Knowledge about and follow-up of air gap information

It is unclear whether all relevant players had knowledge of all the calculations and comments on the air gap. Conflicting information on these conditions was provided in interviews. It is also unclear whether design changes might have been made if relevant players were in possession of this knowledge. The yard was suffering big delays at the time this occurred.

12.2 Communication on the model trials

The PSA has requested documentation on the scope of work in the order placed for the model tests conducted, and a specific video of one test (IRR004). These have not been forthcoming. According to Stansberg's[46,55] assessments, the IRR004 test should have been treated more thoroughly and further communicated in the report, since the measurement data reveal several simultaneous registrations of a negative air gap at the front of the unit. To assess the significance of the actual registrations from the model trials, the videos need to be obtained so that specialists can assess whether the incidents of negative air gap were under-communicated in the report's conclusions.

12.3 Unit's motion characteristics when the incident occurred

Kongsberg Maritime has tried to synchronise information from the DPS-4D system and audio recordings from the marine black box (MBB) in order to identify the exact time of the incident. It has transpired that time registrations in these two systems are not synchronised. This creates uncertainty about the unit's exact orientation (heave, roll and pitch) relative to the wave when the incident occurred.

12.4 Wave crest increase around the unit (asymmetry factor)

DNV-RP-C103 originally recommended an asymmetry factor of 1.2. This was later changed so that a factor of 1.1 could be applied if the 90 per cent fractile for the wave crest estimate was used. This opportunity does not appear to be provided in DNV-RP-C205, which still recommends a factor of 1.2. Expert comments on this area have been obtained from Haver[54] and Stansberg.[55] The latter makes reference to experience from model trials, which show that a general asymmetric factor in the order of 1.20-1.23 is reasonable, and that a specific asymmetric factor in the order of 1.5–1.7 can occur around the columns. These variations in factors show that uncertainty prevails about the estimate of wave amplification around units, particularly relating to the local effects close to the columns.

[54] *Review of 4 reports assessing airgap for COSL semi*, S Haver, 7 February 2015.

[55] *Gjennomgang av dokumentasjon på air gap forutsetninger for COSL Innovator*, Carl Trygve Stansberg, dated 10 February 2016.

12.5 Influence of thrusters on roll and pitch

After the unit became operational, the DP system was updated with a damping function intended to reduce the influence on the thrusters on roll and pitch. The DP log[56] noted at 14.56 on 28 December 2015 that this system had been switched off. According to a description from COSL,[57] use of the system was limited to operational draught. Kongsberg Maritime has provided information on thruster use during the period around the incident, where a steady increase in correction can be observed as the unit is pushed northwards by the waves. The measurements do not provide any immediate basis for noting anything unusual. No detailed analyses or assessments have been conducted concerning thruster influence on roll and pitch at the time of the incident.

12.6 Stability of the unit

Immediately after the incident, the Kongsberg DPS-4D system makes it possible to identify that the unit develops a list of about -8 degrees to port. The unit then rights itself and rolls for a time around a steady position of about -4 degrees[41] to port (see appendix 14.1.2). COSL has confirmed that the stability margins were positive with the largest list, based on an estimated water intake of 37 tonnes. The PSA has received information on the calculations which form the basis for COSL's conclusions. These assessments are based on a LODIC printout for a load condition several hours after the incident, while the unit was in transit. This printout also contains information on a "ghost weight" of 520 tonnes, which is fictionally positioned one metre above the main deck and 50 metres aft of the unit's CoG. Uncertainty prevails about how the analysis represents the loading condition at the time of the damage, and the quantity and location of the water on board.

12.7 Wave height and steepness

Based on the unit's position in the sea around the time the wave struck (see chapter 8, times A-D) and the extent of window damage in the forward bulkhead of the forward box girder (up to about six metres above its underside), it is possible to estimate that a wave-crest height of about 12-15 metres could have caused the damage. The estimate of wave-crest height established by Haver (see Table 2) shows that corresponding conditions were possible in the specific sea state.

Several uncertainties nevertheless prevail in the description of the wave which struck. The interaction of the structure with the wave is mentioned in section 12.4. Some others are:

- measured Hs values provided by the wave radar (measurements with or against the wave direction)
- model for estimating wave height and associated wave crest heights based on measured Hs
- statistical probability for exceeding a certain wave crest height (percentile value)
- measured value for the wave spectrum's peak period (Tp).

The greatest uncertainty over the wave incident relates to the timing between the unit's motion and the wave's arrival. That relates in turn to the unit's motion characteristics and the specific wave periods, and possible connections between swell and wind-generated waves at the time of the incident.

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[56] Copy of DP log from CI for 28-30 December 2015.

[57] Extract from Kongsberg Maritime document on roll-pitch damping. Email from COSL, dated 18 February 2016.

The sea state at the time of the incident (Hs = 9.5 metres and Tp = 12-14 s seconds, see section 4.2) was within the design criteria for wave steepness set by DNV. Stansberg also considers that there is no indication the wave was breaking.

The term freak wave is included in DNV's recommendations[20]. Without measuring the specific wave, it is impossible to say with any certainty that it failed to meet the criteria for a freak wave. Based on Haver's estimates (Table 2) it has nevertheless been established that less frequent waves (90 or 99 percentiles) had the potential to create the registered damage even if they cannot be characterised as freak.

Uncertainty will prevail about the specific wave which caused the damage to CI because no measurements or observations are available.

13 Other observations

Observations which emerged from the investigations and are not considered to have a direct bearing on the course of events, but which could have played a secondary role, are listed below.

13.1 Deadlights

Drawing 10113217-GAD-J-0015 shows windows with deadlights for positions W01 and W02 (lower deck, port), and W23 and W24 (lower deck, starboard). The position of these windows is shown on drawing 10113217-GAD-J-0009. Confirmation has been received that the deadlights were not installed in accordance with the drawings referred to. According to COSL,[58] watertight integrity was approved without deadlights on the basis of assessments and tests by DNV and the yard. Which assessments and tests were made has not been clarified.

13.2 Ghost weight

The term ghost weight (GW) is used for the difference between variable deck weights calculated in the Lodic stability computer (based on draught sensors from the Kongsberg system), and those manually entered with associated local CoGs. Exact knowledge of all weights on board would give a GW of zero. Ahead of the incident time, variations in the GW were in the order of 200-500 tonnes, with relatively large associated moment arms in the horizontal plane. COSL regards the location of the vertical CoG in GW as conservative, and has therefore not considered these variations in GW as critical for stability. No written routines or instructions exist in COSL[59] concerning the acceptable discrepancy in GW and associated local moment arms.

GW is not regarded as directly related to the incident. Substantial imprecision in GW and the associated local CoGs will create uncertainty about the unit's global CoG. In particular, CoG discrepancies in the horizontal plane could produce errors in estimated trim and list[60] both in Lodic and with manual calculation. That could make it difficult to calculate the exact weight corrections required to right a listing unit.

13.3 Windows with attachments

TeamTec (now IMS) designed and delivered products for windows and associated attachments for CI. The company received specifications from the yard via the agent and delivered to order. The delivery was a glass package comprising pressure, soundproofed and fireproof glass in a galvanised steel frame with attachments and a steel frame for welding to the bulkhead.

The type approval certificate received from IMS shows that the window with frame is type-approved for fire loads. Associated hydrostatic pressure tests and strength calculations for the window and attachments have not been obtained for the specific window dimensions. IMS has produced documentation for hydrostatic testing of comparable dimensions.

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[58] Email from COSL, dated 16 March 2016.

[59] Interview with COSL, dated 10 February 2016.

[60] List: static/mean angle of transverse listing by the unit's hull (around the longitudinal axis).

A prototype of the means of closure (window) must be pressure-tested[48] at the manufacturer. No traceability is provided for a pressure test of the strength of the specified glass and attachment details in the type approval certificate

13.4 Weathertight doors at forward end of box girder

Pneumatic weathertight sliding doors delivered by Rapp Bomek opened at the time of the incident. They are assumed to have opened because of water pressure on the pushbuttons for air-assisted opening. This weakened weathertight integrity and allowed water into the corridors. Water intruded on several deck levels during the incident. The pneumatic system was rendered inoperable on the two lowest levels, so that the doors had to be closed manually and secured with wedges. Such unintentional activation of the opening mechanism means that the doors did not function as intended.

14 Appendices

Appendix A: Mandate

The PSA resolved on 31 December 2015 to investigate the incident with the following mandate.

1. Clarify the incident's scope and course of events from the start of the incident until the unit left the Troll field, with an emphasis on safety and emergency preparedness aspects. Psycho-social working environment conditions relevant for the incident and the response to this during the same period will also be clarified.
2. Assess the actual and potential consequences.
3. Assess direct and underlying causes, with an emphasis on technical, operational and organisational aspects.
4. Discuss and describe possible uncertainties/unclear aspects.
5. Identify nonconformities and improvement points related to the regulations (and internal requirements).
6. Discuss barriers which have functioned.
7. Assess the investigation report from the players.
    a. Assuming that this is available within the time frame specified below.
8. Prepare a report in accordance with the template.
9. Recommend – and contribute to – further follow-up, which includes providing on-going information to current internal PSA projects during the period of the investigation about relevant conditions related to technical issues, determining parameters and the PSA's administrative routines.

Composition of the investigation team

Irja Viste-Ollestad, logistics and emergency preparedness discipline area - investigation leader
Terje L Andersen, structural integrity discipline area
Narve Oma, structural integrity discipline area
Sigvart Zachariassen, occupational health and safety discipline area.

Appendix B: Motion of the unit before and after the incident

Measurements from the Kongsberg DPS-4D dynamic positioning system have been processed by Kongsberg,[41] with computer files sent to the PSA. Measurement data specifying the six degrees of freedom registered for the unit's CoG are provided below.

- Height over geoid. Proportional to heave
- Roll around the unit's longitudinal axis, positive when the port side rises.
- Pitch around the unit's transverse axis, positive when the forward end rises.
- Heading the unit is pointing towards, proportional to yaw.
- North position which, with the relevant direction of rotation, is almost wholly opposite to the unit's surge.
- East position which, with the relevant direction of rotation, is almost wholly opposite to the unit's sway.

The graphs present two-minute intervals from 15.37.00 to 15.39.00 UTC. Four times are marked, which are described in section 8. These are positive positions for the damaging impact on the unit:

a. local minimum for pitch, where the forward part of the unit rotates down
b. local maximum heading, where the unit changes its direction of rotation (possibly as a result of slamming to the forward port side)
c. the time C T Stansberg has assessed as the most likely moment of slamming
d. minimum for pitch, when the forward part of the unit has rotated down to its lowest point.

Table 5 presents the resulting still-water air gap for the four positions. The graphs on the following pages present details of these motions.

Table 5 Reduced air gap as a result of the unit's motion.

<table>
<tr><th></th><th>Time
UTC DPS-4D</th><th>Still-water air gap (nominal)</th><th>Heave effect in centre</th><th>Roll effect port @ 32.5 m</th><th>Pitch effect forward @ 40.5 m</th><th>Resulting air gap port side forward</th></tr>
<tr><td></td><td></td><td>(a_0)</td><td>(a_H)</td><td>(a_R)</td><td>(a_S)</td><td>$(a=a_0+a_H+a_R+a_S)$</td></tr>
<tr><td></td><td></td><td>[m]</td><td>[m]</td><td>[m]</td><td>[m]</td><td>[m]</td></tr>
<tr><td>A (+)</td><td>15:38:06.9</td><td rowspan="4">+13.5</td><td>-2.2</td><td>+0.0</td><td>-3.2</td><td>8.1</td></tr>
<tr><td>B (◊)</td><td>15:38:08.7</td><td>-3.8</td><td>-1.0</td><td>-2.4</td><td>6.3</td></tr>
<tr><td>C (o)</td><td>15:38:10.0</td><td>-3.6</td><td>-1.6</td><td>-0.9</td><td>7.4</td></tr>
<tr><td>D (+)</td><td>15:38:18.5</td><td>-0.6</td><td>+1.5</td><td>-5.6</td><td>8.8</td></tr>
</table>

14.1.1 Vertical height, proportional to heave

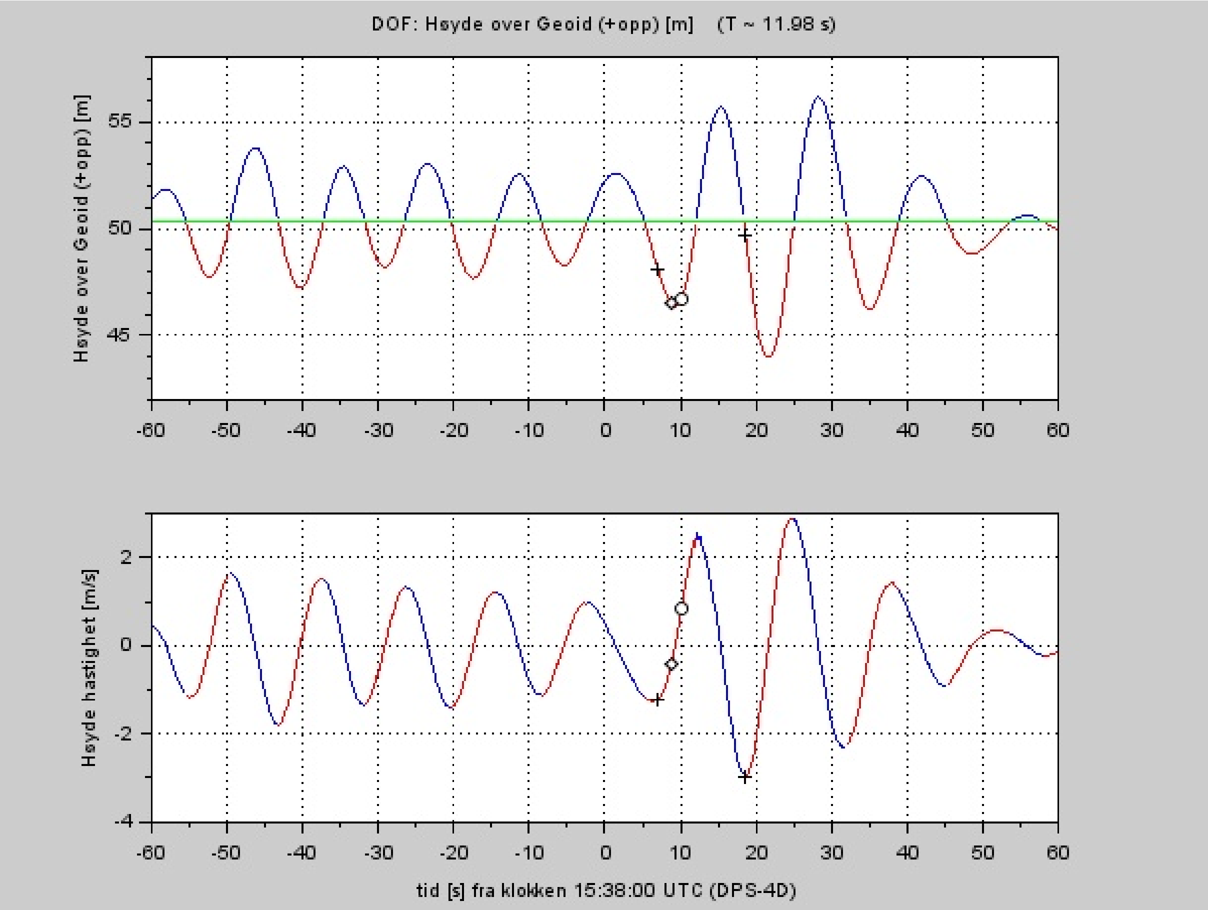


Figure 5 Vertical position of CI's CoG during the period from one minute before 15.38.00 UTC to one minute after on 30 December 2015. The green line marks the short-time average (still-water position of the unit). The blue line shows that the unit has a CoG above the short-time average (lifted by a wave). The red line shows that the unit has a CoG below the short-time average (in a trough). The top graph presents the motion's position, the lower one presents its speed.

	Time UTC DPS-4D	Mean height	Height (over geoid)	Heave (+ rising)	Speed (+ rising)
		(μ)	(h)	(heave = h - μ)	(v_h)
		[m]	[m]	[m]	[m/s]
A (+)	15:38:06.9	50.32	48.12	-2.20	-1.21
B (◊)	15:38:08.7		46.49	**-3.83**	-0.39
C (o)	15:38:10.0		46.69	-3.63	+0.83
D (+)	15:38:18.5		49.69	-0.63	-3.00

The heave graph defines the colour coding on the graphs below:

Blue: Heave is up in relation to the mean height (unit on a crest)

Red: Heave is down in relation to the mean height (unit in a trough)

14.1.2 Roll

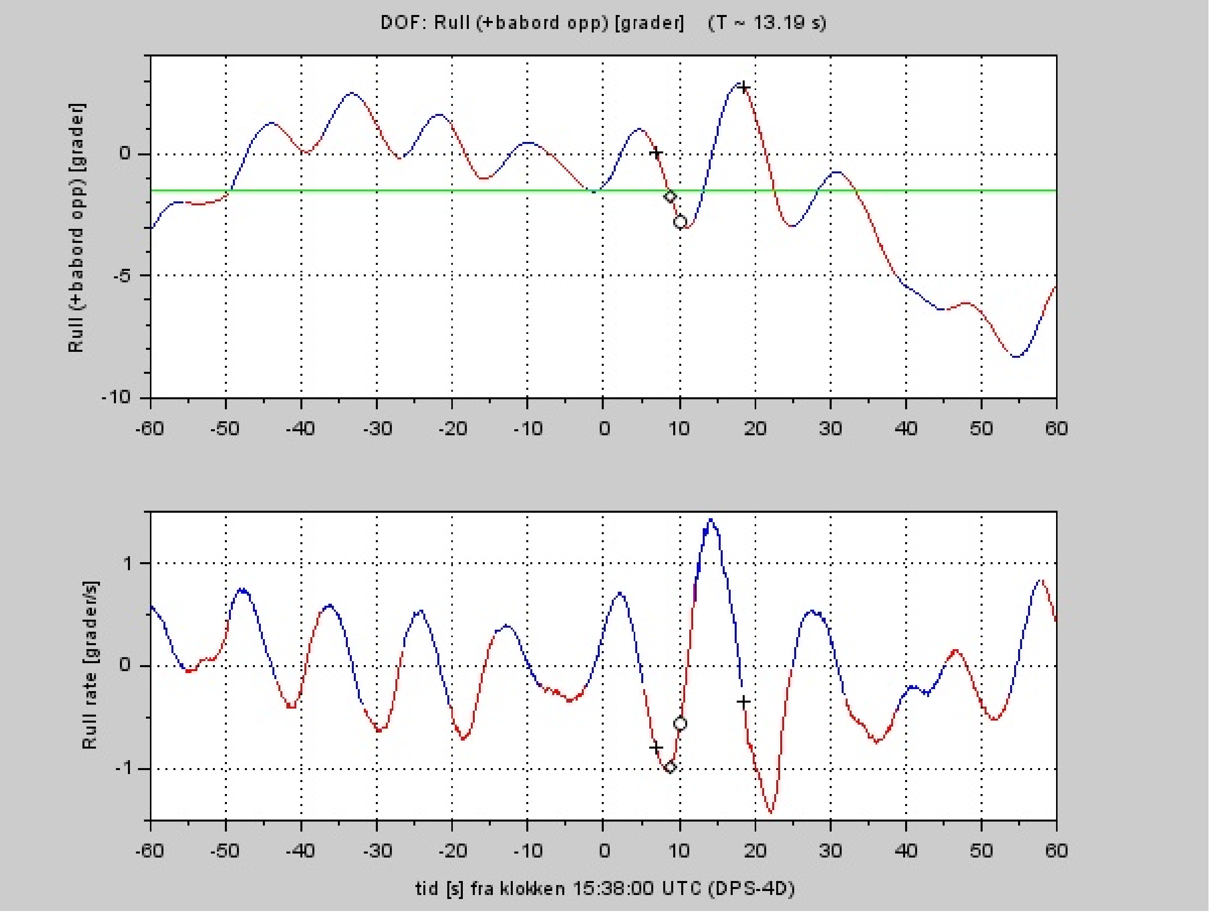


Figure 6 Roll in the period before and after the incident. The top graph presents the motion's position, the lower one its speed.

	Time UTC DPS-4D	Mean roll (+ port up)	Roll (+ port up)	Speed (+ port up)	Speed (absolute)
		[°]	[°]	[°/s]	[°/min]
A (+)	15:38:06.9	-1.52	+0.01	-0.80	48
B (◊)	15:38:08.7		-1.72	-0.98	59
C (o)	15:38:10.0		**-2.76**	-0.57	34
D (+)	15:38:18.5		+2.72	-0.35	21

14.1.3 Pitch

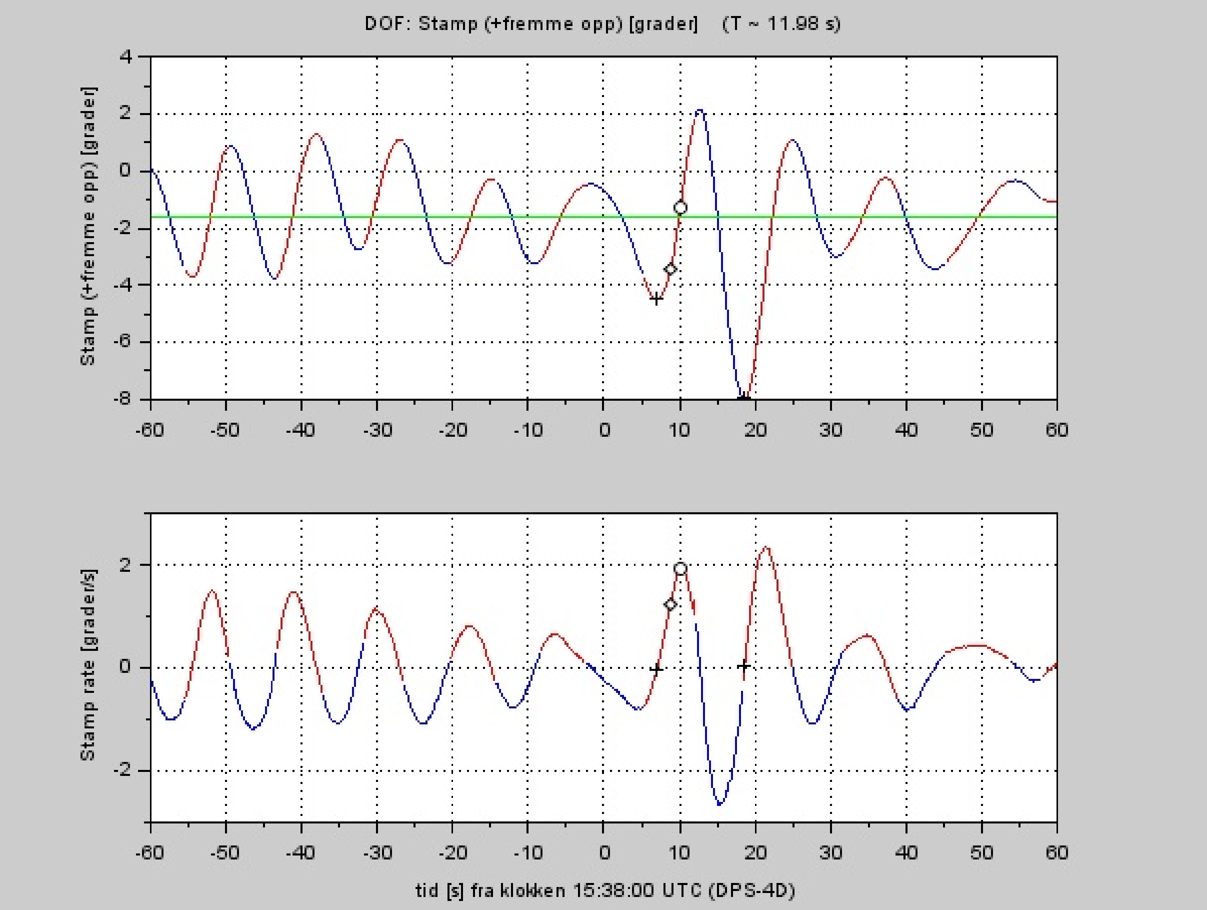


Figure 7 Pitch in the period before and after the incident. The top graph presents the motion's position, the lower one its speed.

	Time UTC DPS-4D	Mean pitch (+ forward up)	Pitch (+ forward up)	Speed (+ forward up)	Speed (absolute)
		[°]	[°]	[°/s]	[°/min]
A (+)	15:38:06.9	-1.64	**-4.49**	-0.03	2
B (◊)	15:38:08.7		-3.44	+1.23	74
C (o)	15:38:10.0		-1.28	+1.91	115
D (+)	15:38:18.5		**-7.98**	+0.04	2

14.1.4 Heading and yaw

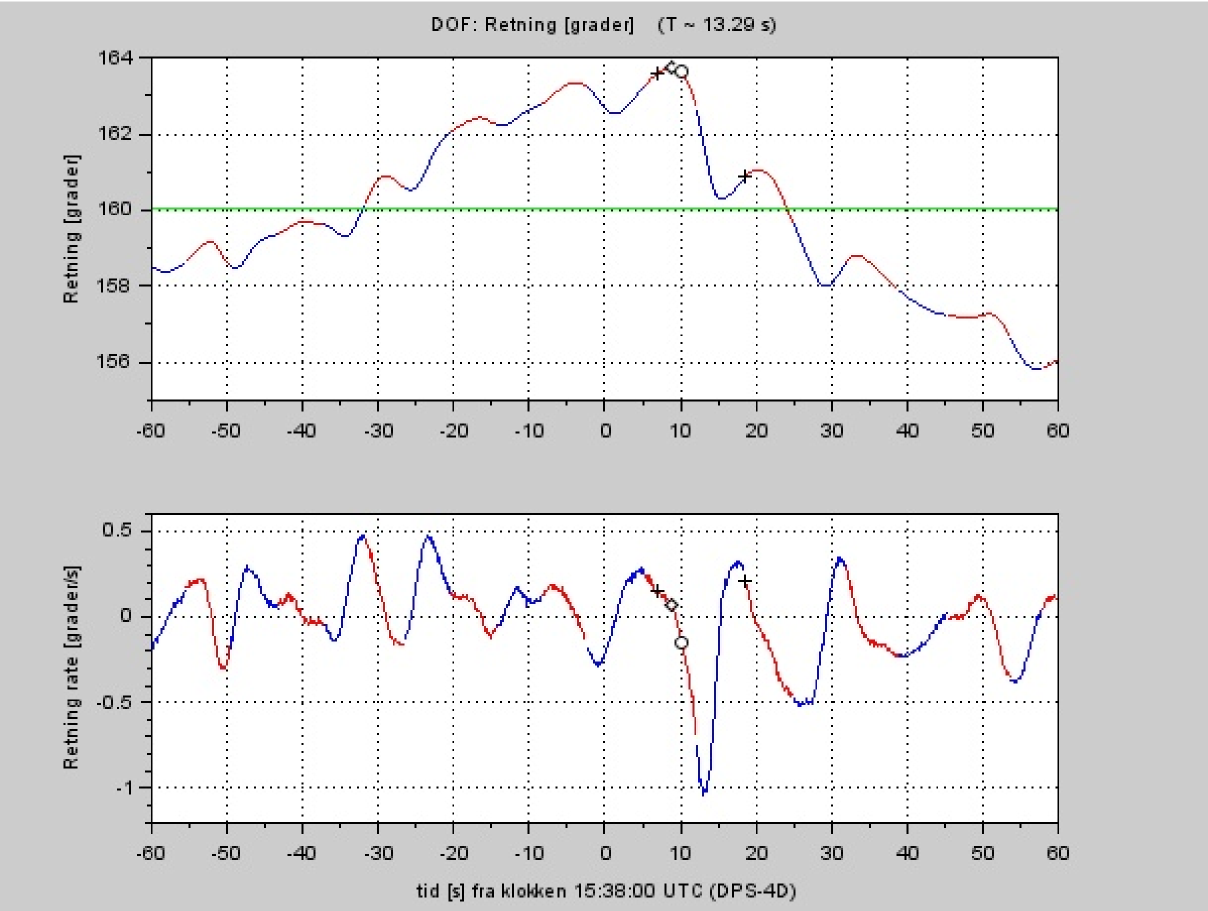


Figure 8 Vessel heading in the period before and after the incident. The top graph presents the motion's position, the lower one its speed.

	Time UTC DPS-4D	Compass heading	Speed	Speed (absolute)
		[°]	[°/s]	[°/min]
A (+)	15:38:06.9	163.59	+0.15	9
B (◊)	15:38:08.7	**163.77**	+0.07	4
C (o)	15:38:10.0	163.64	-0.15	9
D (+)	15:38:18.5	160.88	+0.21	13

14.1.5 North position [~opposing surge]

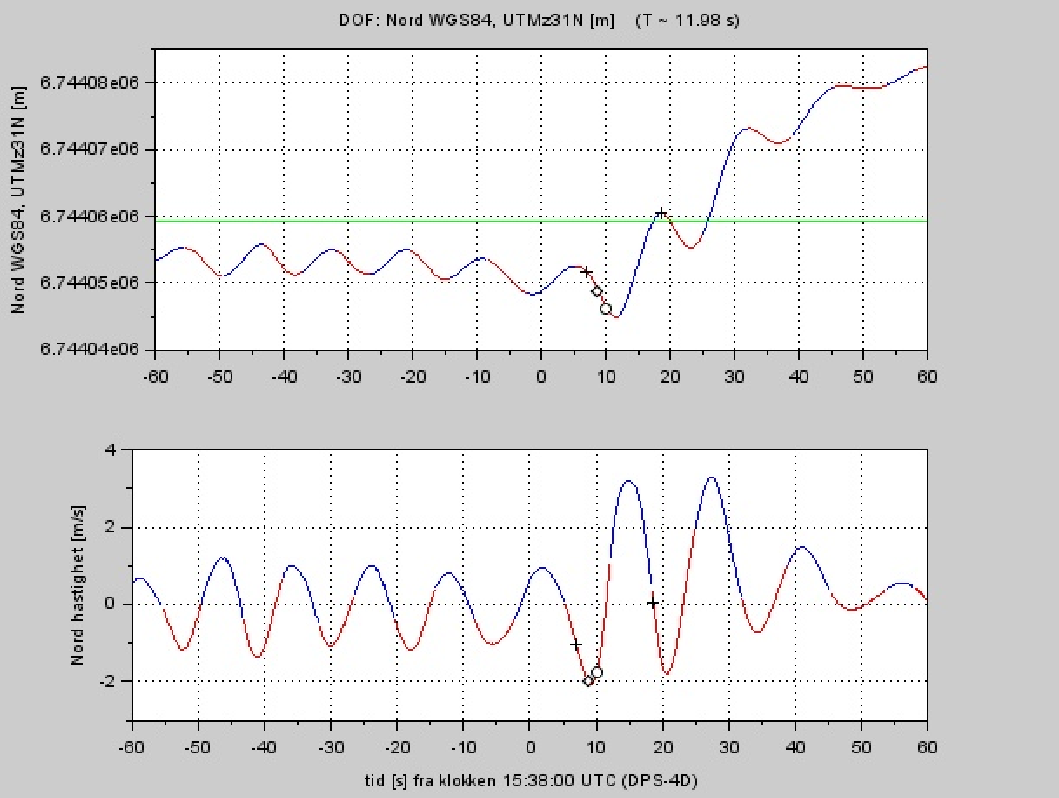


Figure 9 North position and speed in the period before and after the incident. The top graph presents the motion's position, the lower one its speed.

14.1.6 East position [~opposing sway]

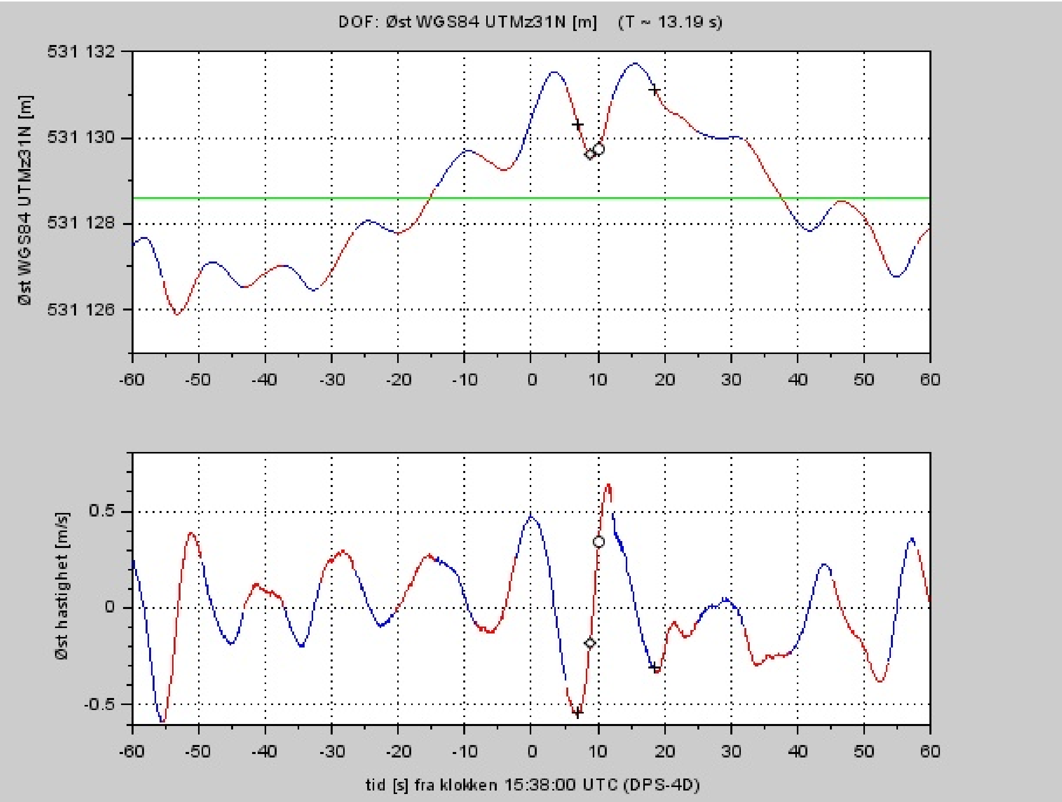


Figure 10 East position and speed in the period before and after the incident. The top graph presents the motion's position, the lower one its speed.

14.1.7 The unit's motion in the horizontal plane

The figures below present the unit's motion before and after it was struck by the wave.

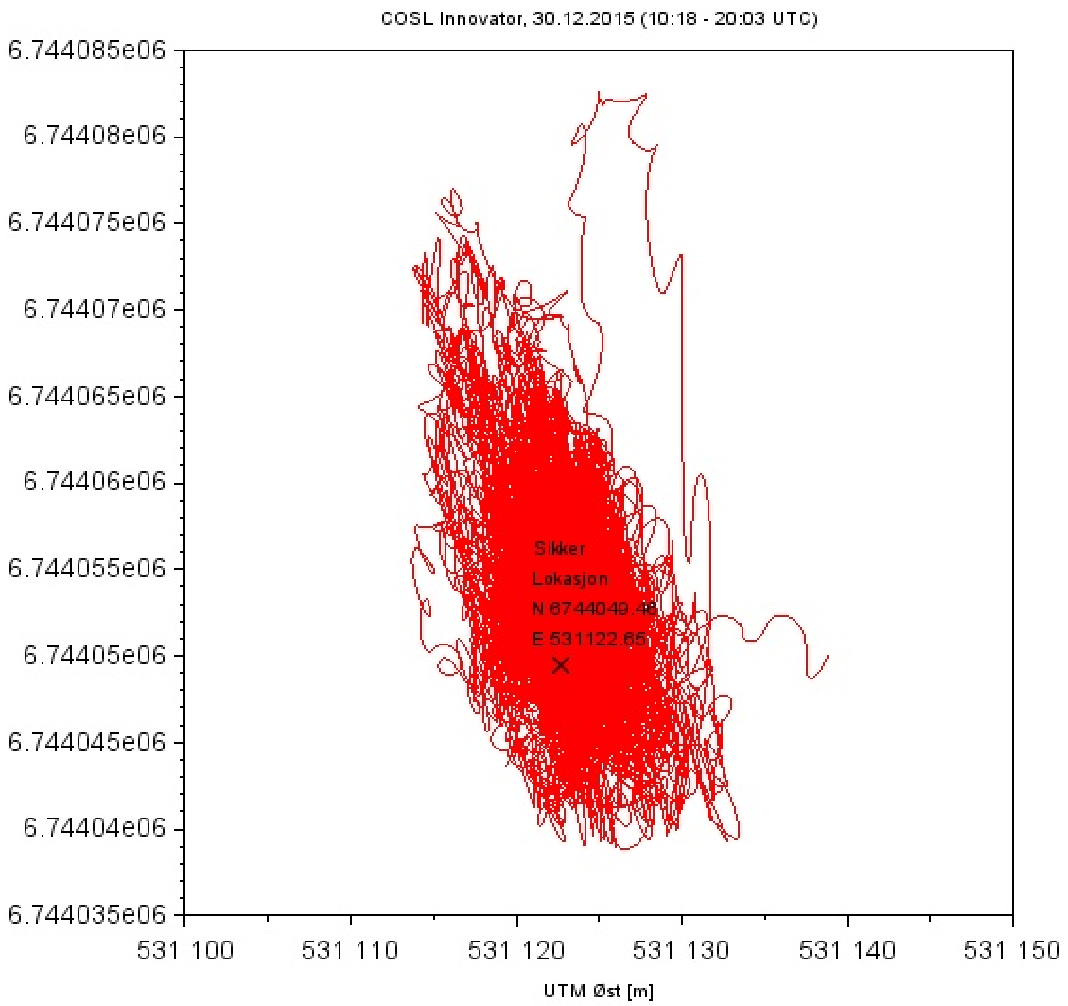


Figure 11 Motion trace for CI on the incident day. Data from Kongsberg DPS-4D.

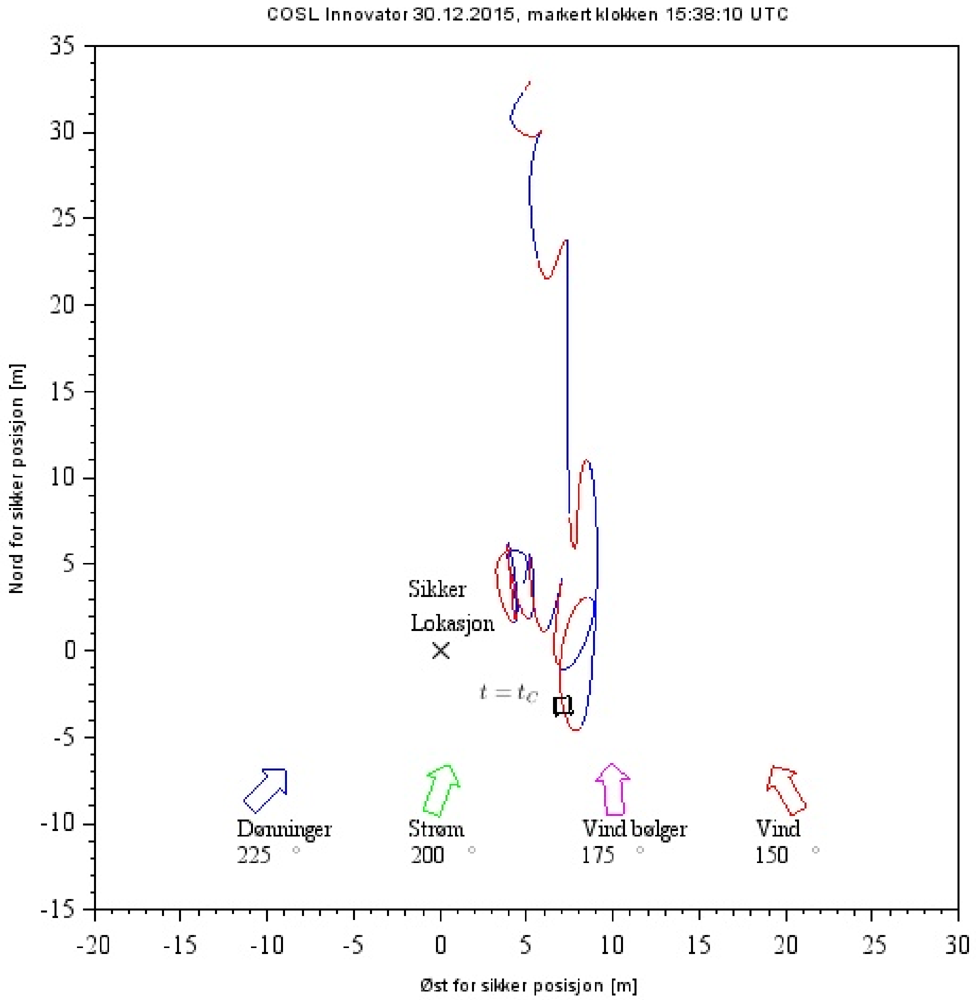
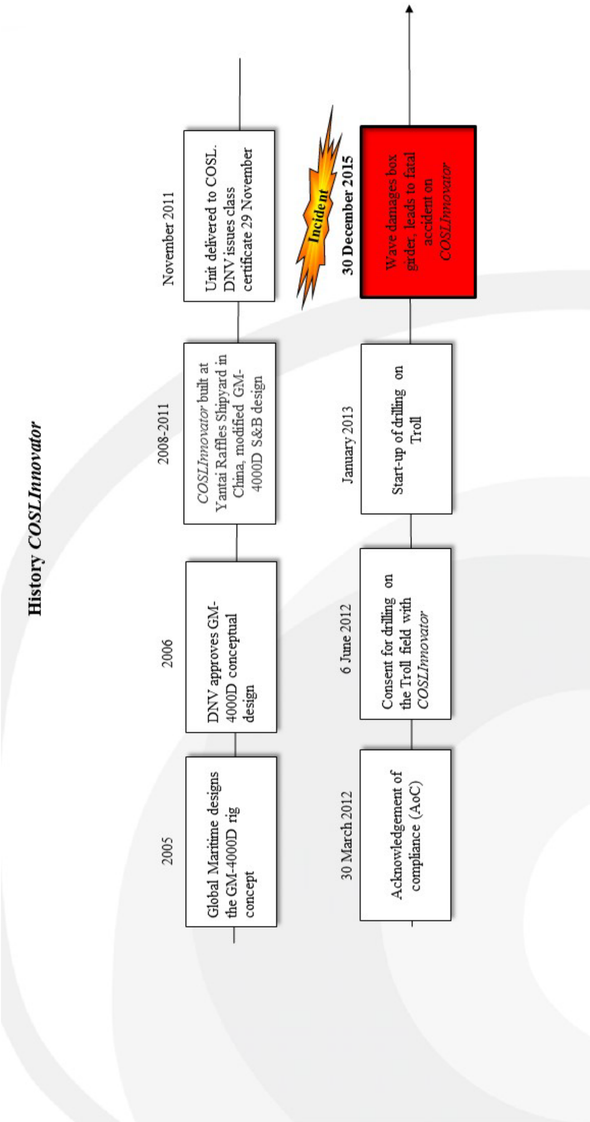
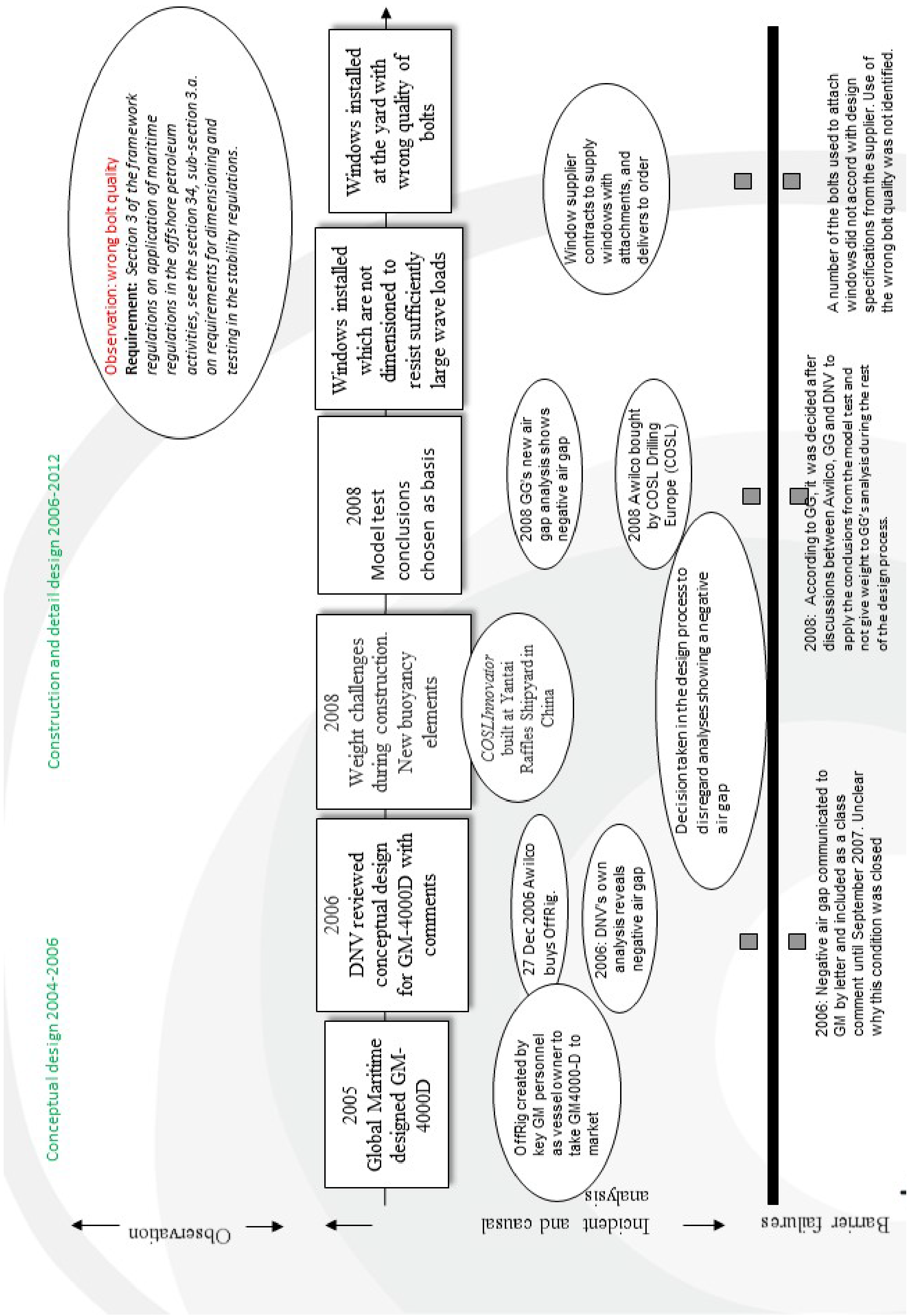


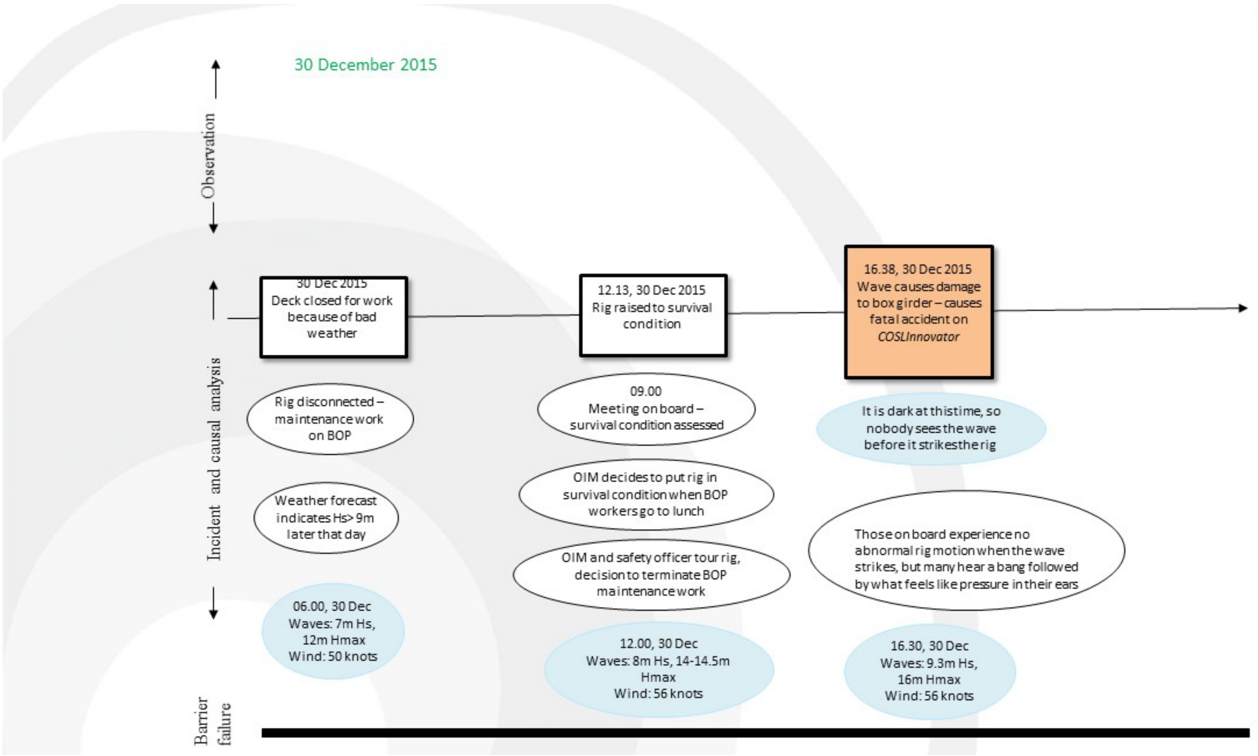
Figure 12 Position during the period around the incident, showing the general direction of the weather. The colours of the trace correspond with the description in Figure 5.

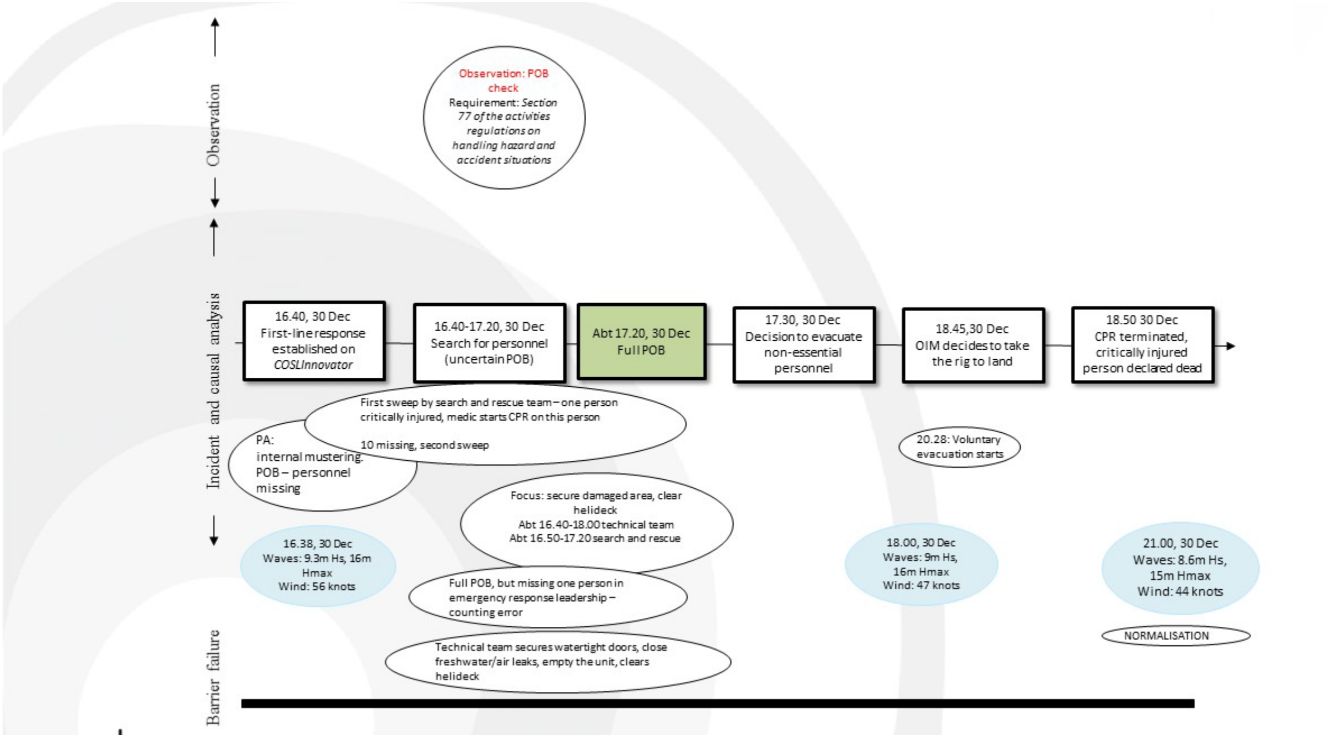
Appendix C: Human, technological, organisational (HTO)





[1] Interview with Wood Group Mustang (formerly Grenland Group), 12 February 2016


30 December 2015
Observation
Incident and causal analysis
Barrier failure
30 Dec 2015 Deck closed for work because of bad weather
12.13, 30 Dec 2015 Rig raised to survival condition
16.38, 30 Dec 2015 Wave causes damage to box girder – causes fatal accident on COSLInnovator
Rig disconnected – maintenance work on BOP
Weather forecast indicates Hs> 9m later that day
06.00, 30 Dec Waves: 7m Hs, 12m Hmax Wind: 50 knots
09.00 Meeting on board – survival condition assessed
OIM decides to put rig in survival condition when BOP workers go to lunch
OIM and safety officer tour rig, decision to terminate BOP maintenance work
12.00, 30 Dec Waves: 8m Hs, 14-14.5m Hmax Wind: 56 knots
It is dark at this time, so nobody sees the wave before it strikes the rig
Those on board experience no abnormal rig motion when the wave strikes, but many hear a bang followed by what feels like pressure in their ears
16.30, 30 Dec Waves: 9.3m Hs, 16m Hmax Wind: 56 knots


Observation
Observation: POB check
Requirement: *Section 77 of the activities regulations on handling hazard and accident situations*
Incident and causal analysis
16.40, 30 Dec First-line response established on *COSLInnovator*
16.40-17.20, 30 Dec Search for personnel (uncertain POB)
Abt 17.20, 30 Dec Full POB
17.30, 30 Dec Decision to evacuate non-essential personnel
18.45,30 Dec OIM decides to take the rig to land
18.50 30 Dec CPR terminated, critically injured person declared dead
First sweep by search and rescue team – one person critically injured, medic starts CPR on this person
10 missing, second sweep
PA: internal mustering. POB – personnel missing
20.28: Voluntary evacuation starts
Focus: secure damaged area, clear helideck
Abt 16.40-18.00 technical team
Abt 16.50-17.20 search and rescue
16.38, 30 Dec Waves: 9.3m Hs, 16m Hmax Wind: 56 knots
18.00, 30 Dec Waves: 9m Hs, 16m Hmax Wind: 47 knots
21.00, 30 Dec Waves: 8.6m Hs, 15m Hmax Wind: 44 knots
Full POB, but missing one person in emergency response leadership – counting error
NORMALISATION
Barrier failure
Technical team secures watertight doors, close freshwater/air leaks, empty the unit, clears helideck