

**ANALYSIS OF OFFSHORE GEOTHERMAL
PILE FOR
WIND TURBINES**

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**DEPARTMENT OF CIVIL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
SEPTEMBER 2018**

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ANALYSIS OF OFFSHORE GEOTHERMAL PILE FOR WIND TURBINES

by

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DEPARTMENT OF CIVIL ENGINEERING

Submitted

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

to the



**DEPARTMENT OF CIVIL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
SEPTEMBER 2018**



**IMAGINATION IS MORE IMPORTANT
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CERTIFICATE

This is to certify that the thesis entitled, “**ANALYSIS OF GEOTHERMAL MONOPILE FOR OFFSHORE WIND TURBINES**” which is being submitted by **Ms. Arundhuti Banerjee (2012CEZ8524)** to the Indian Institute of Technology (IIT) Delhi for the award of the degree of **DOCTOR OF PHILOSOPHY** is a record of the student’s bonafide research work carried out by her. She worked under our supervision for the submission of thesis, which to our knowledge has reached the requisite standard as demonstrated by excellent international publications in journals and conferences.

Further, the contents of her research work, in full or in parts, have not been submitted to any other institute or university for the award of any degree or diploma to the best of our knowledge and belief.

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ACKNOWLEDGEMENT

This thesis represents not only my work at the keyboard, it is a milestone in more than half a decade of work at Indian Institute of Technology (IIT) and specifically in the Geodyn Laboratory. My experience at IIT has been nothing short of amazing. Since my first day, on January 1st 2013, I have felt at home in IIT. I have availed unique opportunities like presenting my research work in National Aeronautics and Space Administration (NASA), Ames Center and University of California (UC) Berkeley during my stay in IIT. This thesis is the result of many experiences I have encountered at IIT from dozens of remarkable individuals who I also wish to acknowledge.

First and foremost I wish to thank my advisors, **Dr. Tanusree Chakraborty and Dr. Vasant A. Matsagar** for their constant guidance, support and inspiration. I gratefully acknowledge their crucial contributions towards the completions of this research work. I am particularly grateful to Dr. Tanusree Chakraborty for her important observations and exceptionally thoughtful approach that actually shaped my doctoral research. She has always showed confidence on my ability, and encouraged me to deliver the best. Whenever I found myself stuck in the research, her immense patience to understand the problem and helpful technical discussion have always paved the way for progress. She has ensured that I have had all possible opportunities that will provide a firm establishment for my career. I am grateful to Dr Vasant Matsagar for generously sharing his time and knowledge in our cooperative work on building a strong foundation for my research. He has played a major role in making me understand the concept of the proposed system and simplifying the complexities involved in the problem.

I specially thank **Prof. T. K. Datta** for sharing his excellent expertise in the domain of offshore structures. I would like to express my sincere thanks to him for generously sharing his

time and knowledge. He has played a major role in making me understand the concept of offshore structures.

A very special gratitude to Prof. Samit Ray Chaudhuri and Prof Martin Achmus for providing such valuable insights and comments for improving the quality of my thesis.

I extend my deepest gratitude to my research committee members, **Prof. M. Khare, Dr. B. Manna** and **Dr. Pradyumna** for their precious advices that have helped to make my objectives more focused.

I would like to express sincere appreciation to the **Department of Civil Engineering**, IIT Delhi for providing excellent academic environment and computation facilities.

This is the right occasion to thank all the persons attached to the **Geodyn Laboratory and Multi-Hazard Protective Structures (MHPS) Laboratory**, for maintaining such a nice research environment. I would like to specially thank Ms. Rajni Saggu, Mr. Pravin Jagtap, Ms. Sunita Mishra, Ms. Harshda Sharma, Ms. Debashree Roy, Ms. Kavita Ganorkar and Mr. Tathagata Roy and Mr. Niranjana Muley for their contribution in making my stay at IIT Delhi fruitful.

I would like to specially thank my friends, specially Mr. Ketan Arora and Ms. Divya Gautam for their constant support and love. Without their presence in my life, this journey would have been impossible.

Last, but not least, I would like to dedicate this thesis to my **family**. I am forever indebted to my parents, my sister, my husband, in-laws, whose blessing and affection have always encouraged me to reach for the stars. Whatever I have achieved in my life till now was not possible without constant support from my parents. Finally my lifecoach, my husband Mr. Deep Banerjee who have provided me thorough moral and emotional support all along the way.

Date:

(Arundhuti Banerjee)

ABSTRACT

Today geothermal energy is utilized on land worldwide and the geothermal resources have a potential of being one of the greatest sustainable energy choices there is. However, offshore geothermal energy has not been considered a feasible option so far, but with increasing energy prices and increasing knowledge of the utilization of this resource the choice becomes more attractive.

The concept of an offshore wind turbine capable of generating electricity and simultaneously extracting geothermal energy has been investigated. Hence, the prime focus of the present study is to explore the possibility of using an offshore monopile wind turbine structure, combined with an active heat exchanger system for extracting geothermal power from the oceanic crust. In the thesis, we have first considered dynamic analysis of the offshore wind turbine structure modeled as multi-degree of freedom system and analysed it for offshore wind and wave loading considering soil structure interaction. In the later half of the thesis, three dimensional finite element modeling of offshore monopile foundation with heat exchanger pipes have been modeled and consequently, the geotechnical aspect of the analysis which involves thermo-hydro-mechanical analysis has been performed. The last chapter considers coupling of the tower with the monopile foundation and thereby considering the whole structure for the thermo-mechanical analysis.

First, a single degree of freedom (SDOF) system, multi-degree of freedom (MDOF) system and a three-dimensional(3D) continuum model and has been analysed for offshore random wind and wave loading using Pierson Moskowitz and Kaimal spectrum, respectively. The main contribution to knowledge from this study is to evaluate the dynamic response of an offshore wind turbine structure using reduced order model SDOF and MDOF system for offshore loading. In order to investigate the effect of soil structure interaction on the dynamic response of the offshore wind turbine structure modelled as a MDOF system, an equivalent spring-

dashpot model for embedded foundations is considered herein. The rotational effect of the blades is taken into account considering shape filters using von Karman spectrum. A spectral analysis of the MDOF model has also been studied in detail using frequency dependent Cone model approach for soil structure interaction. It has been observed that incorporating blade-tower coupling with soil structure interaction significantly amplifies the response of the structure specifically for wave induced loading.

Next, a three dimensional thermo-hydro-mechanical (THM) model of an offshore monopile foundation with fluid carrying pipes embedded on a saturated clay soil from the North Sea has been developed using finite element software ANSYS (2010). A series of heat transfer, coupled field pore pressure and structural analyses are performed in the THM model to (i) understand the complex heat transfer process of convection through the fluid pipes and conduction between the pipe-soil-monopile system, (ii) investigate the effect of thermal loading-unloading on the steel monopile, the temperature distribution in the monopile and the clayey soil, resultant pore pressure development in the soil, the axial stress and strain in the pile and the shear stresses in soil, and (iii) understand the combined effect of offshore and thermal loading on the response of the monopile in terms of axial and radial stresses, strains, and shear stresses developed in the soil around the foundation. The effect of soil parameters as well as duration of the thermal loading has also been considered in the study. Higher amount of axial stresses and strains are generated in the monopile with increase in soil shear modulus, higher thermal expansion coefficient of soil and increasing duration of thermal loading. It has been observed that thermal expansion coefficient of surrounding soil, excess pore pressure and the ambient temperature of the soil play dominant roles in the thermal behaviour of geothermal pile systems.

It is also observed through a power output calculation that a maximum yield of 242 kilowatt (kW) could be extracted out of the proposed system employing thermoelectric generators for power conversion. It has been further evaluated through a careful study that the costs associated

with constructing and setting up the proposed offshore wind turbine-geothermal system would be in the range of 51-135 US Million dollars as of 2017.

सार

आज भू-तापीय ऊर्जा का उपयोग दुनिया भर में भूमि पर किया जाता है और भू-तापीय संसाधनों में सबसे बड़ी टिकाऊ ऊर्जा विकल्पों में से एक होने की संभावना है। हालांकि, अपतटीय भू-तापीय ऊर्जा को अब तक एक व्यवहार्य विकल्प नहीं माना गया है, लेकिन ऊर्जा की बढ़ती कीमतों और इस संसाधन के उपयोग के ज्ञान को बढ़ाने के साथ पसंद अधिक आकर्षक हो जाता है।

बिजली उत्पन्न करने और साथ ही भू-तापीय ऊर्जा निकालने में सक्षम एक अपतटीय पवन टरबाइन की अवधारणा की जांच की गई है। इसलिए, वर्तमान अध्ययन का मुख्य फोकस समुद्र तट की परत से भू-तापीय शक्ति निकालने के लिए एक सक्रिय ताप विनिमायक प्रणाली के साथ संयुक्त अपतटीय मोनोफाइल पवन टरबाइन संरचना का उपयोग करने की संभावना का पता लगाने के लिए है। थीसिस में, हमने पहले अपतटीय पवन टरबाइन संरचना के गतिशील विश्लेषण को बहु-स्वतंत्रता प्रणाली के रूप में मॉडलिंग किया है और इसे मिट्टी संरचना परस्पर क्रिया पर विचार करते हुए अपतटीय हवा और तरंग लोडिंग के लिए इसका विश्लेषण किया है। थीसिस के बाद के आधे भाग में, हीट एक्सचेंजर पाइप के साथ ऑफशोर मोनोफाइल नींव के तीन आयामी परिमित तत्व मॉडलिंग का मॉडल किया गया है और इसके परिणामस्वरूप, विश्लेषण के भू-स्थानिक पहलू में थर्मो-हाइड्रो-मैकेनिकल विश्लेषण शामिल किया गया है। अंतिम अध्याय मोनोफाइल नींव के साथ टावर के युग्मन को मानता है और इस प्रकार थर्मो-मैकेनिकल विश्लेषण के लिए पूरी संरचना पर विचार करता है।

सबसे पहले, स्वतंत्रता की एक डिग्री (एसडीओफ़) प्रणाली, बहु-आजादी की स्वतंत्रता (एम.डी.ओ.एफ) प्रणाली और एक त्रि-आयामी (३ डी) निरंतर मॉडल और क्रमशः पीरसन मोस्कोविट्ज़ और कैमल स्पेक्ट्रम का उपयोग करके ऑफशोर यादृच्छिक हवा और तरंग लोडिंग के लिए विश्लेषण किया गया है। । इस अध्ययन से ज्ञान में मुख्य योगदान ऑफशोर लोडिंग के लिए कम ऑर्डर मॉडल एसडीओफ़ और एमडीओफ़ सिस्टम का उपयोग

करके ऑफशोर पवन टरबाइन संरचना की गतिशील प्रतिक्रिया का मूल्यांकन करना है। एमडीओएफ सिस्टम के रूप में मॉडलिंग किए गए अपतटीय पवन टरबाइन संरचना की गतिशील प्रतिक्रिया पर मिट्टी संरचना परस्पर क्रिया के प्रभाव की जांच करने के लिए, एम्बेडेड नींव के लिए समकक्ष वसंत-डैशपॉट मॉडल यहां माना जाता है। ब्लेड के घूर्णन प्रभाव को वॉन कर्मण स्पेक्ट्रम का उपयोग करके आकृति फिल्टर पर विचार करने के लिए ध्यान में रखा जाता है। एमडीओएफ मॉडल का एक वर्णक्रमीय विश्लेषण भी मिट्टी संरचना बातचीत के लिए आवृत्ति निर्भर शंकु मॉडल दृष्टिकोण का उपयोग करके विस्तार से अध्ययन किया गया है। यह देखा गया है कि मिट्टी संरचना बातचीत के साथ ब्लेड-टावर युग्मन को शामिल करने से विशेष रूप से लहर प्रेरित लोडिंग के लिए संरचना की प्रतिक्रिया में काफी वृद्धि होती है।

इसके बाद, उत्तरी सागर से संतृप्त मिट्टी की मिट्टी पर एम्बेडेड तरल पदार्थ वाली पाइप के साथ एक अपतटीय मोनोपाइल नींव का एक तीन आयामी थर्मो-हाइड्रो-मैकेनिकल (टी. एच. एम) मॉडल परिमित तत्व सॉफ्टवेयर एनसीस (२०१०) का उपयोग करके विकसित किया गया है। गर्मी हस्तांतरण की एक श्रृंखला, युग्मित क्षेत्र के दबाव और संरचनात्मक विश्लेषण टी. एच. एम मॉडल में किए जाते हैं (i) तरल पाइप के माध्यम से संवहन की जटिल ताप हस्तांतरण प्रक्रिया और पाइप-मिट्टी-मोनोपाइल प्रणाली के बीच चालन को समझते हैं, (ii) जांच स्टील मोनोपाइल पर थर्मल लोडिंग-अनलोडिंग का प्रभाव, मोनोपाइल में तापमान वितरण और मिट्टी की मिट्टी, मिट्टी में परिणामी पोयर दबाव विकास, धुरी में अक्षीय तनाव और तनाव और मिट्टी में कतरनी तनाव, और (iii) नींव के आसपास मिट्टी में विकसित अक्षीय और रेडियल तनाव, उपभेदों और कतरनी तनाव के मामले में मोनोपाइल की प्रतिक्रिया पर अपतटीय और थर्मल लोडिंग के संयुक्त प्रभाव को समझें। अध्ययन में मिट्टी के मानकों के साथ-साथ थर्मल लोडिंग की अवधि पर भी विचार किया गया है। मिट्टी के कतरनी मॉड्यूलस में वृद्धि, मिट्टी के उच्च तापीय विस्तार गुणांक और थर्मल लोडिंग की अवधि में वृद्धि के साथ मोनोपाइल में अक्षीय तनाव

और उपभेदों की उच्च मात्रा उत्पन्न होती है। यह देखा गया है कि आसपास के मिट्टी के थर्मल विस्तार गुणांक, अतिरिक्त पोयर दबाव और मिट्टी के परिवेश तापमान भू-तापीय ढेर प्रणालियों के थर्मल व्यवहार में प्रमुख भूमिका निभाते हैं।

यह बिजली उत्पादन गणना के माध्यम से भी देखा जाता है कि विद्युत रूपांतरण के लिए थर्मोइलेक्ट्रिक जनरेटर को नियोजित प्रस्तावित प्रणाली से २४२ किलोवाट (किलोवाट) की अधिकतम उपज निकाली जा सकती है। सावधानीपूर्वक अध्ययन के माध्यम से इसका मूल्यांकन किया गया है कि प्रस्तावित अपतटीय पवन टरबाइन-भू-तापीय प्रणाली के निर्माण और स्थापना के साथ जुड़े लागत २०१७ के अनुसार ३१-१३५ यूएस मिलियन डॉलर की सीमा में होंगे

TABLE OF CONTENTS

CHAPTER	TITLE	PAGE NO.
	Abstract (English)	iv
	Abstract (Hindi)	vii
	Table of Contents	x
	List of Tables	xiv
	List of Figures	xv
	Nomenclature	xxvi
Chapter 1	Introduction	1
1.1	General	1
1.2	Geothermal Heat Exchanger (GHE) Systems	2
1.3	Offshore Wind Turbines	6
1.3.1.	<i>Offshore Wind Turbine Tower</i>	6
1.3.2.	<i>Soil Structure Interaction</i>	7
1.3.3.	<i>Blade Rotation</i>	9
1.4	Need and Relevance of the Present Study	10
1.5	Objectives of the Present Study	10
1.6	Organization of Thesis	12
Chapter 2	Dynamic Analysis of an Offshore Wind Turbine using SDOF, MDOF and 3D Models	16
2.1	General	16
2.2	Structural Modeling	17
2.2.1.	<i>MDOF and SDOF Systems</i>	16
2.2.2.	<i>Continuum System (3D)</i>	20
2.3	Finite Element Formulation	22
2.3.1.	<i>Governing Equation</i>	22
2.4	Loads Acting on an Offshore Wind Turbine (OWT)	24
2.4.1.	<i>Wave Load</i>	24
2.4.2.	<i>Along-Wind Load</i>	25
2.4.3.	<i>Artificial Time History Conversion</i>	29
2.5	Solution Scheme	29
2.5.1.	<i>Transient Dynamic Analysis</i>	29
2.6	Numerical Study	30
2.6.1.	<i>Wind and Wave Excitations</i>	31
2.6.2.	<i>Load Cases</i>	31
2.7	Results and Discussion	32
2.7.1.	<i>Modal Analysis</i>	32
2.7.2.	<i>Wind-induced Loading</i>	33
2.7.3.	<i>Wave-induced Loading</i>	35
2.7.4.	<i>Combined Wind and Wave Loading</i>	36

CHAPTER	TITLE	PAGE NO.
2.8	Closure	38
Chapter 3	Dynamic Analysis of an Offshore Wind Turbine using SDOF, MDOF and 3D Models	57
3.1	General	57
3.2	Soil Structure Interaction	61
3.3	Rotationally Sampled Wind Spectrum	63
3.4	Numerical Model	67
3.5	Numerical Study	68
3.6	Results and Discussion	70
	3.6.1. <i>Validation</i>	70
	3.6.2. <i>Wind Loading with and without SSI Effect</i>	70
	3.6.3. <i>Wave Loading with and without SSI Effect</i>	73
	3.6.4. <i>Combined Wind and Wave Loading with and without SSI Effect</i>	74
	3.6.5. <i>Blade-Tower Coupling Effect</i>	75
3.7	Closure	78
Chapter 4	Stochastic Dynamic Analysis of an Offshore Wind Turbine Considering Frequency Dependent Soil-Structure Interaction Parameters	98
4.1	General	98
4.2	Double Cone Model	102
4.3	Numerical Model	104
4.4	Numerical Study	105
4.5	Results and Discussion	106
	4.5.1. <i>Validation</i>	106
	4.5.2. <i>Wind-Induced Response</i>	107
	4.5.3. <i>Wave Induced Response</i>	110
	4.5.4. <i>Combined Wind and Wave Response</i>	111
4.6	Closure	112
Chapter 5	Evaluation of Possibilities in Geothermal Energy Extraction from Oceanic Crust Using Offshore Wind Turbine Monopiles	123
5.1	General	123
5.2	Heat to Electricity: Seebeck Effect	126
5.3	Proposed Monopile-Geothermal System	127
5.4	Model Development	128
	5.4.1. <i>Background: Heat Transfer</i>	128
	5.4.2. <i>Numerical Model</i>	130
	5.4.3. <i>Boundary Conditions</i>	131

CHAPTER	TITLE	PAGE NO.
5.5	Results and Discussion	132
5.5.1.	<i>Validation</i>	132
5.5.2.	<i>Inlet Temperature</i>	133
5.5.3.	<i>Mass Flow Rate</i>	137
5.5.4.	<i>Thermal Conductivity</i>	138
5.6	Performance of Offshore Geothermal System	139
5.6.1.	Thermoelectric Power Generation	139
5.6.2.	<i>Offshore Wind Power</i>	142
5.6.3.	<i>Cost Analysis</i>	143
5.7	Closure	145
Chapter 6	Thermo-Hydro-Mechanical Analysis of an Offshore Monopile Foundation used for Geothermal Energy Extraction and Storage	163
6.1	General	163
6.2	Pile Heat Exchangers: Thermal Behavior and Interactions	167
6.3	Thermo-Hydro- Mechanical (THM) Model	169
6.4	Numerical Model	171
6.4.1.	<i>Geological, Geotechnical, and Thermal Description of the Soil</i>	171
6.4.2.	Constitutive Model of Soil: Modified Drucker-Prager Cap Model	173
6.4.3.	<i>Finite Element Model</i>	174
6.4.4.	<i>Boundary Conditions</i>	176
6.5	Monopile Analysis Methodology	177
6.6	Load Cases	179
6.7	Results and Discussion	180
6.7.1.	<i>Validation</i>	180
6.7.2.	<i>Thermo-Mechanical Analysis</i>	181
6.7.3.	<i>Study of Pore Pressure</i>	183
6.7.4.	<i>Study of Pile Response: Axial Stress</i>	184
6.7.5.	<i>Study of Pile Response: Axial Strain</i>	187
6.7.6.	<i>Shear Resistance: Pile-Soil Interface</i>	189
6.8	Closure	191
Chapter 7	Dynamic Analysis of an Offshore Monopile Foundation used as Heat Exchanger for Energy Extraction	206
7.1	General	206
7.2	Pile Heat Exchangers: Thermo-Mechanical Behavior	208
7.2.1.	<i>Effect of Mechanical Load Only</i>	209
7.2.2.	<i>Combined Thermo-Mechanical Loading</i>	209

CHAPTER	TITLE	PAGE NO.
7.3	Offshore Loading	209
7.4	Numerical Modeling	210
	7.4.1. <i>Thermal Description of the Soil</i>	210
	7.4.2. <i>Finite Element Model</i>	212
7.5	Offshore-Wind-Wave-Thermal Load Analysis Methodology	213
7.6	Results and Discussion	215
	7.6.1. <i>Validation</i>	215
	7.6.2. <i>Thermal Analysis</i>	216
	7.6.3. <i>Study of Pore Pressure</i>	217
	7.6.4. <i>Study of Pile Response: Axial Stress</i>	220
	7.6.5. <i>Study of Pile Response: Axial Strain</i>	223
	7.6.6. <i>Study of Pile Response: Radial Stress</i>	224
	7.6.7. <i>Study of Pile Response: Radial Strain</i>	225
	7.6.8. <i>Study of Pile Response: von Mises Stress</i>	226
	7.6.9. <i>Study of Soil Response: Shear Stress</i>	227
7.7	Closure	229
Chapter 8	Summary and Conclusion	262
8.1	<i>Summary</i>	262
8.2	<i>Conclusions</i>	262
8.3	<i>Future Scope of Work</i>	269
Appendix-1	Parameters	270
Appendix-2	Manuscript	270
A2.1	General	271
A2.2	Power of the ocean: solution for energy	272
A2.3	Potential Heat Tap Zones	273
A2.4	Proposed Coupled Offshore-Geothermal System	275
A2.5	Power-Output	276
A2.6	Cost Analysis	277
A2.7	Heat Transfer Study	278
A2.8	Discussion and Conclusion	280
	References	287
	List of Publications	319
	Curriculum Vitae	322

LIST OF TABLES

TABLE	CAPTION	PAGE NO.
2.1	Summary of loads applied at the respective nodes	39
2.2	Summary of displacement and acceleration response	40
3.1	Summary of results	79
4.1	Structure and soil properties	114
4.2	First 5 frequencies of structure with and without soil-structure interaction	114
4.3	Summary of result	115
5.1	Thermal properties of materials	146
5.2	Mechanical properties used in analyses	146
6.1	Thermal properties of materials	193
7.1	Thermal properties	230
7.2	Summary of load cases considered in the analyses	231
7.3	Summary of results for thermal and combined loading	232
7.4	Summary of results for offshore loading	233

LIST OF FIGURES

FIGURE	CAPTION	PAGE NO.
1.1	Global emissions from fossil fuel and industry, rise in population, growth rate of GDP year wise, and (b) global energy consumption of fossil and non-fossil fuel resources [IEA (2017), UN (2017)]	14
2.1	(a) Offshore structural model, and (b) lumped mass model representation	41
2.2	(a) Equivalent SDOF system, (b) MDOF system, and (c) 3D system modeled using finite element method	42
2.3	Mode shapes of the MDOF system in ANSYS 14	42
2.4	(a) Mass per unit length distribution of structural mass, m and added mass m_w , (b) equivalent mass calculation	43
2.5	Equivalent SDOF conversion for (1) wind loading (case 1), and wave loading (case 2)	43
2.6	3D model of offshore wind turbine tower using SHELL 181 and MASS 21 elements in ANSYS.14	44
2.7	Demonstration of load distribution around the circumference	44
2.8	Structural idealization of wind turbine (a) finite element representation (b) real model and, (c) analytical model using lumped mass approach	45
2.9	Wind force spectrum at node 7, node 6, and node 5 with and without correlation	45
2.10	(a) Wave elevation spectrum and wave force spectrum for submerged nodes in MDOF system	46
2.11	Flow chart of the analysis	47
2.12	Load time history (a) wind at node 7, and (b) wave at node 4	48
2.13	(a) Side to side (SS), and (b) fore-aft (FA) bending mode of an OWT	48

FIGURE	CAPTION	PAGE NO.
2.16	Fast Fourier transform of displacement and acceleration time history for wind load (Case 1) at node 7	51
2.17	Base moment and base shear for wind loading (Case 1)	51
2.18	Fast Fourier transform of base moment and base shear for wind loading (Case 1)	52
2.19	Displacement and acceleration time history for wave load (Case 2) at node 7, node 6, and node 4	53
2.20	Fast Fourier transform of displacement and acceleration time history for wave load (Case 2) at node 4	54
2.21	Bending moment and base shear at ground level for wave loading (Case 2)	54
2.22	Fast Fourier transform of base moment and base shear for wave loading (Case 2)	54
2.23	Displacement and acceleration time history for combined wind and wave loading at node 7, node 6, and node 4	55
2.24	Bending moment and base shear at ground level for combined wind and wave loading	56
2.25	Frequency spectrum of the dynamic loads and the rotor and blade passing frequency of 5MW wind turbine with an operational interval of 6.9 to 12.1 rpm	56
3.1	Physical representation of soil structure interaction model using springs and dashpots	80
3.2	(a) In plane (side to side) and, (b) out of plane (fore-aft) bending mode of an offshore wind turbine system	81
3.3	(a) Wave induced loading, and (b) Fast Fourier Transform (FFT) of wave force	82

FIGURE	CAPTION	PAGE NO.
3.4	(a) Variation of normalized autocorrelation function K_v with rotational speed of shaft ψ , (b) with variation in blade length, r for a particular rotational speed shaft value of 1.57 rad/sec, and (c) fixed point spectrum $S_u(f)$ and the rotationally sampled spectrum $S_u(r, f)$ for different length of blades	83
3.5	(a) Drag force with and without considering blade rotation, (b) Fast Fourier Transform (FFT) of fixed as well as rotationally sampled time history	84
3.6	FFT of rotationally sampled and fixed point time history of wind drag force at different rotating shaft values	85
3.7	Frequency spectrum of the dynamic loads and the rotor and blade passing frequency of 5 MW wind turbine with an operational interval of 6.9 to 12.1 rpm	85
3.8	Mode shapes of MDOF system with and without considering SSI for different soil types	86
3.9	Comparison of nodal displacement at top node (node 7) due to (a) wind loading, and (b) combined wind-wave loading	87
3.10	Time history of (a) displacement, (b) acceleration, (c) rotation at tower top at node 7 for wind loading only	88
3.11	Fast Fourier transform of displacement and acceleration time history for wind load at node 7	89
3.12	Time history of (a) displacement, (b) acceleration, (c) rotation at tower top at node 7 for wave loading only	90
3.13	Fast Fourier transform of displacement and acceleration time history for wave load at node 7	91
3.14	Time history of (a) displacement, (b) acceleration, (c) rotation at tower top at node 7 for combined wind loading and wave loading	92
3.15	Fast Fourier transform of displacement and acceleration time history for combined wind and wave load at node 7	93

FIGURE	CAPTION	PAGE NO.
3.16	Time history of response under wind loading considering rotation of blades at node 7	94
3.17	Time history of response under wave loading considering rotation of blades at node 7	95
3.18	Time history of response under combined wind and wave loading considering rotation of blades at node 7	96
4.1	Reference soil systems and substructures	116
4.2	Offshore wind turbine model used in present study	116
4.3	Translational and rotational spring constants obtained from Dynamic stiffness of soil using Double Cone's Model for shear velocity of 40 m/sec (<i>V</i> 40), 70 m/sec (<i>V</i> 70), 100 m/sec (<i>V</i> 100) and 200 m/sec (<i>V</i> 200) for $z_0 = 40$ m and $r_0 = 2.5$ m	117
4.4	Noormalised modal displacement with frequency for structure (a) no SSI effect, (b) <i>V</i> 40, (c) <i>V</i> 70, (d) <i>V</i> 100, and (e) <i>V</i> 200	118
4.5	Natural frequency variation with soil shear velocity	119
4.6	(a) Wind and wave spectral load as obtained by Manenti et al. (2010), (b) Comparison of results of Manenti et al. (2010) with ANSYS for wind load only, (c) wave load only, (d) both wind and wave load	119
4.7	Effect of Soil structure interaction on peak PSDF of relative translational displacement for wind, wave and combined loading for the structure	120
4.8	Effect of Soil structure interaction on peak PSDF of acceleration for wind, wave and combined loading	121
4.9	Peak values for RMS displacement obtained from PSDF plots for wind, wave and combined loading for different shear wave velocities	122
5.1	World map for high-temperature zones highlighting tectonic plates, oceanic ridges and existing geothermal power plants	147

FIGURE	CAPTION	PAGE NO.
5.2	Schematic representation of (a) thermoelectric generator with <i>P</i> -type and <i>N</i> -type semiconductors, and (b) thermocouple	148
5.3	Schematic representation of an offshore geothermal system proposed with temperature gradient variation with depth given by Harper (1971)	149
5.4	Heat transfer through conduction and convection	150
5.5	Finite element (FE) model of pile, soil, and fluid pipe with spring and dashpots in the model.	151
5.6	Boundary conditions imposed on the monopile - soil system	152
5.7	Comparison of ground temperature with the numerical and analytical results	152
5.8	Temperature contour for heating period in an onshore concrete energy pile [Laloui et al. (2006)]	153
5.9	Temperature distribution in surrounding soil and steel monopile for a maximum thermal load of 100° C, mass flow rate 40 kg/sec, and diameter of the fluid pipe of 0.15 m at steady state conditions	154
5.10	Temperature distribution in steel pile for a temperature load of 100°C in the outlet pipe	155
5.11	Temperature variation in (a) pile with depth, and (b) fluid outlet pipe with depth (z)	155
5.12	Variation of temperature distribution along the radial distance at different depths (z), (a) $z = 1$ m, and (b) $z = 15$ m and , (c) $z = 36$ m, for the mass flow rate of 20 kg/sec ($T_{\max} = T_{\text{out}}$) [66-68]	156
5.13	Variation of temperature distribution at (a) steel monopile, and (b) fluid pipe at different depths (z)	157

FIGURE	CAPTION	PAGE NO.
5.14	Variation of temperature in soil and steel pile at different time durations at (a) 100 sec, (b) 200 sec, (c) 500 sec, (d) 700 sec, (e) 1000 sec, (f) 5000 sec, and (g) 10000 sec for a single fluid inlet pipe with temperature in pipe to 100°C	158
5.15	Variation of temperature distribution at (a) steel monopile at 1 m depth, (b) fluid pipe at top, and (c) bottom of the fluid pipe	159
5.16	Variation of temperature in soil and steel monopile for the maximum fluid temperature of 100°C for a mass flow rate of (a) 20 kg/sec, and (b) 5 kg/sec at 10000 seconds.	160
5.17	Variation of temperature distribution with radial distance when grout soil filling is introduced	162
5.18	Thermoelectric generator set up with dimension	161
5.19	Total temperature - output curve for the system, and (b) temperature-current-voltage curve for the offshore geothermal system	162
5.20	Comparison of cost expenditures of deep drilled (a) on shore geothermal projects and (b) offshore oil and gas projects	162
6.1	Schematic representation of using a geothermal system installed in the seabed [Interpolated from the temperature vs. Depth for the wells of Dansk Nordsfi and East Dogger Bank Graben in the North Sea, Madsen (1974)]	193
6.2	Finite element (FE) model of the pile, soil, and fluid pipe modeled using ANSYS finite element software	194
6.3	Illustration of the boundary condition considered in the analysis	194
6.4	Temperature load time history used for the analysis	
6.5	Flowchart of the analysis.	195

FIGURE	CAPTION	PAGE NO.
6.6	Comparison of results obtained from the study of Laloui et al. (2006) and the present study for (a) temperature load for the study, (b) temperature variation in soil with depth after cooling, (c) radial strain in the pile, and (d) vertical displacement in pile tip, (e) and Amatya et al. (2012) axial strain at Lausanne site	196
6.7	Fluid flow analysis with (a) temperature variation in steel pile, (b) temperature variation across radial distance, (c) temperature variation in steel at different depths, and (d) temperature variation in the fluid pipe at top and bottom of the pipe	197
6.8	Temperature distribution in surrounding soil and steel monopile for a maximum thermal load of 100° C and diameter of the fluid pipe of 0.15 m, fluid discharge rate of 43.8 kg/sec at steady state conditions	198
6.9	Illustration of (a) pore pressure variation in soil with time for an end bearing pile and thermal expansion coefficient of $10^{-5}/^{\circ}\text{C}$, (b) decrease in shear stress in soil after thermal loading of 60°C is applied on the pile	199
6.10	Illustration of pore pressure variation in soil with depth with the radial distance of (a) 3.75 m, and (b) 12 m from the centre	199
6.11	Axial stress in floating pile: (a) for soil with thermal expansion coefficient of $10^{-5} /^{\circ}\text{C}$ post heating; (b) for soil with thermal expansion of $1.2 \times 10^{-4} /^{\circ}\text{C}$ post heating, (c) for soil with thermal expansion coefficient of $10^{-5} /^{\circ}\text{C}$ post cooling; (d) for soil with thermal expansion of $1.2 \times 10^{-4} /^{\circ}\text{C}$ post cooling	200
6.12	Axial stress in end bearing pile: (a) for soil with thermal expansion coefficient of $10^{-5} /^{\circ}\text{C}$ post heating; (b) for soil with thermal expansion of $1.2 \times 10^{-4} /^{\circ}\text{C}$ post heating, (c) for soil with thermal expansion coefficient of $10^{-5} /^{\circ}\text{C}$ post cooling; (d) for soil with thermal expansion of $1.2 \times 10^{-4} /^{\circ}\text{C}$ post cooling	201

FIGURE	CAPTION	PAGE NO.
6.13	Axial strain in floating pile: (a) for soil with thermal expansion coefficient of 10^{-5} /°C post heating; (b) for soil with thermal expansion of 1.2×10^{-4} /°C post heating, (c) for soil with thermal expansion coefficient of 10^{-5} /°C post cooling; (d) for soil with thermal expansion of 1.2×10^{-4} /°C post cooling	202
6.14	Axial strain in end bearing pile: (a) for soil with thermal expansion coefficient of 10^{-5} /°C post heating; (b) for soil with thermal expansion of 1.2×10^{-4} /°C post heating, (c) for soil with thermal expansion coefficient of 10^{-5} /°C post cooling; (d) for soil with thermal expansion of 1.2×10^{-4} /°C post cooling	203
6.15	Shear stress in floating pile: (a) for soil with thermal expansion coefficient of 10^{-5} /°C post heating; (b) for soil with thermal expansion of 1.2×10^{-4} /°C post heating, (c) for soil with thermal expansion coefficient of 10^{-5} /°C post cooling; (d) for soil with thermal expansion of 1.2×10^{-4} /°C post cooling	204
6.16	Shear stress in end bearing pile: (a) for soil with thermal expansion coefficient of 10^{-5} /°C post heating; (b) for soil with thermal expansion of 1.2×10^{-4} /°C post heating, (c) for soil with thermal expansion coefficient of 10^{-5} /°C post cooling; (d) for soil with thermal expansion of 1.2×10^{-4} /°C post cooling	205
7.1	Physical representation of an offshore geothermal energy system [Banerjee et al. (2018)]	234
7.2	Physical representation of pile and soil movement under mechanical loading only, (b) strain in pile under mechanical load, (c) strain in pile under thermal loading (heating) only, and (d) strain in pile under combined thermal and mechanical loads for end-bearing pile during heating [Bourne-Webb et al. (2012)]	235
7.3	Physical representation of pile and soil movement under mechanical loading only, (b) strain in pile under mechanical load, (c) strain in pile under thermal loading (heating) only, and (d) strain in pile under combined thermal and mechanical loads for end-bearing pile during cooling [Bourne-Webb et al. (2012)]	236

FIGURE	CAPTION	PAGE NO.
7.4	Load time history- (a) wind loading, and (b) wave loading to be applied on the tower	237
7.5	Finite element (FE) model (a) of the tower, soil, and fluid pipe modeled using ANSYS finite element software, and (b) spring-dashpots used for far field effect	238
7.6	Finite element modeling of soil domain using structural and thermal elements in ANSYS	239
7.7	Thermal load time history applied on the monopile foundation for 60°C temperature	239
7.8	Flow chart of the analysis	240
7.9	Comparison of results obtained from the study of Colwell and Basu (2009) and the present study	241
7.10	Fluid flow analysis with (a) temperature variation in steel pile, (b) temperature variation across radial distance	241
7.11	Vertical path around the steel pile for radial pore pressure study	242
7.12	Vertical excess pore pressure developed under (a) hydrostatic condition in S20 soil and S60 soil, (b) thermal loading in S20 and S60 soil for a duration of 17 days, (c) thermal loading in S20 soil for a duration of 17 days, (d) combined loading in S20 soil for a duration of 17 days, (e) thermal loading in S20 soil for a duration of 17 days and 30 days, (f) thermal loading for different thermal expansion coefficients	243
7.13	Radial pore pressure under (a) hydrostatic condition in S20 soil, (b) hydrostatic condition in S60 soil, (c) offshore loading in S20 soil, (d) offshore loading in S60 soil, (e) combined loading in S20 soil, and (f) combined loading in S60 soil	244
7.14	Radial excess pore pressure under combined loading in S20 and S60 soil	245
7.15	Axial stress developed in the monopile under different load conditions	246

FIGURE	CAPTION	PAGE NO.
7.16	Axial stress developed in the monopile under different load conditions for higher soil thermal expansion coefficient	247
7.17	Axial strain developed in the monopile under different load conditions	248
7.18	Axial strain developed in the monopile under different load conditions for higher soil thermal expansion coefficient	249
7.19	Axial strain contours with deformed shape of steel monopile for S20 and S60 soil	250
7.20	Radial Stress developed in the monopile under different load conditions	251
7.21	Radial Stress developed in the monopile under different load conditions for higher soil thermal expansion coefficient	252
7.22	Radial Strain developed in the monopile under different load conditions	253
7.23	Radial Strains developed in the monopile under different load conditions for higher soil thermal expansion coefficient	254
7.24	Radial strain contour with deformed shape of monopile Profile for S20 and S60 soil	255
7.25	Von Mises stress developed in the monopile under different load conditions	256
7.26	Von Mises stress developed in the monopile under different load conditions for higher soil thermal expansion coefficient	257
7.27	Shear Stress developed in the monopile-soil interface under different load	258
7.28	Shear Stress developed in the monopile-soil interface under different load conditions for higher soil thermal expansion coefficient	259

FIGURE	CAPTION	PAGE NO.
7.29	Radar charts representing response in terms of (a) x -displacement (m), (b) z -displacement (m), (c) axial strain (10^{-3}), and (d) radial strain (10^{-3}) in the monopile for different soil conditions at $\delta t_{\max} = 60^{\circ}\text{C}$.	260
7.30	Comparison of peak response in steel monopile for different load cases	261
A2.1	(a) Global emissions from fossil fuel and industry, rise in population, growth rate of GDP year wise, (b) global energy consumption of fossil and non-fossil fuel resources, and (c) composition of renewable sources of energy in 2017 [IEA (2017), UN (2017)].	283
A2.2	World map for high-temperature zones highlighting tectonic plates (sub-duction zones), hydrothermal vents, oceanic ridges, thin oceanic crusts, existing major offshore-geothermal projects [Barbier (2002)] and high wind load zones that can be a potential site for extracting geothermal power along with wind load.	284
A2.3	Proposed coupled offshore-geothermal system	285
A2.4	Total temperature - output curve for the offshore geothermal system	285
A2.5	Comparison of cost expenditures of deep drilled (a) on shore geothermal projects and (b) offshore oil and gas projects	286
A2.6	Temperature distribution in the proposed system	287
A2.7	Variation of temperature distribution at (a) steel monopile, and (b) fluid pipe at different depths (z)	288

NOMENCLATURE

$[M_{xx}]$	Mass matrix
$[K_{xx}]$	Stiffness matrix
$[C_{xx}]$	Damping matrix
x	Translational degrees of freedom
$f(t)$	Loading as a function of time.
m_w	Added mass
t	Thickness of tower
D	Diameter of the tower
M_1	Tip mass for wind load (Case 1)
K	Bending stiffness
M	Mass of the model at the top
E	Modulus of elasticity
I	Moment of inertia
L	Length of the tower
M_2	Equivalent mass for wave load (Case 2)
K_s	Bending stiffness of SDOF system
M_s	Mass of the model at the top of SDOF system
L_s	Length of the equivalent SDOF system
f	Natural frequency
ζ	Damping ratio
α_r	Mass proportional Rayleigh damping coefficients
β	Stiffness proportional Rayleigh damping coefficients
ω	Angular frequency
ϕ	matrix whose columns are the eigenvectors of the structure
T	Transpose
$P(t)$	Time varying load vector.
P	Vector of nodal loads
\dot{x}	Time-dependent velocity vector
\ddot{x}	Time-dependent acceleration vector
C_D	Drag coefficient
C_M	Inertia coefficient
A	Area of the body
V	Volume of the body
u	Horizontal velocity of water particles
\dot{u}	Water particle acceleration
$\eta(t)$	Local free surface elevation with respect to the above mean sea level (MSL).
V_m	Intensity of characteristic wind speed at the reference height of 19.5 m above mean sea level (MSL)
V_{10}	Mean wind speed at 10 m above sea level
z	Elevation (m)

NOMENCLATURE

k	Wave number
d	Depth (m)
$S_v(z, f)$	Power spectral density function of the fluctuating wind velocity
v_*	Friction velocity
K^*	Von Karman constant
n_m	Monin coordinate
χ	Aerodynamic admittance function
$e^{-\psi}$	Narrow-band cross-correlation
$\phi_j(k)$	Nodal k components of the j^{th} mode shape
$\phi_j(l)$	Nodal l components of the j^{th} mode shape
$S_{v_{kvl}}$	Velocity auto-PSDF
$v'(t)$	Fluctuating velocity component
$S_v(f_i)$	Power spectral density function (PSDF) for the fluctuating component of wind velocity
θ_i	Phase angle with a uniform probability distribution function that varies randomly between 0 and 2
$\{\ddot{\mathbf{u}}\}$	Nodal acceleration vector
$\{\dot{\mathbf{u}}\}$	Nodal velocity vector
$\{\mathbf{u}\}$	Nodal displacement vector
$\{\mathbf{F}(t)\}$	Load vector
q_{in}	The displacement of the tower in the side-to-side mode
q_{out}	The displacement of the tower in the mode
$I_{f,in}$	In-plane mass moments of inertia of the foundation
$I_{f,out}$	Out-of-plane mass moments of inertia of the foundation
$q_{b,in}$	displacement of the blades in side to side mode
$q_{b,out}$	displacement of the blades in fore-aft mode
q	Displacement vector
$k_{n,in}$	In-plane stiffness stiffness of the tower/nacelle
$k_{n,out}$	Out-of-plane stiffness of the tower/nacelle
$k_{b,in}$	In-plane stiffness a stiffness of the blade
$k_{b,out}$	Out-of-plane stiffness of the blade
k_θ	Rotational stiffness of the foundation
L	Length of the blade
E	Modulus of elasticity of the blade
Ω	Rotational speed of the rotor in rad/sec
h	Height of the tower
M_n	Mass of the tower/nacelle
\bar{K}	Dynamic stiffness a
\bar{C}	Frequency dependent damping
K_h	Translational static stiffness coefficients for rigid embedded circular

NOMENCLATURE

	foundations in half space
K_v	Vertical static stiffness coefficients for rigid embedded circular foundations in half space
K_r	Rotational static stiffness coefficients for rigid embedded circular foundations in half space
D	Diameter of the foundation
H	Depth of the soil strata
R	Radius of the foundation
G	Soil shear modulus
ν	Poisons ratio
σ_u	Turbulence standard deviation
L_u	Turbulence length
$K_v(f)$	Autocorrelation function
$K_v(r, \tau)$	Autocorrelation function of rotating blade
r	Distance from the blade
ψ	Rotating speed of the blade (rad/sec)
$u(\omega)$	Displacement response
$[S_{ss}]$	Stiffness matrix of the nodes on the structure
$[S_{sb}]$	Stiffness matrix of the nodes of the structure that lies on the ground
$[S_{bs}]$	Stiffness matrix of the nodes of the ground that lies on the structure
$[S_{bb}]$	Stiffness matrix of nodes on the ground
(u_b^t)	Vector of the total displacement amplitude
$[S(\omega)]$	Dynamic stiffness matrix
ρ	Mass density
G	Shear modulus
K_s	Static stiffness (for translation)
K_r	Static stiffness (for rotation)
z_0	Embedded depth
A_0	Area of the disc
I_0	Moment of inertia about the axis of rotation
v_s	Shear wave velocity
v_p	Primary wave velocity
a_0	Dimensionless frequency parameter
r_0	Radius of the disc
Q_h	Heat input in the thermoelectric module
ΔT	Temperature difference between the hot and the cold side of the thermoelectric module
T_h	Temperature on the hot side of the thermoelectric module
T_c	Temperatures on the cold side of the thermoelectric module
R_L	Load resistance
α_t	Seebeck coefficient

NOMENCLATURE

K	Thermal conductivity.
T	Temperature of the fluid
α_f	Fluid thermal diffusivity
v	Fluid velocity
ρ_f	Fluid density
C_f	Specific heat capacity
\dot{m}	Mass flow rate
h	'Film' (or convective heat transfer) coefficient
K_s	Effective thermal conductivity of the solid medium
ρ_s	Density of the solid medium
C_s	Specific heat capacity of the solid medium
$R_b,$	Thermal resistance
R_{steel}	Thermal resistance provided by steel monopile
R_g	Thermal resistance by soil
R_{pipe}	Thermal resistance by the pipe carrying the fluid
T_g	Ground temperature
T_∞	Undisturbed temperature far field
q_b	Heat exchange rate per depth
α_p	Seebeck coefficient for P -type semiconductor
α_n	Seebeck coefficient for N -type semiconductor
ρ_p	Electrical resistivity for P -type semiconductor
ρ_n	Electrical resistivity for N -type semiconductor
R_c	Internal resistance
K_c	Thermal conductivity of module
I	Electric current per module
V	Voltage per module
W	Maximum power output per module
ZT	Figure of merit
ϵ_{free}	Free axial thermal strain without any restraint
α	Coefficient of thermal expansion or contraction of steel
$\epsilon_{\text{restrained}}$	Restrained axial strain
ϵ_{obs}	Observed axial strain
P	Mechanical load
E	Young's modulus of the pile
A	Area of the pile
ϵ_m	Mechanical strain of the pile
ϵ_{total}	Total mobilized strain
P_{total}	Total load
$P_{\text{restrained}}$	Total restrained load
$\nabla \cdot$	Divergence
∇	Gradient

NOMENCLATURE

σ'_{ij}	Effective stress tensor
σ_{ij}	Total stress tensor
δ_{ij}	Kronecker's delta
ρ_w	Density of water
t	Time
β_w	Volumetric thermal expansion coefficient for water
β_s	Volumetric thermal expansion coefficient for the solid medium
v_i	Relative velocity of water with respect to soil
k	Hydraulic conductivity
g	Gravity
z	Depth of pile
F_s	Drucker-Prager shear failure surface
β	Material friction angle, is its
c	Cohesion
σ	Stress tensor
q	von-Mises equivalent stress
I	Identity matrix
S	Stress deviator
γ	Small number (typically 0.01-0.05)
R	Material parameter (between 0.0001 and 1000.0)
F_c	Yield surface
p_a	Evolution parameter
ρ'	Current relative density
e_{pv}	Volumetric plastic strain
ρ_0	Initial relative density