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Irregular Wave Generation and Assessment of Static Air Gap of Offshore Structures

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Abstract

The assignment of air gap is iterative and complex task in the design process of a new offshore structure. Negative air gap due to the reduction in design deck clearance above still water level can lead to severe wave-in-deck impact loads by abnormal waves. In this paper, risk matrix and fuzzy logic techniques are adopted in order to assess the risk level of deck impact events. Incident irregular waves of 50-year, 100-year and 10,000-year sea states were generated in towing tank. The time history of wave elevation measured at a point was used to perform hazard identification of wave crest(s) that exceed a selected still-water/static air gap. Risk parameters including frequency and severity indices were quantitatively identified and used for fuzzy logic model to estimate a fuzzy risk value.

Introduction

In the design of an offshore platform, lower decks are necessary to be located at a sufficient air gap, between the deck underside and the ocean surface, to avoid severe wave impacts. A minimum air gap of 1.5 m is required to provide a safety margin between the 100-year crest and the underside of the lowest deck of a platform [1, 2]. Nevertheless, numerous reports have been published over the past decade detailing damage of the deck structure of offshore platforms owing to wave impacts. It was found that such damage seems to occur more frequently than it can be predicted using theoretical techniques. The insufficient air gap has been reported to be one of the major reasons for many sustained damages in offshore structures, for instance, in the North Sea and in the Gulf of Mexico [5].

Air Gap Problem

Consider a fixed deck structure located above the sea level where the vertical distance between the bottom of the deck and the mean water level is called the still-water air gap, a_0. In the absence of waves, the air gap is equal to a_0. In the presence of waves, the instantaneous air gap, a(x,y,t), at a given horizontal location (x,y) is different from a_0 and can be defined by [3]:

$$\mathrm{a}(x,y,t) = a_0 - \eta(x,y,t) \tag{1}$$

where η(x,y,t) is the instantaneous surface elevation at (x,y). Deck impact occurs if $a(x,y,t) < 0$ (negative air gap). The surface elevation η(x,y,t) includes global upwelling due to diffraction of incoming waves with the structure. However, for fixed structures such as jacket or jack-up type of structure where the surface piercing elements have small horizontal dimensions, diffraction effects can usually be neglected and the free surface elevation taken as the incident wave ($\eta = \eta_I$) [3]. It can be appreciated that the problem of air gap involves many uncertainties, particularly, in wave elevation measurement at a location. Therefore, attention is focused here on η(x,y,t).

Tank Experiment

Model tests were conducted at the towing tank of AMC. The AMC towing tank is 100 m long and 3.55 m wide and is equipped with a hydraulically driven flap-type wavemaker. A diagram of the towing tank and the experimental setup is presented in Figure 1. The wavemaker is capable of generating monochromatic waves of both regular and irregular type. The area of interest, highlighted in Figure 1 by hidden lines 5 m × 2.55 m, was designed to be between 15 – 20 m away from the wavemaker. This allowed for sufficiently long run times without interference from reflected waves travelling back up the tank. The wave height was measured using six capacitance-type (Churchill Model) wave probes; denoted as WP in Figure 1, installed at different locations with respect to the wavemaker. The location of each wave probe is presented in Table 1, where the origin is located at the centreline of the tank and adjacent to the flap of the wavemaker.

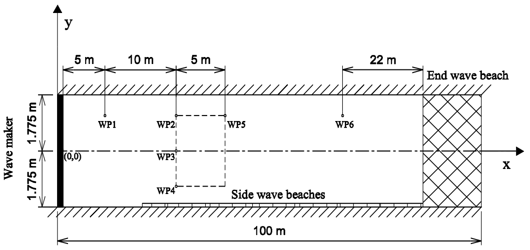

Figure 1. A plan view of AMC towing tank and locations of wave probes [not to scale].

Wave probe (WP)	Location (x,y), [m]
1	(5,1.275)
2	(15,1.275)
3	(15,0.0)
4	(15,-1.275)
5	(20,1.275)
6	(70,1.275)

Table 1. The coordinates of wave probes (WP) used in the experiment with respect to the wavemaker.

The tested sea states were modelled to a scale of 1:100 at a constant water depth of 1.5 m. Table 2 summarises the testing program designed for experimental setup. The average wave steepness S_p is equal to $\frac{2\pi}{g}\frac{H_s}{T_p^2}$, where g is acceleration due to gravity. The collected wave data consists of four realizations per each sea state. Each realization was acquired at 200 Hz for 175 sec; this gives a total time of 700 sec model scale (≈ 2 hours full scale). The JONSWAP spectrum was used to describe the characteristics of irregular waves with different significant wave heights and different peak periods. The parameter γ is chosen to be equal to 3.3.

Sea state	H_s (m)	T_p (s)	S_p
50-yr cyclonic	12.3	12.7	0.0488
100-yr cyclonic	14	14.5	0.0426
10,000-yr cyclonic	21	18	0.0415

Table 2. Wave conditions given at full-scale.

Up-scaling of Wave Measurements

According to Froude's law, the measured wave elevations were extrapolated to the full scale to find the minimum air gap at a point. Figure 2 shows time history of wave elevation of a single realization of 100-year sea state extracted from WP3. The emphasis of this paper focuses not only on the extreme value, but also on crests with less extreme heights that may violate the safe air gap requirements. Hence, the temporal information of wave elevation is employed throughout this investigation. As can be seen, there are only two crests exceeding the selected a_0 =12 m. However, there is another wave crest just misses this level at t ≈ 1200 sec; other wave crests have height enough to not satisfy the 1.5 m requirement. These observations reveal the amount of uncertainties when one wishes to assign the minimum air gap at a given point.

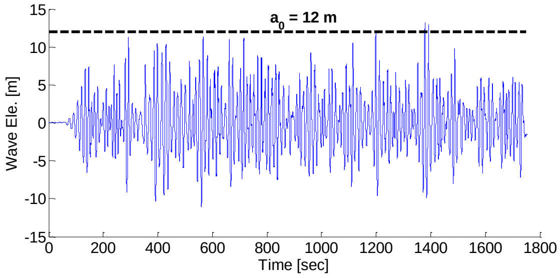

Figure 2: Time history of wave elevation by WP3 [100-yr: H_s = 14 m, T_p = 14.5 sec].

For every sea state, the time series is constructed by sampling the available realizations of the random wave train at WP3 location and extracting the extreme value. The minimum a(x,y,t) is equivalent to the maximum crest height which is the most severe event in terms of deck impact. The instantaneous air gap is calculated by equation (1), using the maximum crest height (extreme value observed within a 2-hour duration) associated with each sea state. Figure 3 shows the calculated minimum air gap at WP3 as a function of still-water air gap, a_0. The dash dotted line indicates the minimum air gap/safety margin of 1.5 m required by API and classification societies [1, 2]. There are many points located under the permissible/safe level. At the "zero air gap", when wave crest can reach the deck level, the deck structure is unlikely safe. However, based on the information provided by this graph no judgement can be made about the risk associated with the zero or negative air-gap. In other words, if the still-water air gap, a_0, results in a negative air gap, what is the overall risk of the expected wave-in-deck impact? To answer this question, a risk assessment should be performed.

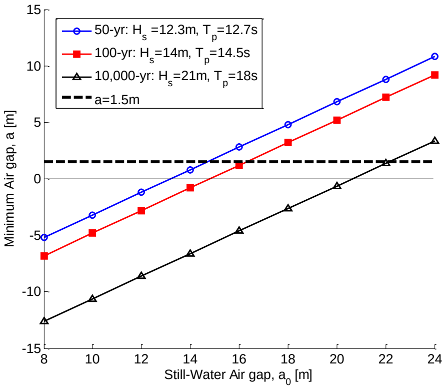

Figure 3. The minimum air gap corresponding to each sea state at different values of a_0.

The Assessment of Air Gap

The first step of the risk assessment process is to identify the possible hazards/events owing to the selection of still-water air gap, a_0. Due to the nature of risk uncertainties and its imprecise data, the frequency and severity levels were quantified based on the short-term statistics of wave elevation measured at a given point. The methodology is to break down the complex air gap problem into smaller simple problems in order to enable reliable analysis and decision making that takes into account the risk level. The proposed methodology is demonstrated on the collected wave data of 100-year sea state; however, the same procedure can be adopted for other sea states. The solution procedure/process of the proposed methodology is given as a flowchart (Figure 4). The procedure starts with a selection of a_0. In this work, a realistic a_0 ranging from 8 to 15 m is selected to represent a deck height at a given location (herein the wave probe location). The increment in a_0 is driven by many design parameters such as environmental criteria, payload, stability and etc. It is obvious that this value cannot be a unified/unique value due to the change in operating draft of an installation over its life time. Thus, in practice to satisfy the design requirements of the safe air gap, a_0 could be a range rather than a single value. The risk level imposed on the structure in turn becomes no longer constant over time. The instantaneous air gap, a(x,y,t) is then calculated based on the measured wave elevation at the same location. The hazard identification (HAZID) is performed such that severity and frequency can be identified based upon the acceptance criteria of the minimum air gap required by certification bodies [1, 2]. Eventually the aim is to calculate the fuzzy risk index (FRI) using fuzzy inference system and to evaluate the risk level of wave-in-deck events that a fixed deck of offshore structure may be subjected to. Table 3 through Table 5 summarise the HAZID information for the air gap problem. The frequency index (FI), the number of crests exceed a_0, is given as a function of the tested time span (700 sec model scale, 2-hour full scale). Neither FI nor SI can be precise due to limited information (short-term statistics), however, they are quantitative within the time frame tested in this study, 2-hour storm. The severity levels are in the range of 1 "negligible" up to 4 "severe" (Table 3). These numbers define the assumed quantitative scale of the impact severity [4]. When a(x,y,t) ≥ 1.5 m the consequence severity is assumed to be negligible. When a(x,y,t) becomes negative the severity index (SI) increases and in this work was obtained as a function of (a_0,a) using equation (2) such that SI is assigned as a fraction out of 4 based on the wave inundation level/impact height. For instance, SI = 3.25 when the ratio ≤ 0.19 and 4.0 when the ration ≥ 0.4, with 0.25 increment for every 10 % ratio. In the design, it may be possible to relate SI to potential extent of damage or cost of its rectification or even cost of the complete platform if the wave impact is expected to result in the total loss of the platform.

$$SI = f\left(\frac{|a|}{a_0}\right) \tag{2}$$

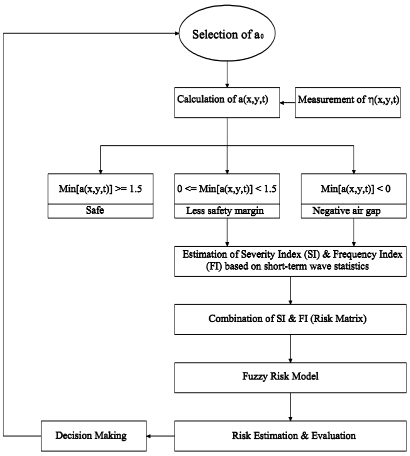

Figure 4. The proposed methodology and solution procedure for the minimum air gap problem.

Category	Definition	SI
Negligible	The deck level is complied with the requirement of the safety margin. [a ≥ 1.5] m.	1
Minor	The deck level is not complied with the requirement of the safety margin. Due to uncertainties, impact(s) with a minor severity are expected. [0.5 ≤ a < 1.5] m.	2
Major	The deck level is not complied with the requirement of the safety margin. The wave may reach the deck level causing a major impact. [0.0 ≤ a < 0.5] m.	3
Severe	The deck level results in negative air gap. The wave impact at this location could be severe based on the inundation level/impact height. [a < 0.0]	4

Table 3. Severity identification for 100-year sea state based on minimum air gap values.

Likelihood or probability of wave-in-deck impact describes the impact frequencies in a certain period of time (herein 2-hours). The frequency of crests that exceed each range of a_0 was obtained using equation (3) and employed as frequency index (FI) against each linguistic variable such as “frequent”, “probable”, “occasional”, “remote” and “improbable”, which are denoted by A to E (Table 5).

$$FI = \frac{n}{N} \tag{3}$$

where n is the number of crests that exceed a certain range of deck level in 100-year sea state (including all realizations), N = 539. Table 5 describes the range of the frequencies of the impact occurrence due to wave exceedance.

Realization	N	8:10	10:12	12:14	> 14 m
1	132	24	10	2	0
2	132	25	11	2	1
3	138	16	6	4	1
4	137	19	8	7	1
Total	539	84	35	15	3
FI	-	0.156	0.065	0.0278	0.0056

Table 4. Example of estimation of frequency index based on a_0 and WP3 time history.

Symbol	Category	Definition	FI
A	Frequent	It will occur frequently	> 0.156
B	Probable	It may occur several times	0.156
C	Occasional	It is likely to occur	0.065
D	Remote	It is unlikely to occur	0.0278
E	Improbable	It may not be experienced	0.0056

Table 5. Frequency identification for 100-year sea state with 539 wave crests in 2-hour duration.

The risk matrix combines frequency and severity into an output linguistic risk level for each scenario/selection of a_0. The present risk model used a 5 × 4 (Frequency × Severity) matrix as shown in Table 6. The risk level is categorised as “Low”, “Medium” or “High” denoted by L, M, and H, respectively [4].

		SEVERITY			
		1	2	3	4
FREQUENCY	A	M	H	H	H
	B	M	M	H	H
	C	L	M	M	H
	D	L	L	M	M
	E	L	L	L	L

Table 6. A risk matrix combines severity and frequency.

Fuzzy Logic Technique

A fuzzy logic system is fundamentally divided into three steps: fuzzification, inference and de-fuzzification [6]. For air gap problem, the fuzzy model has two inputs including severity and frequency indices given by Gaussian function which provides more flexibility to the user to handle their values obtained from short-term statistics. The membership function using Gaussian formula can be expressed as follows [6]:

$$f(x) = e^{\frac{-(x-c)^2}{2\sigma^2}} \tag{4}$$

where the nomenclatures c and σ are the mean and standard deviation, respectively and *f(x)* is the membership function of a variable x. The range of c and σ of each membership function are chosen based on the indices estimated above (Table 3 and Table 5) as shown in Figure 5 and Figure 6. For example, the linguistic variable “A or frequent” has a Gaussian membership function which is normally distributed on the value of the interval (0 – 1) corresponding to a mean value $c = 0.5$ (Figure 5). Having set the membership functions, the fuzzification takes a real time input value and compares it with the stored membership function information so that the fuzzy input values can be produced.

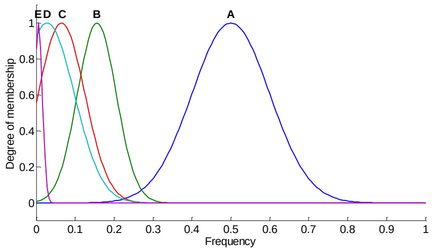

Figure 5. Fuzzy sets of frequency for 100-yr sea state.

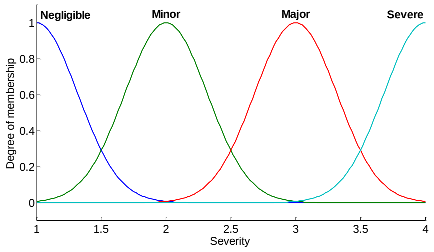

Figure 6. Fuzzy sets of severity for 100-yr sea state.

Fuzzy logic based systems use *rules* to represent the relationship between observations and actions. These rules consist of a precondition (*if*-part) and a consequence (*then*-part). The precondition can consist of multiple conditions linked together with *AND/OR* conjunctions. For example, in the risk matrix (Table 6) if frequency is “frequent” and severity is “severe” then risk is “high”. Thus, the risk matrix plays an important role in establishing the fuzzy risk model. The computation of fuzzy rules is called *fuzzy inference*. Sugenos’s fuzzy inference method was chosen for this work [6]. The final output of the system (fuzzy risk index) is the weighted average of all rule outputs and computed as:

$$\mathrm{FRI} = \frac{\sum_{i=1}^{N} w_i z_i}{\sum_{i=1}^{N} w_i} \qquad (5)$$

where N is the number of rules. The final output is the fuzzy risk value of an expected wave impact/hazard. The defuzzification step is used to convert the fuzzy output set to a crisp number. The *centred method* was employed in which the crisp value of the output variable is computed by finding the value of the centre of gravity of the membership function [6].

Fuzzy Risk Results

Figure 7 shows the overall risk value represented by FRI as a function of a_0 with increment of 0.5 m. The risk results were obtained using WP3 wave data. The risk level was found to be inversely proportional to the a_0, where a high risk value (14.4) at $a_0 = 8$ m and a low risk value (8.07) when $a_0 = 15$ m are obtained. The qualitative risk levels are also shown using three regions: “Low” form 0 – 5, “Medium” from 5 – 10 and “High” from 10 – 15. The computed FRI values are found to be consistent with the qualitative risk levels. However, the fuzzy logic approach provides more information about risk levels than the risk matrix technique. Figure 8 shows the FRI versus a_0 at different locations. It was found that the risk value obtained by WP2, WP3 and WP4 are almost identical. The difference in the maximum crest height was too small to change the FRI values across the tank. This reveals that the effects of the tank walls have negligible implications on the assigning the minimum air gap in this case. However, a deviation between WP5 and WP2/WP3 having the same FI values can be noticed. The reason is due to the difference in the maximum crest height measured at WP locations where it was 14.86 m at WP2, 14.8 at WP3 and 16.56 m at WP5 (full scale).

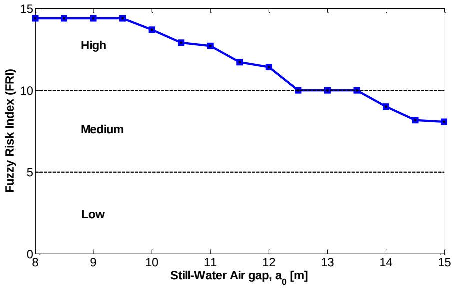

Figure 7. The expected risk value given by FRI at different values of a_0.

Conclusions

Hazard Identification (HAZID) technique has been adopted to identify some significant scenarios when a still-water air gap is selected in the early design stage of a new offshore structure. The use of fuzzy sets and a fuzzy inference engine was found to be suitable for handling imprecision often associated with deck impact probability and its severity. A fuzzy risk index was calculated as a function of the still-water air gap for 100-year sea state with multiple realizations.

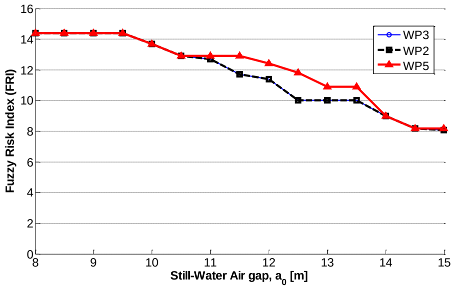

Figure 8. Effect of wave probe (WP) location on FRI value.

Acknowledgments

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References

[1] ABS, Floating Production Installations, American Bureau of Shipping, Houston, USA, 2013.

[2] API, Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms–Working Stress Design, *2A-WSD*, 2007.

[3] DNV, Recommended practice DNV-RP-C205: Environmental Conditions and Environmental Loads, Det Norske Veritas, Høvik, Norway, 2010.

[4] IMO, International Maritime Organisation: Guidelines for formal safety assessment (FSA) for use in the IMO rule-making process, IMO, London, UK, 2002.

[5] Kaiser, M.J., Yu, Y. & Jablonowski, C.J., Modeling Lost Production from Destroyed Platforms in the 2004–2005 Gulf of Mexico Hurricane Seasons, *Energy*, **34**(9), 2009, 1156-1171.

[6] Sivanandam, S., S. Sumathi, and S. Deepa, *Introduction to Fuzzy Logic Using MATLAB*. Vol. 1, Springer, 2007.