南海环境和深水平台

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摘要：

环境和响应是海洋平台设计的两个重要因素。根据西北太平洋和我国南海60年资料进行统计分析，表明在气候变化的背景下，台风和强台风发生的频次增加；以PDI指数为表征的热带气旋的强度很可能在缓慢增加。因此，非平稳过程对若干年一遇的极值风速参数的影响不可忽视。给出了南海内波频发的时间、海域和流场特征，表明潮流和南海复杂地形相互作用，是在南海北部产生孤立子群的物理原因。深水平台动力学特性和概念设计方面，给出了质量配置对半潜式平台动力响应影响的计算公式，与WAMIT计算结果一致，为实现深水平台选型和设计优化提供了理论和方法。

关键词：

流体力学 热带气旋 内波 深水平台 半潜式平台 气候变化 非平稳过程

1 引言

为满足日益增长的能源需求，海洋开发受到国内外工程界的重视。我国南海油气资源丰富，经过30多年的努力，我国海洋工程关注的重点正由300米的浅海走向3000米的深水，拟自主创新地设计深水平台。但深水平台是否安全，依赖于对环境参数的确定，其中热带气旋和海洋内波是南海环境中需要特别考虑的两个重要因素。同时，深水平台的概念设计及其优化依赖于我们对各种平台动力响应的认识。本文主要讨论南海特殊环境和平台响应的研究进展。

2007年IPCC评估报告[1]肯定了气候变化及其影响程度。以往的海洋平台设计中，极值参数的估计往往忽视了气候变化的非平衡过程的影响。为此，有必要对西北太平洋和南海台风发生频率和强度变化的趋势进行分析。根据西北太平洋和我国南海60年资料进行统计分析，表明在气候变化的背景下，台风和强台风发生的频次增加；以PDI指数为表征的热带气旋的强度很可能在缓慢增加，并导致风载和波浪载荷的相应增加。因此，非平稳过程对若干年一遇的极值风速参数的影响不可忽视，并应在设计规范中予以考虑。中国南海海域广泛存在内波活动，它们对海洋平台的安全有严重威胁[2,3,4]。本文分析了南海内孤立波产生的物理机制，发生规律和内波特征参数，这是计算海洋平台内波载荷的前提。在设计深水平台（如：半潜式平台，FPSO等）时，以往都是完全依靠软件分析动力响应。我们发现，在排水量给定的条件下，立柱和浮筒的质量配置对平台的动力响应（如：垂荡）有重要影响，我们给出了理论公式，与WAMIT计算结果一致，表明在给定平台排水量的情况下，质量配置因子Φ增大，平台固有周期增大，垂荡RAO幅值相应减小。这一规律的认识为平台概念设计和结构优化提供了理论和方法。

2 南海特殊环境——热带气旋和海洋内波

2.1 热带气旋频次及强度变化

热带气旋是发生在热带海洋上的强烈天气系统。当其最大风速大于32.7m/s和41.3m/s时，分别称为台风和强台风。本文根据收集到的1945～2007年经过西北太平洋的热带气旋数据，分别对西北太平洋和南海地区共63年台风，强台风的频次和强度变化规律进行了统计分析。

根据统计，西北太平洋年平均发生13.6个台风和9个强台风，从20世纪50年代到20世纪末，台风和强台风的频次明显增加。若把63年的数据段分为1945-1977、1978-2007年两段，可得台风由每年平均发生11.5个上升到16个，强台风由7个上升到11个，台风和强台风在30年间发生的个数分别增加了39%和57%。对于南海地区平均每年发生4.3个台风和2.4个强台风。由于南海地区相对于广阔的西北太平洋来说是小样本，所以其频次变化波动性较强，但仍表现出了缓慢的增长趋势。若像西北太平洋

地区一样把数据分成两段对发生频次求平均值，可得台风由平均每年 4 个上升到 5 个，强台风由 2.4 个上升到 3 个。台风和强台风在 30 年间发生的个数都增加了 25% 左右。

至于热带气旋强度的变化。Kerry Emanuel[5]认为用其最大风速及持续时间表征其强度不一定是最合适的。因此，定义热带气旋的总能量耗散系数 PDI：

这里 V_{max} 是热带气旋的最大风速，为热带气旋从发生到消亡的持续时间。本文利用已有的数据，用

$$PDI = \int_0^{\tau} V_{\max}^3 dt \tag{1}$$

每个热带气旋每隔 6 小时的最大风速值的立方对时间积分，得到每个热带气旋的能量耗散系数，再将每年所有热带气旋的 PDI 相加，作为这一年的总热带气旋能量耗散系数来表征该年热带气旋的强度，分别计算了西北太平洋（图 1）和南海（图 2）地区的 PDI。如图 1 所示，从 20 世纪 70 年代起西北太平洋的 PDI 明显增强，到 20 世纪末的 PDI 值为 20 世纪 70 年代的两倍左右。图 2 显示南海地区的 PDI 在波动过程中的缓慢上升趋势，从 20 世纪 70 年代到 20 世纪末上升了约 1.3 倍。

2.2 南海内波特征

南海的潮流分布和复杂地形是决定南海内波状况的两个关键因素。内潮被认为是南海内孤立波生成的主要驱动机制，内潮波在传播过程中受到地形等各种环境因素影响发生变形，并最终分裂成孤立子群。根据南海地形，东部菲律宾以北，台湾岛以南，有巴士、巴林唐和巴布延海峡，那里的海底有一高耸的海脊。我们通过数值模拟结果表明，当潮汐发生往复运动时，确实可以在此海域产生内波和孤立波群，并向南海北部传播，其主要参数与实际观测一致[6]。

鉴于内波流场是对海洋结构物作用的关键环境要素，而对其研究相对较薄弱。因此，开展对内波流场特性分析很有必要。结合目前中国南海内波观测资料和一些数值模拟结果表明[6,7,8]，南海内波及其波致流场具有下列特征：

（1）南海北部区域是内波的高发区，其发源地在吕宋海峡中巴坦岛、富加岛和巴布延岛附近；通常以孤立内波的形式出现，东沙岛附近海域内波出现最频繁，且传播方向以西向为主；由于夏季海洋层化明显，以 4~9 月为高峰期，1~3 月和 11~12 月为低峰期，在每个月里以 16~19 日为高峰期，与潮流在该时期较强烈有关。

（2）南海内孤立波振幅一般在几十米甚至上百米量级，最大振幅 170m，波致流达 2.5m/s 的内波在南海也已经被观测到[9]。数值模拟发现[6]，东沙岛以东海域，内波波幅可达 100m 以上，东沙岛以西则一般衰减为 70m 量级，大致符合观测事实。

（3）内波诱导的流场的水平速度沿水深分布几乎均匀，但在跃层上下速度存在剪切。因此，海洋内波的作用最终表现为带有剪切的流速分布，并对平台产生整体推移或扭转，可能导致平台破坏。

3 质量配置对半潜式平台动力学特性的影响

半潜式平台已发展到第六代，作业于超深水海域，其型式也趋于简洁化，大体上有四柱、六柱或八柱式；单浮箱或双浮箱式。不同平台结构形式在波浪中的运动性能不同，垂荡运动振幅传递函数（RAO）是衡量深海半潜式钻井平台优劣的关键水动力性能指标，它们主要由平台的作业环境、船型、主尺度所决定。根据给定深水平台总排水量的原则，对半潜式平台的立柱和浮筒形式，尤其是质量配置进行设计，使平台的水动力性能得到优化。

3.1 问题描述和控制方程

本文在选择半潜式平台结构形式和主尺度时，采用圆形截面立柱，浮筒两端为半圆（直径与浮筒宽相同）。其简化模型和选用坐标系如图 3-4 所示。

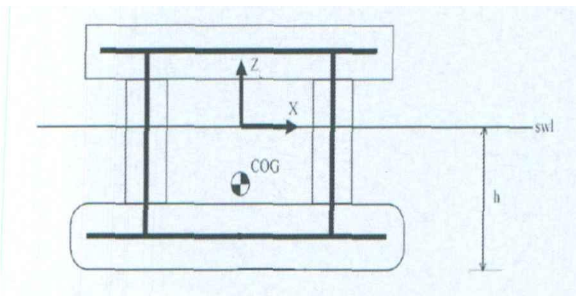

图 3 半潜式平台的简化模型及其坐标系

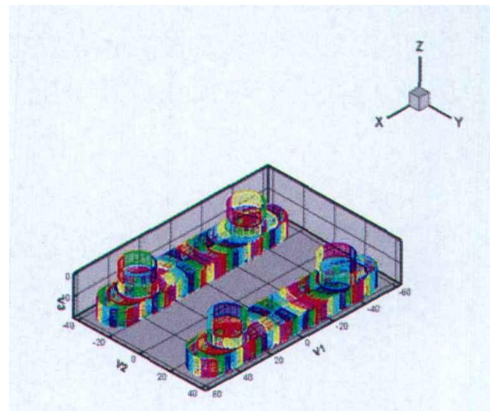

图 4 目标半潜式平台湿表面模型

置于等深度、无旋、不可压缩波浪环境中的半潜式平台，在线性入射波作用下平台运动响应的方程为：

$$(M+M_a)\frac{\partial^2 x_G}{\partial t^2}+B\frac{\partial x_G}{\partial t}+Kx_G=f \qquad (2)$$

式中，t 为时间，xG 为平台 6 个自由度上的运动位移，外力由平台的直接湿表面压力积分计算求得，M、K 分别为质量矩阵和刚度矩阵，Ma 和 B 分别为附加质量矩阵和阻尼矩阵。

表 1 给出了半潜式平台水线以下主尺度参数。

表 1 平台主尺度参数

浮箱长(m)	114.07
浮箱宽(m)	20.12
总宽(m)	78.68
柱间距(m)	70.0
吃水(m)	19.0
排水量(m^3)	46128.3
水深(m)	3000
立柱半径(m)/ 浮箱高(m)	9.0/7.88
	8.0/8.54
	7.5/8.81

3.2 垂荡运动响应（RAO）

如上表所示，在排水量和其他主尺度参数一定前提下，我们通过改变浮箱高度和立柱半径来改变质量配置，计算了平台的固有频率和垂荡幅度。

图 5 为三种情况下的垂荡 RAO 随波浪周期的变化曲线。浮箱高度 7.88m 时，RAO 幅值已超过了 3.

5，大约在入射波浪周期 23s 处取得；浮箱高度增加到 8.54m 时，RAO 幅值不到 2.5，约在 26s 处达到最大幅值；而浮箱高度增到 8.81m 时，RAO 幅值更小，且在 28s 处取得。这说明较高浮箱情形下垂荡 RAO 幅值不仅较小，并且最大 RAO 幅值响应频率远离常见波浪频率。表明了在排水量一定前提下，立柱与浮箱的不同质量配置可以在很大程度上影响着垂荡 RAO 幅值，并使其响应发生明显频移现象。因此，在实际设计平台时，在满足其他工程要求的前提下，尽量增加浮箱高度和减小立柱半径，则可以相当程度的降低垂荡 RAO 幅值并且避开常见波浪周期，达到提高运动性能的目的。

另一方面，半潜式平台立柱与浮筒不同质量配置因子 Φ 与其固有频率之间的关系经过详细推导，如下公式：

$$\omega = \sqrt{\frac{g}{l}}\left(\frac{1}{1+(1+\kappa)\frac{\phi}{1-\phi}}\right)^{\frac{1}{2}} \tag{3}$$

这里，l 为立柱的吃水深度，κ 为附加质量系数，g 为重力加速度，Φ 为半潜式平台下浮筒的排水体积 Vp 与总排水体积 V 之比,即，

$$\phi = \frac{V_p}{V} \tag{4}$$

由式（4）的定义可知 0<Φ<1。根据式（3）可得出 Φ 与固有周期的关系曲线如图 6 中的实线，表明平台固有周期随着 Φ 的增加单调增加。对应表 1 立柱半径与浮筒高度三种不同质量配置 9.0/7.88、8.0/8.54 和 7.5/8.81（Φ分别为 0.75、0.82 和 0.84）情形下的垂荡 RAO 最大幅值对应的入射波浪周期见图 6 的离散点，我们发现，所给出的理论公式关系曲线与 WAMIT 计算结果（图 5）基本吻合，这表明式（3）预测立柱与浮筒不同质量配置对半潜式平台固有周期的影响规律是非常合理的。

4 结语

本文分析了我国南海两种典型特殊环境：台风和内波和浮式深水平台概念设计问题。

通过对西北太平洋 1945 ~ 2007 年 63 年的热带气旋资料统计分析，发现西北太平洋的热带气旋活动明显增强，具体表现为台风，强台风发生频次的增加和 PDI 的明显增加。而南海地区相对于整个西北太平洋来说是小样本，其热带气旋活动在波动中显示出缓慢上升趋势。我国南海尤其南海北部内孤立波频发，传播以西向为主，时间分布上夏季为高峰期，内波流场水平速度几乎均匀，但跃层上下存在速度剪切，可对海洋平台产生推移和扭转。

在海洋平台动力响应方面，研究发现平台固有周期随着质量配置因子 Φ 的增加而增加，而垂荡 RAO 幅值相应减小，理论结果与数值计算结果吻合良好，得到的最佳参数组合可为浮式深水平台概念设计和选型优化提供依据。

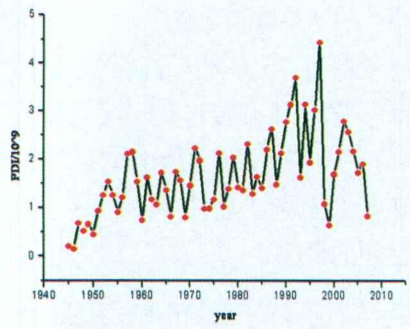

图 1 西北太平洋 PDI

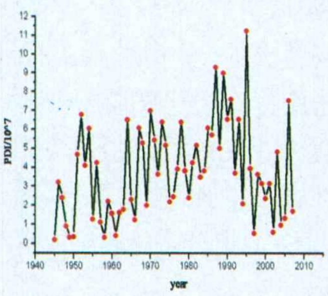

图 2 南海 PDI

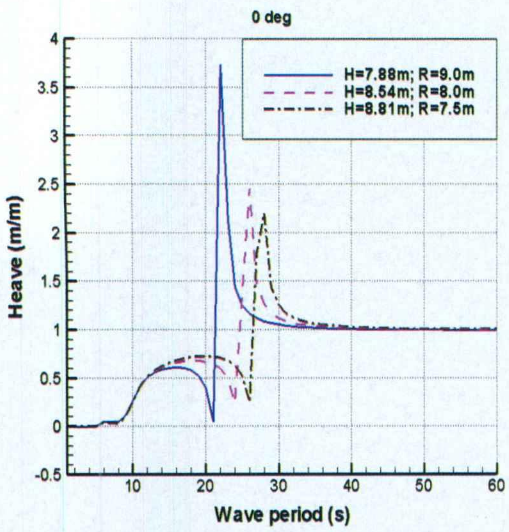

图 5 浮箱与立柱不同质量配置下的垂荡 RAO

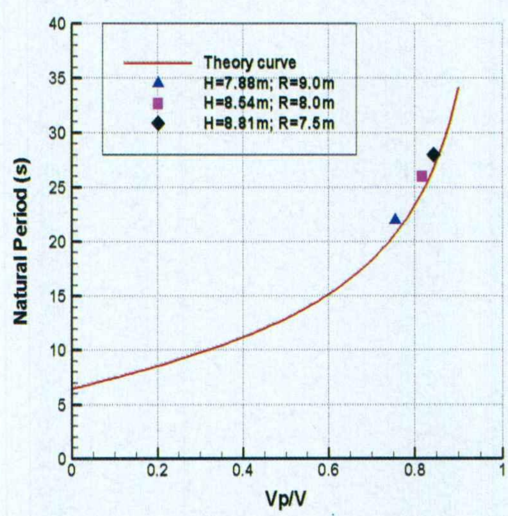

图 6 Φ 与固有周期关系曲线与数值结果比较

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Marine Environment and Deep-Sea Platforms

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Abstract:

Marine environment and dynamic response are two major factors in deep-sea platforms design. Based on the database of more than 60 years tropical cyclones, we find that very probably the frequency and intensity are gradually growing in terms of PDI due to climate change. As a result, the effects of non-stationary variation in atmospheric general circulation can no longer be neglected and should be considered in the standard or criterion revision. Furthermore, we have also provided time intervals and locations for internal wave occurrence along with corresponding parameters for internal wave velocity field, revealing that the interaction of tides and undulant topography is responsible for internal soliton trains genesis in the north of the South China Sea. In regard to dynamic features and conceptual design of platforms, we have proposed a theoretical approach to estimate the effects of mass allocation on dynamic responses (RAO) in heave, which is in good agreement with the computational results by WAMIT.

Keywords:

Fluid Mechanics; Tropical cyclone; Internal waves; Deep-sea platform; Semi-submersible; Climate change; Non-stationary variation

1 Introduction

With ever-growing needs for oil and gas resources, the ocean engineering has been paid much attention to by world engineering community. In the South China Sea (hereafter "SCS") known as the second Persia Bay, there deposit a large amount of oil and natural gas. China has started to stride forward from coastal regions with depth under 300 meters to off-shore regions as deep as 3000 meters, aiming at deep-sea platform design by independent innovation. Whether the deep-sea platforms are safe or not depends on the insight into the marine environment parameter. Tropical cyclones and internal waves are two factors in the SCS we should lay special emphasis on in addition to conventional wind, wave and current. At the same time, conceptual design and optimization lie on our understanding in dynamic features of various styles of deep-sea platforms. Therefore, we mainly discuss the typical marine environment in SCS and dynamic responses of platforms in the current paper.

The annual report [1] released by IPCC in 2007 confirmed the global warming and the degree of influence. In the previous platform design, we ignored the non-stationary variation induced by climate change in the evaluation of extreme parameters. So we need to analyze the trend of typhoon' s intensity and frequency. Based on the database of more than 60 years typhoons, we have found that very probably the frequency of typhoon and strong typhoon is gradually growing and the intensity of tropical cyclone is growing slowly in terms of PDI due to climate change which results in the increasing wind and wave loads. As a result, the effects of non-stationary variation in the evaluation of extreme winds velocity parameters can no longer be neglected and should be considered in the standard or criterion revision. Internal waves, which may cause serious threat to offshore structures [2,3,4], are ubiquitous in the SCS. In this paper, the generation and propagation mechanism of internal solitary wave trains and corresponding velocity field as a basis of internal wave load calculation have been analyzed. In designing deep-sea floating platforms, i.e. semi-submersible and FPSO, software is usually applied to analyze dynamic response of platforms in the past. Nevertheless, we have proposed a theoretical approach to estimate the effects of mass allocations between columns and pontoons on dynamic responses (RAO) in heave. The result shows that the natural period increases and the maximum RAO in heave decreases with non-dimensional mass allocation coefficient Φ, which agrees well with calculation by WAMIT. The progress in this regard has laid foundation for conceptual design and structure optimization.

2 Typical marine environments in SCS---Tropical cyclones and internal waves

2.1 The variation of frequency and intensity of tropical cyclone

Tropical cyclone is a kind of intense weather system occurring in tropical marine region. When the maximal velocity is larger than 32.7 m/s and 41.3m/s, meteorologically we call it typhoon and strong typhoon respectively. Based on the analysis of the databases of tropical cyclones in the northwest Pacific Ocean (hereafter "NWPO") from 1945-2007, we have obtained the law of frequency and intensity variation of typhoon and strong typhoon in the NWPO and SCS.

According to the statistics, there are 13.6 typhoons and 9 strong typhoons occurring in the NWPO every year and the frequency of typhoon and strong typhoon increase significantly. If dividing the 63 years data into two interval groups: 1945-1977 and 1978-2007, we can see that the average number of typhoon occurs in one year from 11.5 to 16 and strong typhoon from 7 to 11. As a result, the number of typhoon and strong typhoon in the past 30 years increases by 39% and 57% respectively. Regarding to the region of the SCS, there are 4.3 typhoons and 2.4 strong typhoons on average. The variation of frequency shows slow increase with strong fluctuation due to the small amount of samples in the SCS as compared with vast area of the NWPO. If we divide data in the same way as did in the NWPO, the average number of typhoon occurring in one year from 4 to 5 and strong typhoon from 2.4 to 3 with a growth rate of 25%.

In regard to tropical cyclone, Kerry Emanuel [5] thought that the maximal velocity or lifetime is not always suitable for an appropriate measure of tropical cyclone intensity, so he defined the power dissipation index (PDI) as:

$$PDI = \int_0^{\tau} V_{\max}^3 \, dt \qquad (1)$$

where V_{max} is the maximal wind speed, is the life time of the tropical cyclone. The PDI is calculated by summing up cubes of the maximal wind speed reported every 6 hours over the lifetime . We integrated over an entire year as the characterization of the tropical cyclone' s intensity in one year in the NWPO (Fig.1) and SCS (Fig.2) region respectively. As shown in Fig.1, the growth of the PDI in NWPO is increasing significantly since 1970s and by the end of the twentieth century the PDI even reached 2 times of that in 1970s. The PDI in the SCS shows strong fluctuation with slow increase, which reached 1.3 times by the end of the twentieth century from 1970s.

2.2 Internal waves properties in SCS

Tidal current distributions and undulant topography in SCS are two major decisive factors which almost account for the behaviors of internal waves there. Long internal solitary waves are presumably generated by tides, which may also be expressed as that when the internal tides propagate over undulant topography, they will change in shape and finally split into internal solitons trains. According to the topography in SCS, in the north of Fillipine and the south of Taiwan, there are Bashi, Balintang and Babuyan straits and a sea ridge stands here. Numerical results show that soliton wave trains generated there propagate to the north of the SCS when the tides to-and-fro pass through the ridge. The main parameters we have obtained agree with observations [6].

Internal wave velocity field is significant for examining interactions between internal waves and floating structures, but few researches are available, so it is necessary to study the flow field induced by internal waves. Observational data and some numerical results show that [6,7,8] the internal waves in SCS have the following properties:

(1) The north of the SCS is one of the most active areas for internal wave occurrence, and the origins of internal waves come from Batan, Fujia and Babuyan islands near Lusong strait; Internal waves often appear in the form of internal solitary wave trains which mainly propagate to the west and occur frequently in Dongsha islands; The internal waves reach to a high peak in April to September due to strong stratified ocean in summer, while keep at lower level in other seasons. Because of the strong tide currents, internal waves reach to a high peak on 16-19th every month.

(2) The amplitude of internal solitary waves as large as tens of meters, or even up to 100 meters often appear, and waves of 170m-amplitude at speed of 2.5m/s have already been observed in SCS[9]. Numerical simulation shows that [6] amplitude of internal waves can reach to 100m or more in the east of Dongsha island while they attenuate to 70m in the west, and good agreements have been reached to observations.

(3) The horizontal flow field induced by internal waves is almost uniform, but has a strong shear between pycnocline of the upper and lower layer. Therefore, the strong shear current caused by long nonlinear internal waves may lead to displacement and torsion of the platforms.

3 The effects of mass allocation on dynamic response of semi-submersible

The semi-submersibles, which operate in extra deep sea, have already been developed to the sixth generation. Their pattern tends to simpler compared to past with four, six or eight columns and single or double pontoons. Different types of deepwater semi-submersible have different performance in waves. Dynamic response (RAO) in heave is crucial to evaluate hydrodynamic performance and mainly depend on operation environment, prototype and main dimensions of the platforms. Assuming total displacement is given, the semi-submersibles have been designed according to the type of the columns and pontoons, especially according to the mass allocation in order to optimize structure design and dynamic response.

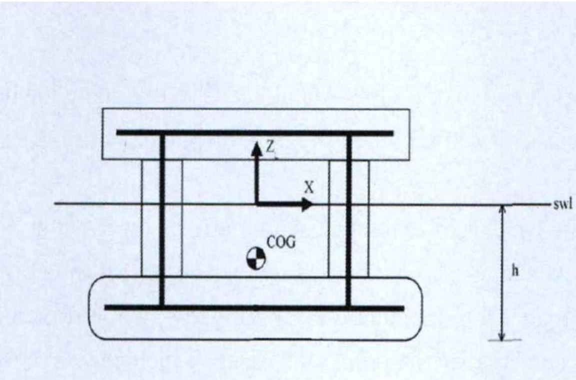

Fig.3 Schematic of semi-submersible and its coordinate system

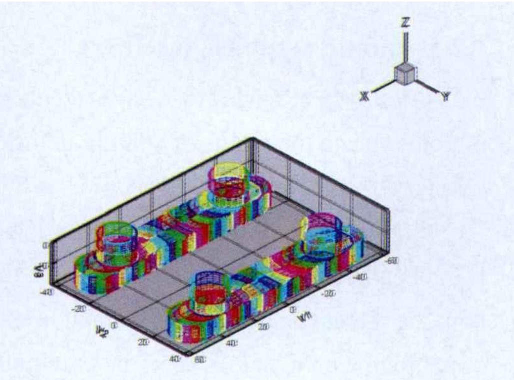

Fig.4 Discretization of the wetted surface of semi-submersible

3.1 Problem description and governing equations

In this paper, a general semi-submersible with two rectangular pontoons which ends are semi-circular and two equally-spaced circular columns on each pontoon is analyzed. The simplified model and its coordinate system are shown in Figs.3-4.

The semi-submersible interacting with linear progressive waves in 3000m water depth is discussed. A six-DOF dynamic equation of motion is expressed as follows

$$\left(M+M_a\right)\frac{\partial^2 x_G}{\partial t^2}+B\frac{\partial x_G}{\partial t}+Kx_G=f \tag{2}$$

where, t is time; xG denotes unknown motion vector (6x1) in the sequence of surge, sway, heave, roll, pitch and yaw, respectively; is wave load which is obtained from direct integration of hydrodynamic pressure on the wet surfaces; M and K are mass matrix (6x6) and stiffness matrix (6x6); Ma and B are added mass matrix and damping matrix (6x6), respectively.

To demonstrate the dynamic response of the semi-submersible, three case studies have been followed and the semi-submersible parameter is given in Table 1.

Table 1 Semi-submersible main parameters

Length of pontoon(m)	114.07
Beam of pontoon(m)	20.12
Beam outside pontoon(m)	78.68
Column space(m)	70.0
Draught(m)	19.0
Displacement(m^3)	46128.3
Water depth(m)	3000
Radius of column(m)/Height of Pontoon(m)	Case 19.0/7.88
	Case 18.0/8.54
	Case 17.5/8.81

3.2 Dynamic response in Heave

As shown in Table 1, we have calculated natural period and maximum RAO in heave by changing the height of pontoon and the radius of column in order to adjust mass allocation when the total displacement of the semi-submersible is given.

Fig.5 illustrates three mass allocations, as shown in Table 1 of cases 1-3, which affects on RAO in heave. If the height of pontoon is 7.88m, the maximum RAO exceeds 3.5 in incident wave period 23s; if the height of pontoon increases to 8.54m, the maximum RAO is less than 2.5 in incident wave period 26s; while if the height of pontoon increases to 8.81m, the maximum RAO is much smaller than previous cases in incident wave period 28s.

This shows that the higher the height of pontoon is, the smaller maximum RAO in heave is, and meanwhile the natural period keep off surface wave period. This further shows that mass allocation between columns and pontoons can not only influence the maximum RAO to a large extent, but also change the natural period of the semi-submersible. Therefore, we should increase the height of pontoon at the same time decrease the radius of the column provided other conditions in engineering are satisfied. Thus we are able to improve the dynamic performance of the platforms.

On the other hand, when considering mass allocation between pontoons and columns, a formula has been obtained as follows:

$$\omega = \sqrt{\frac{g}{l}} \left(\frac{1}{1+(1+\kappa)\frac{\phi}{1-\phi}} \right)^{\frac{1}{2}} \tag{3}$$

where, l denotes the draught of the column, κ stands for the added mass coefficient, g represents the acceleration of gravity and Φ is defined as follows:

$$\phi = \frac{V_p}{V} \tag{4}$$

here Vp and V are the displacement of the pontoons and total displacements of the whole semi-submersible, respectively. We can easily conclude $0<\Phi<1$ from (4).

According to (3), the general diagram is reproduced as Fig.6 (solid line). It has been found that the natural period will increase monotonously with Φ. As compared with numerical results (Φ is 0.75、0.82 and 0.84) in Fig.5, it has been noticed that theoretical formula are in good agreement with the corresponding numerical results. This shows that formula (3) is reasonable to figure out the mass allocation influence on the natural period of platforms.

4 Conclusions

This paper introduces two typical marine environments in SCS: typhoons and internal waves and the conceptual design of deep-sea floating platforms.

Based on the database of more than 60 years tropical cyclones, we have found an evident intensification of typhoon activity, which mainly manifested as the frequency increase of typhoon and strong typhoon and evident increase of PDI. Because of small amount of sample in SCS relative to the NWPO, the activity of tropical cyclone in the SCS shows slow increase with strong fluctuation. Internal solitary waves are ubiquitous and active in SCS. The internal solitons mainly propagate to the west and reach to a high peak in summer. The

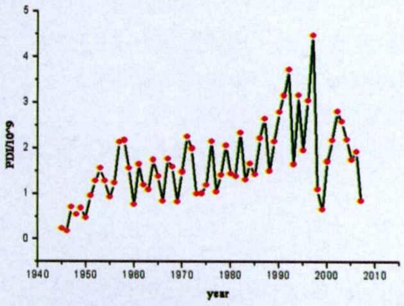

Fig.1 The variation of PDI in the NWPO

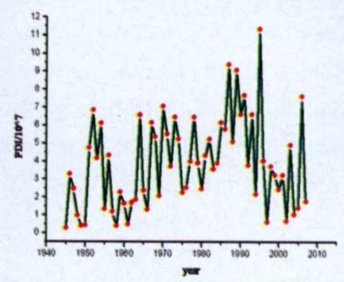

Fig.2 The variation of PDI in the SCS

horizontal flow field induced by internal waves is almost uniform with the velocity shear between upper and lower layers and this may lead to displacement and torsion of the platforms.

It has been found that the natural period increases monotonously with the mass allocation factor Φ, meanwhile the maximum RAO decreases with it. Theoretical results are in good agreement with the corresponding numerical results. The progress in this regard may be applied in deep-sea floating platform conceptual design, which will be highlighted in future works.

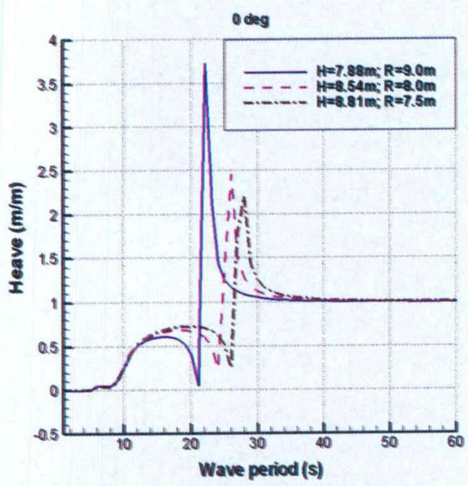

Fig.5 RAO in Heave under three mass allocations between pontoon and column

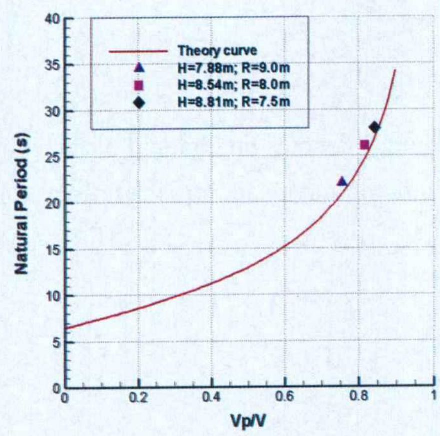

Fig.6 Comparison of theoretical and numerical results

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