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Analysis of green water susceptibility of FPSO/FSU's on the UKCS

Prepared by **BOMEL Limited**
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Analysis of green water susceptibility of FPSO/FSU's on the UKCS

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EXECUTIVE SUMMARY

Owing to the fundamental requirement of Floating Production, Storage and Offloading / Floating Storage Units (FPSO/FSUs) to remain moored at their location, they are unable to avoid severe weather. The potential occurrence of unbroken waves (green water) landing on deck can cause damage and, over the past few years, a number of these Installations in UK and Norwegian waters have suffered in this respect. The Health and Safety Executive (HSE) commissioned this study to examine the 16 UK FPSO/FSUs for green seas susceptibility specifically using the MARIN software 'GreenLab'.

It is important to note that this study considered only the susceptibility and not the consequences of shipping green water on deck.

Basic comparisons of the Installation particulars at their fully-loaded draughts have initially been made. Where possible, Norwegian FPSOs were included in the comparisons of green water susceptibility expressed in terms of freeboard exceedence at defined points above the uppermost deck or bulwark.

A sensitivity analysis was carried out to investigate the separate effects of different wave parameters and draught changes on the magnitude of freeboard exceedence. Further, the mitigation of green water 'risk' was briefly studied to explore options available in design and operations to reduce the likelihood of significant green water occurrences.

In an attempt to indicate the relative level of susceptibility for individual Installations based on the 'GreenLab' predictions, band of green water severity have been defined for degrees of freeboard exceedence.

Conclusions have been reached in relation to the general population of the UK FPSO/FSUs, fully loaded, for bow, side and stern green water as follows:-

- nearly one-half may be exposed to high bow green water susceptibility,
- compared with the maximum design condition, significantly more green water volume is likely to occur in certain situations with lower wave height and period,
- freeboards are generally insufficient at maximum draughts to prevent green water occurring on deck,
- the majority are susceptible to side green water loading - the most likely area being aft of midships, made worse by larger vessel heading angles relative to the waves,
- none was at a high susceptibility to stern green water.

For each of the UKCS Installations, separate reports of the 'GreenLab' results were prepared and issued by the HSE to the individual Duty Holders. Furthermore, the results (in an anonymised and generalised form) were reviewed collectively by the HSE with the Duty Holders at a meeting in Aberdeen during September 2000. At this meeting the HSE expected Duty Holder follow-up actions on the topic of green water susceptibility were agreed.

In a second part of this study, the recorded UKCS and Norwegian Waters wave incidents causing damage to deck equipment and structures were sourced and collated. A comparison with the

susceptibility levels of the FPSO/FSUs from the 'GreenLab' exercise confirmed a correlation with the recorded incidents. It also indicated that the months of January and February have the highest number of green water events. There is a trend for an increased number of events as more Installations come into service. An analysis of green water incidents from 1995 would indicate a frequency rate of one incident per Installation every 3.6 years approximately.

Differences between the 'GreenLab' predictions on the exposure to green water and the recorded number of wave events may in part be due to operating practices and mitigation measures already in place. There may also be a tendency not to record wave incidents if there is no resultant damage.

The incident data that has been recorded also confirms that the wave incidents have occurred in wave conditions less than the design maxima. This is in accordance with previous work that implies that the frequency of wave events could be of concern for some FPSO/FSUs unless operational procedures/mitigation measures are introduced.

Finally, a summary is provided outlining an industry supported Joint Industry Project (JIP) currently underway investigating the physics of green water and wave slam in order to improve knowledge and application in future FPSO/FSU projects.

MARIN have conducted a peer review of the technical quality of the 'GreenLab' results produced during this study and their comments have been included in this report.

CONTENTS

1 OBJECTIVE

The objective of this study was to examine the 16 FPSO/FSUs operating in UK waters for green water susceptibility using the MARIN software 'GreenLab'.

This initiative follows several incidents of wave damage to this type of offshore Installation in UK and Norwegian waters - often occurring after short operational experience. Although none of the wave incidents directly endangered life, the unexpected nature of the events prompted this study to investigate the magnitude of green water likely to occur on deck i.e. calculated by 'GreenLab' in terms of freeboard exceedence.

Also, as a secondary objective to the study, the FPSO/FSU wave incidents that have occurred in the UK and Norwegian waters have been collated in a database. From this database a comparison of the areas of deck damage has been made with the 'GreenLab' predictions.

It is intended that Duty Holders, Operators and Designers benefit from this study, with a view to improving the understanding of the circumstances under which green water occurs, and developing possible methods to mitigate against risk.

2 INTRODUCTION

This report examines the green water susceptibility of 16 FPSO/FSUs operating on the UKCS using the MARIN 'GreenLab' software. The results give an indication of whether serious green water can be expected, where on deck it might occur and the magnitude and the load levels that might be experienced. Defined levels of susceptibility were attributed to each Installation at the bow, sides and stern regions based on the freeboard exceedences predicted. Anonimity of the FPSO/FSU Installations has been respected by removing the Installation names in this report.

Section 3 describes the green water phenomenon, and Section 4 describes the background to the 'GreenLab' software development. Brief details of the size and locations of the UK and Norwegian Installations follow in Section 5. The basis of the 'GreenLab' analysis is given in Section 6 and the results are described in Section 7 in terms of the susceptibility defined as levels of freeboard exceedence at the bow, sides and stern of the Installations.

Section 8 describes the sensitivity of green water to wave parameters and Installation draught. The correlation of 'GreenLab' predictions with the recorded wave incidents is investigated in Section 9 and Section 10 contains some general guidance on mitigation of risk. The conclusions of the study are given in Section 11, followed by Section 12 on future research developments into the green water and wave slam physics to improve understanding.

3 GREEN WATER LOADING

Green water is defined as unbroken waves overtopping the bow, side or stern structures of monohull shaped FPSO/FSUs.

With the trend to install 'permanent' FPSO/FSUs in increasingly harsh environments, the problem of green water spilling over the bow in large waves becomes an important design aspect. Due to the weathervaning character of turret moored systems, the bow of an FPSO/FSU is always exposed to the waves. Green water can cause damage to sensitive equipment at the bow, such as control valves, ESD systems, fire detection / protection systems, cable trays etc.. For FPSO types with the accommodation at the bow, the same susceptibility to damage applies to the front of the accommodation deckhouse and helideck.

Recent experience with FPSOs in the North Sea confirms that green water loading can cause serious damage in the bow region. This can result in the need for repairs and production downtime. It has also been observed that in slightly non-collinear wind, waves and current, green water can occur over the sides around midships. In addition, green water has been observed at the stern particularly in the case of traditional tankers converted to FPSOs with no poop deck.

4 BACKGROUND TO 'GREENLAB' DEVELOPMENT

To take into account the aspect of green water loading in the design of FPSO/FSUs for harsh environments, the Joint Industry Project 'F(P)SO Green Water Loading' was carried out in 1997 by the Maritime Research Institute Netherlands (MARIN). The main results of the Joint Industry Project (JIP) have been published in the open literature to make them available to the industry (Ref 1 - 5).

The JIP was based on extensive tests of instrumented models with different hull shapes and deck configurations. The JIP followed an integrated approach that considered green water loading in combination with drift forces and ship motions. Both new builds as well as existing tankers were considered in the study.

The results and conclusions of the JIP were made available to the participants in a report together with a computer design tool ‘GreenLab’. This software can be applied to specific monohull-shaped FPSO/FSUs, enabling measures against green water to be evaluated interactively. It should be noted that in developing the 'GreenLab' software package, it was not the intent to displace the value and importance of running model tests to evaluate green water susceptibility.

The ‘GreenLab’ methodology for the prediction of extreme freeboard exceedences is based on a combination of linear diffraction analysis with non-linear corrections based on the JIP model test results. The methodology is further described schematically in Figure 1. As soon as the maximum freeboard exceedence is known, other aspects (such as water heights and impact loads) are calculated based on the relations found in the model tests. The relative motions between the waves and the vessel form the basis of the green water calculations. When these exceed the freeboard level, green water will flow over the deck or bulwark.

5 NORTH SEA FPSO/FSU LOCATIONS, SIZES AND OPERATIONAL HISTORY

Recently there were 16 FPSOs located on the UK Continental Shelf: the majority situated in the Central North Sea, two located West of Shetland and one in the Liverpool Bay area, (refer to Figure 2).

'Schiehallion' is currently the largest with a displacement of nearly 200,000 tonnes and the smallest is the 'Ramform Banff' at 32,000 tonnes. The average size is 120,000 tonnes displacement corresponding to the size of a medium crude carrier. Some are tanker conversions (Maersk D-class) or similar new hull designs.

There are also five FPSOs employed in Norwegian waters. The largest in displacement terms is 'Asgard A' (slightly smaller than 'Schiehallion') and the smallest is 'Balder' which is slightly larger than 'Petrojarl Foinaven'.

The increase in numbers of these North Sea Installations from 1982 onwards is shown in Figure 3 and the approximate operational history is shown diagrammatically in Figure 4. The total operational experience amounts to some 88.5 vessel years. 'Petrojarl 1' has the longest track record of 12 years and has operated on several fields in both the UK and Norwegian sectors of the North Sea.

6 BASIS OF 'GREENLAB' ANALYSIS

Because this work formed part of a 'GreenLab' review exercise of UKCS FPSO/FSUs, certain assumptions were necessary which might not, in practice, best represent the true operational situation, particularly in adverse weather conditions. For example, the maximum operational draught and zero trim have been assumed throughout the exercise. In all the green water calculations, a wave spectrum peak enhancement factor (gamma) was assumed to have a value of 3.3 which is typical for a North Sea environment.

'GreenLab' uses standard peak period values of 12, 14 and 16 seconds and the associated significant wave height defined by the user for the specific field location. It was necessary to devise a relationship between these peak periods and the corresponding wave heights. An approximate formula was therefore developed to calculate the required wave heights for peak periods lower than the maximum, as follows:

$$H = (8Hs - 9(Tp-T))/8 \qquad (1)$$

where T is the period for which H is required, with the condition that H cannot be greater than the extreme design return values. This line would follow the upper contour of the scatter diagram (see Figure 14 for a plot of this line for a representative FPSO).

The probability of exceedence of green water on deck calculated in 'GreenLab' is approximately 1 in 1000 which corresponds to the most probable maximum value for a storm duration of 3 hours. The program produces a curve of probability of exceedence vs relative motion that intersects this probability level to give a Most Probable Maximum (MPM) relative wave motion in metres, see Figure 5.

The 'GreenLab' program predicts green water exceedences at the bow, side and stern of an FPSO/FSU. More specifically, the water height on deck is determined at three locations at the bow, five positions along the side and one position at the extreme aft end as shown in Figure 6.

The side freeboard exceedence predictions are made at positions defined by the intersection with the side shell of 30-degree sectors from the vessel centre (in plan). Stern exceedence is determined at the transom on the centre line.

In addition to the green water height predictions, the corresponding pressures are given as program output. Furthermore, for the FPSO/FSU bow, the loads on a reference structure and horizontal pipe are calculated although not included in this report.

The data required to run 'GreenLab' consists of the principal particulars of the hull, maximum loaded draught, bow and stern shape, the contour of the deck edge (to define the freeboard), the maximum design environment in terms of significant wave height (Hs), the peak wave period (Tp) and the design current (Vc).

The data was initially compiled from the Installation Safety Case (as submitted to the HSE) and requests for information from the FPSO/FSU Duty Holder. The freeboard contour definition was determined from the general arrangement drawings, and the bow flare determined from the body plan.

Before embarking on the analysis, this data was confirmed with the Installation Duty Holders as an accurate basis for the study.

Definitions of the ‘GreenLab’ output are given in Tables 1 to 3 and the units are defined as follows:

- Freeboard exceedence in metres of water head (m)
- Water velocity in m/s
- Pressure in kPa = 0.01 Bar = 0.10 tonnes / m2
- Force in kN = 0.102 tonnes
- Moment in kNm

MPM F’bd Exceedence (m)	**Green water on deck (m)**	**Velocity (m/s)**	**Water pressure (kPa)**	**Structural Load** (A flat plate reference structure 15 m wide and 20 m high at the centreline of the Installation, with its flat front 20m from the fore perpendicular)			**Pipe load (kN/m)**
				Load (kN)	**Mmt (kNm)**	**Press (kPa)**	
Most probable maximum exceedence of freeboard by the (relative) waves at the bow centreline	Actual green water height on the deck at the fore perpendicular (FP), (H0) and 10m (H10) and 20m (H20) aft of FP	Maximum expected velocity of the green water front over the deck	Water pressure on the deck at the fore perpendicular (P0) and 10m (P10) and 20m (P20) aft of FP	Maximum total horizontal force on the structure	Maximum total moment (around the deck level) on the structure	Local peak impact pressure on the lower part of the structure	Total force (per meter length) on a 200 mm diameter pipe on the bow at H2O, placed athwartship and 0.5 m above the deck

It should be noted in the above table all pressures and pipe loads assume a standard 1.4m high bulwark is installed.

Table 1 Bow Green Water

MPM Freeboard Exceedence	Load at 10m from side (kPa)
Position from midships (m)	Position from midships (m)
Freeboard level at this point (m)	Freeboard (m)
Most probable maximum exceedence of the freeboard (deck) level at 5 positions along the side of the Installation by the (relative) waves. Positions are given relative to midships, positive is to the bow. The local freeboard levels at these points are taken into account.	Local peak impact pressure on a structure placed 10 m from side of the Installation (not directly applicable to slender structures such as pipes and cable trays).

Table 2 Side Green Water

MPM Freeboard Exceedence	Load at 10m from stern (kPa)
Most probable maximum exceedence of the freeboard (deck) level by the (relative) waves at stern centreline.	Local peak impact pressure on a structure placed 10 m from stern of the Installation

Table 3 Stern Green Water

7 RESULTS OF GREEN WATER SUSCEPTIBILITY ANALYSIS

The most probable maximum (MPM) values of freeboard exceedence (i.e. the values that have a probability of exceedence of about 1E-03 in the investigated storm condition and duration) were predicted using 'GreenLab' for the bow, sides and stern regions of the UKCS Installations.

A LOW level of freeboard exceedence was defined as less than 3 metres water height, between 3 and 6 metres was classed as a MEDIUM susceptibility, and above 6 metres as a HIGH susceptibility. These three categories of susceptibility were devised for reference only to indicate those areas of deck that may be more prone to shipping green water.

Because of the unusual hull shape and dimensions of 'Ramform Banff', this FPSO was not included in the analysis as it did not fit well with the model shapes and proportions tested during the JIP development of 'GreenLab'.

The ‘GreenLab’ analysis results for the remaining 15 UKCS Installations indicate the following notional values for green water susceptibility at the bow, sides and stern. The 5 Norwegian Installations taken from Ref 7 are shown in brackets.

Bow Area

- 7(3) Installations susceptible to a HIGH level
- 5(1) Installations susceptible to a MEDIUM level
- 3(1) Installations susceptible to a LOW level

Side Area

For 15 degrees heading angle to waves

- 2(1) Installations susceptible to a HIGH level
- 12(4) Installations susceptible to a MEDIUM level
- 1 Installation susceptible to a LOW level

For 30 degrees heading angle to waves

- 13 Installations susceptible to a HIGH level
- 2 Installations susceptible to a MEDIUM level

Stern Area

- 10 Installations susceptible to a MEDIUM level
- 3(2) Installations susceptible to a LOW level
- 2(3) Installations not susceptible

It is important to note that the levels of green water susceptibility defined above (i.e. LOW, MEDIUM and HIGH) do not necessarily imply that there is likely to be a serious safety implication for the FPSO/FSU. The different 'levels' only give an indication of the likelihood of green water occurrences and not the consequences of such events. An Installation with a HIGH ranking of green water susceptibility can still be safe if appropriate prevention and/or protection measures have been implemented.

Conclusions from the 'GreenLab' predictions, stated above, can be summarised as follows:

Bow Area

- Nearly one-half of UK FPSO/FSUs may be exposed to HIGH bow green water susceptibility

Side Area

- The majority of FPSO/FSUs are susceptible to side green water
- Vessel heading significantly influences green water on the side and the majority would be highly exposed to waves for a high incident angle of 30 degrees relative to head seas

Stern Area

- None of the FPSO/FSUs are at HIGH susceptibility to stern green water

8 SENSITIVITY OF BOW GREEN WATER TO TP, HS, FREEBOARD AND GAMMA

A limited sensitivity study was carried out for one of the Installations representative of a number of Installations susceptible to green water at the bow. The intention was to investigate how bow green water varies with wave height and period together, wave height separately, draught and gamma (the spectral peak factor).

Results from 'GreenLab' show the sensitivity of freeboard exceedence and hence water on deck over a range of periods and the corresponding significant wave heights derived from equation (1) in Section 6. The conclusion was that the maximum freeboard exceedence (water on deck) occurs at conditions less than the design maximum condition (refer to Figure 7). The significance of this is that the frequency of bow green water occurring may be greater than was first thought, as the wave height and period (showing maximum response) could be closer to the 1-year return period values rather than the design return period (e.g. 100-year). For this representative Installation, the extent of bow green water reduced steeply for smaller waves below the peak response.

With reference to Figure 8, a near linear increase of bow green water occurrence with increasing significant wave height was demonstrated (for the same Tp) for this representative hull shape and flare angle.

Bow green water becomes less likely with decreasing draught (as expected and demonstrated in Figure 9). However, it should be noted that for a fixed draught, an increase in freeboard (by raising bulwark height) does not result in the same decrease in freeboard exceedence due to the non-linearities in the green water phenomenon (see Ref 4).

The wave spectrum is defined mathematically by a JONSWAP spectrum formulation matching measured data for an area. The peak enhancement factor, gamma, depends principally on the sea and swell components, and a value of 3.3 is typically adopted for North Sea applications. However, gamma can vary between about 1.0 and 5. From the results of 'GreenLab' (for the same Hs and Tp), a lower gamma produced a lower freeboard exceedence and less green water on deck. The sensitivity is shown in the Figure 10 indicating approximately a 1.5 metre reduction in freeboard exceedence between a gamma of 5 and 1. Green water heights on deck will therefore be correspondingly less.

There appeared to be no correlation of freeboard exceedence with FPSO length, displacement, maximum design wave height and period or location. There was some correlation of freeboard exceedence with freeboard (rather obviously) at the bow, sides and stern regions (Figure 11).

9 GREEN WATER INCIDENTS AND 'GREENLAB' CORRELATION

Following a data collection exercise, recorded wave incidents on UKCS and Norwegian FPSO/FSUs were examined. From 1995 to date, 17 green water and 2 wave slam incidents have been identified on 12 FPSO/FSU Installations, two of which are not currently operating. Some Installations have experienced more than one incident. No wave incidents have been reported prior to 1995, but half of the Installations have been affected to some extent by wave damage since then.

Figure 12 shows the cumulative number of incidents divided by the cumulative operating years. To date, the available data indicates an average frequency of between 0.21 and 0.28 incidents per operating year, depending on the number of operating years assumed. The lower figure includes an incident-free period prior to 1995, whereas the higher figure relates only to operating years accumulated post 1995. These figures represent a frequency of 1 incident occurring every 3.6 to 4.8 operating years approximately.

Further inspection of the data shows that January and February contain the highest number of events, which is to be expected, compared with summer months. It is further believed that the recorded wave events were only the major incidents causing damage, and that there may be substantially more unreported.

There is good correlation between the locations of wave incidents with the predetermined green water susceptibility levels (Figure 13 refers). For example, 7 green water incidents at the bow occurred on the 10 Installations categorised in Section 7 as having a HIGH susceptibility rating at the bow. An almost equal number of incidents have occurred at the bow and sides of the Installations (which is perhaps surprising), whereas the stern has few recorded wave incidents.

Having established a correlation between the predictions of FPSO/FSU susceptibility to green water events and the wave incidents reported, the freeboard exceedences were estimated (again using 'GreenLab') for the conditions prevailing at the time of the incidents.

The recorded wave incidents consisted of 26 areas of damage classified as at the bow, sides and stern. Two of these were bow slam incidents not expected to show green water on deck (and are not included in Figure 13). The ‘GreenLab’ analysis correctly predicted green water on the deck for all (24) of the recorded damage areas. 18 of the 24 damages (75%) show agreement with the predicted maximum susceptibility levels (HIGH, MEDIUM or LOW). The remainder underpredicted by one susceptibility category. This effectively gave confidence in the 'GreenLab' software to predict levels of potential freeboard exceedence and the areas susceptible to green water damage.

A comparison of the maximum design conditions for the Installations, with the Hs and Tp determined (as far as possible) at the time of the wave incidents, showed that all the incidents occurred at lower values of height and period than the design conditions (refer to Figure 14 where an example Hs-Tp relationship has been included). This is in agreement with previous work that implies that conditions lower than the design maxima for FPSO/FSUs are more likely to give rise to wave incidents. This has implications for the expected frequency of wave events, operational procedures and future requirements for design and model testing.

10 GENERAL GUIDANCE ON MITIGATION OF RISK

Several of the UK sector FPSO/FSUs have experienced green water damage to topside equipment to some degree, and four out of the five Norwegian sector FPSOs have also reported such incidents (Ref. 7). Some of the measures which can be investigated to reduce the effects of green water for FPSO/FSUs are summarised here.

The FPSO/FSU originated from tankers where green water is an accepted risk and the equipment is designed for resistance to green seas, although tankers have forward speed and are not tethered. For early FPSO/FSUs, the phenomenon of green water may not have been given the attention necessary by the topside or hull designers, and model tests have not always included the critical wave conditions for green water. Recent experience has led to a greater awareness of potential damages from green water and in some cases actions and procedures have been implemented to reduce the risk. These include the following:

Physical actions

- Bow protection structures such as breakwaters and higher bulwarks
- Side protection walls
- Raising poop deck or bulwark aft
- Raising equipment / piping to reduce the loading
- Protection of process, deck equipment, cable trays, hydrants and evacuation equipment
- Resiting local services and structures
- Redesign of structural details to resist wave loads
- Reassessment of green water using mathematical or physical models

Operational actions

- Restriction of draught (storage) particularly in winter conditions
- Operation of the FPSO/FSU with stern trim where bow green water is more likely than elsewhere
- Heading control to reduce wave incidence angles and side green water
- Restriction of personnel access in green water zones

All of these actions may not be possible or appropriate for any given existing Installation. Principal attention should be paid to personnel safety, evacuation and escape, and the safety of the Installation. Also, some actions may not be desirable for a particular FPSO/FSU. For instance the effect of increasing bulwarks could adversely impact on the environmental loads transmitted to the mooring system.

Because green water loading is an important aspect in the safety of FPSO/FSUs, it should be taken into account in the design. Generally, there are three ways to manage the problem of green water:

- prevention
- protection
- prevent it as far as possible and protect against the remaining part.

This requires an optimum design of the hull shape and the (protecting) structure on the upper deck. It should be noted, however, that an optimisation with respect to green water prevention can affect other aspects, such as wave drift (and mooring) forces on the ship. In Ref 3 it was concluded that "it is not possible to optimise a bow of an FPSO/FSU on one aspect only. A bow optimised on green water loading may increase the mooring forces and vice versa". An integrated approach is therefore necessary, which considers green water loading, drift forces and ship motions. The optimum design is then dependent on the combination of environmental conditions, water depth, functional requirements and given boundary conditions.

11 CONCLUSIONS FROM THE 'GREENLAB' ANALYSIS AND INCIDENT CORRELATIONS

This report has described a study for the UK Health and Safety Executive that examined the susceptibility of UKCS FPSO/FSUs to green water. The intent was to raise awareness of potential incidents and the predictions from the 'GreenLab' software have been communicated to the Duty Holders of these Installations.

The Norwegian FPSOs have been included (as far as possible) in the summaries of freeboard exceedence expressed in terms of susceptibility levels or bands of severity for bow, side and stern locations. All Installations were subject to the assumptions of operating at full draught and even keel in environmental conditions up to and including their design maxima.

Observations have been made in relation to the general population of FPSO/FSUs installed in the UKCS and it is found that:

- nearly one-half may be exposed to HIGH bow green water levels
- compared with the maximum design condition, significantly more green water volume is likely to occur in certain situations with lower wave height and period
- freeboards are generally insufficient to prevent green water occurrence in the fully-loaded condition
- the majority are susceptible to side green water loading - the worst area being aft of midships, made worse by larger heading angles relative to waves
- none is at a HIGH susceptibility to stern green water. There is, however, a trend for the larger, longer period waves to show more green water at that location.

It is important to note that the analysis dealt with susceptibility and not the consequences of shipping green water on deck.

The greatest number of wave incidents occur in the winter months. Also, it was shown that with the growing number of these units in the UKCS and Norwegian waters, the incident rate is increasing. About half of the Installations currently in service have been affected by wave incidents of some kind. There appeared to be reasonable correlation between the recorded green water incidents and the predictions produced by the 'GreenLab' software.

The data has shown that the 19 incidents have generally occurred in wave conditions much less severe than their design maxima. This is not a new finding, but the implication is that the frequency of wave incidents could be an annual event for some FPSO/FSUs unless operational procedures / mitigation measures are applied. However, the levels of green water susceptibility predicted do not necessarily imply that there are serious safety implications for the FPSO/FSUs operating today provided appropriate prevention and/or protection measures have been implemented.

It should be emphasised that the 'GreenLab' software used in this present study indicated whether and where (heavy) green water can be expected. The study enabled a comparison to be made between different FPSO/FSUs. A more detailed diffraction analysis and a large-scale model test with the actual deck configuration is still recommended for a complete analysis of a specific FPSO/FSU, with inputs and test parameters that reflect the actual operating conditions (e.g. draught, trim, environment etc.).

12 FUTURE RESEARCH DEVELOPMENT WORK

12.1 THE 'FLOW' - JOINT INDUSTRY PROJECT

The results presented in this paper have shown that green water loading and wave impact loading on the hull are important aspects for FPSO/FSUs. To take these aspects into account in the design of safe and economical floaters, the 'FLOW' (Floater Loading by Waves)-JIP was initiated by a number of specialist companies/organisations in this field and co-ordinated by MARIN (see Ref 8).

The main objective of the FLOW-JIP is to develop guidance, calculation methods and risk assessment procedures for green water and wave impact loadings appropriate to each stage of an FPSO/FSU project, namely: concept development, detailed design and operation. This will be achieved, firstly, by fully understanding the problem of green water and wave impact loading and then, by developing methods either to avoid the problem, or to predict its effects so that these can be taken into account in the design and operation of safe and economical FPSO/FSUs. It is also expected that the methodology and design tools developed in this JIP will give valuable input to solving other important wave impact aspects like; run-up, wave-on-deck loads on fixed platforms etc.

The 'FLOW' - JIP focuses on all aspects that are important in the problem of green water and wave impact loading. Four JIP subtasks and objectives have been identified:

- WAVES: Identification of critical wave (weather) conditions for wave impact problems and their physics and development of probabilistic wave models

- HYDRODYNAMIC LOADING: Understanding of wave impact and green water physics, and development of methodology for the prediction of impact loading.

- STRUCTURAL: Define a wave impact loading and response calculation methodology

- RISK AND DESIGN: Develop a risk-based methodology for wave impact loading issues in different phases of an FPSO/FSU project

JIP participants can be actively involved in the project, lessons learned from previous work will be used in the project and there will be a strong coupling between different tasks. The JIP makes use of state-of-the-art numerical simulation methods, model tests and full-scale measurements on the bow of the UKCS 'Schiehallion' FPSO.

There are two phases in the JIP:

- First phase: problem identification and preliminary design guidance
- Second phase: development of prediction method and final design guidance

The main deliverable of the project will be a methodology for the evaluation of wave impact and green water effects in the design of FPSO/FSUs. All results of the project will be reported in detailed as well as summary reports. A design tool will also be one of the deliverables. The project will be implemented in such a way that the results can be used by FPSO/FSU designers, oil companies, shipyards, ship operators and Classification Societies. At the moment this JIP has 26 participants. It is to be started at the end of this year and will be completed in 2002 (interim results will be available in 2001).

12.1 RESEARCH ON NUMERICAL PREDICTION OF GREEN WATER LOADING

Although green water on the decks of fishing vessels has been predicted numerically in the past, the use of complex numerical methods for the prediction of green water loading on the bow of FPSO/FSUs is fairly recent. At the latest 'Numerical Ship Hydrodynamics' Symposium in July 1999 (Ref 6), new promising results were presented for the software program 'ComFlo', of which an example is shown in Figure 15.

The typical flow and impact loading of the green water on the bow deck can be predicted surprisingly well. Although their computation time is still enormous - four hours on a fast workstation for the simulation of 10 seconds reality - in the future, these computer tools will be important for design evaluations and improvements.

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FIGURES

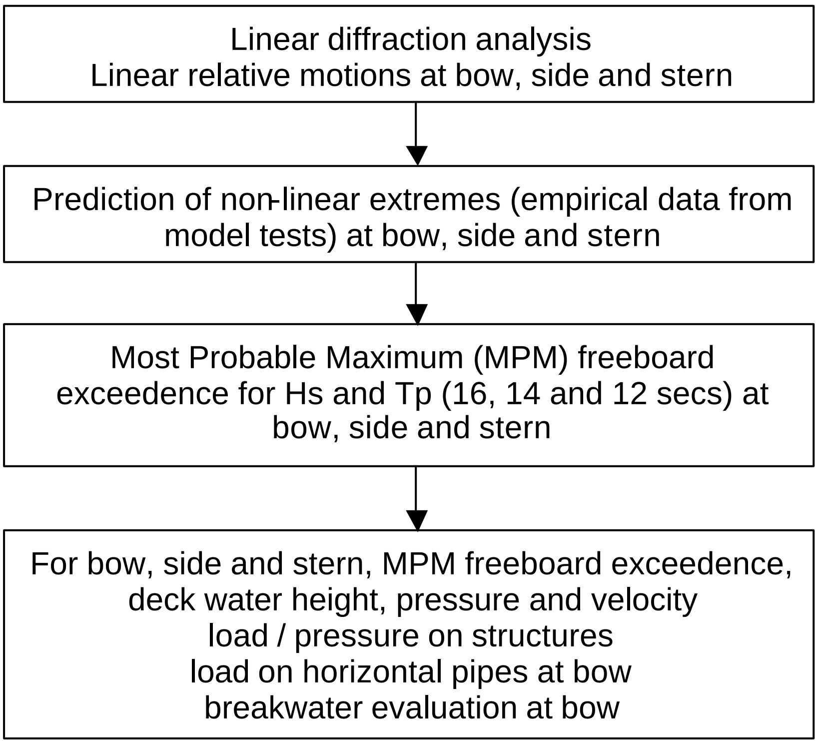


Figure 1 'GreenLab' Methodology

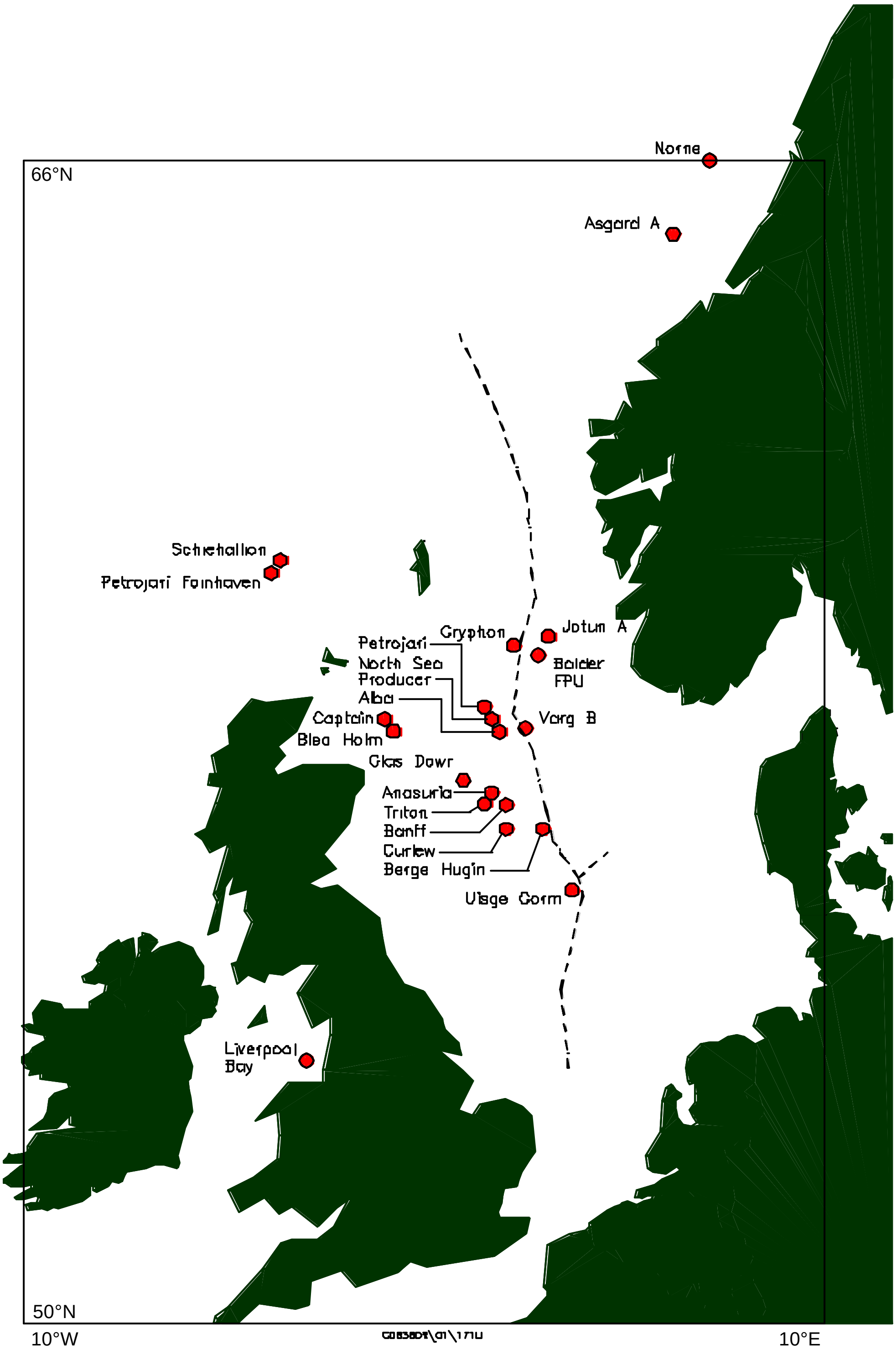


Figure 2 UKCS and Norwegian FPSO/FSU Locations

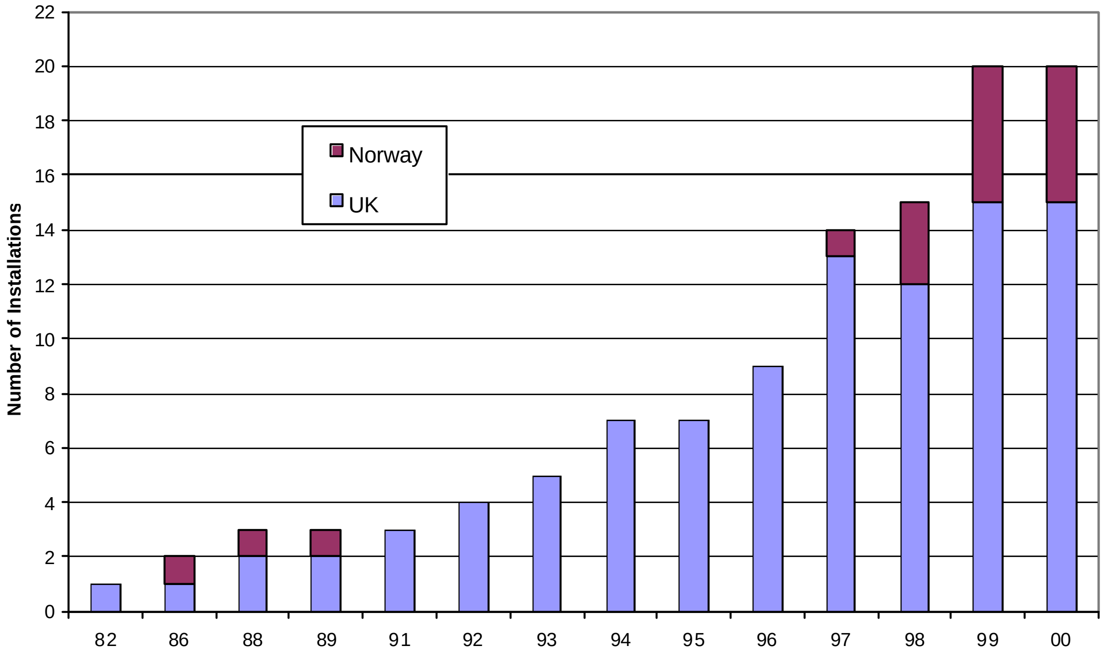
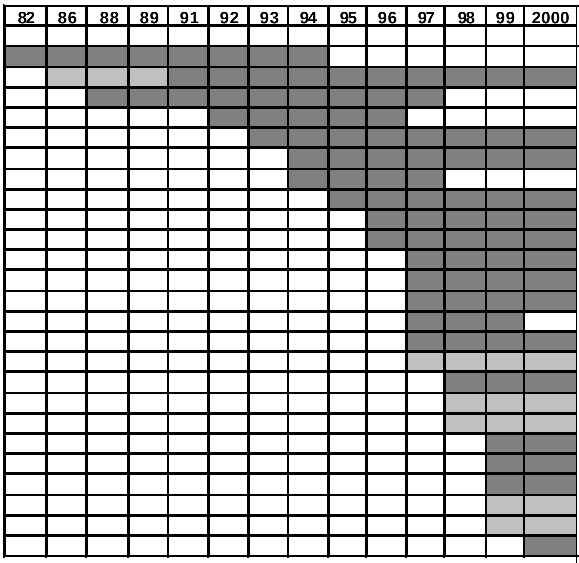


Figure 3 Growth of FPSO/FSUs in the UKCS and Norwegian Waters

	Name	Producing	Decommissioned	Operating Years
1	Fulmar FSU	1982	1994	7
2	Petrojarl 1	1986		12
3	Seillean (SWOPS)	1988	1997	8
4	Ailsa Craig	1992	1996	4
5	Gryphon A	1993		7
6	Alba FSU	1994		6
7	Vinga STL	1994	1997	3
8	Uisge Gorm	1995		5
9	Liverpool Bay OSI	1996		4
10	Anasuria	1996		4
11	Captain	1997		3
12	Petrojarl Foinaven	1997		3
13	N.Sea Producer	1997		3
14	Glas Dowr	1997	stacked 2000	2
15	Curlew	1997		3
16	*Norne*	1997		3
17	Schiehallion	1998		2
18	*Asgard A*	1998		2
19	*Varg B*	1998		2
20	Ramform Banff	1999		1
21	Bleo Holm	1999		1
22	Berge Hugin	1999		1
23	*Jotun*	1999		1
24	*Balder*	1999		1
25	Triton	2000		0.5
				88.5



	82	86	88	89	91	92	93	94	95	96	97	98	99	2000
UK	1	1	2	2	3	4	5	7	7	9	13	12	15	15
Norway		1	1	1							1	3	5	5
Total Units	1	2	3	3	3	4	5	7	7	9	14	15	20	20
Op Years	0	1	2	3	3	3	4	5	6	7	8	12	15	19.5
Cum Years	0	1	3	6	9	12	16	21	27	34	42	54	69	88.5

Figure 4 Operating History of UKCS and Norwegian FPSO/FSUs

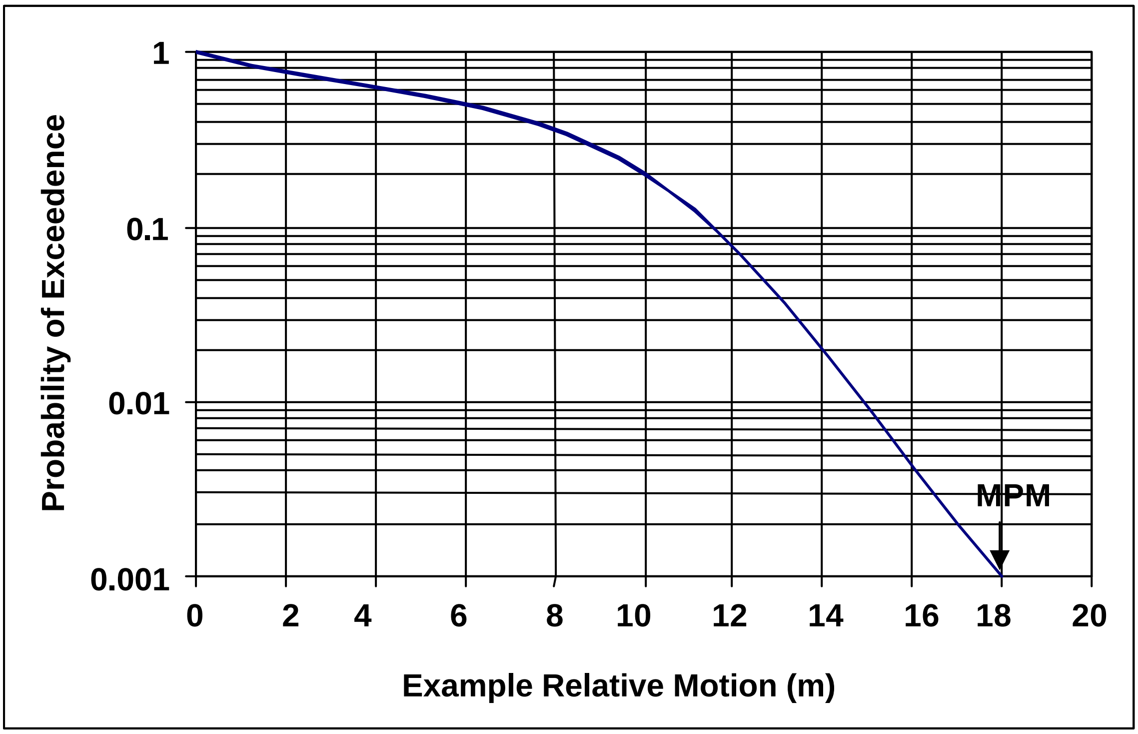


Figure 5 Probability of Exceedence vs Relative Motion (MPM = Most Probable Maximum)

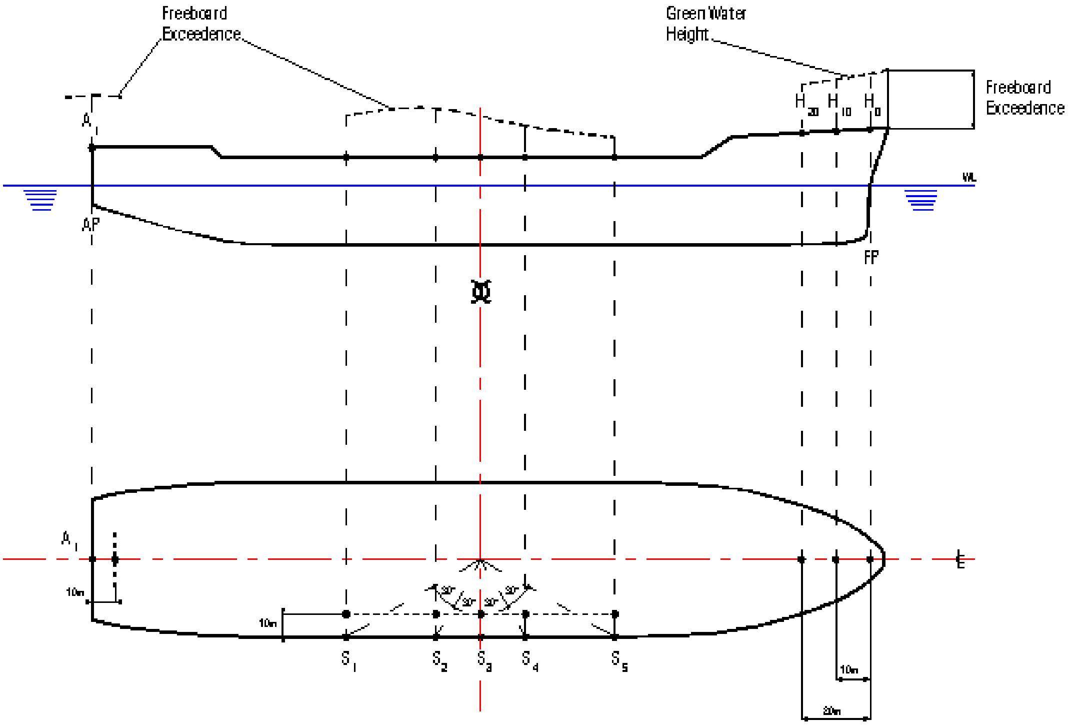


Figure 6 Positions of Green Water Predictions

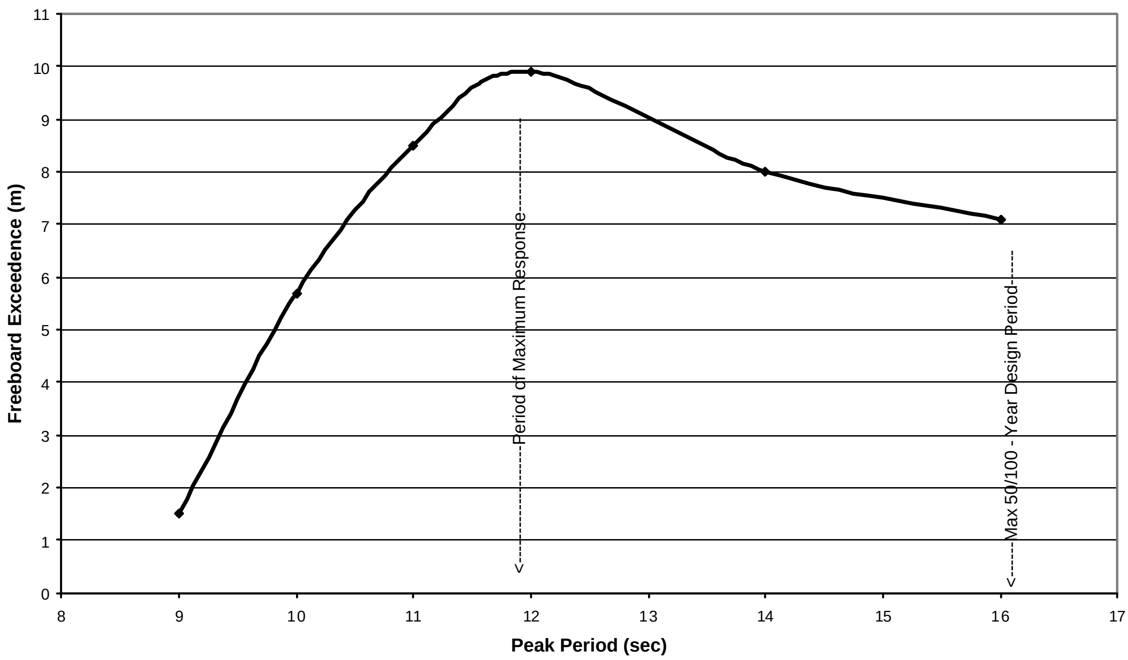


Figure 7 Sensitivity of Green Water with Hs and Tp

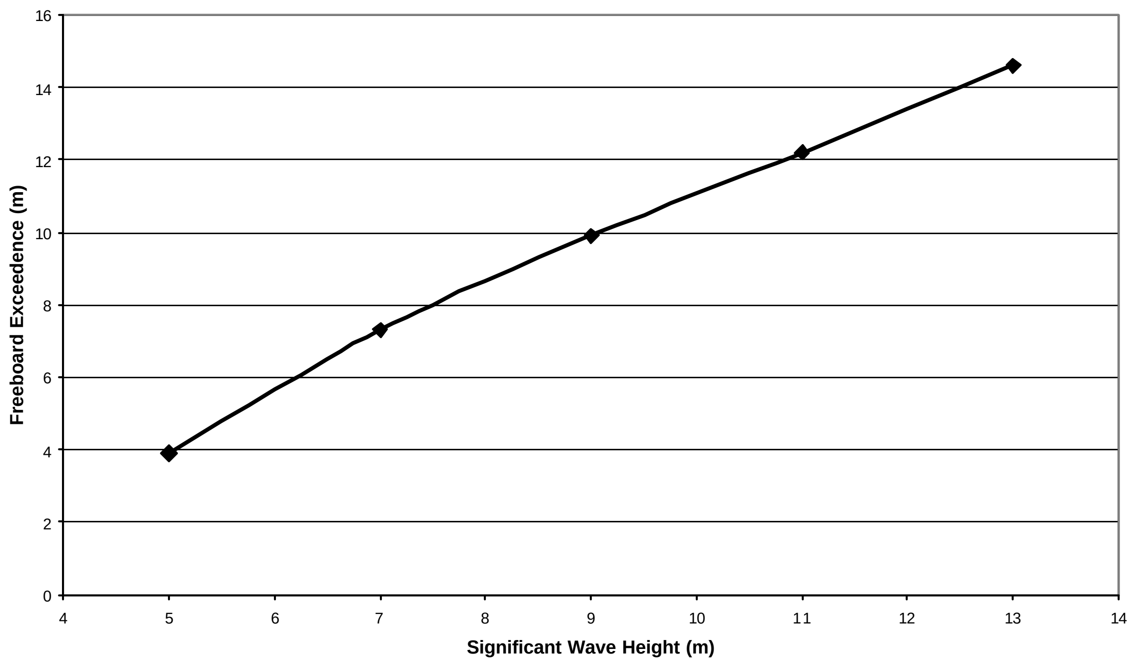


Figure 8 Sensitivity of Green Water with Hs

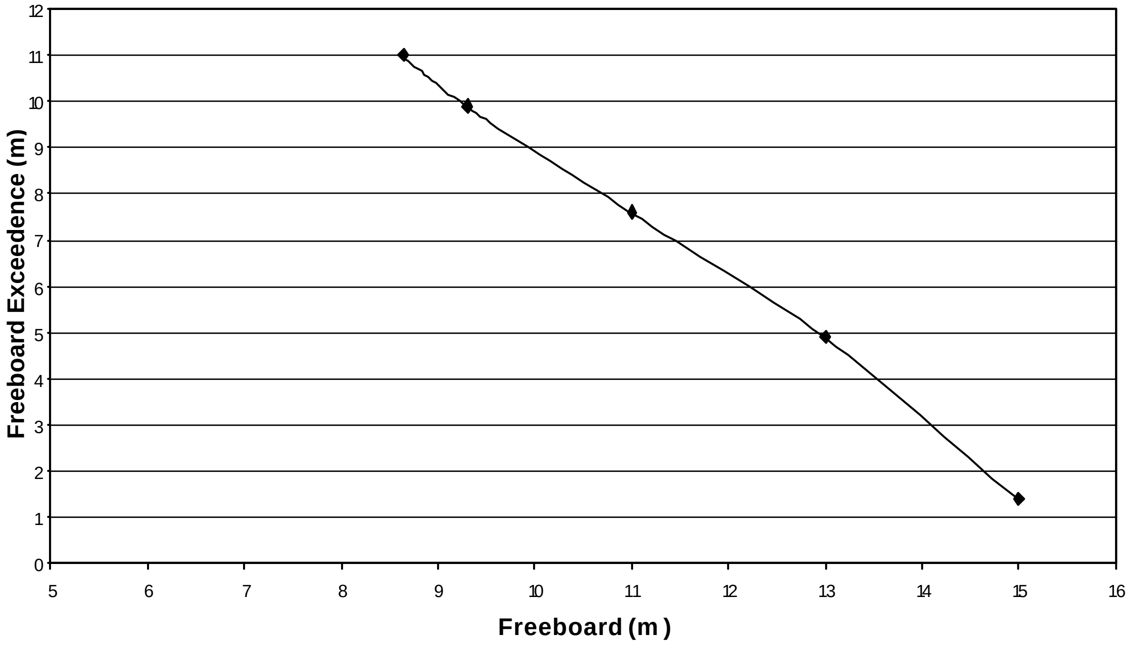


Figure 9 Sensitivity of Green Water with Freeboard (draught changes)

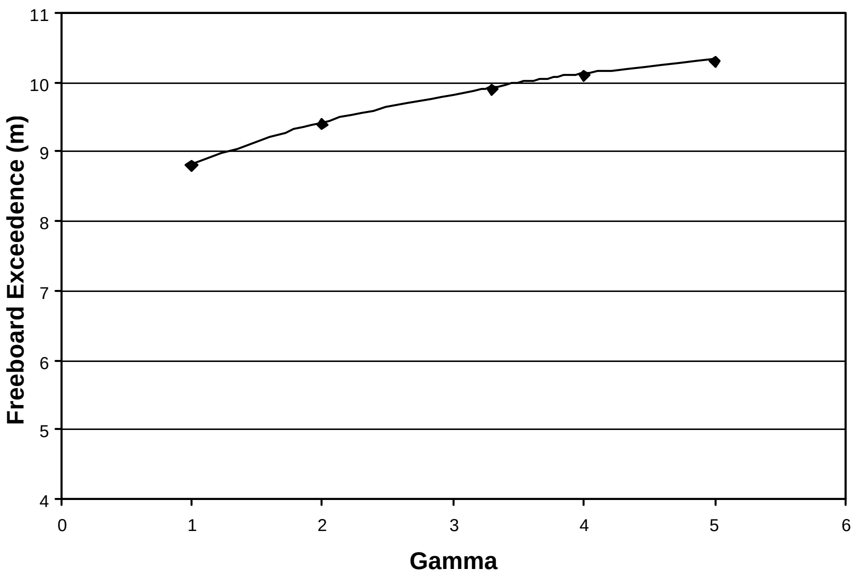


Figure 10 Sensitivity of Green Water with Gamma

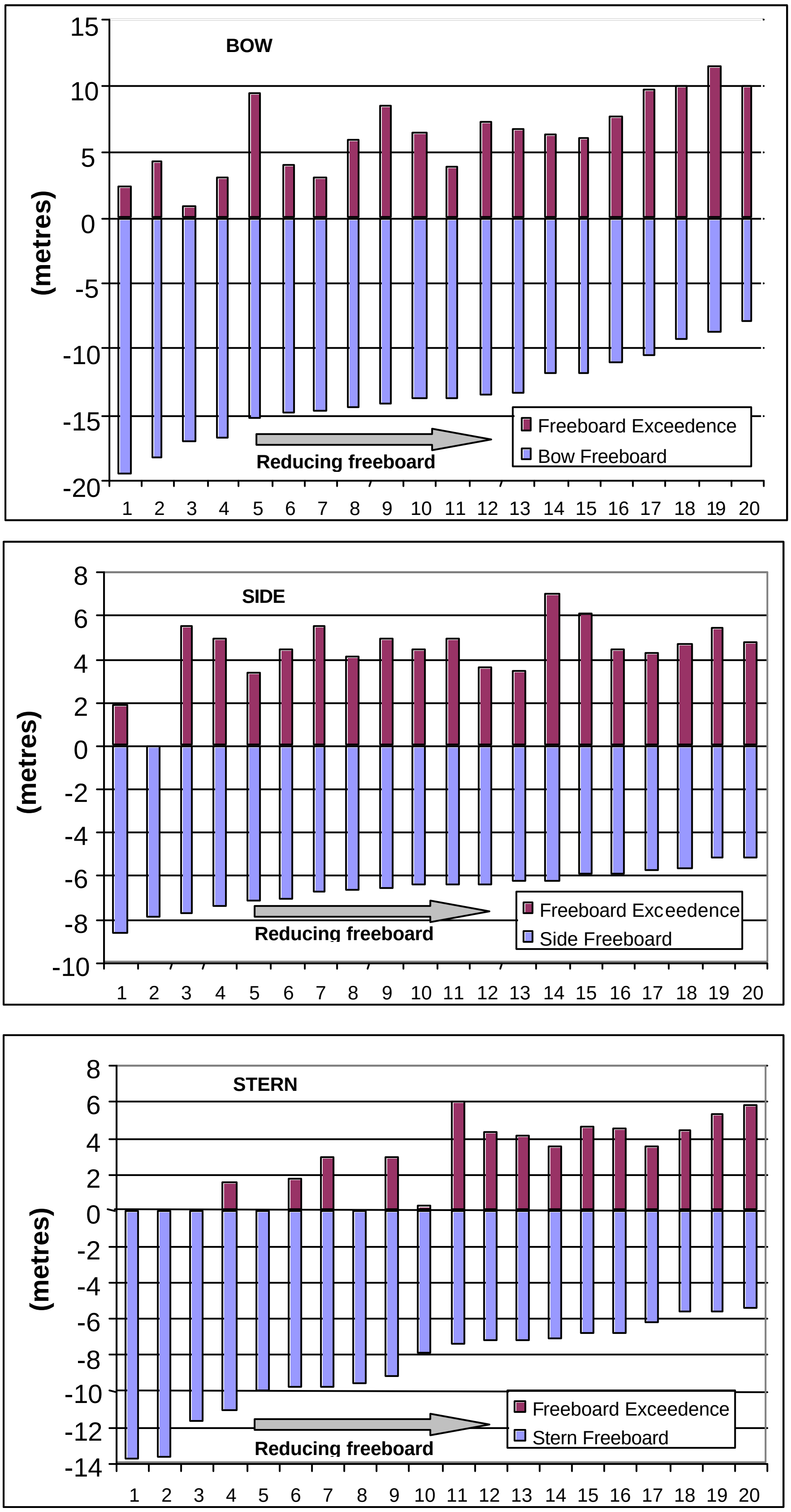


Figure 11 Correlation of Green Water with Freeboard (for Installations numbers 1 to 20)

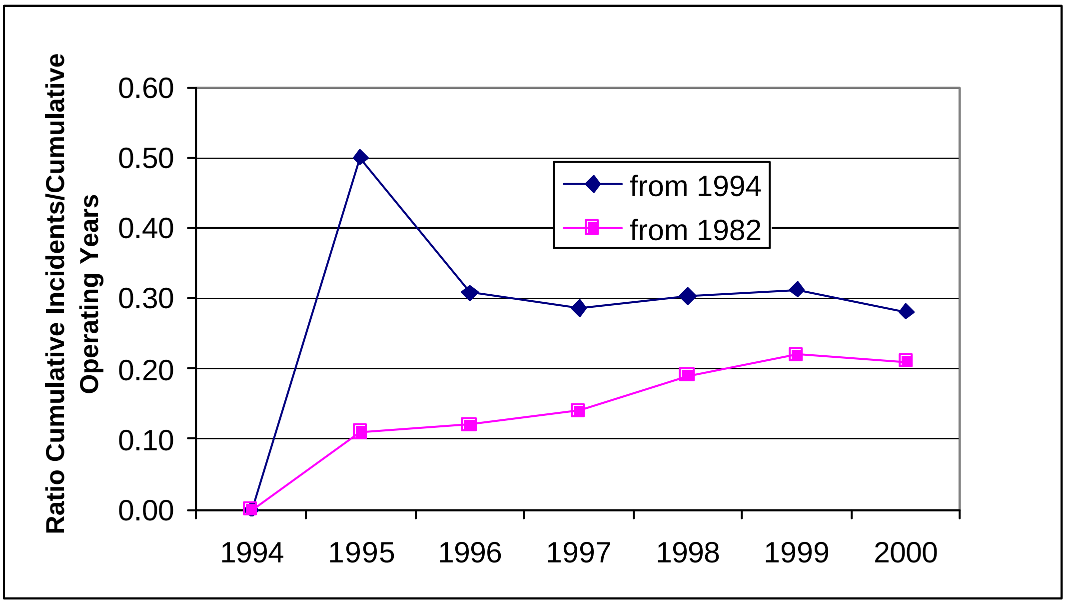


Figure 12 Statistics of Wave Incidents

FPSO/FSUs		VESSEL INCIDENTS					Freeboard Exceedence Matching Susceptibility Category	Operating Years
UKCS Installation No.	Norway (from Ref 7)	Incidents	Location: Bow	Location: Side	Location: Stern	Total Locations Affected		
1		1	1	1		2	**	3
	Norne	1		1		1	**	3
3		2	1	1		2	1	6
4		3	3	1	1	5	4	5
6		1	1	1	1	3	2	3
	Varg B	2	1	2	1	4	4	2
8		1	1			1	1	2
10		1		1		1	1	2
12		1	1			1	1	7
	Balder	2	1	2		3	3	1
	Asgard A	1		1		1	1	2
16		1	No 'GreenLab' Analysis			?		2
	Totals	17	10	11	3	24	18	38

Key (cell shading):
- High susceptibility
- Medium susceptibility
- Low susceptibility
- None / not known

** lower susceptibility predicted

Figure 13 Green Water Incidents (1995 - 2000) and 'GreenLab' Comparisons

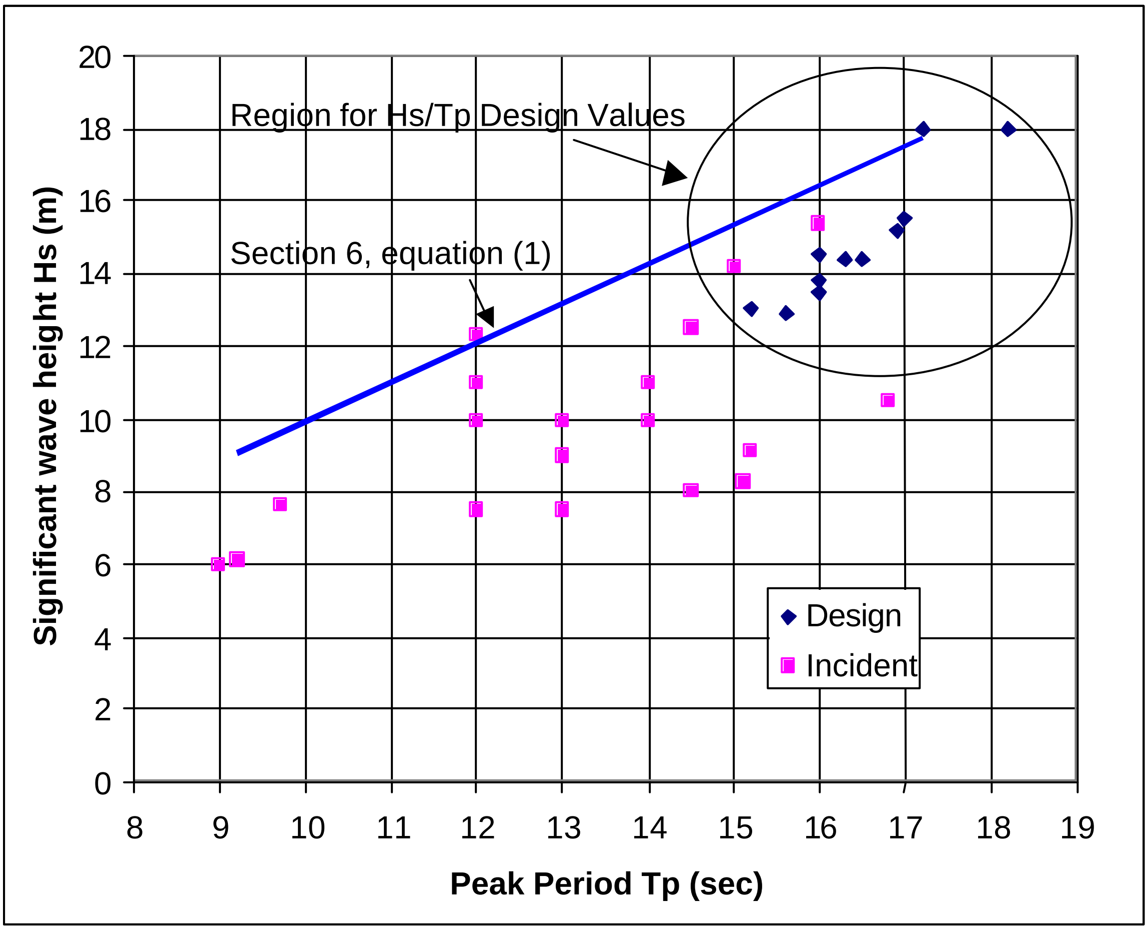


Figure 14 Scatter Plot of Wave Incidents and Hs-Tp Design Maxima

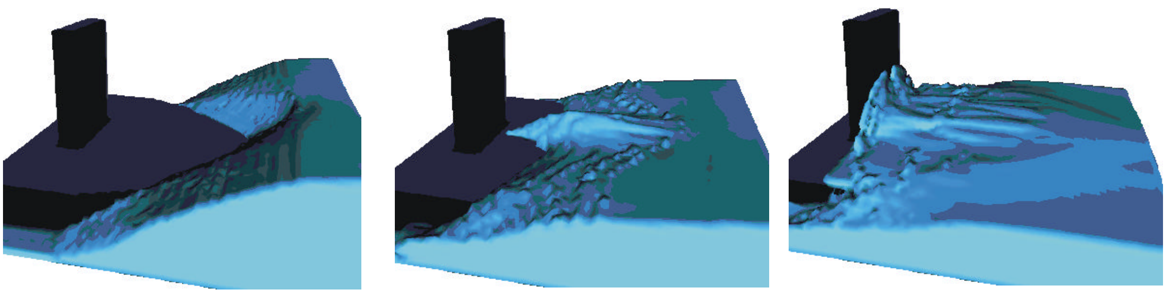


Figure 15 Green Water Flow Prediction with the Program 'ComFlo'

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