# NONLINEAR DYNAMIC BEHAVIOUR OF OFFSHORE SPAR PLATFORMS


by

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**Submitted**

**in fulfilment of the requirements of the degree of Doctor of Philosophy**

**to the**


**INDIAN INSTITUTE OF TECHNOLOGY, DELHI**

**INDIA**



**DECEMBER 2002**

*Dedicated to*

*Late dadajee and Late dadijee*

# CERTIFICATE

This is to certify that the thesis entitled, "**Nonlinear Dynamic Behaviour of Offshore Spar Platforms**" being submitted by **Amit Kumar Agarwal** to the Indian Institute of Technology, Delhi for the award of the degree of **Doctor of Philosophy in Civil Engineering** is a record of the bonafide research work carried out by him under my supervision and guidance. He has fulfilled the requirements for submission of this thesis, which to the best of my knowledge has reached the requisite standard.

The materials contained in this thesis have not been submitted, in part or full, to any other University or Institute for the award of any degree or diploma.

Dated: December 2002

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## *ACKNOWLEDGMENT*

*I express all my gratitude to* ***GOD*** *for successful completion of this thesis under the able guidance and supervision of* ***Prof. A. K. Jain*** *who introduced me the area of offshore structures. In my whole research experience I have found guiding a Ph.D student to be tougher than doing Ph.D itself. Its like watering a plant and seeing it grow everyday. As a newcomer to the area of offshore structure I shall always be indebted to* ***Prof. A. K. Jain*** *for his patience, invaluable guidance, help, inspiration, motivation and constant encouragement throughout this study. With his magnificent understanding and in-depth knowledge of offshore structural engineering he has motivated and cultivated in me a very deep interest and ability to understand the behaviour of offshore structures.*

*I thank Prof. S. N. Sinha, Professor and Head of Civil Engineering Department, IIT Delhi, for his constant encouragement and facilities provided to me.*

*I am thankful to my Student Research Committee members, Prof. T. K. Datta, Prof. K. G. Sharma and Prof. Suhail Ahmad for their valuable suggestions and guidance during my comprehensive exam and pre Ph.D synopsis.*

*I feel immense pleasure in expressing my deep sense of gratitude to Prof. Ashok Gupta for his encouragement to complete this work.*

*I thank Dr. M. Hariharan, Head of the Offshore Structure Division, Engineers India Limited (EIL), India for giving me his valuable time to guide me.*

*I am thankful to Prof. R. Sundaravadivelu, Ocean Engineering Center, IIT Madras, for extending his help and guidance during my visit to IIT Madras.*

*I would like to extend my sincere thanks to the staffs of libraries of IIT Delhi; IIT Madras; EIL Delhi; SERC Madras; NIOT Madras and OEC, IIT Madras.*

*I am heartily thankful to the Government of India for providing scholarship and assistantship to me.*

*I would like to thank the staffs of Civil Engineering Department, IIT Delhi for their kind support and help extended to me. Special thanks are due to Shri V. P. Gulhati, Shri Vikram, Shri R. Agarwal and Mr. Vinod for their cooperation.*

*I would like to thank Dr. Sreekumar for sending me research papers.*

*I deeply acknowledge Dr. Ajay Jain's personal care towards my health during my stay at IIT Delhi.*

*I owe my sincere thanks to Dr. M. N. Gupta, Shri. N. C. Kalra, Shri Sunil Kak, Shri R. K. Chauhan and Dr. M. M. Rao for providing me good computational facilities.*

*I am thankful to Mr. Vikas for drawing all figures in AUTOCAD and to Shri N. L. Arora for tracing and lettering the figures.*

*I am indebted to a number of my colleagues and friends for their help and advice during the preparation of this thesis. My special thanks are due to Dr. Savita Maru who motivated me in getting started and helped me whenever it was required. I fail to find words to acknowledge Dr. R. K. Gupta, Dr. S. I Anwar, Mr. Mohd. Umair, Mr. Quamrul Hassan, Dr. Rajesh Dwivedi, Mr. Umesh Maheshwari, Mrs. Tabassum Naqui, Dr. C. S. Gokhale, Mr. Ravi Sharma, Dr. Hasan, Mr. M. K. Bhardwaj, Mrs. Sheela, Miss Gayathri, Mr. Atul K. Banik, Mr. Sandeep Choudhary, Dr. R. D. Singh, Dr. Rakesh Datta, Dr. Shipra, Dr. Anu, Miss Anju Pani, Mr. M. K. Mahesh, Mr. R. Senthavil, Miss Chitra, Mr Javed, Dr. Santosh, Mr. Umesh Pandey, Mr. Munish Chandel, Mr. Rao Martand Singh, Mr. Abhijit Pawar, Mr. Avinash Shinde, Mr. Nitin Patil, Mr. Sunil Patil, Mrs. Lopa, Mr. Madhur Tripathi, Mr. Vivek Singh, Mr Javed Khan, Mr. Sanjeev Mukherjee, Mr. Deven Sinha, Mr. Jitender Choudhary, Mr. Narendre Shastri, Mr. Ashok Sharma, Mr. Mukesh Kumar Pankaj, Mr. Rajesh Talele, Mr. Siddharth Agarwal, Mr. Shailendre Agarwal and all others who may not have helped me directly but their constant encouragement, inspiration and suggestions and timely help pushed me to work with a renewed vigor.*

*I am heartily thankful to the family members of my supervisor Prof. A. K. Jain, who were very kind enough to cooperate during long hours of discussion at their house.*

*I would like to express my sincere regards to my* ***mummy, papa, nanajee, nanijee and other family members****, who gave me the sense of direction in life and who always wanted to see me progressing. I would like to appreciate my brother* ***Prabhat*** *who stood always behind me in every stage of my life and sisters* ***Ritu & Shweta*** *for their moral and mental support, without whom this work would never have been completed. I should not forget to acknowledge a newcomer in my family my dearest bhabhi who is always concerned about my health and studies.*

*(Amit Kumar Agarwal)*

# ABSTRACT

Offshore structures are used for the exploration and production of oil and gas from sea bed. Various types of offshore platforms such as fixed bottom offshore platforms, bottom supported compliant offshore platforms and floating compliant offshore platforms are discussed. One of the types of floating compliant offshore platforms is offshore Spar platform, which is used for the deep water applications for the drilling, production, processing, storage and offloading of ocean deposits. Of the various types of offshore Spar platforms, one of the types of Spar platform with full hull cylinder is the structure under study and its dynamic response behaviour has been evaluated under different environmental sea wave loads.

Literatures related to offshore structures, offshore Spar platforms, cable structures, hydrodynamic wave forces have been studied to form the basis of the present study. Many authors have studied higher order effects and modifications to Morison's equation to account for various diffraction effects for force evaluation, considering only horizontal spring (modeling the mooring line with multi linear massless spring, nonlinear massless spring and considering hydrodynamic forces in mooring line) with hull/mooring coupled and uncoupled dynamic analysis for various environmental loadings. Whereas the main emphasis of the present research work is to study the nonlinear dynamic response analysis of offshore Spar platform under various environmental loads with all six degree-of-freedom at the center of gravity, CG considering both horizontal spring as well as vertical springs (effect of vertical spring has been ignored in the above literatures). The various nonlinearities considered in the present study are: geometric nonlinear static force-excursion relationship of cables, interaction of all degrees-of-freedom is considered giving rise to response dependent stiffness matrix, nonlinear hydrodynamic drag force due to relative velocity square term

in Morison's equation, variable submergence effect in wave forces, added mass and force evaluation at the instantaneous position of structure.

The offshore Spar platform virtually derives all its stability and stiffness from the restraint provided by number of cables symmetrically arranged around the platform. The integrity of the offshore Spar platform is critically dependent on the characteristics of the cable system. The nonlinear static force-excursion relationship of multi component (consisting of mooring line, clump weights and anchor line) single cable and 4 cables placed perpendicular to each other including the horizontal as well as vertical excursion in cables at the fairlead attachment point of offshore Spar platform are studied. Equation of a catenary is used for evaluation of nonlinear static force-excursion relationship for single cable system, and then for the entire cable system. Detailed analysis of cable system with distributed clump weight for horizontal as well as vertical excursion is presented. Parametric studies for the influence of different parameters (initial horizontal force at the top of mooring line, initial inclination at the top of mooring line, submerged unit weight of clump weight, length of clump weight, length of anchor line, height of cable attachment point) on the nonlinear static force - excursion relationship of the cable system has been carried out.

For all the studies carried out, the Spar platform and the cable system (replaced with an equivalent horizontal and vertical spring) are treated as a single system for the analysis. The Spar platform is modelled as a rigid cylinder with six degrees-of-freedom at its CG. Two different models of stiffness matrix have been considered in the present study which are **Case A:** In the first model the response dependent stiffness matrix consists of two parts: (a) the hydrostatics provide restoring force in heave, roll and pitch; and (b) the cables provide the restoring force in all degree-of-freedom which are represented here by nonlinear horizontal spring (ignoring the effect of vertical excursion of cables) located at the fairlead. **Case B:** In the second model the response dependent stiffness matrix consists of three parts: (a) the hydrostatics provide restoring force in heave, roll and pitch; (b) the cables provide the restoring force in all degree-of-freedom which are represented here by nonlinear horizontal spring; and (c) vertical spring located at the fairlead. Structural mass is assumed to be lumped at each degree-of-freedom, hence the mass matrix is diagonal and constant. Damping matrix is dependent on initial mass and initial stiffness matrix.

The effect of only horizontal excursion of cables on the response of offshore Spar platform for regular wave is carried out. The structural model of offshore spar platform is same as discussed in earlier section. Nonlinear static force-excursion relationship for only horizontal excursion of cable is considered. Stiffness matrix is evaluated considering only Case A. An unidirectional regular wave model is used for computing the wave kinematics. The kinematics of the water particles has been evaluated by Airy's linear wave theory. Modified Morison's equation has been used for the evaluation of hydrodynamic forces (which meets the applicability criteria for the regular waves considered in the study). Diffraction effects have been ignored. The equation of motion has been solved by an iterative procedure using unconditionally stable Newmark's Beta method in time domain. Parametric studies to evaluate the influence of different parameters (Hogben's modifications in hydrodynamic force to account for variable submergence of the structure with the passage of waves, effect of initial horizontal force in the cable at the fairlead attachment point, wave height, wave period, current velocity, hydrodynamic coefficient of inertia and hydrodynamic coefficient of drag) on the response of Spar platform have been carried out.

The effect of vertical excursion of cables in addition to horizontal excursion of cables on the dynamic response of offshore Spar platform for regular wave is carried out. The structural model of offshore spar platform is same as discussed in earlier section. Nonlinear static force-excursion relationship for both horizontal and vertical excursion of cable is considered. Stiffness matrix is evaluated considering both Cases A and B. An unidirectional regular wave model is used for computing the incident wave kinematics. The kinematics of the water particles has been evaluated by Airy's linear wave theory. Modified Morison's equation has been used for the evaluation of hydrodynamic forces (which meets the applicability criteria for the regular waves considered in the study). Diffraction effects have been ignored. The equation of motion has been solved by an iterative procedure using unconditionally stable Newmark's Beta method in time domain. Parametric studies to evaluate the influence of different parameters (inclusion of vertical spring in addition to horizontal spring in the stiffness matrix, Hogben's modifications in hydrodynamic force to account for variable submergence of the structure with the passage of waves, effect of initial horizontal force in the cable at the fairlead attachment point, wave height, wave period, current velocity, hydrodynamic coefficient of inertia and hydrodynamic coefficient of drag) on the response of Spar platform have been carried out.

Random nature of sea waves has been considered for analyzing the dynamic response of offshore Spar platform. The extreme response of a structure in random ocean waves should be known for the adequate design of the offshore Spar platform. The structural model of the offshore Spar platform is same as discussed in earlier section except the evaluation of wave loading. Nonlinear static force-excursion relationship for both horizontal and vertical excursion of cable is considered. Stiffness matrix is evaluated considering both Cases A and B. The random wave loading for given wave conditions are simulated using modified Pierson-Moskowitz sea surface elevation spectrum (Pierson and Mosowitz, 1964), with the simulation technique suggested by Goda (1970). An unidirectional random wave model is used for computing the wave kinematics. The kinematics of the water particles has been evaluated by Airy's linear wave theory. Modified Morison's equation has been used for the evaluation of hydrodynamic forces. Applicability of linear wave theory and modified Morison's equation has been assumed. Diffraction effects have been ignored. The equation of motion has been solved by an iterative procedure using unconditionally stable Newmark's Beta method in time domain. Response time histories are statistically analyzed and its characteristics like maximum, minimum, mean and standard deviation are evaluated. Power Spectral Density Function (PSDF) of responses is analysed and peak frequency and mean square of the process is evaluated. The Probability Distribution Function of responses is also evaluated. Parametric studies to evaluate the influence of different parameters (inclusion of vertical spring in the stiffness matrix, Hogben's modifications in hydrodynamic force to account for variable submergence of the structure with the passage of waves, effect of initial horizontal force in the cable at the fairlead attachment point, significant wave height, zero up crossing period, current velocity, hydrodynamic coefficient of inertia and hydrodynamic coefficient of drag) on the response of Spar platform have been carried out.

Conclusions have been drawn on the basis of the investigations, and subsequent discussions of the results obtained for different parameters considered for cable analysis for horizontal and vertical excursions, for the responses under regular and random wave loads considering only horizontal excursion of cables and considering both horizontal and vertical excursion of cables. Recommendations for the scope of future work to be carried out are given at the end of the thesis.

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