Regression Analysis to Determine the Reserve Strength Ratio of Fixed Offshore Structures

by

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the requirements for the
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CERTIFICATE OF APPROVAL

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Approved by,

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CERTIFICATION OF ORIGINALITY

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

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(NABILA AISYAH BINTI ISKANDAR)

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ABSTRACT

This study estimates the Reserve Strength Ratio (RSR) of fixed offshore structures with the utilization of regression analysis, which is capable in replacing the conventional expensive and time consuming methods currently adapted in the oil and gas industry. Offshore structures from the three regions of Malaysian Waters namely Peninsular Malaysia, Sarawak and Sabah were used to perform the analysis of different jacket configurations and sea-states accordingly. The pushover analysis of this study was performed by SACS program version 5.3 and the regression analysis was done using Microsoft Excel. Finding has revealed that regression analysis is able to produce regression coefficients to formulate non-linear regression equations fitting to the set of data to estimate the platform RSR.

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CHAPTER 1

1.0 INTRODUCTION

1.1 Background of Study

Fixed offshore structures have been commonly used for oil and gas fields particularly in shallow water depths of 500m or less. Almost 95% of platforms in the world are fixed steel type. The robustness and performance of the structure has led to the use of the platforms beyond their original design lives (Chakrabarti, 2005). From 1970 to 2013, there have been more than 200 offshore facilities in Malaysian Waters. Most of these facilities are fixed steel jacket platforms ranging from drilling, wellhead, living quarters, production, riser and vent. Exploration showed that the water depth in South China Sea where the prospects blocks are anticipated is not more than 200m. Economically, fixed steel jacket platform is the best option for operators when developing the field. However, in 2007, Malaysia’s first deep-water field was developed by PETRONAS located offshore of Sarawak in 1,350m water depth. Therefore the research and development of jacket platforms to be more diverse in design specifically improved in reliability and serviceability are supported by the advancement and sustainability of technology with the continuous demand of hydrocarbon energy.

Ultimate strength analysis is done to ensure adequate strength and ability of existing platforms to withstand environmental loading criteria with local overstress or damage allowed, but without global collapse. Non-linear static pushover analysis is a common approach to assess structural strength of platforms in extracting the base shear and displacement.

With the advancement of technology, the concept of regression is adapted in this study where in the world of statistics, regression can be used to the future outcome with available present data. (Stinson et. al., 2003) Regression analysis is a statistical technique that finds a mathematical expression that best describes a set of available data. Regression analysis will be further explained in Chapter 3.

1.2 Problem Statement

At present, there are more than 10,000 offshore production structures worldwide and in Malaysian waters, there are more than 250 fixed platforms in South China Sea, which includes Terengganu, Sarawak and Sabah regions. Platform design life is 25 years and the majority of the platforms in those regions has exceeded or is going to exceed their design life. In order to accommodate for the Enhanced Oil Recovery (EOR), the re-assessment of aged platforms is required and is based on the following:

- Structure is subjected to increased loading due to modifications
- Structure is damaged due to severe storms
- Structure is damaged due to accidental loadings such as boat impact or dropped objects
- Structure suffers deterioration from fatigue, corrosion, scour, subsidence, marine growth, fire/blast and shallow gas.
- Change of codes and regulations
- Change of environmental loading

The reliability for each platform must be identified for economic decision-making. To assess the structural strength and safety of a platform especially to be used beyond its design life, two approaches are introduced, namely non-linear static and Risk-based method. Most of the analysis captured reserve strength ratio (RSR) and mechanism of failure as well as the probability of failure. However, this approach leads to time-consuming and costly procedure. Therefore, this study aims to develop mathematical formulas by utilizing regression analysis to predict platform RSR obtained from the results of non-linear static pushover analysis with the purpose to minimize cost and time.

1.3 Objectives of Study

The objectives of study can be outlined as follows:

1. To study the sensitivity of reserve strength ratio (RSR) of fixed offshore structures with respect to water depth, platform age, air gap and metocean data.
2. To establish regression equations to predict reserve strength ratio (RSR) in order to minimize time and cost.

1.4 Scope of Study

The scope of study covers:

1. To set a number of platform models from the regions of Malaysian waters, namely Terengganu, Sarawak and Sabah with various parameters as below:
    - Water depth
    - Platform age
    - Air gap
    - Metocean data
2. To apply regression analysis to derive the formulas for predicting the platform RSR.
3. To run pushover analysis in order to validate the regression equation produced.

1.5 Relevancy and Feasibility of the Project

This project is relevant to the author's field of study and major in Coastal and Offshore Engineering. The topic is in line with what the industry is applying and would be valuable once the objective is met. As this study aims to quantify the strength of existing platforms by using a much faster and less expensive method than what the industry is practicing at the moment. The author would look into the parameters that could affect the strength of the structures namely the water depth, wave height, air gap, age of platform, wave period, current profile, and wind speed.

The project is feasible since the author has completed the preliminary research by doing literature reviews within the time frame and scope of Final Year Project 1 (FYP 1). Final Year Project 2 (FYP 2) is focused more on processing the raw data obtained from reliable sources and to implement the methodology identified from various previous works in the same field or other fields relevant to the project as well as new methods discovered that are relevant to be applied in order to achieve the objective. This research is mainly done with the utilization of Microsoft Excel's powerful tool of Data Analysis and its advantageous functions.

CHAPTER 2

2.0 LITERATURE REVIEW

2.1 Historical Development

The offshore exploration of oil and gas dates back to the 19th century when the first offshore oil wells were drilled from extended piers into the water of Pacific Ocean offshore Summerland, California in the 1890s and offshore Baku, Azerbaijan in the Caspian Sea in 1923 (Fadly, 2011). However, the beginning of the offshore industry is commonly considered as in 1947 when the first fixed offshore platform was successfully installed by Kerr-McGee off the coast of Louisiana. Since this installation of this first platform in the Gulf of Mexico over 50 years ago, the offshore industry has seen many innovative structures, both fixed and floating, placed in gradually deeper waters and in more aggressive environments. Since 1947, more than 10,000 offshore platforms of various types and sized have been constructed and installed worldwide. Recently, new crude oil discoveries have been made in increasingly deeper waters and in 2003, 3% of the world's oil and gas supply came from deepwater (>305 m) offshore production (Westwood, 2003). This is projected to grow to 10% in the next 15 years. The bulk of the new oil will come from deep and ultra-deepwater production from three offshore areas, known as the Golden Triangle; the Gulf of Mexico, West Africa and Brazil (Chakrabarti, 2005).

2.2 Structural Integrity Assessment

a) ISO 19902

ISO 19902, 2004 states that it is the owners' responsibility to maintain and demonstrate the fitness of purpose of the platform for the particular site and operating conditions. The goal is to demonstrate that the annual probability of failure is sufficiently low. The acceptable annual probability depends on regulatory requirements supplemented by regional or industry standards and practices. The ISO 19902 clearly states that the design fundamentals for existing structures allows for accepting limited damage to individual components, provided that both the reserve against overall system failure and deformation remain acceptable. The standard is intended for application to existing jacket substructure, but could also be applied for topside structures. Generally if one of the platform assessment initiators exists, the structure shall undergo an assessment with possibly two empirical methods and five analysis levels. The first empirical method is to compare the structure with similar structures and the second empirical methods is to assess by prior experience. Level 1 is linear analysis and component check. Level 2 is also a linear analysis and component checks but with refined actions and resistance. Level 3 is a linear elastic redundancy analysis. Level 4 is a non-linear analysis on system level including component checks as an integrated part of the non-linear system analysis. Finally, Level 5 is a check by using structural reliability analysis. If the structure is found acceptable at a level, no higher levels of checking are necessary. Prevention and mitigation measures to reduce occurrence rate and consequence of structural failure should be considered at all stages of the assessment procedure.

Changes from the design basis or assessment basis, as the indication of more difficult environment conditions should be the trigger for new assessment. “The metocean data required for an assessment are the same as for design, as are environmental design situations and actions” (ISO 19902, 2004). “The existing deck height, with an allowance for any future subsidence within the design service life, shall be determined. The deck height shall be checked for potential inundation as this can limit overall structural reliability” (ISO 19902, 2004).

An ultimate strength analysis, which is in Level 4 – Non-linear analysis and component check, is intended to demonstrate adequate structural strength and stability to withstand a significant overload, with respect to the applied load. Local overstress and potential local damages are allowed, but total collapse or excessive deformations are to be avoided. Reserve strength ratio (RSR) is determined for typically eight directions and the lowest value obtained from the analysis shall be the structure’s RSR. The general acceptance criterion of RSR for ISO 19902 is set to 1.85 while in API RP 2A WSD 21st Edition is set to 1.6. If the RSR is found acceptable, no further analysis is necessary.

b) American Petroleum Institute Recommended Practice – Working Stress Design

The API RP 2A WSD 21st Edition, 2007 is the most commonly used standard for design of fixed offshore structures in the United States. However, the standard is only focusing on existing offshore standard that takes assessment to a detailed level. The standard is stated to be applicable only for the assessment of platforms, which were designed according to the 20th or earlier editions of the same API standard and structures designed after the 21st edition, should be assessed according to the criteria originally used for the design. By this clause, API is limiting the possibility for using assessment of existing platform to minimize the structural cost.

There are two potential analysis checks mentioned in the API RP 2A WSD 21st Edition, 2000, a design level analysis and an ultimate strength analysis. The analysis itself seems to be the same as mentioned in ISO 19902, but the acceptance criteria are different. The procedure for design level analysis are similar to those used for new platform design, including the application of all safety factors, the use of characteristic rather than mean yield stress, etc. In the ultimate strength analysis, the reserve strength ratio (RSR) is defined as the ratio of platform collapse load to its 100-year environmental condition lateral loading. An RSR of 1.6 is required for high consequence platforms, usually manned and 0.8 for low consequence platforms, usually unmanned.

2.3 Application of Ultimate Strength Analysis

Dalane, 1996 studied about the seabed subsidence due to compaction of oil reservoir, which causes air gap reduction, therefore increasing the probability that a wave will hit the deck. The objective of this study was to assess the safety of the platform by determining the capacity using a non-linear structural analysis, to estimate the annual probability of failure for different subsidence level, to build a reliability formulation and to do a cost optimal decision regarding corrective measures. Environmental loads of wave, wind and current are not likely to occur simultaneously, which calls for joint probability. In pushover analysis using USFOS, the annual largest load is assumed to occur as the annual largest wave possible to pass through the structure. Reliability analysis is to estimate the annual probability of failure that the load exceeds resistance. Based on his study, it is found that as long as the wave crest does not reach deck level, thus no loading on large beams carrying deck loads, therefore no threat to structural safety. Structural failure depends if the probability of failure increase with the increase of subsidence as well as the increase of impact area.

Onoufriou, 2001 presented a study on the developments in structural system reliability assessments of fixed offshore platforms. It is mentioned that although there are various probabilistic and deterministic aspects associated with the structural resistance of system, such aspects need to be addressed carefully under uncertainties and sensitivities as well as analysis software and benchmarking. Various studies that included non-linear foundation modeling indicated a number of foundation failures. However, these results do not appear to be supported by past observations where very few platforms are known to have failed due to weakness in foundation. This indicates that the foundation failure predictions are more likely to be a result of high conservatism in foundation models used. Redundancy is an important characteristic of fixed offshore structures because they have a large number of load paths such that the failure of a single component does not necessarily lead to global structural collapse. It can be generally defined in terms of ultimate strength and the capacity at first component failure. An important issue in the pushover analysis is the variability between various analyses software and the high dependency on the user competence and assumptions made. A benchmarking exercise initiated by HSE with a number of organisations with experience in non-linear analysis to perform ultimate strength and large variations were observed both in the failure models and ultimate strength predictions. It is found that the material properties, strain hardening in particular, proved to be a very sensitive parameter. In another study by Shell concludes that the observed differences in member behaviors may be expected to be larger in structural forms other than X-braced and non-linear foundation models was found not to be significant for the specific structure considered in the study.

Seung-Kyun Choi, 2007 presented in his book that the study of structural reliability is concerned with the calculation and prediction of the probability of limit-state violations at any stage during a structure’s life. Once the probability is determined, the next goal is to choose the design alternatives that improve structural reliability and minimize the risk of failure. He discussed probabilistic analysis to characterize structural reliability and its methods that includes first and second-order reliability methods, (FORM and SORM) and Monte Carlo Sampling. The structure is considered unreliable if the failure probability of the structure limit-state exceeds the required value. Ultimate limit-state is the structural collapse that involves corrosion, fatigue, deterioration, fire, plastic mechanism, progressive collapse and fracture. Since it may risk the loss of life and major financial loss, is should have a very low probability of occurrence. As for serviceability limit-state, it is a disruption of a normal use of a structure that involves excessive deflection and vibration, drainage, leakage and local damage. It encompasses less danger than ultimate limit state; therefore higher probability of occurrence may be tolerated. The safety index approach in reliability analysis is actually a mathematical optimization problem for finding the point on the structural response surface that has the shortest distance from the origin to the surface in the standard normal space.

Pueksap-anan, 2010 did a study to develop formulas for the prediction of ultimate strength to be expressed in terms of Reserve Strength Ratio by simple derivation of formulas in order to minimize time-consuming and costly work. He studied the sensitivity of RSR with respect to water depth, topside payload, jacket side diagonal bracing scheme and jacket leg batter. He also identified the critical structural members and joints to platform structure failures. The application of energy method in the derivation of relation between forces and displacement and the stress-strain diagram to represent the strength of material on its ability to sustain load without rupture is used in this study. Metocean (meteorology and oceanography) loading used in the analysis include storm wave height, wave periods, storm wind spends, gust condition, tides, current and earthquake. However the most important parameters are wave, wind and current. Other loadings include gravity load, which is the selfweight of jacket, miscellaneous dead load, live load, and environmental load which uses the Morison Equation and Stoke's 5^{th} Order according to API RP 2A WSD, marine growth profile as well as wave-in-deck. To determine the ultimate strength of the offshore platform, non-linear static pushover analysis applies. The environmental load is incremented until the structure collapse. The global failure in indicated by load-deflection curve obtained from the analysis. The results from the pushover analysis are used to derive the formulas for predicting a platform RSR by regression analysis. Based on this study, it is determined that the base shear generated for lower water depth is larger than the base shear at deeper water depth. This phenomenon is supported by larger wave exposed area at lower water depth. The idea of redundancy applies where it is found that X-braced structure is 15% stronger than K-braced structure in terms of higher RSR value.

Fadly, 2011 studied the relationship between the return period and the reliability index of typical jacket platforms in the three Malaysian offshore regions by using pushover analysis and simplified structural reliability assessment (SSRA). The study also stated that the establishment and incorporation of bracing type factor with respect to redundancy analysis into SSRA calculation might improve the reliability index estimations since X-braced structures are more robust than K-braced structures.

2.4 Application of Regression Analysis

Brown, 2000 did a study to describe a method of non-linear regression using the SOLVER function of Excel. The first step to analyze data is by using a curve to determine the goodness of fit. The most commonly used measure of the goodness of fit is least squares. This is based on the principal that the magnitude of the difference between the data points and the curve is a good measure of how well the curve fits the data. The best fit of the data is the linear function that has the smallest value for the squared sum (SS) of all the differences. The r^2 value, the correlation index or the coefficient of determination, is a value between 0 and 1. It expresses the proportion of variance in the ‘dependent’ variable explained by ‘independent’ variable. As the r^2 increases towards 1, the more accurately the function fits the data. Previously, non-linear data would be transformed to linear form and subsequently analyzed by linear regression. However, these transformations could yield inaccurate analysis as the linear regression may distort the experimental error or alter the relationship between *y* and *x*. A method that is suitable for this procedure is called iterative non-linear least squares fitting. It differs from linear regression in a way that it is an iterative process and involves in making an initial estimate of the parameter values. His paper illustrates how to use the SOLVER function in Excel to fit data with user-input non-linear functions.

Seber, 2003 stated that it is an important task in statistics to find the relationship that exists in a set of variables, being subjected to random variations and possible measurement errors. In regression problems, typically one of the variables, which are the dependent variable, is of particular interest and is denoted by y. The other variables $x_1, x_2,..., x_k$, often called independent variables are primarily used to explain the behavior of y. If plots of the data suggest some relationship between y and the x_i's, then the relationship can be expressed via some function namely

Equation 1: Relationship of dependent variable y and independent variable x.

$$y \approx f(x_1, x_2, ..., x_k)$$

Non-linear models tend to be used either when they are suggested by theoretical considerations or to build known non-linear behavior into a model. Even when a linear approximation works well, a non-linear model may still be used to retain a clear interpretation of the parameters. The application of non-linear models is widely used in various situations, even to finite populations (Valiant, 1985).

Ryan, 2009 mentioned that there are certain characteristics in non-linear regression that are not part of linear regression. In particular, the experimenter may start off with linear terms, and may elect to use some non-linear terms for a selected number of regressors or independent variables. The obvious nonlinearity of the data plotted on a graph can suggest at least three possible options: (1) fit a linear regression model with at least one non-linear term, (2) transform Y and fit a simple linear regression model, or (3) search for non-linear regression model that fits the data.

Liu, 2009 came up with a study of estimating the strength of concrete by the application of regression analysis. He identified the design parameters of concrete material to build the regression models and used 146 standard training specimens and 20 test examples to determine the accuracy of the regression equation. Out of the seven design parameters, he narrowed down to the parameters with positive correlation coefficients. Root mean square error (RMSE) is calculated in order to test the statistical regression analysis.

Lambert, 2010 did a study to describe a method to obtain parameter confidence intervals from the fitting of non-linear functions to experimental data, using the SOLVER and Analysis ToolPak Add-In of the Microsoft Excel. However a disadvantage of using the Excel method was the inability to return confidence intervals for the computed parameters or the correlations between them. Using a simple Monte Carlo procedure within the Excel spreadsheet, using SOLVER can provide parameter estimates, for multiple data sets, and obtain the required confidence interval and correlation index.

Spiess et. al., 2010 mentioned in his study that the R^2 observation is still frequently being used in the context of validity of a certain model when fit to non-linear data. R^2 is not an optimal choice in a non-linear analysis as the total sum-of-squares (TSS) is not equal to the regression sum-of-squares (REGSS) plus the residual sum-of-squares (RSS), as is the case of linear regression and hence lacks the appropriate interpretation of the goodness of fit. His study in the field of pharmacology, pointed out the low performance of R^2 and its inappropriateness for non-linear data analysis.

CHAPTER 3

3.0 RESEARCH METHODOLOGY

3.1 Procedure of Analysis

The methodology consists of three main parts. First part is data preparation and structural modeling followed by structural model analysis, using Progressive Collapse Analysis of SACS software to obtain the increasing load factor and platform RSR value. The third step would be to perform regression analysis to develop formulas in predicting the reserve strength ratio (RSR).

Typically, the environmental loads acting on the structure are incremented until the collapse of the structure. The steps required in performing non-linear collapse analysis are as follows:

1. Development of a detailed structural model where additional detail needs to be taken into consideration to ensure the ultimate load carrying capacity of the structure is accurately predicted and modeled.
2. Application of appropriate combination of live and dead loads to the structure. Applied loads comprise of gravity load, self-weight of jacket structure, appurtenance, operating loads and environmental loads. The most important parameter for environmental loads include wave height, wind speed and current profile.
3. Conducting the analysis. For more complex structures where pile-soil interaction is involved, this stage can be considered to be difficult and requires detailed data for accurate results. Note that foundation is not the main concern in this study. (*can be included as parameters for further research)
4. Verifying the results against known and past examples.
5. Interpreting the results to understand the behavior of the structures and to extract information gained from the analysis.

3.2 Data Preparation

Prior to analysis, the review of structural configuration as well as properties of materials used in the structural platforms must be done. Dimension and function of platform is identified for the possible load of topside and gravity load from the self-weight of the jacket. Since the purpose of structural analysis is to achieve adequately safe and effective structures, the method of designing structures has developed from trial and error to linear elastic design by load and strength calculation as well as code check. Figure 1 show SACS platform model.

Figure 1: SACS Platform Model

The environmental data in Malaysian waters include wind speed, wave height, current profile and soil data will be applied to all structures in this study. The basic assumptions for model offshore platforms in computer program will follow the guidelines of API RP 2A WSD 21st Edition, 2000 and the pile-soil foundation will be modeled using non-linear spring elements. The metocean data incorporated into programs to generate load to structures will be obtained from reliable sources. Figure 2 shows the application of appropriate combination of dead and live loads to the structure.

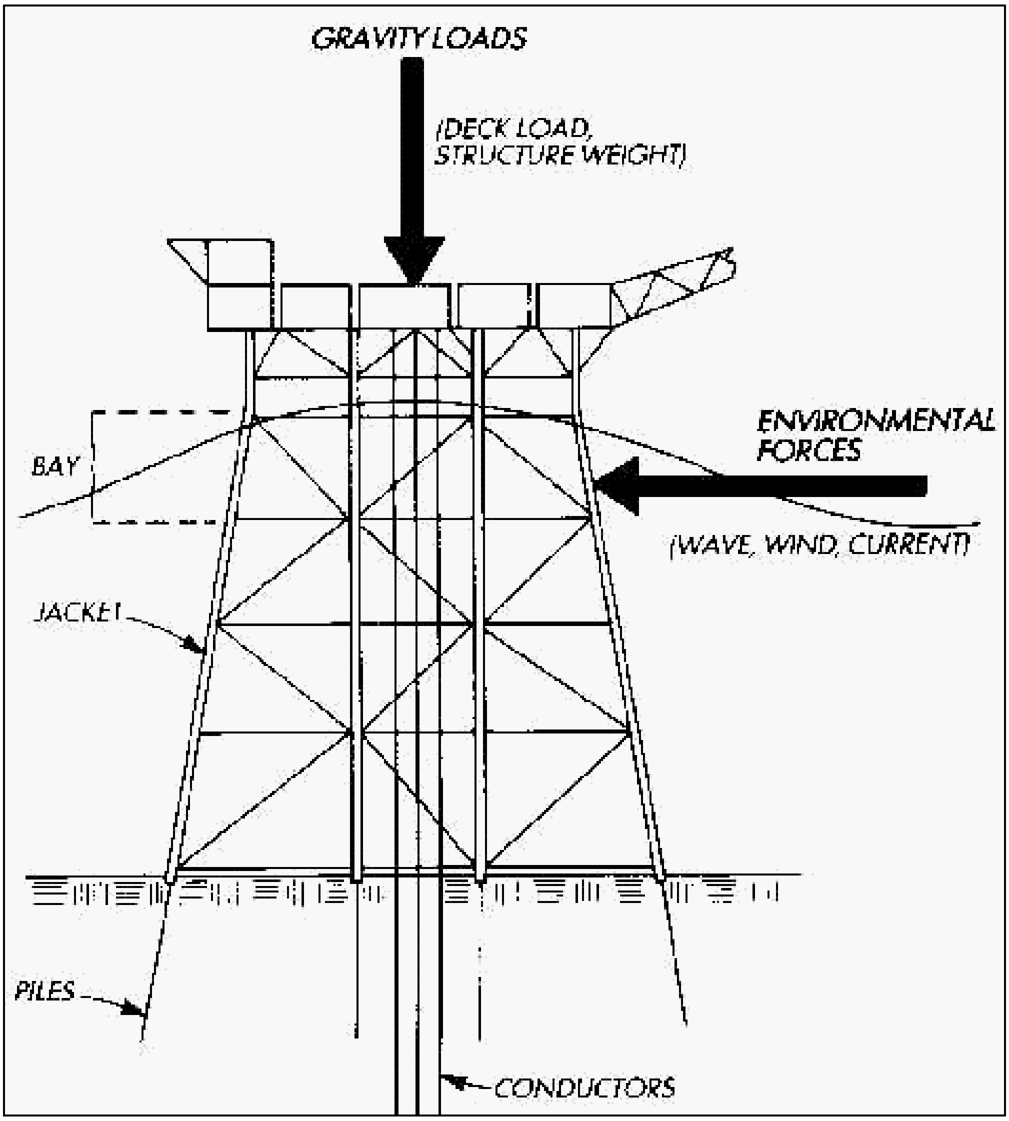

Figure 2: Application of Appropriate Combination of Dead and Live Loads

3.3 Progressive Collapse Analysis

The non-linear collapse analysis method adopted in this theory is a non-linear static analysis under permanent vertical load and progressively increasing lateral loads, which will result in the yield of plastic hinge formations, failure of various structural components and finally the global collapse of the structure. The behavior of structural collapse can be characterized using a plot of the total base shear against displacement. In this study, the gravity loading is applied first followed by the gradual increment of lateral load until structural collapse. By definition, the strength capacity of a structure is presented in terms of Reserve Strength Ratio (RSR), which is the ratio of collapse load of structure at failure to the total load of structure at 100-year design condition as shown below.

Equation 2: Calculation of RSR

$$RSR = \frac{BS_{collapse}}{BS_{100\text{-}year}}$$

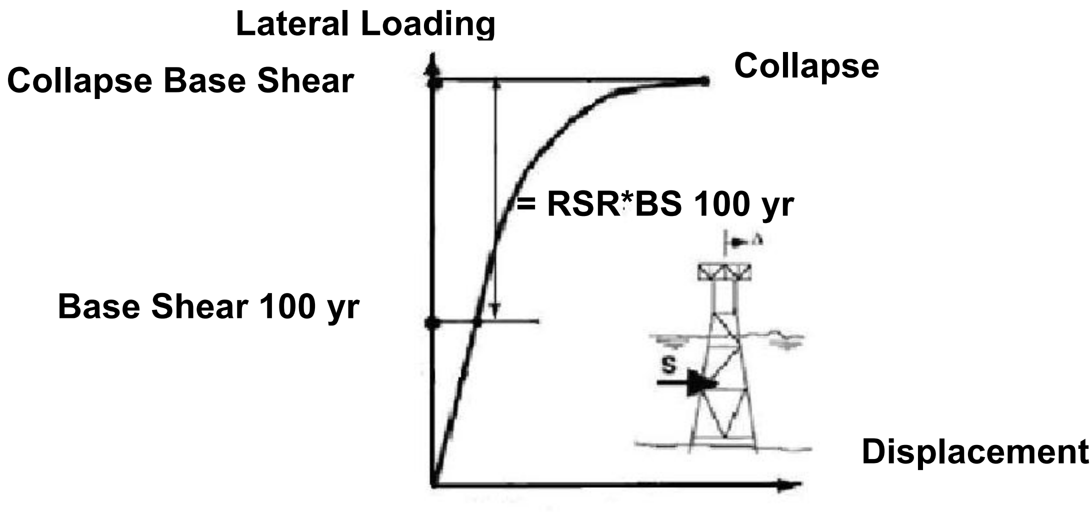

Figure 3: Definition of Reserve Strength Ratio (RSR)

The structure is "pushed" with the increment of lateral environmental load until collapse. Important parameters that affect the strength of the structure when performing Pushover Analysis include water depth using omnidirectional wave height, wind speed and current velocity as shown in Figure 4.

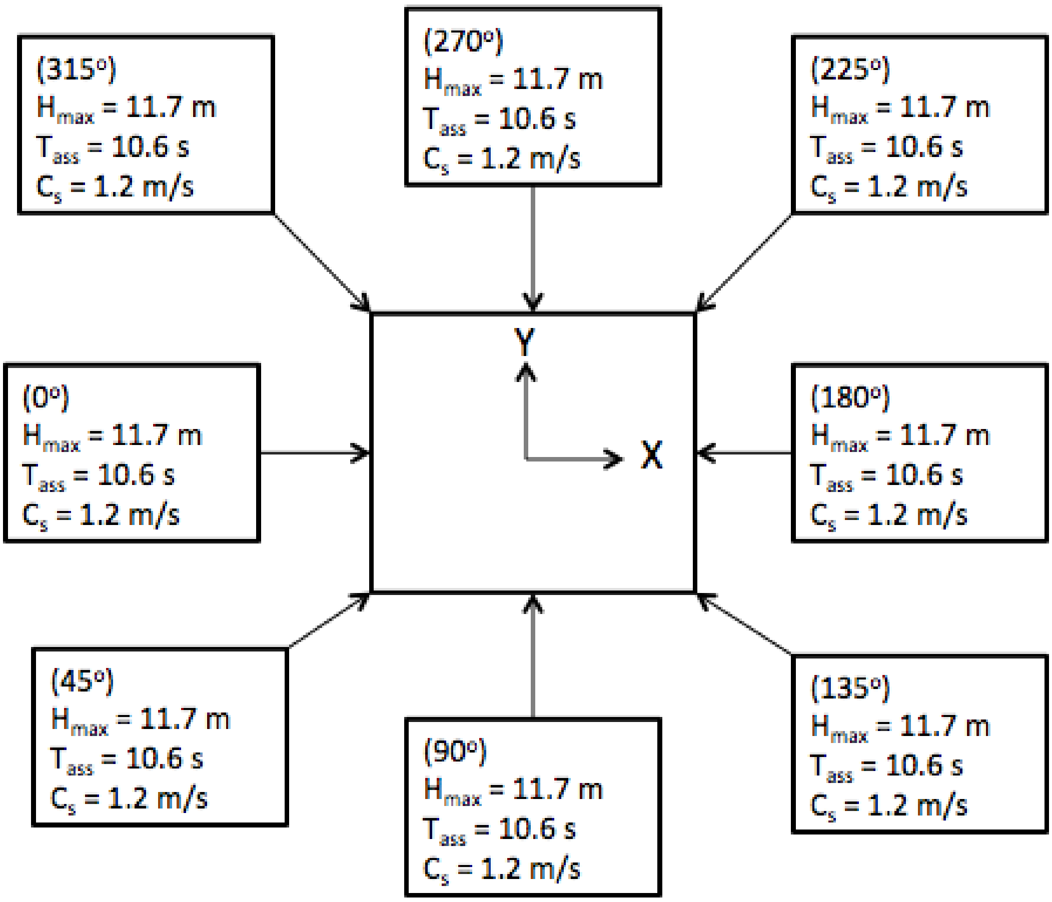

Figure 4: Omni-Directional Environmental Load Applied On The Structure

The results of the pushover analysis are tabulated in Table 1 below:

Table 1: Results from Pushover Analysis

Direction	Base Shear (kN)	Collapse Load (kN)	RSR
(0°)	8177.59	33605.34	4.11
(45°)	9357.83	46127.36	4.93
(90°)	8798.44	33413.07	3.79
(135°)	8895.93	45105.56	3.79
(180°)	9137.97	35376.20	3.87
(225°)	8732.56	33643.47	3.85
(270°)	**9004.62**	**23410.78**	**2.60**
(315°)	8972.33	28359.86	3.16

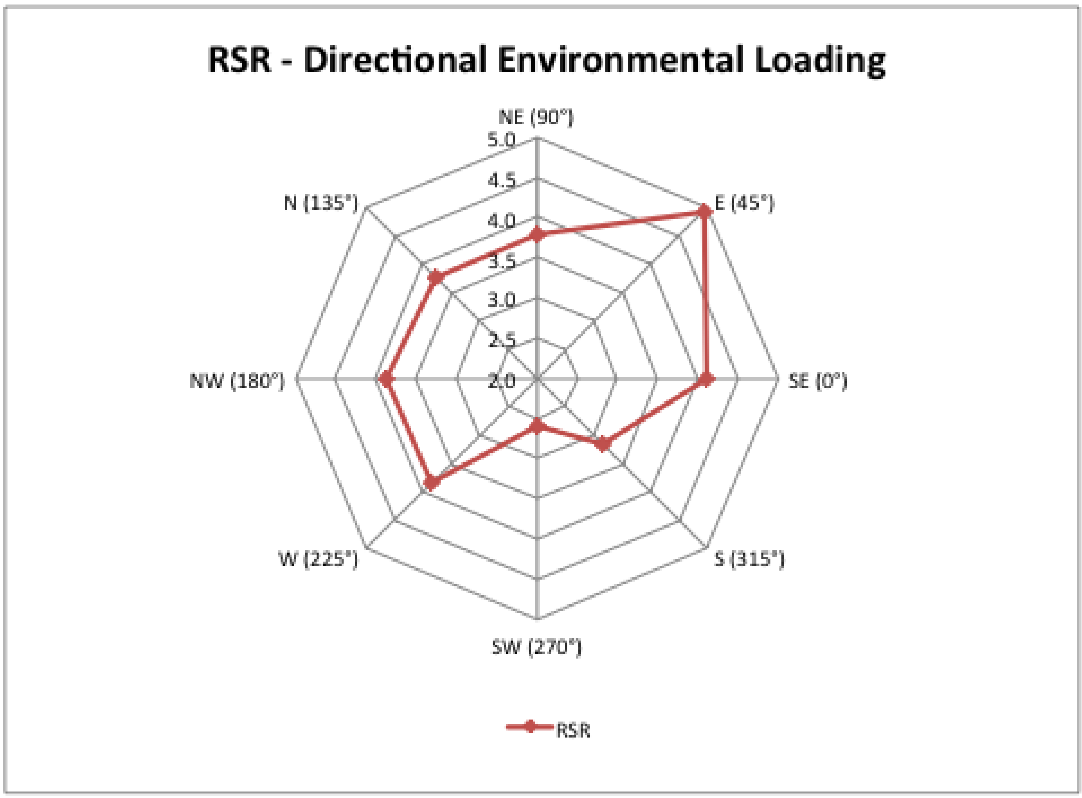

Figure 5: Contour Plot of RSR Values For 8 Directions

Figure 5 above shows the contour plot of the RSR values for 8 directions and it can be seen that the lowest RSR is 2.60 at 270º and represents the platform RSR. Water depth, initial air gap and wave height will be taken as the key parameters to be identified as the independent variable(s) that can explain the Reserve Strength Ratio (RSR) as the dependent variable in regression analysis.

3.4 Regression Analysis

The analysis described above is currently being used by the Oil and Gas industry to determine the strength of the existing platforms in order to decide whether the reserve strength left will meet the safety requirement for further extension of platform lifetime. It requires costly software and comprehensive training as well as competent expertise to maneuver the software with expert knowledge.

Throughout the years of sensitivity studies, the governing parameters that affect the integrity of the structures had been identified and can be used for alternative methods, which aims to minimize time-consuming analysis and expensive work. Regression analysis is typically used to model and analyze several variables and to formulate a relationship between single or multiple independent variables and dependent variable.

Regression analysis can be divided into two categories, namely linear and non-linear regression analysis. Linear regression is a process where the relationship between the dependent and independent variables can be represented in a linear function. However, some of the parameters might not be explained in a linear function. Therefore an iterative non-linear least square fitting can be implemented to fit a non-linear function to the data (Brown, 2000). Based on preliminary runs on the available parameters and the relationship between the independent and dependent variables, this study will adopt non-linear methods in order to obtain the most accurate results. The results and validations will be discussed further in Chapter 4.

3.4.1 Non-linear Regression Analysis

A method in obtaining the regression parameters is by utilizing the Regression Analysis provided in Microsoft Excel's Data Analysis, which returns the regression coefficient in order to formulate the regression equation. This analysis also gives the coefficient of determination R^2, standard error and ANOVA table.

The analysis was performed using the logarithmic of parameters, as shown in Equation 3 below:

Equation 3: Logarithmic of parameters

$$\log RSR = \log a + b \log Y + c \log D + d \log G + e \log H$$

where Y is the platform age, D is water depth, G is air gap and H is wave height, while a, b, c, d and e are the regression coefficients that can be obtained from regression analysis. Platform age, water depth, air gap and wave height are taken as independent variables while RSR is taken as dependent variable. The regression analysis will produce a summary output as shown in Table 2.

Table 2: Regression parameters returned from Data Analysis

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.8284
R Square	0.6862
Adjusted R Square	0.6078
Standard Error	0.1169
Observations	21

ANOVA

	df	*SS*	*MS*	*F*	*P-Value*
Regression	4	0.4784	0.1196	8.7470	0.0006
Residual	16	0.2188	0.0137		
Total	20	0.6972			

	Coefficients	*Standard Error*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	**-0.9064**	0.7794	-2.5586	0.7458	-2.5586	0.7458
log Y	**-0.0653**	0.1624	-0.4097	0.2790	-0.4097	0.2790
log D	**-0.6276**	0.2016	-1.0551	-0.2002	-1.0551	-0.2002
log G	**-0.2278**	0.3343	-0.9364	0.4808	-0.9364	0.4808
log H	**2.2539**	0.4279	1.3469	3.1610	1.3469	3.1610

3.4.2 Regression Parameters

Based on the summary output of the regression analysis, the regression coefficients can be found and used to formulate the non-linear regression equation. The relationship that satisfies the non-linear regression equation formulated from the logarithmic parameters and regression coefficients are as follows:

Equation 4: Non-linear regression equation

$$RSR = aY^b D^c G^d H^e$$

Coefficient of determination or R^2 is typically used as a measure of goodness of fit of a regression equation. Unfortunately, it is not considered in this study because it does not reflect the true fit of a non-linear regression parameters returned. It is long known in the mathematical literature that R^2 is inadequate to measure the goodness of fit in nonlinear models (Spiess et. al., 2010). In performing nonlinear regression analysis, it is significant that the authors as well as reviewers should be aware to refrain from looking for the R^2 values.

Thus, the approach taken in this study is to calculate the standard error of the data around the regression model of the dependent variable, or in this study, the validated RSR and the estimated RSR. This is calculated by dividing the sum of the squares of the residuals by the degree of freedom to get the variance of the data (Brown, 2000).

3.5 Project Activities

The flow chart of the methodology is as shown below:

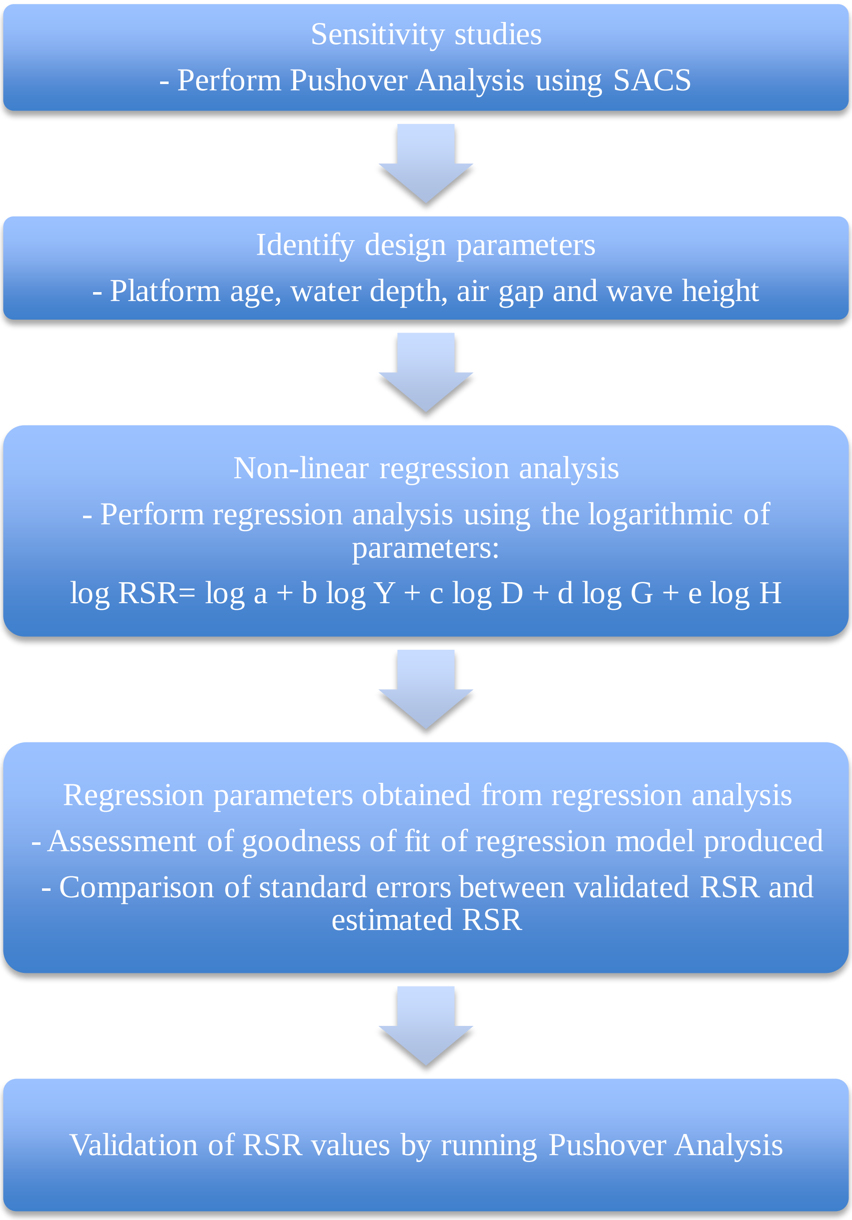

Figure 6: Research Flow Chart

3.6 Project Timeline/Gantt Chart

No	Detail/Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14	15
1	Project Work Continues • Identify design parameters that affect platform RSR • Logarithmic of parameters to obtain equation that satisfies the equation • Regression analysis using Microsoft Excel's Data Analysis to obtain regression coefficients	■	■	■	■	■	■	■	Mid Semester Break								
2	Submission of Progress Report									★							
3	Project Work Continues • Statistical tests, standard errors and R^2 value • Estimate platform RSR • Comparison between validated RSR and estimated RSR									■	■	■	■	■			
4	Pre-SEDEX												★				
5	Submission of Draft Report													★			
6	Submission of Dissertation (soft bound)														★		
7	Submission of Technical Paper														★		
8	Oral Presentation (VIVA)															★	
9	Submission of Project Dissertation (hard bound)																★

■ Progress

★ Key Milestone

CHAPTER 4

4.0 RESULTS AND DISCUSSION

4.1 Non-linear Regression Equations

Input parameters used in this study based on available design reports include platform age, water depth, air gap and wave height. These parameters are used to estimate the reserve strength ratio (RSR) of fixed offshore platforms. In total, 103 platforms from Malaysian Waters were grouped into 93 training samples to be analyzed and 10 test samples to estimate platform RSR.

The 93 data were ranged into five practical wave heights of H<8m, 8m≤H<10m, 10m≤H<12m, 12m≤H<15m and H>15. Regression analysis were applied to the variables according to different wave height range in order to produce a more accurate regression model respectively as shown in the table below:

Table 3: Regression equations suggested for varying wave height ranges

Wave Height Range	Non-linear Regression Equation	Standard Error of RSR
H<8m	$RSR=516.02Y^{-2.08}D^{-0.22}G^{0.04}H^{1.47}$	0.1695
8m≤H<10m	$RSR=56.17Y^{-1.14}D^{-0.09}G^{-1.12}H^{0.49}$	0.1844
10m≤H<12m	$RSR=11.51Y^{-0.43}D^{-0.41}G^{0.07}H^{0.54}$	0.1279
12m≤H<15m	$RSR=58.22Y^{0.14}D^{-0.31}G^{-0.46}H^{-0.61}$	0.1382
H>15m	$RSR=0.156Y^{-0.09}D^{-0.63}G^{-0.25}H^{2.22}$	0.1248

Table 4: Input and output data for H<8m

Platform Age	Water Depth (m)	Air Gap (m)	Wave Height (m)	Validated RSR	log Y	log D	log G	log H	log RSR	Estimated RSR	Error %
21	30.8	5.4	2.2	1.41	1.32	1.49	0.73	0.34	0.15	1.47	3.87
33	45.1	7.74	5.66	2.08	1.52	1.65	0.89	0.75	0.32	2.14	2.94
23	29.1	4	5.7	4.87	1.36	1.46	0.60	0.76	0.69	4.92	1.06
37	75.3	9.01	5.99	1.72	1.57	1.88	0.95	0.78	0.24	1.65	4.12
37	9.75	3.6	6.5	1.81	1.57	0.99	0.56	0.81	0.26	2.80	35.34
33	9.75	10	6.5	4.38	1.52	0.99	1.00	0.81	0.64	3.70	18.41
37	9.75	3.6	6.5	4.45	1.57	0.99	0.56	0.81	0.65	2.80	58.92
30	28.35	4.6	6.7	3.00	1.48	1.45	0.66	0.83	0.48	3.63	17.25
42	40.8	3.3	6.8	1.42	1.62	1.61	0.52	0.83	0.15	1.68	15.41
35	77.57	2	6.9	1.75	1.54	1.89	0.30	0.84	0.24	2.14	18.19
37	75.59	7.86	6.9	1.94	1.57	1.88	0.90	0.84	0.29	2.02	3.98
41	31.4	2.3	6.9	3.22	1.61	1.50	0.36	0.84	0.51	1.88	71.08
41	32.6	7.53	7.31	1.78	1.61	1.51	0.88	0.86	0.25	2.13	16.33
38	48.6	1.8	7.1	3.67	1.58	1.69	0.26	0.85	0.56	2.07	77.05
42	37.49	5.5	7.5	2.42	1.62	1.57	0.74	0.88	0.38	2.01	20.19
44	24.4	1.8	7.6	1.00	1.64	1.39	0.26	0.88	0.00	1.96	48.95
										Mean	**25.82**

Based on available parameters as in Table 4 above, the utilization of regression analysis of Microsoft Excel produced the regression equation as follows:

Equation 5: Regression equation for H<8m

$$RSR = 516.02Y^{-2.08}D^{-0.22}G^{0.04}H^{1.47}$$

The comparison between the validated RSR and estimated RSR can be seen in Figure 7:

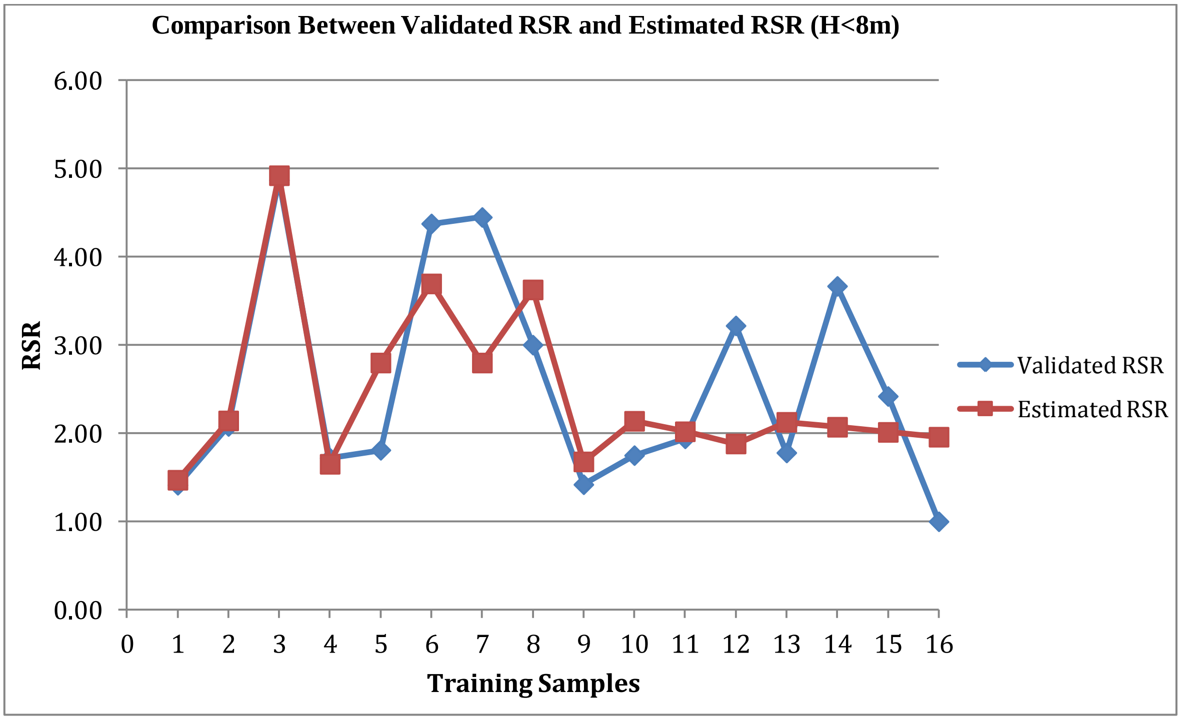

Figure 7: Comparison between validated and estimated RSR (H<8m)

Table 5: Input and output data for 8m<H<10m

Platform Age	Water Depth (m)	Air Gap (m)	Wave Height (m)	Validated RSR	log Y	log D	log G	log H	log RSR	Estimated RSR	Error %
38	10.67	7.47	8	1.20	1.58	1.03	0.87	0.90	0.08	1.56	22.97
37	9.1	2.05	8	1.63	1.57	0.96	0.31	0.90	0.21	1.89	13.89
29	10.1	1.22	8	3.14	1.46	1.00	0.09	0.90	0.50	2.63	19.21
20	46.9	5.2	8.5	3.78	1.30	1.67	0.72	0.93	0.58	3.07	23.01
37	7.9	1.9	8.6	1.54	1.57	0.90	0.28	0.93	0.19	2.00	23.11
29	21.9	4.3	8.6	2.95	1.46	1.34	0.63	0.93	0.47	2.20	33.80
19	46.63	4.1	8.9	8.72	1.28	1.67	0.61	0.95	0.94	3.43	154.36
40	61	9.79	9	1.15	1.60	1.79	0.99	0.95	0.06	1.30	11.39
36	76.2	2	9	1.22	1.56	1.88	0.30	0.95	0.09	1.73	29.41
39	75.9	2	9	1.32	1.59	1.88	0.30	0.95	0.12	1.58	16.32
19	50.6	9.49	9	1.36	1.28	1.70	0.98	0.95	0.13	3.10	56.19
34	76.2	1.8	9	1.40	1.53	1.88	0.26	0.95	0.15	1.87	25.05
40	62.9	1	9	1.44	1.60	1.80	0.00	0.95	0.16	1.69	14.65
36	77.11	2.3	9	1.57	1.56	1.89	0.36	0.95	0.20	1.70	7.57
40	77.3	6.66	9	1.61	1.60	1.89	0.82	0.95	0.21	1.33	21.05
35	77.14	2.3	9	1.89	1.54	1.89	0.36	0.95	0.28	1.75	7.74
35	74.3	2.3	9	1.97	1.54	1.87	0.36	0.95	0.29	1.76	11.99
36	75.9	2	9	2.12	1.56	1.88	0.30	0.95	0.33	1.73	22.62
37	47.5	3.1	9.1	3.21	1.57	1.68	0.49	0.96	0.51	1.67	92.60
40	61	11.4	9.7	1.46	1.60	1.79	1.06	0.99	0.16	1.32	10.38
23	79.2	4.9	9.7	1.55	1.36	1.90	0.69	0.99	0.19	2.69	42.24
44	38.1	10.39	9.76	1.65	1.64	1.58	1.02	0.99	0.22	1.25	31.78
										Mean	**31.42**

Based on available parameters as in Table 5 above, the utilization of regression analysis of Microsoft Excel produced the regression equation as follows:

Equation 6: Regression equation for 8m<H<10m

$$RSR = 56.17Y^{-1.14}D^{-0.09}G^{-1.12}H^{0.49}$$

The comparison between the validated RSR and estimated RSR can be seen in Figure 8:

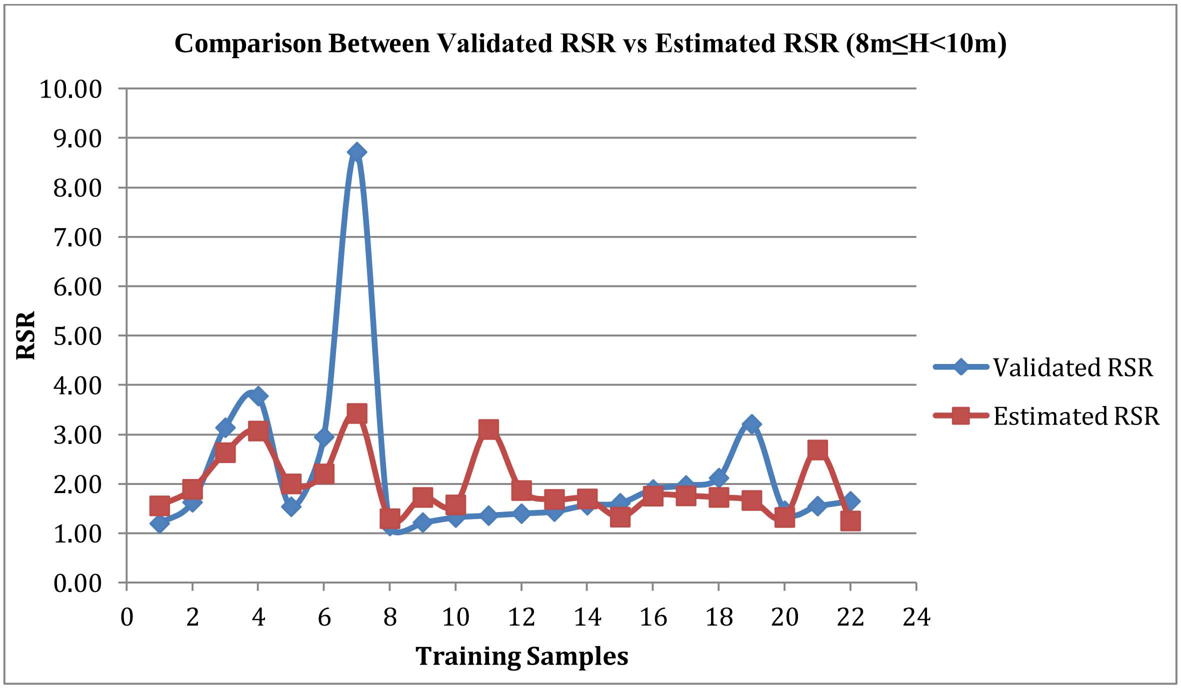

Figure 8: Comparison between validated and estimated RSR (8m<H<10m)

Table 6: Input and output data for 10m<H<12m

Platform Age	Water Depth (m)	Air Gap (m)	Wave Height (m)	Validated RSR	log Y	log D	log G	log H	log RSR	Estimated RSR	Error %
32	36.3	8.935	10.169	2.15	1.51	1.56	0.95	1.01	0.33	2.48	13.39
35	83.2	4.7	10.2	1.57	1.54	1.92	0.67	1.01	0.20	1.64	4.08
33	62.2	4.6	10.2	1.95	1.52	1.79	0.66	1.01	0.29	1.88	3.46
41	31.69	10.71	10.23	1.95	1.61	1.50	1.03	1.01	0.29	2.40	18.64
15	75	12.32	10.28	2.19	1.18	1.88	1.09	1.01	0.34	2.63	16.80
15	74	12.4	10.28	3.96	1.18	1.87	1.09	1.01	0.60	2.65	49.57
37	47.6	3.4	10.8	1.46	1.57	1.68	0.53	1.03	0.16	2.02	27.69
31	67	10.48	10.8	2.97	1.49	1.83	1.02	1.03	0.47	2.05	44.76
34	71.4	9.19	10.87	1.56	1.53	1.85	0.96	1.04	0.19	1.91	18.38
35	70.1	3.7	10.87	1.62	1.54	1.85	0.57	1.04	0.21	1.78	9.35
30	73.3	5.1	10.9	1.68	1.48	1.87	0.71	1.04	0.23	1.92	12.33
6	60.7	14.44	10.9	5.01	0.78	1.78	1.16	1.04	0.70	4.42	13.26
6	61	14.36	12.71	3.54	0.78	1.79	1.16	1.10	0.55	4.79	26.12
29	63.1	3	11	2.98	1.46	1.80	0.48	1.04	0.47	2.00	48.90
31	72.7	1.7	11.1	1.72	1.49	1.86	0.23	1.05	0.24	1.77	3.06
35	25.9	6.65	11.99	4.11	1.54	1.41	0.82	1.08	0.61	2.93	40.27
										Mean	**21.88**

Based on available parameters as in Table 6 above, the utilization of regression analysis of Microsoft Excel produced the regression equation as follows:

Equation 7: Regression equation for 10m<H<12m

$$RSR = 11.51Y^{-0.43}D^{-0.41}G^{0.07}H^{0.54}$$

The comparison between the validated RSR and estimated RSR can be seen in Figure 9:

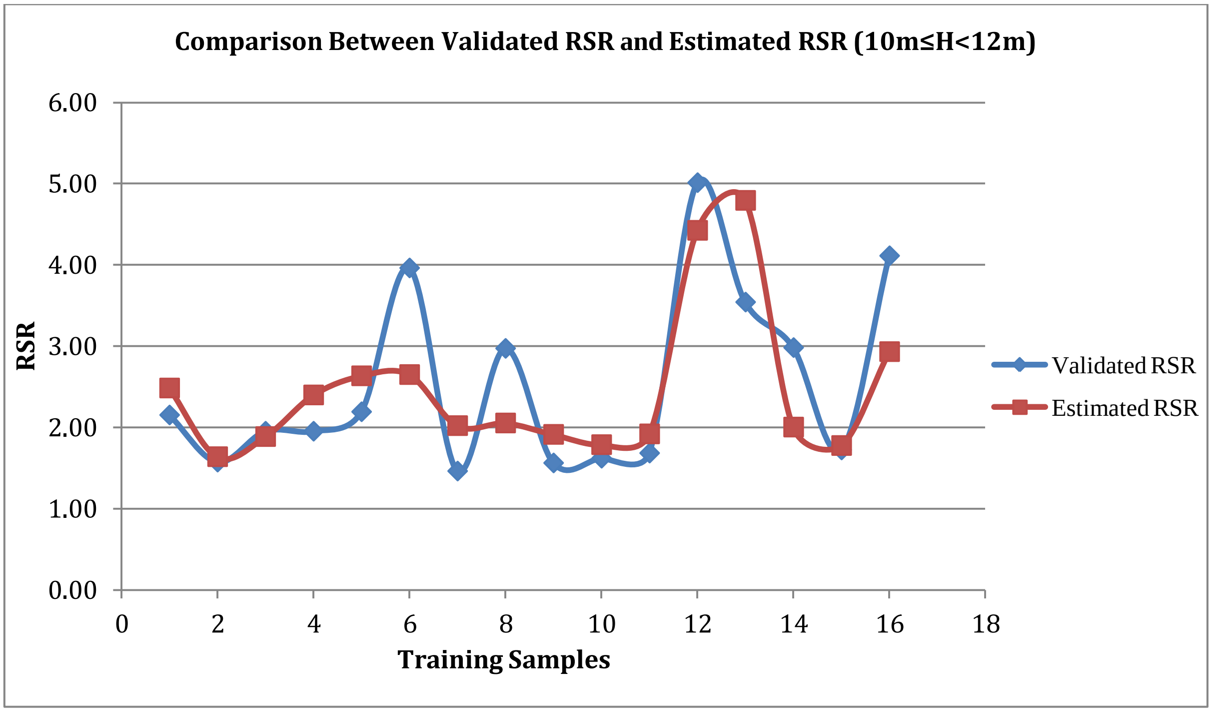

Figure 9: Comparison between validated and estimated RSR (10m<H<12m)

Table 7: Input and output data for 12m<H<15m

Platform Age	Water Depth (m)	Air Gap (m)	Wave Height (m)	Validated RSR	log Y	log D	log G	log H	log RSR	Estimated RSR	Error %
38	46.3	7.34	12.03	1.81	1.58	1.67	0.87	1.08	0.26	2.64	31.40
29	63.1	3.2	12.12	2.38	1.46	1.80	0.51	1.08	0.38	3.37	29.33
32	46.03	7.73	12.32	2.85	1.51	1.66	0.89	1.09	0.45	2.48	14.76
38	46.9	8.865	12.371	2.57	1.58	1.67	0.95	1.09	0.41	2.37	8.47
40	60.7	9.6	12.5	2.72	1.60	1.78	0.98	1.10	0.43	2.11	28.64
31	73.2	12	12.6	1.39	1.49	1.86	1.08	1.10	0.14	1.73	19.76
42	26.2	6.5	12.6	3.15	1.62	1.42	0.81	1.10	0.50	3.27	3.59
24	63.87	9.51	12.68	1.51	1.38	1.81	0.98	1.10	0.18	1.93	21.78
19	17.57	10.08	12.71	2.73	1.28	1.24	1.00	1.10	0.44	2.69	1.60
34	29	6.9	12.783	3.95	1.53	1.46	0.84	1.11	0.60	2.97	33.13
38	10.1	16.5	12.9	2.54	1.58	1.00	1.22	1.11	0.40	2.77	8.22
10	70.1	9.94	13.08	1.49	1.00	1.85	1.00	1.12	0.17	1.60	6.72
39	46	7.496	13.166	2.77	1.59	1.66	0.87	1.12	0.44	2.49	11.41
35	26.09	7.07	13.2	4.93	1.54	1.42	0.85	1.12	0.69	2.98	65.28
35	71.6	7.96	13.4	2.13	1.54	1.85	0.90	1.13	0.33	2.06	3.34
24	29.14	8.94	13.88	3.99	1.38	1.46	0.95	1.14	0.60	2.38	67.41
21	15.55	7.74	13.97	3.26	1.32	1.19	0.89	1.15	0.51	3.01	8.26
40	86	8.392	14.75	2.05	1.60	1.93	0.92	1.17	0.31	1.83	12.14
31	67.1	9.8	14.98	1.50	1.49	1.83	0.99	1.18	0.18	1.76	14.53
38	11.2	9.8	14.98	1.73	1.58	1.05	0.99	1.18	0.24	3.11	44.38
										Mean	**21.71**

Based on available parameters as in Table 7 above, the utilization of regression analysis of Microsoft Excel produced the regression equation as follows:

Equation 8: Regression equation for 12m<H<15.m

$$RSR = 58.22 Y^{0.14} D^{-0.31} G^{-0.46} H^{-0.61}$$

The comparison between the validated RSR and estimated RSR can be seen in Figure 10:

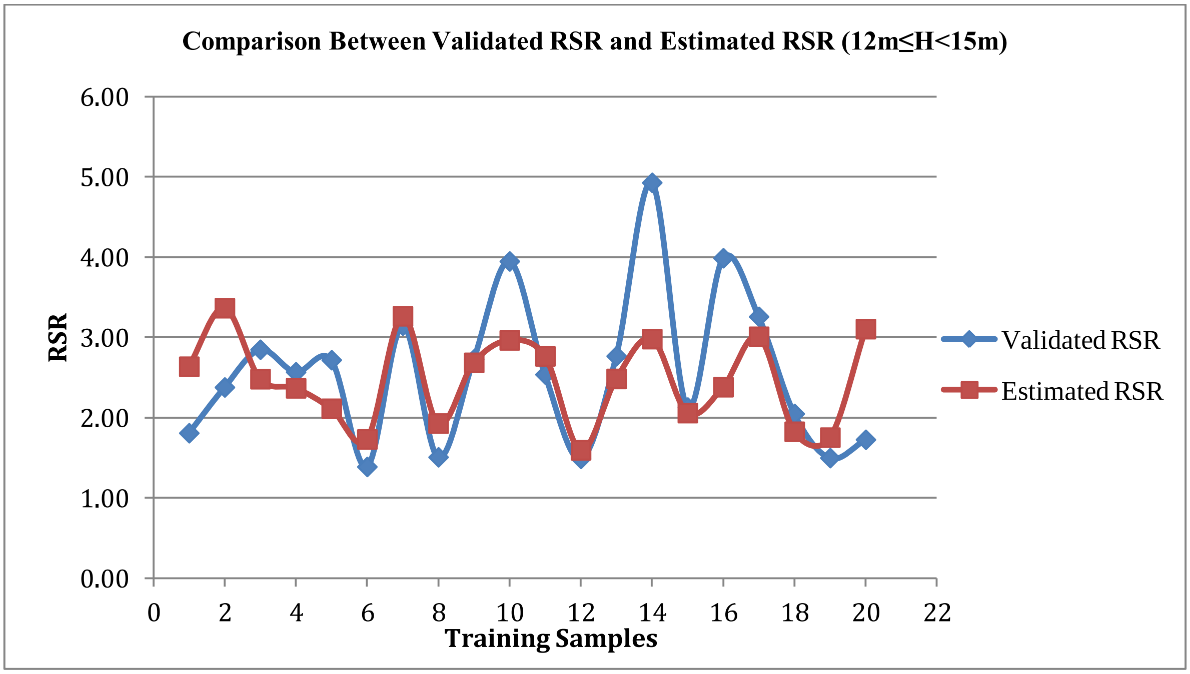

Figure 10: Comparison between validated and estimated RSR (12m<H<15m)

Table 8: Input and output for H>15m

Platform Age	Water Depth (m)	Air Gap (m)	Wave Height (m)	Validated RSR	log Y	log D	log G	log H	log RSR	Estimated RSR	Error %
30	75	8.966	15.184	1.72	1.48	1.88	0.95	1.18	0.24	1.85	7.21
30	76.2	16.34	15.53	1.76	1.48	1.88	1.21	1.19	0.25	1.66	5.87
12	76.2	10.84	15.66	2.10	1.08	1.88	1.04	1.19	0.32	2.03	3.46
32	28.3	12.08	16.422	6.04	1.51	1.45	1.08	1.22	0.78	3.78	59.80
21	61.9	10.7	16.43	2.07	1.32	1.79	1.03	1.22	0.32	2.46	15.94
42	74.4	8.58	16.44	3.58	1.62	1.87	0.93	1.22	0.55	2.18	63.98
22	78.18	8.88	16.55	3.38	1.34	1.89	0.95	1.22	0.53	2.25	50.13
31	67.1	11.31	16.68	1.49	1.49	1.83	1.05	1.22	0.17	2.31	35.43
32	70.1	11.31	16.68	1.75	1.51	1.85	1.05	1.22	0.24	2.24	21.81
14	62.5	9.398	17.292	2.58	1.15	1.80	0.97	1.24	0.41	2.93	12.03
23	63.4	10.09	17.44	2.99	1.36	1.80	1.00	1.24	0.48	2.79	7.25
32	66.1	10.2	17.57	1.99	1.51	1.82	1.01	1.24	0.30	2.68	25.62
12	68.9	10.84	17.96	2.72	1.08	1.84	1.04	1.25	0.43	2.93	7.29
27	68.9	7.2	18.06	2.62	1.43	1.84	0.86	1.26	0.42	3.07	14.42
35	28.3	8.29	19.26	5.31	1.54	1.45	0.92	1.28	0.73	5.87	9.52
18	75.6	11.44	20.33	3.00	1.26	1.88	1.06	1.31	0.48	3.47	13.59
21	77.4	8.11	21.26	4.52	1.32	1.89	0.91	1.33	0.66	4.06	11.33
10	162.2	13.4	23.93	3.91	1.00	2.21	1.13	1.38	0.59	3.11	25.69
20	77.04	9.65	27.25	6.58	1.30	1.89	0.98	1.44	0.82	6.80	3.25
										Mean	**20.72**

Based on available parameters as in Table 8 above, the utilization of regression analysis of Microsoft Excel produced the regression equation as follows:

Equation 9: Regression equation for H>15.m

$$RSR = 0.156Y^{-0.09}D^{-0.63}G^{-0.25}H^{2.22}$$

The comparison between the validated RSR and estimated RSR can be seen in Figure 11:

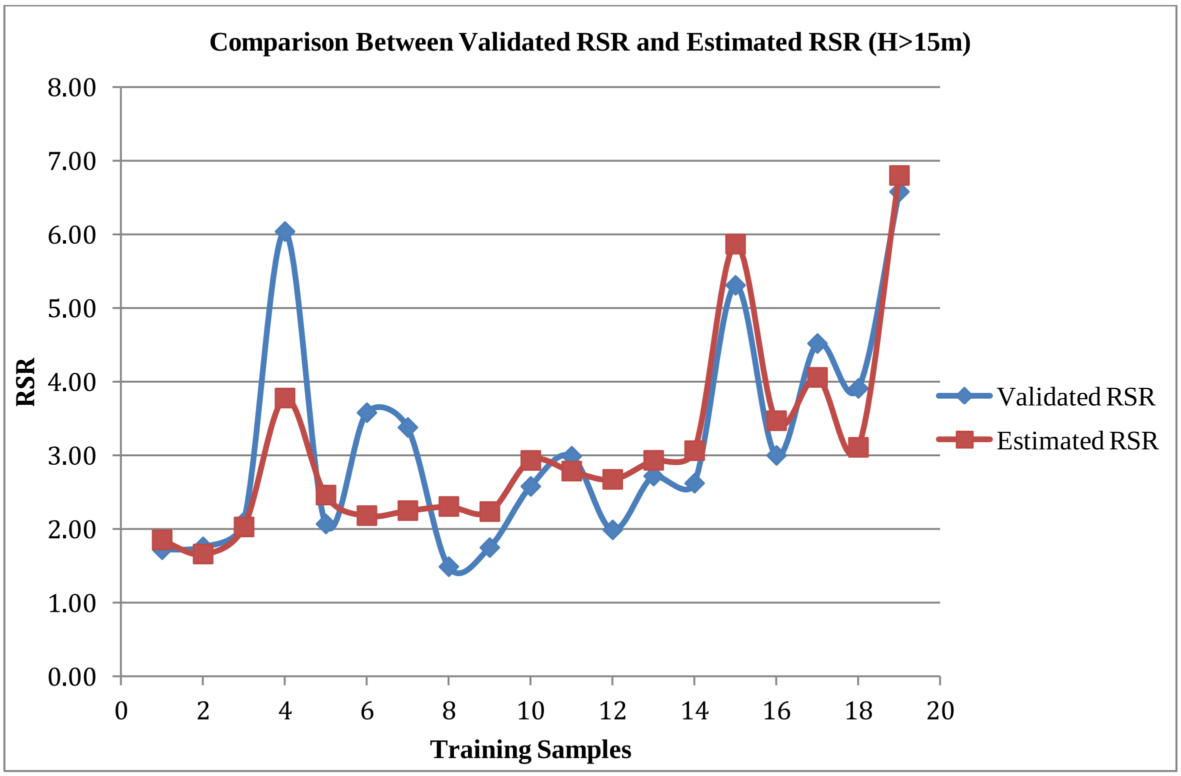

Figure 11: Comparison between validated RSR and estimated RSR for H>15m

4.2 Validation Samples

For validation purposes, 10 test samples were taken put from the 103 raw samples in order to test the formulated regression equations. Two samples from each of the wave height range were separated and were put to test.

Table 9: Comparison of validated and estimated RSR of 10 validation samples

Years Installed	Water Depth (m)	Air Gap (m)	Wave Height (m)	Validated RSR	Estimated RSR	Error %
42	55.1	1.2	6.3	1.61	1.35	19.07
37	47.5	8.4	10.8	1.96	2.15	8.94
12	69.9	8.84	15.22	1.99	2.12	5.98
29	10.06	8.44	8	2.06	2.10	2.07
34	62.2	9.79	11	2.40	2.04	17.49
19	17.57	10.08	12.71	2.73	2.69	1.60
26	9.1	2.97	8	2.93	2.72	7.91
31	47.55	7.07	7.1	3.09	3.35	7.86
42	26.2	6.5	12.6	3.15	3.27	3.59
14	62.5	9.483	18.764	3.37	3.51	3.96
					Mean	**7.85**

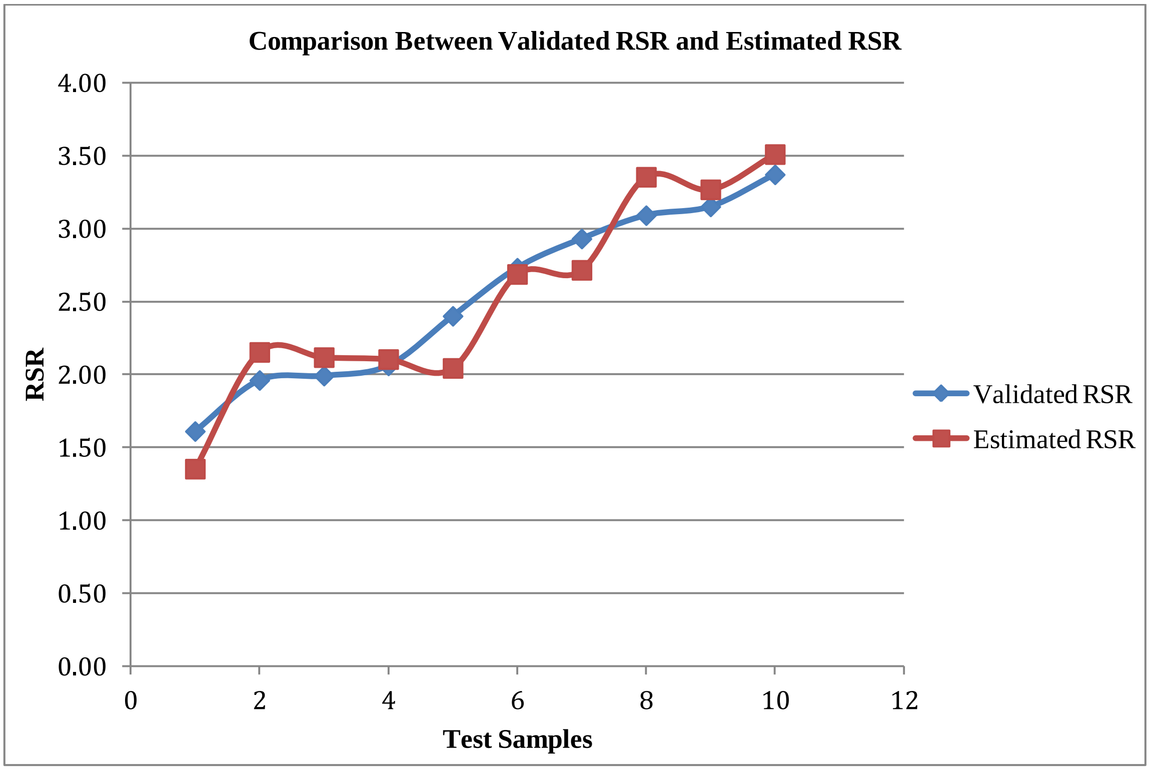

Figure 12: Comparison graph between validated and estimated RSR

4.3 Case Study

A case study is conducted by running Pushover Analysis using Structural Analysis Computer Software (SACS) on platform A. The platform is as shown in Figure 13 and the design parameters of the platform are as in Table 10.

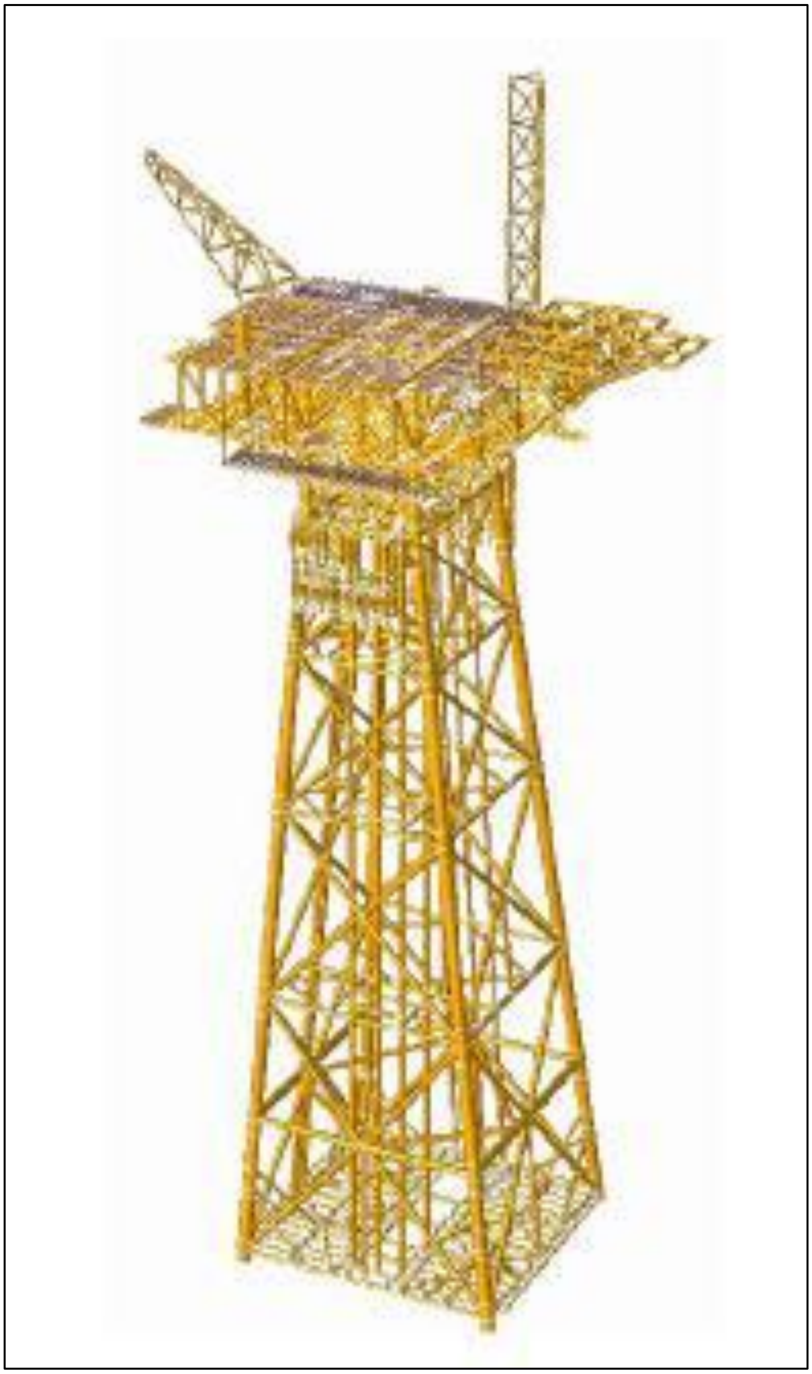

Figure 13: Model of fixed offshore structures

Table 10: Design parameters of case study platform

Platform Age	Water Depth (m)	Air Gap (m)	Wave Height (m)	Validated RSR	Estimated RSR	Percentage Error (%)
4	94.8	13.1	11.7	4.838	4.532	6.76

Figure 12 shows the comparison of validated and estimated RSR curves and it is noticeable that the regression curve with the estimated RSR agrees well with the validated RSR with a percentage error of 7.85% as shown in Table 9. It should be noted that the data used for regression analysis consists of 103 platforms from Malaysian Waters and another 10 platforms were separated for validation purpose in order to achieve a more assured result from the formulated regression equations respective of the wave height ranges. The platform used for case study is also separated from the 103 platform data to ensure the regression equation formulated would fit accordingly to its purpose. The RSR returned from Pushover Analysis is performed using directional metocean data, which is more accurate and different from the data used for Pushover Analysis as mentioned in Chapter 3. As shown in Table 10, the percentage difference returns 6.76% shows a promising number for this study.

As an assessment of goodness of fit, the R^2 is calculated. The R^2 value is called the coefficient of determination where it represents the variance of the dependent variable explained by the independent variable. However, as mentioned in Chapter 3, R^2 does not play a significant role for non-linear regression. Rather, standard error of RSR being the dependent variable is used in this study to measure the goodness of fit of the regression models formulated. This is calculated by dividing the sum of the squares of the residuals by the degree of freedom to get the variance of the data. As shown in Table 3, the standard errors for non-linear regression equations are 0.1695, 0.1844, 0.1279, 0.1382 and 0.1248 respective of each wave height range. Percentage error is also used in this study as a basis to validate the fit of the regression equations formulated.

CHAPTER 5

5.0 CONCLUSIONS AND RECOMMENDATIONS

The conclusion of this study is based on the results of the regression analysis which are conducted for the 5 different sets of platforms respective of varying wave height range. The set of data did not pass the hypotheses and significant tests for linear regression, thus non-linear regression is chosen as a more fitting analysis. The structural strength or the ultimate strength is performed by Pushover Analysis of SACS which returns strength of the platform in terms of reserve strength ratio (RSR) and the regression analysis is performed by using Microsoft Excel's Data Analysis ToolPak.

The aim of establishing the regression equations for the prediction of RSR is to minimize both time and costly work. It will be an alternative for the offshore industry to determine the quantified strength of their platforms for an inexpensive and quicker way. The objective has been achieved and finding has revealed that it is possible to obtain the estimate of platform RSR in a shorter time and inexpensive method.

The non-linear regression equations formulated can be used by the industry to estimate platform RSR and eliminating the lengthy process. It is beneficial in a way that it saves both time and cost. It should be noted that the RSR values returned from the regression equations are only an estimate of the RSR. It should give the practicing engineer a rough idea of the current condition of the platform at hand and proceed with the appropriate mitigations actions, wherever economical and safe.

Platform RSR can be affected by both load and resistance factor. However due to confidentiality, some of the information are classified and held private. In order to obtain a more precise and accurate value of RSR in comparison with the validated RSR, future studies could include realistic data such as 8-directional metocena data, pile-soil interaction, seismic analysis, seabed subsidence due to compaction of reservoir, corrosion, configuration of jacket legs and marine growth.

The risks for life extension of existing platforms should describe the feasibility of additional risks of the structures to be assessed. Some other considerations when dealing with aged platforms to be used for life extensions should include the following:

a) Design intent and specifications of the platform
b) Fabrication inspection
c) Operational error, maintenance and inspection
d) Degradation of platform that include subsidence, scour, corrosion and fatigue.
e) Environmental load, vortex induced vibration and update of metocean data
f) Additional load and modifications on topside
g) Accidental loads that include dropped objects, boat impact, explosion, fire and blast.

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