INVESTIGATION OF GUYED TOWER AND ARTICULATED TOWER AS A DEEPWATER PLATFORM

by

NORAZIAH MOHD NOR

FINAL YEAR PROJECT REPORT

A project dissertation submitted in partial fulfilment of
the requirements for the
Bachelor of Engineering (Hons)
(Civil Engineering)

Universiti Teknologi PETRONAS
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Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

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TRONOH, PERAK
December 2007

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.

NORAZIAH BINTI MOHD NOR

ABSTRACT

This final dissertation is a continuation of the interim report which has concluded all research works that have been done in the first and second part of this Final Year Project (FYP). At the beginning of the project, author has been briefed by the supervisor on the offshore technologies and offshore platform. From time to time, author has conducted research from appropriate books and journals, and furthermore gained related information regarding to this field through the course of Construction and Maintenance of Marine Structures and Foundation. In Chapter 1, author has presented background of the study, defined the problems associated and specified the scope of the study. In Chapter 2, valuable information are presented where these are the theory and literature produced by the expertise of the field. In Chapter 3, methods that have been used for this research work are defined. In Chapter 4, some of the analysis results done by the expertise were attached and nevertheless the analysis that carried out by the author was also included. Author has conducted a simple hydrodynamic analysis with the aid of Microsoft Excel. The analysis only involved articulated tower due to limited information on guyed tower. In Chapter 5, author has summarized all the works done and highlighted some recommendations that appropriate to be adapted in Malaysian environment.

ACKNOWLEDGEMENTS

All praise is to Allah, Lord of the worlds, who, through His mercy and grace, has revealed some of His knowledge and given me strength and opportunities in completing this final dissertation as the university's requirement for my Final Year Project (FYP). Verily all goods are from Allah and all shortcomings are due to my own weaknesses.

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CHAPTER 1
INTRODUCTION

1.1 Background of Study

Deepwater platform is one of the offshore structures which serve as a place where drilling, production, storage and offloading of hydrocarbon namely oil and gas field development take place. For these purposes, offshore structures may be required to stay in position in all weather conditions. These activities have started since late of 1940s where fixed type platforms also known as conventional platforms were used in the beginning. The platforms maybe bottom-supported or floating and have no fixed access to dry land. Bottom-supported structures are either "fixed" such as jackets and concrete gravity base structures, or "compliant" such as the guyed tower and other articulated towers. A structure is considered fixed if it withstands the environmental forces on it without substantial displacement or deformation. A compliant structure may be of two types: one is rigid and floating but connected to the seafloor by some mechanical means, while the other allows large deformation of its members when subjected to waves, wind and current. Compared to compliant structure, fixed structures experience greater forces. Fixed structures may be economically viable for water depths of up to 1,000-1,600 ft while compliant structures experience smaller wave forces and can be adapted in deeper waters. Floating structures are compliant by nature which can be viewed either as "neutrally buoyant" such as semi-submersible-based FPSs, Floating Production, Storage and Offloading vessel (FPSO) and monocolumn Spars, or "positively buoyant", such as the Tension Leg Platforms (TLP). The primary functional requirements for an offshore facility are determined by reservoir and fluid characteristics, water depth and ocean environment. The current deepwater systems that adapted to various water depths is presented in Figure 1.1. For this report purposes, investigation that are to be carried out by the author will only focus on Compliant Tower in order to make a comparison between Fixed Platform.

1.2 Problem statement

Hydrocarbons fuel the majority of the world's energy needs and economic growth and will continue to do so well into the next thirty years (See Figure 1.3). As demand increases, so does the oil and gas industry's need for technology – to produce the reserves of today and explore for the reserves of tomorrow. New technologies are continually required, focused both on increasing recovery from fields already in production, and enabling exploration in the more and more complex and challenging environments of the future. Today, most exploration is in frontier, deepwater areas which according to US Mineral Management Service (MMS), water depths greater than 1,300 ft classified as deepwater and water depth greater than 5,000 ft classified as ultra-deepwater, however this classification is subject to change depending on different understanding.

Maus, L. D and Finn, L. D (1983) stated that as water depths of interest increased, the size and cost of conventional, pile-founded steel jacket platforms increased at an ever-greater rate. The size of growth was influenced by (1) the increasing lever arm on which the environmental forces act to create moments at the base of the structure and (2) the tendency of the natural period of vibration of the structure to increase into the range of wave periods.

It is also recognized that conventional structures would have to carry severe foundation loading even in the static mode and that because of their increased fundamental period excessive dynamic amplification of stresses and displacements is a serious design problem. Recognizing that the dynamic amplification of response is the main problem, designers have to come with the structures which have the fundamental period well above that of the predominant waves. The increase in the fundamental period can be achieved by increasing either the structural weight or its flexibility, or both. Since the primary aim is to reduce weight, these structures are essentially flexible or in other word are 'compliant'. These reasons create the need for a stiff, wider structure and more extensive foundation as the platform is required to remain rigidly based on the seafloor but moves slightly with the waves.

Achieving compliant response requires controlling the mass and stiffness characteristics to de-tune the natural frequencies of vibration, relative to the frequencies of the periodic forces of wind and waves, in combination with current. Compliant towers, with the use of flex elements such as flex legs or axial tubes, typically achieve sway periods of 30 - 33 seconds. As a result, resonance is reduced and wave forces are de-amplified. By comparison, typical shallow water platforms will have periods 3 - 4 seconds. De-amplification of hurricane forces enhances efficiency levels with respect to tonnages and construction requirements, as the structure can be configured to adapt to existing fabrication and installation equipment and facilities.

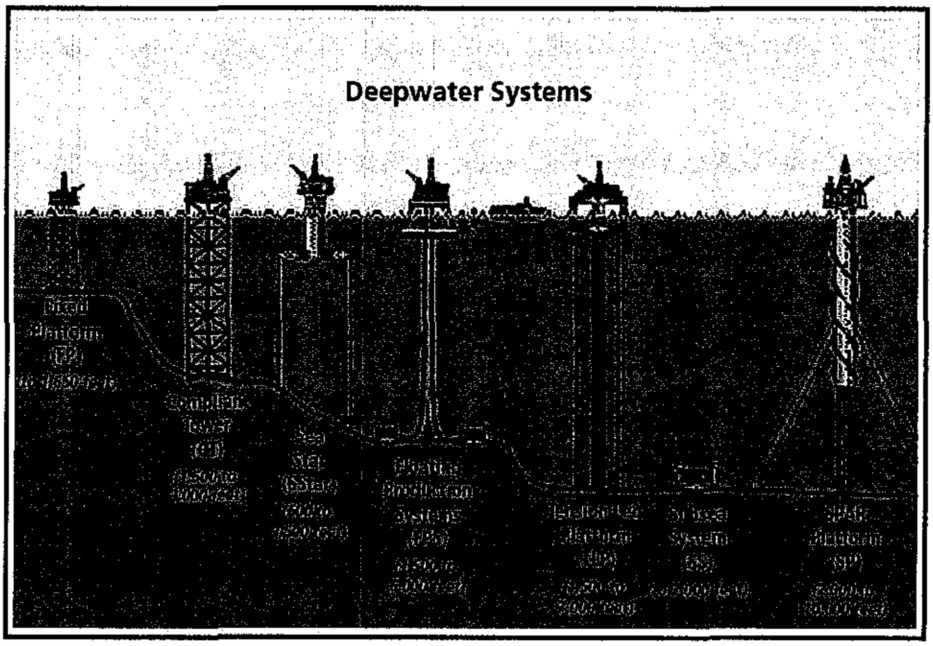
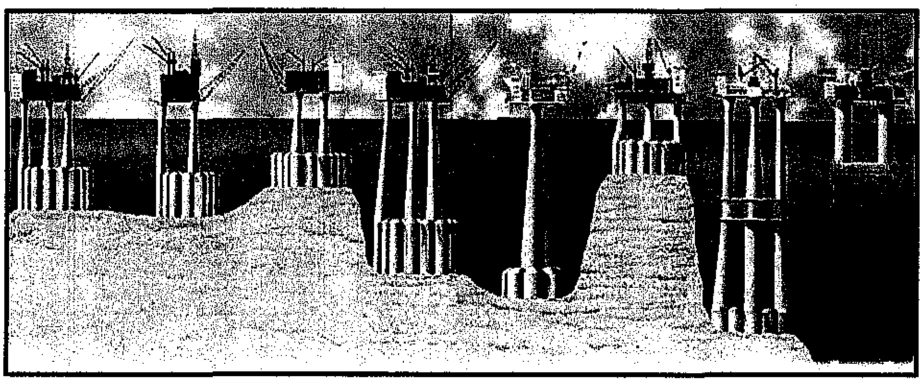


Figure 1.1: Deepwater system

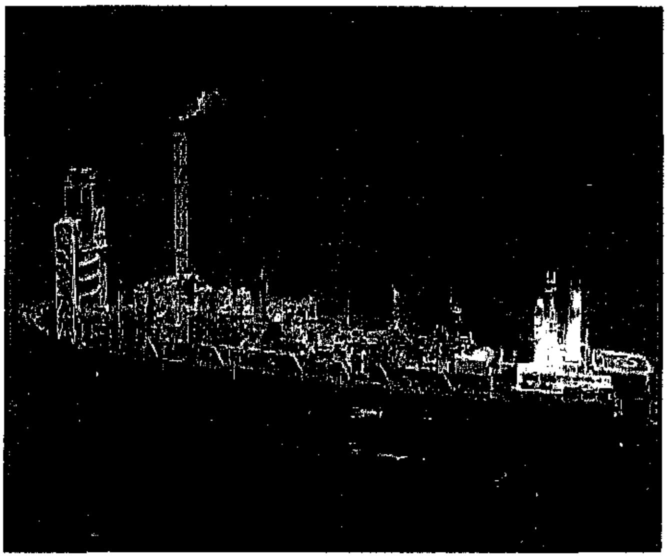
1.3 Objectives

The objectives expected to be met in this project include:

- First phase - to collect all technical details regarding the existing guyed towers and articulated tower (compliant tower) in the world and also the conventional platforms.
- Second phase - to perform a hydrodynamic analysis of an existing guyed tower or articulated tower and find the tower responses.



(a)



(b)

Figure 1.2: (a) Concrete Gravity Base Structure (b) Floating Production, Storage and Offloading vessel, FPSO

1.4 Scopes of study

The scopes of concern for this project are:

- First part - Collect all technical information on the existing guyed towers, articulated towers (compliant tower) and conventional platform available and used in the world.
- Second part - Conduct a simple hydrodynamic analysis using MS Excel to one of the compliant tower

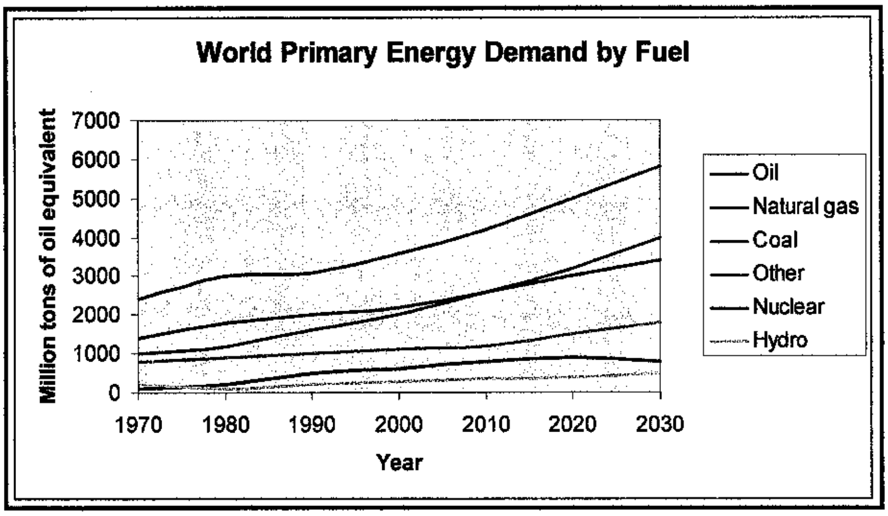


Figure 1.3: World Primary Energy Demand by Fuel (Sources: International Energy Agency – World Energy Outlook 2004)

CHAPTER 2

LITERATURE REVIEW AND/OR THEORY

2.1 Fixed Platform/Conventional Platform

Fixed platform (FP) is supported by piles driven into the seabed which supporting a deck with space for drilling rigs, production facilities and crew quarters. It is remains in place for many years because it is immobility and for that was designed for very long term use. It is economically feasible for water depths up to 1,650 ft (503 m) and varies in size and height. Within this category there are 4-leg, 6-leg, and 8-leg towers and also minimal structures whose decks are supported by a single unbraced or pile-braced caisson. Various types of structure are used, steel jacket, concrete caisson, floating steel and even floating concrete. Steel jackets are vertical sections made of tubular steel members, and are usually piled into the seabed. Concrete caisson structures, often have in-built oil storage in tanks below the sea surface and these tanks were often used as a flotation capability, allowing them to be built close to shore and then floated to their final position where they are sunk to the seabed. There are recorded 63 fixed steel platforms in the Gulf of Mexico in water depths greater than 400 ft (2003). Most of these platforms have jacket weight in excess of 10,000 short tons. For this report purposes, one Fixed Platform will be presented which is Cognac, 1977.

Campo and McDermott (1998) say that many factors are contributed to the selection of platforms concepts which the most important factors fall in the following categories:

- Platform function: well protector, protection, production, drilling, living accommodations, or a combination of all these
- Production elements (gas, oil or both) and rates
- Soil conditions
- Fabrication yard and installation capabilities
- Owner/Designer preferences

As more reserves are being discovered in deep water, the technology needed to design and build deep-ocean compliant structures, continues to evolve to meet technical and economic needs for deepwater development. This rapid evolution in technology needs to be independently verified to ensure continued safety of operations and protection of the environment. Some of the jacket platforms information that installed around the world is shown in Table 2.1 presented in Appendix I.

2.1.1 Cognac

Cognac (Figure 2.1 in Appendix II) was installed in 1977, in average water depth of 1,020 ft (311 m) by Shell Oil Company. At the elevation of 14 ft (4.3 m) above the mean water line (MWL), the jacket measures 84 x 164 ft (26 x 50 m) while at the mudline, the jacket base section measures 380 x 400 ft (117 x 122 m). There are eight main legs which extend the full height of the jacket and two framing legs which extend from elevation -400 from MWL to the ocean bottom. The jacket was divided into three sections due to the water depth where these sections were fabricated, transported and launched independently (Figure 2.2 and Figure 2.3 in Appendix II). All of legs are seven ft (2.1 m) in diameter and the base is held in position by 24 vertical skirt piles driven 450 ft (137 m) into the soft clay bottom. The piles are seven ft (2.1 m) in diameter and are grouted into skirt pile sleeves eight ft (2.4 m) in diameter. The three jacket sections weigh a total of 30,386 tonnes where the total weight of the steel used to build the platform is 53,515 tonnes.

Hurricane waves, wind and current are the environmental forces that determined the platform size and weight. These forces were controlling factors in the fatigue behaviour analysis. The oceanographic criteria for this construction is shown in Table 2.2 presented Appendix I as well as the installation procedure in Figure 2.2 and Figure 2.3 respectively in Appendix II.

2.2 Compliant Tower

Compliant towers are similar to fixed platforms in the way that they have a steel tubular jacket that is used to support the surface facilities. However, according to Ronalds and Lim (2001), compliant towers differ from jackets in that they are configured to respond flexibly to large waves. They are usually designed so that their lowest natural frequency is below the energy in the wave. It can be adapted for the water depth ranges from 1,500 feet to 3,000 feet. Waves, wind and current cause these structures to deflect, but the magnitude of the dynamic loads is greatly reduced. Unlike fixed platforms, compliant towers yield to the water and wind movements in a manner similar to floating structures. At the other hand, compliant towers are secured to the seafloor with piles similar to the fixed platform, however the jacket of a compliant tower has a smaller dimensions than those of a fixed platform and may consist of two or more section. It can also have buoyancy sections in the upper jacket with mooring lines from jacket to seafloor (guyed-tower designs) or a combination of the two. The surface facilities are smaller by design on compliant towers than on fixed platforms because of the decreased jacket dimensions that support them.

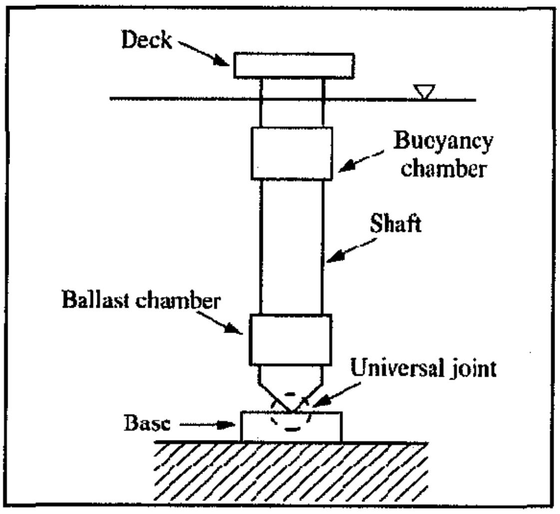
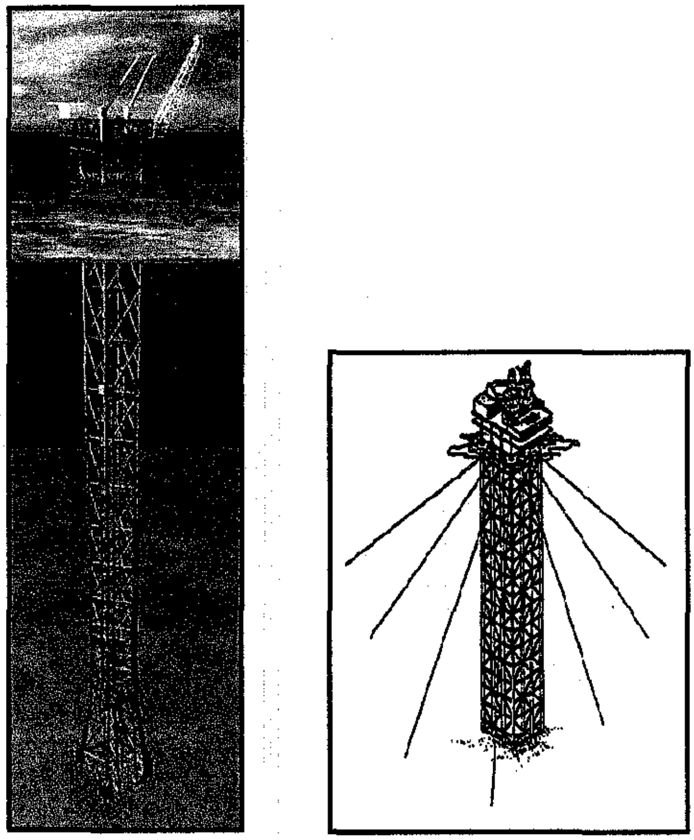


Figure 2.4 Compliant tower

According to Steve (1999), the compliant tower concept has essentially progressed through an evolution of three configurations.

i. The first emerged in the early 1980s with the installation of Exxon's Lena platform, a guyed tower in a water depth of 1,018 ft and supported by 20 weighted guy wires to achieve compliancy and stability.
ii. A second generation of structures, compliant piled towers, was introduced during late 1980s which relies on the piles for its flexibility and stability.
iii. The newest generation of compliant tower designs is represented by the 1998 installation of Amerada Hess' Baldpate compliant tower at Garden Banks Block 260 in 1,650 ft water depths and Texaco's Petronius tower which designed for installation at Viosca Knoll Block 786 offshore Louisiana in 1,754 ft water depths. The Baldpate tower gained its compliancy by utilizing axial tubes affixed to its legs and an articulation points approximately 500 ft above the sea floor. The Petronius structure, referred to as a flex-leg structure, relied on flexible legs for its stability and flexure.

These three compliant towers were presented in this report which are Lena Guyed Tower, Baldpate Tower and Petronius Tower. Some of these tower's configurations are included in Table 2.3 presented in Appendix I.



(a) (b)

Figure 2.5 (a) Compliant tower (b) Guyed tower

2.2.1 Lena Guyed Tower

Finn (1978) says that the guyed tower is a trussed structure that rest on the ocean floor, extends upward to a deck supported above the waves and is held upright by multiple guy lines. Percy and Massey (1984) idealized guyed tower as a ball and socket which resists the overturning forces of nature through the guylines attached near the top of the tower.

As bottom-supported structure, guyed tower (Figure 2.5(b)) is typically constructed from welded steel tubular members. These members act as a truss supporting the weight of the processing equipment, and the environmental forces from waves, wind and current. They are called "fixed" when their lowest natural frequency of flexural motion is above the highest frequency of significant wave excitation. They behave as rigid body and must resist the full dynamic forces of the environment. Guyed tower is one of the compliant towers which mean it is not fixed neither floating structures. Compliant structures include those structures that extend to the ocean sea bottom and directly anchored to the seafloor by piles and/or guidelines. It is a simple square space frame with a small projected area to minimize applied excitation loads. The function of framing system is to transmit the functional deck loads to the foundation material while the guy wires attached to the tower resist the excitation forces due to wind, wave and current as the unit behave like a fixed platform.

The world's first guyed tower production platform was installed in the Gulf of Mexico in 1,000 ft (305 m) water depth in 1983 Mississippi Canyon Block embarked a major milestone in the development of this concept for deepwater petroleum production. This concept has been developed by Exxon Production Research Co. and Exxon Co. U.S.A. Principal Features of the Lena Guyed Tower and Major Components of Lena Guyed Tower are presented in the Figure 2.6 and Figure 2.7 respectively in Appendix III.

According to Finn and Maus (1984), Lena Guyed Tower resembles a jacket structure, which has a constant cross-sectional dimension of 120 ft (37 m) square. The tower is supported vertically by eight main piles, which are located in a circular array near the center of the jacket. Twisting restraint is enhanced by six short piles driven through guides placed around the perimeter of the base. Twelve buoyancy tanks with 20 ft in diameter and 120 ft in length were located centrally in the upper part of the jacket, which support about 75 percent of the deck load. They were designed and arrayed on three levels of four tanks each. The tower is supported laterally by 20 guylines (5½ - inch diameter each up to 4,000 ft of line) symmetrically located around the jacket and anchored to the seafloor with driven piles. A 120 ft x 8 ft x 200-ton clump weight is attached to each guyline, partially rests on bottom and move as the tower moves with the wind and wave forces. The principal supporting members (the piles, buoyancy tanks, and guylines) are located in the upper region of the jacket. A strong central core region of the jacket was designed to transmit the applied loads and generated internal forces.

2.2.2 Baldpate Tower

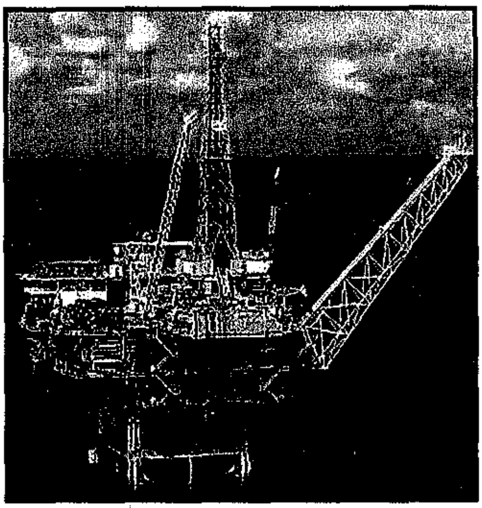


Figure 2.8 Baldpate topsides and boom

Baldpate Tower was named after Baldpate Field which located in Garden Banks Block 260 in the Gulf of Mexico, 120 miles off Louisiana coast and operated by Amerada Hess Oil Company. Engineered and built by McDermott the Baldpate was designed to be more flexible in bad weather allowing it to move 10 ft laterally. The Baldpate hold the honour to be the first free – standing offshore compliant tower ever, as well as one of the tallest free – standing structures in the world. The tip of the flare boom extends 1,902 ft (580 m) above the seafloor. This platform is installed in the water depth averages approximately 1,650 ft (503 m) which consists of a compliant tower, configured with axial tubes (two at each of the four legs of the tower section) and an articulation point that governs the dynamic characteristics of the structure. Being 'compliant', the tower is designed to be more flexible than conventional platforms and has a sway-response cycle, if subjected to a storm wave, of approximately 30 seconds. Such a long period makes the tower less sensitive to storm wave forces and it can move up to 10 ft, laterally, during storms. The

Baldpate-compliant tower structure was constructed in several pieces. The platform configuration is presented in Appendix III. The jacket-base section is 351ft-tall and 140 x 140 ft at the base, tapering to a 90 x 90 ft cross-section (the equivalent of the tower section) at the top. The base weighs 8,700t and its largest structural members (the legs) have diameters up to 144-in. and wall thicknesses up to 3,5/8-in. Attached to the base at each of the bottom four corners are three 84 in-diameter, 530 ft skirt-pile sleeves. These were driven through twelve sleeves into the seafloor, with penetrations approaching 430 ft. The jacket-tower section is 1,320 ft tall and has large pins at the bottom of each of the four legs, to mate with receptacles built into the top of the jacket-base section. The tower section is 90 x 90 ft in cross section, weighs 20,200t and its largest structural members (the legs) have diameters up to 128-in and wall thicknesses up to 3¾ in.

2.2.3 Petronius Tower

The Petronius field is located in Viosca Knoll, block 786, approximately 130 miles (208 km) south-east of New Orleans. It lies in water depths of 1,754 ft (535 m). The field was discovered in 1995 and contains estimated recoverable reserves of 80-100 million barrels of oil equivalent. Petronius has been developed as a compliant tower - the largest free-standing structure in the world. It was developed by Texaco Exploration & Production Inc. and the Marathon Oil Company. Similar to the other compliant structures, Petronius was designed to flex with the forces of waves, wind and current rather than to resist forces formerly. The design specified a height of 1,870 ft and a weight (including two tower sections, a foundation template, piles and conductors) of 43,000ton. The tower accommodates 21 well slots. The jacket supports topsides of 7,500ton.

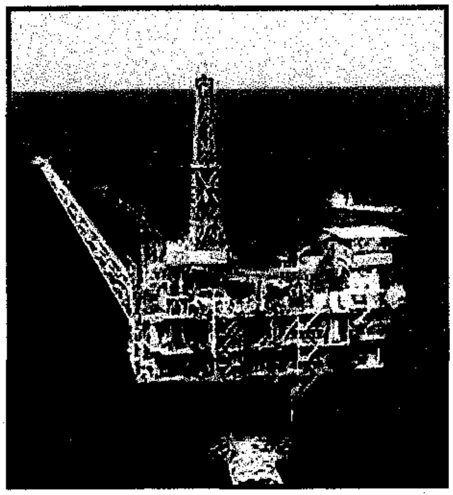


Figure 2.16 Petronius Tower

2.3 Offshore environment

Nowadays, environmental forces are, of course, the important factors in successful operations in the ocean since new advanced technologies have been explored day by day in the design of huge drilling barges, subsea systems, producing equipment, oil transfer and storage systems. Gulf of Mexico was the active place for exploration activities where it is also severely expose to hurricane waves of great height and force. Wave-height information is the starting point for platform design where the elevation of the platform deck and the basis for wave forces is determined. Piling structures are relatively transparent exposed to wave action whereas the deck structure has much more surface area and would receive a massive force if struck by a wave. The bottom of the deck structure, therefore, is placed above the highest wave the platform is expected to experience however the highest wave a platform will experience is difficult to answer. The offshore environment can be characterized by:

i. water depth at location
ii. soil, at sea bottom and in-depth
iii. wind speed, air temperature
iv. waves, tide and storm surge, current
v. ice (fixed, floes, icebergs)
vi. earthquakes (if necessary)

2.3.1 Wind Forces

Wind loads act on the portion of a platform above the water level, as well as on any equipments that located on the deck. Graff (1981) points out that the force of the wind on a structure is a function of the wind velocity, the orientation of the structure, and the aerodynamic characteristics of the structure and its members (p.66). The important parameter regarding the wind forces is the time interval over which wind speeds are averaged. Wind speeds that blow in averaging intervals less than one minute are classified as gusts while for intervals of one minute or longer are classified as sustained wind speeds. Gust speed is obtained by applying the gust factor on the sustained wind speed. The velocity of the wind used in design should be consistent with the risk assumptions for the structure. Wind forces contribute about 25 percent of the total overturning moment of the offshore structure in water depth over 150 ft (46 m) and an even larger percent for structures in shallow water. These structures should be designed for the fastest-mile-velocity with a period of recurrence at a given site of 100 years. The term "fastest-mile-velocity" is equivalent to the sustained wind speed multiplied by a gust factor. All orientation of the structures should be analyzed to ensure a safe design as the structures will oppose to a large variation of wind direction which may occur during a severe storm.

2.3.2 Wave Height

Aagard and Besse (1973) point that wave-height information is the starting point for platform design. From it the elevation of the platform deck and the basis for wave forces is determined. Wave height calculation for a particular site involves consideration of the physical wave growth and propagation processes, starting with the generation of waves in the open ocean and tidal phenomenon. Tide is a long period surface wave in the oceans, mostly with dominant period 12 hours 25 minutes (half of a lunar day). This phenomenon is caused by the gravitational attraction between the earth-moon-sun system and centrifugal system which lead to periodic rising and falling of sea levels, causing the changes in current speed and direction. As waves move into shallower water, they "feel" the bottom and gradually steepen until they expend their energy as breakers on the beach. For platforms in very shallow water, the breaker height controls the maximum wave height that the platform will experienced. Usually the breaker height is considered to be between 0.7 and 0.8 of the water depth where the storm intensity does not control. In deeper water, the upper bound of wave height is governed by the hydrodynamic stability of the wave form and by wind blowing away the wave crest. Various observation done in the open ocean found that the highest wave occur at over 100 ft (30m). However, for a given platform location, waves seldom reach their maximum height and a designer must use statistical information derived from studies of historical storms to estimate what the height of the highest wave will probably be during the life of the structure using wave-height distribution. The Rayleigh distribution, the statistical distribution which now widely used for estimating the "expected maximum wave height" for a given sea state was proposed by Longuet-Higgins.

2.3.3 Wave Force

Waves are generated by the action of wind on the surface of the sea. However, underwater disturbances such as earthquake, volcanic eruption and landslide can produce long period wave almost 12 hours and destructive waves which can reach heights of 40 meters or more. Because most platforms are structurally stiff and their natural periods of vibration are short compared with the periods of waves acting on them, the structures respond to the repeated wave loads as though they were a series of static loads. According to Aagard and Besse (1973), the determination of wave loads, therefore, has been on a single-wave basis until the platforms have been installed in deeper water. As a wave propagated, the water particles move in roughly circular orbits in vertical planes where the velocities and accelerations of the particles moving through their paths induced the forces on structural members struck by a wave. Morrison's Equation was used for calculating the force on cylindrical members typical of space-frame structures where the equation separates the total force into two additive components; (1) a drag component containing the orbital velocity and an empirical drag coefficient and (2) an inertia component containing the orbital acceleration and an empirical inertia coefficient.

2.3.4 Ice and Snow

Artic and sub-artic zones are the primary area that exposed to the ice problem. Ice formation and expansion can create large pressure which gives rise to horizontal as well as vertical forces. Large block of ice that driven by the current, winds and waves with speeds that can approach 0.5 to 1.0 m/s may hit the structure and produce great impact loads.

2.3.5 Piling Capacity and Soil

The tremendous loads caused by storm waves pounding on the structure must be countered by lateral and axial reactions between the structure's foundation piling and soil. Therefore, information on the character and properties of near surface layers of the sea floor to be penetrated by piling and the resistance of these layers against piling movement must be predicted properly. Terzaghi, had established rational approaches for foundation design that gave confidence to axial load requirements for early platform construction. Uncertainties became apparent as pile loads and pile penetration requirements far exceeded those customarily used onshore because the deep layers of soft clay below the bottom of the Gulf of Mexico near the Mississippi Delta. Additional data on the driving and load behaviour of long piling therefore were required. Several load-capacity measurement programs were conducted and studies continues on axial load capacity, lateral load capacity, and lateral load degradation under cyclic wave loads.

2.4 Hydrodynamic Analysis

2.4.1 Morrison's Equation

In ocean engineering, flow past a circular cylinder (Figure 2.17) is identified as a problem. The resulting force on a body in an unsteady viscous flow can be determined using Morrison's Equation, which is a combination of an inertial term and a drag term. Some assumptions have to be made in order to use this formula which are the structure must be cylinder and the diameter is not too large. The force in x-direction on a body in unsteady flow with velocity U(t) is governed by this formula;

$$F_x(t) = C_M A_I \dot{\upsilon} + C_D A_D U|U|$$

Where;

C_M	=	Inertia coefficient (to be taken as 2)
C_D	=	Drag coefficient (to be taken as 1.0 – 1.4)
A_I	=	$\rho(\Pi/4)D^2$ (ρ is the sea water density to be taken as 1035 kg/m^3 and D is diameter of the cylinder
A_D	=	½ ρD
U	=	Horizontal wave velocity
$\dot{\upsilon}$	=	Horizontal wave acceleration

For this report purposes, linear wave theory is selected to ease the analysis processes in latter phase. The range of drag coefficient is allowed to account for roughness and Reynolds number effects. These values are rough estimates where in the real life these coefficients vary widely with the various flow parameters and with time. The inertia coefficient is influenced by the changes in the boundary layer and is thus also affected Reynolds number and roughness.

2.4.2 Wave energy-density spectral

Chakrabarti (1987) points that wave spectrum is one of the approaches for selecting the design wave environment besides single wave method. However, this wave spectrum is only describes a short-term wave condition where the measured design wave spectrum at the site is seldom available. Spectrum models are generally based on one or more parameters, such as significant wave height, wave period and shape factor. The most common single-parameter spectrum is the Pierson-Moskowitz model which based on the significant wave height or wind speed. The basic notation and terminology and offshore related formula of the wave spectrum is presented in Appendix IV. Typical wave period for normal sea state ranged from 5 – 25 seconds and produced frequency ranged from 0.2 to 0.04 Hz. These values were used in the hydrodynamic analysis done for this report.

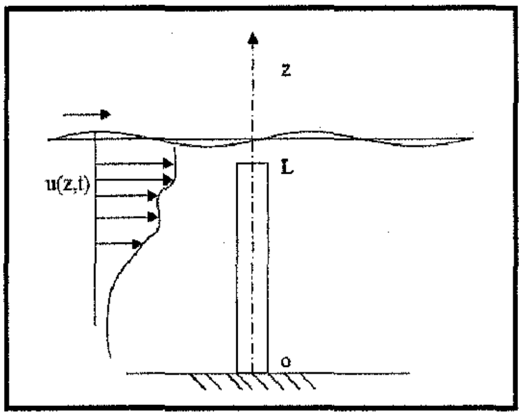


Figure 2.17 Flow past a circular cylinder

2.4.3 Response Amplitude Operators (RAO)

The amplitude of the structural response is generally normalized with respect to the amplitude of the wave. For a linear system the normalized response is invariant with the wave amplitude at a wave frequency. According to Chakrabarti (1987), Response Amplitude Operators (RAO) is defined as response function is normalized with a range of wave frequencies of interest for a given offshore structure or response amplitude per unit wave height. RAO also known as Transfer Function because it allows the transfer of the exciting waves into the response of the structure. In the computation of an RAO, the waves are considered regular and a sufficient number of frequencies are chosen to cover the entire range of frequencies covered by the wave spectrum.

2.5 Health and Safety Environment

Many countries that have major offshore oil activities in their economic zones have established regulatory agencies to control and supervise their development. These government agencies are typically assigned responsibility for ensuring safety during development and operation with respect to the following:

i. Prevention of pollution

ii. Prevention of loss or waste of resources

iii. Prevention of injury and death to personal working on or in conjunction with the development.

Prevention of pollution is the key element to environmental protection besides intensive effort on safe drilling and production equipment and practices is making a major contribution to safety. The growth in knowledge of environmental forces and the resulting improvement in reliability have made possible increased safety in offshore installations.

CHAPTER 3

METHODOLOGY/PROJECT WORK

In achieving the objectives set up in the early stage by discussion with supervisor, it was decided to divide the work progress into two phases. The first phase will be collecting and study all information (if possible) regarding the existing guyed towers and articulated tower in the world which includes the history, the technical data, the performance, photos and video presentation if available. The sources of information can be from internet, journals, books, visual presentation and mass media. Construction of small scale of the compliant tower is performed in order to enhance the understanding of the panels as well as audiences on the behaviour and the differences among other types of conventional platforms during the presentation.

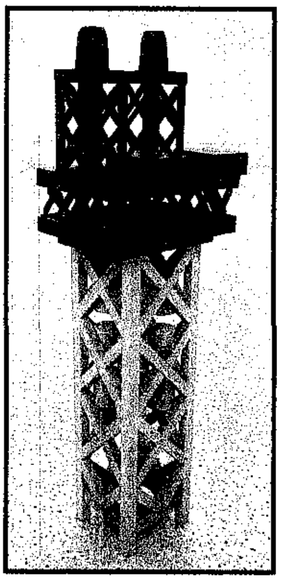


Figure 3.1 Small scale model of compliant tower

In the second phase, student is expected to carry out a hydrodynamic analysis based on the data collected during the first phase. Some of the parameters will be assumed within the acceptable range if the field data were not available. The analysis will be carried out with the aid of Microsoft EXCEL. The analysis results will be compared with the actual available performance data and the deviations will be objectively investigated. Recommendations on the applicability of this type of platform for the Malaysian context will be arrived later.

Frequency Domain Analysis

Wave Spectral Energy Density

↓

Time Series

↓

Response Amplitude Operator (RAO)

↓

Spectrum of Response (Rotation)

↓

Time Series of Rotation

Figure 3.2 Analysis flow chart

CHAPTER 4
RESULTS AND DISCUSSION

4.1 Results

Hydrodynamic analysis conducted by the author considers wave period 5 - 25 sec which are typical for normal wave condition. These produced values ranged from 0.04 to 0.20 Hz for wave frequency respectively. The analysis was aimed to get the wave energy-density spectral followed by the random wave profile (time-series) for 400 sec (can be calculated up to any time) and finally come out with the structural response due to rotation. The assumptions made were that the waves are regular and only act from one direction.

4.1.1 Hydrodynamic Analysis

Table 4.1 in Appendix V summarizes the analysis which include the energy-density, $S(f)$, wave height, H corresponding to each wave frequency, total area under the energy-density graph, and Response Amplitude Operators (RAO). By using wave period 5 – 25 sec wave spectral energy density graph is plotted (Figure 4.1) by initially converting these period into wave frequency, f. Wave height, $H(f)$ correspond to each frequency is also determined. Wave spectral energy density graph shows the wave energy for each frequency. The area under the graph represents total energy of the wave system and by using that area, significant wave height, H_s can be also determined (calculation shown in Appendix V). Corresponding wave spectral energy density in the function of natural wave frequency, $S(\omega)$ can also be plotted where energy density in this plot is $1/2\pi$ times that in frequency plot.

By using some configurations of Baldpate Tower, such as the water depth in the field, the structural view, tubular member diameters, and structural weight, the response of the tower is calculated. These tower configurations are shown in Appendix III. The position of tubular members is defined by Cartesian method and the total moment act at the articulation point is calculated by taking some approximation on the structural weight. For this calculation, only vertical members

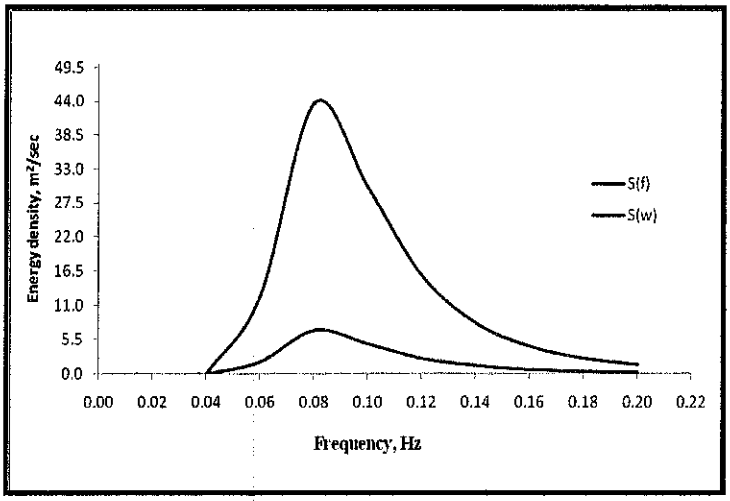


Figure 4.1 Wave energy density spectrum

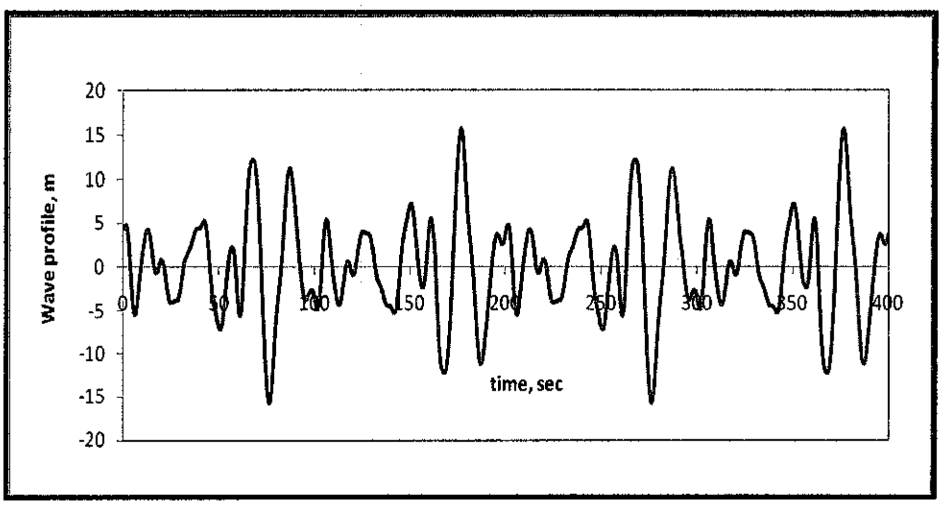


Figure 4.2 Random wave profile

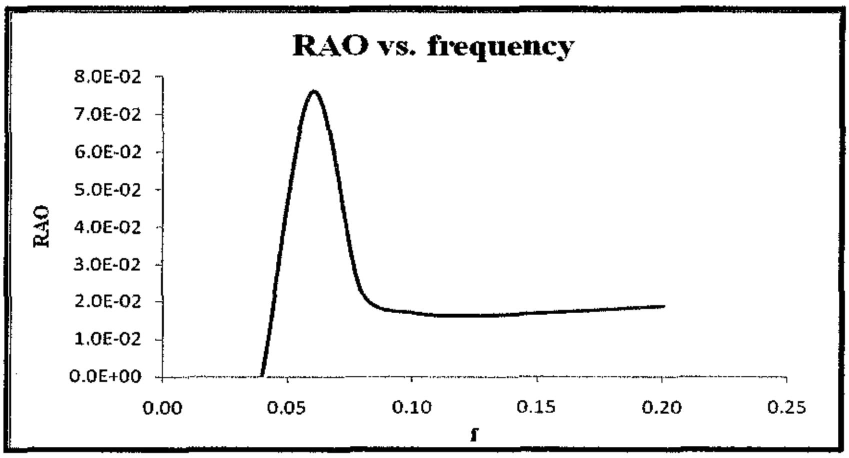


Figure 4.3 Graph of RAO vs. frequency

of the structure are considered to ease the calculation procedure. Total moments that act about the articulation point is used to find the Response Amplitude Operator, RAO. After finding RAO, response in term of rotation, $S_\theta(f)$ can be determined and finally time series of rotation is presented.

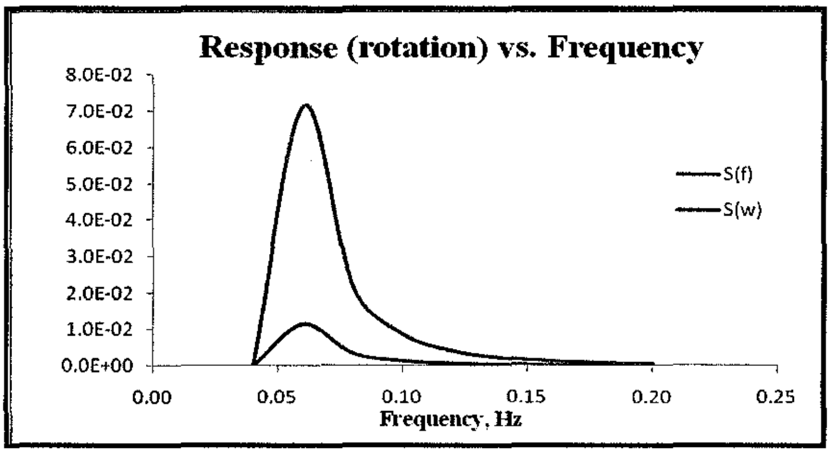


Figure 4.4 Response (rotation) vs. frequency

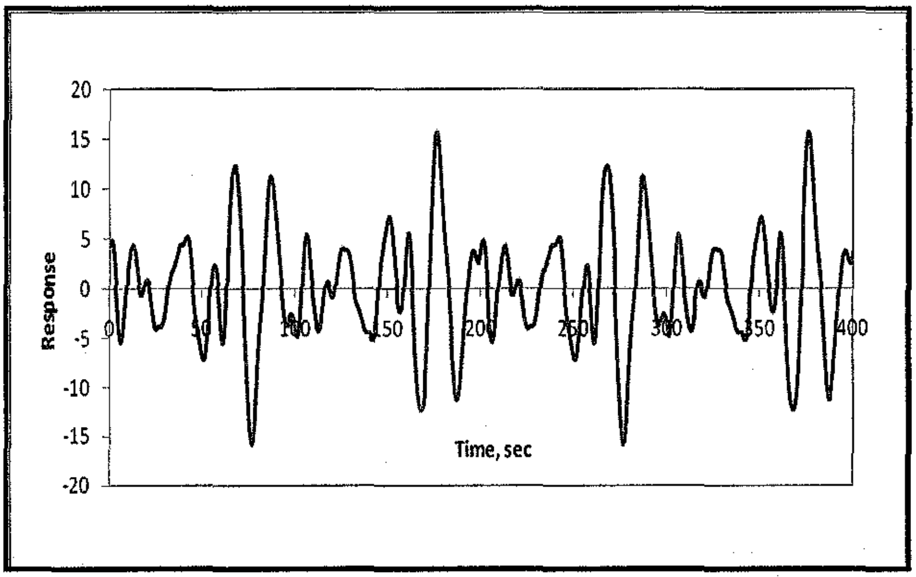


Figure 4.5 Time series of response (rotation)

4.2 Discussion

Discussions made here are referred to the journals read by the author published by Society of Petroleum Engineers (SPE) and also the analysis conducted by the author.

4.2.1 Analysis

Based on the analysis done by the author, it shown that from the wave spectral energy-density, the highest wave energy occur at the frequency of 0.08 Hz and this is known as peak frequency and really crucial to the platform. The area under the graph can be used to find the significant wave height, H_s where the significant wave height is the mean height of the highest one-third off all waves in the wave record. Maximum wave height, H_{max} calculated for 10 years is 18.2 m which is the maximum trough-to-crest height. Random wave profile (time-series) is done to predict the wave fluctuation and the highest wave height to occur can be observed. The other application of random wave profile is computation of response due to a random sea however it requires a large number of harmonic components and time consuming. As stated in previous chapter, RAO is defined as response function which normalized with a range of wave frequencies of interest for a given offshore structure or response amplitude per unit wave height. In the other word, RAO gives the responses of the structure at the different wave frequencies which will help to determine the maximum response that are required for the design of the structure. As the wave energy density spectrum give the different wave heights corresponding to each frequency, spectrum of response gives the whole range of responses (rotation) corresponding to the various waves and finally the time series of response (rotation) will absolutely gives the response (rotation) at the different times.

4.2.2 Compliancy

According to the paper written by Nair and Duval (1982) the action of lateral wave forces due to the design storm on a shallow water fixed platform is known to be static. The distribution of wave forces and associated inertial loads on a deepwater fixed platform is shown in figure below.

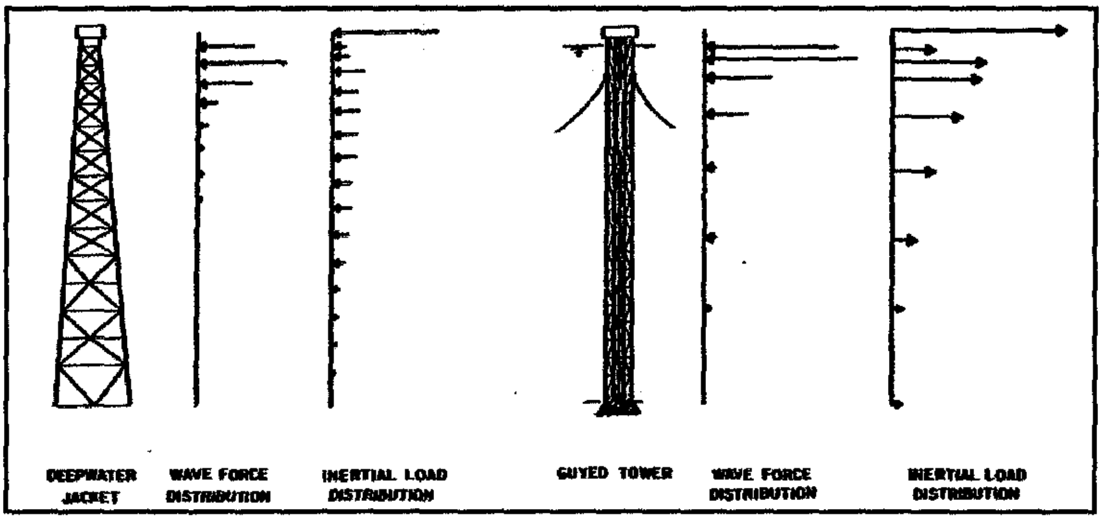


Figure 4.6 Deepwater jacket and guyed tower, wave force and inertial load distribution

From the observation made to the figure above, the inertial forces that act toward the deepwater jacket act in the same direction as the wave forces and thus the designed total force for that particular platform is increased. However, the guyed tower experiences an inverse phenomenon and an interesting to discover in which the inertial forces act opposite to the wave forces and thus decrease the magnitude of the lateral force for which the platform must be designed. In most instances dynamic response leads to amplified design forces, however in guyed tower dynamic action is utilized to reduce the design forces and commonly referred to as compliancy. Figure 4.7 represents the above concepts in the term of ratio of the dynamic lateral wave force to the force computed in the Y- axis while for X – axis, the ratio of the fundamental natural period of the platform to the period of the exciting forces assuming the latter to be periodic.

Nair and Duval (1982) had divided this amplification diagram into four regions. In region I, the amplification of the wave forces is negligible where shallow water platforms fall into this category. In order to assume the wave forces to act in a static manner, the period of the platform must be less than about 20 percent of the design wave period. Region II is characterized by dynamic amplification where deepwater fixed platforms fall under this region. The upper limit of this region is governed by a number of factors including fatigue, practical design and construction considerations and above all platform cost. At the present state-of-the-art it is believed that the platform period can be as high as 40-45 percent of the period of the design wave.

Region III is characterized by high dynamic amplifications where economic considerations discourage design and construction of such structures. Compliant structures such as guyed tower or buoyant tower belong to region IV where the design forces for structural in this region are only a fraction of the forces computed assuming static behaviour of the structure.

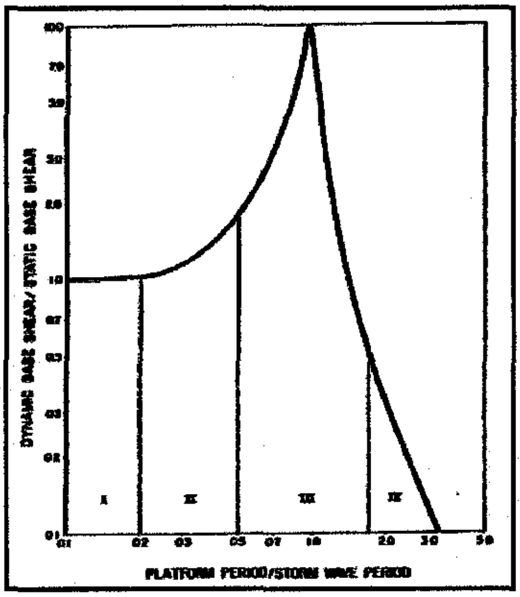


Figure 4.7 Amplification diagram

4.2.3 Dynamic behaviour of Guyed Tower

The dynamic behaviour of a guyed tower platform subjected to a wave excitation is governed by three types of modes of vibration which are the sway, flexural and torsional modes (Figure 4.8). The sway mode is the fundamental mode in a particular lateral direction and is basically a rigid body mode with little or no bending. The natural period of this mode is depending by the height of the tower, the magnitude and distribution of the mass and above all by the lateral stiffness of the mooring system. Under wave excitations the tower movements are controlled by the sway mode. In typical guyed tower designs the period of the sway mode is about twice the predominant period of the design sea state.

The second category of vibrational mode which applies to the guyed tower design is torsion. The primary source of torsional stiffness is the foundation. The design should minimize the torsional period so that dynamic amplifications in torsional excitation can be avoided, especially under the frequently occurring small waves.

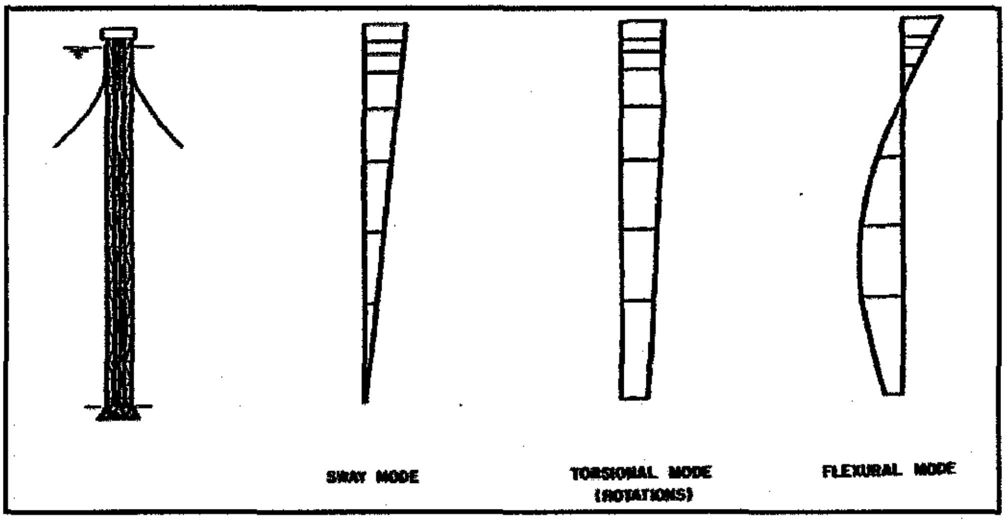


Figure 4.8 Three types of modes of vibration for guyed tower

The third mode of vibration is the flexural (bending) mode. The period and the associated mode shape of this mode are primarily governed by the magnitude and distribution of the mass and the stiffness of the tower as well as the lateral stiffness of the foundation. Practically, the stiffness of the mooring system has no effect on the flexural period of he guyed tower. A good approximation to the flexural period of the guyed tower can be obtained by idealizing it as a beam pinned at the base and free at the other end. However, the shape of this mode is strongly influenced by the lateral restraint provided by the foundation. The properties of the flexural mode are important for prediction of stresses and deformations in the tower. The tower should be proportioned such that its flexural period is much shorter than the predominant period of the design wave so that excessive stresses in the tower can be avoided.

CHAPTER 5
CONCLUSION AND RECOMMENDATION

5.1 Conclusion

After two semesters work on this project, author can conclude that the objectives set up at the early stage are successfully accomplished. Even though information collected pertaining to this project are not much, the value of the information seem really worthy on understanding of type of offshore platform. Continuation of this project is really appreciated to perform advanced analysis using specialized software and more structured activities. Throughout these periods, some problems were faced by the author, however these problems were solved by discussion with the supervisor.

5.2 Recommendation

5.2.1 Operating Advantages

The compliant tower offers many of the same advantages of any bottom-founded structure producing in shallower water depths. Additionally, the compliant tower approach allows certain pluses when compared to floating methods. Among them are:

i. Drilling and production operations

   The compliant tower's topside structure enables drilling and production to be carried out simultaneously without the need for attendant mobile drilling equipment that can be difficult and expensive to contract. For example, the Baldpate platform's 9,800-ton total topsides weight included a tri-level deck section with a 28-man quarters and facilities sufficient to support an API 20,000 ft. drilling rig along with the processing equipment necessary to accommodate production from the 18 wells. Like the fixed platform, the compliant tower can also support workover or well servicing operations without having to rely on external floating support equipment. The compliant tower is very stable. Its displacement, even under 100-year hurricane conditions, might be only 25-30 ft, or 1.5-2.0% of the water depth. In contrast, floating systems generally have lateral movement of up to 10% of water depth. Spars, with riser constraints, have a maximum lateral displacement at the water line of approximately 6% of water depth. The stability of this tower means that its downtime is limited to only the most extreme events, similar to shallow water platforms. This stability also reduces the complexity of operations. There are no specially-trained crews needed to operate ballast/deballast tanks or to adjust riser tensions. Because it is not a floating system, it does not require ABS classification.

ii. Production riser and wellhead support

With the compliant tower, all wells can have dry trees in lieu of subsea wet trees. They can also serve effectively as a central production facility, supporting platform drilled wells or satelite subsea tiebacks. Also, wells can be predrilled and temporarily abandoned and tied back following installation of the tower. The surface completions improve accessibility for controls, maintenance and future well servicing. Compared with floating systems, such as tension leg platforms (TLP), mini-TLPs and Spars, the production risers are conventional and are subjected to less structural demands and flexing, as they are afforded maximum support and protection by the compliant structure. This factor is particularly important in fields where high currents are prevalent, such as in the Campos Basin offshore Brazil. The production risers use conventional well systems, with conductors and casings that become structural elements. Once again, the simplicity of the operation reduces material costs. Production tubulars are generally made of carbon steel as opposed to special materials needed to support flexing. The weight of the risers extends directly directly into the seabed and along with the wellheads ans BOP stack, necessitates only minimum support by the jacket.

iii. Export riser support

The compliant tower has an advantage in that it can effectively support large diameter steel export risers, including steel catenary risers (SCR), J-tubes, or pre-installed risers. In the case of the Baldpate installation, the 16-in. oil and 12-in. gas SCRs were suspended from clamps attached to the jacket legs approximately 400 ft below the waterline, with the pipeline extending from the platform to touch the seabed nearly 650 ft from the substructure's base.

5.2.2 Improved Constructability

The compliant tower is a more slender, less complex structure than is a conventional deepwater fixed platform. As such, it presents fewer fabrication constraints and more opportunity for economy. For example, when comparing footprints, existing deepwater structures for depths of 1,290 ft and 1,350 ft have base widths exceeding 400 ft. by comparison, the Baldpate structure has a base width of 90 ft, with the base expanding to 140 ft at the mudline.

The Petronius flex-leg structure has base and tower widths of 110 ft square. The dramatic reduction of tonnages and fabrication heights allows yard fabrication and assembly with a minimum of large capacity, heavy lift and extended reach cranes and specialized equipment. In addition, the reduced fabrication heights provide significant safety enhancements.

Reduced design force levels have also led to compactness. As a graphic example, the design footprint of the Baldpate tower sufficiently compact to fit comfortably within the 140 ft by 200 ft launchbox created for the 1,290 ft jacket. In the Baldpate assembly, the largest members were the 144-in. diameter legs of 3 5/8-in. rolled plate. These material dimensions can be accommodated by multiple rolling mills and fabrication yards along the Texas/Louisiana Gulf Coast.

Construction complexity of compliant towers is minimal. The design of these structures is simplistic, with a square plan and repetitive framing used throughout the entire length of the tower section. There are no high cost mechanical system components required for long-term performance by compliant towers. Rather, all structural systems are composed of field proven, low unit cost materials and components which have been fabricated numerous times in fabrication yards experienced with the fabrication of offshore structures.

This relatively simplistic structure contains no items which have more complex construction requirements, such as buoyancy tanks, mooring systems, ballast/deballast systems, riser tensioners, or flexible risers. In short, compliant towers are simple to build and easy to maintain.

5.2.3 Installation

The installation procedures for the two-piece compliant tower are proven and can be handled by suitable launch barges residing in the Gulf of Mexico. Following the installation of foundation leveling piles on which the base is to be set, and tow docking piles to guide the setting of the base, the base itself is launched and installed.

In the case of Baldpate, 12,400-ton skirt piles (three per base leg) were driven to a depth of 430 ft. Following the setting of the base, the tower was tower similarly by launch barge and launched end-on to then upright itself and be lowered by a derrick barge, having been ballasted to 900 tons.

The underside of each tower leg had a docking pin that stabbed into the receiving cones of the structure's base. Once positioned, it was additionally ballasted and connections grouted. Shortly thereafter, the deck was transported to the site and installed by derrick barge in a single lift.

Subsequently, the main deck package including the quarters was lifted and set on the deck. Following hookup of flow lines and facilities, first oil production was recovered within two months. Using Baldpate and Petronius as examples, the conventional manner in which the compliant tower can be installed, requiring no special equipments, add to its attractiveness.

5.2.4 Suitability to Malaysian Environment

At the end of this project, author was pleased to have this opportunity to introduce this type of platform within the community (UTP) and giving some ideas and glance of offshore platform behavior. This type of research project, even though look very simple but it required full commitment to accomplish it. Yet, this hydrodynamic analysis can be used as a preliminary design for any compliant tower. Further study and effort can be made to enhance the credibility of the analysis by using different parameters namely significant wave height, water depth, wave period and also size and weight of the platform.

To the author's knowledge, guyed tower and articulated tower have very big potential to be explored in Malaysia context since the hydrocarbon exploration is getting into deeper and deeper water level. Conventional platforms are not suitable since it is costly due to the structural weight, high level of difficulty of installing and the future risk it may taken. The performance shown by the existing compliant tower is just enough to show that this type of platform is reliable and the best option to choose in term of flexibility and economic for respective water depths.

As the author study and review on the journals, author found that this topic is very interesting to explore and get better understanding on the type of platform available in the world. With this research work, author hope this kind of information collection can be valuable to present since PETRONAS is a company dealing with oil and gas industries. It also can be a preliminary view for all who aim to work offshore. New imaginative ideas can also be generated with this basic understanding of the compliant tower presented in this research work.

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APPENDIX I

Table 2.1	**Deepwater Jackets and Concrete Gravity Structures installed up-to-date**
Table 2.2	**Oceanographic Criteria for Cognac Platform**
Table 2.3	**Compliant Towers installed up-to-date**

Table 2.1 Deepwater Jackets and Concrete Gravity Structures installed up-to-date

No	Field	Oil Com.	Location	Water Depth (m)	First Oil	Field Reserves (Mmboe)	Drilling	Rigid Riser Slots	Production Capacity Oil (k.bbl/d)	Production Capacity Gas (MMm3/d)	Topsides Operating Weight (t)	Substructure Weight (t)	Pile Weight (t)	Base Dim. (m x m)
Steel Jackets														
1	Cognac	Shell	USA	312	1979	500	Yes	62	80	2.8		35000	12000	122 x 116
2	Bullwinkle	Shell	USA	412	1989	195	Yes	60	200	8.7	17000	49400	10500	148 x 124
3	Amberjack	BP	USA	315	1991	34		35	22	0.6	3800	22000		99 x 91
4	Heritage	Exxon	USA	326	1993		Yes	60	60	2.8	3200	26000		110 x 85
5	Harmony	Exxon	USA	366	1993		Yes	60	60	2.1	3600	33000		118 x 91
6	Pompano	BP	USA	393	1994	200		40	40	1.4	3100	35000		
7	Virgo	Elf	USA	344	2000			14	23		5000	25000		
Concrete Gravity Structures														
1	Troll	Shell	Norway	303	1996		Yes	40		100	32000	656000		150 x 150

Table 2.2 Oceanographic Criteria for Cognac Platform

Environmental load	Current considered	Current combined into design wave
Design wave	Height: 70 ft	78 ft
	Period: 11.5 sec	12 sec
Wind speed	125 mph: structural members	0
	150 mph: deck equipment	
Current	4 ft/sec at surface	0
	0 ft/sec at 150 ft	
Cd	0.6	0.6
	2.0	2.0

Note: 3.28 ft = 1 meter
1 mph = 26.8 m/sec
1ft/sec = 0.305 m/sec

Table 2.3 Compliant Towers installed up-to-date

No	Field	Oil Com.	Location	Water Depth (m)	First Oil	Field Reserves (MMboe)	Drilling	Rigid Riser Slot	Production Capacity		Topside Operating Weight (t)	Substructure Weight (t)	Pile Weight (t)	Base Dim. (m x m)	Guys	Natural Period		
									Oil (K.bbl/d)	Gas (MMm3/d)						Sway (s)	Bending (s)	Torsion (s)
1	Lena	Exxon	USA	305	1984	100	Yes	58	30	1.4	9500	21000	7700	37 x 37	20	28	3.8	5.7
2	Baldplate	Amerada	USA	503	1998	150	Yes	19	60	5.7	9000	26200	5000	43 x 43	0	32	5.0	6.4
3	Petronius	Texaco	USA	535	2000	100	Yes	21	60	2.8	8000	33000	8800	34 x 34	0			

APPENDIX II

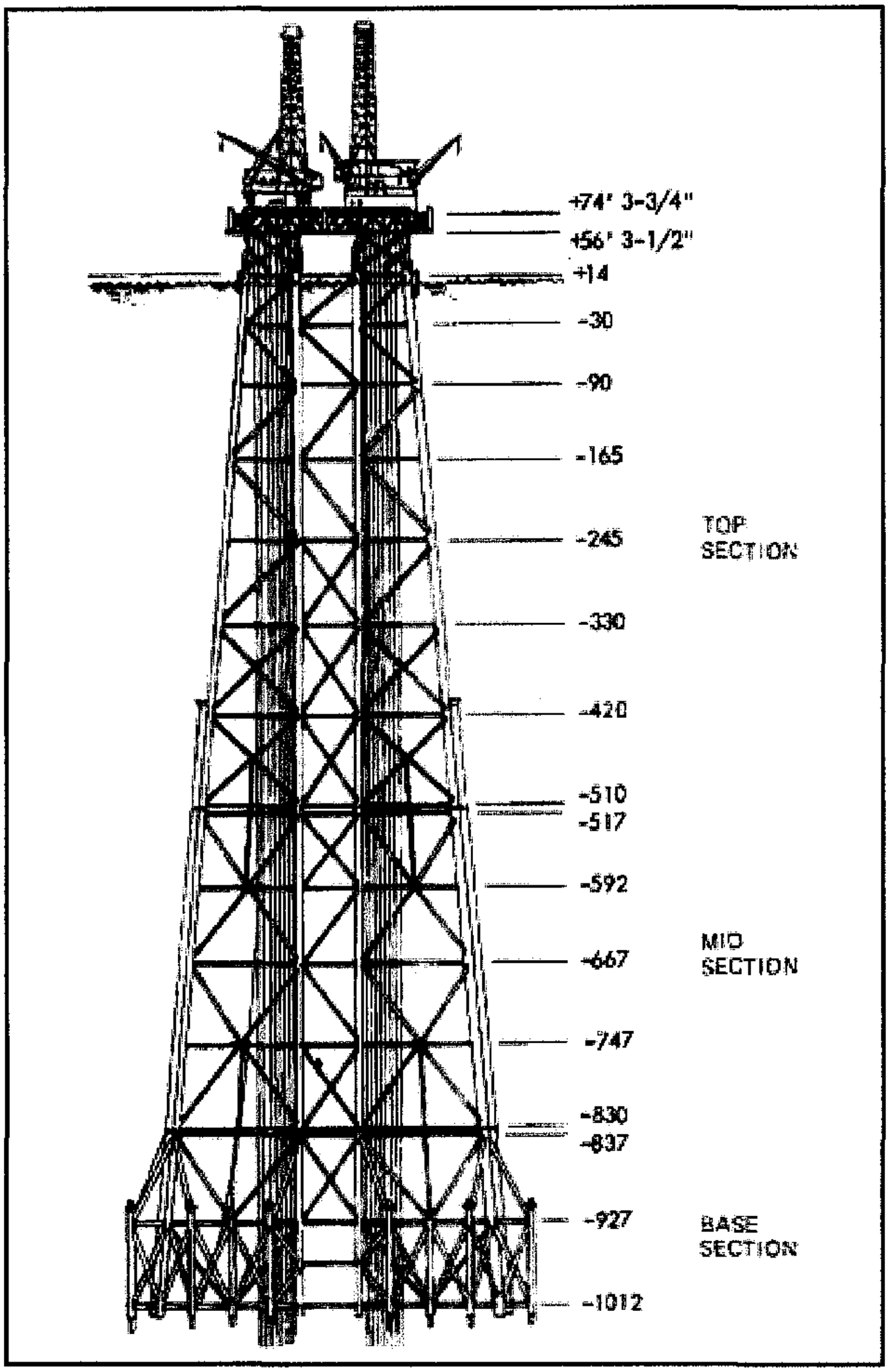
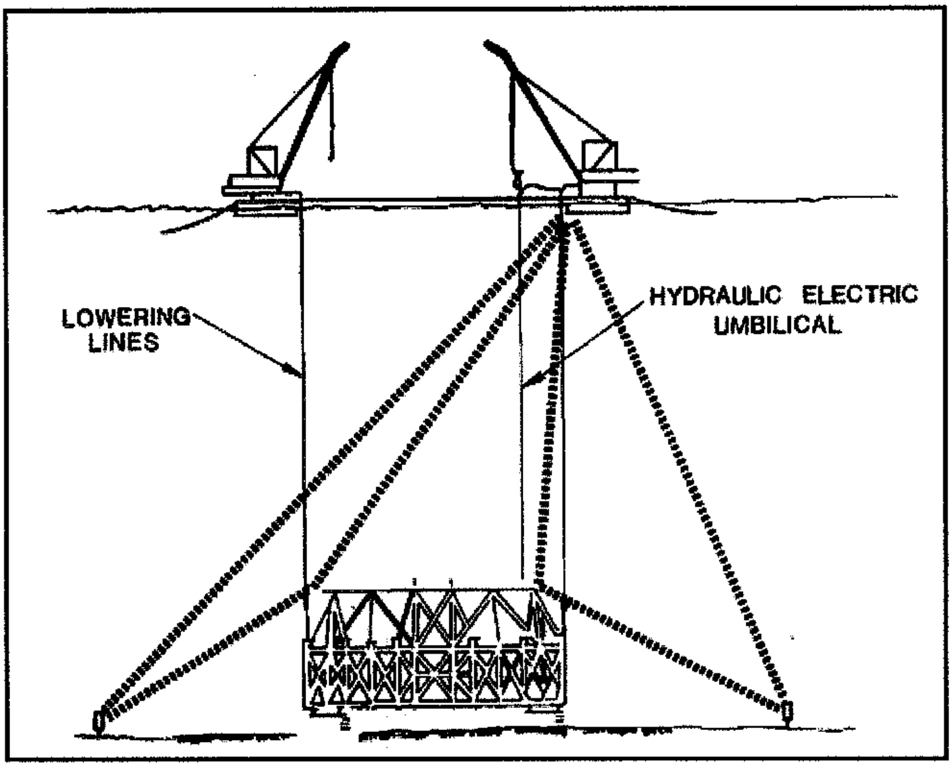


Figure 2.1 Assembled Cognac platform. (Copyright © 1979 Offshore Technology Conference)



- Lower base to ±20 ft off bottom
- Orient platform with acoustics
- Adjust mudmats
- Lower and release lines

Figure 2.2 Lowering Cognac base section to the bottom. (Copyright © 1979 Offshore Technology Conference)

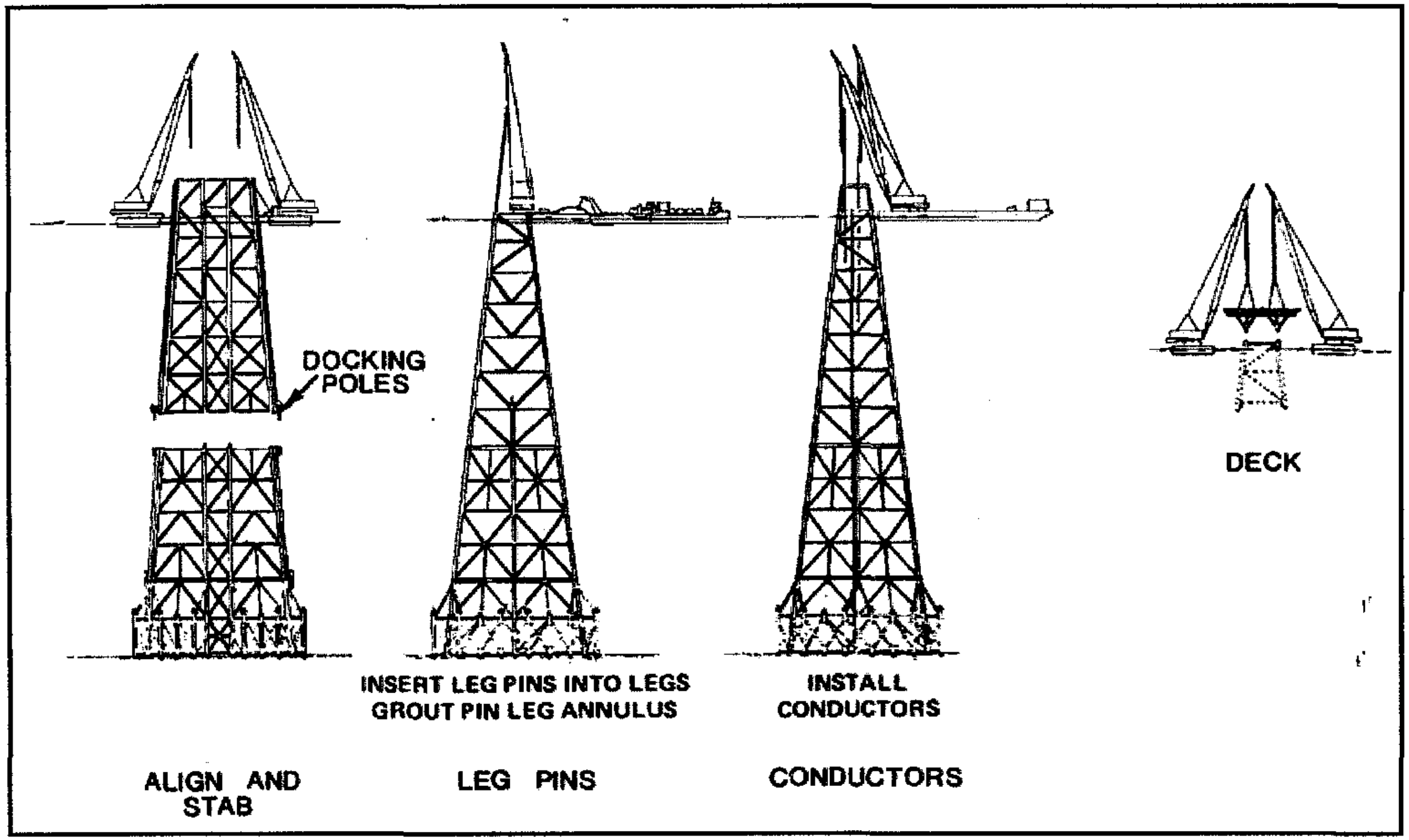


Figure 2.3 Cognac platform installation concept. (Copyright © 1979 Offshore Technology Conference.)

APPENDIX III

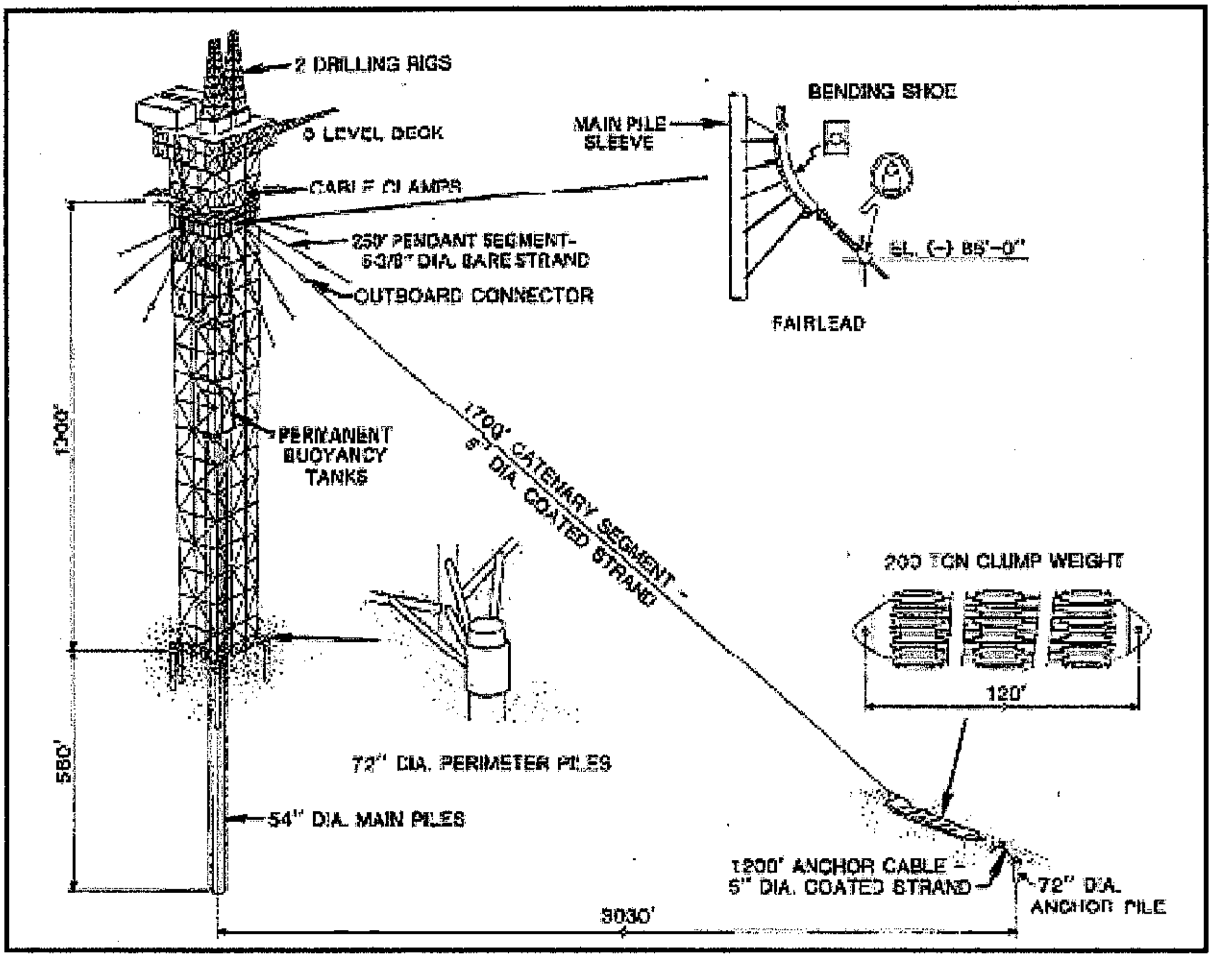


Figure 2.6 Principal features of the Lena Guyed Tower

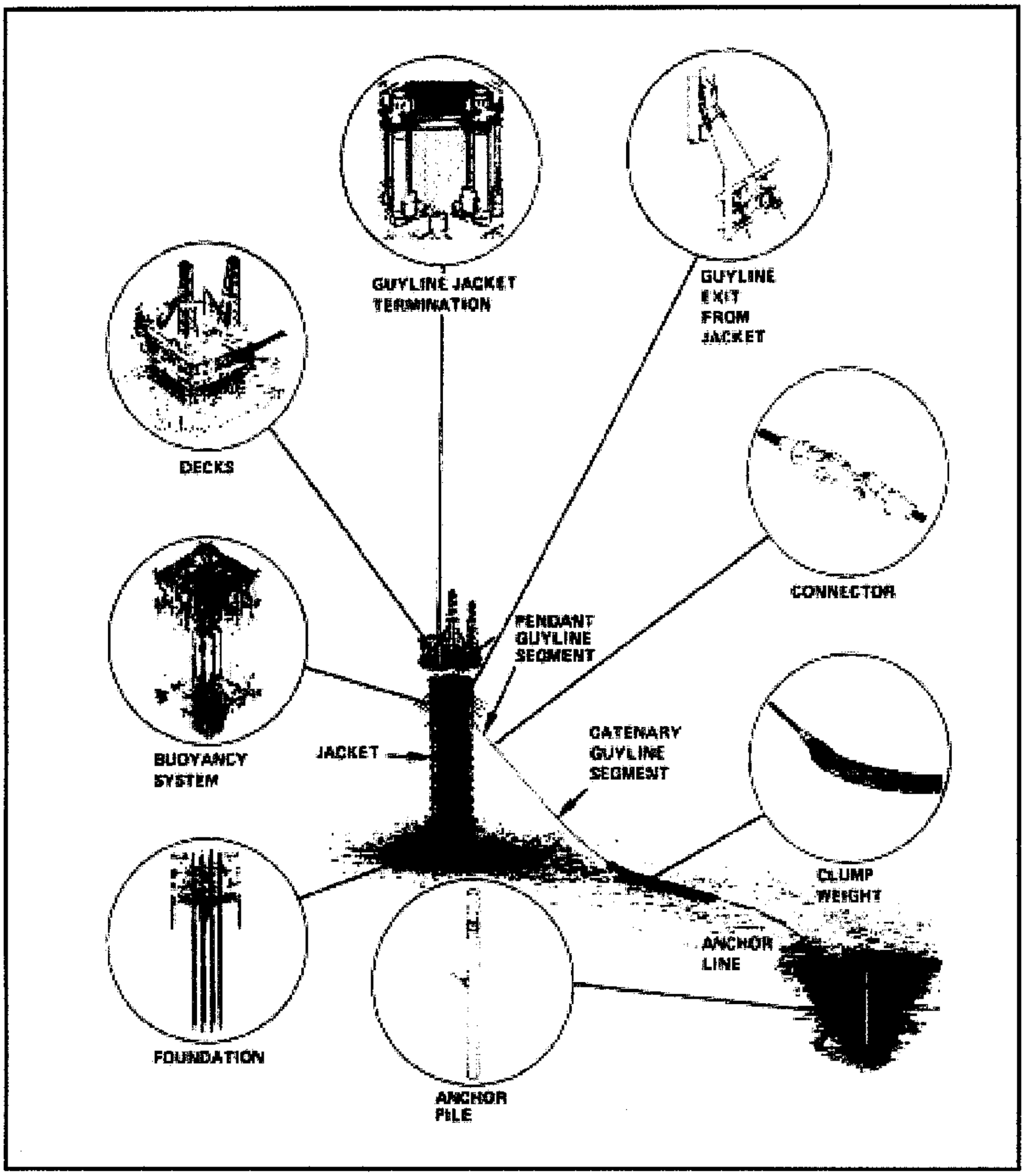


Figure 2.7 Major Components of Lena Guyed Tower

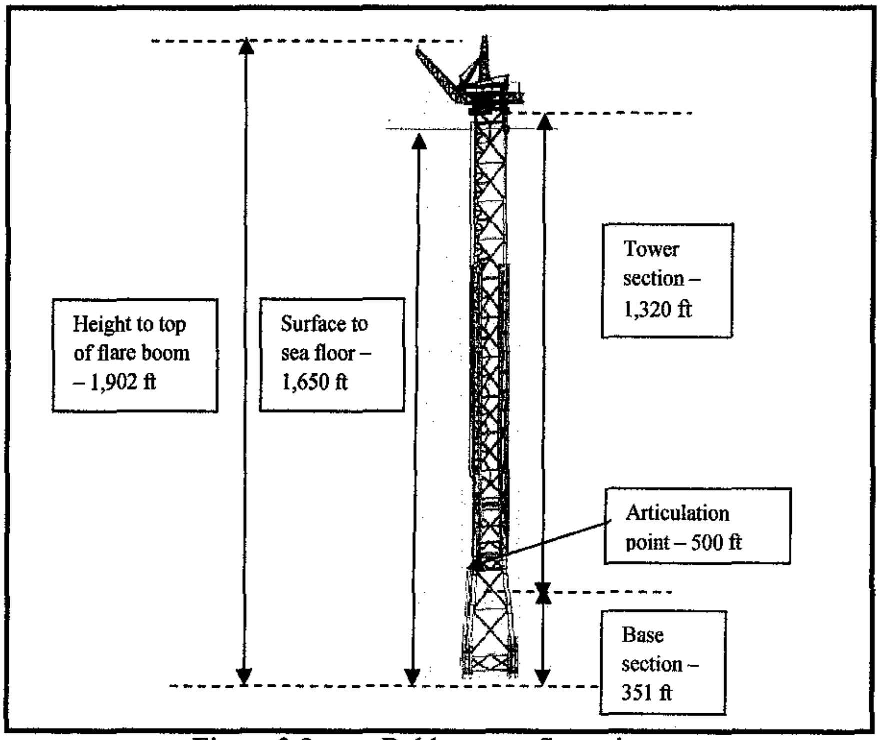


Figure 2.9 Baldpate configuration

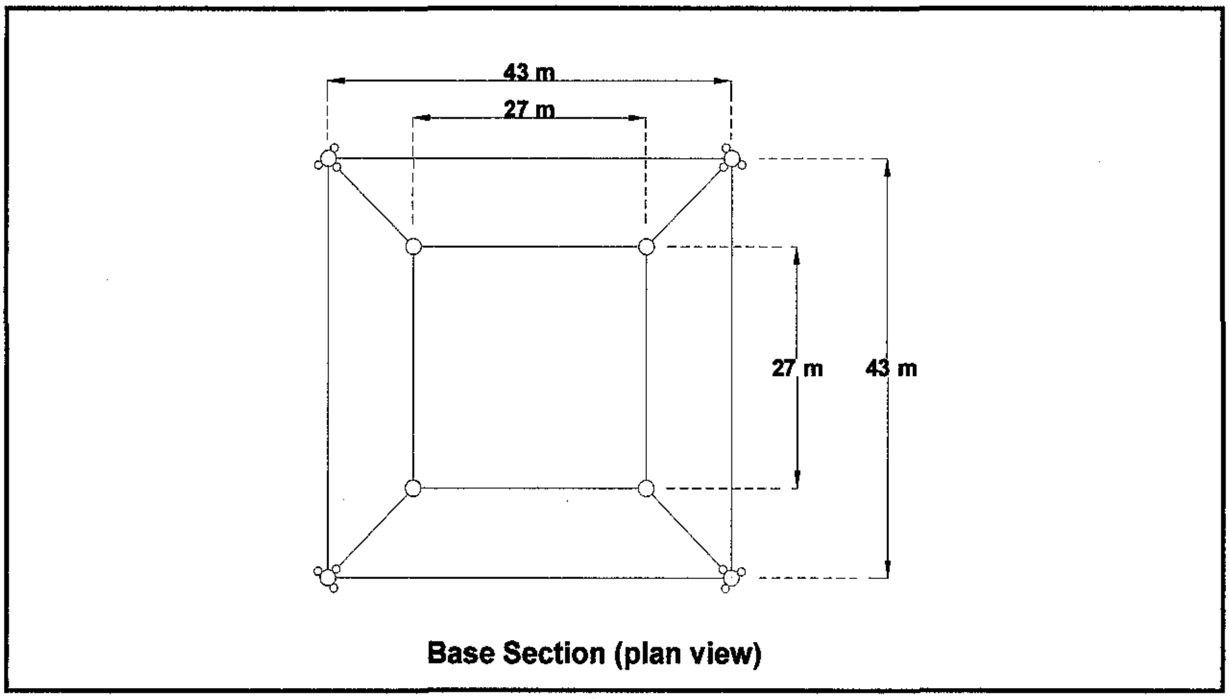


Figure 2.10 Base section of Baldpate (plan view)

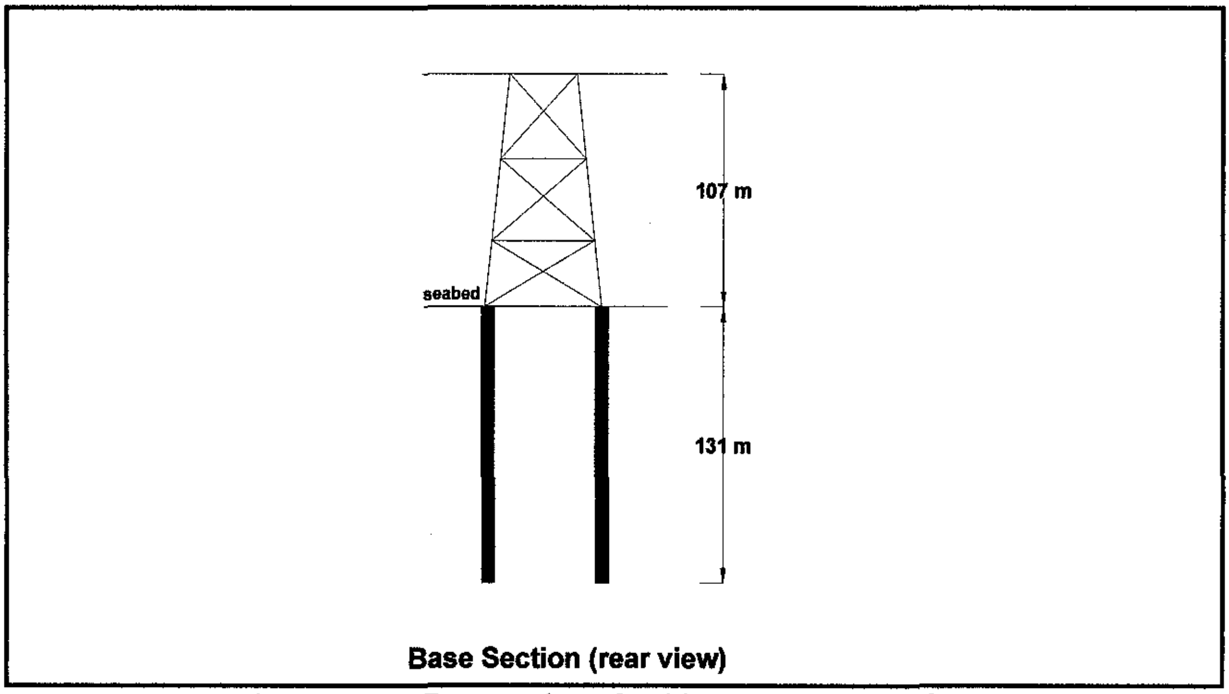


Figure 2.11 Base section of Baldpate Tower (rear view)

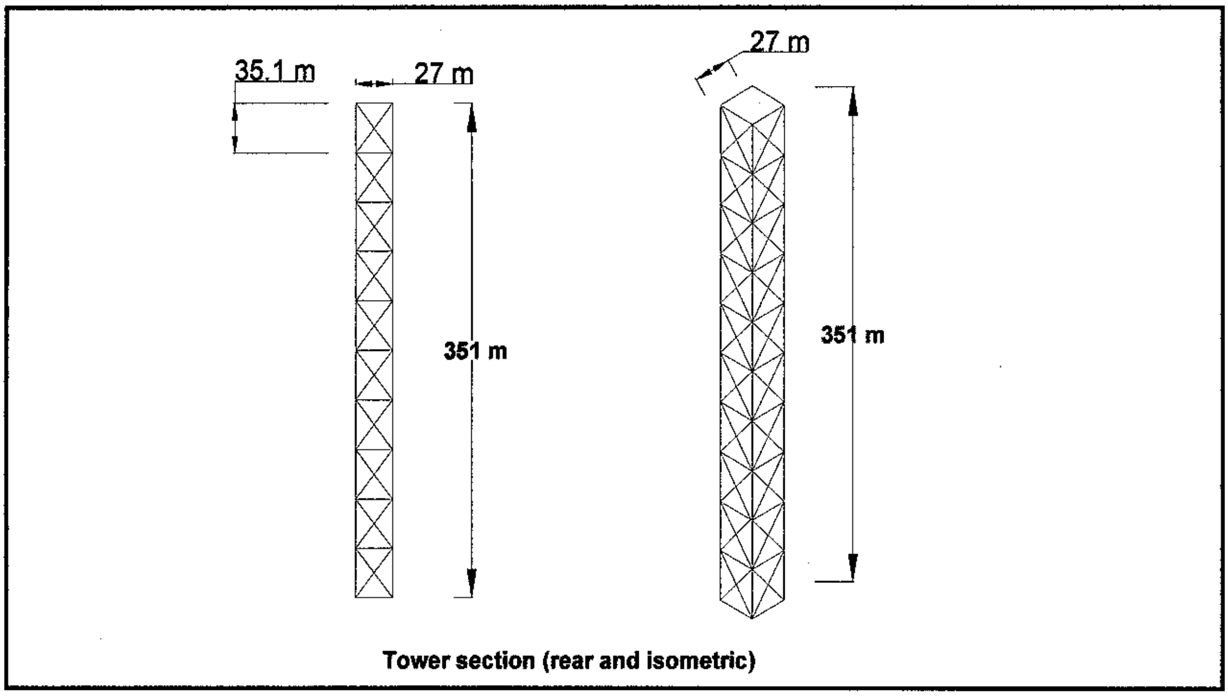


Figure 2.12 Tower section of Baldpate tower (rear and isometric)

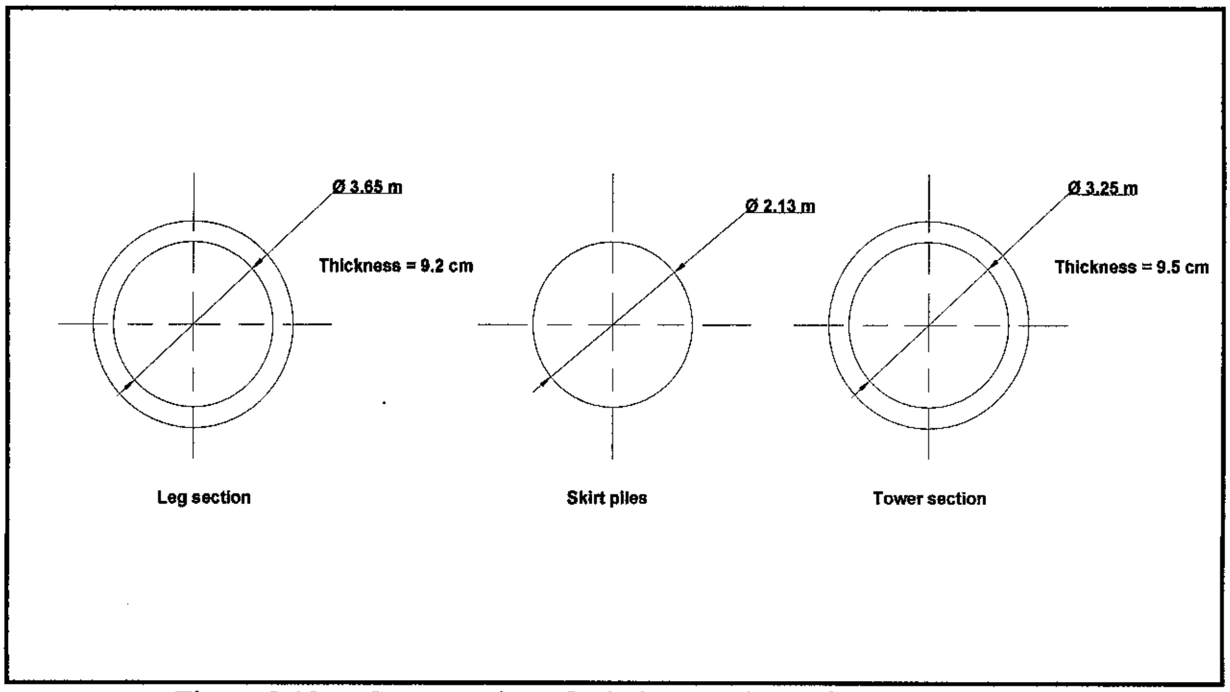


Figure 2.13 Cross-section of tubular members of Baldpate Tower

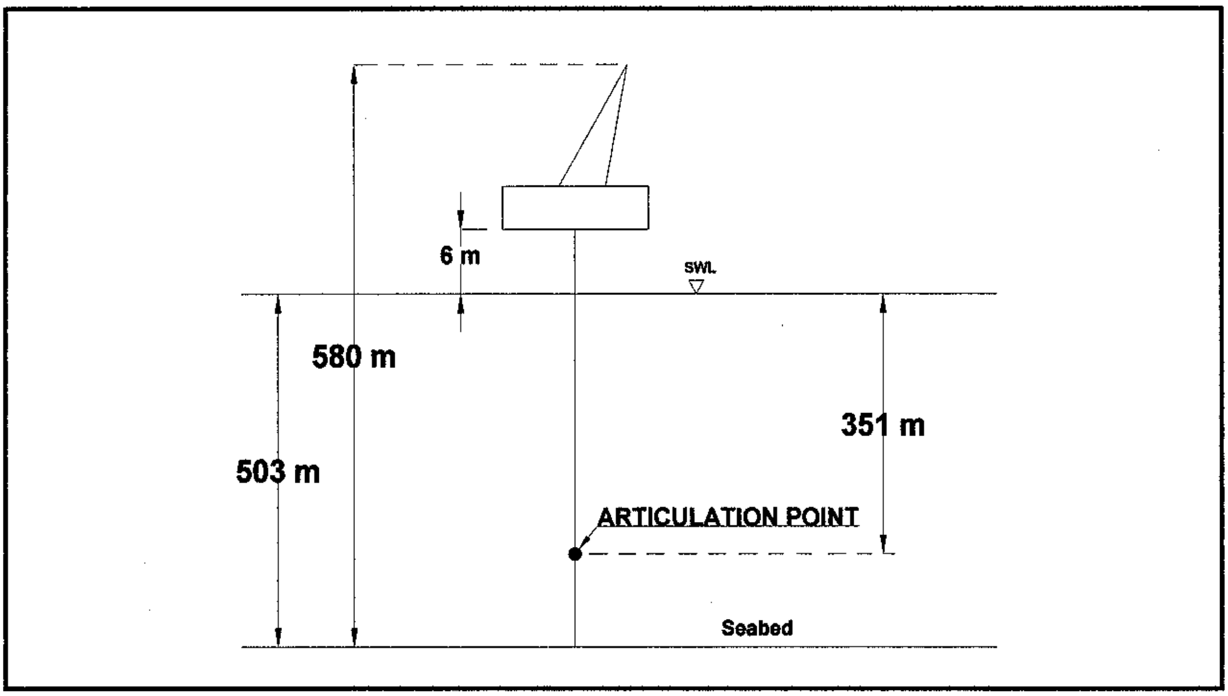


Figure 2.14 Articulation point for Baldpate Tower

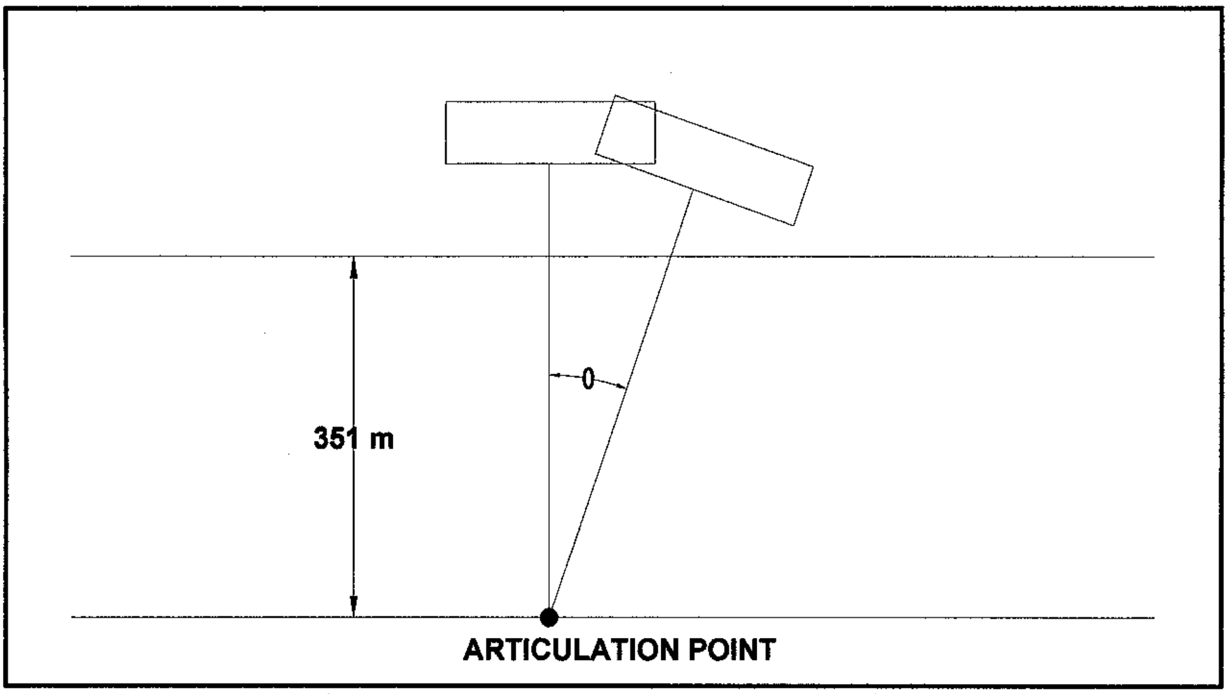


Figure 2.15 Tower corresponding to rotation

Table 2.4 Specifications – Baldpate, Gulf of Mexico, USA

Location	:	**Garden Banks Block 260**
Water depth	:	1,650 ft (503 m)
<u>Discovery</u>		
Discovery	:	1991
Reservoir	:	Pliocene big sand and twin sand
Porosity	:	29%
Permeability	:	500 md
Hydrocarbon column	:	1,600 ft (488 m)
<u>Production</u>		
Production	:	50,000 bopd and 150,000 MMSCFD
Recoverable reserves	:	104 million barrels of oil equivalent
<u>Jacket</u>		
• **Base section**		
height	:	351 ft (107 m)
width	:	140 ft x 140 ft (43 m x 43 m) at its base
		90 ft x 90 ft (27 m x 27 m) at top
weight	:	8,700 t (87,000 kN)
• **Tower section**		
height	:	1,320 ft (402 m)
width	:	90 ft x 90 ft (27 m x 27 m)
weight	:	20,200 t (202,000 kN)
leg diameter	:	128 in (3.25 m)
<u>Topsides</u>		
No. of decks	:	3
Weight	:	2,400 t (24,000 kN)
Accommodation	:	28

APPENDIX IV

Basic terminology and notation

Offshore related formula

Pierson – Moskowitz Spectrum

Force calculation on the members

Basic terminology and notation

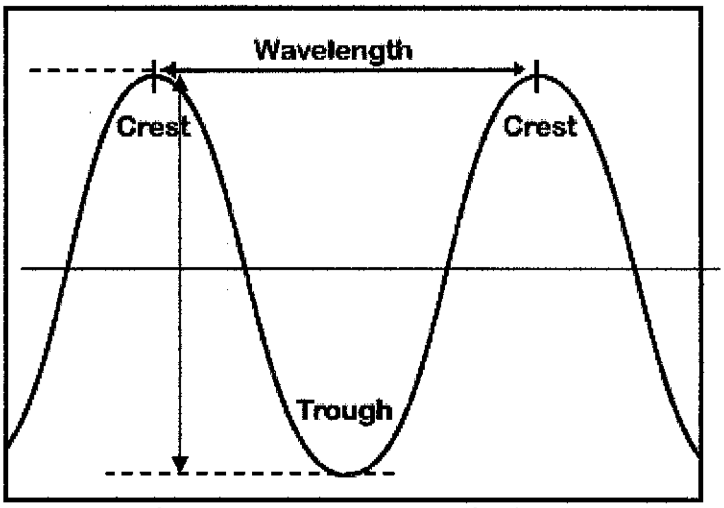


Figure 2.18 Wave terminology

- Wave crest = the highest point of the wave
- Wave trough = the lowest point of the wave
- Wave height, H = vertical distance between crest and trough
- Wave amplitude, A = H/2 (first linear theory)
- Wave length, L = horizontal distance between two successive crest/trough
- Wave period, T = time taken to produce a complete wave cycle
- Water depth, d = vertical distance from the sea surface to the seabed
- Wave frequency, ω = $2\pi/T$
- Wave number, k = $2\pi/L$
- Cyclic frequency, f = 1/T (Hertz)
- Wave celerity, C = L/T

Offshore related formula

- Wave surface elevation, $\eta = H/2 \cos\theta$ [1]
- Deepwater wave length, $L_0 = gT^2/2\pi = 1.56\,T^2$ [2]
- Horizontal velocity, $\upsilon = \dfrac{\pi H}{T}\dfrac{\cosh ks}{\sinh kd}\cos\theta$; where $s = y + d$ [3]
- Vertical velocity, $\nu = \dfrac{\pi H}{T}\dfrac{\sinh ks}{\sinh kd}\sin\theta$ [4]
- Horizontal acceleration, $\acute{\upsilon} = \dfrac{2\pi^2 H}{T^2}\dfrac{\cosh ks}{\sinh kd}\sin\theta$ [5]
- Vertical acceleration, $\nu = -\dfrac{2\pi^2 H}{T^2}\dfrac{\sinh ks}{\sinh kd}\cos\theta$ [6]
- Dispersion relation, $\omega^2 = gk\tanh kd$ [7]
- $c^2 = \dfrac{g}{k}\tanh kd$ [8]
- Dynamic pressure $= \rho g\dfrac{H}{2}\dfrac{\cosh ks}{\cosh kd}\cos\theta$ [9]
- Total pressure $\dfrac{P}{\rho g} = -y + k_p.\eta$; [10]

  where k_p (pressure coefficient/hydrodynamic) $= \dfrac{\cosh ks}{\cosh kd}$

- Energy density, E (in unit J/m^2) $= \dfrac{\rho g H^2}{8}$ [11]
- Wave power, P (in unit Watt/m) $= EC_g$; [12]

  where C_g = group velocity of wave = ηC

  where $\eta = \dfrac{1}{2}\left[1 + \dfrac{2kd}{\sinh 2kd}\right]$

Pierson – Moskowitz Spectrum

- $S(\omega) = \alpha g^2 \omega^{-5} \exp\left[-1.25\left(\frac{\omega}{\omega_0}\right)^{-4}\right];$ [13]

  where ω_0 = peak frequency given / assumed

  $$\alpha = \frac{5\sigma^2\omega^{-4}}{g^2}$$

- Total area under spectrum, $M_0 = \sigma^2 = \int_0^\infty S(\omega)d\omega = \left(\frac{S(f_0)+S(f_i)}{2}\right)\Delta f$ [14]
- Significant wave height, $Hs = 4\sigma = 4\sqrt{M_0}$ [15]
- Mean wave height, H = $\sqrt{2\pi\sigma}$ [16]
- Hrms = $2\sqrt{2}\sigma$ [17]
- $S(f) = \frac{\alpha g^2}{(2\pi)^4} f^{-5} \exp\left[-1.25\left(\frac{f}{f_0}\right)^{-4}\right];$ [18]

  where peak frequency, $f_0 = \omega_0 / 2\pi$ (to be taken as 0.08)
  Phillip number, $\alpha = 0.0081$

  i. From above equation, graph of $S(f)$ against f was plotted where f is ranges from 0.04 to 0.2 (frequency increment, $\Delta f = 0.02$)
  ii. The wave surface elevation, η, for every specified time period are then calculated and presented in graph named Time – Series plot.

- Wave surface elevation,

  $$\eta_{t=0} = \frac{H_i}{2}\cos[-\omega_1 t + \epsilon_1] + \frac{H_2}{2}\cos[-\omega_2 t + \epsilon_2] + \frac{Hi}{2}\cos[-\omega_i t + \epsilon_i] \quad [19]$$

  where $\varepsilon(n) = 2\pi . R_N$; R_N is random number

  From the Time – Series plot, information of wave elevation at any time can be gained. This simulates the wave configuration when act toward the structure.

- Wave height correspond to frequency, $H(f_i) = 2\sqrt{2S(f_i)\Delta f}$ [20]

Force calculation on the members

This calculation is made based on assumption that the wave is come from one direction only, and at $t = 0$ sec. Only vertical members are considered for this project from Mean Sea Level (MSL) to articulation point.

- Water particle velocities and accelerations

$$\theta = kx - \omega t \quad [21]$$

Horizontal velocity, $u = \frac{\pi H}{T}\frac{\cosh kz}{\sinh kd}\cos\theta$ [22]

Vertical velocity, $v = \frac{\pi H}{T}\frac{\sinh kz}{\sinh kd}\sin\theta$ [23]

Horizontal acceleration, $\dot{u} = \frac{2\pi^2 H}{T^2}\frac{\cosh kz}{\sinh kd}\sin\theta$ [24]

Vertical acceleration, $\dot{v} = -\frac{2\pi^2 H}{T^2}\frac{\sinh kz}{\sinh kd}\cos\theta$ [25]

- Force on the cylinder

$f = C_M\frac{\rho\pi D^2}{4}\dot{U} + C_D\frac{\rho D}{2}|\omega|U; where\ C_M = 2,\ C_D = 0.7, \rho = 1030kg/m^3$ [26]

D = Diameter of cylinder (tower section)

$$U_x = u - C_x(C_x u + C_y v) \quad [27]$$

$$U_y = v - C_y(C_x u + C_y v) \quad [28]$$

$$U_z = 0 - C_z(C_x u + C_y v) \quad [29]$$

$$C_x = \frac{x_B - x_A}{L}, C_y = \frac{y_B - y_A}{L}, C_z = \frac{z_A - z_B}{L} \quad [30]$$

Length of cylinder, $L = \sqrt{(x_B - x_A)^2 + (y_B - y_A)^2 + (z_B - z_A)^2}$ [31]

$$|\omega| = \sqrt{U_x^2 + U_y^2 + U_z^2} \quad [32]$$

$$f = \sqrt{f_x^2 + f_y^2 + f_z^2} \quad [33]$$

Total force, $F = f\ x\ member\ length$ [34]

APPENDIX V

Response Amplitude Operator (RAO)

Table 4.1	**Results correspond to each frequency**
Table 4.2	**Random wave statistical (Frequency domain analysis)**

Response Amplitude Operator (RAO)

$$S_x(\omega) = \left[\frac{F_I/(^H/_2)}{[(k-m\omega^2)^2+(C\omega)^2]^{1/2}}\right]^2 S(\omega) \quad [35]$$

$$S_\theta(\omega) = \left[\frac{M_I/(^H/_2)}{[(k-m\omega^2)^2+(C\omega)^2]^{1/2}}\right]^2 S(\omega) \quad [36]$$

$$S_\theta(\omega) = RAO^2\ S(\omega) \quad [37]$$

$$S_\theta(f) = RAO^2\ S(f) \quad [38]$$

- M_I =Total moment of the wave forces about the hinge
- H = Wave height (m)
- k = Moment per unit rotation (N.m/radian)

$$k + Moment\ of\ wave\ force\ about\ hinge + (W.x_w) - (B.x_B) = 0 \quad [39]$$

Moment of wave force about hinge = 15,174,103.02 kN.m
Where weight of structure 202,000 kN and topside 24,000 kN
Total weight, W = 202,000 + 24,000 = 226,000 kN

Total buoyancy force, B is calculated by assuming;

Horizontal member	= 2.5 m diameter
Diagonal member	= 2.0 m diameter
Vertical member	= 3.25 m diameter

B = total volume of submerged members

$$B = \pi\left(\frac{3.25}{2}\right)^2(4)(351) + \pi\left(\frac{2.5}{2}\right)^2(4x10level)(27) + \pi\left(\frac{2.0}{2}\right)^2(8x10)(44.2)$$

$$B = 11647.26 + 5301.44 + 11108.67$$

$$B = 28057.37m^3$$

Where 1m^3 = 10.3 kN

$$\therefore B = 288991\ kN$$

x_w = Distance from the center of gravity to the articulation point
x_B = Distance from the center of buoyancy to the articulation point

$$k = -(15,174,103.02\ x\ 10^3 - (226,000x10^3x242.18) + (288,991x10^3x273.33)$$

$$k = 9.08x10^9 N.m/rad$$

- m =Moment of inertia of the tower about base

  $m = I_m + Added\ mass, I_{ma}$ [40]

$I_m = 4\pi(R^2 - r^2)lx\rho\left(\frac{l^2}{12} + \frac{R^2+r^2}{4} + \frac{l^2}{4}\right) where\ \rho = 7850\,kg/m^3\ (kg - m^2)$[41]

Where R = Diameter of tubular member + thickness
r = Diameter of tubular member
l = Length of main member (from surface to articulation point)
ρ = Unit weight of steel

$$I_m = 4\pi(3.345^2 - 3.25^2)(357)(7850)\left(\frac{357}{3} + \frac{3.345^2 + 3.25^2}{4}\right)$$

$$I_m = 2.746x10^9 kg - m^2$$

$$I_{ma} = 4\pi a^2 l\rho\left(\frac{l^2}{3} + \frac{a^2}{4}\right) where\ \rho = 1030\ kg/m^3 \quad [42]$$

Where a = Diameter of tubular member + thickness
l = Length of main member (immersed length only)
ρ = Unit weight of sea water

$$I_{ma} = 4\pi(3.345)^2(351)(1030)\left(\frac{351^2}{3} + \frac{3.345^2}{4}\right)$$

$$I_{ma} = 2.088x10^{12} kg - m^2$$

$$\therefore m = (2.746x10^9) + (2.088x10^{12}) = 2.091x10^{12} kg - m^2$$

- Natural wave frequency, $\omega = 2\pi f$ (Calculated for each wave frequency)
- $C = 2\delta\omega_N m\ where\ \omega_N = \sqrt{\frac{k}{m}}\ and\ \delta = 0.1\ (10\%\ damping)$ [43]

$$\omega_N = \sqrt{\frac{9.08x10^9}{2.091x10^{12}}} = 0.066\ rad/sec$$

$$C = 2(0.1)(0.066)(2.091x10^{12}) = 2.76x10^{10}$$

Table 4.1 Results correspond to each frequency

Wave frequency, f (Hz)	Energy density, S (f) (m^2/secs)	f_i	Wave height, H (f)	Wave period, T (secs)	Area (m^2)	Natural wave frequency, ω (rad/sec)	S (ω)	RAO	Response (Rotation) $S\theta$ (f)	Response (Rotation) S_θ (ω)
0.04	0	-	0.0013	25.0	0	0.25133	0	-	-	-
0.06	12.3770	0.05	1.4072	16.7	0.1238	0.37699	1.9702	0.0760	7.145E-02	1.137E-02
0.08	43.7306	0.07	2.6452	12.5	0.5611	0.50265	6.9603	0.0223	2.171E-02	3.455E-03
0.10	29.9740	0.09	2.1899	10.0	0.7370	0.62832	4.7706	0.0171	8.727E-03	1.389E-03
0.12	15.7023	0.11	1.5850	8.3	0.4568	0.75398	2.4991	0.0163	4.167E-03	6.632E-04
0.14	8.1392	0.13	1.1412	7.1	0.2384	0.87965	1.2954	0.0166	2.236E-03	3.558E-04
0.16	4.4114	0.15	0.8401	6.3	0.1255	1.00531	0.7021	0.0172	1.305E-03	2.078E-04
0.18	2.5209	0.17	0.6351	5.6	0.0693	1.13097	0.4012	0.0180	8.128E-04	1.294E-04
0.20	1.5138	0.19	0.4921	5.0	0.0403	1.25664	0.2409	0.0188	5.323E-04	8.471E-05
				Total	**2.3522**					

From Figure 4.1;

Significant wave height, $Hs = 4\sqrt{M_0} = 4\sqrt{2.3522} = 6.13m \approx 6m$

Root mean square, $Hrms = 2\sqrt{2}\sqrt{M_0} = 2\sqrt{2}\sqrt{2.3522} = 4.3m$

$$H\max = \left[\sqrt{\ln N} + \frac{0.2886}{\sqrt{\ln N}}\right] Hrms$$

Where for 10 years;

Number of waves, $N = \left(\frac{10x365x24x3600}{10}\right) = 3.15x10^7$ and

$\sqrt{\ln N} = 4.16$

$$H\max = \left[4.16 + \frac{0.2886}{4.16}\right] 4.3 = 18.2m$$

Table 4.2 Random wave statistical (Frequency domain analysis)

Significant wave height, H*s*	6.0 m
Root-mean square wave height, H*rms*	4.3 m
Maximum wave height, H*max*	18.2 m