Computer Aided Design of Semi-Submersibles for Deepwater Operations

by

Nur Syaheerah Binti Khamis

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Universiti Teknologi PETRONAS
Bandar Seri Iskandar
31750 Tronoh
Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

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Approved by,

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(Assoc. Prof. Dr. Fakhruldin B Mohd Hashim)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

September 2012

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 person.

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(NUR SYAHEERAH BINTI KHAMIS)

ABSTRACT

Current selection work for offshore floaters typically engaged to detail calculations and scaled-model testing. Design library for offshore floaters may ease the design and selection process by providing instant result for basic performance analysis of the floaters. The project "Computer Aided Design of Semi-submersibles for Deepwater Operations" is a project made in order to improve the work made in previous projects on offshore platforms libraries. The main objective of this project is to improve the variation of the semi-submersibles model platform from previous project and also to evaluate the performance of the semi-submersible using parameters chosen. A proper research work has been made before specifying any design criteria and parameters. The scope of work of the study is to develop the hull section for semi-submersible model of six-column twin-pontoon. The design of the floaters and the libraries are developed using CATIA V5R20 with focusing on the vertical center of gravity and draft of the floater. The performance of the semi-submersibles is supported using established numerical methods and calculations. The results are divided to three components of the semi-submersibles floater and its individual stability analysis. As a conclusion, this project is the improved version of currently existed offshore floaters design library and may be a stage for any future library enhancement.

ACKNOWLEDGEMENTS

Alhamdulillah, praise to Allah s.w.t that I could complete this project successfully after been working on it about 8 months. I would like to take this opportunity to thank everyone that involved directly or indirectly along the completion period of this project.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 Introduction

Oil and gas industry nowadays are in desperate needs of technologies to allow them to keep up in developing new wells. There are lots of wells that are waiting to be developed which were located in deepwater fields or ultra deepwater fields. Technologies used for developing shallow water wells are now not applicable for deepwater field so as demand in new technologies for deepwater operations increases. Generally, oil and gas exploration in deepwater field requires different structures compared to the shallow water fields and the structures such as Tension Leg Platform (TLP) are hardly applied. Based on ENSCO website, floating structure is the best to be used in the conditions of deepwater operations and the best technology to be used today. This project is basically to enhance a project of designing a semi-submersible floater for deepwater operations completed in 2010.

1.2 Problem Statement

Petroleum exploration nowadays requires a lot of expertise and new technologies especially when facing challenges such as deepwater and ultra-deepwater field. Floating offshore structure such as semi-submersibles and drill ships had become much of help to the industry recently. Lack in availability of design library for offshore floaters is one of the setbacks for the industry. Besides, most offshore structure model testing requires specific parameters and cross referencing between numerical analysis so as experimental testing.

1.3 Objectives

The objectives of this project are:

1. To develop an improved model of a semi-submersible using Computer Aided Design (CAD) based on previous project of deepwater floaters.
2. To evaluate the performance of the semi-submersible platform with respect to stability for design and selection work.

1.4 Scope of Study

This study consists of furthering the parameters of previously done project on the design of deepwater floaters (semi-submersible floaters). This project will include the design using Computer Aided Design (CAD) with software CATIA V5R20 while developing the hull section of 6 column twin pontoon semi submersible platform. Parameters chosen to be varied along the project is the water plane area of the column under fixed design specifications, the metacentric height and the restoring moment of the structure with effects of the sea conditions. On top of that, the project will also include the vertical movement of the platforms to proof stability of the design. Lastly, the analysing of the design stability is to be done considering the X, Y and Z axis as the angular motions along the water plane area.

Design specifications for the study from Saipem website:

- Platform name: Scarabeo 8
- Rated Water depth: 1000 m
- Max Drilling Depth: 35000 ft = 10660 m
- Location : Offshore
- Derrick Dimensions: 83.2 m x 72.7 m x 11.5m
- Derrick Loads: 3 000 000 lbs = 1 360 777 kg

CHAPTER 2

COMPUTER AIDED DESIGN OF SEMI-SUBMERSIBLES FOR DEEPWATER OPERATIONS

2.1 Introduction

Computer aided design of semi-submersibles for deepwater operations project was once done by Ruzanna Abu Bakar back in 2010. Ruzanna highlighted the main reason of the project is to create a library to ease one of the process in designing semi-submersible platform which is to test and proof on the stability of the semi-submersible [1]. Few other similar projects were also done with different types of offshore platforms such as tension leg platform (TLP) and FPSO.

2.2 Computer Aided Design

CAD is a computer technology used to design objects and to provide electronic drafting board for 2D drawings and 3D wireframes, surface and solid models. Currently, there are a few analysis can be done to the solid model such as kinematic, stress and thermal. Advantages of using CAD is to design by solid modelling to create a digital geometric database which can be transferred downstream to permit engineering analysis and simulation, thus decrease the cost of testing prototypes [2].

CAD systems build the backbone of modern product development processes by offering the most simple and natural way of representing complex mechanical structures that are heavily constrained through a variety of functional, aesthetic and manufacturing demands [3]

Computer Aided Design (CAD) system is commonly used in designing. Nowadays in CAD system, the main focus of interest lies in the knowledge application that would allow further improvement in designing process and designing object [3]. Therefore, one of the ways to reduce time consumption on concept design and selection work is by having a CAD model depository for offshore floaters.

2.3 Semi-submersibles

A semi-submersible is a specialised marine vessel with good stability and sea-keeping characteristics. The semi-submersible vessel design is commonly used in a number of specific offshore roles such as for offshore drilling rigs, safety vessels, oil production platforms and heavy lift cranes [5].

Semi-submersible are four- to six-legged floating structures with a large deck. The legs are connected by two parallel horizontal buoyant members called pontoons. Sometimes the pontoons are streamlined to minimize towing resistance during transportation from site to site. Although the semi-submersible provides a more stable platform because of its geometry, it is slower to move and more expensive to build and operate [6]. According to Mather, a semi-submersible is a semi floating structure that represents a good choice of vessel for accurate positioning and good stability [7].

Semi-submersible platform were initially designed to be used in shallow waters rated depth up to 30 metres but innovations of marine equipment improves every year. First recognized semi-submersible vessel launched in early 1960 by Blue Water Drilling Company. From that, sum-submersible vessel is now well acknowledged and used widely throughout oil and gas industry [8].

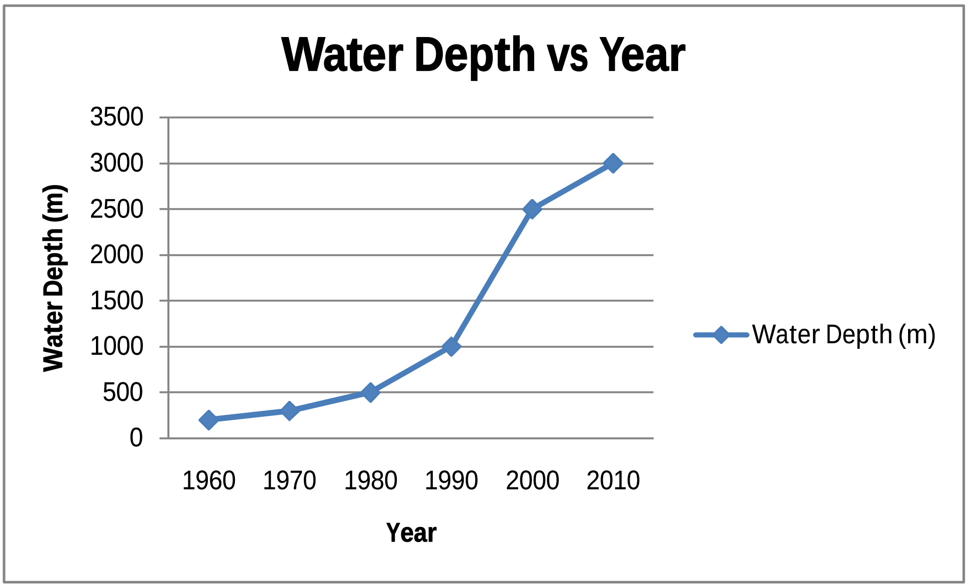

Figure 1: Semi-submersible technology development [9]

2.3.1 Semi-submersible Design and Structure

Floating offshore structure or more familiar to be called offshore floaters come in many size and shapes but the main functions of the floaters are to provide an area for exploration equipments and operations to be done. Most popular offshore floaters for deepwater explorations are the drillships and the semi-submersibles as it is more practical to have non-attached to sea bed type of platform [10]. Main components of semi-submersible are:

i. Topside/deck
ii. Column
iii. Pontoon

Figure 2 shows a typical semi-submersible platform and the the main components of a semi-submersible and its related functions are discussed in Table 1.

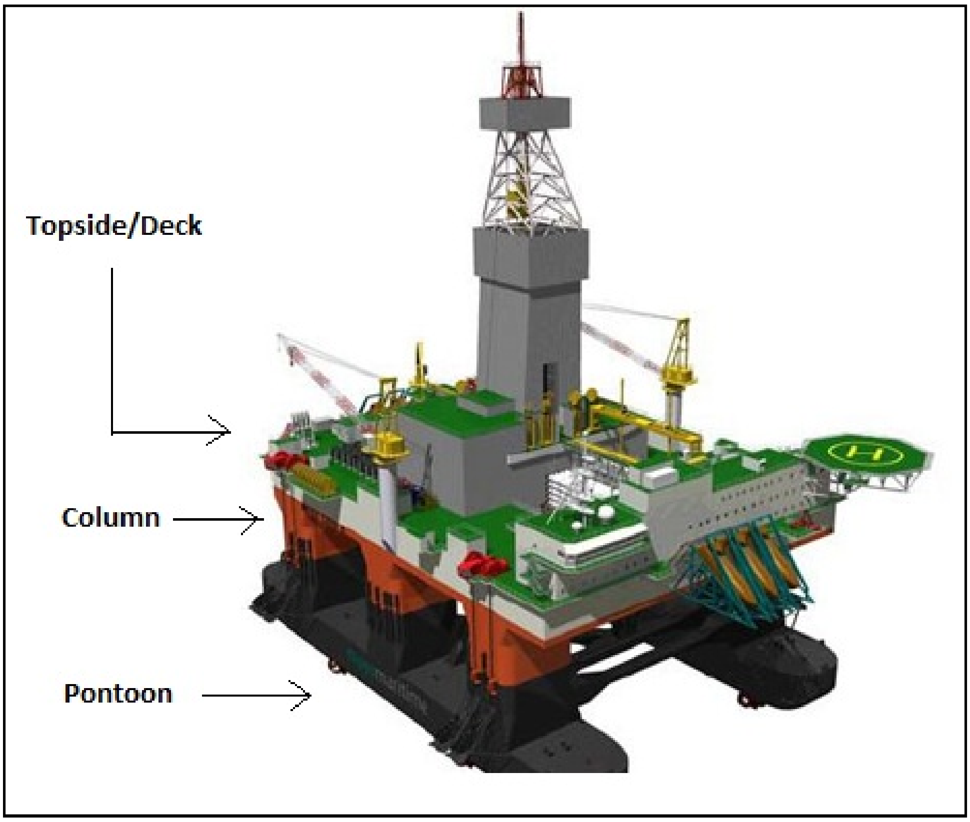

Figure 2: Semi-submersible platform [11]

Table 1: Components of semi-submersibles and its function [9]

Component	Function
Topsides	The deck which have all the production equipment used to treat the incoming well streams. Pumps and compressors needed to transfer oil and gas to next destinations. Normally, topsides include living accommodations for the crew. In most cases, the export lines are connected to the deck.
Column	Controls waterplane area and draft height to ensure semi-submersible less affected by wave loadings to maintain stability.
Pontoon	Provide buoyancy for semi-submersible by its ballasted watertight structure located below ocean surface.

The design of semi-submersibles depends on these principle considerations which are generic to floater concepts [4]:

- Weights and centre of gravity
- Hydrostatics, tank capacities
- Intact and damaged stability
- Wind forces (stability and mooring loads)
- Current forces (mooring loads)
- Ballast system performance
- Motions (seakeeping, drift and low frequency mooring loads)
- Global strength
- Fatigue

2.4 Deepwater Operations

As the most promising oil and gas investment nowadays, the deepwater field are categorized as a very costly development and requires high technology in developing the field. The Malaysian Deepwater Production Sharing Contracts (PSC) stated that the depth of the deepwater are between 200m and 1000m and depth greater than 1000m is called ultra-deepwater [12]. Initial discovery in deepwater development came at Shell Oil Company's Cognac field around the year 1975. Technology still evolve with time to adapt from shallow to deepwater, just as it took a while to develop from onshore to offshore. Cognac adapted the fixed platform technology from shallow water, which proved economically impractical for moving much further from the coast [13]. Deepwater operations differ from shallow water oil and gas exploration by some characteristics which is the operations/developments, the high reservoir pressure, high temperature conditions, low sea bed temperature and also large variation of water depth range. Because of those different, there are lots of challenges faced by engineers to improve deepwater technology as the conventional offshore technologies could not be apply in deepwater field [14]. Deepwater fields have potentials to produce until 100 billion bbl of oil. Industry experts estimate that 2500 wells will be drilled in next 30 years to fulfil fuel needs throughout the world [15]. Below is the development of the deepwater area of Gulf of Mexico:

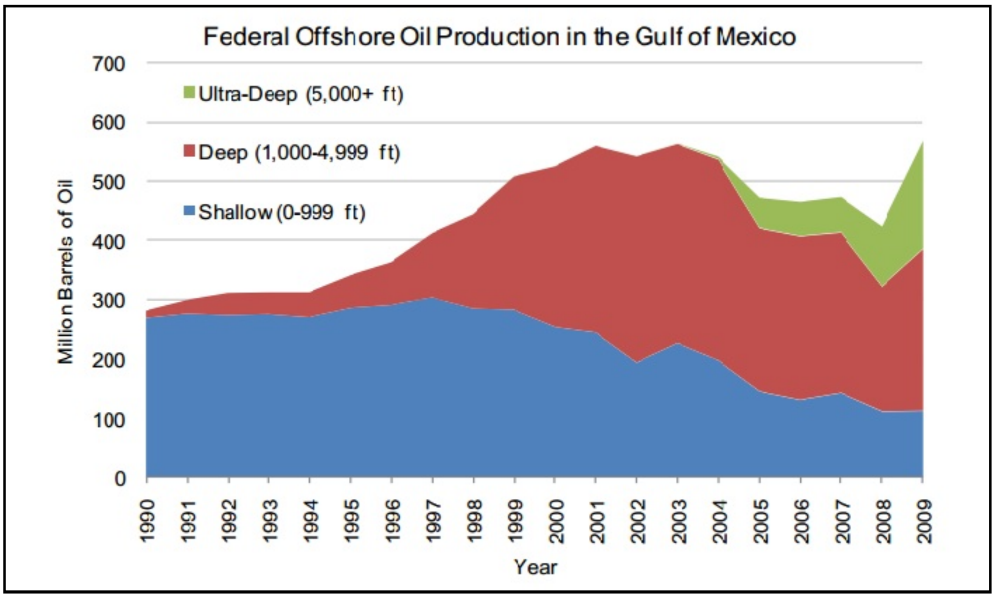

Figure 3: Oil Production Statistics [14]

CHAPTER 3

METHODOLOGY

3.1 Introduction

This project focuses on the main parts of the semi-submersible which is the topside, columns and also pontoons. Topside is the most upper part of the semi-submersible while the pontoon is the lowest part of the structure.

This project will consider the semi-submersible while working only at operating condition. From the Saipem website, the operating condition for the semi-submersible requires the minimum draft height of 23.5m. Operating condition for the semi-submersible is where the maximum load applied on topside of the platform. Greater weight of the semi-submersible requires the high value of draft to ensure semi-submersible will show minimum response to wave and ocean [15].

3.2 Project Flow Chart

Figure 4 shows the key stages of the project undertaken, the key stages are:

i. Preliminary research work
ii. Literature review
iii. Design specification of criteria and parameters
iv. Formulation and calculation of chosen parameters
v. CATIA model development
vi. Data generation
vii. Analysis and validation

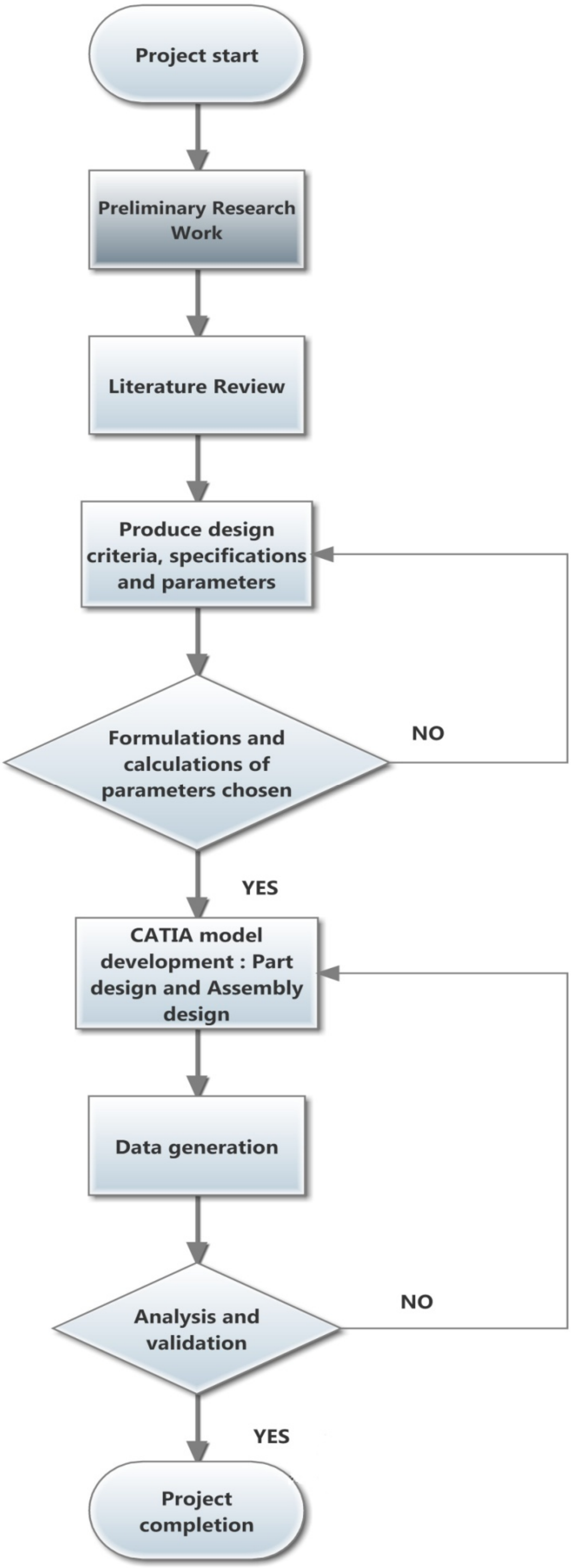

Figure 4: Project flow chart

3.3 Semi-Submersibles Design Criteria and Specifications

Most of semi-submersibles platform normally consists of the same structure which is deck, multiple columns and pontoons. They only differ by the number of columns or the pontoons. All semi-submersibles are column stabilized which means that the center of gravity is situated above the center of buoyancy. The stability of the semi-submersibles can be determined by the restoring moment of the columns. In general, all semi-submersibles are a floating structure stabilized by the columns.

Based on a previous project of designing a semi-submersible platform by Ruzanna Abu Bakar in July 2010, there are few improvement that been suggested in order to improve the design. One of the recommendations stated to improve the design by developing the six-column twin pontoons semi submersible’s hull model in order to meet the industries’ requirement. Besides that, other parameters to analyze stability to be included for further enhancement are the metacentric height, angle of heel restoring moment and also the righting arm.

In designing a better semi-submersible, first consideration should involve the weight and the center of gravity for the semi-submersible. The center of gravity is divided to horizontal and vertical center of gravity and to determine the initial stability for the semi-submersible, the vertical center of gravity should first be known. Stability for the six column twin pontoon semi-submersible can be achieved by calculating the vertical center of gravity so as the draft (draught) of the semi-submersible.

For the selected design of semi-submersible, stated below are the criteria of the semi-submersible before the semi-submersible flood:

- Maximum draft value = 23.5 m
- Minimum VCG value = 28.0 m

3.4 Formulation and Calculation

Stability is the tendency to return to a previous condition when there is external force acting on it. If a semisubmersible rolls or pitches, the center of buoyancy shifts and it can determine the stability of the semi-submersibles. For this project, the scope is to focus on evaluating stability therefore; two parameters are chosen for the quick analysis. Formulas needed to evaluate stability are stated accordingly.

3.4.1 Draft

In calculating the buoyancy of the structure, draft theory are used which draft is the height from the bottom of the pontoon to the waterline level. Height of draft can be calculated using the formula of Buoyancy. Archimedes principle stated that buoyancy of an object is equal to the weight of the displaced fluid so as stated below:

$$Buoyancy = Displaced\ Fluid\ Weight \quad \text{(Equation 1)}$$

In order to change the water plane area of the column, the above rule must be obeyed.

$$Buoyancy = [(6 \times waterplane\ area\ of\ column\ \times draft) + (2 \times cross\ sectional\ area\ of\ pontoon\ \times length\ of\ pontoon)] \times density\ of\ seawater \quad \text{(Equation 2)}$$

Buoyancy can be calculated by using dimension chosen and the value obtained will be held constant. Draft will be changes as the water plane area of column are varied through this project.

3.5.2 Vertical Center of Gravity

The vertical center of gravity can be calculated by knowing all the dimension of the semi-submersible and by using the centroid formula.

$$\bar{y} = vertical\ center\ of\ gravity\ \ ;\ \ \bar{x} = horizontal\ center\ of\ gravity$$

$$\bar{y} = \frac{y_1A_1+y_2A_2+y_3A_2+y_4A_4+y_5A_5}{A_1+A_2+A_3+A_4+A_5} \quad \_\_\_\_\_\_ \text{ Equation 3(i)}$$

$$\bar{x} = \frac{x_1A_1+x_2A_2+x_3A_2+x_4A_4+x_5A_5}{A_1+A_2+A_3+A_4+A_5} \quad \_\_\_\_\_\_ \text{ Equation 3(ii)}$$

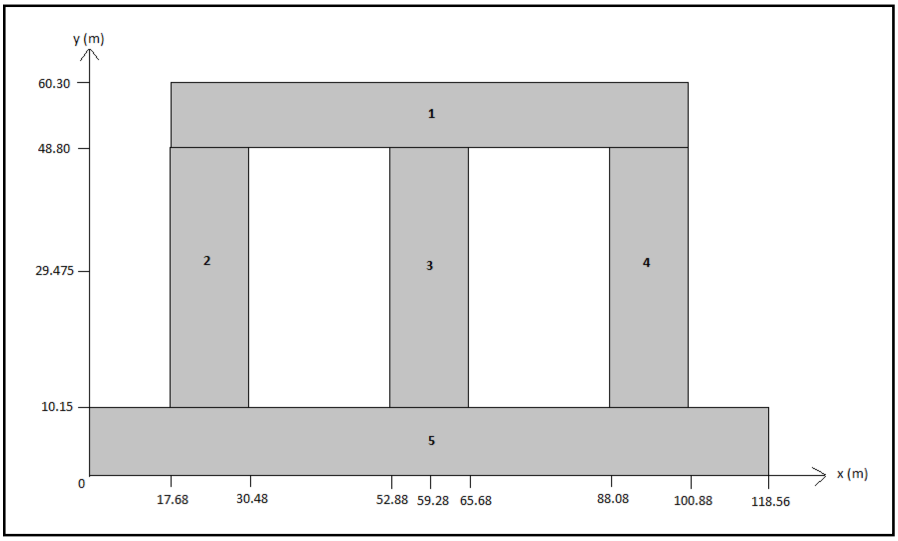

Figure 5: Centroid Diagram (Side view)

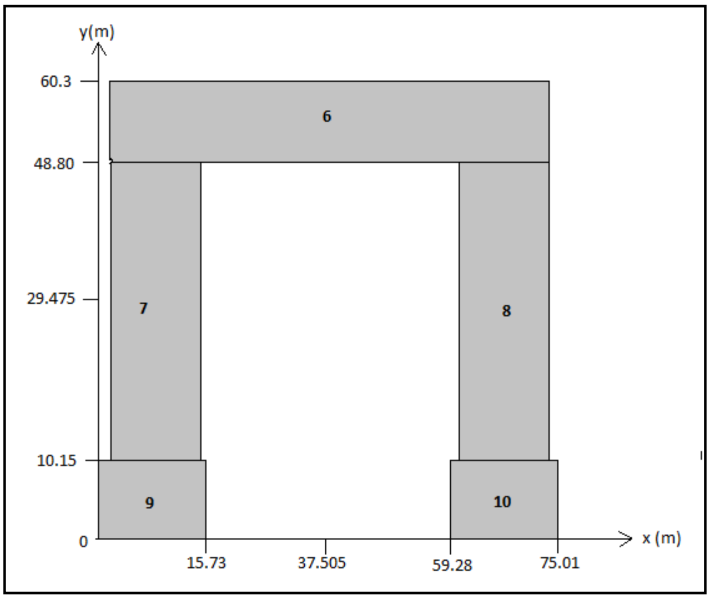

Figure 6: Centroid Diagram (Front view)

3.5.3 Metacentric Height

Metacentric height is a measurement in any floating body which is the distance between the centre of gravity and its floating body's metacentre. A ship with a greater metacentric height will produce more stable condition compared to a ship with a smaller metacentric height [17]. In ship's stability, metacentric height will be very useful as suitable metacentric height can be assumed to have a sufficient righting moments exists at any practical angles of heels [18]. For the vessel to be adequately stable, the metacentric height (GM) required to be above minimum value. Metacentric height can be calculated using the formula:

$$GM = KB + BM - KG \qquad \text{\_\_\_\_\_\_\_ Equation 4}$$

$$GM = 0.35 \; is\ the\ recommended\ minimum\ guidance\ value$$

Based on Figure 7, M is the metacentric point and is defined as the point where the vertical through the new center of buoyancy meets the original vertical through the center of gravity after a very small angle of rotation. Distance of MG is called the metacentric height.

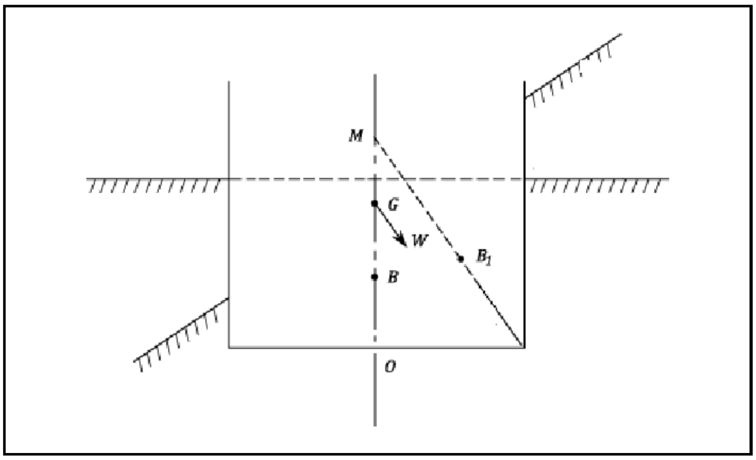

Figure 7: The metacentric height of a floater. [19].

If:

- B and G are coincident in **Neutral** Equilibrium.
- B is below G then the Body is in **Unstable** equilibrium.
- B is above G then the body is in **Stable** equilibrium.

3.5 CAD Model Development

Figure 8 shows the basic design of a semi-submersible platform and it parts, figure shown drawn using CATIA V5R20.

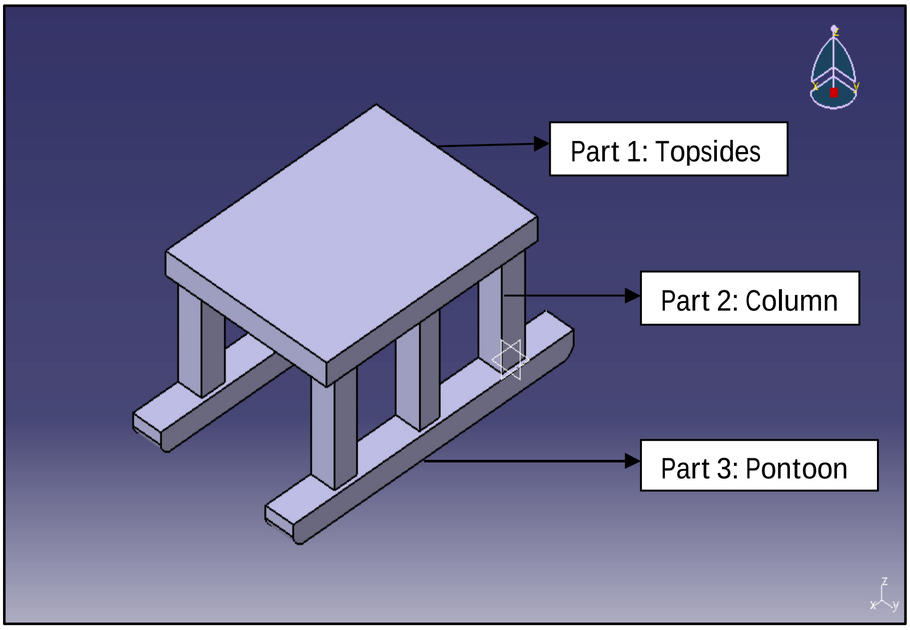

Figure 8: Part Design

Based on figure above, the assumption made that the topsides of the platform will be weigh equally at all direction. The rectangular shape of the topsides is measured to be 83.2m x 72.7m x 10.0m depth.

Column and pontoon which are represented by part 2 and part 3 are both has ballast tank inside them which the function is to hold empty spaces for stability and for floating. Two pontoons are made to ensure small waterplane area can be achieved. By minimizing the area of the vessel's contacting the water, stability may be increased.

3.6 Parameters and Functions

Software CATIA V5R20 contains lot of design structure to be chosen. Modules used in this project are the Mechanical Part Design, Assembly Design and Generative Shape Design.

Other functions used to produce the semi-submersible model are the basic functions of sketchers for two dimensional sketch and isometric design to produce three dimensional (3D) models. 3D model created are then enhanced using functions of pad, groove and fillet. Assembly design uses constraint functions of coincidence, offsets and contact constraint.

Final touch for the model is to insert parameters and relations for the parts of the semi-submersible model. Using sub-modules Generative Shape Design of Functions, all parameters of length, volumes, force and others were inserted to compute vertical center of gravity and also draft value.

CHAPTER 4

RESULT AND DISCUSSION

4.1 Improved Semi-submersible CAD Model

CAD models of semi-submersibles are made using CATIA V5R20 software and all the dimensions and specifications are referring to literature chosen based on currently existing semi-submersible design. Semi-submersible model chosen is the six-column twin-pontoon model. Four sets of CAD model which differ in the measurement of the columns with automated selected parameters computation. Dimensions varied as shown in Table 2:

Table 2: Dimensions used for columns

Waterplane Area of Column	
Column Width (m)	**Column Length (m)**
13.00	12.50
13.44	12.80
14.20	13.00
15.00	13.50

Results shown are for different dimensions of semi-submersible CAD models that were converted using CATIA V5R20. The basic components of a semi-submersible drilling rig are the topsides, the most upper part of the semi-submersible, columns and pontoons, the lowest part of the model. All the models are developed with the formula function for all parts and then combined in assembly design module.

Dimensions of the CAD models were specified in the formula and function tree which also covers the relations of every parameter and dimensions for every part. For this project, the waterplane areas of columns were varied from 12.5m of length to 13.5m and the widths were varied from 13.0m to 15.0m. From the various waterplane area of column, different output of VCG and draft was obtained.

From the value obtained, it can be an idea of creating a library for any offshore floaters so that engineers will have instant value of the parameter chosen and stability can be analyzed. Other parameters also can be varied in the CAD model library so that it may help engineers to produce a better stability semi-submersible.

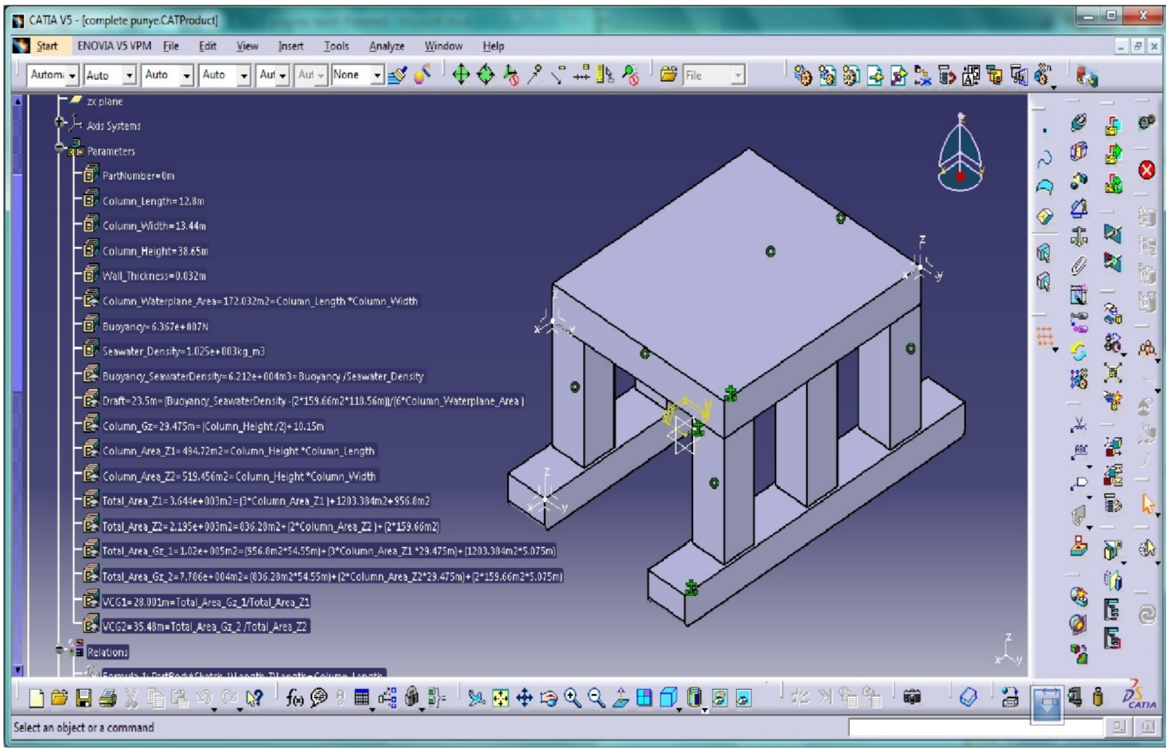

Figure 9: Parameters used to compute VCG and Draft

4.2 Performance Analysis of Semi-submersible

Analysis of the relationship of waterplane area of column with VCG and draft height of the semi-submersible. Figure 11 shows that draft will be decreases with increasing waterplane area of column. From results, it shows that increasing waterplane area of column will reduce the semi-submersible stability as the draft became smaller. Semi-submersible should react minimally to any wave motion or any wind motion so that the semi-submersible can be called stable [20]. Deep draft semi-submersible will minimize the exposed area of column from wave impact thus stabilize the semi-submersible [21]. For operating condition, the draft values of minimum 23.5m and 21.5m for survival condition.

Table 3: Draft Values

Waterplane Area of Column		Draft (m)
Column Width (m)	Column Length (m)	
13.00	12.50	24.88
13.44	12.80	23.50
14.20	13.00	21.90
15.00	13.50	19.96

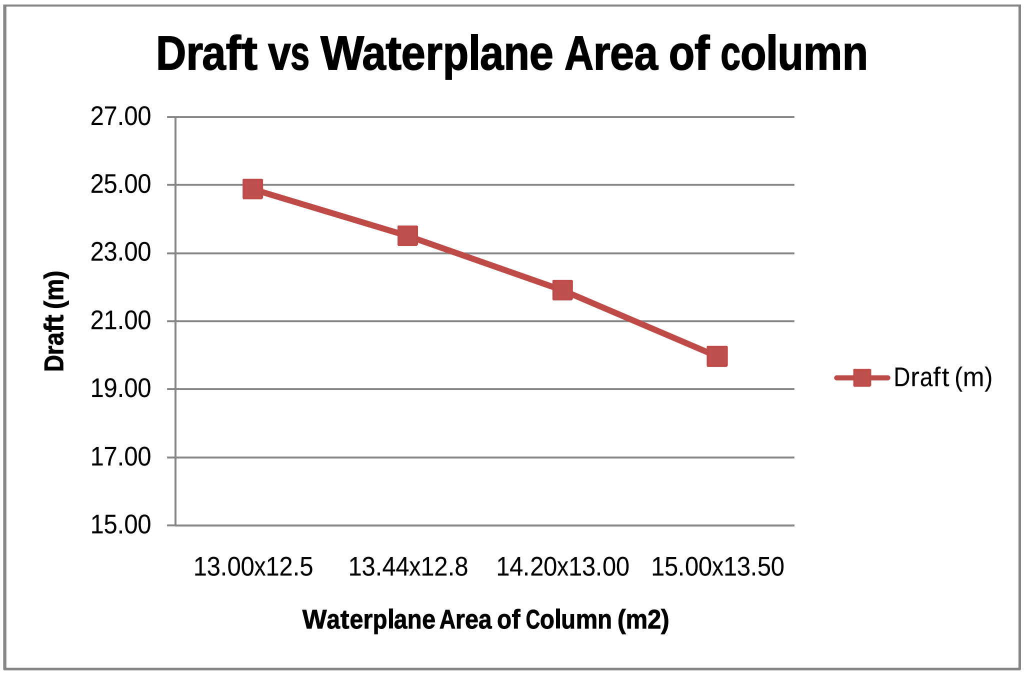

Figure 10: Draft against Waterplane Area of Column

All three-dimensional object has three centers of gravity which divided to horizontal, lateral and vertical center of gravity. The center of gravity is the midpoint for the whole vessel weight to be distributed in order to achieve stability. Vertical Center of Gravity (VCG) has a direct correlation of the floaters rollover stability as the value get higher. Figure 12 shows that the increment of waterplane area of column will reduced the VCG value concluded that chance of the semi-submersible to topple will be reduced.

Table 4: VCG Values

Waterplane Area of Column		**VCG (m)**
Column Width (m)	**Column Length (m)**	
13.00	12.50	35.58
13.44	12.80	35.48
14.20	13.00	35.32
15.00	13.50	35.17

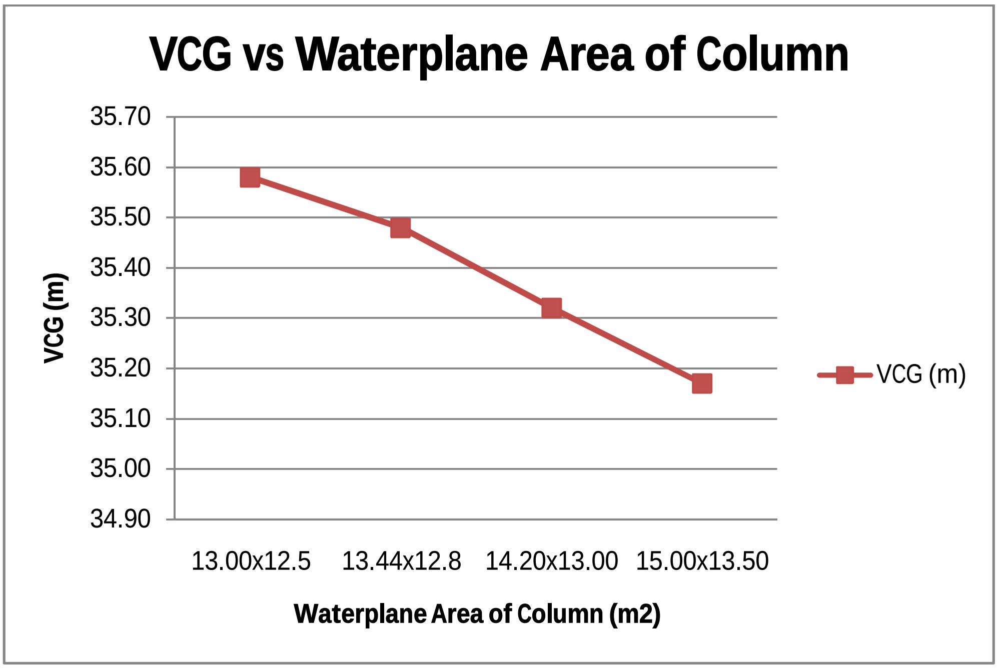

Figure 11: VCG against Waterplane Area of Column

Figure 13 shows that relation between VCG and draft. From graph, it shows that when the value of draft increases, VCG will decrease. For this study, minimum value of draft is 21.9m and the VCG value is 35.3m and if the parameters go beyond this value, the probability of the semi-submersible to flood is high.

Table 5: VCG and Draft Values

Waterplane Area of Column		**Draft (m)**	**VCG(m)**
Column Width (m)	**Column Length (m)**		
13.44	12.80	23.50	35.58
13.00	12.50	24.88	35.48
14.20	13.00	21.90	35.32
15.00	13.50	19.96	35.17

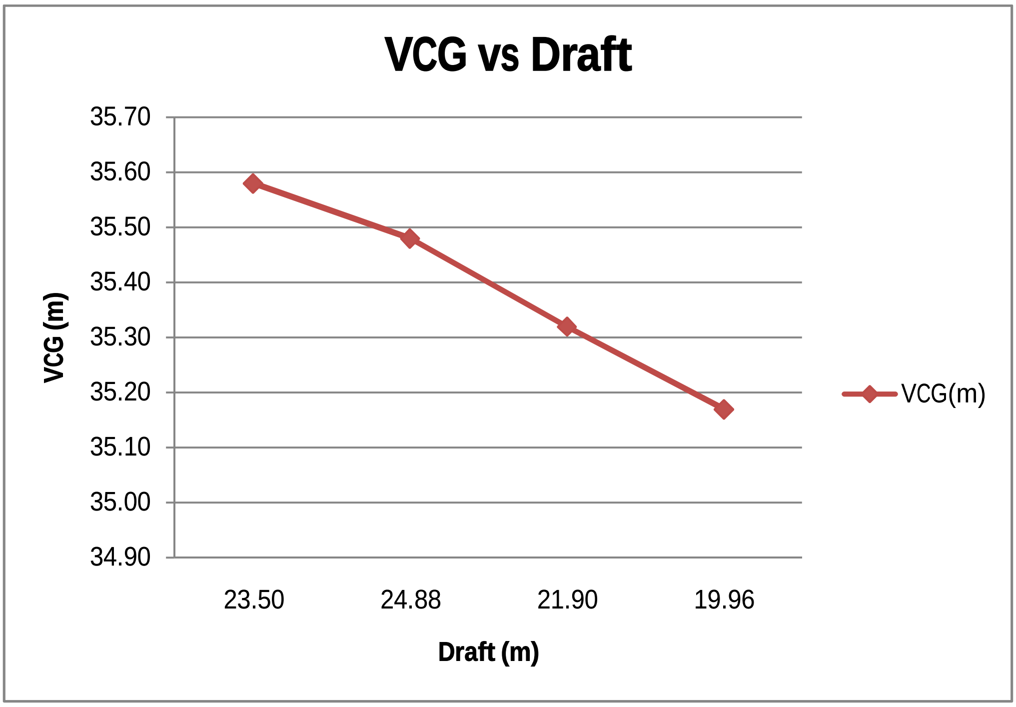

Figure 13: VCG against Draft

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusions

An improved semi-submersible model was developed. Key improvements are to develop the hull section of semi-submersible of six-column twin-pontoon model which is widely used in oil and gas rig. The model hull analysis can be the pioneer of any offshore design library which can help the conceptual design stage and may ease the selection work of the floaters.

With regards to the performance of the proposed ne semi-submersible model, the analysis has indicated that by varying the parameters of vertical center of gravity and draft height, a basic stability performance can be concluded. The increment of the waterplane area of column will reduce the draft height and the vertical center of gravity so that the probability of the model to flood will increase due to low stability.

5.2 Recommendations

It is recommended that further enhancement on the library should be made. The variation of the type of the semi-submersible should be added such as to develop hull model of eight-column twin-pontoon and to put more variation on the specification size.

Based on the performance analysis, other parameters can also be added to produce more precise result. Parameters suggested are:

- Angle of heel
- Restoring moment
- Righting arm

Further study on the weight of the semi-submersible can also be made to widen the scope of dimensions.

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3.3 Project Gantt Chart

No	Details / Week	Timeline																												
		1	2	3	4	5	6	7	8	9	10	11	12	13	14		1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Preliminary Research Work • Literature Review		①																											
2	Design specifications • Criteria • Parameters							②																						
3	Formulation and Calculation • Vertical Center of Gravity • Draft												③			Semester Break														
4	CAD Modelling • Part Design • Assembly Design																							③						
5	Validation • Comparison with similar project																											④		

Key Milestones:
① : Completion of Semi-submersibles Research
② : Completion of Semi-submersibles detail design
③: CATIA model development
④ : Project completion and validation

STEPS IN DEVELOPING THE FORMULA FUNCTION

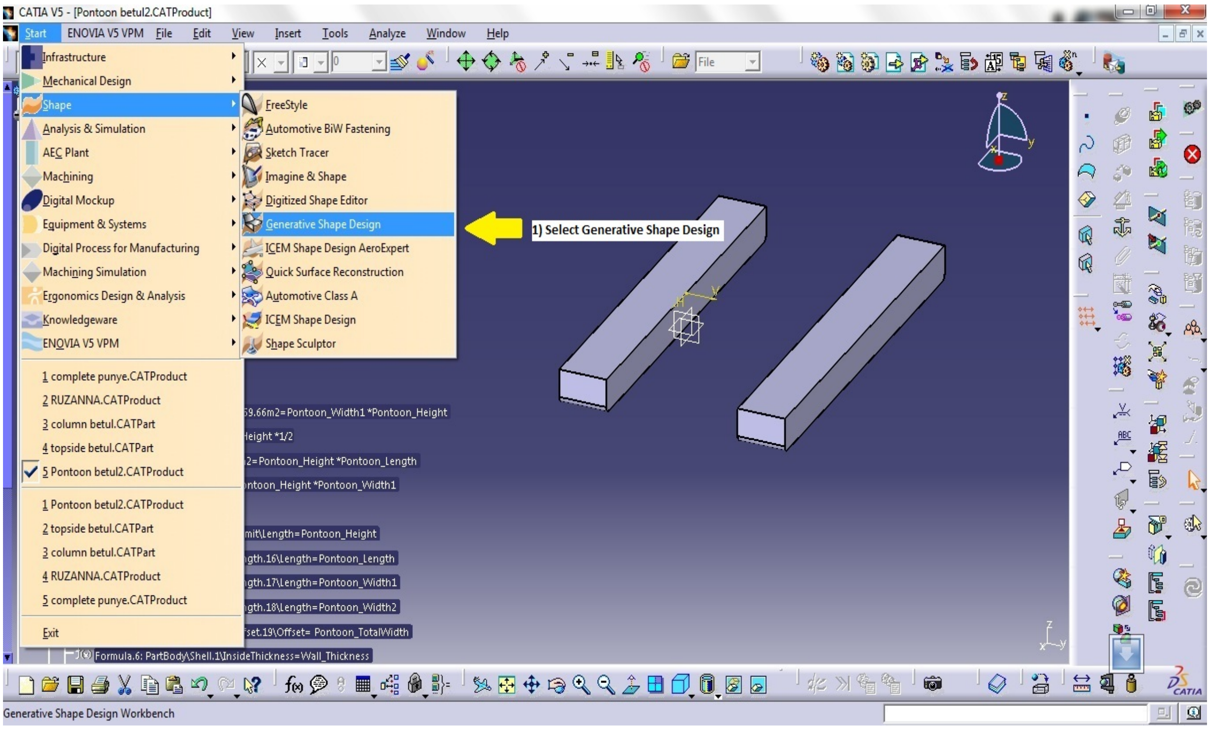

FIGURE A1: Step 1

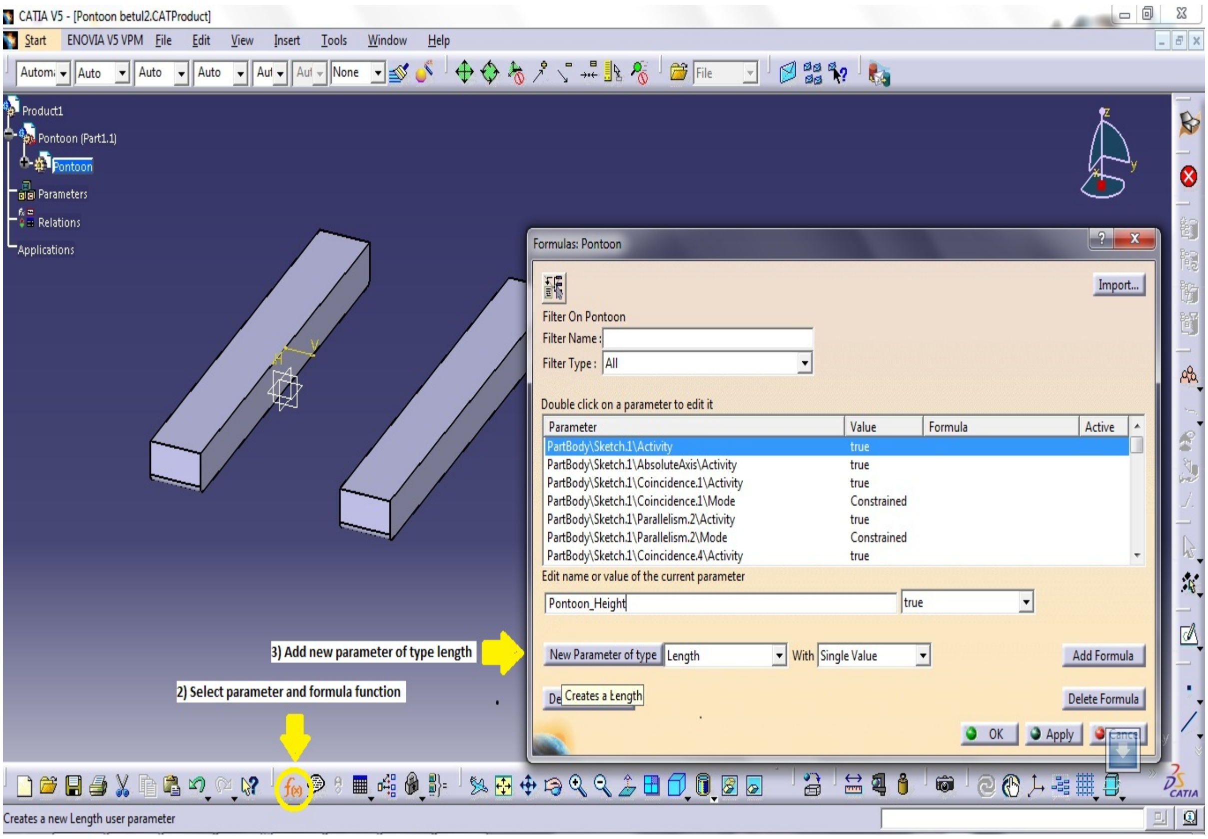

FIGURE A2: Step 2

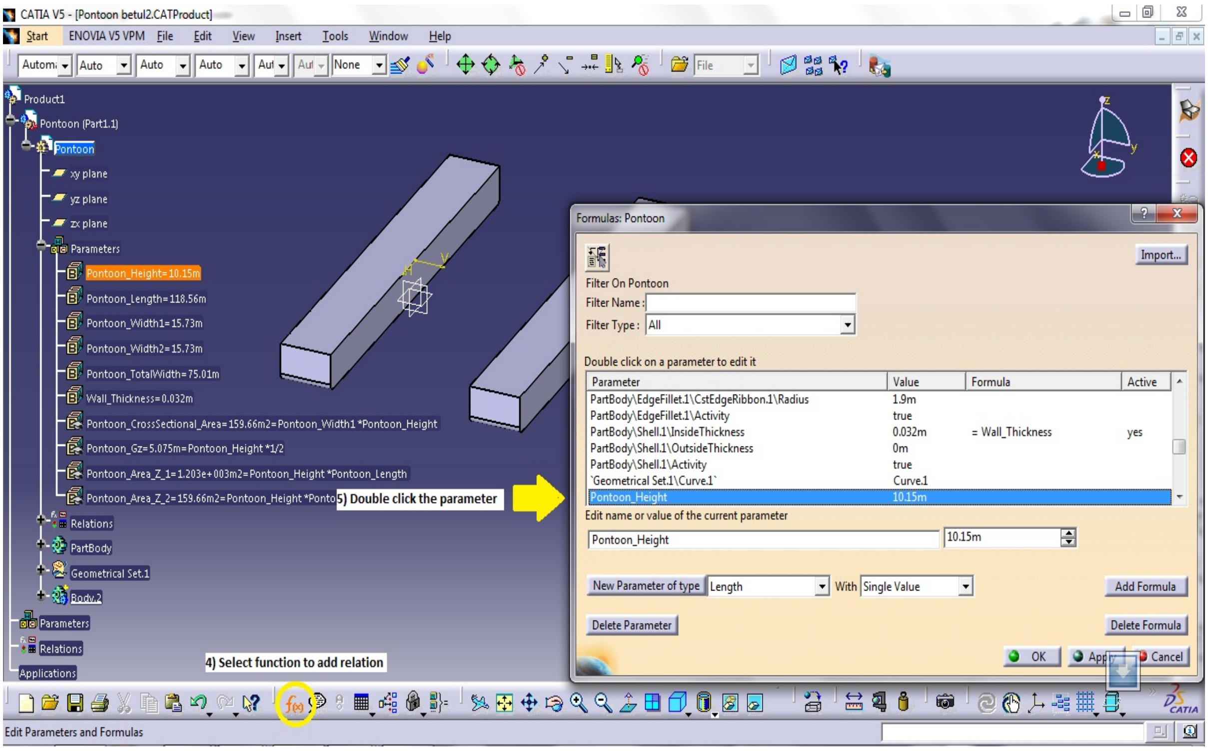

FIGURE A3: Step 3

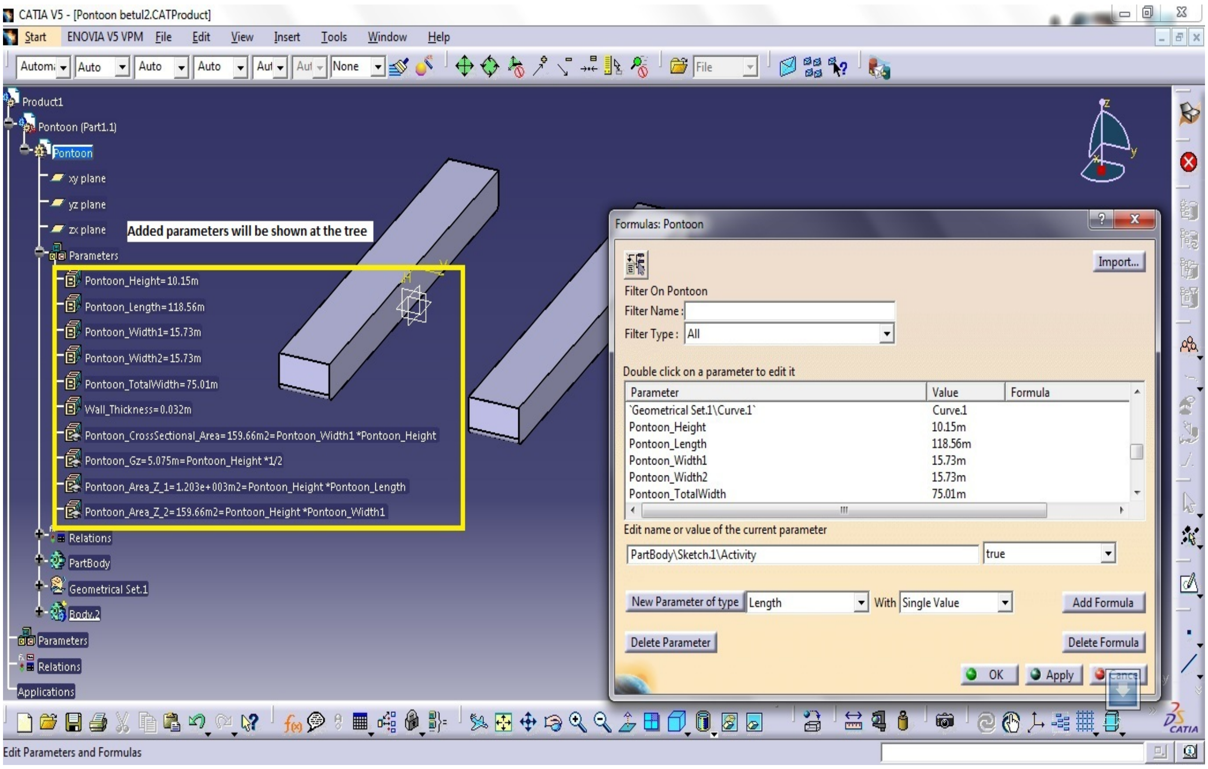

FIGURE A4: Step 4

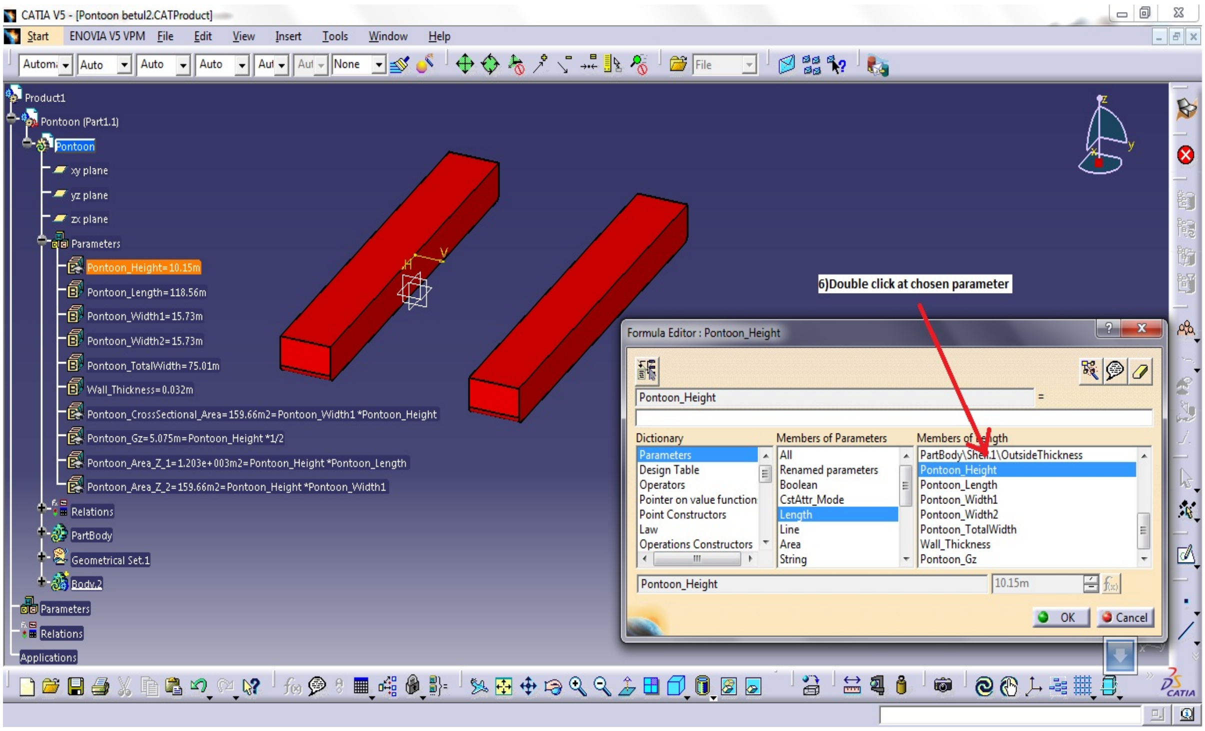

FIGURE A5: Step 5

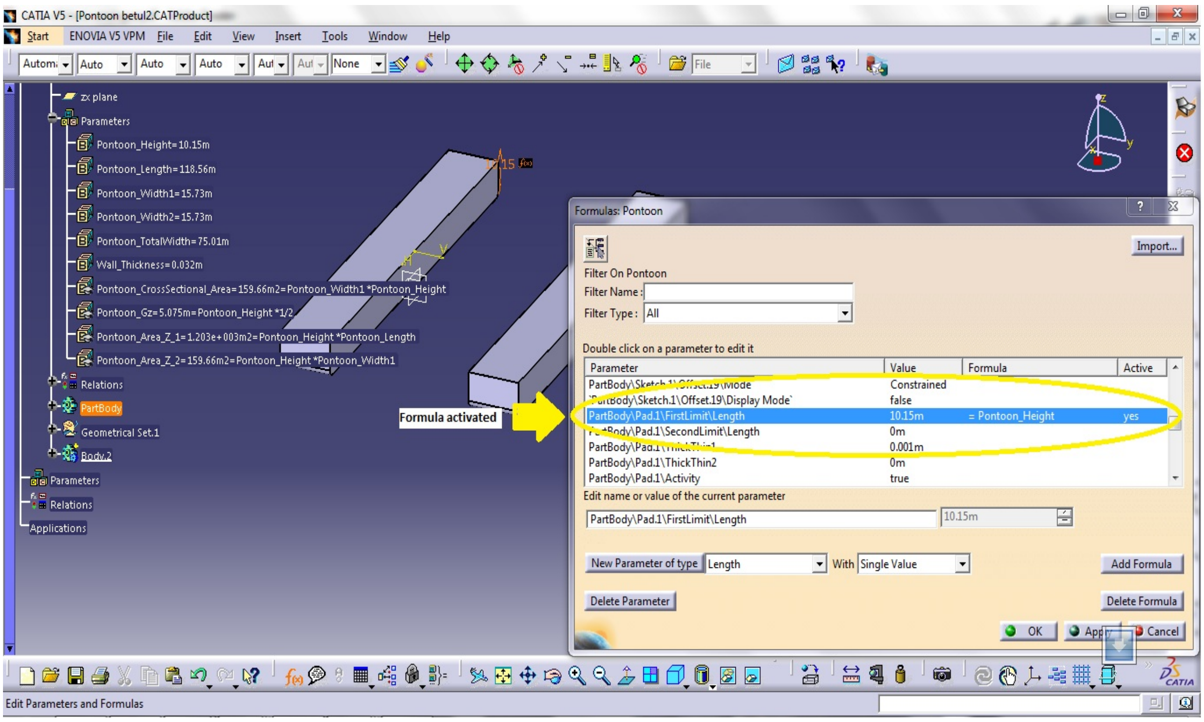

FIGURE A6: Step 6

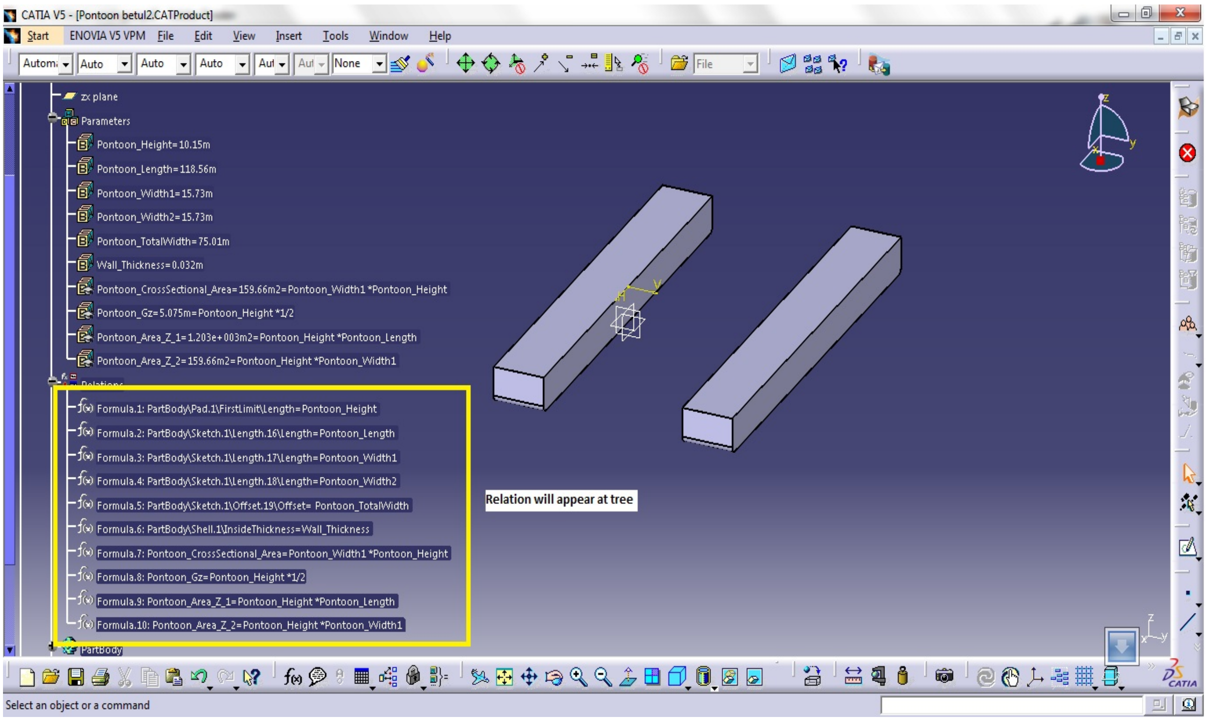

FIGURE A7: Step 7

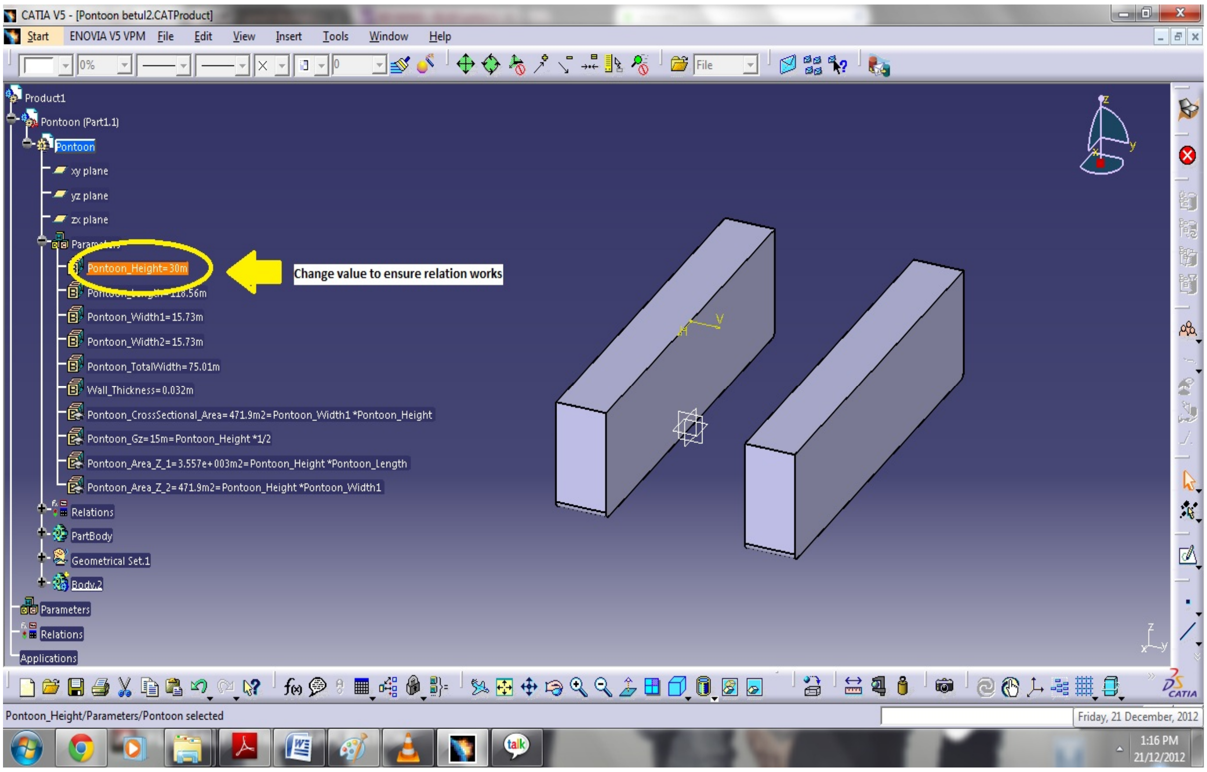

FIGURE 8: Step 8

VCG AND DRAFT CALCULATIONS

Waterplane area of column: 12.8m x 13.44m, Side View

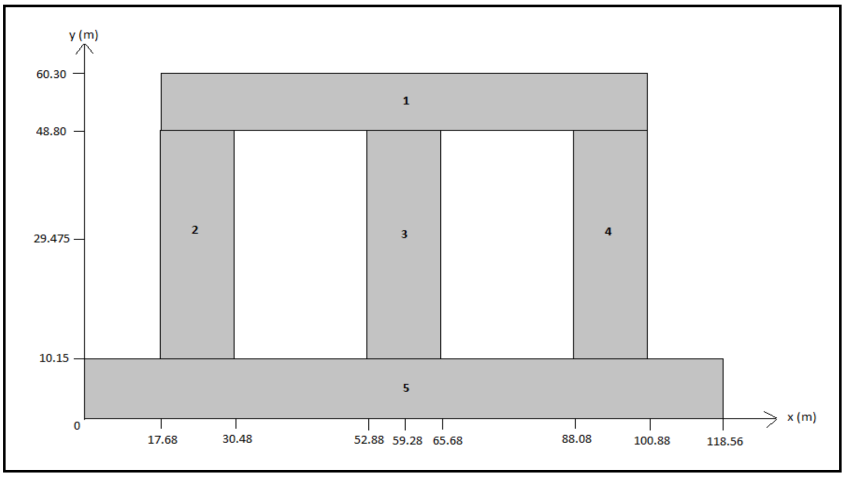

Figure C1: Centroid diagram for 12.8m x 13.44m, side view

Area 1: 83.2m (L) x 11.5m (D) = 956.8 m^2

Area 2: 12.8m (L) x 38.65m (D) = 494.72 m^2

Area 3: 12.8m (L) x 38.65m (D) = 494.72 m^2

Area 4: 12.8m (L) x 38.65m (D) = 494.72 m^2

Area 5: 118.56m (L) x 10.15m (D) = 1203.38 m^2

$$\bar{x} = \frac{x_1A_1 + x_2A_2 + x_3A_2 + x_4A_4 + x_5A_5}{A_1 + A_2 + A_3 + A_4 + A_5}$$

$$\bar{x} = \frac{(956.8 \times 59.28) + (494.72 \times 24.08) + (494.72 \times 59.28) + (494.72 \times 94.48) + (1204.384 \times 59.28)}{956.8 + 494.72 + 494.72 + 494.72 + 1203.384}$$

$$\bar{x} = \frac{216036.7123}{3644.344} = 37.505\ m$$

$$\bar{y} = \frac{y_1A_1 + y_2A_2 + y_3A_2 + y_4A_4 + y_5A_5}{A_1 + A_2 + A_3 + A_4 + A_5}$$

$$\bar{y} = \frac{(956.8 \times 54.55) + 3(494.72 \times 29.475) + (1203.384 \times 5.075)}{956.8 + 494.72 + 494.72 + 494.72 + 1203.384}$$

$$\bar{y} = \frac{102046.2298}{3644.344} = 28.0\ m$$

Waterplane Area of Column, Front View: 12.8m x 13.44m

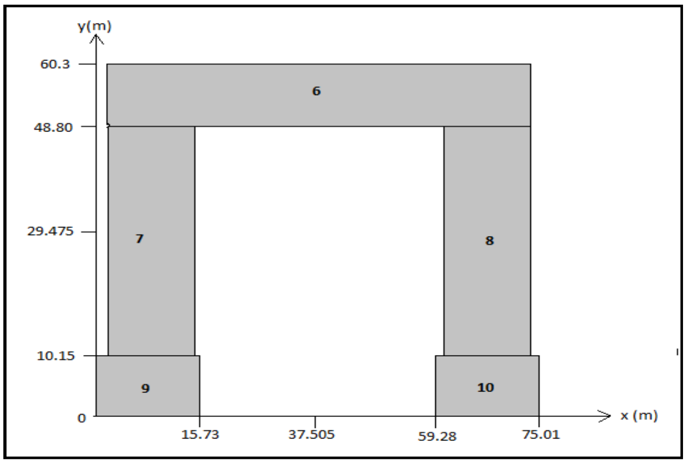

Figure C2: Centroid Diagram for 12.8m x 13.44m, front view

Area 6: 72.72m (W) x 11.5m (D) = 836.28 m^2

Area 7: 13.44m (W) x 38.65m (D) = 519.456 m^2

Area 8: 13.44m (W) x 38.65m (D) = 519.456 m^2

Area 9: 15.73m (W) x 10.15m (D) = 159.66 m^2

Area 10: 15.73m (W) x 10.15m (D) = 159.66 m^2

$$\bar{x} = \frac{x_6A_6 + x_7A_7 + x_8A_8 + x_9A_9 + x_{10}A_{10}}{A_6 + A_7 + A_8 + A_9 + A_{10}}$$

$$\bar{x} = \frac{(836.28 \times 37.505) + (519.456 \times 7.865) + (519.456 \times 67.415) + (159.66 \times 7.865) + (159.66 \times 67.145)}{846.28 + 519.456 + 519.456 + 159.66 + 159.66}$$

$$\bar{x} = \frac{83205.1726}{2194.512} = 37.505\,m$$

$$\bar{y} = \frac{y_6A_6 + y_7A_7 + y_8A_8 + y_9A_9 + y_{10}A_{10}}{A_6 + A_7 + A_8 + A_9 + A_{10}}$$

$$\bar{y} = \frac{(836.28 \times 54.55) + 2(519.456 \times 29.475) + 2(159.66 \times 5.075)}{846.28 + 519.456 + 519.456 + 159.66 + 159.66}$$

$$\bar{y} = \frac{77861.5542}{2194.516} = 35.48\,m$$

Waterplane area of column: 12.5m x 13.0m, Side View

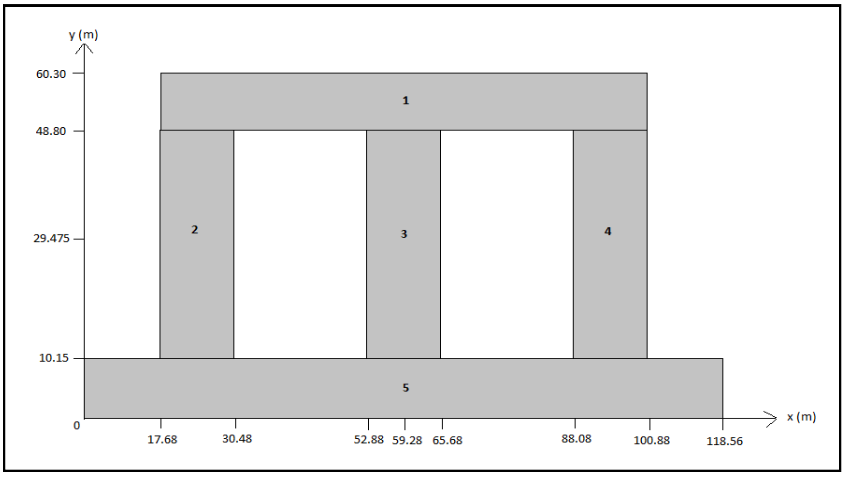

Figure C3: Centroid diagram for 12.5m x 13.0m, side view

Area 1: 83.2m (L) x 11.5m (D) = 956.8 m^2

Area 2: 12.5m (L) x 38.65m (D) = 483.13 m^2

Area 3: 12.5m (L) x 38.65m (D) = 483.13 m^2

Area 4: 12.5m (L) x 38.65m (D) = 483.13 m^2

Area 5: 118.56m (L) x 10.15m (D) = 1203.38 m^2

$$\bar{x} = \frac{x_1A_1 + x_2A_2 + x_3A_2 + x_4A_4 + x_5A_5}{A_1 + A_2 + A_3 + A_4 + A_5}$$

$$\bar{x} = \frac{(956.8 \times 59.28) + (483.13 \times 24.08) + (483.13 \times 59.28) + (483.13 \times 94.48) + (1204.384 \times 59.28)}{956.8 + 483.13 + 483.13 + 483.13 + 1203.384}$$

$$\bar{x} = \frac{214034.8267}{3609.574} = 59.3m$$

$$\bar{y} = \frac{y_1A_1 + y_2A_2 + y_3A_2 + y_4A_4 + y_5A_5}{A_1 + A_2 + A_3 + A_4 + A_5}$$

$$\bar{y} = \frac{(956.8 \times 54.55) + 3(483.13 \times 29.475) + (1203.384 \times 5.075)}{956.8 + 483.13 + 483.13 + 483.13 + 1203.384}$$

$$\bar{y} = \frac{101021.3841}{3609.574} = 27.9\,m$$

Waterplane Area of Column, Front View: 12.5m x 13.0m

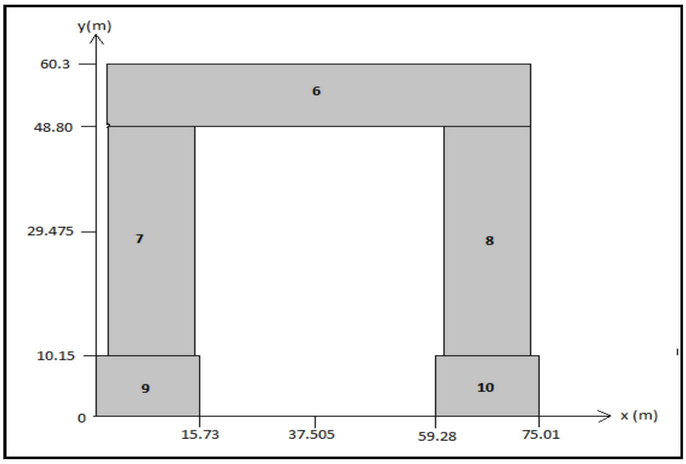

Figure C4: Centroid Diagram for 12.5m x 13.0 m, front view

Area 6: 72.72m (W) x 11.5m (D) = 836.28 m^2

Area 7: 13.0m (W) x 38.65m (D) = 502.45 m^2

Area 8: 13.0m (W) x 38.65m (D) = 502.45 m^2

Area 9: 15.73m (W) x 10.15m (D) = 159.66 m^2

Area 10: 15.73m (W) x 10.15m (D) = 159.66 m^2

$$\bar{x} = \frac{x_6A_6 + x_7A_7 + x_8A_8 + x_9A_9 + x_{10}A_{10}}{A_6 + A_7 + A_8 + A_9 + A_{10}}$$

$$\bar{x} = \frac{(836.28 \times 37.505) + (502.45 \times 7.865) + (502.45 \times 67.415) + (159.66 \times 7.865) + (159.66 \times 67.145)}{846.28 + 502.45 + 502.45 + 159.66 + 159.66}$$

$$\bar{x} = \frac{81165.214}{2170.5} = 37.39\ m$$

$$\bar{y} = \frac{y_6A_6 + y_7A_7 + y_8A_8 + y_9A_9 + y_{10}A_{10}}{A_6 + A_7 + A_8 + A_9 + A_{10}}$$

$$\bar{y} = \frac{(836.28 \times 54.55) + 2(502.45 \times 29.475) + 2(159.66 \times 5.075)}{846.28 + 502.45 + 502.45 + 159.66 + 159.66}$$

$$\bar{y} = \frac{76859.05}{2170.5} = 35.41\ m$$

Waterplane area of column:13.0m x 14.2m, Side View

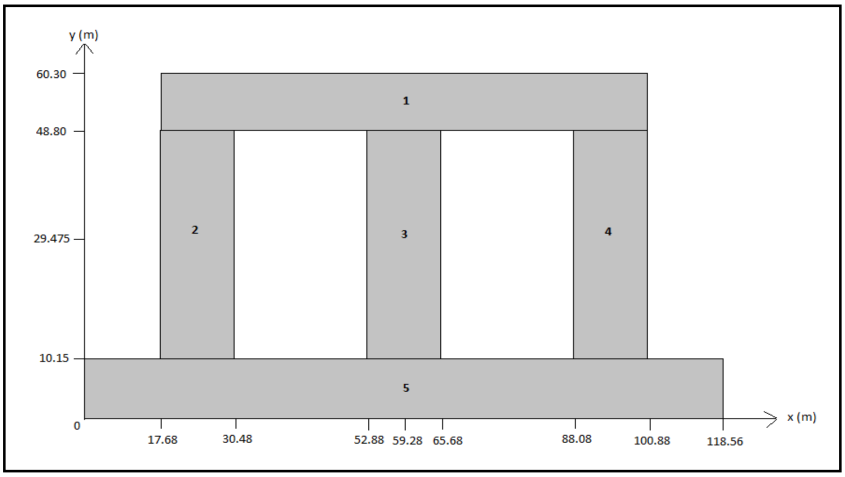

Figure C5: Centroid diagram for 13.0m x 14.2m, side view

Area 1: 83.2m (L) x 11.5m (D) = 956.8 m^2

Area 2: 13.0m (L) x 38.65m (D) = 502.45 m^2

Area 3: 13.0m (L) x 38.65m (D) = 502.45 m^2

Area 4: 13.0m (L) x 38.65m (D) = 502.45 m^2

Area 5: 118.56m (L) x 10.15m (D) = 1203.38 m^2

$$\bar{x} = \frac{x_1A_1 + x_2A_2 + x_3A_2 + x_4A_4 + x_5A_5}{A_1 + A_2 + A_3 + A_4 + A_5}$$

$$\bar{x} = \frac{(956.8 \times 59.28) + (502.45 \times 24.08) + (502.45 \times 59.28) + (502.45 \times 94.48) + (1204.384 \times 59.28)}{956.8 + 502.45 + 502.45 + 502.45 + 1203.384}$$

$$\bar{x} = \frac{217472.47}{3667.534} = 59.3\ m$$

$$\bar{y} = \frac{y_1A_1 + y_2A_2 + y_3A_2 + y_4A_4 + y_5A_5}{A_1 + A_2 + A_3 + A_4 + A_5}$$

$$\bar{y} = \frac{(956.8 \times 54.55) + 3(502.45 \times 29.475) + (1203.384 \times 5.075)}{956.8 + 502.45 + 502.45 + 502.45 + 1203.384}$$

$$\bar{y} = \frac{102729.7551}{3667.534} = 28.01\ m$$

Waterplane Area of Column, Front View: 13.0m x 14.2m

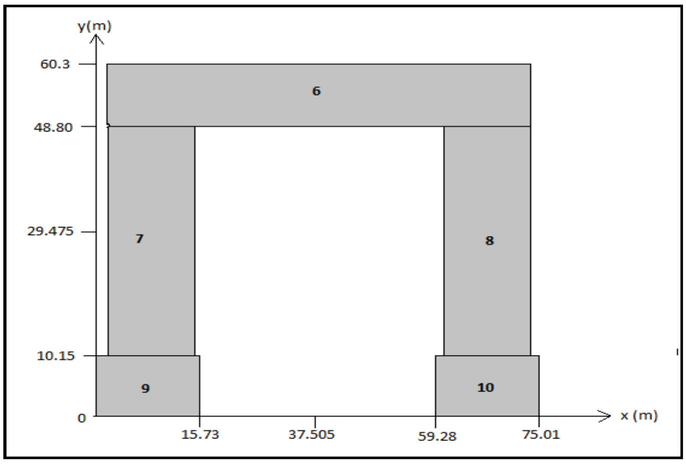

Figure C6: Centroid Diagram for 13.0m x 14.2m, front view

Area 6: 72.72m (W) x 11.5m (D) = 836.28 m^2

Area 7: 14.2m (W) x 38.65m (D) = 548.83 m^2

Area 8: 14.2m (W) x 38.65m (D) = 548.83 m^2

Area 9: 15.73m (W) x 10.15m (D) = 159.66 m^2

Area 10: 15.73m (W) x 10.15m (D) = 159.66 m^2

$$\bar{x} = \frac{x_6A_6 + x_7A_7 + x_8A_8 + x_9A_9 + x_{10}A_{10}}{A_6 + A_7 + A_8 + A_9 + A_{10}}$$

$$\bar{x} = \frac{(836.28 \times 37.505) + (548.83 \times 7.865) + (548.83 \times 67.415) + (159.66 \times 7.865) + (159.66 \times 67.145)}{846.28 + 548.83 + 548.83 + 159.66 + 159.66}$$

$$\bar{x} = \frac{84656.70}{2263.26} = 37.405\,m$$

$$\bar{y} = \frac{y_6A_6 + y_7A_7 + y_8A_8 + y_9A_9 + y_{10}A_{10}}{A_6 + A_7 + A_8 + A_9 + A_{10}}$$

$$\bar{y} = \frac{(836.28 \times 54.55) + 2(548.83 \times 29.475) + 2(159.66 \times 5.075)}{846.28 + 548.83 + 548.83 + 159.66 + 159.66}$$

$$\bar{y} = \frac{79593.1515}{2263.26} = 35.17\,m$$

Waterplane area of column: 13.5m x 15.0m, Side View

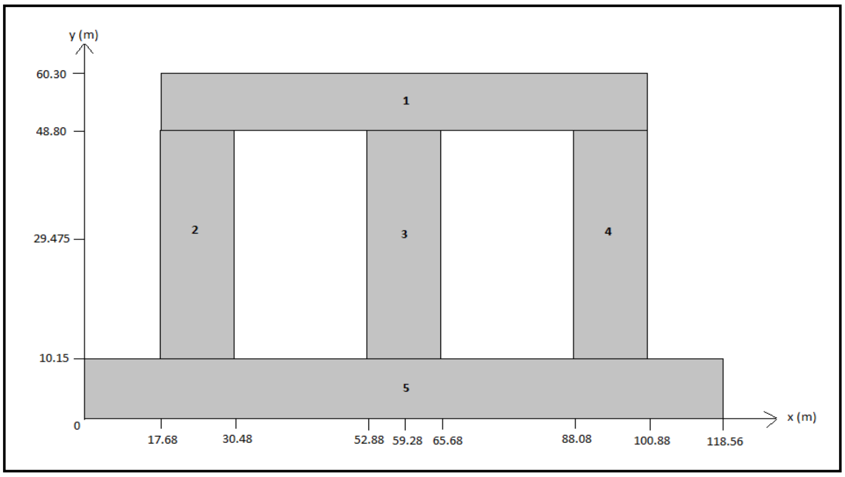

Figure C7: Centroid diagram for 13.5m x 15.0m, side view

Area 1: 83.2m (L) x 11.5m (D) = 956.8 m^2

Area 2: 13.5m (L) x 38.65m (D) = 521.78 m^2

Area 3: 13.5m (L) x 38.65m (D) = 521.78 m^2

Area 4: 13.5m (L) x 38.65m (D) = 521.78 m^2

Area 5: 118.56m (L) x 10.15m (D) = 1203.38 m^2

$$\bar{x} = \frac{x_1A_1 + x_2A_2 + x_3A_2 + x_4A_4 + x_5A_5}{A_1 + A_2 + A_3 + A_4 + A_5}$$

$$\bar{x} = \frac{(956.8 \times 59.28) + (521.78 \times 24.08) + (521.78 \times 59.28) + (521.78 \times 94.48) + (1204.384 \times 59.28)}{956.8 + 521.78 + 521.78 + 521.782 + 1203.384}$$

$$\bar{x} = \frac{220908.34}{3725.524} = 59.3m$$

$$\bar{y} = \frac{y_1A_1 + y_2A_2 + y_3A_2 + y_4A_4 + y_5A_5}{A_1 + A_2 + A_3 + A_4 + A_5}$$

$$\bar{y} = \frac{(956.8 \times 54.55) + 3(521.78 \times 29.475) + (1203.384 \times 5.075)}{956.8 + 521.78 + 521.78 + 521.78 + 1203.384}$$

$$\bar{y} = \frac{104439.01}{3725.524} = 28.03\,m$$

Waterplane Area of Column, Front View: 13.5m x 15m

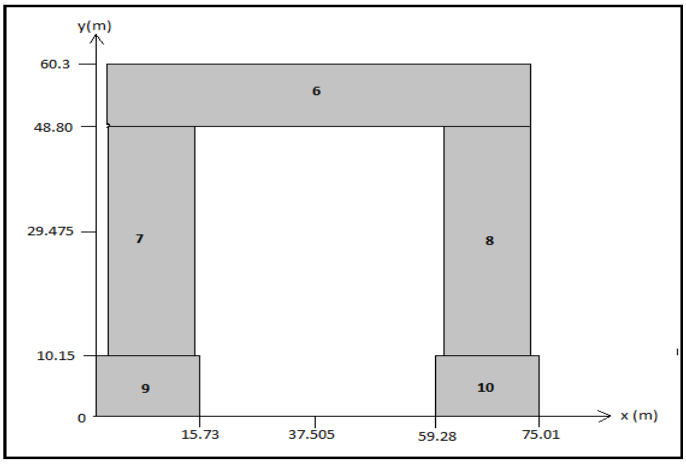

Figure C8: Centroid Diagram for 13.5m x 15.0m, front view

Area 6: 72.72m (W) x 11.5m (D) = 836.28 m^2

Area 7: 15.0m (W) x 38.65m (D) = 579.75 m^2

Area 8: 15.0m (W) x 38.65m (D) = 579.75 m^2

Area 9: 15.73m (W) x 10.15m (D) = 159.66 m^2

Area 10: 15.73m (W) x 10.15m (D) = 159.66 m^2

$$\bar{x} = \frac{x_6 A_6 + x_7 A_7 + x_8 A_8 + x_9 A_9 + x_{10} A_{10}}{A_6 + A_7 + A_8 + A_9 + A_{10}}$$

$$\bar{x} = \frac{(836.28 \times 37.505) + (579.75 \times 7.865) + (579.75 \times 67.415) + (159.66 \times 7.865) + (159.66 \times 67.145)}{846.28 + 579.75 + 579.75 + 159.66 + 159.66}$$

$$\bar{x} = \frac{87027.47}{2325.1} = 37.43\, m$$

$$\bar{y} = \frac{y_6 A_6 + y_7 A_7 + y_8 A_8 + y_9 A_9 + y_{10} A_{10}}{A_6 + A_7 + A_8 + A_9 + A_{10}}$$

$$\bar{y} = \frac{(836.28 \times 54.55) + 2(579.75 \times 29.475) + 2(159.66 \times 5.075)}{846.28 + 579.75 + 579.75 + 159.66 + 159.66}$$

$$\bar{y} = \frac{81415.89}{2325.1} = 35.02\, m$$

Draft Calculation

$$Buoyancy = [(6 \times waterplane\ area\ of\ column \times draft) + (2 \times cross\ sectional\ area\ of\ pontoon \times length\ of\ pontoon)] \times seawater\ density$$

Waterplane area of column = 12.8m x 13.44m =172.032 m^2

Draft = 23.5 m

Seawater density = 1025 kg/m^3

Length of pontoon = 118.56 m

Cross sectional area of pontoon = 159.66 m^2

$$Buoyancy = [(6 \times 172.032 \times 23.5) + (2 \times 159.66 \times 118.56)] \times 1025$$

$$Buoyancy = 63.668 \times 10^6\ N$$

Buoyancy is set as constant to find draft:

Waterplane area of column: 12.5m x 13.0m = 162.50 m^2

$$63.668 \times 10^6 = [(6 \times 162.5 \times draft) + (2 \times 159.66 \times 118.56)] \times 1025$$

$$draft = 24.88\ m$$

Waterplane area of column: 13.0m x 14.2m = 184.60 m^2

$$63.668 \times 10^6 = [(6 \times 184.6 \times draft) + (2 \times 159.66 \times 118.56)] \times 1025$$

$$draft = 21.90\ m$$

Waterplane area of column: 13.5m x 15.0m = 202.50 m^2

$$63.668 \times 10^6 = [(6 \times 202.5 \times draft) + (2 \times 159.66 \times 118.56)] \times 1025$$

$$draft = 19.96\ m$$