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Procedia Structural Integrity 48 (2023) 113–118

Structural Integrity
Procedia

www.elsevier.com/locate/procedia

Second International Symposium on Risk Analysis and Safety of Complex Structures and components (IRAS 2023)

Selection of Safety Level for Marine Structures

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Abstract

The selection of the safety level for design of marine structures being used in the ***oil and gas industry*** is made in view of the potential danger to personnel working on manned structures, the potential for huge negative effects on the environment in case of hydrocarbon spills and the large asset values involved. Unmanned structures could be designed for lower safety level, provided the environmental pollution be limited in case of failure. The design shall be in accordance with the International Standardization Organization's (ISO) 19900-series of standards for the Petroleum and natural gas industries. For marine structures in the offshore wind engineering business and for marine structures in the aquaculture business, lower safety levels are specified by international standards. The set of design requirements provided by the International Electrotechnical Commission (IEC); IEC 61400 ensure that wind turbines are appropriately engineered against damage from hazards within the planned lifetime. It should be noted, however, that wind farms will require transformer stations, which from time to time must be manned. These substations have a considerable volume of toxic transformer oil for cooling of the transformers and represent large investments. The safety level selected for the design of these substations will depend on the consequences of failure to or loss of the stations. For the marine fish farms, it should be noted that aquaculture nets contain a huge number of fishes that will mix with wild fish and destroy the genes of the wild fish population in case of massive escape of fish from the nets. The fish population needs to be fed every day and personnel must be available to ensure the operation of the fish farms. The selection of safety level is crucial to protect the personnel involved and the environment. Presently, the ISO standard ISO 16488 related to "Marine finfish farms - Open net cage" applies. This paper discusses the relevant safety factors for marine structures in the offshore wind industry and the aquaculture business and calls for awareness related to personnel safety, environmental pollution, and the potential for loss of costly assets, A reminder that the "new industries" must set sustainable goals should be in place.

Keywords: *Marine structures; safety level; 0il and gas industry; offshore wind; fish farms; personnel safety; environmental damage; loss ofassets.*

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10.1016/j.prostr.2023.07.117

1. Objective of the paper

The objective of the paper is to discuss the safety level in the new maritime industries; the offshore wind industry, and the offshore aquaculture industry. Reference is made to the safety level adapted in the oil and gas industry, an industry that is handling products which are highly flammable and explosive as well as representing threats to the marine environment while the industry is highly profitable.

The objective of the paper is, thus, to investigate whether the safety level should be improved for the new maritime industries:

- The wind industry is moving from shallow waters and bottom fixed turbine foundation structures to deeper waters, where new types of very costly floating structures will be installed with use of anchor systems. Furthermore, offshore substations with transformers contain not negligible volumes of toxic transformer oil, which, if spilled, will cause large damage to the environment.
- The aquaculture industry is moving into open seas to escape fish lice and to reduce the effects of the pollution from the excess food not consumed by the fishes and the manure from the living fish.

2. Introduction

2.1. The required safety level in the oil and gas industry

For the protection of personnel, the environment and the assets, international standards are setting requirements to the safety level for marine structures. The oil and gas industry is subject to strict safety regulations in view of the potential consequences caused by damage or failure (see, for example, ISO 19902, 2007 or ISO 19906, 2010).

The required reliability depends on the exposure level. For different life safety categories and consequence categories, the exposure level, L, is determined in the ISO documents in accordance with Table 1. Here, L1 is the highest exposure level, L2 is the intermediate exposure level and L3 represents the lowest exposure level. The reliability targets expressed as annual failure probabilities are given in Table 2. (ISO 19906, 2010).

Table 1. Determination of exposure levels L1 to L3 for consequence categories C1 (High), C2 (Medium) to C3 (Low).

	Consequence category		
Life Safety Category	**C1**	**C2**	**C3**
S1 Manned non-evacuated	L1	L1	L1
S2 Manned evacuated	L1	L2	L2
S3 Unmanned	L1	L2	L3

Table 2. Reliability targets for each exposure level

Exposure level	Reliability target expressed as annual failure probability
L1	$1,0 \times 10^{-5}$
L1	$1,0 \times 10^{-4}$
L1	$1,0 \times 10^{-3}$

Applying the method of limit states, the exposure level is defined for the no-damage ultimate limit state (ULS) and the abnormal limit state (ALS). Note that in the ALS condition, damage is expected, however, structural failure/ collapse shall not occur. The discussion related to determination of exposure level is very clearly stated in ISO 19902 (2007) or ISO 19906 (2010).

In the ULS no-damage condition, the design condition shall be the extreme-level events while the ALS design condition shall be the abnormal-level events. The extreme-level events shall be determined based on an annual probability of exceedance not greater than 10-2 (1%). For the ALS no-collapse limit state, the abnormal-level events shall be determined as follows:

- For L1 structures, the events shall be based on an annual probability of exceedance not greater than 10-4

- For L2 structures, the annual probability of exceedance shall not be greater than 10-3
- For L3 structures, abnormal-level events need not be considered.

It should be noted that the facilities exposed to an extreme-level ALS event shall not collapse and that the reliability targets as given in Table 2 ensure that collapse could be expected at one order of magnitude lower annual failure probability.

Furthermore, for events with extreme consequences (like iceberg impact events, see ISO 19906, 2010), the design events shall be chosen as:

- For L1 structures, the annual probability of occurrence of the ALS event shall be determined to be between 10-4 and 10-5
- For L2 structures, the probabilities shall be determined to be between 10-3 and 10-4.

This requirement is emphasized by Gudmestad (2019) for extreme consequence cases, also noting the extreme safety design requirements to nuclear power plants.

One should be reminded that the Arctic Standard (ISO 19906, 2010) incorporates the highest level of safety due to large consequences of failures; survivability in cold water and the effects on the cold climate environment due to pollution, related to possible release of hydrocarbons and the limited possibility to collect oil spills in open waters in the cold regions.

The selection of safety factors, i.e., the load factor (also denoted the partial action factor) and the material resistance factor are important when identifying the reliability level for the ULS design condition. The load factor to be applied on environmental loads for ULS design is 1.3 and the material resistance factor for steel is set as 1.15 in the oil and gas industry. For the ALS limit state, values of 1.0 are to be used.

2.2. Safety level in other Maritime Sectors.

According to International standards (IEC 61400-1, 2021), (see also DNV-GL 2020), wind turbines are required to be designed to resist without any damage (ULS condition) environmental loads with an annual probability of exceedance of 2%. This is equivalent to a 50-year return period. The safety factor for environmental loads is as for the offshore oil and gas standards. However, the material factor is set to 1.1 for steel, compared to 1.15 for the offshore oil and gas standards. There is no ALS requirement related to the physical environment.

MMI Engineering Inc. (2009) presents a discussion of the requirement of IEC 61400 (2007-edition) in view of the requirements of API RP2a WSD (2000). The API document is specifying the 100-year recurrence level for the load calculations. It is concluded by MMI Engineering that the safety factors applied to the load and material resistance are adjusted so the safety levels are comparable for these codes. It should be noted that API RP2a WSD (2000) does not apply a load and resistance factor approach and that the code is more than two decades old, The ALS limit state is, furthermore, not assessed. However, the comparison shows that it is possible to obtain the required safety level through the selection of recurrence period for the load or through the selection of the safety factors. Reference is also made to Stieng & Muskulus, 2020.

For fish farms, the annual probability of exceedance of the physical environmental conditions is set to 2% as for wind turbines (Standards Norway, 2021).

3. Discussion of safety levels

3.1. Wind farms

It should be noted that a wind turbine contains gear oil for lubrication (typically in the order of 300 l for large wind turbines) and transformer oil to cool the transformer (that is installed in the nacelle of the wind turbine) to boost the electric current so it can be sent to a central transformer station. Note in this respect, that the statistics of wind turbine failures show that many (onshore) wind turbines have failed over the years (Kavakli & Gudmestad, 2023). This happens regularly, the latest incident was reported on 11th May 2023 in Sweden (Ny Teknik, 2023). As the offshore wind turbines get older, we must expect failures of these as well. Note that the gear oil must be replaced at regular intervals.

At the central transformer station, the electricity is transformed from Alternating Current (AC) to Direct Current (DC) to reduce the energy loss in transporting the electricity to the marked. A typical 3,000 kVA (kilo volt-amps) transformer contains in the order of 1,500 l of transformer oil (Daelim Belefic). For the larger wind farms, very large transformers must be used. For a 100 MVA transformer (Daelim Transformer), the total weight of the oil is quoted to be 28.300 kg (30m^3). The amount of oil will represent a considerable pollution in case it is being spilled into the sea. Even though there is a drive to use nontoxic, biodegradable, and renewable lubricants for wind turbines, mineral oil is normally used.

Further to the wind turbines and the transformer station, it must be noted that a large wind farm may require a central living quarter to accommodate operation and maintenance personnel. Any accommodation unit must be designed to exposure Level L1, as in the oil and gas sector. The safety level for personnel must be the same in all offshore industries.

Regarding the exposure level for wind turbines and transformer stations, it is suggested that *individual wind turbines* be designed to exposure level L2, i.e., to Life safety category S3 (*unmanned*) and Consequence category C2. The main reason for suggesting consequence category C2 is that extreme weather might cause a situation of progressive collapse of several turbines in a wind farm so the total environmental damage cannot be considered very low. Of concern here is effects of breaking waves. Fixed wind turbines are located in shallows, often in shoaling waters where breaking waves will build up. In case of long fetch, the water level will also build up due to the storm surge and the waves may break, exposing the turbine foundations to large loads and large base moments. The actual design loads under these conditions are difficult to estimate because the loads from breaking loads are not well defined. Jose (2017) summarizes the state of art regarding knowledge about breaking waves and slamming wave loads.

For the *central transformer station*, often termed an offshore substation, it is suggested that the station be designed to exposure level L1 as the consequences to the clean environment is high (C1). The avoidance of pollution caused by the transformer oil necessitate larger investments in safety measures, although the life safety category is S3 (unmanned). Furthermore, the failure of the trans-former station will cause loss of the entire electricity production from the wind farm until a replacement is available. The potential economic loss cannot be dis-regarded.

It shall be noted that for exposure levels L1 and L2, the support structures shall be designed to the appropriate levels for no-collapse:

- For L1 structures, the ALS events shall be based on an annual probability of exceedance not greater than 10-4
- For L2 structures, the annual probability of exceedance or the ALS event shall not be greater than 10-3.

Economic analysis can also be carried out to identify whether the additional investments in selecting stricter design criteria are warranted. Using a net present value (NPV) approach, one can compare the economic benefits of the additional investments. Knowing that the expected discount rate in the wind industry is considerably lower than in the oil and gas industry, say 5% versus 15%, respectively, the long-term benefit of early investments could be documented. It could be expected, however, that the wind industry will oppose the suggested stricter design criteria. The industry has continuously repeated that the earnings from offshore wind turbines are marginal, dependent on state subsidies and that costs must be reduced.

By using transformer oils with limited environmental damage potential, a risk analysis could possibly document, using the ALARP principle (As Low as Reasonably Practical), that the environmental damage is limited. However, as the sizes of the wind turbines are growing and thus the investments made in each single wind turbine, economic indicators may confirm the need for the increased structural safety. Furthermore, when wind power is getting an important and substantial part of the energy supply of a country, long-term loss of wind power due to failures will become a concern for the national energy security.

It is potentially an idea to carry out a qualitative risk analysis to determine the safety level for an offshore substation (transformer station). DNV (2021) in Appendix A, Risk Management Concepts, outlines the risk concept. The key part of the qualitative risk analysis suggested by DNV is to set the risk criteria prior to the risk assessment (identification of the probability of failure and the consequences of failure). Thereafter the risk assessment is carried out for safety to personnel, for the clean environment and for the value of the asset., and, for the reputation of the company/ the owner. When the risk (the combination of probability of failure and consequence of failure) exceeds the value set prior to the assessment, mitigating measures must be in place, such as requiring limiting wave conditions for access, increasing the air gap for fixed structures to avoid wave in deck loads and taking properly into account the uncertainty in the breaking wave load by designing robust structures. The use of less toxic transformer oil used on the substations (transformer stations) should be given priority to limit environmental damage.

There is a need to maintain and repair offshore wind turbines regularly. Personnel transfer is done by transfer vessels and walk to work (WtoW)solutions. As wind turbines can be left idle until the weather is suitable for maintenance repair crew transfer, the criticality of the operation is low. However, the limited weather conditions for personnel transfer must be strictly adhered to. (Gudmestad &Viddal, 2022).

3.2. The aquaculture industry

For design of fish farms, at present the ISO standard ISO 16488 related to "Marine finfish farms - Open net cage" applies. With the needs to move large fish farms out in open water, to reduce effects of fish lace and to avoid pollution under the fish cages in fjord systems with limited exchange of water, the fish farms are becoming more susceptible to loads from waves and currents. A large fish farm consists of the cage housing thousands of fish specimens and a feeding barge that is normally manned but can be evacuated in case of storms coming up. In that case, the exposure level for the feeding barge is L2. The fish cage must be designed to exposure level L1 as the consequence category is C1 due to the environmental damage caused by the possible escape of thousands of fish. When farmed fish mingle with wild fish, the genes of the wild fish population are irreparably damaged. An environmental crime of this order should be regarded as belonging to the high consequence category C1. The resulting action is that the design of the anchor system of the fish cage should be to the required L1 level, a requirement that could be costly if the fish cage is placed at a harsh weather location.

In addition to the concerns raised regarding the design of the fish cage, the transfer of personnel to the feeding barge and onto the fish cage to provide maintenance, are critical operations. It should be noted that a fish farm cannot stay unmanned for long periods due to the needs for ensuring food to the fish. There is presently a request in Norway for improved safety culture in the aquaculture industry (T.U., 2022), following the recent death of a worker transiting from a vessel to a fish cage.

4. Summary and conclusions

In this paper a discussion of the safety levels for the design of structures in new maritime industries, the wind industry, and the aquaculture industry, is presented. In view of the probabilities for increased extreme environmental loads when moving facilities to deeper and more exposed waters, the increased size of the facilities compared to previous designs and thus, due to the larger consequences to the clean environment and the value of the assets, it is suggested to review the safety level philosophy incorporated by the oil and gas industry:

- Where personnel are involved in operations and maintenance, there should be no reason to allow for higher risks for personnel, related to the probability of situations that could escalate to consequences as severe injuries or fatalities.
- The larger transformer stations contain a considerable volume of toxic oil which has large pollution potential and the large fish farms contains a very large number of fish that potentially could escape.
- The larger wind turbines and the large offshore fish farms also require large investments, and the investors do demand that their investments are safe and secure.

As the wind industry and the aquaculture industry may hesitate to take the lead to ensure the suggested safety upgrading, the responsibility to update the standards are to be taken by national and international authorities.

This reminder that the "new industries" must set "sustainable goals", should be in place.

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