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Structural Responses of Offshore Jacket Platform Subject to Seismic Ground Acceleration and Wave Forces

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Abstract

In this paper, the effect of seismic ground acceleration on offshore platforms in the Malaysian waters has been investigated. In the Malaysian region of South China Sea, the conventional practice applied to design of offshore structures is to assume that forces induced on the platforms due to waves, current and wind control the overall response of the structures. Seismic analysis is not conducted since Malaysia is not located in a seismic-sensitive zone. Local standards have been lacking in recommendation to include seismic ground motion in the design. However, recent earthquake events from far-field have been felt by the platform operators in Malaysian waters and new perceptions in the field question the validity of this assumption. A series of computer-driven dynamic spectral earthquake analyses has been carried out for a jacket-type fixed offshore platform using the finite element software SACS. By incrementally changing the inputs for ground acceleration, the dynamic behavior of the 3D model of the platform is investigated. The result defines the threshold, at which the ground motion induced forces control the structure. Further, a combined analysis of both seismic and wave forces have been carried out, as to define how the two different types of forces contribute to the resulting stresses and deflection of structural members respectively.

Keywords: *Seismic, offshore structures, South China Sea*

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INTRODUCTION

In the past years, severely damaging earthquakes have proven the great impact forces, induced by the ground acceleration, on structures. The selected platform is located in Sarawak, in the eastern territories of Malaysia. Although no Malaysian regions, neither onshore nor offshore, can be defined as seismically active, platform operators have felt impacts from far-field earthquakes (Sumatra Subduction Zone and Sumatra fault). Short-period compression waves triggered from earthquakes in these regions travel far underground. Rigid structures, such as the conventional jacket-type platform, are especially vulnerable to these types of waves due to dynamic amplification. However, lack of data on seismic activity for the South China Sea makes it hard to evaluate the risk of earthquakes.

A collapse of an offshore oil production structure would be a major environmental hazard and has to be prevented at all costs. Hence, to ensure structural integrity, it is important to check which criteria control the design. For offshore structures in the South China Sea, there are three important standards defining the design criteria for the region The PETRONAS Technical Standard (PTS, 34.19.10.30, 2010, Revision No.6), the Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms – Working Stress (API, API Recommended Practice 2A-WSD, twenty-first edition, 2000, Errata and Supplement 3, October 2007) and a series of ISO standards (e.g., ISO 19902:2007, ISO 19901-02:2004). In Malaysian regions of the South Asian Sea, seismic design is mostly neglected. This is due to the fact that the PTS for offshore projects in this area does not include any recommendation on seismic design. So far, this was justified by assuming that wave, current and wind forces control the design of structures. Recent research justifies questioning the assumption that seismic criteria can be neglected completely in the design of offshore platforms. One research states that ocean waves do not always act as a damping medium for seismic loads as was assumed so far. Non-collinear seismic and ocean waves acting simultaneously are anticipated to result in larger displacements and induced stresses on the jacket as compared to collinear excitation, as will be addressed in this study. In addition, a seismic hazard study for offshore Sabah, Sarawak and West Malaysia carried out by an Italian consultancy reported values that describe the seismic activity and return period for seismic activities. These values update and exceed the so far utilized values from ISO or GSHAP (Global Seismic Hazard Assessment Program).

This study addresses the following objectives:

- Ascertaining threshold on controlling ground acceleration versus wave forces by conducting computer-driven static wave analyses and dynamic spectral earthquake analyses.
- Study on combined effects of ground acceleration with wave forces using computer-driven static analyses.
- Determining the integrity of the platform subject to seismic loads using values recommended by 'D'Applonia Report' and Gumbel's Extreme Value Distribution.

BACKGROUND STUDY

Seismicity

Seismicity is the field that deals with the movements of the tectonic plates. Normally these movements are not perceptible, but under special conditions the earth's tremors are so strong that they are not only perceptible but can have devastating impacts. These events are called earthquakes and can never be predicted with absolute certainty. Malaysia is located on a stable part of the Eurasian-Sunda Plate which means there are no real earthquake events in Malaysia. However, Malaysia is affected by far-field earthquakes originating for instance in the Sumatra Subduction Zone or the Sumatra fault [1]. These earthquakes accelerate the ground and instill motion into it. Waves travel through the ground, similar to the effect seen if you drop a pebble into the water. Due to the geological conditions, low period compression waves travel all the distance to Malaysia. There they hit the structure which responds by vibrating. The amplitude and period of the waves encountered are especially influenced by the distance to the hypocenter, the magnitude of the total released energy and the geological conditions at the site [2].

For offshore Malaysia, there are different recommendations on the experienced ground acceleration. The most recent research carried out by an Italian consultancy found values that exceed the values recommended by notable bodies like ISO or GSHAP (Global Seismic Hazard Assessment Programme). The established values shall be a foundation for seismic design criteria by defining earthquake events according to ground acceleration and the corresponding return period [3, 4].

Standards and Regulations

Currently, there are three major standards and regulations being applied for Malaysian waters: The PETRONAS Technical Standard 34.19.10.30, Revision No.6 (PTS), the Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms – Working Stress API, 2A-WSD, twenty-first edition, 2000, Errata and Supplement 3, October 2007 (API) and lastly ISO 19902:2007 (E) [3, 5–7].

PTS does not include any recommendation for seismic criteria. API and ISO 19902 have similar recommendation to design in two steps. First, proofing the ultimate limit state (ULS) is designed for a strength-level earthquake (SLE-API) which has 100 to 200 year return period. Second is on reserve strength and energy dissipation which has to be designed for a ductility level earthquake (DLE-API) with 1000 to 5000 year return period [5, 6].

Forces and Responses due to Ground Motion

The predominant forces induced into the structure by ground motion are horizontal; they are called lateral forces. The vertical forces induced by the earth's tremors are mostly negligible as the structure's self-weight counteracts them. The total magnitude is derived from Newton's second law, as the weight of the structure is accelerated. The direction of the lateral forces is difficult to predict, which is why the seismic design criteria require to apply them from different directions; if need be they can be split into perpendicular acting portions. These forces are distributed over the whole height of the structure. Simplified, the distribution can be described as triangularly shaped, having its biggest value at the top and a value of zero at the bottom. However, with the help of design codes such as UBC-91, a more accurate distribution can be derived. The recommended computations take the total base shear, the mass concentration and the heights to the respective floors of the structure into consideration. It is well known that the two central aspects that affect the structure's response are its fundamental period and shape [8–11].

There are several methods to calculate the responses induced on a structure due to ground motion: the linear elastic dynamic analysis using elastic modal response spectrum or numerical integration and the non-linear inelastic response time history dynamic analysis. In this research, the linear dynamic analysis with elastic modal response spectrum is utilized. It is suitable as it can be assumed that the platform responds predominantly in its first mode, idealized like a cantilever [12].

MODELLING METHODOLOGY

Ascertaining Threshold

To ascertain the threshold ground acceleration where the seismic forces would control the design over waves, it is necessary to first define the responses. Thus, the integrated finite element suit SACS 5.3 that is used for all analyses in this research is utilized to run a static analysis with non-linear pile/structure interaction (PSI). The only metocean criteria applied are wave forces; wind and current are neglected, as wave is assumed to be the controlling force. The PSI is used as it simulates more accurate support conditions so that the responses are closer to the actual ones. All types of analyses in this research are done in eight directions, every 45°. Thereby the worst responses can be found. Figure 1 show cases the design of the methodology used in this study. To ascertain the threshold ground acceleration, an incremental dynamic base driven spectral earthquake analysis is performed, also in all eight directions. This type of analysis uses the elastic modal response spectrum.

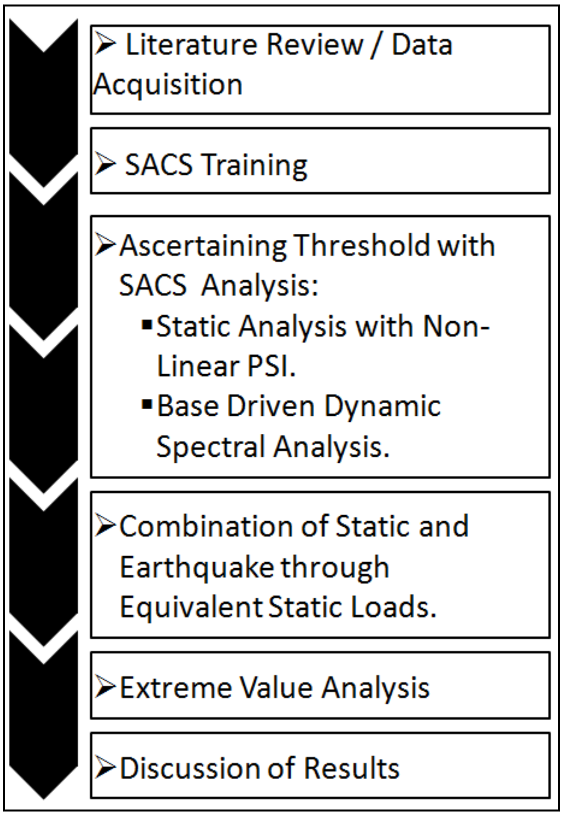

Fig. 1: *Methodology Flow Chart.*

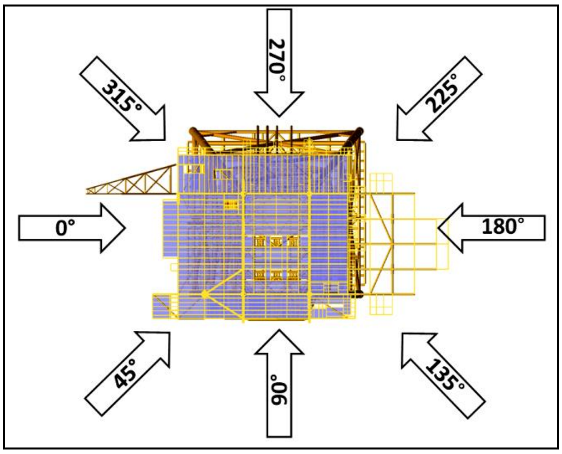

Fig. 2: *Loading Directions.*

The analysis in SACS requires four input files: the modal input file, the dynamic mode shape file, the dynamic mass file and the spectral input file. Information on modal damping (3%) [13], fluid damping (neglected), soil type (API type C) and spectral ground acceleration (in factors of g differs for every incremental step) have to be factored into the analysis. The only values that differ in the steps are the ones for ground acceleration which is incremented from 0.02 to 0.18 g. Figure 2 show cases various loading directionality employed in this analysis.

Combined Analyses

The next part of the research is on the effects of combining wave and earthquake forces. The static PSI analysis is again utilized. The wave forces are applied similarly as in the analyses before. However, for the seismic forces static equivalent values have to be computed. UBC-91 recommendations are employed to determine the equivalent static loading. The base shear input for the UBC-91 computations are obtained from the SACS generated base shear results from the dynamic earthquake analysis. The predominant directions (45°/225°) are taken into consideration in this step. It should be noted that both directions induce equal and opposite base shears. The equations UBC-91 recommends are as displayed in Eqs. (1) thru (3) [14]. For simplicity, the forces are only computed for three sections of the structure, which is anticipated to yield sufficiently accurate results.

These forces are applied at the diaphragms, as these structural elements are strongest in resisting the lateral forces [8–10]. Thus, the seismic forces will be concentrated there. Furthermore, the forces are assumed to be lumped on one joint per diaphragm. This is another simplification that will distort the results to some extent and is considered in the discussion of the results.

There are two stages to this analysis: the forces due to the recommended 475 return earthquake event (SLE according to API) are used to represent the ULS check; the forces due to the recommended 2475 return earthquake event (DLE according to API) are used to represent the reserve strength check. The responses are compared to the actual design criteria (operating metocean, storm).

$$F_{px} = \frac{F_t + \sum_{i=x}^{N} F_i}{\sum_{i=x}^{N} W_i} * W_{px} \quad (1)$$

$$F_t = 0.07 * T * V \quad (2)$$

$$F_x = (V - F_t) * \frac{W_x h_x}{\sum_{i=1}^{N} W_i h_i} \quad (3)$$

where,
x = level from base
N = total number of floors
Fpx = forces at diaphragm
V = total base shear
hx = height to level x from base
Wx = weight at level from top
Wpx = weight of diaphragm and attached parts of the structure

Determining Return Periods

By utilizing Gumbel's extreme value distribution and plotting position a function is found that can correlate ground accelerations to their respective return period. The function is based on the values recommended by D'Appolonia. Drawing a best fit logarithmical graph through the D'Appolonia recommended values Microsoft Excel provides the function.

With the help of the function, the return period to the threshold acceleration can be determined and thereby the integrity is evaluated [11]. Figure 3 illustrates the three-point qualitative earthquake load distribution on the platform.

DISCUSSION AND RESULTS

Finite Element Analyses

The lateral forces due to seismic acceleration, different to those induced by waves, are distributed over the whole height of the structure. Thus, the stresses induced into the structural elements are not as concentrated as those induced due to waves; those act very focused close to the water level. Furthermore, the biggest part of the forces acts on the topside, as the forces increase with height and mass concentration. For the purpose of this study, the effects of the excitations are represented by displacements of the jacket. The displacement induced into a structure is caused by its internal forces or stresses. The internal forces are the fractions of the external forces that are applied on the respective member itself. By knowing these internal forces, we can define the unity check which shows, how much of its capacity is used. By the use of incremental steps, the author defines the threshold to be at a ground acceleration of 0.180 g. It is a value that, if corresponding to a 1000 year return period, can be defined as moderate [15].

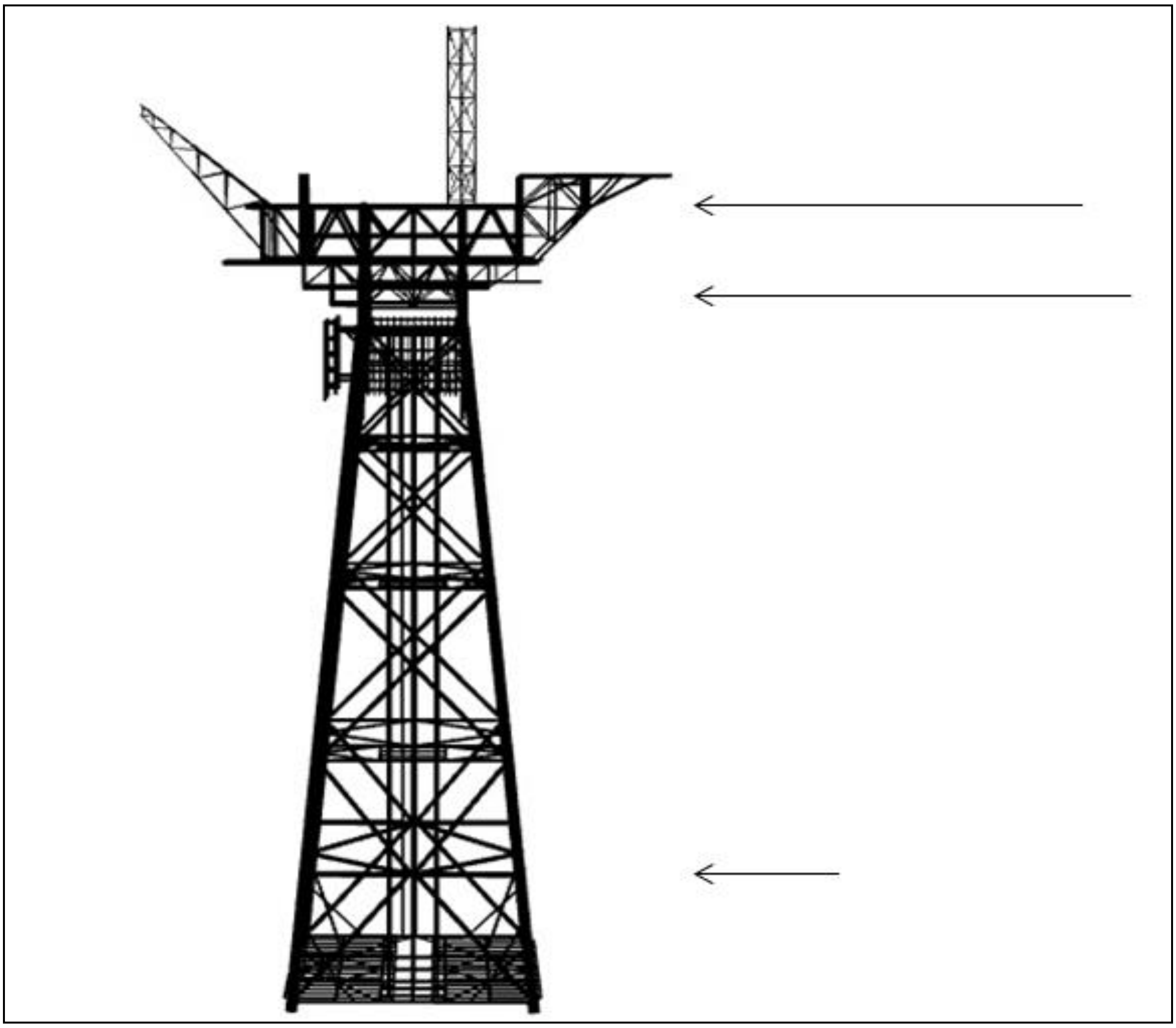

Fig. 3: *Qualitative Earthquake Load Distribution.*

As rigid structures, such as jacket-type platforms, are prone to damage due to the earthquake waves, the platform may suffer damage under such moderate ground accelerations. Malaysia, however, is located in a seismically stable region of the Sunda Plate. Hence, such ground acceleration should not be experienced in a very long time. Figure 4 illustrates the determination of threshold acceleration.

Combined Effects of Seismic and Waves

It was found that the platform can withstand the ultimate limit state (ULS) check as required by ISO standards. The displacements and forces of a combination of seismic at a 475-year return earthquake event and operating wave is far below the responses due to storm criteria. The structure can withstand the loading without taking damage. The extreme earthquake event required by API corresponds only to a return period of 100 years. Thus the responses at an extreme earthquake event are even lower. Hence, the initial assumption that waves are the controlling force has been somewhat verified. The displacement induced to the structure at this ground acceleration creates, in the worst case scenario (225°), only 28% (Figure 2) more of what the wave forces creates alone.

In the next check for ductility and reserve strength the structure may already suffer damage. However, the maximal displacements the structure suffers at this level if combined with operating wave forces exceeds the value of storm metocean criteria only by 1.7 cm (Table 1). So the responses are rather similar.

Figure 5 illustrates a critical comparison between standalone met ocean and combined metocean-seismic loading.

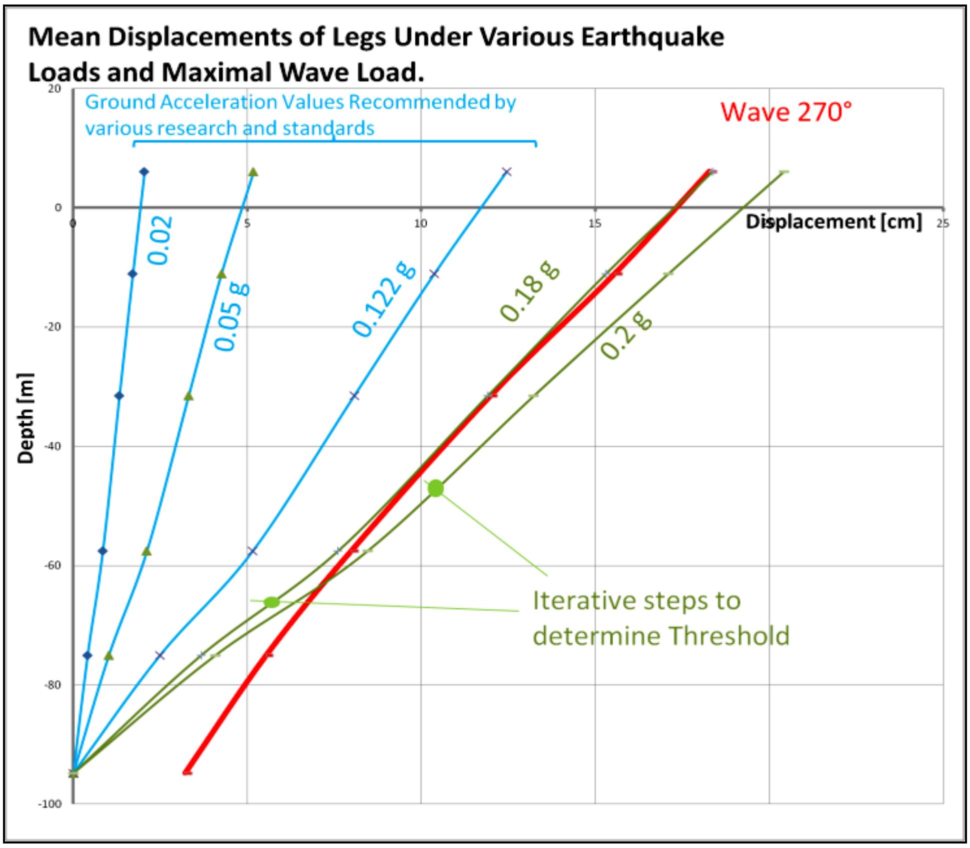

Fig. 4: *Threshold Acceleration.*

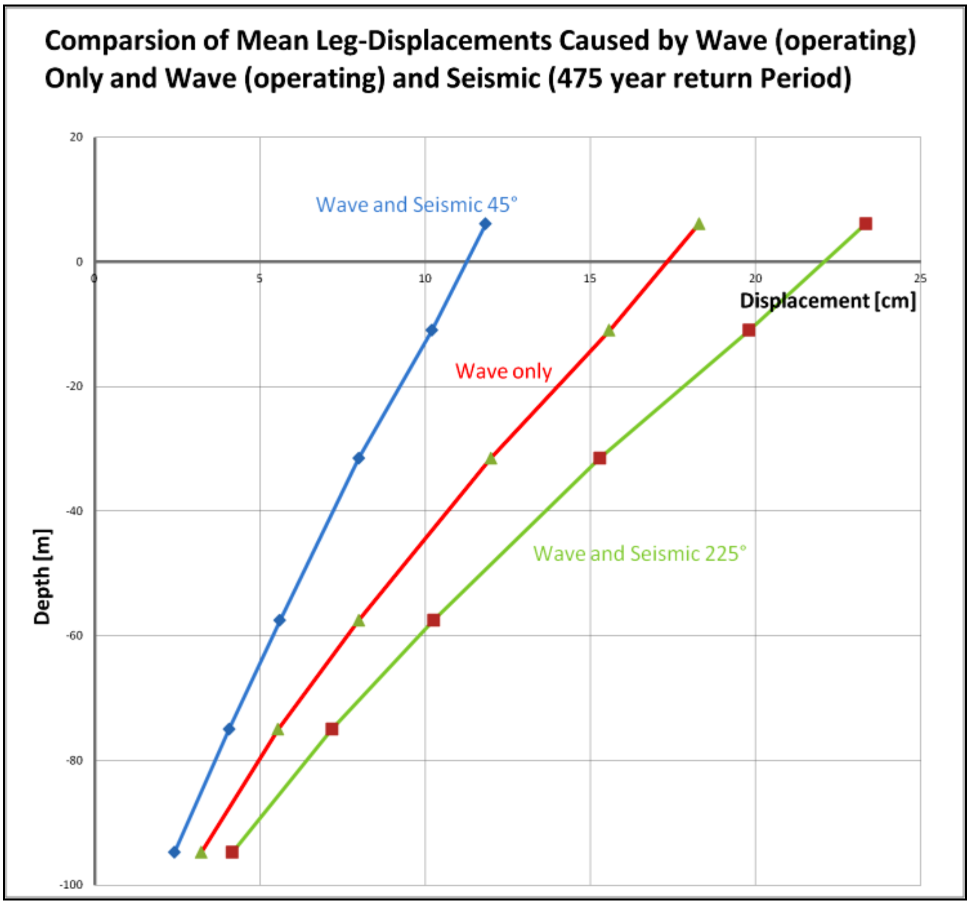

Fig. 5: *Comparison Combined Effect to Wave Only.*

Reviewing the unity check of important structural members subject to this load shows that the structure is still safe. Although the UC exceeds the maximal value of 1.0 in four cases, two can be justified by the fact that the simplification used for earthquake loading concentrates the equivalent static loads onto joints and these two members are in direct adjacency to these loads. The other two are also close to this concentrated load and are under compression, thus, it is possible that they suffer damage. Table 1 show cases the maximum recorded mean leg displacement when the platform is subjected to the various conditions stipulated in the table. However, the UC values for these members only exceed the limit of 1.0 by 0.022 and 0.052 (2 to 5%). But as some damage is allowed under the ductility level earthquake, as long as the reserve strength prevents a collapse, it is safe to assume, that the structure, after all, is safe.

Determining Return Periods

The threshold acceleration, however, exceeds API's recommendation to carry out the check on ductility requirements. Thus the threshold acceleration corresponds to an earthquake which probability is so low, that the design recommendations do not even have provisions to take it into consideration. Figure 6 show cases the return period plot.

Table 1: *Comparison of Responses.*

Condition	Max. force		Max. mean leg displacement	
	LC Dir	[kN]	LC Dir	[cm]
Operating wave only	0°	4557	270°	18.3
Operating metocean	0°	6438	270°	23.2
Combined ULS	45°	6741	270°	23.3
Storm metocean	0°	9761	270°	30.0
Combined ductility	45°	10416	270°	31.7
Combined threshold	45°	13339	270°	42.6

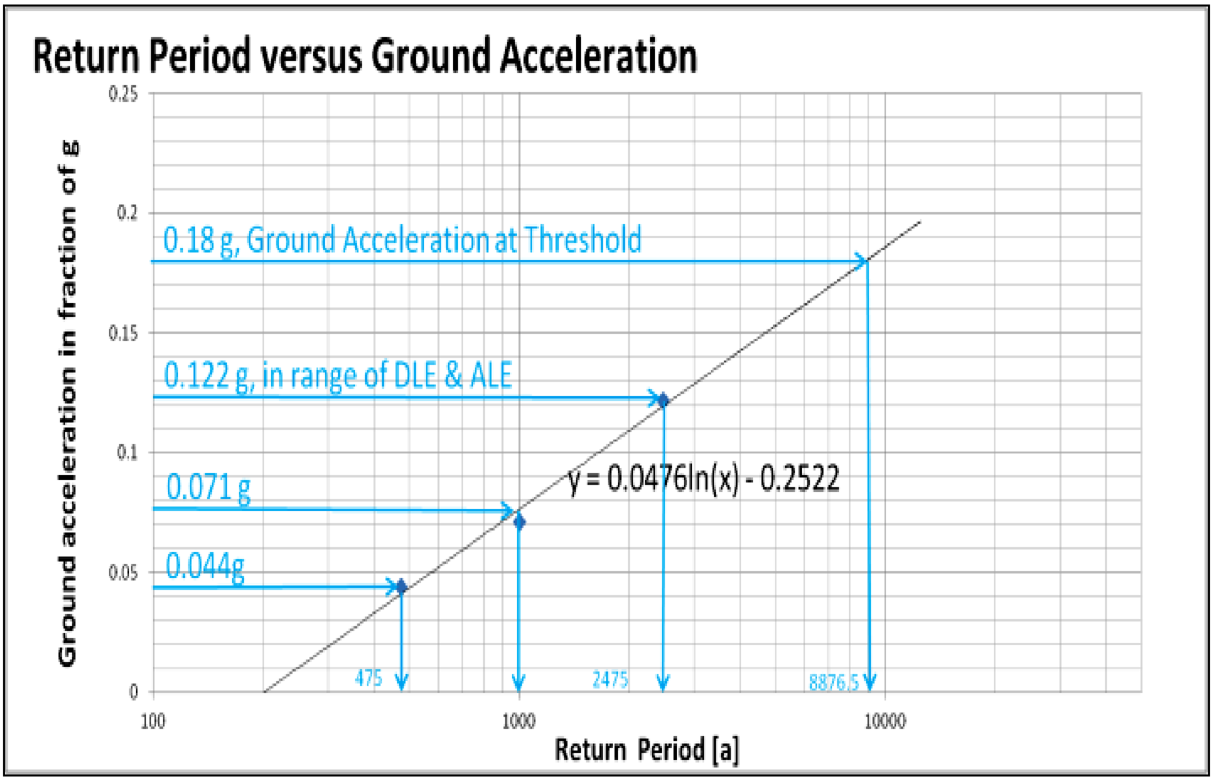

Fig.6: *Plotting Position for Return Period.*

SUMMARY AND CONCLUSIONS

A series of computer-driven dynamic spectral earthquake analyses have been carried out for a jacket-type fixed offshore platform using the finite element software SACS. By incrementally changing the inputs for ground acceleration, the dynamic behavior of the 3D model of the platform is investigated. Several outcomes can be concluded from this study. They are summarized below.

- The threshold at which seismic starts to control the design is at a ground acceleration of 0.180 g; the wave forces are exceeded prior.
- The biggest forces the structure experiences act in 0° direction (metocean) or 45° direction (wave + seismic); due to differences in stiffness, the maximal responses in terms of displacements are always encountered when the forces act in 270° direction.
- The Platform does not suffer damage under the strength level earthquake (SLE) or ductility level earthquake (DLE) even when combined with the operating wave forces.
- The threshold (0.180 g) at which seismic controls corresponds to an earthquake event of 8877 years return period; a value exceeding API's definition for ductility level earthquake (1000–5000 years).

This study essentially proves that the assumption of wave forces controlling the structural responses is fundamentally correct for low-seismic regions such as Malaysia. However, due to the unstudied extensive nature of the Malaysian basin, the results of this case study should not be generalized for all of Malaysia but when combined with more, similar research covering different parts of the Malaysian basin, it can be a foundation for new design criteria. By performing similar studies on other platforms, a data base of platform responses can be created.

This empirical foundation can provide recommendation, under which condition seismic criteria have to be included in the design.

This will ensure that future offshore structures in Malaysian waters can be designed more accurately and with greater optimization.

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