THE CASE STUDY OF GUMUSUT DEEPWATER PROJECT

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CIVIL ENGINEERING
UNIVERSITI TEKNOLOGI PETRONAS
JUNE 2010

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Muhammad Fadzli bin Zaudi

AP. Dr. Nasir Shafiq

Dissertation submitted in partial fulfilment of
the requirements for the
Bachelor of Engineering (Hons)
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CERTIFICATION OF APPROVAL

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CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

MUHAMMAD FADZLI BIN ZAUDI

ABSTRACT

Shell announced that Final Investment Decision has been taken to jointly develop the Gumusut-Kakap field, located in deepwater, offshore Sabah, Malaysia.

Sabah Shell Petroleum Company will be operator of the development, which will employ the region's first deepwater Floating Production System (FPS), with a processing capacity of 150,000 barrels of oil per day. The field, which is in waters up to 1,200 metres deep in blocks J and K, will be developed using 19 subsea wells with oil exported via a pipeline to a new oil and gas terminal, which will be built in Kimanis, Sabah.

The Gumusut and Kakap fields were combined into a single development under a Unitisation and Unit Operating Agreement signed by the co-venturers in 2006. Shell and ConocoPhillips Sabah Ltd each hold 33% interests in the development; PETRONAS Carigali has 20% and Murphy 14%.

The study of offshore floating structure subjected to random waves is focused on semi submersible with cylinder column. In this study, the motion responses in surge and heave have been evaluated.

ACKNOWLEDGEMENT

In the name of Allah, the Most Gracious, the Most Merciful. Praise to Him the Almighty that in His will and given strength, had I managed to complete this research in my Final Year Project.

My deepest gratitude goes to my supervisor for this final year project, Associate Professor Ir. Dr. Nasir Shafiq whose has proposed, supervised and supported this project continuously in making this project a success.

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CHAPTER 1

1 INTRODUCTION

1.1 Background of Study

For oil and gas offshore Exploration and Production (E&P) operations in deep waters, floating platforms such as Semi-Submersible Platforms are used. Floating structure is maintained by a variety of mooring line types and systems to keep it stationary at desired locations. Historically, ships were moored using a single anchor chain from the bow. In 1962, the first semi-submersible, the Blue Water 1 began drilling operations in the Gulf of Mexico. After few years later, the semi-submersible Santa Fe Choctaw was designed and built as an offshore construction barge. Since that time, the offshore Industry has gradually utilized the potential of the semi-submersible unit to assist the offshore operations.

A semi-submersible is a compliant structure used in drilling for oil and natural gas in offshore environments. This superstructure is supported by columns sitting on hulls and pontoons which are ballasted below the water surface. It provides excellent stability in rough, deep seas. Semi-submersible platform has number of legs to provide sufficient buoyancy to cause the structure float, and its weight will keep the structure upright. This structure is generally anchored by cable anchors during drilling operations, though they can also be kept in place by dynamic positioning. Semi-submersible rigs are always spread moored with mooring lines emanating from the four corner columns. Such a spread mooring is possible because unlike ships, the environmental force on a semi-submersible is relatively insensitive to direction.

The Gumusut-Kakap field is the first deepwater opportunity in Malaysia. Sabah Shell Petroleum Company will be operator of the development, which will employ Malaysia's first deepwater semi-submersible production system. The field will be developed using 19 subsea wells with oil exported via a pipeline to a new oil and gas terminal, which will be built in Kimanis, Sabah. The production system will have a capacity of 135,000 bbl/d. Natural gas that is produced along with the oil will be re-injected into the reservoir to help improve oil recovery.

1.2 Problem Statement

Nowadays, offshore industry requires continuous development of new technologies in order to explore the potential oil region. Petroleum exploration in deepwater has become a major challenge because of large environmental loads acting on the platform. Offshore operations of floating systems like the semi submersibles in this paper illustrated in Figure 1.1 usually cope with severe and hostile seas. Economic advantages in avoiding restrained operation or weather induced downtime are yield when such systems are design with favorable motion behavior. Hence, those structures need to be uniquely designed in many aspects (Adjami M. and Shafieefar M. 2007). Efficient and economical designs are a challenge to the offshore community. Semi-submersible platforms have widely been operating for the exploration and production of ocean resources, and many such platforms are now in operation. They are required to be properly designed in order to keep it in position at certain water depth when they are subjected to external forces induced by ocean current, wind and waves.

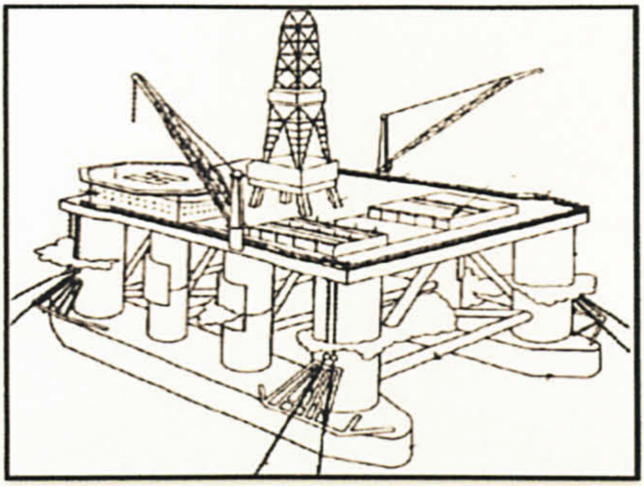


Figure 1.1: Semi submersible based floating production system

1.3 Objective

- The main objective of this study was to investigate the actual design of Gumusut semi submersible platform.
- To perform an alternatives design by changing the size and configuration of the columns and compare with the existing design in terms of stability responses.

1.4 Scope of study

This study is based on existing platform and Gumust Kakap Deepwater Project submersible platform. A few tasks and research need to be carried out by collecting all technical details regarding the project and by studying the fundamental behavioral aspects of the platforms. A recommendation is to be made based on the findings of this study regarding the applicability of the semi-submersible platform in the Malaysian context.

CHAPTER 2

2 LITERATURE REVIEW

Semi-submersible platforms are well known in the oil and gas industries. These semi-submersibles have a relatively low transit that allows them to be floated to a stationing location. Semi-submersible platform is a drilling rig that heaves, pitches and yaws with each passing wave, and the industry needs more stable drilling platforms. Semi-submersible obtains its buoyancy from ballasted, watertight, pontoons located below the ocean surface and wave action. The operating deck is located above the tops of the passing waves. Structural columns connect the pontoons and operating deck. When it has a movement, the pontoons will de-ballast so that the platform can float on ocean surface. Semi-submersible drilling units utilize water ballast to minimize the up and down motion of waves. They are the most stable floating offshore drilling unit available.

The forerunner of the semi-submersible was the submersible. A submersible barge is floated to location and then ballasted down to sit on the seafloor prior to operation. As the deck must remain above water, submersibles are suitable only for shallow water. The first submersible for open water use was constructed in 1948 and the last was built in 1963 for a water depth of 53m.The semi-submersible major advantage when compared to a ship-shaped unit is in reduced motions when subjected to wave. The indications used for describing semi-submersible motion in the translational and rotational directions are shown in Figure 2.1. Roll, pitch and heave are greatly reduced by the transparency and by spreading the water plane area. With the spreading of the water plane area, the natural period of the unit increases proportionately. The natural period of a semi-submersible in heave is normally about 20 seconds, which is far above the everyday wave period experienced during drilling. Heave motion is most critical because the basic objective is to drill a hole and to do this one must keep the bit on the bottom of the hole with the proper weight and rotation. Other motions, such as roll and pitch decrease the efficiency of the people working on the vessel and can become critical when severe.

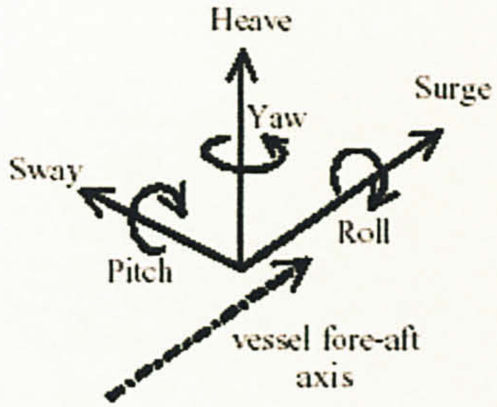


Figure 2.1: Semi-submersible Motion Indication

Generally, the semi-submersible as shown in Figure 2.2 is a floating column-stabilized platform consisting structurally of:

- Lower Hulls – for attaining transit draft and maintaining a low center of gravity at drill draft
- Column – for a highly transparent buoyancy at the water plane
- Deck – for the equipment, storage, housing and work areas
- Truss – to join all the structures together

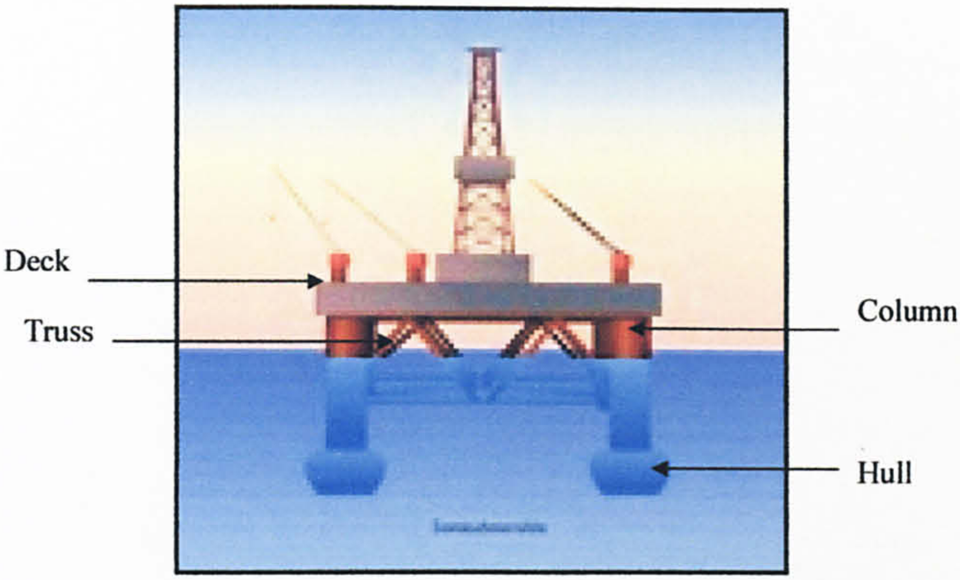


Figure 2.2: Semi-submersible platform

The structure of the platform is steel and depends upon welded joints. Normal fabricated steel weight varies between 6,000 and 12,000 tons. The primary structure and the tubular truss joints are designed, fabricated and inspected to a very high quality. The buoyancy of the unit is like a ship with many compartments that can be flooded or de-ballasted to change the draft of the semi-submersibles. The operating draft of the platform varies between 70 and 90 feet with an air gap from the water surface to the main deck of approximately 30 to 50 feet.

The design of the semi-submersibles platform should incorporate the water depth, the design wave, the wind loading and soil conditions while performing the required operations. Each of these items individually may have significant impact on cost and configuration of the structure and collectively may have devastating impact. Increasing water depths, of course involve additional materials, which result in greater cost, and increasing wave size with its larger loading, has a similar effects. Wind loads are usually relatively small, however for high winds and larger projected areas, they form a significant part of the overall loads imposed on the structure.

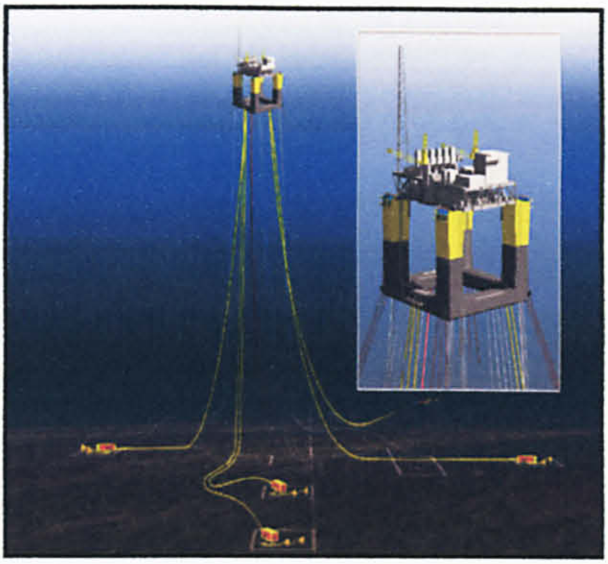


Figure 2.3: Semi-submersible Platform with Mooring Chain

The stability of the platform is the most important condition where is the effectiveness mooring system will lead to kept in position. Therefore, the platform must have means of producing forces and momentum to counterbalance the environmental forces like wind, currents and wave induces in order to keep it at a standstill. Mooring system is a connection of chain or wire from the structure itself to the sea floor as shown in Figure 2.3. Soil conditions play an important role in stability of the platform where is a hard soil creating difficulty because it is difficult and expensive to obtain the necessary mooring system in order to connect a platform to the sea. On the other hand, the soft soil often yields a condition whereby almost no strength may be obtained during the soil connection.

Hull is the semi-submersible part in the deepwater platform. It is the main part to support the topside of the platform. There are some term have important meaning in hull design rules for strength and stability. Tank is a compartment or space designs to hold fluids (cargo or ballast). Void is sealed compartment providing buoyancy but not containing fluids while bulkhead is a vertical membranes to a tank and void. And deck is a horizontal membrane to a tank and void.

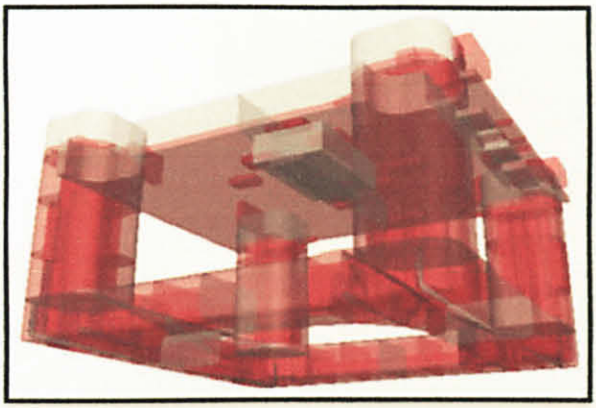


Figure 2.4: Hull Compartments

For Gumusut Deepwater project, the base hull concept will follow be same geometry as Na Kika platform (Figure2.5). But it wills different in shallower draft due to integration constrains, has less mooring lines and simpler hull system. Na Kika is a complex projects that involving Shell. It is the first semi-submersible host permanently moored in 6350 ft of water and deepest permanently moored semi-submersible development and production system. The Na Kika semi-submersible is based on four square steel columns with 56 ft wide and 142 high. The columns are connected by four rectangular steel pontoons with 41 ft wide and 35 ft high. The hull weighs 20000 tons and provides 64000 tons of displacement. While the topside facilities measure 335 ft x 290 ft, with a 130 ft x 120 ft central opening.

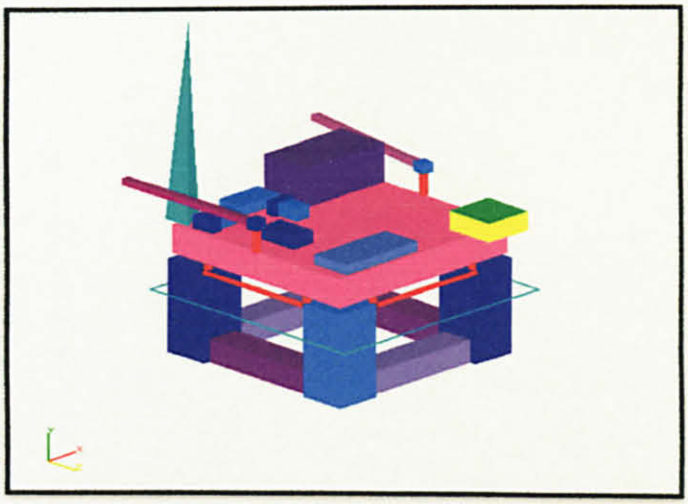


Figure 2.5: Modified Na Kika (Windos)

While Gumusut hull system has been design with hull weighs 15300 tons and provides 50000 tons pf displacement. The hull dimension is assumed as follows:

– 64.0 m Column Spacing

– 16.9 m Column Width (required to support deck modules)

– 2.0 m Corner Radius

– 8.8 m Pontoon Height

– 12.6 m Pontoon Width

– 39.0 m Column Height (limit for 25 m freeboard at 14 m Integration draft)

– 15.0 m Freeboard (to provide adequate Dead Oil Storage in Upper Column)

– 24.0 m Operating Draft

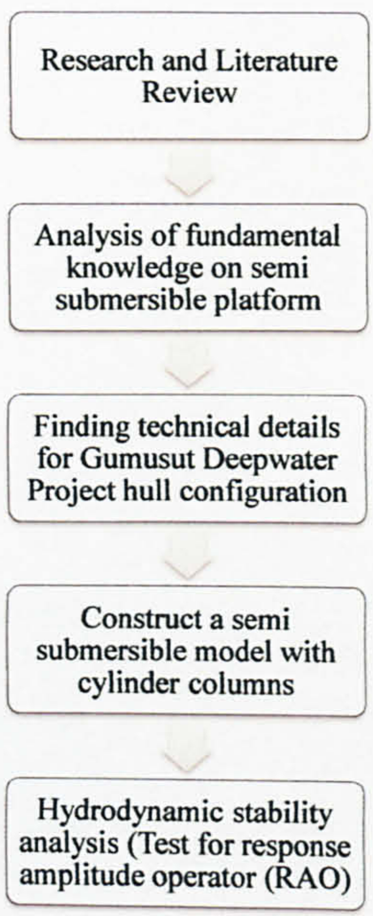
This design is used to develop the hull system for Gumusut Deepwater Project along with other details.

CHAPTER 3

3 METHODOLOGY

3.1 PROJECT FLOW

There are some procedures developed in order to carry out this project. This is to ensure that the project flow is smooth and accomplish within the period given. Figure 3.1 shows workflow and subsequently the details of each point.



3.2 RESEARCH AND LITERATURE REVIEW

First of all, a thorough research through the internet and from Information Resource Centre is done. Explore on this study to enable to grab as many information and records available so that better comprehension is obtained before carrying out further study and analysis. The records are for instance online journals, handbook and literature review.

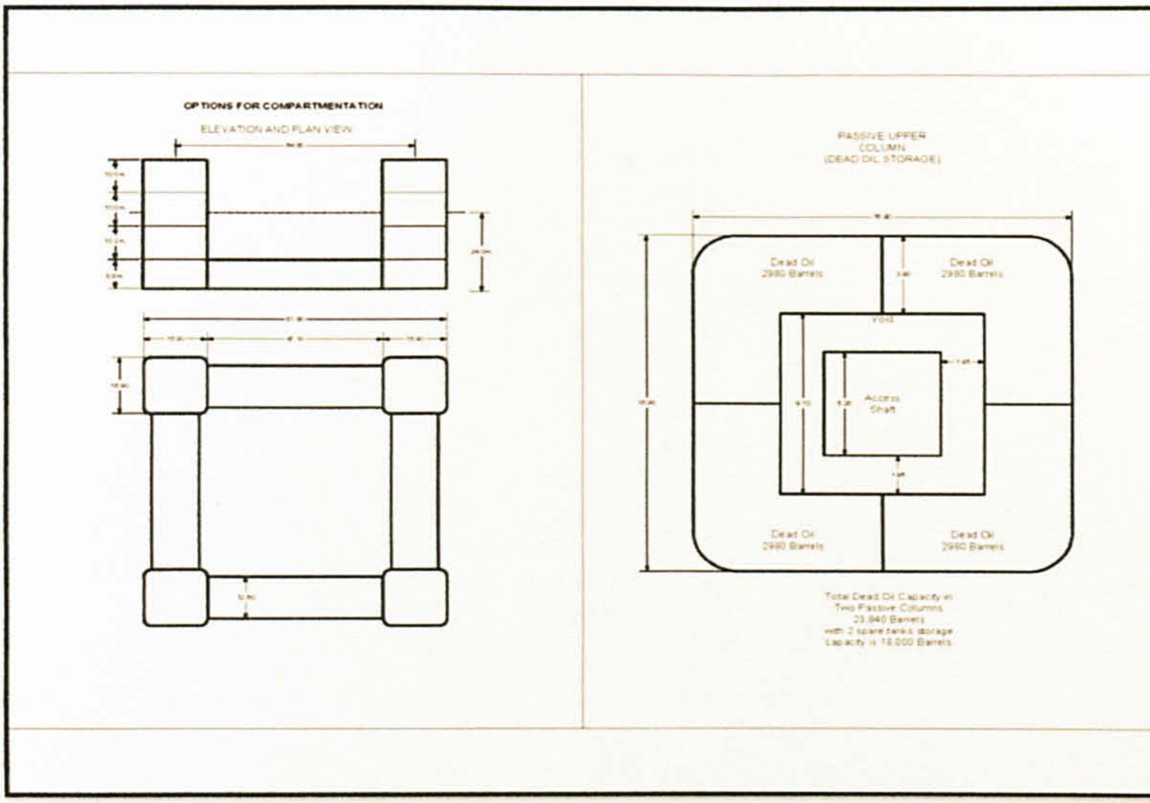
As of fundamental knowledge, historical background of semi submersible platform, the development of this type of platform and deep water oil and natural gas expansion are beneficial information to enhance understanding on this study.

3.3 ANALYSIS OF FUNDAMENTAL KNOWLEDGE OF SEMI SUBMERSIBLE PLATFORM

Number of platform designs have been observed and study. The semi submersibles design basis is obtained from the research through the internet and journals. This task is to study the effect of hydrodynamic stability on the semi submersible model. It is also to compare the differences between existing platform and Gumusut Kakap Deepwater Project.

3.4 FINDIING TECHNICAL DETAILS FOR GUMUSUT KAKAP DEEPWATER PROJECT

All the technical details for hull and mooring for Gumusut Kakap Deepwater Project are gathered from the designer. The details of the compartmentation are below:



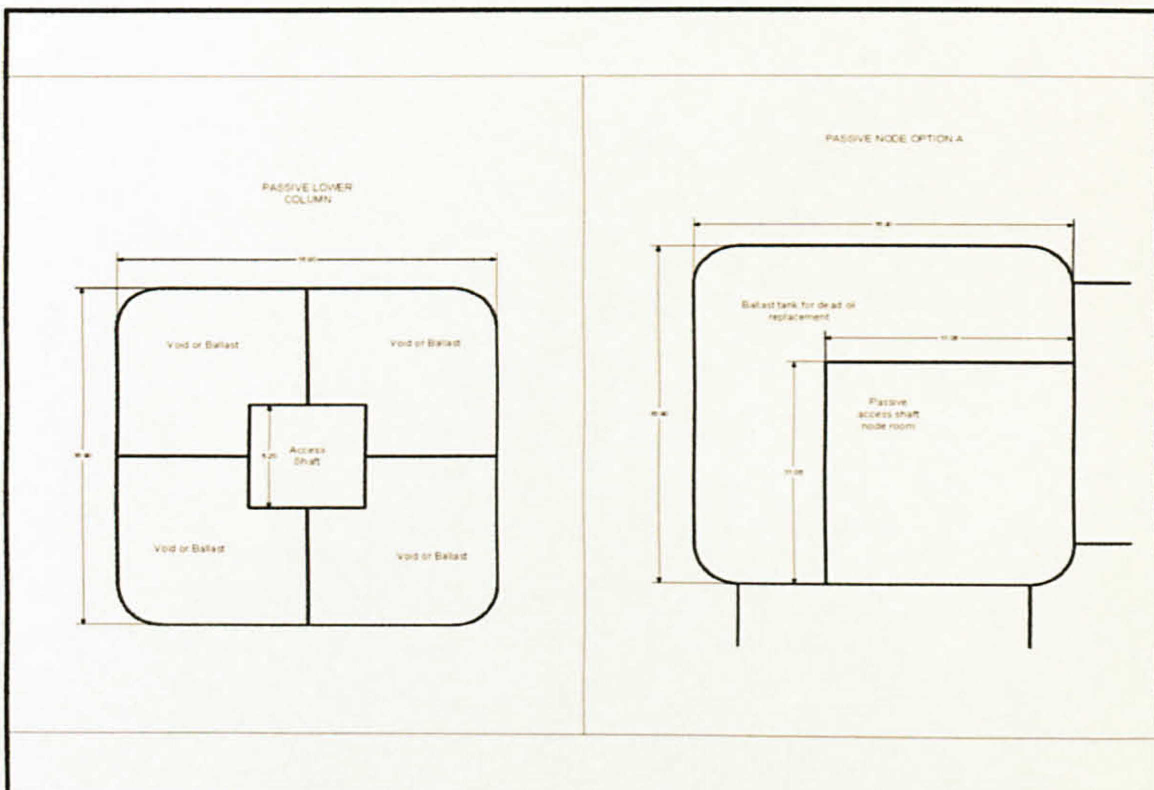


Figure 3.1 & Figure 3.2: Conceptual Compartmentation

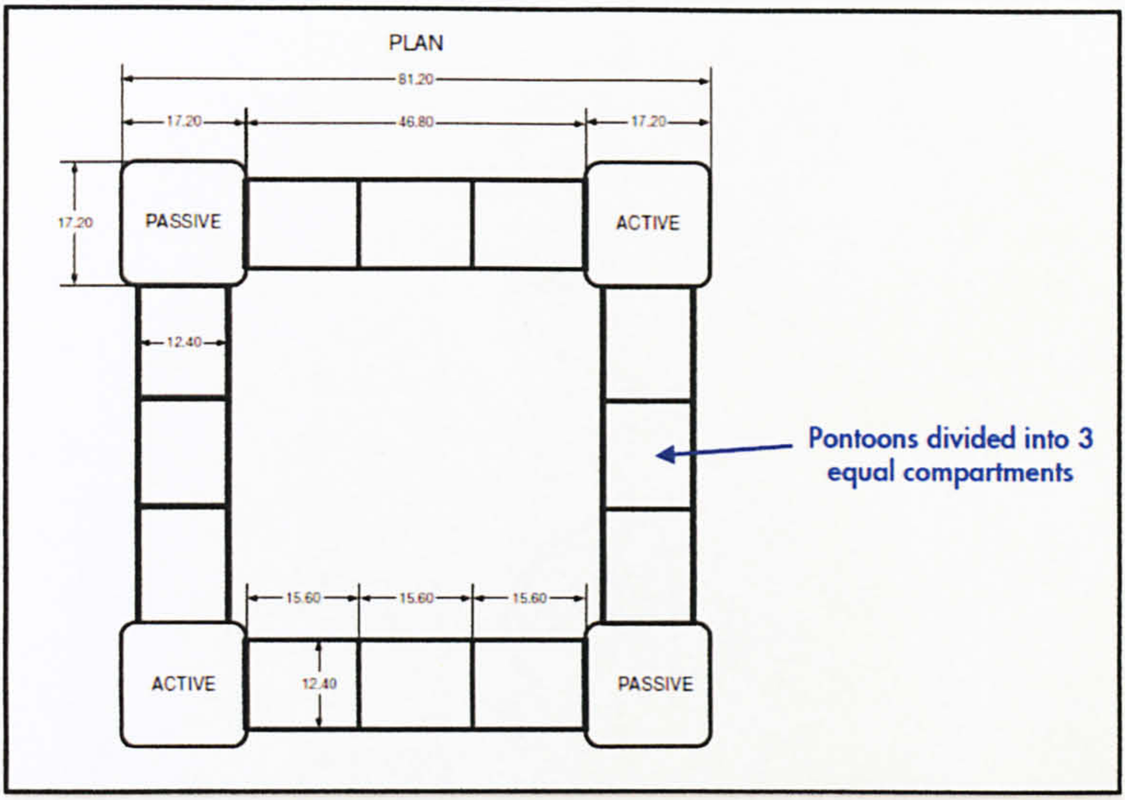


Figure 3.3: Compartmentation – Plan

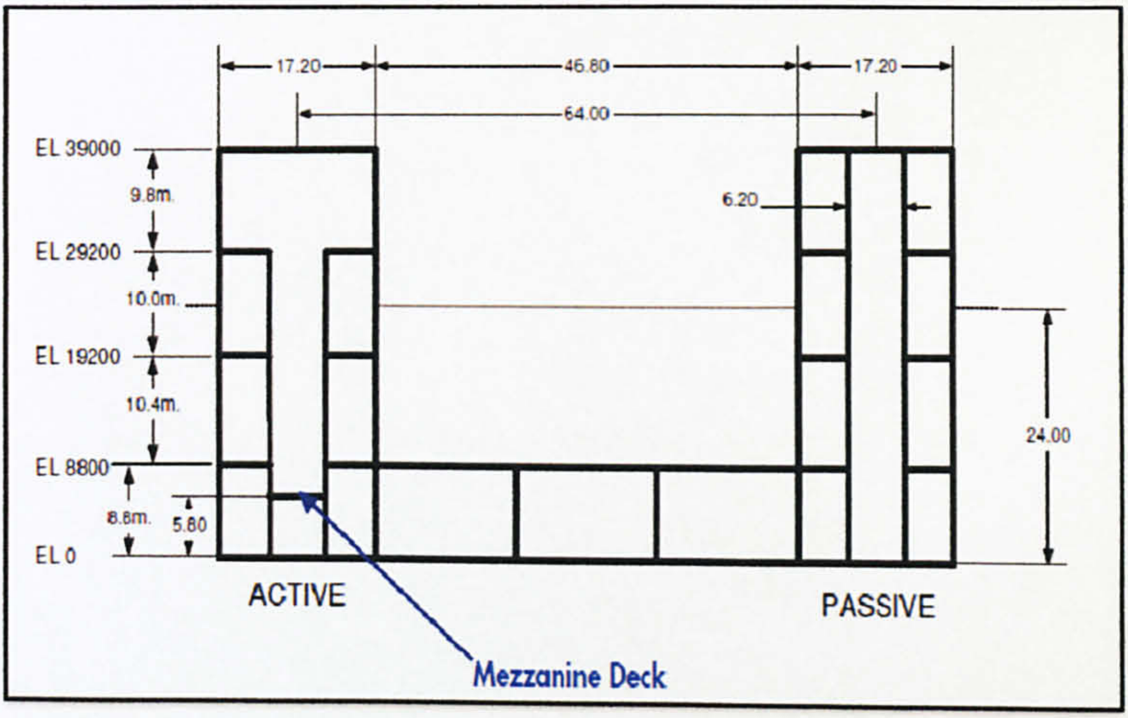


Figure 3.4: Compartmentation – Elevation

3.5 CONSTRUCT A SEMI SUBMERSIBLE MODEL WITH CYLINDER COLUMNS.

Using data from Figure 3.3 and Figure 3.4, a new model base on the Gumusut Kakap Deepwater project is constructing using Perspex. The size of the platform is scale to 1:81 from the actual model. It means that the model is reduced to 0.5m height and 1.0m length and width. Columns for this model will be cylinder with is differing to Gumusut Kakap platform with is rectangular as shown below:

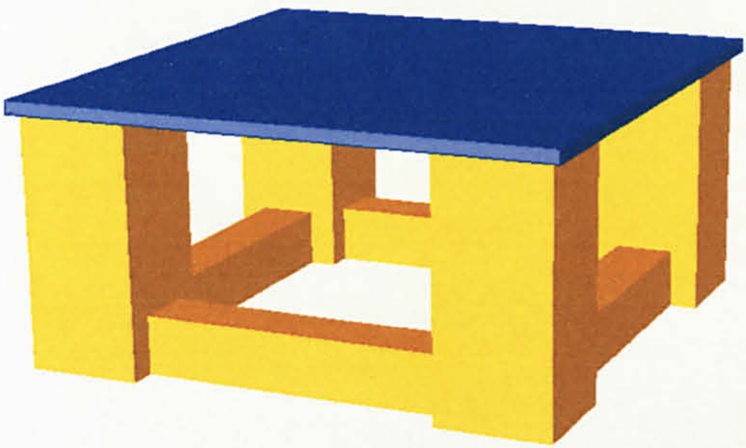


Figure 3.5: Gumusut Kakap original platform.

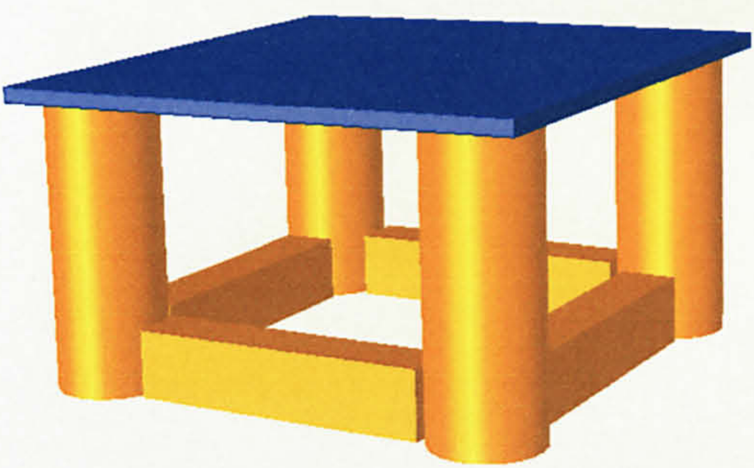


Figure 3.6: New Model with cylinder column with scale of 1:81

3.6 HYDRODYNAMIC STABILITY ANALYSIS (TEST FOR RESPONSE AMPLITUDE OPERATOR)

This analysis is done at Offshore Laboratory. The actual frequency and wave height are 2.0 Hz and 2.0 m respectively. The model is tested with random wave (P-M spectrum) with frequency of 0.06 Hz and wave height of 0.06 m (reduced by scale of 1:34). From test, the expected response profile in a given time interval can be easily plotted. Parametric studies have been made also by varying parameter of different water depth.

CHAPTER 4

4 RESULT AND DISCUSSION

4.1 RESPONSE OF SEMISUBMERSIBLE ON SURGE AND HEAVE MOTIONS.

After the experiment, the results for the 50 seconds time interval are shown below:

Surge:

t(s)	η (cm)
0	0
1	0.2
2	0
3	-0.2
4	0
5	0
6	0.2
7	0.2
8	-0.2
9	0
10	0
11	0
12	0.2
13	0.2
14	0
15	0
16	-0.2
17	0
18	-0.5
19	0
20	0
21	0.2

Heave:

t(s)	η (cm)
0	0
1	0.75
2	0.5
3	-0.2
4	0
5	0.2
6	0.5
7	0
8	-1
9	-1.5
10	-0.5
11	-0.2
12	0
13	1
14	0.75
15	0
16	-0.2
17	-0.5
18	-2
19	-1.75
20	0
21	2

22	0
23	0
24	0.2
25	-0.2
26	0
27	-0.2
28	-0.5
29	-0.2
30	-0.2
31	0
32	0.2
33	0
34	0.2
35	0
36	0
37	-0.2
38	-0.5
39	-0.5
40	0
41	0
42	-0.2
43	-0.5
44	-0.5
45	0
46	0.2
47	-0.2
48	-0.2
49	0
50	0

22	0
23	0
24	1
25	0.5
26	-0.2
27	-1
28	-1.2
29	-1
30	-0.5
31	-0.2
32	0
33	0.5
34	0.75
35	1
36	0.75
37	0
38	1
39	0.5
40	-0.5
41	-1.5
42	-2
43	-1
44	0
45	0.5
46	0
47	0
48	0.5
49	1
50	2

From the table, graph of response of semi submersible platform on surge and heave motions are plotted.

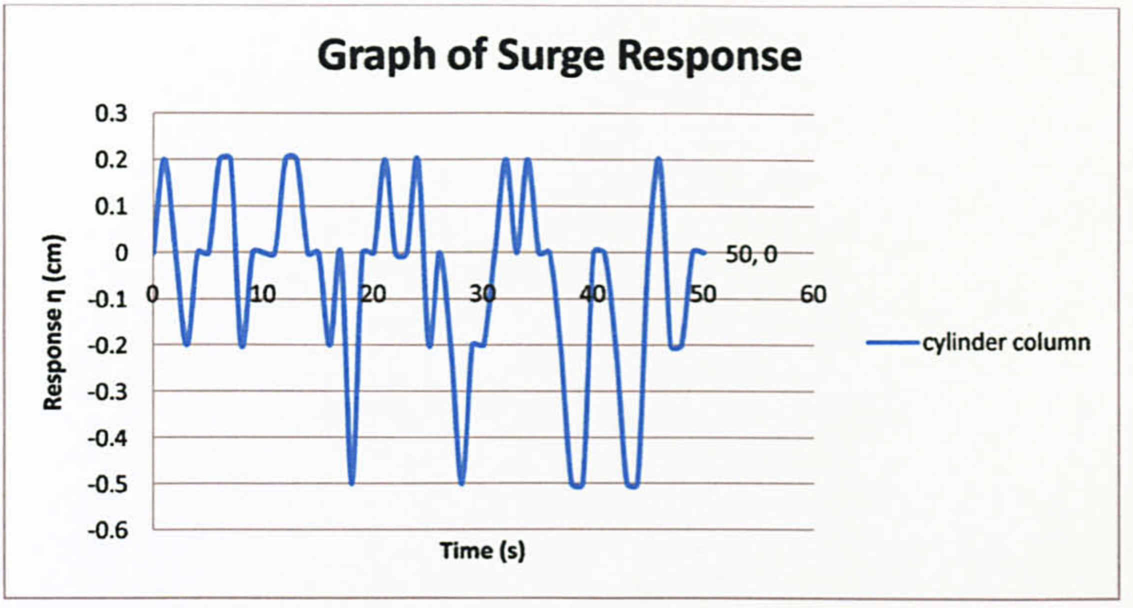


Figure 4.1: Stimulated surge profile from surge response spectrum

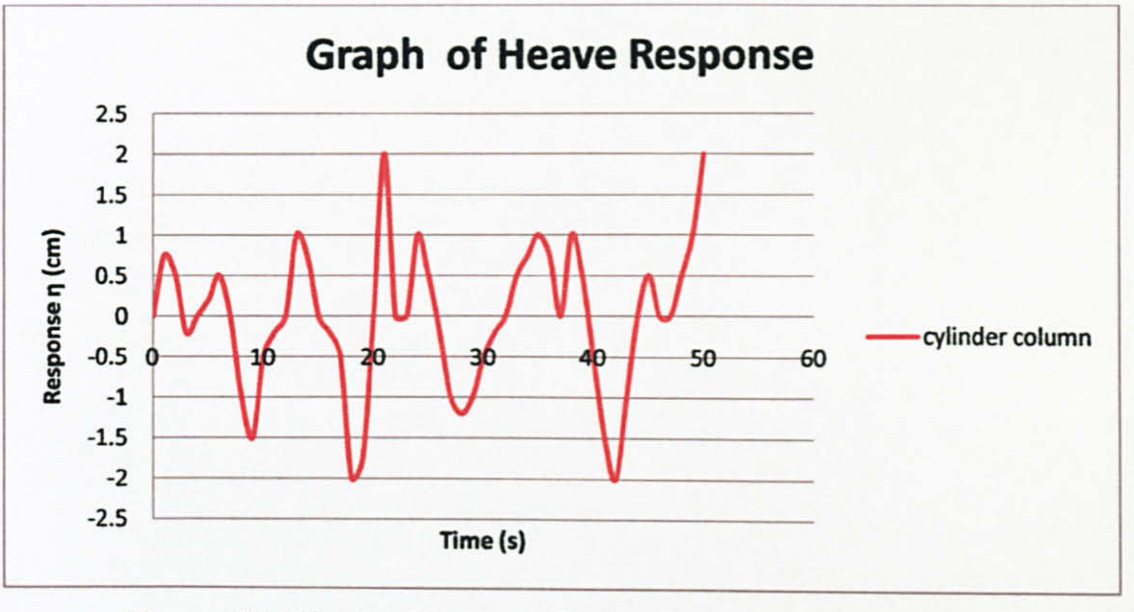


Figure 4.2: Stimulated heave profile from heave response spectrum

The plotted responses of the structure are shown in Figure 4.1 and 4.2. From the graphs, the maximum amplitudes of the two motion responses were as follows:

- Surge : 0.2 cm
- Heave : 2 cm

The maximum heave response is higher than the maximum surge response. The tension of the mooring allows the platform move in the heave direction but restrain the platform from moving in surge direction.

The predicted responses of the semi submersible were only approximate due to the following reasons:

- There is limitation of frequency can be tested in laboratory.
- The laboratory in not advance enough to make the experiment successful.
- The actual stiffness of mooring lines was not known and thus the computation of stiffness was simplified by using static equilibrium conditions.

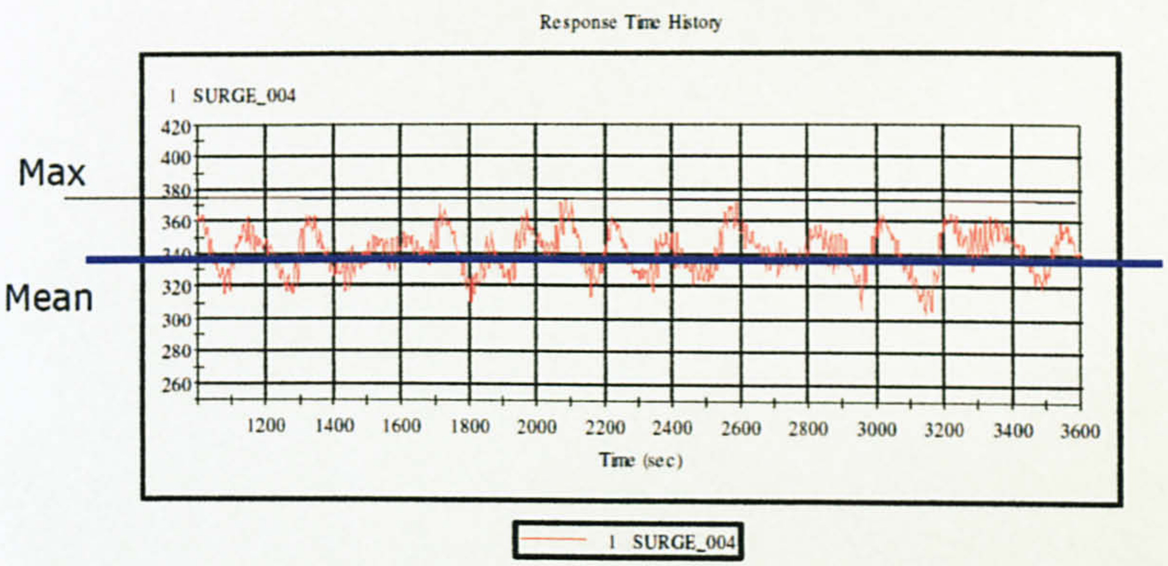


Figure 4.3: Surge of a semi submersible

Graph in Figure 4.3 shows the responses of a semi submersible platform for global responses. The maximum response is 375 ft (11430 cm). The plotted graph pattern in Figure 4.1 follows the global response pattern for the surge but limited to 0.2 cm due to the limitation mention above.

For this experiment, some considerations need to be added to make it accuracy.

- Stiffness and Mass Properties are a key input to any dynamic analysis.
- Need a distributed weight model for the floater to determine mass properties.
- Stiffness comes from Hydrostatic and from risers and mooring.

For heave responses, two forces are needed to be consider which is inertial forces on pontoon and pressure forces on column.

4.2 PARAMETRIC STUDIES

Water depth was chosen to study the effect on the response of the semi submersible platform. The changing parameter used in the study is water depth (0.8m and 1.0m). The comparisons between surge and heave responses of the parameter were represented by the time series curve. However, change of water depth did not have significant effect on the responses of semi submersible platform in terms of its surge and heave.

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CHAPTER 5

5 CONCLUSION AND RECOMMENDATION

5.1 CONCLUSION

Floating production systems were developed in the 1970s for their advantages in deeper water and for shorter production lives. In the early years, semi-submersibles were a natural choice for floating production systems; they offered drilling and work over capability for wells located beneath the vessel, good motion response and drilling rigs were available for conversion. In the late 1980s and early 1990s, the advantages of semi-submersibles for very deep water become apparent.

In this study, the response of the semi submersible with the cylinder columns has been presented. This study also developed a simplified method to calculate responses of the semi submersible to random wave loading.

Based on the discussion in the previous section, the most important conclusions from the work are summarized as follows:

- The maximum amplitudes obtained were 0.2 cm for surge and 2.0 cm for heave. The predictions using frequency domain were not very accurate as it could not take the nonlinearities into account. However the responses followed the same trend of the global response of floating platforms.
- Change of water depth did not have significant effect on the responses of semi submersible platform in term of its surge and heave response.

5.2 RECOMMENDATIONS

Based on present study, the following recommendations are made for further improve the dynamics analysis and future work:

- The time histories for plotting the waves can be extended to thousand second to obtain more random wave.
- Further refinement needed of the simplified dynamic analysis will be necessary to incorporate nonlinear properties of the mooring line in the frequency domain by the formulation of a stiffness matrix considering mooring line tension fluctuations,
- Perform the response analysis in time domain to solve the dynamic behavior of the moored semi submersible platform. The time domain analysis allows the inclusion of all system nonlinearities and is able to produce more accurate results on semi submersible responses.
- The laboratory should be improve in order to make the experiment in future more successful and the data collected more accurate for actual condition.

CHAPTER 6

6 ECONOMIC BENEFITS

The semi-submersible is a type of floating structure that has vertical columns supporting topsides and supported on large pontoons. The structure is held in position by the use of spread mooring lines that are anchored to the seafloor. The semi-submersible has a number of unique characteristics compared with other floating structures such as a spar and TLP (tension leg platform). These advantages include: The semi-submersible has good stability because of a large footprint and low center of gravity for the topsides. The hull requires lower steel tonnage. The hull can be a new build or converted from an existing drilling semi. The semi-submersible may include drilling capability. The semi-submersible can support a large number of flexible risers or SCRs (steel catenary risers) because of the space available on the pontoons. The topsides can be integrated at quayside and thus reduce cost and save scheduling time. The semi-submersible has a relatively short to medium development schedule. The initial investment is relatively low.

The conventional fixed platform has provided the cost effectiveness and a safe method of producing offshore fields. But in deepwater, fixed platforms are less economical. The expansive cost of fixed platforms in deep water leads to subsea platforms in deep water. So, the semi-submersible rigs are used as floating production facilities for deepwater. Utilizing Floating Production Facilities (FPF) of semi submersible will make the reservoirs more economically than fixed platform development. The floating project payout and return on investment when compared to fixed platform on these economic terms offered sufficient advantage. In the 1970's, several oil companies to develop offshore fields using semi-submersible floating facilities because of the economic advantages.

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APPENDICES

Hydrodynamics 101

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Deepwater Floating Structures Symposium
Shell/Petronas
Bangi, Kuala Lumpur, Malaysia
March 5, 2009

Mod 5

GLOBAL RESPONSE OF FLOATING PLATFORMS

Topics

- Fixed vs. Floating Structures
- Importance of Global Responses
- Mean Forces (and slow drift)
- 1^{st} Order Wave Responses
- Example of Heave RAO for Semi
- Model Testing
- Full Scale Measurements

Fixed vs. Floating Structures: Reaction to Dynamic Loads

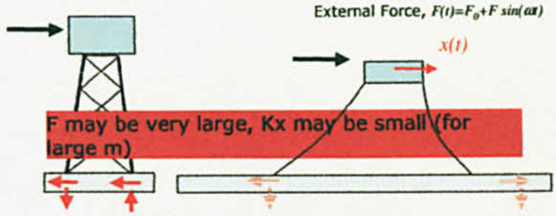
"Fixed" Structures: Static Equilibrium $\sum \vec{F} = 0$

External Force, $F(t)=F_0+F\sin(\omega t)$

Compliant Structures: Dynamic Equilibrium

$$\sum \vec{F} = m\ddot{x} + Kx$$

External Force, $F(t)=F_0+F\sin(\omega t)$



"FIXED" Structure = - Fohn "Compliant" Structure = $-Kx$

Foundation Loads

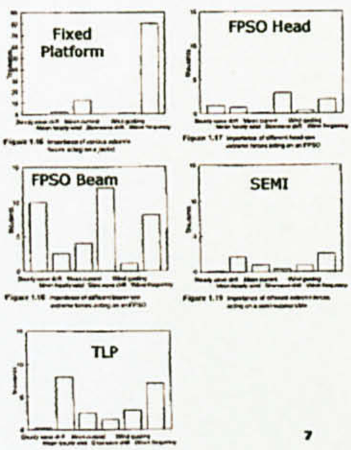
Anchor force for floating structure $Kx = \sum \vec{F} - m\ddot{x}$

K = Stiffness of mooring system

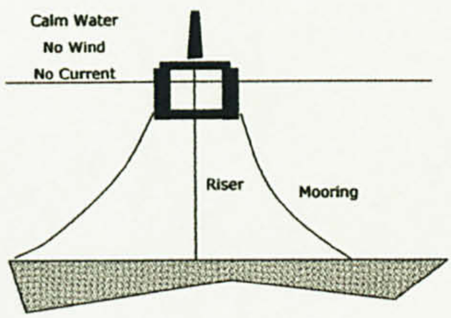
Force Components

- Waves
  - Mean (drift)
  - Wave Frequency
  - Slowly varying wave drift
- Wind
  - Mean
  - Varying (gusts)
- Current

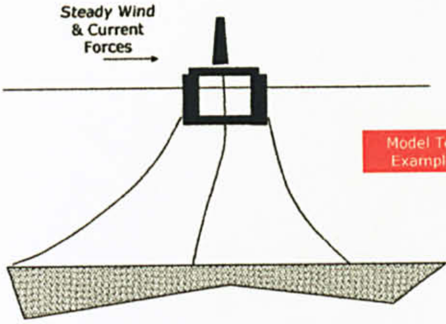
Importance of various force components



Global Motions [8]



Steady ("mean") Offset from Wind and Current 9

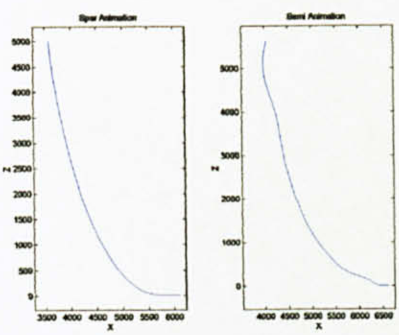


Model Test Examples

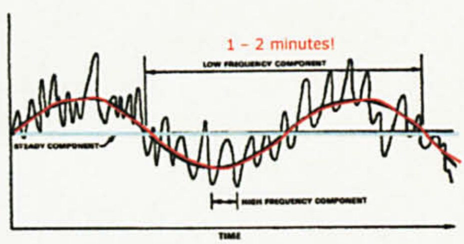
Why are we concerned about Global Responses? 10

- Maximum offsets
  - Top tensioned riser bending loads at sea floor
  - Steel Catenary Riser bending loads at sea floor
  - Maximum mooring line tension
  - TLP Setdown
  - TLP Flex joint angles for the tensons
  - Riser stroke
- Maximum angles and lateral accelerations
  - Riser bending or flex joint design at the connection to the platform
  - Lateral forces on the topsides and platform (e.g. truss spar truss loads, global loads)
- Maximum heave
  - Riser stroke
  - Mooring line dynamics
  - Riser dynamic loadings: SCR extreme bending moments at touchdown
- Cyclic loads: riser and mooring fatigue

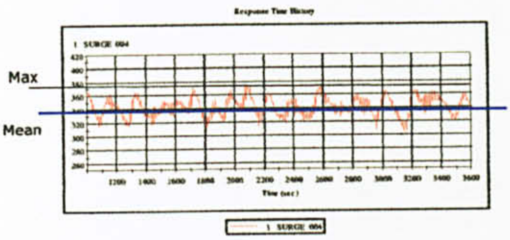
Example of Riser Response to Platform Motions: Spar vs. Semi



Mean, Slowly Varying and Wave Frequency Motions 12



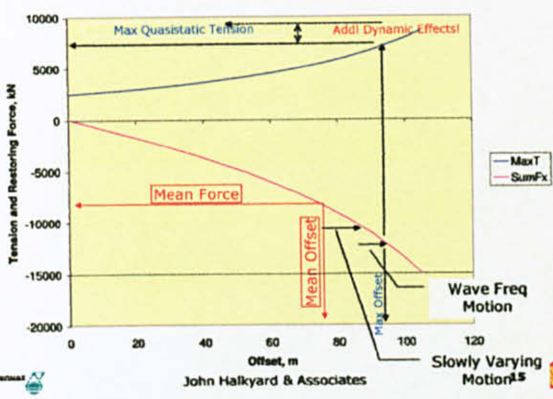
Surge of a Semi (1- hour) 13



Sources of Motion 14

- Mean
  - Wind (average part)
  - Current
  - Wave Drift
- Slowly Varying (at resonance)
  - Non-linear wave forces
  - Wind gusts
  - Current (Vortex Induced Motions)
- Wave Frequency
  - 1st Order Wave Forces

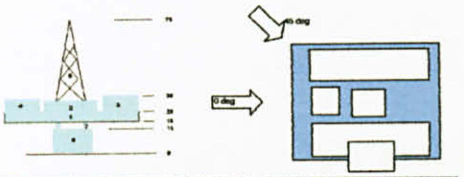
Maximum Mooring Tension 15



Mean Loads 16

- Wind
- Current
- Wave Drift

Wind Load Example



Stack	Desc	z center	Ch (ABS)	Length	Height	Area	Area Correl	Adj Area	Cs	CsChArea	Force/Ur^2
1	Lower Decks	23.5	1.1	100.0	9.0	900	1.0	900	1.00	990	605
2	Rig	31.5	1.2	30.0	7.0	210	1.0	210	1.00	252	154
3	Quarters	33.0	1.2	20.0	10.0	200	1.0	200	1.00	240	147
4	Process	32.0	1.2	20.0	8.0	160	1.0	160	1.00	192	117
5	Derrick	48.0	1.3	15.0	40.0	600	0.6	360	1.25	585	357
6	Hull	7.5	1.0	21.9	15.0	329	1.0	329	1.00	329	201
7	Deck Supports	17.8	1.1	21.9	4.0	88	0.6	53	1.00	58	35

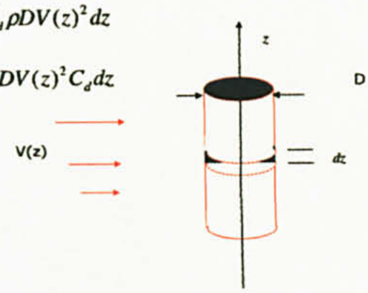
Force at 0 deg — Total Force/Ur² 1617 N/(m/s)²
Equivalent Area = Force/(.5ρaUr²) 2646 m²
Centroid of Force 28.6
Force at 45 deg ~ 1.2* Force at 0 deg — Total Force/Ur² 1940 N/(m/s)²
Equivalent Area = Force/(.5ρaUr²) 3175 m²
Force Coefficient 0.198 t/(m/s)²

Rev 14/10/08

Current Force - Drag

$$dF_c = \frac{1}{2} C_d \rho D V(z)^2 dz$$

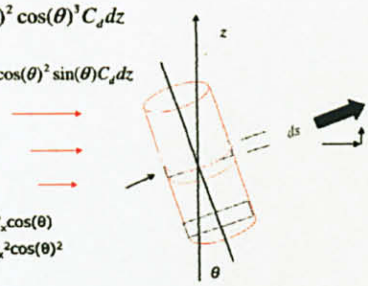
$$F_c = \int \frac{1}{2} \rho D V(z)^2 C_d dz$$



Current Force - Inclined Cylinder

$$F_{cx} = \int \frac{1}{2} \rho D V(z)^2 \cos(\theta)^3 C_d dz$$

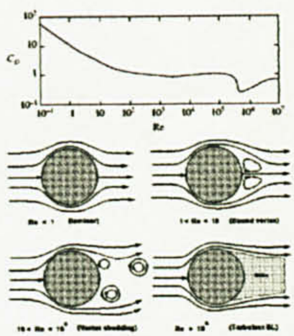
$$F_{cz} = \int \frac{1}{2} \rho D V(z)^2 \cos(\theta)^2 \sin(\theta) C_d dz$$



$V_n = V_x \cos(\theta)$

$V_n^2 = V_x^2 \cos(\theta)^2$

Steady Drag Coefficient (smooth cylinder)



$$Re = \frac{UD}{\nu}$$

$U = velocity(m/s)$

$D = Diameter(m)$

$\nu = Kinematic\_Viscosity(10^{-6} m^2/s)$

Example:

U = 1 m/s
D = 10 m
Re = 10^7
C_D = 0.8

Drag Coefficient – Shapes with Flat Surfaces (API RP 2SK)

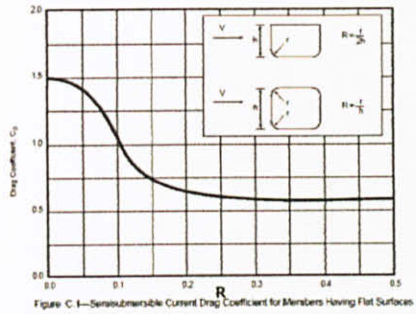
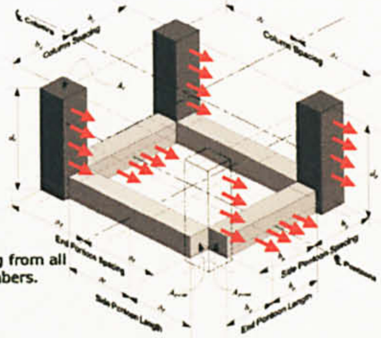


Figure C.1—Semisubmersible Current Drag Coefficient for Members Having Flat Surfaces

Assumes $Re > 10^6$, height = width

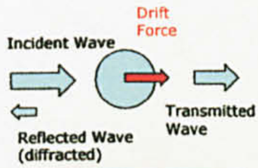


Add drag from all members.

Figure 7.41 Initial Design Underwater Model – Closed Array Pontoon, 4 Columns

Wave Drift

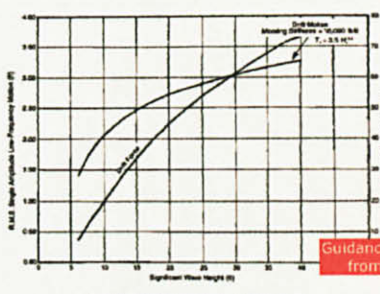
- Drift Force preserves conservation of momentum
- Magnitude is proportional to wave height squared.
- Magnitude is two orders of magnitude less than linear wave load!



The importance of wave drift is not the steady loads, but the slowly varying wave drift due to grouping which can excite large resonant responses at long periods for moored platforms in deep water!

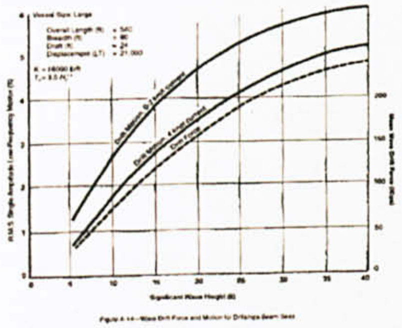
Wave Drift

Several causes of wave drift: variations in wetted area (non-linear), diffraction (reflected energy), viscous drag (third order)



Guidance on drift forces from API RP-2SK

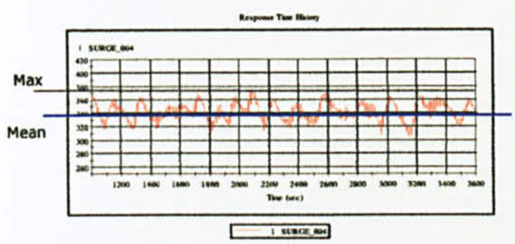
Wave Drift Particularly Important for Ship Shaped Bodies



Wave Motions

- Regular vs. Irregular Seas
  - Motion equations are solved for regular waves
  - Motions are a function of frequency
  - Real seas have many frequencies
  - Combine the motions by superposition

Surge of a Semi (1- hour)



Computing Linear Wave Motions (Equation of Motion)

$$(M_i + A_i)\ddot{x}_i + C_i\dot{x} + K_i x_i = F_i$$

$$F_i = |F_i| e^{i\omega t}$$

$$x_i = \frac{|F_i| / K_i}{\sqrt{(1-\beta^2)^2 + (2\varsigma\beta)^2}} e^{i\omega t + \varphi}$$

$$\beta = \omega / \omega_{ni}$$

$$\omega_{ni} \cong \sqrt{K_i / (M_i + A_i)}$$

A_i is the Added Mass (matrix)

The "RAO" is x_i for a unit wave amplitude!

No quadratic drag or other non-linear terms.

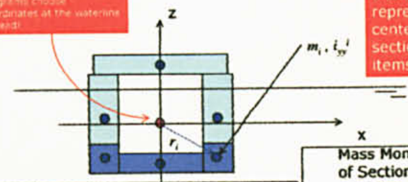
Stiffness and Mass Properties

- Stiffness ($[K]$) and Mass Properties ($[M]$) are a key input to any dynamic analysis.
- You need a distributed weight model for the floater to determine mass properties.
- Stiffness comes from Hydrostatics and from risers and mooring.

Mass Moments of Inertia

Equations of motions are simpler if coordinate system is chosen at the CG. Many programs choose coordinates at the waterline instead!

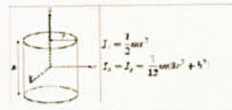
Divide structure into elements representing mass centers (e.g. ballast sections, big deck items).



Parallel Axis Theorem Yields I about any axis!

$$M_{55} = I_{yy} = \sum (m_i r_i^2 + i_{yy}^i)$$

Mass Moment of Inertia of Section (about it's own CG) = i_{yy}^i



In detailed design the mass properties spreadsheet can be vary large. Each item of equipment is defined!

Stiffness and Mass Matrix Results

Stiffness Matrix wrt ORIGIN for Chem3D Coupled Analysis

0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.000
0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.000
0.0000E+00	0.0000E+00	7.4695E+05	0.0000E+00	0.0000E+00	0.000
0.0000E+00	0.0000E+00	0.0000E+00	3.5953E+09	0.0000E+00	0.000
0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	3.5953E+09	0.0000E+00
0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00

Only hydrostatics stiffness here.. Mooring added later

Mass Matrix wrt ORIGIN for Chem3D Coupled Analysis

5.1277E+06	0.0000E+00	0.0000E+00	0.0000E+00	-1.0152E+09	0.0000E+00
0.0000E+00	5.1277E+06	0.0000E+00	1.0152E+09	0.0000E+00	0.0000E+00
0.0000E+00	0.0000E+00	5.1277E+06	0.0000E+00	0.0000E+00	0.0000E+00
0.0000E+00	1.0152E+09	0.0000E+00	4.9509E+11	0.0000E+00	0.0000E+00
1.0152E+09	0.0000E+00	0.0000E+00	0.0000E+00	4.9509E+11	0.0000E+00
0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	1.1913E+10

Off-diagonal mass terms are generally zero for symmetrical structure, here they are not because coordinate system is not a CG!

Linear Waves Forces Slender Body

- Fixed Platform – Morrison's Equation
- Floating Body – Modified Morrison's Equation

Morrison's Equation for Fixed Cylinders

$$dF_{fixed} = \left[\rho A C_M \frac{\delta u}{\delta t} + \frac{1}{2}\rho D u|u|\right]dz$$

Hydrodynamic Force on a Slender Member – Floating Body 34

$$\vec{F} = \iint p\vec{n}ds + \frac{1}{2}\rho D C_d \vec{u}_n|u_n|$$

$$\vec{F} = \iint p_0\vec{n}ds + \rho A_c C_a(\vec{a}_n - \ddot{\vec{x}}) + \frac{1}{2}\rho D C_d \vec{u}_n|u_n|$$

$$\iint p_0\vec{n}ds = \rho A_c \vec{a}_n$$

$$\vec{F} = \rho A_c(1+C_a)\vec{a}_n - \rho A_c C_a \ddot{\vec{x}} + drag$$

$$A_c = \pi D^2/4$$

"Froude-Krlylov" Force.
This approximation only for slender members compared to wavelength!

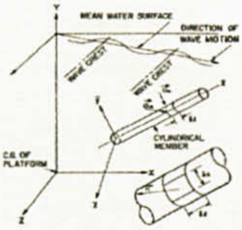


Fig. 11 Nomenclature for fluid forces on a cylinder

Move the inertial term (radiation force) to the left hand side of the equations of motion 35

$$\vec{F} = \rho A_c(1+C_a)\vec{a}_n - \rho A_c C_a \ddot{\vec{x}} + drag$$

$$\vec{F}_{excitation} = \rho A_c(1+C_a)\vec{a}_n$$

$$(M_i + A_i)\ddot{x}_i + C_i\dot{x} + K_i x_i = F_i$$

A_i is the "added mass"

Morrison vs. Modified Morrison for slender members

- Exciting force is the same as for fixed cylinders
- Added Mass must be added to solve dynamic equations. Use C_a to compute added mass.
- $C_M=1+C_a$

Slender vs. "non-slender" members

Wave Loading Regime

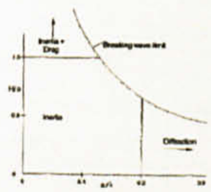


Figure 3.12 a) Wave loading regime: first order force (from Standing, 1986)

Wave Loading Regimes

- Normally added mass coeffients are frequency dependent.
- If the Diameter/ Wavelength ratio is less than 5 ... assume these are constant and use slender body theory.

Example of when to use slender body theory

- Diameter = 12 m
- Wave Period = 10 sec
- Wave length = 1.56*102 = 156 m
- 156/12 = 13 > 5
- OK to use slender body theory

For semi-submersibles, spars, TLPs it is generally ok to use slender body theory for design and extreme waves (100-year storms) but not for operational or fatigue sea states.

Wave Loads on Non-Slender Bodies

- Requires calculation of flow for each wave frequency..
- This is divided into two problems
  - o Diffraction (body fixed)
    - Excitation forces (like Morrison only frequency dependent C_M!)
  - o Radiation (body moving)
    - Added Mass (C_a is frequency dependent)
    - Damping

Solution Process: Basic Equations

Velocity Potential *[$\varphi(x,y,z)$]* **Satisfies Laplaces Equation:**

$$\vec{V} = \Delta\varphi = \hat{i}\frac{\delta\varphi}{\delta x} + \hat{j}\frac{\delta\varphi}{\delta y} + \hat{k}\frac{\delta\varphi}{\delta z}$$

$$\frac{\delta^2\varphi}{\delta x^2} + \frac{\delta^2\varphi}{\delta y^2} + \frac{\delta^2\varphi}{\delta z^2} = 0$$

Boundary Conditions

$$\frac{\delta\varphi}{\delta n} = \vec{U} \bullet \hat{n}$$ Velocity matches body on boundary

$$\frac{\delta^2\varphi}{\delta t^2} + g\frac{\delta\varphi}{\delta z} = 0 \rightarrow (z = 0)$$ Free surface

Additional boundary condition: wave energy radiates outward...

Solution Process: Basic Equations

Velocity Potential $[\varphi(x,y,z)]$ is split to simplify solution

$$\varphi = \varphi_{incident} + \varphi_{diffraction} + \varphi_{radiation}$$

- "Incident" = Wave without body
- "Diffraction" = Result of Fixed Body
- "Radiation" = Result for body moving in calm water
- Total is the sum of all three.

Finding φ (e.g. WAMIT)

Velocity Potential May be Found from Integral Equation over the Surface of the Body...

$$\varphi(x_1, y_1, z_1) = \frac{1}{4\pi} \iint_{Surface} \left(\varphi(x, y, x) \frac{\partial G}{\partial n} - G \frac{\partial \varphi(x, y, z)}{\partial n} \right) ds$$

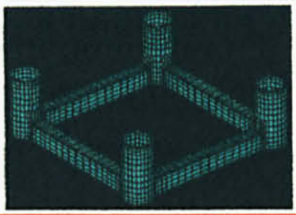
$$G = G(x, y, z \mid x_1, y_1, z_1)$$

"G" is a special "Green's Function" which is the velocity potential at point (x,y,z) of a pulsating source of unit amplitude at point (x_1,y_1,z_1). It satisfies Laplace's equation and the free surface an radiation conditions. Closed form solutions are in the text books!

The integral equation is descretized for numerical solution. The body surface is divided into N facets and the linear matrix equation is solved either by direct reduction or by a iterative method:

$$\varphi_i = \frac{1}{4\pi} \sum_{j=1}^{N} \left\{ \varphi_j \left(\frac{\partial G}{\partial n} \right)_{i,j} - G_{i,j} \left(\frac{\partial \varphi}{\partial n} \right)_j \right\} A_j$$

Typical Mesh for Solving Green's Integral Equation (WAMIT)



The number and size of elements affects accuracy. Use mesh dimensions about 1/10 of the shortest wavelength of interest!

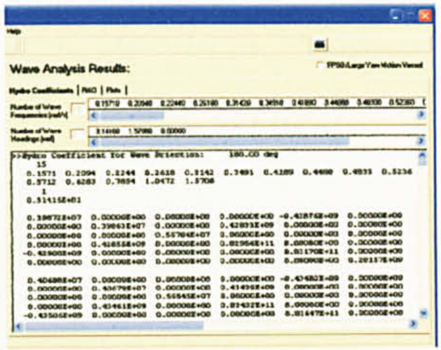
Output for Radiation Diffraction Program

- The matrix is solved for every wave frequency specified.
- Velocity Potential on Surface is Used to Compute Pressures
- Pressures are integrated to get global forces

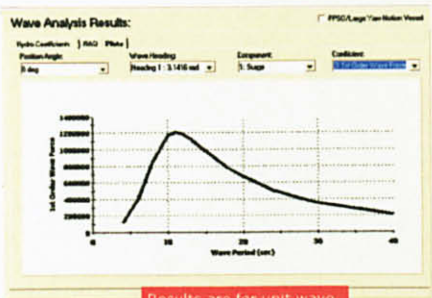
Output for Radiation Diffraction Program

- Excitation Force Coefficients (fixed body)
  - Hydrostatic stiffness (a bonus)
  - Froude-Krylov Force (from $\varphi_{incident}$)
  - Diffraction Force (from $\varphi_{diffraction}$)
- Radiation Force Coefficients (Moving Body)
  - Added Mass (from $\varphi_{radiation}$)
  - Damping
- Mean Drift Coefficients

Note: WAMIT does not separate these! There is one excitation force provided.

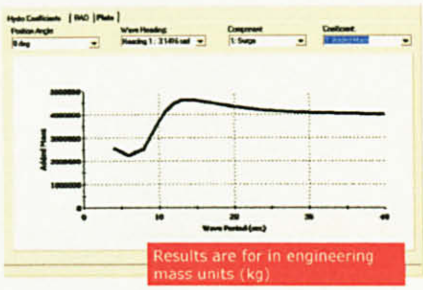


Example Output (Wave Excitation Forces)



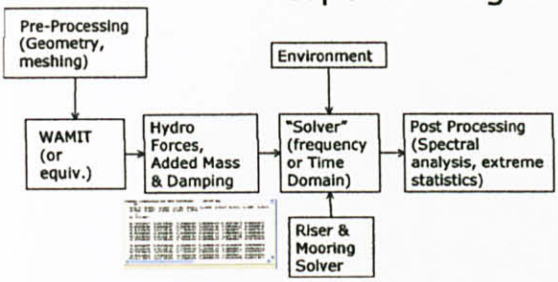
Results are for unit wave amplitude

Example Output (Added Mass)



Results are for in engineering mass units (kg)

Anatomy of Typical Global Response Program



Why the ratio of column to pontoon area makes a difference

EXAMPLE: HEAVE RAO FOR A SEMI

Deepwater Linear Wave Properties

$$\eta(x,t) = A\sin(\omega t - kx)$$

$$p(x,z,t) = -\rho g z + \rho g A e^{kz}\sin(\omega t - kx)$$

$$u(x,z,t) = \omega A e^{kz}\sin(\omega t - kx)$$

$$\dot{u}(x,z,t) = \omega^2 A e^{kz}\cos(\omega t - kx)$$

$$w(x,z,t) = \omega A e^{kz}\cos(\omega t - kx)$$

$$\dot{w}(x,z,t) = -\omega^2 A e^{kz}\sin(\omega t - kx) \qquad k = \frac{2\pi}{\lambda}$$

Heave Forces on Barge and Spar (or semi column)

Forces are due to pressures on keel

Spar = Deep Draft, hence small forces & small heave!!

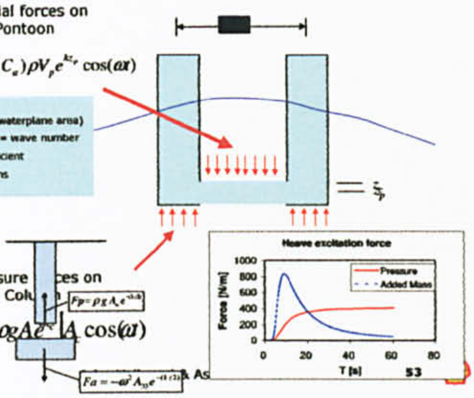
Forces are due almost entirely to Wave Pressure Acting on Bottom

Heave Forces on a Semi 53

Inertial forces on Pontoon

$$F_p = -A\omega^2(1+C_a)\rho V_p e^{kz_p}\cos(\omega t)$$

A = Wave amplitude
Ac = Area of Columns (waterplane area)
ω = wave frequency; k = wave number
Ca = Added Mass Coefficient
Vp = Volume of Pontoons



Pressure forces on Column

$$F_c = \left|\rho g A e^{kz}\right| A_c \cos(\omega t)$$

Wave Force Example 54

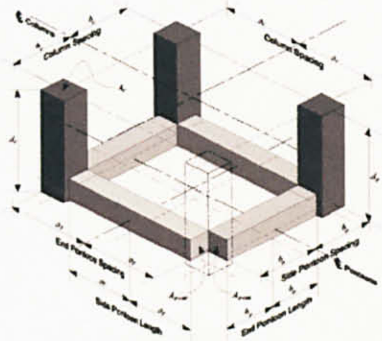


Figure 7.41 Initial Design Underwater Model – Closed Array Pontoon, 4 Columns

Closed Form Heave Force and RAO (using slender body assumptions) 55

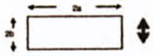
$$F_3 = \rho g \eta_a \left\{ A_{wp} e^{-kd_c}\cos(ka_c) - 4A_p(1+C_a)e^{-kd_p}\left\{\sin(ka_p) + ka_p\cos(ka_c)\right\}\right\}\sin(\omega t)$$

$$RAO = \frac{|F3| / (\rho g A_{wp}\eta_a)}{\sqrt{(1-\beta^2)^2 + (2\zeta\beta)^2}}$$

Nomenclature 56

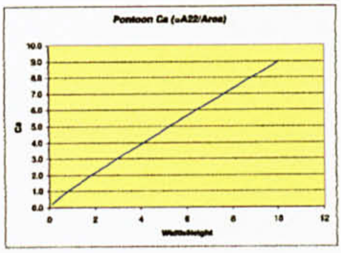
- A_{wp} = Total waterplane area = $4A_c$
- d_c = column draft (= $-z_b$ in Faltinsen)
- d_p = pontonnmidsection draft (= $-z_m$ in Faltinsen)
- C_a = Pontoon vertical added mass coefficient = $A_{33}/(\rho A_p)$
- A_p = Pontoon cross section area
- a_p = B/2 = Half-Length of Pontoons
- a_c = l/2 = Half-Spacing of Columns
- β = ratio of ω/ω_n
- ζ = critical damping ratio

Definition of Ca for Pontoon Heave 57



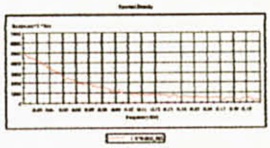
a/b	A22/([illegible])	Ca A22/Vol
inf	1	
10	1.14	9.8
5	1.21	4.8
2	1.38	2.1
1	1.51	1.2
0.5	1.7	0.7
0.2	1.98	0.3
0.1	2.25	0.2

Data from Sarpkaya, Table 2.3



Example: Spreadsheet

Wind Gust Spectrum (RP2A) 58



$$S(f) = \frac{320 \times \left(\frac{U_o}{32.8}\right)^2 \times \left(\frac{z}{32.8}\right)^{0.45}}{(1+\tilde{f}^n)^{\frac{5}{3n}}} \qquad (2.3.2\text{-}4)$$

$$\tilde{f} = 172 \times f \times \left(\frac{z}{32.8}\right)^{\frac{2}{3}} \times \left(\frac{U_o}{32.8}\right)^{-0.75} \qquad (2.3.2\text{-}5)$$

where

$n = 0.468$,

$S(f)$ (ft^2/s^2/Hz) = spectral energy density at frequency f (Hz).

z (ft) = height above sea level.

U_o (ft/s) = 1 hour mean wind speed at 32.8 ft above sea level.

Considerations with Model Testing

- Scale Selection
  - Model size (weight of model & ballasting), truncated moorings (shallow water), size of waves, accuracy of instruments
- Mooring
  - Non-linear behavior
- Wind and Current
  - Current turbulence may be unrealistic
  - Using string vs. actual wind or current
- Waves
  - Matching spectra or max wave height?

Scaling

Table 13.1 Common dimensionless quantities in offshore engineering

Symbol	Dimensionless number	Force ratio	Definition
Fr	Froude Number	Inertia/Gravity	u^2/gD
Re	Reynolds Number	Inertia/Viscous	uD/ν
Eu	Euler Number	Inertia/Pressure	$p/\rho u^2$
Ch	Cauchy Number	Inertia/Elastic	$\rho u^2/E$
KC	Keulegan Carpenter Number	Drag/Inertia	uT/D
St	Strouhal Number	Eddy/Inertia	$f_v D/u$

Froude Scaling is Normally Used. This satisfies the KC and Strouhal scaling as well, but Reynold's (viscous effects) are not scaled. Caution when drag and damping are important!

Converting from Prototype to Model Units (Froude Scaling):

$$L_m = \frac{L_{prototype}}{\lambda} (length)$$

$$U_m = \frac{U_{prototype}}{\sqrt{\lambda}} (velocity)$$

$$F_m = \frac{F_{prototype}}{(\rho_{sw} / \rho_{fw})\lambda^3} (force)$$

$$a_m = a_{prototype} (acceleration)$$

Example of Scaling Ratios

Variable	Symbol	Scale factor	λ=50	λ=100
All linear dimensions	D	λ	50	100
Fluid or structure velocity	u	$\lambda^{1/2}$	7.07	10
Fluid or structure acceleration	$\dot{u}$	1	1	1
Time or period	t	$\lambda^{1/2}$	7.07	10
Structure mass	m	λ^3	1.25E3	1.0E6
Structure moment of inertia	I	λ^5	3.125E8	1.0E10
Section moment of inertia	I	λ^4	6.25E4	1.0E8
Structure displacement volume	V	λ^3	1.25E3	1.0E6
Structure restoring moment	C	λ^4	6.25E4	1.0E8
Force	F	λ^3	1.25E3	1.0E6
Moment	M	λ^4	6.25E4	1.0E8
Stress	σ	λ	50	100
Spring constant	K	λ^2	2500	1.0E4
Wave period	T	$\lambda^{1/2}$	7.07	10
Wave length	L	λ	50	100
Pressure	p	λ	50	100
Gravity	g	1	1	1
Fluid density	ρ	1	1	1
Fluid kinematic viscosity	ν	1	1	1
Reynolds number	Re	$\lambda^{3/2}$	353.6	1000
Keulegan Carpenter number	KC	1	1	1

Selected Model Basins

No.	Facility	Size	Depth	Centre hole	Type waves	Periods	Wave height	Tow speed	Current	Wind
		(m)	(m)	(m)		(s)	(m)	(m/s)	(m/s)	(m/s)
1.	Bassin d'Essais des Carènes, France www.bdsr.org/hydrolab	545 × 15	7	none	long	0.3–5.0	1.0	12		
2.	CEHIPAR, Madrid, Spain www.cehipar.es/English	152 × 30	5	5	long and short	1.7 m–15 m length	0.9	5.0		
3.	Danish Hydraulic Institute, Denmark www.dhi.dk	30 × 20	3	12	long and short	0.5–4.0			none	fans
4.	Danish Maritime Institute, Lyngby, Denmark www.danmar.dk	240 × 12	5.5	none		0.5–7.0				fans
5.	DTMB (MASK), CDNSWC, MD www.dt.navy.mil	79.3 × 73.2	6.1	none	long and short	0.5–3.0			none	fans
6.	DTMB, CDNSWC, MD (Deep Basin) www.dt.navy.mil	846 × 15.5	6.7	none	long	1.0–3.0				
7.	IMD, NRC, Newfoundland www.nrc.ca/imd/	200 × 12	7	none	long and short	0.5–10				fans
8.	KRISO, Korea www.kriso.re.kr	56 × 30	4.5	12	long and short	0.5–5.0	0.8	-	0.5	20.0
9.	MARIN, The Netherlands (Seakeeping and Manoeuvring) www.marin.nl	170 × 40	5		long and short		0.45	6.0		

Updated Model Basin List for Deepwater with Contact info…

Basin/Location	Water Depth	Contact
Offshore Technology Research Center, Texas A&M University, College Station, Texas	5.8m / 16.7 m (pit)	rsmercier@tamu.edu
David Taylor Model Basin, Carterock, MD (US Navy facility)	6.7 m	Thomas.fu@navy.mil
IMD Offshore Basin, Newfoundland, Canada	3.2 m	don_spencer@oceaniccorp.com
IMD Towing Tank, Newfoundland	7 m	Same as above
Laboceano, Federal University of Rio de Janeiro, Brazil	15 m / 24 m (pit)	acfernandes@alternex.com.br
Maritime Research Institute Netherland (MARIN), Ocean Basin	10.5 m / 30.5 m (pit)	b.buchner@MARIN.NL
Force Technology, Denmark	5.5 m (towing tank)	crs@force.dk
Marintek, Norway	10 m	Carl.T.Stansberg@marintek.sintef.no
Shanghai Jiao Tong University Deepwater basin, Shanghai	10m / 40 m (pit)	rpli@sjtu.edu.cn

Example: MARIN (Netherlands)

Model size range

- Ship model length of 3 - 6 m.
- Floating structures of any kind, size depending on water depth and wave conditions (usually between 0.2 m for buoys and 4 m for platforms).

Depth: 10.5M+20m (in pit)

Test capabilities

- Offshore structure models, fixed, moored or controlled by dynamic positioning in waves, wind and current.
- Captive or free sailing manoeuvring tests in shallow water.

For more information please contact the department Offshore
T +31 317 493 465
E Offshore@marin.nl

Full Scale Measurements

Figure 2: Marco Polo Instrumentation

Full Scale Measurements

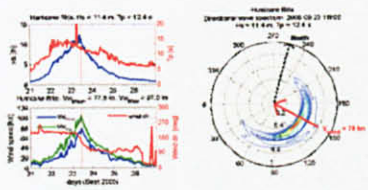


Figure 1: Measured waves & wind and calculated wave spreading on Marco Polo

Full Scale Comparisons

- Wave and wind responses generally show agreement with predictions when actual environment (e.g. spreading) is considered.
- Real environments are generally less sever that the assumed design environment.. E.g. non-colinear.
- Damping appears higher in real environments.

Some Programs for Global Analysis

- WAMIT (www.wamit.com)
- SESAM Suite (www.dnvsoftware.com)
- ASAS/AQWA (http://www.ansys.com/products/aqwa.asp)
- DIODORE (http://www.principia.fr)
- MOSES (http://www.ultramarine.com)

Questions?