Computer Aided Design (CAD) of Tension Leg Platform (TLP) Hull for Deepwater Operation

by

Khairul Izzat Bin Amriem

Dissertation submitted in partial fulfilment of
the requirements for the
Bachelor of Engineering (Hons)
(Mechanical Engineering)

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
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Approved by,

____

(AP Dr. Fakhruldin Bin Mohd Hashim)

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
June 2010

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 of persons.

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(Khairul Izzat Bin Amriem)

ABSTRACT

Tension Leg Platform (TLP) is a floating structure, vertically moored to seabed by a system of pre-tension tethers held in tension by the buoyancy of the hull. This method restrain vertical motions (heave, pitch and roll) but allows horizontal movements (sway, yaw and surge). The objective of the project is initiating a design library of floaters by developing a Computer Aided Design (CAD) model of TLP. This project involved numerical analysis and 3D Modelling. The numerical analysis that has been done is the forces acting on TLP, surge and heave by using Morison equation and the Response Amplitude Operator (RAO). The study on various dimension of the hull of the TLP was conducted and the result indicates the effect of the various dimension of the TLP's hull to the response of the TLP. The CAD model was developed by using an engineering software name CATIA. Then the animation simulation was done by using ADAMS. The challenge in this project is to design the TLP as it will affect the performance of the structure. Lastly, it is recommended that other parameters are to be analyzed in the future to improve the applicability of research.

ACKNOWLEDGEMENT

First and foremost, pray to god the Al-Mighty for His bless and love, giving me all the strength to complete the final year project. After everything had been planned, efforts were made, the project managed to be finished within the time frame. Without the help and guidance from other people, this study would not be able to complete successfully. Hence, on this page I would like to express my gratitude to those parties who had directly or indirectly involved in helping me for this project.

I would like to dedicate this project as a token of gift to my beloved parents, Amriem b Rasid and Puziah bt Dzulkifli for their support and pray.

My truly deepest appreciation goes to my supervisor, AP Dr Fakruldin Mohd Hashim. Without his guidance and patience, I would not succeed to complete the project. His advices were of valuable and priceless. To the Final Year Research Project Coordinator, Mr Saravanan and for provide me with all the initial information required to begin the project.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.0 INTRODUCTION

1.1 Background of Study

For oil and gas offshore Exploration and Production (E&P) operations in deep waters, floating platforms such as Tension Leg Platforms (TLP) are used. Floating structure is maintained by a variety of mooring line types and systems to keep it stationary at desired locations.

TLP is a buoyant platform held in a place by a mooring system. TLP’s are similar to conventional platform except that it is maintained on location through the use of moorings held in tension by the buoyancy of the hull. The mooring system is a set of tension legs or tendons attached to the platform and connected to a template or foundation on the sea floor. The template is held in place by piles driven into the sea floor. This method allows the horizontal movement but dampens the vertical movement of the platform. The topside facilities of TLP and most of the daily operations are the same as the conventional platform.

Historically**,** TLP's have been in use since the early 1980s. The first TLP was built for Conoco's Hutton field in the North Sea in the early 1980s. The hull was built in the dry-dock at Highland Fabricator's Nigg yard in the north of Scotland, with the deck section built nearby at McDermott's yard at Ardersier. The two parts were mated in the Moray Firth in 1984. Since that time, the offshore Industry has gradually utilized the potential of the TLP unit to assist the offshore operations [1].

1.2 Problem Statement

1.2.1 Problem Identification

Concept design and selection, which is part of the Front End Engineering Design (FEED), is a critical stage in the design of offshore floaters. Such an exercise is based on a structured approach to meet specific requirement or criterion. Extensive iterative process is typically being engaged in such an exercise. In addition, determination of specific parameters with respect to scaled model testing and calibration is not always straightforward, and involves cross referencing between numerical analysis and experimental testing. They are required to be properly designed in order to keep it in position at certain water depth when they are subjected to forces.

1.2.2 Significance of the Project

For oil and gas industries, deepwater operation becomes more important. This is when the development of deepwater technology comes. Floating structures is one of the deepwater technologies that have been developed. However, there is no development of Computer Aided Design (CAD) models of various floaters for the selection of floaters to be use in certain oil and gas field. This work is basically an initial effort to establish a design library of CAD models of various floaters to help the future floater’s selection for PETRONAS as we know that most of the reservoirs now are in deepwater.

1.3 Objective and Scope of Study

The main objectives of this research are:

- Initiate design library of offshore floaters.
- To develop a CAD model of the hull of Tension Leg Platform (TLP).
- Investigate the behavior of TLP (offset) when the geometry of the structure changes.

The objectives of this study are to design and develop a CAD model of TLP based on the specific requirement and investigate the behavior of the TLP by using the simple numerical analysis and to observe the motion (CATIA and ADAMS). For this project, only the hull of the TLP is considered in the analysis. In order to achieve this objective, a few tasks and research need to be carried out by collecting all technical details regarding the existing TLP in the world and by studying the fundamental aspects of the platforms. A study in using the CAD and ADAMS as the design tools also need to be done in to achieve this objective.

The project is subjected to certain assumption, as to be mentioned in the following:

- Dimensional platform (draught, diameter of member, height, etc) and environmental data (wave height, significant wave height, etc) are assumed to certain values but based on real dimensional data and site condition.

- There are no effects of wind speed in the study.

CHAPTER 2
LITERATURE REVIEW

2.0 LITERATURE REVIEW

Due to urbanization, the production and consumption of oil and other petroleum products have been rapidly increasing over the years. As a result, oil companies are motivated to go to deeper ocean to extract oil and other resources. This interest in deep water drilling has led to the in-depth study and analysis of deep water structures, like the Tension Leg Platform (TLP). TLPs are compliant structures consisting of a foundation, hull and Tendons. It is vertically moored at each corner by tendons. Each tendon is pre-tensioned so that it does not go slack due to variations in the extreme ocean environment. A picture of a typical TLP is shown in Figure 1[1].

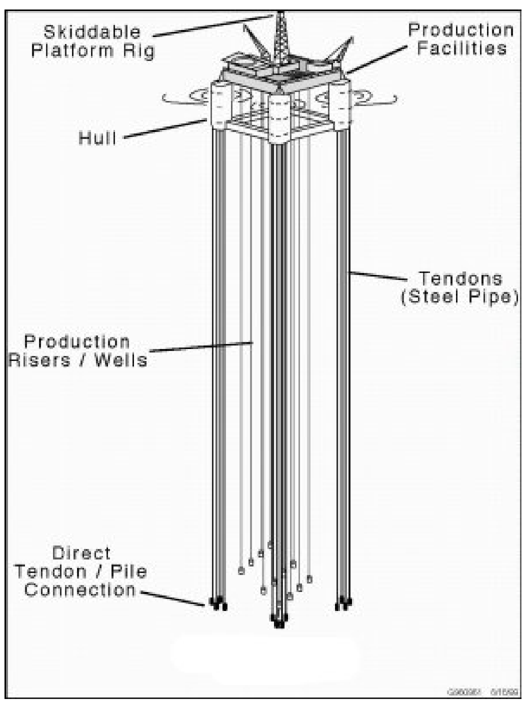


Figure 1: Tension Leg Platform (TLP) [1]

2.1 TLPs Compliant Structure

The foundation is the link between the seafloor and the TLP. Most foundations are templates laid on the seafloor, then secured by concrete or steel piles driven into the seafloor by use of a hydraulic hammer, but other designs can be used such as a gravity foundation. The foundations are built onshore and towed to the site [1].

The hull is a buoyant structure that supports the deck section of the platform and its drilling and production equipment. A typical hull has four air-filled columns supported by pontoons, similar to a semi-submersible drilling vessel. The buoyancy of the hull exceeds the weight of the platform, requiring moorings or tension legs called tendons to secure the structure to the seafloor. The columns in the hull range up to 100ft (30.48m) in diameter and up to 360ft (109.728m) in height. The hull (vertical column) provides the buoyancy for the TLP to float in the water and supports the platform. The hull contains several of the mechanical systems needed for platform operation. Hull-related equipment includes ballasting and trim, drain and bilge systems including emergency drain, HVAC, and utility systems [1, 2].

Deck structure is a multilevel facility consisting of trusses, deep girders and deck beams for supporting operational loads [2].

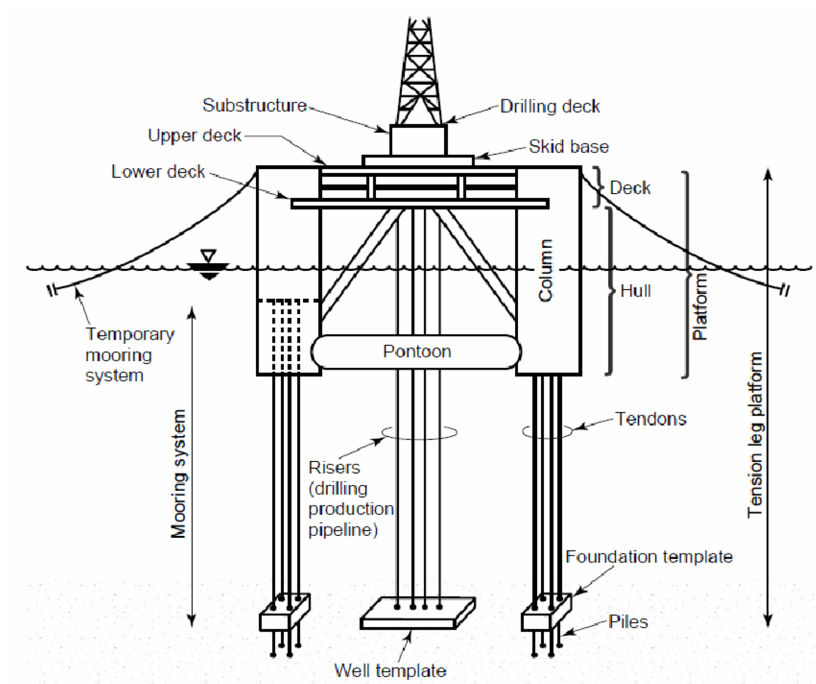


Figure 2: Tension Leg Platform terminology [2]

Tension Legs (tendons) are tubular that secure the hull to the foundation. This is the mooring system for the TLP. Tendons are typically steel tubes with dimensions of 2-3 ft in diameter with up to 3 inches of wall thickness, the length depending on water depth. A typical TLP would be installed with as many as 16 tendons [1].

The pontoons are flooded during inshore construction, module mating, and TLP installation. De-ballasting is done through pumps located in the caissons. During normal operations, the pontoons are dry [2].

2.2 6 Degree of Freedom (DOF) Motions of a Floating Rigid Body

A TLP is subjected to three translational degrees of freedoms and three rotational degrees of freedom which are surge, sway, heave, yaw, pitch, and roll. Surge, sway and yaw natural frequencies tend to be low, on the order of 1/30 to 1/200 Hz. Heave, pitch and roll natural frequencies tend to be much higher, on the order of 1/5 to 1 Hz. All six degree of freedom contributes to the important of TLP responses [3].

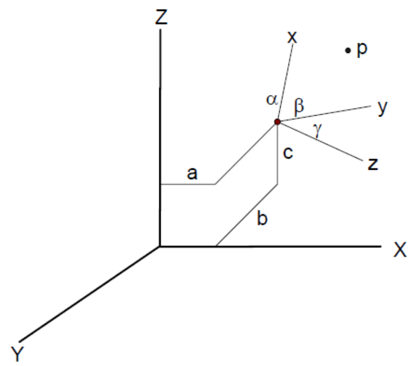


Figure 3: Fixed and Moving Coordinates for a Rigid Body Motion [3]

2.3 Motion of Floating Structure

The motion of floating structure depend on the 6-degree of freedom of the structure [4].

The 6 motions are:

1. Heave and Yaw are the translational and rotational movement with respect to Y-axis.
2. Sway and Pitch are the translational and rotational movement with respect to Z-axis.
3. Surge and Roll are the translational and rotational movement with respect to X-axis.

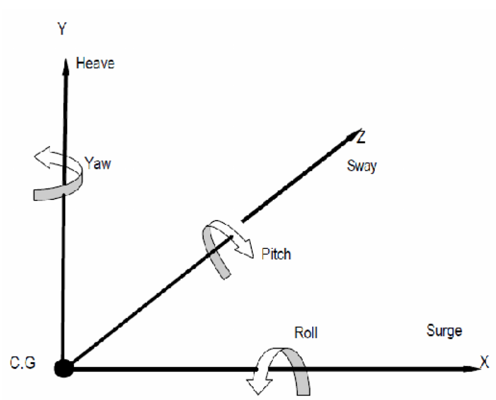


Figure 4: Motion of Floating Structure [4]

However the tendon system restrains motion of the platform in response to wind, waves, current, and tide to within specified limits. By restraining the platform at a draft deeper than that required to displace its weight, the tendons are ideally under a continuous tensile load that provides a horizontal restoring force when the platform is displaced laterally from its still water position. The tendon system limits heave (almost eliminated), pitch, and roll response of the platform to small amplitudes while its softer transverse compliance restrains surge, sway, and yaw response to within operationally acceptable limits. But the vertical degree of freedom (heave, pitch and roll) can be neglected because the vertical degree of freedom is fixed due to the pretension of the tendons. The only significant motions for TLP are surge and sway [2, 5].

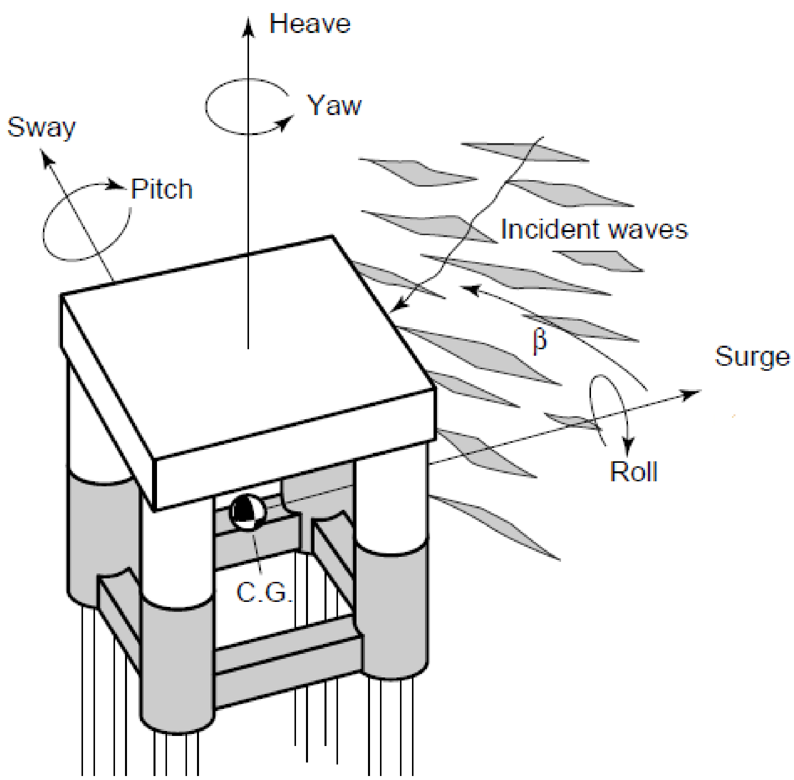


Figure 5: TLP Motion Nomenclature [8]

2.4 Deepwater

With the recent advances in exploration and production technology, the minimum water depth at which a deepwater field starts has had to be redefined. Until 18 years ago, from a European perspective, 200m and deeper is considered as deepwater [6].

When viewed globally the answer is not so simple. The Gulf of Mexico, Brazil and West Africa have seen deepwater records tumble as discoveries and production has come from depths greater than 1,000m. In April 1998 the record was pushed to 1,709m [6].

Therefore, 200m is simply not considered to be deepwater anymore especially as various organizations have their own definitions ranging beyond 500m. To take this into account most deepwater online database drawn the limit for the definition of "deepwater" at 300m [6].

The simple graph below shows the worldwide trend in maximum water depths within each year band [6].

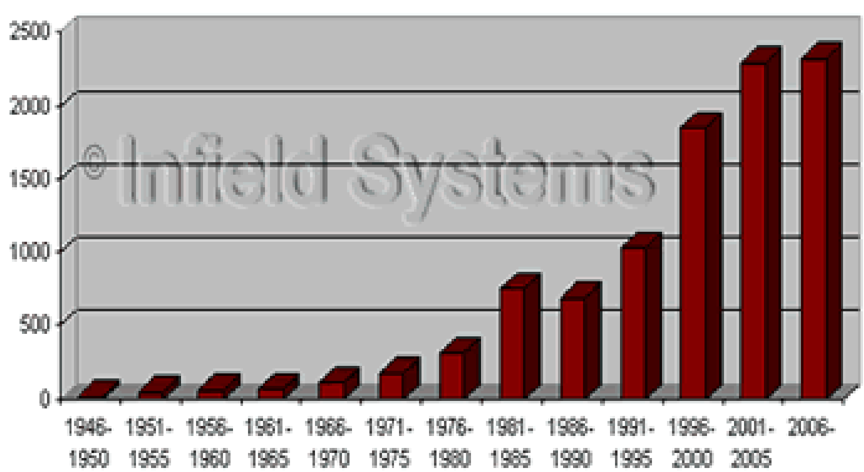


Figure 6: Maximum field water depth (meters) achieve by year range [6]

2.5 Wave Force Measurement

For the purpose of wave force measurement, Morison equation is used. The equation was developed by Morison , O'Brien, Johson and Shaaf (1950). The Morrison equation assumes the force to be composed of inertia and drag force linearly added together. The components involve an inertia coefficient and a drag coefficient which must be determined experimentally. The Morrison equation is applicable when the drag force is significant. This is usually the case when a structure is small compared to the water wave length [7].

Morrison equation is applied by implementing the following formula:

$$f = C_M A_1 \frac{\partial u}{\partial t} + C_D A_D |u| u \quad [7]$$

Where,

$$A_1 = \rho \frac{\pi}{4} D^2 \quad [7]$$

$$A_D = \frac{1}{2} \rho D \quad [7]$$

D = cylinder diameter

$\frac{\partial u}{\partial t}$ = local water particle acceleration

C_M = inertia coefficient

C_D = drag coefficient

P = sea water density

Numerous works had been carried out to compute the amount of forces acting upon an offshore structure. Surge and heave analysis were carried out to analyze the responses of the TLP upon varying dimension of TLP. The data can be referred at Appendix A and Appendix B.

CHAPTER 3
METHODOLOGY

3.0 METHODOLOGY

The methodology is formulated based on Morris Asimov's morphology of design [8]. The research methodology and project activities are summarized in a flow chart as shown in figure 8.

3.1 Problem Definition

It is vital to understand the problem before finding the right solution. This first design process will determine the direction of the problem solving process. The output of problem definition process is a control document named as Product Design Specification (PDS). For the preliminary, various design of TLP is being collected. The general features for the preliminary are taken from the existing TLP, Brutus that has been developed by Shell Deepwater Development as the basis. The PDS for the TLP is as follows:

General Features:

- Configuration : A fourcaissoned square TLP
- Simpler to build in a shipyard than other geometric configurations.
- Allows for a large deck area
- Good stability features

3.2 Conceptual Design

Before producing the design concepts of the TLP, we need to decompose the mechanical system into its subassemblies and components into physical decomposition. The next of step of this phase is to produce design concepts that would perform as required.

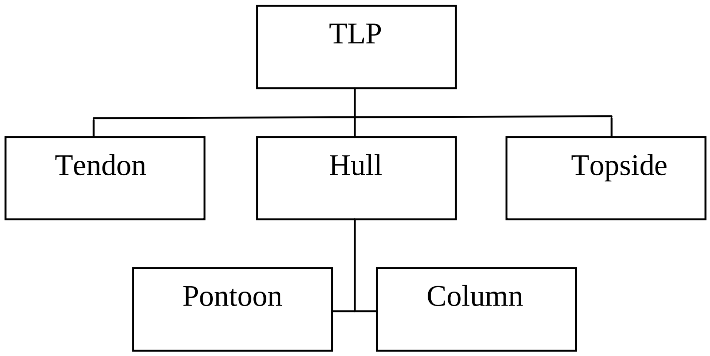


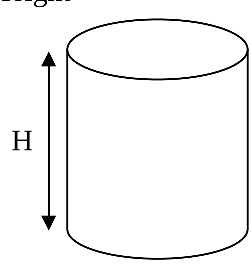
Figure 7: Physical decomposition of TLP

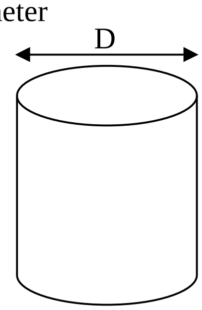
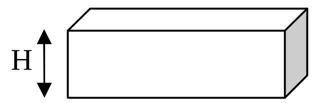
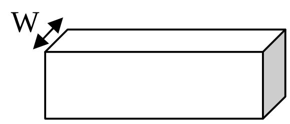
The hull and the pontoon will be consider as critical parameters to design the TLP

3.2.1 Design Concept Generation

Table 1 shows the design concept generation

Table 1: Design variable

COMPONENT	**Variable**
1. Column Cylinder type	• Height 

	• diameter 
2. Pontoon Square type	• height 
	• Width 

For the design concept, the parameter for the column and will be varies. The height of the column is varied from 40m to 60m. The diameter of the column is varied from 17m to 27m.

3.3 Analysis

Analysis is performed for each variation of the design to determine the system's behavior and determine maximum parameters for the TLP. The parameters that will be analyzed are the offset of the motion of TLP when subjected to force (wave) in surge, heave, and pitch degree of freedom.

To establish any relationship or data analysis with the simulation, a few assumption and structural idealization must be made. This is to ensure that the simulation is in control and only the particular parameters will be tested. For this test, initial pre tension in all tethers is equal and remains unaltered over time. It is quite large in comparison to the changes that occurred during the life time of TLP. However, total pretension changes with the motion of platform. Wave forces are estimated at the instantaneous position of the platform by Morison’s equation with Airy’s linear wave theory. Wave is considered to act unidirectional in the surge direction only. Wave diffraction effect and wave forces on the tethers are assumed to be negligible. The low frequencies drift oscillation in surge and high frequency tension oscillation of the tethers are not considered in the analysis.

As a basis of the research, the behavior or relations between the parameters were needed to be familiarized. By using the environmental condition that had been chosen, all force for surge and heave need to be calculated. The forces that are calculated are acting on all four columns and pontoons.

3.4 Animation Simulation

Based on the scope of this project, test and analysis will be conducted for the TLP. The CAD model (3D drawing) for each of design variation will be develop using CATIA. For each of the design variation, the animation simulation recording will be played to show some detailed futures by using ADAMS.

The design concept generation had been conducted in the final year project 1. Surge and heave analysis had been analyzed during final year project 2, including the analysis of varying the dimension of TLP. The methodology flow chart is shown in figure 8.

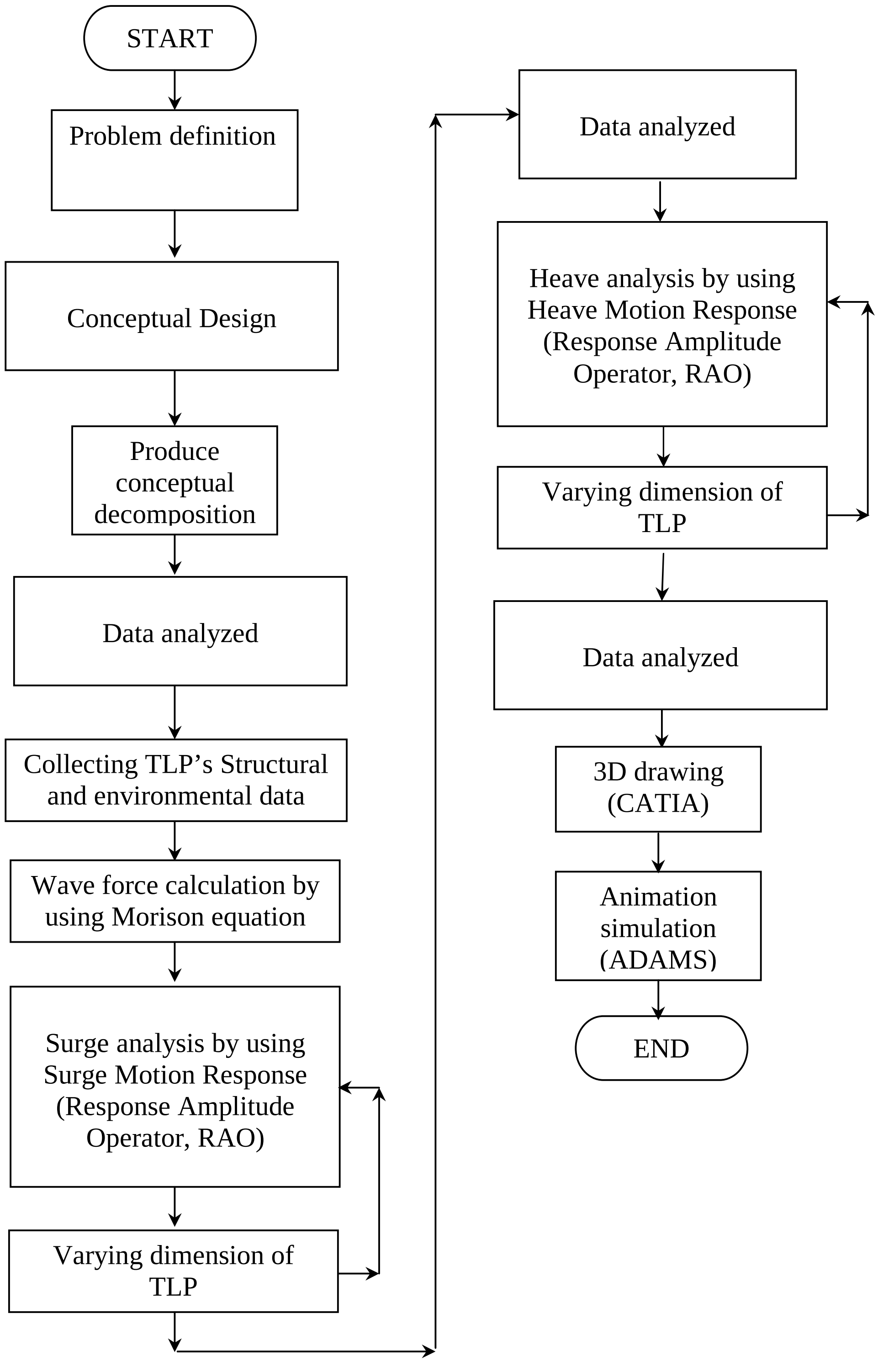


Figure 8: Methodology Flow Chart

CHAPTER 4
RESULT AND DISCUSSION

4.0 RESULT AND DISCUSSION

4.1 Dimensional, Structural and Environmental Data

The dimensional, structural and environmental data of the TLP are shown in Figure below.

Table 2: TLP Dimensional Data [6, 11]

Section	Diameter (m)	Length (m)	Amount
Column	20	50	4
Pontoon	9.9	50	4
Tendons	1	880	16 (4 at each column)

*9.9 is the equivalent diameter for pontoon

Table 3: Structural Data [6, 11]

Total Mass (tonnes)	42440
Total Weight (kN)	416336
Tethers Stiffness (kN/m)	102000
Drought (m)	30
Centre of Gravity (m)	6.1 (below drought)

Table 4: Environmental Data

H_s (m)	12
Drag coefficient, C_D	6.6
Mass Coefficient, C_M	9.3
H_{max} (m)	24
T_{ass} (s)	16.7
Depth (m)	910

4.2 Force on Column

To calculate the resultant force due to the environmental load, Morison Equation is use.

$$f = C_M A_1 \frac{\partial u}{\partial t} + C_D A_D |u|u \quad (1.1)$$

Where,

$$A_1 = \rho \frac{\pi}{4} D^2 \quad (1.2)$$

$$A_D = \frac{1}{2} \rho D \quad (1.3)$$

D = cylinder diameter

$\frac{\partial u}{\partial t}$ = local water particle acceleration

C_M = inertia coefficient

C_D = drag coefficient

P = sea water density

Take C_d = 0.65; C_m = 1.6

The calculations for determining the force acting to the column are done using the computer spread sheet. The summary of the forces calculation is given in the Appendix A.

Summary of the column calculation are shown below in table 5:

Table 5: Force on Column

Column	F_x (kN)	F_y (kN)
1	66561.9	-57238
2	66561.9	-57238
3	67080.79	57117.17
4	67080.79	57117.17
Total	267285.38	-120.83

4.3 Force on Pontoons

Using the same equation as for the columns, force for each pontoon can be determined. The spread sheet of the calculation can be referred to Appendix B. Below is the summary of the Force calculation on all three pontoons.

Table 6: Force on Pontoons

Pontoon	F_x(kN)	F_y(kN)	F_z(kN)
1	0	-35090.5	0
2	0	-35090.5	0
3	35183.2	-35386.6	0
4	35183.2	-35386.6	0
Total	70366.4	-140954.2	0

4.4 Total Force on TLP

Total force on TLP is the sum of forces acting at column and hull are listed in table 7 below.

Table 7: Total Force on TLP

	F_x(kN)	F_y(kN)	F_z(kN)
Column	267285.38	-120.83	0
Pontoon	70366.4	-140954.2	0
Total	**337651.78**	**-141075.03**	**0**

4.5 Calculation on Surge Response

To show the summary of calculation for surge response, the first variations of the dimension of the TLP is used.

4.5.1 Mass of Surge

Mass of Surge, M_{SURGE} = Mass, M + Added Mass, M_{ADD}

Mass of Structure, M = 42440000 kg

Added Mass, M_{ADD} = $[V_{COLUMNS} + 2\pi D^2 (57)/4 + 2\pi D^3 (30)/12]$ x 1025kg/m

= 35459990.88

M_{SURGE} = 42440000 + 35459990.88

= **77899990.90 kg**

4.5.2 Buoyant Force

F_B = $(V_{COLUMNS} + V_{PONTOONS})$ X 1025 X 9.807 /1000

= **420074.14 kN**

4.5.3 Surge Stiffness

Buoyancy, B	= Structure weight in air, W + Pretension, T
B	= 420074.1437 kN
W	= 416336 kN
T	= B-W = 3738.143714 kN
Tether length, L	= 889 m
K_{SURGE}	= T/L = **4.21 kN/m**

4.5.4 Surge's Response Amplitude Operator (RAO)

To calculate the Response Amplitude Operator (RAO) of the surge motion, equation below is used,

$$\text{RAO}_{\text{Surge}} = \frac{F/\frac{H}{2}}{[(K-m\omega^2)^2+(C\omega)^2]^{\frac{1}{2}}} \quad (1.4)$$

Where,	F	=	Total horizontal force
	H	=	Wave height
	K	=	Surge stiffness
	C	=	Dumping with $\xi = 0.05$
	m	=	Total Mass

Using the formulae above, the value of RAO for surge direction is **0.20 m**. Microsoft Excel is used to calculated the surge when the height and diameter of the columns is varied.

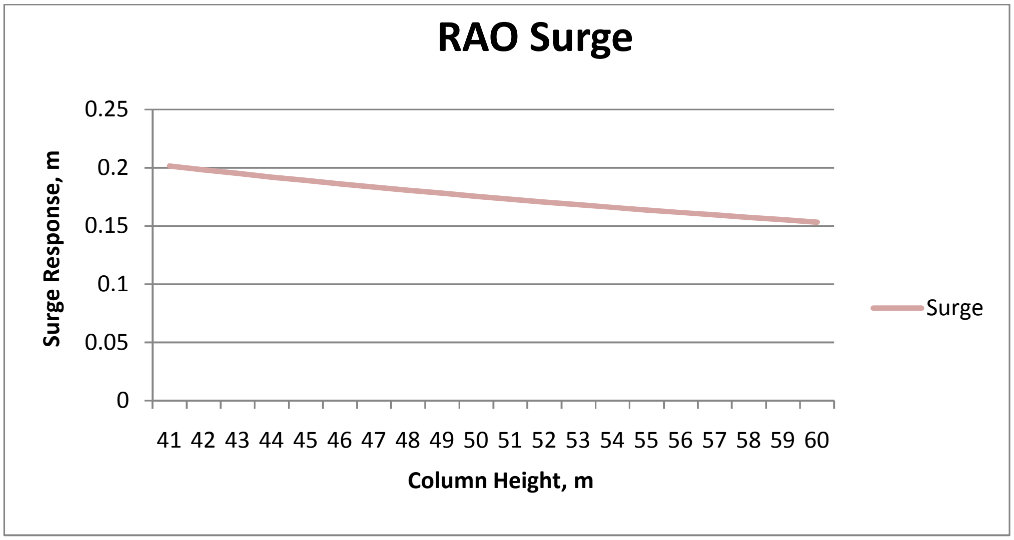


Figure 9: Graph of Surge Response vs Column Height

Figure 9 shows the changes in surge response when the column height is varied. When the column height is increased, the surge response of the TLP is decreased. The surge response of the TLP is inversely proportional to the height of the column.

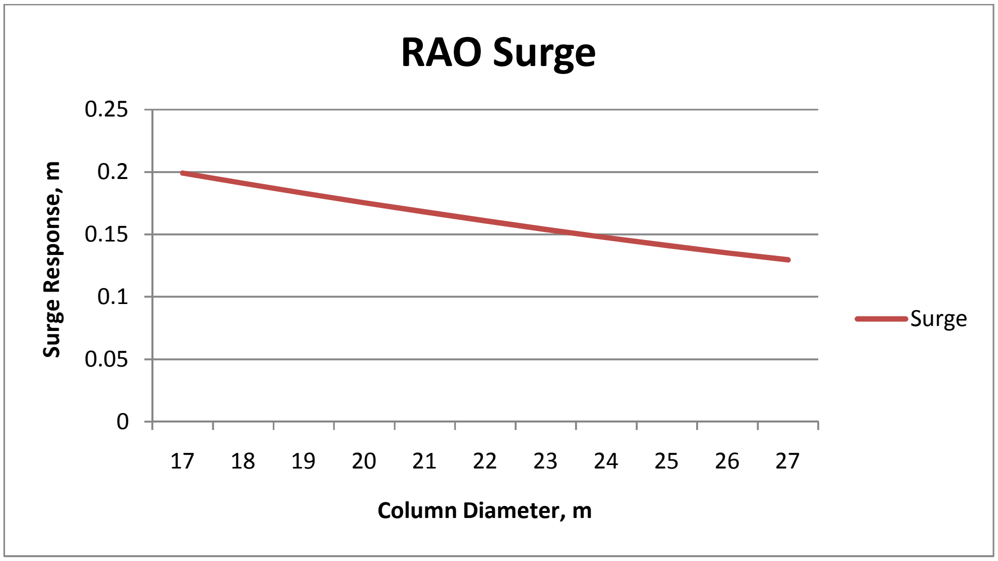


Figure 10: Graph of Surge Response vs Column Diameter

Figure 10 shows the changes in surge response when the column diameter is varied. From the graph, the surge response of the TLP also decreased when the column diameter is increased. The surge response is inversely proportional to the column diameter.

4.6 Calculation on Heave Response

To show the summary of calculation for heave response, the first variations of the dimension of the TLP is used.

4.6.1 Mass of Heave

Mass of Heave, M_{HEAVE} = Mass, M + Added Mass, M_{ADD}

Mass of Structure, M = 102000000kg

Added Mass, M_{ADD} = $[4\pi D^2/4 \times L + 4\pi D^3/12] \times 1025$kg/m

= 24367279.09 kg

M_{HEAVE} = **66807279.1 kg**

4.6.2 Heave Stiffness

Water plane area = $4\pi D^2/4 = 3\pi(25)^2/4 = 1256.637\ m^2$

K_{HEAVE} = Tethers Stiffness + (Water plane area x 1025x 9.807)

= (16 x10200) + (1256.637 x1025 x9.807)

= **14263935.65 kN/m**

4.6.3 Heave's Response Amplitude Operator (RAO)

$$RAO_{Heave} = \frac{F/\frac{H}{2}}{[(K - m\omega^2)^2 + (C\omega)^2]^{\frac{1}{2}}} \qquad (1.5)$$

Where,	F	=	Total vertical force
	H	=	Wave height
	K	=	Surge stiffness
	C	=	Dumping with ξ = 0.05
	m	=	Total Mass

The same RAO formulae as surge is used to calculated the RAO for heave. The value of RAO for heave direction is **0.004 m**. Microsoft Excel is used to calculate the heave when the height and diameter of the columns is varied.

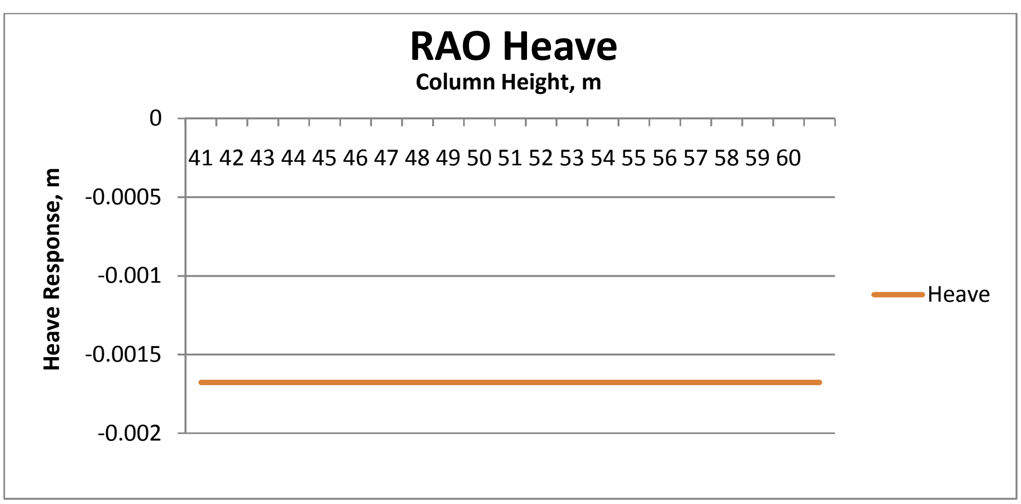


Figure 11: Graph of Heave Response vs Column Height

Figure 11 shows the changes in heave response when the column height is varied. From the graph, the negative value of heave response shows that the heave is moving on vertical axis (y-axis) downward. The graph also shows that the column height of the TLP is insignificant to the heave response.

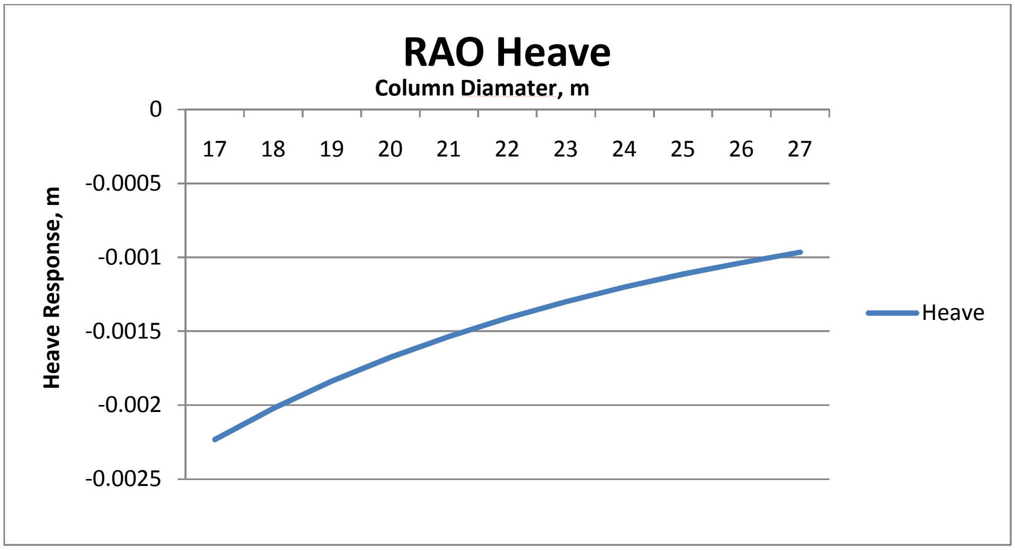


Figure 12: Graph of Heave vs Column Diameter

Figure 12 shows the changes in heave response when the column diameter is varied. The negative value of heave shows that the heave moves downward in vertical axis. As the column diameter is increased, the heave response of the TLP is decreased.

4.7 3D Drawing

CATIA is a one of most common software of Mechanical engineering drawing, it could be use to draw mechanical parts, modeling and simulating easily rather than AutoCAD.

From assembly point of view, the modeling started from the main block which will be referred as Master-Part. This Master-part consists of 2 main sub-assemblies, and from these subassemblies individual components were extracted. From each component, the corresponding part of the hull was designed using different workbenches of CATIA software.

Each sub-assembly (pontoon and column) was drawn separately, ensuring the display of all enclosed details. After completing the design, the generated parts were assembled and all possible interferences were checked to prevent clashes.

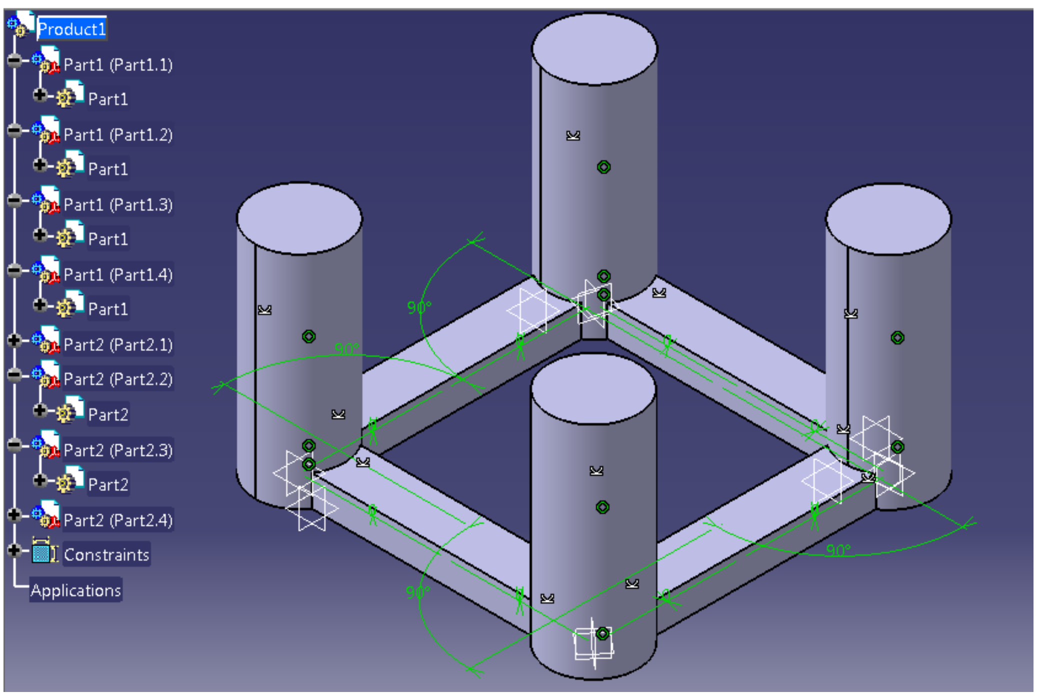


Figure 13: 3D Modeling of TLP's Hull

4.8 Animation Simulation

After assembling these parts, an animation simulation was constructed to demonstrate motion of the designed product. For the animation simulation, engineering software, ADAMS is used. The finished 3D drawing of the hull is then converted to igs file in order to export the modeling to ADAMS. To simulate the animation, motion at translational joint is apply with function.

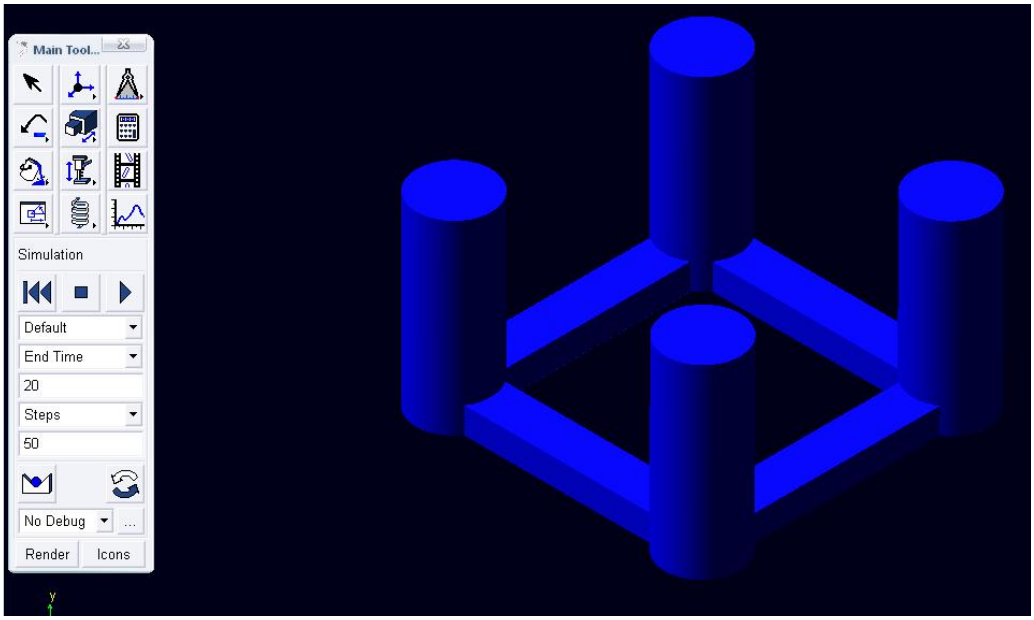


Figure 14: Animation Simulation in ADAMS

CHAPTER 5
CONCLUSION AND RECOMMENDATION

5.0 CONCLUSION AND RECOMMENDATION

For the purpose of wave force measurement, Morison equation is used. The Morison equation assumes the force to be composed of inertia and drag forces linearly added together. Analysis on the wave energy spectrum using Morison equation provides the amount of energy of the wave system.

TLP is compliant in horizontal motion from the surge analysis. From the analysis, the height and the diameter of the column will affect the surge response. This is because the added mass of the TLP increased when the height of the column increased. The surge response is inversely proportional to the height and diameter of the column.

Heave analysis had been conducted and a very small amount of motion been obtained. This is because TLP is not compliant in vertical motion. Tendons which are tensile in normal condition prevent TLP from moving upward or downward. From the analysis, it shows that the height of the column is insignificant to the heave response. This is because the height of the column does not affect the water plane area of the TLP. However, the diameter of the column does affect the heave response because the water plane area change when the column diameter change.

From the animation simulation, the features of the TLP’s hull can be seen. The motion of the TLP can be observed by the animation simulation.

Based on the results of responses subjected to varying the hull dimension, it is concluded that the dimension variations will affect the TLP's responses accept for the column height. However, the case is restricted to only one part of the TLP which is the column dimension. Other important aspects, like the dimension of the pontoon, the material weight, bottom sea pressure, wind force, current etc are not taken into account.

Thus it is recommended that in future, studies on other aspects should be conducted as well to analyze the parameters affecting TLP behavior to improve the applicability of research and contribute to the design library. Studies may include real-life model of TLP, more sophisticated simulation software and laboratory test to compare theoretical results with the experimental result done by the test in laboratory.

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APPENDICES

APPENDIX A

SUMMARY OF FORCE CALCULATION USING MORISON EQUATION

column 1

t	Fx	Fy
0	-28147339	22608526.7
1.7	-59271013	23132770.3
2.7	-66369310	2154612.58
3.7	-63395782	-19124962
4.7	-50875890	-37729077
5.7	-30904435	-51055138
6.7	-6667101.6	-57238915
7.7	18216778	-55415337
8.7	40324037	-49231379
9.7	65954494	-13494928
10.7	65954494	-9686589.9
11.7	66561492	11832945.9
12.7	58605982	31697128.9
13.7	42923148	47127088.3
14.7	21306781	55964272.2
15.7	-3525580.9	56972415.7
16.7	-28147339	50010486.2

column 2

t	Fx	Fy
0	-2.8E+07	22608527
1.7	-5.9E+07	23132770
2.7	-6.6E+07	2154613
3.7	-6.3E+07	-1.9E+07
4.7	-5.1E+07	-3.8E+07
5.7	-3.1E+07	-5.1E+07
6.7	-6667102	-5.7E+07
7.7	18216778	-5.5E+07
8.7	40324037	-4.9E+07
9.7	65954494	-1.3E+07
10.7	65954494	-9686590
11.7	66561492	11832946
12.7	58605982	31697129
13.7	42923148	47127088
14.7	21306781	55964272
15.7	-3525581	56972416
16.7	-2.8E+07	50010486

column 3

t	Fx	Fy
0	36655408	22608527
1.7	-3890516	57117174
2.7	-2.8E+07	50546688
3.7	-4.9E+07	36905046
4.7	-6.3E+07	18100627
5.7	-6.7E+07	-3235953
6.7	-6E+07	-2.4E+07
7.7	-4.5E+07	-4.2E+07
8.7	-2.4E+07	-5.3E+07
9.7	1257409	-2.6E+07
10.7	25613607	-5.4E+07
11.7	46235233	-4.2E+07
12.7	60600543	-2.5E+07
13.7	67080792	-4336037
14.7	64962413	17050839
15.7	54442634	36052412
16.7	36655408	50010486

column 4

t	Fx	Fy
0	36655408	22608527
1.7	-3890516	57117174
2.7	-2.8E+07	50546688
3.7	-4.9E+07	36905046
4.7	-6.3E+07	18100627
5.7	-6.7E+07	-3235953
6.7	-6E+07	-2.4E+07
7.7	-4.5E+07	-4.2E+07
8.7	-2.4E+07	-5.3E+07
9.7	1257409	-2.6E+07
10.7	25613607	-5.4E+07
11.7	46235233	-4.2E+07
12.7	60600543	-2.5E+07
13.7	67080792	-4336037
14.7	64962413	17050839
15.7	54442634	36052412
16.7	36655408	50010486

Pontoon 1

t	Fx	Fy
0	0	-450630.69
1.7	0	-239911.97
2.7	0	-62749.432
3.7	0	128064.518
4.7	0	304320.189
5.7	0	436606.087
6.7	0	500990.818
7.7	0	490314.101
8.7	0	419229.055
9.7	0	294346.148
10.7	0	127604.691
11.7	0	-61406.733
12.7	0	-246172.34
13.7	0	-396998.66
14.7	0	-487245.28
15.7	0	-501292.38
16.7	0	-450630.69

Pontoon 2

t	Fx	Fy
0	0	-450631
1.7	0	-239912
2.7	0	-62749.4
3.7	0	128064.5
4.7	0	304320.2
5.7	0	436606.1
6.7	0	500990.8
7.7	0	490314.1
8.7	0	419229.1
9.7	0	294346.1
10.7	0	127604.7
11.7	0	-61406.7
12.7	0	-246172
13.7	0	-396999
14.7	0	-487245
15.7	0	-501292
16.7	0	-450631

Pontoon 3

t	Fx	Fy
0	-211323	-460056
1.7	-444149	-242983
2.7	-502360	-62796.1
3.7	-490295	126176
4.7	-409640	297496.8
5.7	-271679	427199.8
6.7	-95712.4	497140.3
7.7	93644.05	497534
8.7	269900.3	428326
9.7	408399.2	299197.9
10.7	489765.7	128213.9
11.7	502617.2	-60706.3
12.7	445155.7	-241134
13.7	325419.9	-387829
14.7	160159.9	-480269
15.7	-27505.5	-505522
16.7	-211323	-460056

Pontoon 4

t	Fx	Fy
0	-211323	-460056
1.7	-444149	-242983
2.7	-502360	-62796.1
3.7	-490295	126176
4.7	-409640	297496.8
5.7	-271679	427199.8
6.7	-95712.4	497140.3
7.7	93644.05	497534
8.7	269900.3	428326
9.7	408399.2	299197.9
10.7	489765.7	128213.9
11.7	502617.2	-60706.3
12.7	445155.7	-241134
13.7	325419.9	-387829
14.7	160159.9	-480269
15.7	-27505.5	-505522
16.7	-211323	-460056

APPENDIX B

SURGE AND HEAVE RESPONSE WHEN VARYING COLUMN DIMENSION

Surge Response (Height Variation)

Height Column	Draft	4 columns	2 pontoons	2 Pontoons	Added Mass	Surge Mass	Buoyant Force,$F_{b(KN)}$	Pretension, T	Tether length	Surge stiffness, Ks	Natural Frequency	Damping, C	Surge
41	21	27049112.75	7890129.58	520748.55	35459990.88	77899990.9	420074.1437	3738.143714	889	4.204886067	0.000232332	1809.863493	0.201474383
42	22	28337165.74	7890129.58	520748.55	36748043.87	79188043.9	432706.0794	16370.07937	888	18.43477406	0.000482491	3820.750839	0.198207086
43	23	29625218.72	7890129.58	520748.55	38036096.86	80476096.9	445338.015	29002.01502	887	32.69674749	0.00063741	5129.626319	0.195044091
44	24	30913271.71	7890129.58	520748.55	39324149.85	81764149.8	457969.9507	41633.95067	886	46.99091498	0.000758098	6198.525804	0.191980482
45	25	32201324.7	7890129.58	520748.55	40612202.84	83052202.8	470601.8863	54265.88633	885	61.31738568	0.000859243	7136.206242	0.189011646
46	26	33489377.69	7890129.58	520748.55	41900255.82	84340255.8	483233.822	66897.82198	884	75.67626921	0.000947245	7989.090001	0.186133254
47	27	34777430.68	7890129.58	520748.55	43188308.81	85628308.8	495865.7576	79529.75763	883	90.06767569	0.001025595	8781.994505	0.183341234
48	28	36065483.66	7890129.58	520748.55	44476361.8	86916361.8	508497.6933	92161.69329	882	104.4917157	0.001096453	9529.973647	0.180631756
49	29	37353536.65	7890129.58	520748.55	45764414.79	88204414.8	521129.6289	104793.6289	881	118.9485005	0.001161273	10242.94044	0.178001214
50	30	38641589.64	7890129.58	520748.55	47052467.78	89492467.8	533761.5646	117425.5646	880	133.4381416	0.001221087	10927.81249	0.175446207
51	31	39929642.63	7890129.58	520748.55	48340520.76	90780520.8	546393.5002	130057.5002	879	147.9607511	0.001276665	11589.63073	0.172963527
52	32	41217695.62	7890129.58	520748.55	49628573.75	92068573.8	559025.4359	142689.4359	878	162.5164418	0.001328596	12232.194	0.170550148
53	33	42505748.6	7890129.58	520748.55	50916626.74	93356626.7	571657.3716	155321.3716	877	177.1053267	0.001377347	12858.44309	0.168203207
54	34	43793801.59	7890129.58	520748.55	52204679.73	94644679.7	584289.3072	167953.3072	876	191.7275196	0.001423292	13470.70514	0.165919997
55	35	45081854.58	7890129.58	520748.55	53492732.72	95932732.7	596921.2429	180585.2429	875	206.3831347	0.001466742	14070.85573	0.163697959
56	36	46369907.57	7890129.58	520748.55	54780785.7	97220785.7	609553.1785	193217.1785	874	221.0722866	0.001507952	14660.43021	0.161534665
57	37	47657960.55	7890129.58	520748.55	56068838.69	98508838.7	622185.1142	205849.1142	873	235.7950907	0.001547141	15240.70226	0.159427817
58	38	48946013.54	7890129.58	520748.55	57356891.68	99796891.7	634817.0498	218481.0498	872	250.5516626	0.001584492	15812.74079	0.157375235
59	39	50234066.53	7890129.58	520748.55	58644944.67	101084945	647448.9855	231112.9855	871	265.3421188	0.001620167	16377.452	0.155374848
60	40	51522119.52	7890129.58	520748.55	59932997.66	102372998	660080.9211	243744.9211	870	280.166576	0.001654304	16935.61107	0.15342469

Surge Response (Diameter Variation)

Dia Column	Draft	4 columns	2 pontoons	2 Pontoons	Added Mass	Surge Mass	Buoyant Force,$F_{b(KN)}$	Pretension, T	Tether length	Surge stiffness, Ks	Natural Frequency	Damping, C	Surge
17	30	27918548.51	7890129.58	520748.55	36329426.65	78769426.7	428600.7003	12264.70028	880	13.93715941	0.000420638	3313.339789	0.199257361
18	30	31299687.61	7890129.58	520748.55	39710565.74	82150565.7	461759.5314	45423.53137	880	51.61764928	0.000792673	6511.850037	0.191080296
19	30	34874034.65	7890129.58	520748.55	43284912.79	85724912.8	496813.1528	80477.15281	880	91.45131001	0.00103286	8854.182952	0.183135386
20	30	38641589.64	7890129.58	520748.55	47052467.78	89492467.8	533761.5646	117425.5646	880	133.4381416	0.001221087	10927.81249	0.175446207
21	30	42602352.58	7890129.58	520748.55	51013230.71	93453230.7	572604.7667	156268.7667	880	177.578144	0.001378471	12882.25573	0.168029477
22	30	46756323.46	7890129.58	520748.55	55167201.6	97607201.6	613342.7592	197006.7592	880	223.8713173	0.001514462	14782.23691	0.160896047
23	30	51103502.3	7890129.58	520748.55	59514380.43	101954380	655975.542	239639.542	880	272.3176614	0.001634312	16662.52635	0.154051828
24	30	55643889.08	7890129.58	520748.55	64054767.22	106494767	700503.1152	284167.1152	880	322.9171764	0.001741331	18544.26853	0.147498651
25	30	60377483.81	7890129.58	520748.55	68788361.95	111228362	746925.4787	330589.4787	880	375.6698622	0.001837788	20441.41468	0.141235027
26	30	65304286.49	7890129.58	520748.55	73715164.63	116155165	795242.6326	378906.6326	880	430.5757189	0.001925331	22363.71917	0.135256821
27	30	70424297.12	7890129.58	520748.55	78835175.25	121275175	845454.5768	429118.5768	880	487.6347464	0.002005217	24318.30367	0.129557831

Surge Response (Diameter variation)

Mass (kg)	42440000
Pontoon Equivalent dia(m)	9.9
Free board (m)	20
Pontoon length(m)	50
Structure weight in air(KN)	416336
Water Depth(m)	910
Total Vertical force(KN)	-141075.03
omega	0.05988024
Tether Stiffness(KN)	102000
Water Plane Area(m2)	1256.637061

Dia Column	Draft	4 columns	4 pontoons	Added Mass	Heave Mass	Water Plane Area	Heave Stif	Natural Freq	Damping,	Heave
17	30	5273504	15780259.2	21053762.78	63493762.8	907.9202769	10758574	0.411634544	2613623	-0.00223
18	30	6259938	15780259.2	22040196.69	64480196.7	1017.87602	11863868	0.428943384	2765835	-0.00202
19	30	7362296	15780259.2	23142555.37	65582555.4	1134.114948	13032322	0.445776051	2923513	-0.00184
20	30	8587020	15780259.2	24367279.09	66807279.1	1256.637061	14263936	0.462070022	3086964	-0.00168
21	30	9940549	15780259.2	25720808.1	68160808.1	1385.44236	15558709	0.477770592	3256523	-0.00154
22	30	11429324	15780259.2	27209582.68	69649582.7	1520.530844	16916642	0.492830777	3432546	-0.00141
23	30	13059784	15780259.2	28840043.09	71280043.1	1661.902514	18337735	0.507211239	3615404	-0.0013
24	30	14838370	15780259.2	30618629.59	73058629.6	1809.557368	19821987	0.520880185	3805479	-0.0012
25	30	16771523	15780259.2	32551782.45	74991782.4	1963.495408	21369399	0.533813215	4003160	-0.00111
26	30	18865683	15780259.2	34645941.93	77085941.9	2123.716634	22979971	0.545993093	4208839	-0.00104
27	30	21127289	15780259.2	36907548.3	79347548.3	2290.221044	24653703	0.557409442	4422907	-0.00096

Mass (kg)	42440000
Pontoon Equivalent dia(m)	9.9
Free board (m)	20
Pontoon length(m)	50
Structure weight in air(KN)	416336
Water Depth(m)	910
Total Horizontal force(KN)	-141075
omega	0.05988
Tether Stiffness(KN)	102000
Water Plane Area(m2)	1256.637

				Heave Response (Height Variation)					
Height Co	Draft	4 columns	4 pontoons	Added Mass	Heave Mass	Heave Stiffness, K	Natural Fr	Damping, C	Heave
40	20	8587020	15780259.2	24367279.09	66807279.1	14263935.65	0.46207	3086964.091	-0.00168
41	21	8587020	15780259.2	24367279.09	66807279.1	14263935.65	0.46207	3086964.091	-0.00168
42	22	8587020	15780259.2	24367279.09	66807279.1	14263935.65	0.46207	3086964.091	-0.00168
43	23	8587020	15780259.2	24367279.09	66807279.1	14263935.65	0.46207	3086964.091	-0.00168
44	24	8587020	15780259.2	24367279.09	66807279.1	14263935.65	0.46207	3086964.091	-0.00168
45	25	8587020	15780259.2	24367279.09	66807279.1	14263935.65	0.46207	3086964.091	-0.00168
46	26	8587020	15780259.2	24367279.09	66807279.1	14263935.65	0.46207	3086964.091	-0.00168
47	27	8587020	15780259.2	24367279.09	66807279.1	14263935.65	0.46207	3086964.091	-0.00168
48	28	8587020	15780259.2	24367279.09	66807279.1	14263935.65	0.46207	3086964.091	-0.00168
49	29	8587020	15780259.2	24367279.09	66807279.1	14263935.65	0.46207	3086964.091	-0.00168
50	30	8587020	15780259.2	24367279.09	66807279.1	14263935.65	0.46207	3086964.091	-0.00168
51	31	8587020	15780259.2	24367279.09	66807279.1	14263935.65	0.46207	3086964.091	-0.00168
52	32	8587020	15780259.2	24367279.09	66807279.1	14263935.65	0.46207	3086964.091	-0.00168
53	33	8587020	15780259.2	24367279.09	66807279.1	14263935.65	0.46207	3086964.091	-0.00168
54	34	8587020	15780259.2	24367279.09	66807279.1	14263935.65	0.46207	3086964.091	-0.00168
55	35	8587020	15780259.2	24367279.09	66807279.1	14263935.65	0.46207	3086964.091	-0.00168
56	36	8587020	15780259.2	24367279.09	66807279.1	14263935.65	0.46207	3086964.091	-0.00168
57	37	8587020	15780259.2	24367279.09	66807279.1	14263935.65	0.46207	3086964.091	-0.00168
58	38	8587020	15780259.2	24367279.09	66807279.1	14263935.65	0.46207	3086964.091	-0.00168
59	39	8587020	15780259.2	24367279.09	66807279.1	14263935.65	0.46207	3086964.091	-0.00168
60	40	8587020	15780259.2	24367279.09	66807279.1	14263935.65	0.46207	3086964.091	-0.00168