Lecture Notes in Civil Engineering

Mahendrakumar Madhavan
James S. Davidson
N. Elumalai Shanmugam *Editors*

Proceedings of the Indian Structural Steel Conference 2020 (Vol. 1)

ISSC 2020

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N. Elumalai Shanmugam
Editors

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Foreword I

Civil infrastructure is universally an area requiring continued attention of the engineers and architects, be it because of creation of additions, or, the quest for improved quality. The volume of additional infrastructure needed is huge in many countries including India. Fulfilment of this demand has to be backed by an adequate supply of building materials, of which the two that are most commonly in use are either concrete or steel. Structurally, both these have their merits, whether used separately, or as steel-concrete composites. Steel offers the merits of high strength-to-weight ratio, thus reduced deadweights, superior seismic performance and economy in applications requiring longer spans or greater heights, flexibility in planning, rapid construction, easy repairability and so on. Another reason for considering use of steel as an alternative to concrete wherever possible is the ongoing difficulty in finding adequate quantities of constituents of concrete such as aggregates, river sand and water. In this respect, the substantially increased production of steel in India over the last few decades augers well for the growth of civil infrastructure in the country.

Steel is almost always the major construction material in landmark structures. There is a long list of such examples in both India and abroad. Just to cite a few, the Golden Gate Bridge in San Francisco, the Disney Concert Hall in Los Angeles, the Beijing Olympic Stadium, the Millennium Bridge in London, the Rabindra Setu and the Vidyasagar Setu in Kolkata, India, the upcoming railway arch bridge across the river Chenab in J&K, India, the tower of unity in Gujarat, India and so on. Today, innovative solutions like steel-concrete composites for flooring systems, columns, beams and shear walls are preferred by structural engineers. However, the quest for the economy has been pushing researchers to explore possibilities to obtain more reliable and optimized solutions. Extensive research is actively carried out around the globe on light gauge steel which is observed as a promising building material. In addition, the reduction of the deadweight of composite slab by using lightweight concrete has been intensively studied by the researchers at IIT Hyderabad. The strengthening of existing steel structures using reinforcements like CFRP and GFRPs is another challenging area of research that is carried out around the globe.

The Structural Steel Research Group, Department of Civil Engineering of IIT Hyderabad has organized this, the First Conference focused on structural steel and its applications. This conference envisages boosting the ideology of paradigm shift from conventional wet-based construction to dry-based construction which may offer advantages in meeting rapidly the big demands for additional housing units.

Prof. Prem Krishna
Formerly with Indian Institute of Technology Roorkee
Roorkee, India

Foreword II

Steel structures are the landmarks of modern societies. Examples include the Golden Gate Bridge in San Francisco, the Disney Concert Hall in Los Angeles, the Beijing Olympic Stadium, the Millennium Bridge or the Orbit in London, Calatrava's train stations and thousands more. Steel structures can provide a high strength-to-weight ratio, ultimate flexibility, airy spaces, rapid construction, long spans, superior seismic performance and much more providing economical as well as optimal solutions compared to concrete structures.

Unfortunately, the use of structural steel in India is very less either due to lack of knowledge in structural steel design or outdated codal provisions. Therefore, on the one hand it is necessary to invest more into R&D sector to understand the science behind the behaviour of structural steel in infrastructure applications and update the existing codal provisions. It would encourage and acknowledge the work of young researchers who are investing their lives for a noble cause of providing an affordable, sustainable and respectable shelter for every citizen of our nation through light gauge steel framing systems (LGSFs) and fulfilling the government of India's mission "Housing for all". On the other hand, it is necessary to promote special steels like cold-formed steel for mass housing projects in both rural and urban India which can be done by the establishment of a centre of excellence. It would be a wise decision to invest in emerging areas of research like structural steel which can boost up the national economy tremendously. In addition, it is essential to make the new generation of structural engineers feel comfortable in the design of steel structures by creating chair professorships at leading institutes for both knowledge creation and knowledge dissemination.

Today, innovative solutions like steel-concrete composites for flooring systems, columns, beams and shear walls are preferred by structural engineers. However, the quench for the economy has been pushing researchers to carry out a large number of experiments to obtain more reliable and optimized solutions. Extensive research is actively carried out around the globe on light gauge steel which is observed as a promising building material. In addition, the reduction of the deadweight of composite slab by using lightweight concrete has been intensively studied by the researchers at IITH.

The Structural Steel Research Group, Department of Civil Engineering of IIT Hyderabad has organized the First Conference focused on structural steel and its applications. This conference envisages to encourage the use of structural steel in infrastructure projects in India and explore the unexplored areas of research in special steels like cold-formed steel in India.

Prof. B. S. Murty
Director
Indian Institute of Technology Hyderabad
Sangareddy, India

Foreword III

Currently, India is second in terms of production of crude steel surpassing Japan and USA. The production and consumption figures for FY 20 are 103.044 MT and 94.140 MT, respectively. The capacity augmentation by Indian steel producers is planned in the same way.

However, at present, India is among a handful of countries which suffer from massive deficit in construction. The per capita consumption of steel being 75 kgs in 2019 (19 kgs only in rural sector) compared to world average of 230 kgs, 636 kgs in China and a wobbling 1039 kgs in S. Korea the potential in India looks positive. The projection of steel consumption in the FY 2031 is predicted to be 196 MT of which 73.9 MT is in building construction only. Application of steel may be explored into areas like Infrastructure, rural and urban building et al. The institutes may work in areas of "application" with thrust in developing modular concepts, standard designs, use the results of research in the application field. Use of hot rolled has been pursued for a long time. Advent of cold-formed steel is welcomed as its usage also has a potential. The research in this area and the formulation of proper code and guidebook will ease the designing part culminating to more usage of the same.

The research in the application side needs to be improved in terms of Indian perspective and context. Proper funding from stakeholders and the government needs to be channelized to the research Institutes for developing "India specific" applications with steel and help to make the country be ATMA NIRBHAR.

This conference delves with various topics aiming towards the consumption side, i.e. application of steel. Being the head of this Institute that is into the area of increasing the consumption of steel, I look forward to getting newer ideas from Indian and foreign brains so that the outcome from this conference can be converted to tangible gains for the well-being of the country.

We are proud enough to find that an esteemed Institute like Indian Institute of Technology, Hyderabad, has selected a topic which is the need of the hour and has gathered experts globally.

I wish the conference a great success. Jai Hind.

Pradip Kumar Mishra
Director General
Institute for Steel Development and Growth
Kolkata, India

Foreword IV

Steel construction is a key consideration in the design of buildings and infrastructures. Significant advances in research and development have increased the knowledge of the structural performance of steel structures. To know about the innovation and advances, we need a forum for researchers, practitioners and engineers to share and discuss their research, practical experience and innovations related to steel structures with their peers in an open, international conference forum.

International conference, ISSC 2020 (Indian structural steel Conference), organized by the Structural Steel Research Group, Department of Civil Engineering of IIT Hyderabad is the First Conference focused on structural steel and its applications are scheduled to be conducted via Air meet on 6–8 January 2022 in online mode, with the association of ASCE India Section and Springer Publications.

The aim of the conference is to provide a common platform to share and discuss novel ideas, technologies and research findings to promote interdisciplinary research and to ignite young brains. The conference provides a forum for discussion and dissemination by researchers and designers of recent advances in the analysis, behaviour, design and construction of steel structures. Research papers were contributed from all around the world, with the research ideas in the area of cold-formed steel, structural steel, steel-FRP composites, steel-concrete composites. Dedicated funding from the government and private sectors towards the development of techniques for steel-intensive infrastructure will expedite sustainable construction practices in India.

The efforts of Prof. Madhavan and his entire team at IIT, Hyderabad, to proliferate emerging construction systems including steel-intensive structural systems are laudable.

Wishing the conference grand success.

Dr. Shailesh Kr. Agrawal
Executive Director, Building Materials and Technology Promotion Council
Ministry of Housing and Urban Affairs
Government of India
New Delhi, India

Indian Structural Steel Conference

This international conference organized by the Structural Steel Research Group, Department of Civil Engineering of IIT Hyderabad is the First Conference focused on structural steel and its applications. This conference was planned to be held from 25 to 27 March 2020 in Hyderabad but due to COVID-19, it got postponed and held online from 06 to 08 January 2022. This ISSC 2020 conference is being organized with an association of ASCE India Section and Springer.

It will be of interest to steel and aluminium structure designers and manufacturers, trade associations, design engineers, steel fabricators, architects, owners and developers of steel and aluminium structures, researchers, academics and postgraduate students.

Aim and Scope of the ISSC

Steel structures are a fairly vast field covering different constructional engineering branches and various materials used in combination of steel to provide a composite system. The applications of structural steel encompass various industries including construction, automotive, aerospace and marine. However, the development of novel structural materials and technologies, together with the computational tools and design specifications, is necessary for continuous advancement in the use of structural steel in numerous areas. In addition, the role of the construction engineer is also to maintain the existing structures for the desired load and purpose, and therefore, there is also a need for new retrofitting techniques using sustainable materials.

Hence, this ISSC 2020 conference aims at providing a forum where researchers, designers and construction engineers, structural steel manufacturing engineers and consultants having explicit backgrounds but encountering similar challenges, joining together in a friendly environment, to discuss and disseminate the most recent advances in the analysis, behaviour, design and construction of structural steel.

Message from the Conference Organizing Secretary

The Structural Steel Research Group at the Indian Institute of Technology, Hyderabad, is glad to announce the inauguration of the first Indian Structural Steel Conference (ISSC) to be held at IIT Hyderabad.

As our nation celebrates the 75th Year of its Independence, many challenges lie ahead in terms of basic infrastructure and the difficulties faced by the millions of fellow citizens without proper housing for a safe livelihood. This conference aims to shed light on some of these challenges and is focused on sustainability to promote steel-intensive sustainable construction practices for a sustainable India. A galaxy of eminent keynote speakers from across the globe will present their latest research work which will create awareness among researchers, industry leaders and policymakers.

I am grateful to the IIT Hyderabad Former Director Prof. U. B. Desai and Current Director Prof. B. S. Murty for their continuous encouragement to conduct this conference. I thank all the keynote speakers for the acceptance to deliver a technical session in this conference.

Special thanks to Mr. T. V. Narendran, MD and Global CEO of Tata Steel and President of CII and Mr. P. K. Mishra, Director General, INSDAG (INSTITUTE FOR STEEL DEVELOPMENT AND GROWTH), Ministry of Steel Government of India for accepting to be the chief guest for this conference.

This conference attracted 193 papers from 12 countries. A total of 380 authors from 120 institutions (notably IISc, 11 IITs and 12 NITs) have contributed to this conference.

I would like to express my great gratitude to the reviewers for their excellent work. The editorial team also wish to appreciate the staff at the Indian Institute of Technology Hyderabad who helped to throughout to conduct the conference. Special thanks are owed to my student's team for their effort on this conference. I wish to express my sincere gratitude to all the presenting authors and participants whose contributions have made this conference possible.

Thank you.

Prof. Mahendrakumar Madhavan
Structural Steel Research Group
Department of Civil Engineering
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About the Editors

Prof. Mahendrakumar Madhavan is Professor in the Department of Civil Engineering, Indian Institute of Technology (IIT) Hyderabad, India. He has obtained Ph.D. and MBA (Finance) from the University of Alabama at Birmingham and his master's degree from the National University of Singapore. He is a Registered Professional Engineer (PE) in the State of Alabama USA. Prior to IIT Hyderabad, he worked as a Structural Engineer at Alabama Power Company, Birmingham, USA. He is an international expert in structural steel, cold-formed steel and steel-concrete composite construction and has published more than 50 peer-reviewed internationally reputed journals and holds membership in the "American Society of Civil Engineers (ASCE) Structural Engineering Institute (SEI) Technical Administrative Committee on Metals" and in "ASCE SEI Cold-Formed Steel Members Committee". He has significantly contributed to the revision of IS 801: Indian Design Code for Cold-formed Steel Members based on the original research work carried out at IIT Hyderabad to fulfil the Government of India's goal of "Housing for All" through sustainable construction. He is an editorial board member of the Journal of Structures and is an Associate Editor for the *ASCE Journal of Structural Engineering* and serves as a reviewer for more than ten international journals. He is a Fellow of the Institution of Civil Engineers (ICE), London, and is also the first Indian to be elected as a Fellow of ASCE's Structural Engineering Institute (SEI).

Prof. James S. Davidson is currently the Gottlieb Professor of Structural Engineering in the Department of Civil and Environmental Engineering, Auburn University, USA. He is an expert in mechanics of materials, advanced stress analysis, finite element methods, and stability of structures. He has mentored more than 50 research students including MS and Ph.D., has served as associate editor, review director, and editorial board member on five technical journals and has served as a reviewer for more than 25 different technical journals.

Prof. N. Elumalai Shanmugam has taught for more than 20 years at the National University of Singapore. Prior to this he taught in College of Engineering, Guindy, Delhi University, University of Wales (Cardiff) and Polytechnic of Wales. After

50 years of teaching at graduate and undergraduate levels, he retired recently from National University of Malaysia where he taught for nine years. His research interest includes steel-plated structures, steel-concrete composite construction, long-span structures and connections, cold-formed steel structures, etc. He has published more than 200 research papers in international refereed journals conference proceedings and contributed chapters in *Civil Engineering Handbook*, *Structural Engineering Handbook* and *Bridge Manual*. He is a member of the editorial board of a number of international journals.

Coupled Dynamic Analysis of Deepwater Semi-submersible with Spread Mooring System

S. Chandrasekaran and Syed Azeem Uddin

Abstract Exploration and production in deepwaters are dominated by compliant offshore structural systems due to the advantages that arise from their geometry and construction practices. Semi-submersibles are a class of floating offshore structures, which are widely preferred for deep and ultra-deepwater applications due to their better stability characteristics and lesser sensitivity to the harsh ocean environment. A semi-submersible is positioned-restrained using the spread mooring system with either a steel catenary geometry or taut-mooring. The present study highlights dynamic response analysis of a semi-submersible with the spread mooring system, and its fatigue life under cyclic environmental loads is estimated. Lateral loads that arise from waves, wind, and current cause dynamic tension variations in the moorings, influencing their fatigue life significantly, and it is observed that fatigue life of catenary mooring lines is higher than that of taut mooring lines. Lateral loads under different directions are considered to exhibit the influence of wave directionality on the semi-submersible response. The nonlinear coupled dynamic analysis between the semi-submersible and spread mooring system is carried out using commercially available tool ANSYS AQWA, and fatigue life of the mooring system is evaluated based on the S–N curve approach.

Keywords Coupled analysis · S–N curve · Fatigue · Time domain · Semi-submersible and spread mooring

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1 Introduction

Rapidly depleting oil reserves and proliferate market demand for oil and gas production has shifted from deepwaters to ultra-deepwaters using floating offshore platforms (also known as floaters) like semi-submersibles, Drillships, FPSOs, etc., which are unique based on their geometric form, i.e. they are form dominated designed. However, as we move towards ultra-deepwaters the choice of platform varies depending upon the applications. The development and design of semi-submersible hulls can be traced back to the early 1960s when there was a rapid need to increase the stability of deepwater floating platforms. Bruce Collipp is known as the father of semi-submersible, who first coined the term semi-submersible in 1960. His early design and development of this structure were inspired by the stability, obtained by partially submerging the floating structure to avoid capsizing in rough sea conditions. The configuration of semi-submersible platforms has evolved since the 1960s owing to their good stability even in deepwaters since they have a small water-plane area which makes them less sensitive even under harsh environmental loadings. Due to the few advantages, semi-submersible platforms have best opted as the floating production platform until today.

In the recent past, many scholars studied various models of semi-submersible, design of the mooring system, etc., for reducing the response of the platform. Webster [1] conducted a parametric study on the damping induced by moorings and reveals that for high pretension in mooring lines, damping induced by the mooring lines is inversely proportional to the drag coefficient. Yilmaz and Incecik [2] developed a time-domain model for predicting the dynamic response of moored semi-submersible with thrusters and mooring lines for evaluating platform response and mooring forces. Based on the results obtained, they concluded that for extreme weather conditions maximum surge or sway response occurs based on their mean values. Senra et al. [3] suggested that there is great need of fully integrated design methodology, considering the coupling between structural behaviour of the vessel with mooring lines and risers. Chen et al. [4] studied coupled motion responses of semi-submersible with taut mooring system and found that more the number of mooring lines better will be the performance, mooring arrangement angle has a significant effect on the platform motion and response of dynamic tension of mooring line. Zhai et al. [5] numerically simulated the dynamic behaviour of deepwater semi-submersible and found that heave period as 22 s, while wave period was 8–16 s. By avoiding the maximum response in heave degrees-of-freedom, the peak coefficient has a significant effect on the response of the platform. Ng et al. [6] conducted experimental studies on semi-submersible model for various bi-directional wave crossing angles, to estimate the optimum wave crossing angle at which the response of the semi-submersible is maximum. They found that response of the model is affected by the wave crossing angles and the optimum wave crossing angles 40° and 55° are found to produce maximum heave, surge and pitch responses at low-frequency range.

Zhu and Ou [7], studied the motion performance of semi-submersible with mooring under combined wind and wave loads by numerically and experimentally. He found maximum surge motion of the platform is about 2% of water depth, which is one of the important criteria for drilling operation to run smoothly; otherwise, the riser connected for drilling operation will be subjected to dynamic loads and may even fail due to large surge response of the platform. Qiao and Ou [8] conducted model tests of a semi-submersible and validated with numerical results of semi-submersible with different mooring systems under various water depths and concluded that dynamic forces on mooring lines increases with increase in length of the mooring lines, and low-frequency (LF) motion dominates the surge, sway motion whereas, wave frequency (WF) motion dominates heave motion while pitch motion is due to both LF and WF motions. Wu et al. [9] have conducted analytical studies on the fatigue life of mooring lines and found various factors such as mooring pattern, length of mooring lines, pretension, mass concentration components, damping coefficients, and water depth, etc., are affecting the fatigue damage of mooring lines. They have also found critical locations where fatigue damage can occur such as at fairlead point for catenary mooring and top of the lower chain for taut mooring.

Yang et al. [10] investigated for mooring damping effects due to superimposition of low-frequency motion with wave frequency and concluded that response amplitude operators (RAO's) and pretension of mooring plays a dominant role in damping of the mooring system. Du et al. [11] conducted a dynamic analysis of semi-submersible and estimated the fatigue damage of the mooring lines and concluded that platforms in deepwaters have less stiffness, high damping ratio for which the WF components increases and LF components decreases with increase in water depth due to higher damping. Hence, there is a decrease in LF fatigue damage with an increase in wave periods. Xu et al. [12], conducted model tests and numerical simulations for dynamics of semi-submersible, mooring damping and found that taut mooring with buoy causes stable semi-submersible motion with great mooring damping. The present study is conducted for estimating the motion responses of the semi-submersible under spread catenary (case 1) & taut mooring (case 2) system and evaluating the fatigue life of the spread mooring system.

2 Description of Semi-submersible Platform

The platform geometry selected for present work is based on the configuration of the Hai Yang Shi You–981 which is a sixth generation deepwater semi-submersible platform which was deployed in the disputed waters of the South China Sea and Vietnam. The semi-submersible platform consists of the deck (superstructure) with drilling derrick, accommodation and production facilities, a helipad, accessories, four-column members, and two horizontal pontoons members connected with horizontal cylindrical members (braces). The numerical model of the semi-submersible is shown in Fig. 1, and detailed description is shown in Table 1.

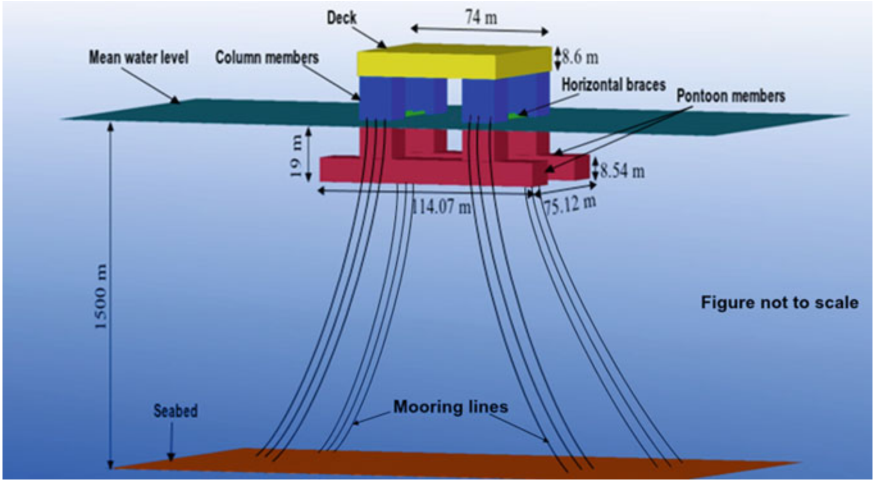

Fig. 1 Numerical model of semi-submersible

Table 1 Detailed description of semi-submersible

Description	Value	Units
Deck	74.42 × 74.42 × 8.6	m
Columns (4 in no's)	17.385 × 17.385 × 21.46	m
Pontoons (2 in no's)	114.07 × 20.12 × 8.54	m
Displacement	48,206,800	kg
Water depth	1500	m
Draft	− 19	m
The diameter of the brace	1.8	m
Centre of gravity below water level	− 5.8	m
The radius of gyration for roll (R_x)	32.4	m
The radius of gyration for pitch (R_y)	32.1	m
The radius of gyration for yaw (R_z)	34.4	m

2.1 Spread Mooring System

During the drilling operation, the platform should not displace too much from its home position; otherwise, connected riser will be damaged. The platform is position-restrained with either of the dynamic positioning system and spread mooring system to avoid large displacements. In present work, a twelve-point symmetric mooring system is used which is made up of studless chain, and the layout of mooring system

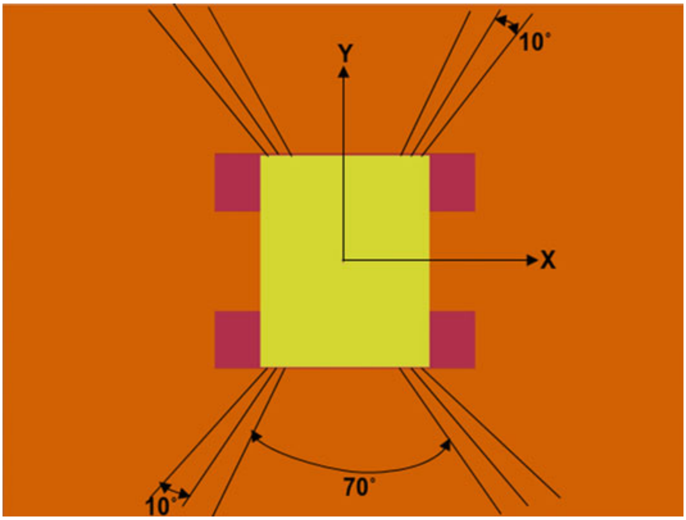

Fig. 2 Layout of the spread mooring system

Table 2 Configuration of the spread mooring system

Mooring type	Length of mooring system (m)			Pretension (kN)
	Upper chain	Middle wire	Bottom chain	
Catenary mooring	500	2000	1500	3500
Taut mooring	900	1000	200	2850

is shown in Fig. 2. The angle between each cable of the bundle is 10°, and the angle between each bundle is 70°.

Each mooring line is a combination of upper section as chain, middle section as wire, and the lower section as chain, and the configuration and properties of spread mooring system used are shown in Tables 2 and 3.

2.2 Environmental Conditions

The environmental conditions to which the semi-submersible is subjected to the present work is considered for 1 year and 100 year return period for the South China Sea. The wave, wind, and current loadings are considered in present work and are along the 0° (following sea condition), 45° (quarter sea condition), and 90° (beam sea condition). Because, a minimum of the bow, beam, quarter, down-line, and between-line environmental conditions should be analysed [13]. The wind spectrum used for the present study is the API spectrum, and the JONSWAP spectrum is used for irregular waves. The current loading (i.e. varying nonlinearly with respect to water

Table 3 Properties of mooring lines

Description	Upper chain (studless K-4 chain)	Middle wire (spiral strand)	Bottom chain (studless K-4 chain)
Mass per unit length (kg/m)	163.86	36.41	163.86
Equivalent cross-section (m^2)	0.014	0.014	0.014
Stiffness (kN)	676,810	833,910	676,810
Equivalent diameter (m)	0.095	0.095	0.095
Longitudinal drag coefficient	0.025	0.025	0.025

Table 4 Environmental loads

Description	The return period of the event		Units
	1 year	100 year	
Wind speed, V_{wind}	23.15	55	m/s
Wave height, H_s	6	13.3	m
Peak period, T_p	11.2	15.5	s
Current speed, V_{current}	0.93	1.97	m/s

depth) is applied to the platform and is user-defined up to a depth of 150 m (i.e. 10% of water depth) below the mean water level. Environmental conditions for which the semi-submersible are subjected are shown in Table 4.

2.3 Governing Equations

2.3.1 Wind Force Calculation

Ansys AQWA calculates the effect of fluctuation of wind about the mean speed on the dynamic load on the structure, and these dynamic loads generate low-frequency motions on floating offshore structures. In the present study, API wind spectrum is used, and Ansys AQWA calculates the wind fluctuation effect about the mean speed on dynamic loads acting on the semi-submersible, and these loads causes low-frequency (LF) motions on the semi-submersible. The API wind spectrum [14] used is represented by the expression given below:

$$S\left(\tilde{f}\right) = \frac{\tilde{f}}{\left(1 + 1.5\tilde{f}\right)^{5/3}} \tag{1}$$